Technologies Underlying Weapons of Mass Destruction

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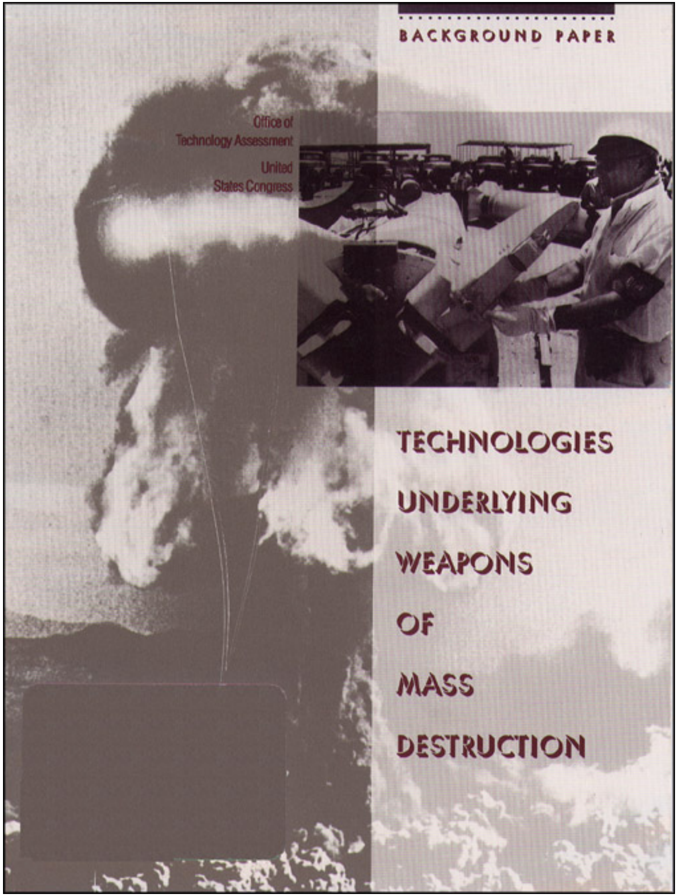

BACKGROUND PAPER

Office of
Technology Assessment
United
States Congress

TECHNOLOGIES
UNDERLYING
WEAPONS
OF
MASS
DESTRUCTION

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Foreword

Controlling the spread of weapons of mass destruction depends on how hard it is to manufacture them and on how easy such weapon programs are to detect. This background paper, a companion volume to OTA's report *Proliferation of Weapons of Mass Destruction: Assessing the Risks,*[1] reviews the technical requirements for countries to develop and build nuclear, chemical, and biological weapons, along with the systems most capable of delivering these weapons to distant or defended targets: ballistic missiles, combat aircraft, and cruise missiles. It identities evidence that might indicate the production of weapons of mass destruction, and technical hurdles that might provide opportunities to control their spread.

Of the weapons considered here, nuclear weapons are the most difficult and expensive to develop-primarily due to the difficulty of producing the required nuclear materials. These materials, and the equipment needed to produce them, have quite limited civilian applications and are tightly controlled. States have produced nuclear weapon materials indigenously by evading international controls, but at great cost and with substantial opportunity for detection. For chemical and biological weapon materials, in contrast, most of the equipment needed also has civilian applications and has become widely available, making the capability to produce such weapons much more difficult to monitor and control.

The level of technology required to produce weapons of mass destruction is relatively modest: ballistic missiles and nuclear weapons date back to World War II, and basic chemical and biological weapons predate even that. Since export controls ultimately cannot block the spread of general technological capability, an effective nonproliferation regime must supplement them with other nonproliferation policy measures. Nevertheless, export controls can prevent states from pursuing the easiest or most direct routes to weapons of mass destruction, and they will remain an important component of nonproliferation policy.

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[1] U.S. Congress, Office of Technology Assessment, *Proliferation of Weapons of Mass Destruction: Assessing the* Risks, OTA-ISC-559 (Washington DC: U.S. Government Printing Office, August 1993).

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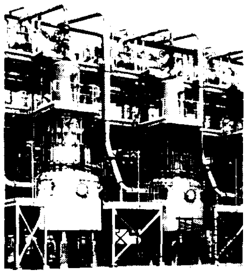

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Introduction and Summary

1

This background paper explores the technical pathways by which states might acquire nuclear, chemical, and biological weapons and the systems to deliver them. It also assesses the level of effort, commitment, and resources required to mount such developments. The paper is a companion to the OTA report *Proliferation of Weapons of Mass Destruction: Assessing the Risks,* which describes what nuclear, chemical, and biological weapons can do and how they might be used.[1] That report also analyzes the consequences of the spread of such weapons for the United States and the world, surveys the array of policy tools that can be used to combat proliferation, and identifies tradeoffs and choices that confront policymakers. A forthcoming report will analyze specific sets of nonproliferation policy options in detail.

The technical hurdles that must be surmounted to develop nuclear, chemical, and biological weapons are summarized in table 1-1, which also appeared in OTA's earlier report.[2] Those steps that are particularly time-consuming or difficult for proliferants to master without outside assistance can be exploited to control proliferation. Conversely, steps that are relatively easy, or that make use of widely available know-how and equipment, make poor candidates for control efforts. Understanding the extent to which ''dual-use' technologies or products—those also having legitimate applications-are involved in the development of weapons of mass destruction is important, since both the feasibility of controlling dual-use items and the implications of doing so depend on the extent of their other applications.

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[1] U.S. Congress, Office of Technology Assessment, *Proliferation of Weapons of Mass Destruction: Assessing the Risks,* OTA-ISC-559 *(Washington* DC: U.S. Government Printing Office, August 1993).

[2] Ibid., pp. 1011.

Table I-I—Technical Hurdles for Nuclear, Biological, and **Chemical Weapon Programs**

	Nuclear	Biological	Chemical
Nuclear materials or lethal agents production			
Feed materials	Uranium ore, oxide widely available; plutonium and partly enriched uranium dispersed through nuclear power programs, mostly under international safeguards.	Potential biological warfare agents are readily available locally or internationally from natural sources or commercial suppliers.	Many basic chemicals available for commercial purposes; only some nerve gas precursors available for purchase, but ability to manufacture them is spreading.
Scientific and technical personnel	Requires wide variety of expertise and skillful systems integration.	sophisticated research and development unnecessary to produce commonly known agents. industrial microbiological personnel widely available.	Organic chemists and chemical engineers widely available.
Design and engineering knowledge	Varies with process, but specific designs for producing either of the two bomb-grade nuclear materials can be difficult to develop: ■ Separation of uranium isotopes to produce highly enriched uranium; ■ Reactor production and chemical processing to produce plutonium,	Widely published; basic techniques to produce known agents not difficult.	Widely published. Some processes tricky (Iraq had difficulty with tabun cyanation, succeeded at sarin alkylation; however, sarin quality was poor).
Equipment	Varies with different processes but difficulties can include fabrication, power consumption, large size, and operational complexity: ■ Electromagnetic separation equipment can be constructed from available, multiple-use parts; ■ Equipment for other processes is more specialized and difficult to buy or build.	Widely available for commercial uses. Special containment and waste-treatment equipment may be more difficult to assemble, but are not essential to production.	Most has legitimate industrial applications. Alkylation process is somewhat difficult and is unusual in civilian applications. Special containment and waste treatment equipment may be more difficult to assemble, but are not essential to production.

Monitoring the proliferation of weapons of mass destruction, or conversely monitoring compliance with nonproliferation agreements, depends on detecting and identifying various indicators or *signatures* associated with the development, production, deployment, or use of such weapons. This paper also identifies signatures that, if detected, might reveal the existence of or progress in programs to develop weapons of mass destruction and their delivery systems.

OTA's earlier report summarized the material included in chapters 2 through 5 of this report.[3]

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[3] *Ibid.,* pp. 33-43.

Table 1-1-(Continued)

	Nuclear	Biological	Chemical
Plant construction and operation	Costly and challenging. Research reactors or electric power reactors might be converted to plutonium production.	With advent of biotechnology, small-scale faclities now capable of large-scale production.	Dedicated plant not difficult. Conversion of existing commercial chemical plants feasible but not trivial.
Overall cost	Cheapest overt production route for one bomb per year, with no international controls, is about $200 million; larger scale clandestine program could cost 10 to 50 times more, and even then not be assured of success or of remaining hidden. Black-market purchase of ready-to-use fissile materials or of complete weapons could be many times cheaper.	Enough for large arsenal may cost less than $10 million.	Arsenal for substantial military capability (hundreds of tons of agent) likely to cost tens of millions of dollars.
Weaponization			
Design and engineering	Heavier, less efficient, lower yield designs easier, but all pose significant technical challenges.	Principal challenge is maintaining the agent's potency through weapon storage, delivery, and dissemination. Broad-area dissemination not difficult; design of weapons that effectively aerosolize agents for precision delivery challenging (but developed by U.S. by'60s).	Advanced weapons somewhat difficult, but workable munition designs (e.g., bursting smoke device) widely published.
Production equipment	Much (e.g., machine tools) dual-use and widely available, Some overlap with conventional munitions production equipment.	Must be tightly contained to prevent spread of infection, but the necessary equipment i snot hard to build.	Relatively simple, closely related to standard munitions production equipment.

SOURCE: Office of Technology Assessment, 1993.

For those readers who do not have a copy of that publication, the summary is repeated below.

NUCLEAR WEAPONS

Material Production

In terms of costs, resources required, and possibility of discovery, the difficulty of obtaining nuclear weapon materials—plutonium or highly enriched uranium—today remains the greatest single obstacle most countries would face in pursuing nuclear weapons. Even straightforward methods of producing such material indigenously (such as building a small reactor and a primitive reprocessing facility to produce plutonium and recover it from irradiated reactor fuel) would require at least a modest technological infrastructure and hundreds of millions of dollars to carry out. Moreover, once such a facility became known, it could generate considerable pressure from regional rivals or the international community. The costs of a full-scale indigenous nuclear weapon program-especially if clandestine-can be substantially higher than for a program largely aimed at producing just one or two bombs and carried out in the open. Iraq spent 10 to 20 times the cost of such a minimal program-many billions of dollars-to pursue multiple uranium enrichment technologies, to build complex and sometimes redundant facilities, to keep its efforts secret, and to seek a fairly substantial nuclear capability. Few countries of proliferation concern can match the resources that Iraq devoted to its nuclear weapon program. (Iran, however, probably could.)

Since production of nuclear materials is generally the most difficult and expensive part of producing a nuclear weapon, the leakage of significant amounts of weapon-grade material from the former Soviet Union would provide a great advantage to potential proliferants. Indeed, the possibility of black-market sales of weapon-usable materials may represent one of the greatest proliferation dangers now being faced. Even the covert acquisition of low-enriched uranium, which can fuel nuclear reactors but is not directly usable for nuclear weapons, could be advantageous to a proliferant by enhancing the capacity of its isotope separation plants.

This ominous prospect notwithstanding, nuclear materials suitable for weapon purposes have to date been extremely difficult to obtain from countries that already possess them. There is no reliable evidence that any militarily significant quantities of nuclear weapon material have been smuggled out of the former Soviet Union. The vast majority of nuclear material in nonnuclear weapon states is safeguarded by a comprehensive system of material accountancy and control administered by the International Atomic Energy Agency (IAEA). These safeguards are not perfect, but they provide high levels of confidence that significant quantities of nuclear material have not been diverted from safeguarded nuclear reactors. Diversion would be more difficult to detect from facilities such as fuel fabrication plants, uranium enrichment plants, and plutonium reprocessing facilities that process large quantities of nuclear material in bulk form, as opposed to handling it only in discrete units such as fuel rods or reactor cores. At present, however, there are no large facilities of this type under comprehensive IAEA safeguards in countries of particular proliferation concern.[4] At least in the short run, the diversion of safeguarded materials poses less of a threat to the nonproliferation regime than the black-market purchase or covert indigenous production of nuclear materials.

Under current European and Japanese plans for reprocessing and limited reuse of plutonium from commercial reactor fuel, the current worldwide surplus of some 70 tonnes of safeguarded, separated reactor-grade plutonium-the type produced by commercial nuclear reactors in normal operation-will likely continue to grow through the 1990s by more than 10 tonnes per year. Reactor-grade plutonium is more radioactive and more difficult to handle than *weapon-grade* plutonium, which is produced specifically for use in nuclear weapons, but it can still be used to make a crude nuclear weapon of significant (though probably less predictable) yield. Nevertheless, the states that have sought nuclear weapons have gone to great lengths to produce weapon-grade materials-either highly enriched uranium or weapon-grade plutonium-rather than reactor-grade plutonium. (Note that some types of nuclear power reactors, including ones in India, South Korea, and North Korea, can produce either reactor-grade or weapon-grade plutonium, depending on how they are operated.)

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[4] Brazil has a medium-sized fuel fabrication facility under IAEA safeguards, and South African enrichment facilities are coming under safeguards with South Africa's announced destruction of its nuclear weapons and its accession to the NPT. Neither state is considered an active proliferation threat at present.

Other Technical Barriers

Unlike chemical and biological weapons, whose lethality is roughly proportional to the amount of agent dispersed, nuclear weapons will not produce any yield at all unless certain conditions are met: a minimum "critical mass" of nuclear materials must be present, and that material must be brought together with sufficient speed and precision for a nuclear chain reaction to take place. A proliferant must master a series of technical hurdles in order to produce even a single working weapon.

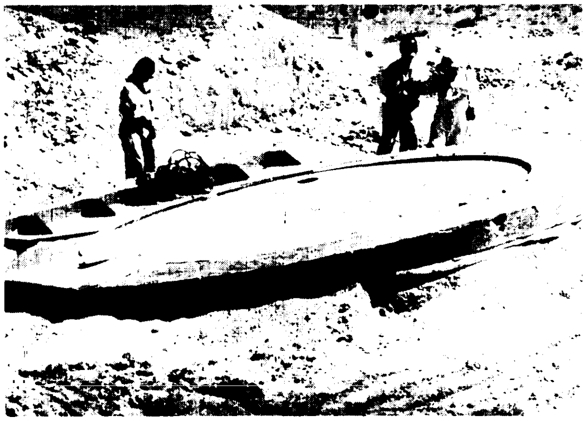
Nuclear weapons are so destructive that they place few requirements on the accuracy of delivery systems for any but the most protected targets. Most proliferants would likely be able to design frost-generation nuclear weapons that were small and light enough to be carried by Scud-class missiles or small aircraft. Given additional technical refinement, they might be able to reduce warhead weights to the point where the 500 kg (1,100 pound) delivery threshold originally established by the Missile Technology Control Regime no longer provides a reliable barrier to nuclear-capable ballistic or cruise missiles.[5]

Although nuclear weapons were first developed 50 years ago and the basic mechanisms are widely known, much of the detailed design information, and particularly the knowledge gleaned by the nuclear weapons states from decades of design and testing, remains classified. Much of this information can be reconstructed by a dedicated proliferant, but it will take time and money. Moreover, ''weaponizing" a nuclear warhead for reliable missile delivery or long shelf-life creates additional hurdles that could significantly increase the required development effort. Therefore, having access to key individuals-such as those from the former Soviet nuclear weapon program---could significantly accelerate a nuclear program, primarily by steering it away from unworkable designs. Specific individuals could fill critical gaps in a given country's knowledge or experience, adding greatly to the likelihood that a program would succeed.

High-performance computers (so-called "supercomputers" in the 1980s) are *not required* to design first-generation fission weapons. Thus, placing strict Limits on their exports would be of minimal importance compared with limiting technologies for nuclear materials production.

Monitoring Nuclear Proliferation

Production of nuclear materials provides many signatures and the greatest opportunity for detecting a clandestine nuclear weapon program. Even so, a large part of the Iraqi program was missed. Since members of the Nuclear Non-Proliferation Treaty (other than the acknowledged nuclear weapon states) are not permitted to operate unsafeguarded facilities handling nuclear materi-



LOS ALAMOS NATIONAL LABORATORY

Iraqi electromagnetic isotope separation (EMS) equipment, uncovered after having been buried in the desert to hide it from United Nations inspectors. Iraq's EMIS program to enrich uranium for nuclear weapons had not been detected by Western intelligence agencies prior to the GuJf War.

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[5] Broadening its focus, the Missile Technology Control Regime now covers missiles capable of delivering chemical and biological weapons as well as those that could be used to deliver nuclear weapons. Consequently, missiles with payloads below 500 kg are included as well.

als, the existence of any such facilities would probably indicate an illegal weapon program.[6]

Nuclear tests at kiloton yields or above would probably be detectable by various means, especially if multiple tests were conducted. However, such tests are not necessary to field a workable weapon with reasonably assured yield. Similarly, the deployment of a very small number of nuclear weapons might not be easily detected.

Implications of Old and New Technologies

Low- and medium-level gas *centrifuge technology* for enriching uranium may become increasingly attractive to potential proliferants for a variety of reasons, including availability of information about early designs, difficulty of detection, ease of producing highly enriched uranium, and potential availability of equipment from the former Soviet Union. Modern, state-of-the-art centrifuges could lead to even smaller, more efficient, and relatively inexpensive facilities that would be diffificult to detect remotely.

In the longer run, *laser isotope separation* techniques and *aerodynamic separation* may have serious proliferation potential as means of producing highly enriched uranium for nuclear weapons. Openly pursued by more than a dozen non-nuclear-weapon states, *laser* enrichment technologies use precisely tuned laser beams to selectively energize the uranium-235 isotope most useful for nuclear weapons and separate it from the more common uranium-238 isotope. Laser facilities would be small in size and could enrich uranium to high levels in only a few stages. They could therefore prove to be difficult to detect and control if successfully developed as part of a clandestine program. Nevertheless, considerable development work remains to be done before this method can be made viable or can compete with existing enrichment technologies. Even for the advanced industrialized countries, constructing operational facilities will remain very difficult Some *aerodynamic techniques*—which use carefully designed gas flows to separate the lighter uranium-235 from the heavier uranium-238-require fairly sophisticated technology to manufacture large numbers of precision small-scale components, but they do not otherwise pose technical challenges beyond those of other enrichment approaches.

CHEMICAL WEAPONS

The technology used to produce chemical weapons is much harder to identify unambiguously as weapons-related than is that for nuclear materials production technology, and relevant know-how is much more widely available. Although production techniques for major chemical weapon agents involve some specialized process steps, detailed examples can be found in the open literature and follow from standard chemical engineering principles. Unlike nuclear proliferation, where the mere existence of an unsafeguarded nuclear facility in an NPT member state could be sufficient evidence of intent to produce weapons, many legitimate chemical facilities could have the ability to produce chemical agent. Intent cannot be inferred directly from capability.

Agent and Weapon Production

Certain chemical agents such as mustard gas are very simple to produce. Synthesis of nerve agents, however, includes some difficult process steps involving highly corrosive or reactive materials. A sophisticated production facility to make militarily significant quantities of one class of nerve agents might cost between $30 and $50

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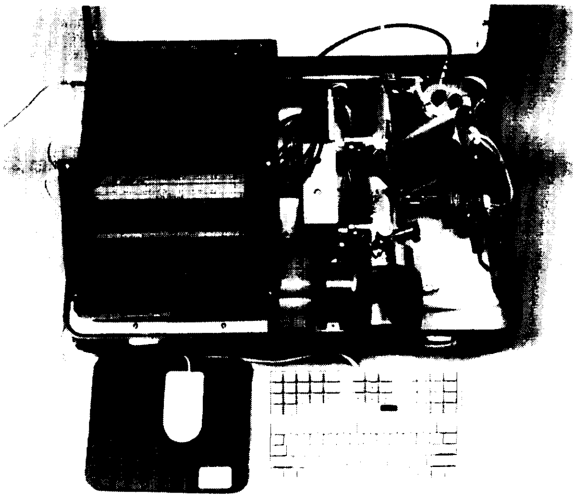
[6] The exception to this statement would be unsafeguarded facilities dedicated to military purposes unrelated to nuclear weapons, such as naval nuclear propulsion. Such uses are not prohibited by the Nuclear Non-proliferation Treaty. They fall outside IAEA jurisdiction however, since IAEA safeguards pertain only to peaceful-e. g., nonmilitary-applications of nuclear power, See Ben Sanders and John Simpson, *Nuclear Submarines and Non-Proliferation: Cause for Concern,* PPNN Occasional Paper Two (Southampton, England: Centre for International Policy Studies, University of Southampton, for the Programme for Promoting Nuclear Non-Proliferation 1988).

million, although dispensing with modem waste-handling facilities might cut the cost in half. Some of the equipment needed may have distinctive features, such as corrosion-resistant reactors and pipes and special ventilation and waste-handling equipment, but these can be dispensed with by relaxing worker safety and environmental standards and by replacing hardware as it corrodes. Moreover, production is easier if a proliferant country is willing to cut corners on shelf-life, seeking only to produce low-quality agent for immediate use.

Chemical-warfare agents can be produced through a wide variety of alternative routes, but relatively few routes are well-suited for large-scale production. Just because the United States used a particular production pathway in the past, however, does not mean that proliferant countries would necessarily choose the same process.

In general, commercial pesticide plants lack the precursor chemicals (materials from which chemical agents are synthesized), equipment, facilities, and safety procedures required for nerve-agent production. Nevertheless, multipurpose chemical plants capable of manufacturing organo-phosphorus pesticides or flame retardants could be converted in a matter of weeks or months to the production of nerve agents. The choice between converting a commercial plant in this manner and building a clandestine production facility would depend on the urgency of a country's military requirement for a chemical weapon stockpile, its desire to keep the program secret, its level of concern over worker safety and environmental protection, and the existence of embargoes on precursor materials and production equipment.

Agent production, however, is several steps removed from an operational chemical weapon capability. The latter requires design and development of effective munitions, filling the munitions before use, and mating them with a suitable delivery system.



LAWRENCE LIVERMORE NATIONAL LABORATORY

Portable gas chromatograph/mass spectrometer (GCl MS) developed to support onsite analysis for the Chemical Weapons Convention. This equipment can detect and identify minute quantities of organic chemicals controlled by the CWC.

I Monitoring Chemical Weapon Proliferation

Direct detection of chemical warfare agents in samples taken from a production facility would be a clear indicator of weapon activity, since these agents have almost no civil applications.[7] However, considerable access to production facilities is required to ensure that appropriate samples have been collected. Moreover, some of the substances produced when chemical agents break down in the environment are also produced when legitimate commercial chemicals break down, so detection of final degradation products does not necessarily indicate agent production. Nevertheless, the suite of degradation products associated with a given chemical agent production process would provide a clear signature.

Other than the agent itself, or an ensemble of degradation products, chemical agent production has few unequivocal signatures. Moreover, highly reliable technologies to detect chemical agent production from *outside the* site are not currently

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[7] Nitrogen mustards have some use in cancer chemotherapy, and phosgene and hydrogen cyanide have industrial applications.

available. Unlike nuclear weapon facilities, which generally exhibit fairly clear signatures, civilian chemical plants have multiple uses, are hundreds of times more numerous than nuclear facilities, and are configured in different ways depending on the process involved. Moreover, many of the same chemicals used to make chemical agents are also used to make pharmaceuticals, pesticides, and other commercial products. Since many different types of equipment are suitable for chemical agent production, plant equipment per se does not provide a reliable means of distinguishing between legitimate and illicit activities. Nevertheless, some potential signatures of chemical weapon development and production exist, and a set of multiple indicators taken from many sources may be highly suggestive of a production capability.

Indicators at suspect locations that may contribute to such an overall assessment include: visual signatures such as testing munitions and delivery systems; distinctive aspects of plant design and layout, including the use of corrosion-resistant materials and air-purification systems; presence of chemical agents, precursors, or degradation products in the facility's production line or waste stream; and biochemical evidence of chemical agent exposure (including that due to accidental leaks) in plant workers or in plants and animals living in the vicinity of a suspect facility. Nevertheless, the utility of specific signatures depends on how a given weapon program operates, including the choice of production process and the extent of investment in emission-control technologies. Detection capabilities that are decisive under laboratory conditions may be rather inconclusive in the field—particularly if the proliferant has been producing related legitimate chemicals (e.g., organophosphorus pesticides) in the same facility and is willing to expend time, effort, and resources to mask, obscure, or otherwise explain away chemical agent production activities. Testing of chemical agents and training troops in their use might be masked by experiments with or training for the use of smoke screens. A robust inspection regime must therefore comprise an interlocking web of inspections, declarations, notifications, and data fusion and analysis, all of which a cheater must defeat in order to conceal his violations. Focusing monitoring efforts at a single point-even one thought to be a crucial chokepoint-would allow the cheater to focus his efforts on defeating them.

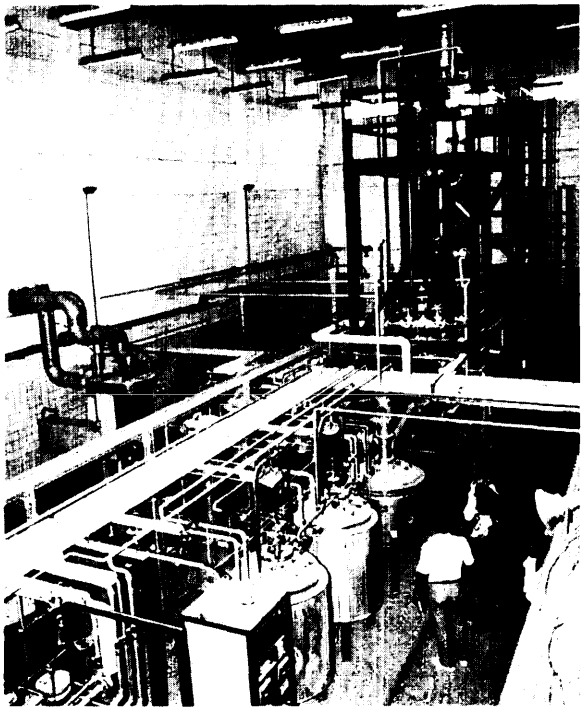
Keeping a production program covert forces other tradeoffs. Some of the simplest production pathways might have to be avoided since they use known precursors or involve known production processes. Purchasing equipment from multiple suppliers to avoid detection, or jury-rigging facilities from used equipment, might increase hazards to the workforce and nearby populations.

BIOLOGICAL WEAPONS

Biological-warfare agents are easier to produce than either nuclear materials or chemical-warfare agents because they require a much smaller and cheaper industrial infrastructure and because the necessary technology and know-how is widely available. Moreover, it would not be difficult to spread biological agents indiscriminately to produce large numbers of casualties, although it is much more difficult to develop munitions that have a predictable or controllable military effect.

Agent and Weapon Production

The global biotechnology industry is information-intensive rather than capital-intensive. Much of the data relevant to producing biological agents is widely available in the published literature and virtually impossible for industrialized states to withhold from potential proliferants. A widespread support infrastructure of equipment manufacturers has also arisen to serve the industry. Therefore, producing biological agents would be relatively easy and inexpensive for any nation that has a modestly sophisticated pharmaceutical industry. Moreover, nearly all the equipment needed for large-scale production of


UN PHOTO, H. ARVIDSSON

United Nations inspectors assessing the biological weapon potential of Iraqi fermenters and other bioprocess equipment.

pathogens and toxins is dual-use and widely available on the international market.

One technical hurdle to the production of biological weapons is ensuring adequate containment and worker safety during agent production and weapons handling, although the difficulty of doing so depends on the level of safety and environmental standards. A government that placed little value on the safety of plant workers or the civilian population might well take minimal precautions, so that a biological-weapons production facility would not necessarily be equipped with sophisticated high-containment measures, Another challenge is ‘‘weaponizing’ the agents for successful delivery. Since microbial pathogens and toxins are susceptible to environmental stresses such as heat, oxidation, and dessication, to be effective they must maintain their potency during weapon storage, delivery, and dissemination.

A supply of standard biological agents for covert sabotage or attacks against broad-area targets would be relatively easy to produce and disseminate using commercially available equipment, such as agricultural sprayers. In contrast, the integration of biological agents into precise, reliable, and effective delivery systems such as missile warheads and cluster bombs poses complex engineering problems. Nevertheless, the United States had overcome these problems by the 1960s and had stockpiled biological warfare agents.

Monitoring Biological Weapon Production

Detection and monitoring of biological and toxin agent production is a particularly challenging task. Even use of biological weapons could in some cases be difficult to verify unambiguously, since outbreaks of disease also take place naturally. Thanks to advances in biotechnology, including improved fermentation equipment as well as genetic engineering techniques, biological and toxin agents could be made in facilities that are much smaller and less conspicuous than in the past. Moreover, the extreme potency of such agents means that as little as a few kilograms can be militarily significant. Since large amounts of agent can be grown from a freeze-dried seed culture in a period of days to weeks, large stockpiles of agent are not required, although some stocks of the munitions to be filled with these agents would be.

There are no signatures that distinguish clearly between the development of offensive biological agents and work on defensive vaccines, since both activities require the same basic know-how and laboratory techniques at the R&D stage. Moreover, almost all the equipment involved in biological and toxin weapon development and production is dual-use and hence will not typically indicate weapons activity. Indeed, the capacity to engage in illegal military activities is inherent in certain nominally civilian facilities. Some legitimate biological facilities can also convert rapidly to the production of biological warfare agents, depending on the degree of sophistication of the plant and on the required scale of production, level of worker safety, and environmental containment. At the same time, however, legitimate applications of biological or toxin agents (e.g., vaccine production and the clinical use of toxins) are relatively few at present. With the exception of a few vaccine production plants, such activities are largely confined to sophisticated biomedical facilities not normally found in developing countries, and these facilities generally do not engage in production except on a small scale. Moreover, given that the global biotechnology industry is still in its infancy, the number of" legitimate activities-from which the illegitimate ones would have to be distinguished-is still relatively small.

Sensitive analytical techniques such as polymerase chain reaction {PCR) analysis or use of monoclinal antibodies can identify trace quantities of biological agents and might be able to do so even after the termination of illicit activities. However, the existence of such sensitive laboratory techniques does not necessarily translate into a negotiated verification regime that might be instituted to monitor compliance with the Biological Weapons Convention, the international treaty that bans biological weapons. Other factors that must be assessed in establishing such a regime include the likelihood of detecting clandestine production sites, the ability to distinguish prohibited offensive activities from permitted defensive efforts, and the risk of divulging sensitive national security or proprietary information during inspections of U.S. facilities.[8]

Because of the difficulty of detecting clandestine biological and toxin weapon development and production, effective tracking of such programs will require integrating data from many sources, with a particular emphasis on human intelligence (agents, defectors, and whistle-blowers). Some weaponization signatures (storage of bulk agents, preparation of aerosol dispensers, field testing, etc.) would probably be easier to detect than production signatures, but many such signatures could be concealed or masked by legitimate activities such as biopesticide R&D or use. Production and storage of components for BW munitions might also be masked by activities associated with conventional weapons, such as production of high explosives, bomb casings, or artillery shells. Since excessive secrecy might itself be indicative of offensive intent, greater transparency would tend to build confidence in a country's lack of offensive intentions.

Implications of New Technology

Genetic engineering is unlikely to result in ‘‘ supergerms’ significantly more lethal than the wide variety of potentially effective biological agents that already exist, nor is it likely to eliminate the fundamental uncertainties associated with the use of microbial pathogens in warfare. However, gene-splicing techniques might facilitate weaponization by rendering microorganisms more stable during dissemination (e.g., resistant to high temperatures and ultraviolet radiation). Biological agents might also be genetically modified to make them more difficult to detect by immunological means and insusceptible to standard vaccines or antibiotics. At the same time, genetic engineering techniques could be used to develop and produce protective vaccines more safely and rapidly.

Cloning toxin genes in bacteria makes it possible to produce formerly rare toxins in kilogram quantities. Moreover, molecular engineering techniques could lead to the development of more stable toxins. Even so, for the foreseeable

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[8] The United States has already determined that inspection procedures under the Chemical Weapons Convention, which allow the inspected party to negotiate the level of access to be provided to international inspectors, are sufficient to protect national security information and trade secrets, However, it is not necessary the case that the same inspection procedures would be suitable for the Biological Weapons Convention should a formal verification regime be instituted.

future, toxin-warfare agents are unlikely to provide dramatic military advantages over existing chemical weapons. It is possible that bioregulators and other natural body chemicals (or synthetic analogues thereof) might be developed into powerful incapacitants, but means of delivering such agents in a militarily effective manner would first have to be devised. Moreover, if warning of their use were provided, chemical weapon protective gear would blunt their impact.


UN PHOTO, H. ARVIDSSON

United Nations inspector measuring an Iraqi Al-Husayn (modified Scud) missile in Baghdad.

DELIVERY SYSTEMS

Although military delivery systems such as ballistic missiles, cruise missiles, and combat aircraft are not essential to deliver weapons of mass destruction, they can do so more rapidly, more controllably, and more reliably than rudimentary means such as suitcases, car bombs, or civilian ships or planes. Controlling the spread of advanced delivery systems by no means would eliminate the dangers posed by weapons of mass destruction, particularly in terrorist applications. However, limiting the availability of these delivery systems would make it harder for states to use weapons of mass destruction for military purposes, particularly against well-defended, forewarned adversaries.

Unlike nuclear, chemical, or biological weapons themselves, which are not traded openly due to treaty constraints or international norms, delivery systems such as aircraft and short-range antiship cruise missiles are widely available on international arms markets. Since the late 1980s, the United States and other Western industrialized countries have had some success at delegitimizing the sale of longer range ballistic and cruise missiles by creating the Missile Technology Control Regime (MTCR), the participants in which refrain from selling ballistic or cruise missiles with ranges over 300 kilometers, or with any range if the seller has reason to believe that they may be used to carry weapons of mass destruction. However, missiles with ranges up to 300 km-and to a lesser extent, up to 600-1,000 km-are already deployed in many Third-World countries. Combat aircraft are possessed by almost all countries of proliferation concern. Cruise missiles or other unmanned aerial vehicles with ranges much over 100 km are not yet widespread outside the acknowledged nuclear weapon states, but large numbers of cruise missiles, including antiship missiles, are available at lesser ranges.

In terms of payloads that can be carried to specfied ranges, the combat aircraft of virtually all countries of proliferation concern far surpass their missile capabilities. However, aircraft and missiles have different relative strengths—particularly in their ability to penetrate defenses—and the two systems are not fully interchangeable. Piloted aircraft have significant advantages over other delivery systems in terms of range, payload, accuracy, damage-assessment capability, and dispersal of chemical or biological agents. They can be used many times, usually even in the presence of significant air defenses. Missiles, however, are harder to defend against, and they offer distinct advantages for a country wishing to deliver a single nuclear weapon to a heavily defended area. Since missiles are not restricted to operating from airfields, they are also easier to hide from opposing forces. The wide range of motivations for acquiring ballistic missiles-prestige, diversifying one's forces, their psychological value as terror weapons, lack of trained pilots, and technology transfer and export opportunities-will continue to make missile technology very attractive for several countries of proliferation concern.

Barriers to Missile and Aircraft Proliferation

The spread of ballistic missiles around the world was greatly facilitated by the export in the 1970s and 1980s of Scud-B missiles from the former Soviet Union. With an increasing number of countries abiding by the MTCR, the number of potential missile suppliers has declined dramatically. Of the principal missile exporters, only North Korea has not agreed to comply. However, Ukraine poses future export concerns, since it contains much of the former Soviet missile production infrastructure, yet has not agreed to comply with the MTCR. Moreover, additional countries have learned to copy, modify, extend the range of, and produce their own missiles, and a small number have developed long-range systems—often in conjunction with space-launch programs and foreign technical assistance. Even so, MTCR constraints can slow the acquisition by developing countries of technologies associated with more advanced missiles--those having ranges in excess of 1,000 km or guidance errors of less than roughly 0.3 percent of their range.

Given the complex set of technologies and expertise used in advanced aircraft, especially high-performance jet engines, it remains virtually impossible for developing countries to acquire these systems without assistance. However, no internationally binding restrictions limit trade in combat aircraft, and such arms transfers continue to be used as an instrument of foreign policy. Moreover, overcapacity in Western defense industries, and the economic difficulties facing newly independent Soviet republics and Eastern European states, provide great incentive to develop arms export markets. Therefore, states can and probably will continue to acquire high-performance aircraft easily, without having to build them. Moreover, other options short of buying aircraft or building them from scratch are available to states wishing to acquire or mod@ combat aircraft, such as engaging in licensed production.[9]

If they have sufficient payload and range-and if they can be procured despite export controls—commercially available unmanned aerial vehicles can be adapted to deliver weapons of mass destruction without much difficulty. Developing cruise missiles requires greater technical capability. Even so, technologies for guidance, propulsion, and airframes are becoming increasingly accessible, particularly with the spread of licensed aircraft production arrangements to many parts of the world. The most difficult technical challenges to developing cruise missiles—propulsion and guidance-do not pose much of a hurdle today. The highest performance engines are not required for simple cruise missiles, and many sources are available for suitable engines. Guidance requirements can be met by satellite navigation services such as the U.S. Global Positioning System (GPS), possibly the Russian Glonass system, or commercial equivalents. Inexpensive, commercially available GPS receivers are becoming available to provide unprecedented navigational accuracy anywhere in the world. Although GPS receivers would have only limited utility to emerging missile powers for ballistic missile guidance, they could be used to reduce uncertainty in the launch location of mobile missiles.

Monitoring Delivery Vehicles

Although individual missiles can be very difficult to detect, a program to develop ballistic missiles is much more visible. Test firing and

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[9] The routes various states around the world have taken to develop defense industries, including aircraft industries, are discussed in U.S. Congress, Office of Technology Assessment, *Global Arms Trade*, OTA-ISC-460 (Washington, DC: U.S. Government Printing Office, June 1991).

launching ballistic missiles can be readily seen. Development of intermediate and long-range ballistic missiles requires extensive flight testing, making it particularly noticeable. Although states pursuing both military and civil space technology may wish to hide their military programs, civilian space-launch programs are usually considered a source of national prestige and proudly advertised.

Even a purely civilian space-launch program provides technology and know-how useful for ballistic missiles. The most important aspects of a missile capability for weapons of mass destruction-range and payload-can usually be inferred from a civil program. (A civil space-launch booster does not need to have high accuracy, but neither does a missile carrying weapons of mass destruction for use against populations.) On the other hand, certain attributes desired for military applications, such as reliable reentry vehicles, mobility, and ease of operation in the field, suggest distinct technical approaches for military and civil applications. Although solid-fueled boosters are in some ways more difficult to develop and build than liquid-fueled boosters, they are easier to use in mobile and time-urgent applications. Liquid-fueled boosters were the first used in military applications and are still more common. (The seemingly ubiquitous Scud missile and its modifications, such as were launched by Iraq against targets in Israel and Saudi Arabia, are liquid-fueled.)

Since combat aircraft are widely accepted as integral to the military forces even of developing countries, there is no reason to hide their existence. Individual planes, however, can be hidden. Moreover, modifications made to aircraft to carry weapons of mass destruction, or training given to pilots for their delivery, might be difficult to detect without intrusive inspections.

Of the three delivery systems, cruise missile development and testing will be the hardest to detect. Several types of unmanned aerial vehicles are being developed and marketed for civil purposes, and without inspection rights it will be difficult to discern whether such vehicles have been converted to military purposes. Therefore, monitoring of delivery systems capable of carrying weapons of mass destruction will continue to be an uncertain exercise, having most success with missiles and highly capable aircraft. Nevertheless, the risk posed by other delivery systems cannot be dismissed. The full range of delivery technology must be taken into account when evaluating a country's overall proliferation capabilities and behavior.

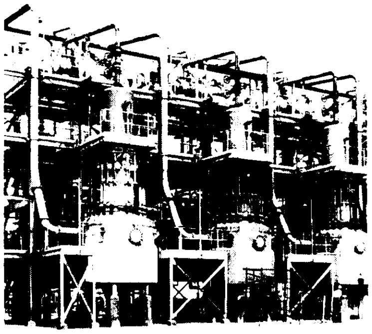
Technical Aspects of Chemical Weapon Proliferation

2

Of the three categories of weapons of mass destruction, chemical weapons are the most likely to be used in warfare, and they remain a serious threat in regional conflicts despite the end of the Cold War. Although well-equipped troops can defend themselves against existing chemical agents with detectors, decontamination equipment, gas masks, and protective garments (albeit at a some cost in military effectiveness), chemical weapons can still have devastating effects when employed against defenseless civilians or poorly equipped (or unprepared) armies or guerrilla fighters. This fact was starkly demonstrated during the 1980s by Iraq's use of chemical weapons against Iran and its own Kurdish population.

The prospects for halting the proliferation of chemical weapons are mixed. On the one hand, several states are currently believed to possessor to be actively pursuing a chemical-warfare (CW) capability. On the other hand, the international community recently achieved a major step forward by concluding the Chemical Weapons Convention (CWC) after more than two decades of arduous negotiations. This treaty, which is expected to enter into force in January 1995, enacts a comprehensive global ban on the development, production, stockpiling, transfer to other countries, and use of CW agents and delivery systems. The CWC also provides for a highly intrusive verification regime that will provide a legal framework for enforcement. However, a number of key countries of concern have not yet signed the treaty.

This chapter describes the chief technical hurdles associated with the process of acquiring a militarily significant CW capability and discusses detectable signatures' associated with each of these steps that might be used for monitoring or verification purposes. A separate report explains the tactical and strategic uses of chemical weapons, and the extent and



consequences of their spread.[1] The analysis here focuses on mustard and nerve agents because they are militarily the most effective and have been weaponized and stockpiled by several countries.

SUMMARY

CW capabilities can vary greatly in sophistication. Although hundreds of tons of chemical agent would be required for large-scale use in a major conflict, smaller quantities could be effective for tactical engagements in regional wars or to terrorize population centers. An advanced CW capability would entail production of several agents with differing toxicities and physical characteristics, mated to different types of munitions, but a crude CW arsenal might contain only one or two agents and a simple delivery system such as an agricultural sprayer. The Iran-Iraq War of the 1980s saw the first protracted use of chemical weapons since World War I and the first use of nerve agents. According to Iranian sources, Iraqi chemical weapons accounted for some 50,000 Iranian casualties, including about 5,000 deaths.[2]

The growing availability of chemical know-how and production equipment, combined with the globalization of chemical trade, have given more than 100 countries the capability-if not necessarily the intent-to) produce simple chemical weapons such as phosgene, hydrogen cyanide, and sulfur mustard. A smaller number have the capability to produce nerve agents such as GA (tabun), GB (sarin), GD (soman), and VX. The reason is that whereas mustard-gas production is very simple-particularly if thiodiglycol is available as a starting material—making nerve agents involves more complex and difficult reaction steps. Technical hurdles associated with the production process include the cyanation reaction for tabun and the alkylation reaction for the other nerve agents. Alkylation requires high temperatures or highly corrosive reagents.

Chemical plants capable of manufacturing organic phosphorus pesticides or flame retardants could be converted over a period of weeks to the production of CW agents, although this would not be a simple process. Multipurpose plants would be easier to convert than single-purpose plants. The hurdles to acquiring a CW production capability are lower if a proliferant country seeks only to produce low-quality agent for immediate use and is willing to cut comers on agent shelf-life, safety, and environmental protection. Even so, CW agent production is still several steps removed from an operational CW capability, which also requires the design and development of effective munitions, the filling of the munitions before use, and mating with a suitable delivery system.

| Indicators of CW Proliferation Activities

Many different types of precursor chemicals and equipment, many of them dual-use, are suitable for CW agent production. As a result, plant equipment or precursor chemicals per se do not provide a reliable means of distinguishing between legitimate and illicit production. Since most chemical facilities are relatively simple and multiuse, nonproliferation policies will need to focus on judgments of intent as well as capability.

Detection of CW proliferation-either within or outside the framework of an international treaty regime requires the correlation of multiple indicators and intelligence sources, ranging from satellites to human defectors. The probability of detecting a clandestine CW capability must therefore be evaluated in the context of the on-site inspection regime established by the Chemical Weapons Convention, as well as unilateral intelli-

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[1] U.S. Congress, Office of Technology Assessment *Proliferation of Weapons of Mass Destruction: Assessing the Risks,* OTA-ISC-559 (Washington, DC: U.S. Government printing Office, August 1993).

[2] Mike Eisenstadt, *The Sword of the Arabs: Iraq's Strategic Weapons,* Washington Institute Policy Papers No. 21 (Washington DC: Washington Institute for Near East Policy, 1990), p, 6.

gence-gathering capabilities outside the treaty regime,

Specific indicators, or “signatures,” of CW acquisition activities may be detected through remote or on-site inspection of a suspect facility. Potential signatures include aspects of plant design and layout, testing of chemical munitions and delivery systems, presence of agents, precursors, or degradation products in samples from the production line or waste stream; and presence of “biomarkers” indicative of CW agent exposure in plant workers or in wild plants and animals living in the vicinity of a suspect facility. The utility of any given signature depends on the precise pathway taken by a given proliferant, including the choice of production process, the investment in emission-control technologies, and the amount of effort taken to mask or otherwise obscure the signature.

The production of both mustard and nerve agents results in long-lived chemical residues that can persist for weeks-in some cases years—after production has ceased. Such telltale chemicals can be detected in concentrations of a few parts per trillion with sensitive analytical techniques such as combined gas chromatography/mass spectrometry. For this reason, the ability to conceal illicit CW agent production in a known facility is probably limited, although a number of possible circumvention scenarios have been suggested. Existing analytical capabilities can be fully exploited, however, only if the inspectors are given intrusive access to a suspect site. Confidence in a country’s compliance may, therefore, diminish if such access is not forthcoming, or if the number of sites to be inspected is impractically large. Furthermore, because chemical analysis has the potential to yield “false positive’ results when in fact no violation has occurred, chemical detection should not be seen as unequivocal evidence of CW production but rather as a key element in a broader array of indicators suggesting a violation.

While detection of CW production with near-site monitoring techniques (such as laser spectroscopy) appears promising, current technology cannot provide a high probability of detection—particularly for plants equipped with sophisticated emission-control systems. Nevertheless, rapid improvements in the sensitivity and specificity of analytical devices, combined with the rapid evolution of computer processing and data-storage technologies, promise to improve the utility of near-site monitoring in the not-too-distant future.

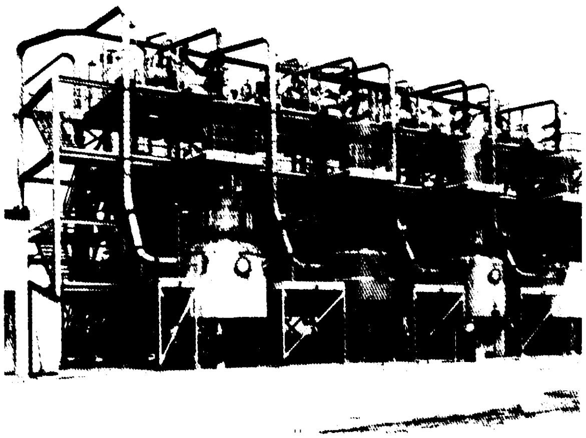
Finally, detection capabilities that are very impressive in certain circumstances maybe rather inconclusive in others-particularly if the proliferant is willing to expend time, effort, and resources to mask, obscure, or explain away his CW production activities. Thus, good detectability in principle does not necessarily mean high-confidence detection in practice. A robust inspection regime must comprise an interlocking web of inspections, all of which a cheater must pass in order to conceal his violations. Focusing inspections at a single point-even one believed to be a crucial chokepoint-would allow the cheater to focus his efforts on defeating the inspections.

| Alternative Proliferation Pathways

Chemical-warfare agents can be produced through a wide variety of alternative routes. Just because the United States used a particular production pathway in the past does not mean that a proliferant country would not chose another route, although only relatively few are suited to large-scale production. For example, the United States and Iraq used different processes for the production of G-category nerve agents.

A proliferant country would either build a dedicated clandestine production facility or convert a commercial (single-purpose or multipurpose) chemical plant to CW agent production. In general, commercial pesticide plants lack the precursor materials, equipment, facilities, handling operations, and safety procedures required for nerve-agent production, and would therefore require weeks to months to convert. Binary agents-consisting of two relatively nontoxic chemical components that when mixed together react to form a lethal agent-might be attractive to a proliferant because they are easier and safer to produce and handle, although they may be more complex to use in combat.

Each of the possible proliferation pathways involves tradeoffs among simplicity, speed, agent shelf-life, and visibility. The choice of pathway would therefore be affected by the urgency of a country's military requirement for a CW stockpile, its desire to keep the program secret, its level of concern over worker safety and environmental protection, and the existence of embargoes on precursor materials and production equipment.



TENNESSEE VALLEY AUTHORITY

Part of the U.S. Army's Phosphate Development Works, located on the grounds of Tennessee Valley Authority's National Fertilizer Development Center in Muscle Shoals, Alabama. Between 1953 and 1957, this facility met the Army's need for dichlor, a precursor needed to produce the nerve agent sarin.

ACQUIRING A CW CAPABILITY

Although hundreds of thousands of toxic chemicals have been examined over the years for their military potential, only about 60 have been used in warfare or stockpiled in quantity as chemical weapons.[3] Physical properties required of CW agents include high toxicity, volatility or persistence (depending on the military mission), and stability during storage and dissemination. Lethal agents that have been produced and stockpiled in the past include *vesicants* such as sulfur mustard and lewisite, which bum and blister the skin, eyes, respiratory tract, and lungs; *choking agents* such as phosgene and chlorine, which irritate the eyes and respiratory tract; *blood agents* such as hydrogen cyanide, which starve the tissues of oxygen; and *nerve agents* such as sarin and VX, which interfere with the transmission of nerve impulses, causing convulsions and death by respiratory paralysis.

Unlike nuclear weapons, which require a large, specialized, and costly scientific-industrial base, CW agents can be made with commercial equipment generally available to any country. Indeed, few military technologies have evolved *as little as* chemical weapons over the past half-century.[4] Current-generation mustard and nerve agents are based on scientific discoveries made during and between the two World Wars, and there have been few major innovations since then in either basic chemicals or manufacturing methods. The vast majority of the U.S. stockpile (in terms of tonnage) was produced during the 1950s and 1960s, when the United States managed to produce high-quality CW agents with what is now 30- to 40-year-old technology. Moreover, production techniques for the major CW agents have been published in the open patent or chemical literature, including data on reaction kinetics, catalysts, and operating parameters. According to one analyst, "The routes of production are generally known, and they can be pursued with relatively primitive

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[3] World Health Organization@ *Health Aspects of Chemical and Biological Weapons: Report of a WHO Group of Consultants* (Geneva: WHO, 1970), p, 23,

[4] In this respect, there is a significant difference between manmade chemical agents and biological toxins, whose production has been transformed by advances in biotechnology. See ch. 3.

equipment, especially by those who are not overly concerned with worker health and safety or environmental impacts.[5]

As the commercial chemical industry has spread around the world in response to the urgent needs of developing countries for chemical fertilizers, pesticides, and pharmaceuticals, the availability of chemicals and equipment required to produce CW agents has increased. At the same time, thousands of applied organic chemists and chemical engineers from developing countries have been trained in related production technologies at universities in the United States, Europe, and the former Soviet Union.[6] According to Rear Adm. Thomas A. Brooks, former Director of Naval Intelligence:

> The substantial pool of Western or Western-trained scientists, engineers and technicians has successfully been tapped for years by Third World states eager to acquire their expertise for missile development, nuclear, chemical and other weapon projects.[7]

The dual-use nature of many chemical technologies has made CW proliferation ‘‘an unfortunate side effect of a process that is otherwise beneficial and anyway impossible to stop: the diffusion of competence in chemistry and chemical technology from the rich to the poor parts of the world.[8] Nevertheless, CW agent production is only one step on the path to acquiring a full capability to wage chemical warfare. A supertoxic agent, despite its lethality, does not become a usable weapon of war until it has been integrated with some form of munition or delivery system and made an integral component of a nation’s military planning and doctrine.

Acquisition Steps

The following steps are required for a proliferant country seeking to acquire a fully integrated CW capability (see figure 2-l):

1. acquire equipment and materials needed for CW agent production and the relevant expertise;
2. produce agents in small quantities at a pilot facility to work out technical details of the synthetic process, and then scale up to a production plant;
3. purchase suitable munitions and delivery systems (or design, prototype, test, and produce them indigenously);
4. fill the munitions with agent;
5. establish bunkers (or other storage facilities) and logistical support networks for the stockpiling, transport, handling, and use of bulk agents and munitions;
6. deliver chemical munitions to the military logistics system for storage and transport to the battle zone;
7. acquire individual and collective chemical defenses and decontamination equipment, and train troops how to fight in a chemical environment; and
8. develop strategic and tactical battle plans for CW use, and practice them in operational tests and field exercises.

To save time or money, a state seeking a more rudimentary CW capability might cut corners on some of these steps, for example, by omitting rigorous safety and waste-treatment measures during the production process. Proliferant states might also settle for a less robust logistical infrastructure than that developed by the United

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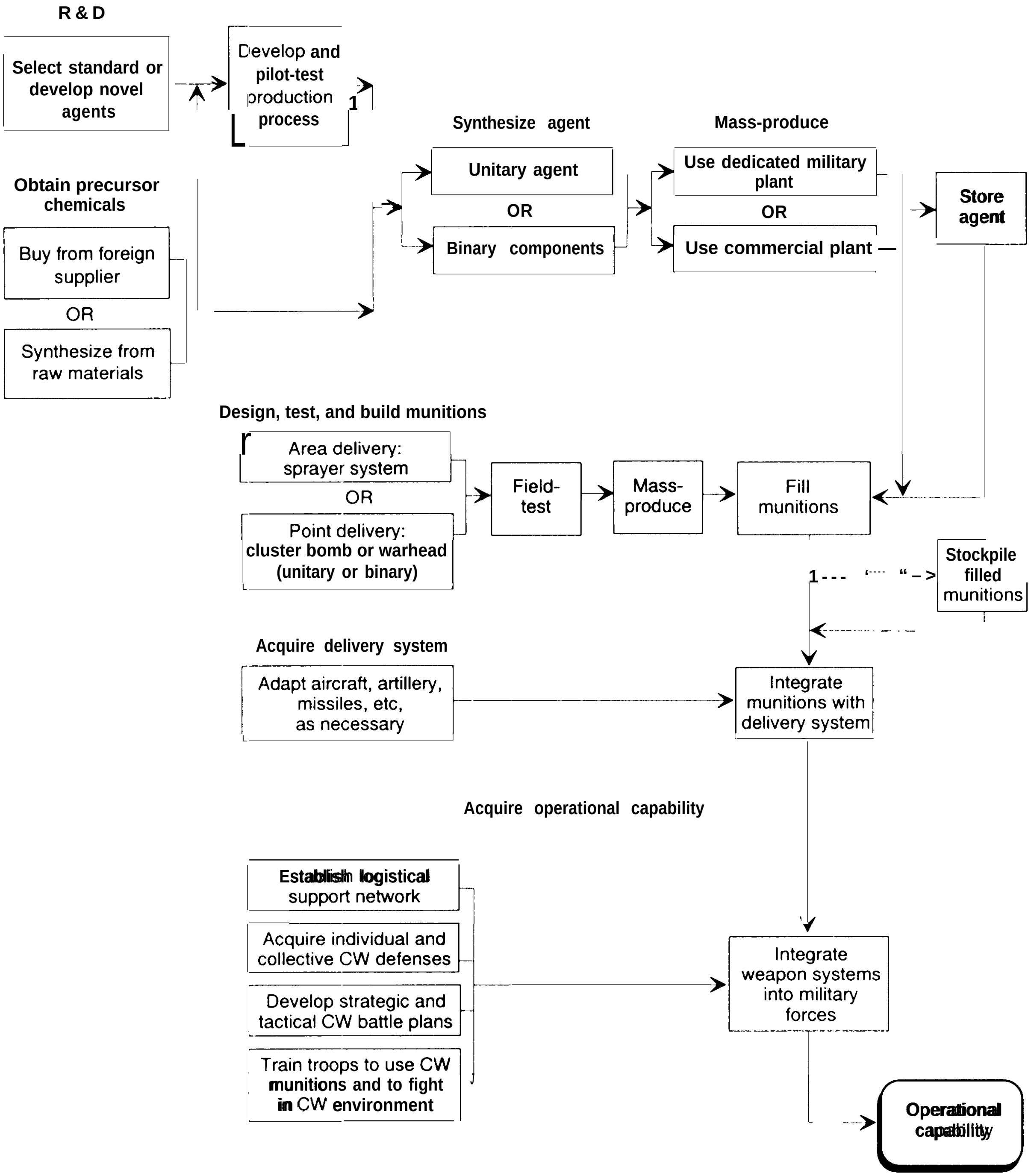
[5] Kyle Olson, “Disarmament and the Chemical Industry, ” Brad Roberts, cd., *Chemical Disarmament and U.S. Security* (Boulder, CO: Westview Press, 1992), p. 100.

[6] In 1990, for example, foreigners accounted for a large fraction of full-time graduate students at U.S. universities studying chemistry (32 percent) and chemical engineering (42 percent). Commission on Professionals in Science and Technology, “Foreign Graduate Students” (table), *Scientific-Engineering-Technical Manpower Comments,* vol. *29, No. 6,* September 1992, p. 13.

[7] Michael R. Gordon, ‘‘The Middle East’s Awful Arms Race: Greater Threats from Lesser Powers, ’ *The New York Times,* Apr. 8, 1990, sec. 4, p. 3.

[8] Julian Perry Robinson, “Chemical Weapons Proliferation: The Problem in Perspective, ” Trevor Findlay, cd., *Chemical Weapons and Missile Proliferation* (Boulder, CO: Lynne Rienner, 1991), p. 26.

Figure 2-1—Chemical Weapon Acquisition



SOURCE: Office of Technology Assessment, 1993.

States and other nations with a broad, integrated military establishment. Finally, proliferants might forego protection and decontamination capabilities if the opponent lacks a CW capability and the losses resulting from "friendly free" are considered an acceptable cost of war.[9]

AGENTS AND PRODUCTION PROCESSES

I Sulfur Mustard

Sulfur mustard (H), the main blistering agent used in warfare, is an oily liquid at room temperature that smells of garlic and ranges in color from clear to dark brown depending on purity.[10] It is readily absorbed by the skin and most clothing. Sulfur mustard is fairly persistent in the environment, presenting a hazard for days or even weeks depending on the weather. Compared with the more toxic nerve agents, sulfur mustard is relatively easy to produce and load into munitions, and it can be stockpiled for decades—especially when distilled-either as bulk agent or in weaponized form. The primary drawbacks of sulfur mustard as a CW agent are that:

- it must be used in relatively high concentrations to produce significant casualties;
- it freezes at a relatively high temperature—about 14 degrees Celsius (57 degrees Fahrenheit) for distilled mustard; and
- if not distilled to high purity, mustard tends to polymerize when stored for long periods, forming solids that precipitate out of solution and reduce the efficiency of dissemination.

Sulfur mustard has diffuse toxic effects on the body that may take as long as 3 hours or more to manifest themselves. The primary effect of an attack with sulfur mustard is to produce painful skin blistering and eye and lung irritation, resulting in a large number of wounded casualties who place an enormous burden on medical services. Heavy exposure to an aerosol of mustard or mustard vapor causes the lungs to fill with fluid, "drowning" the victim from within.[11] Nevertheless, only 2 to 3 percent of hospitalized American and British mustard casualties in World War I died, and a similar low death rate was reported for Iranian mustard casualties during the Iran-Iraq War.[12] Seven to 10 days after exposure, sulfur mustard can also cause a delayed impairment of immune function that increases vulnerability to bacterial infection and may lead to serious medical complications.

PRODUCTION OF SULFUR MUSTARD

Nine production processes for sulfur mustard have been documented in the published chemical literature. During World War I, thousands of tons of mustard gas were produced from alcohol, bleaching powder, and sodium sulfite. During World War II, the two largest producers of mustard gas, the United States and the Soviet Union, used two common industrial chemicals-sulfur monochloride and ethylene----as starting materials.[13] A mustard-gas plant based on this method could be located at an oil refinery, which is an excellent source of ethylene and could also extract the necessary sulfur from petroleum or natural gas.[14]

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[9] U.S. Congress, Office of Technology Assessment, *Who Goes There: Friend or Foe?, OTA-ISC-537 (Washington* DC: U.S. Government Printing Office, June 1993).

[10] Sulfur mustard may be produced in either crude form (H) or washed and vacuum-distilled (HD).

[11] Most of the Iranian fatalities caused by Iraqi use of sulfur mustard during the Iran-Iraq War were caused by liquid on clothing being inhaled over a long period in the hot desert sun. William C. Dee, U.S. Army Chemical-Biological Defense Command, personal *communication 1993.*

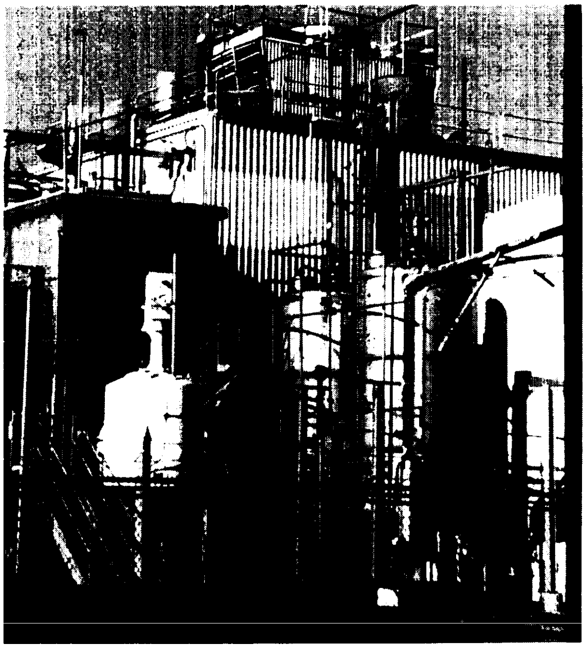
[12] Seth Schonwald, "Mustard Gas," *The PSR Quarterly,* vol. 2, No. 2, June 1992, p. 93.

[13] Gordon Burck et al., *Chemical Weapons Process Parameters, Vol. I: Main Report* (Alexandria, VA: EAI Corp., Report No. DNA-TR-91-217-V1, November 1992).

[14] Gordon M. Burck and Charles C. Flowerree, *International Handbook on Chemical Weapons Proliferation* (New York, NY: Greenwood Press, 1991), p. 50.

Today, the precursor of choice for any large-scale production of mustard gas is thiodiglycol, a sulfur-containing organic solvent that has commercial applications in the production of ballpoint pen inks, lubricant additives, plastics, and photographic developing solutions, and as a carrier for dyes in the textile industry. Thiodiglycol is just one step away from production of sulfur mustard, requiring only a reaction with a chlorinating agent like hydrochloric acid (HC1), a widely available industrial chemical.[15] (See figure 2-2.) Known as the Victor Meyer-Clarke Process, the chlorination of thiodiglycol was developed by Germany during World War I and adopted in the 1980s by Iraq. It does not require a particularly sophisticated chemical industry and could, indeed, be performed in a basement laboratory with the necessary safety precautions.

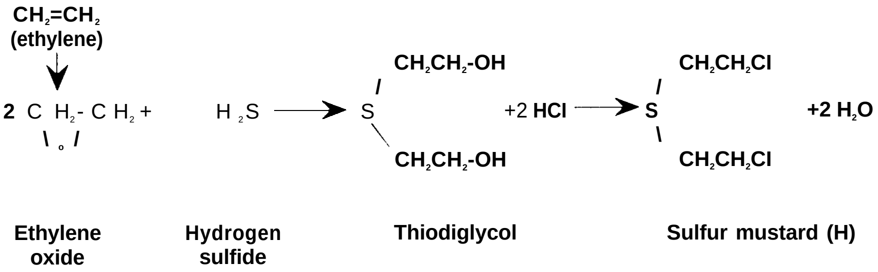
Sulfur mustard can be produced on an industrial scale on either a batch or continuous basis. Given the extreme corrosiveness of hot hydrochloric acid, it is advisable-but not essential-to



R. ECKHAUS

Plant that produces the "dual-use" chemical thiodiglycol, which is both a key ingredient of ballpoint pen ink and an immediate precursor of mustard agent.

Figure 2-2—Production of Sulfur Mustard



SOURCE: Stephen Black, "Vesicant Production Chemistry," In Black, Benoit Morel, and Peter Zapf, *Technical Aspects of Verification of the Chemical Weapons Convention,* Internal Technical Report, Carnegie-Mellon Program on International Peace and Security, 1991, p. 56.

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[15] See Ronald G. Sutherland, "Thiodiglycol," in S. J. Lundin, cd,, *Verification of Dual-Use Chemicals Under the Chemical Weapons Convention; The Case of Thiodiglycol,* SIPRI Chemical & Biological Warfare Series No. 13 (Oxford, England: Oxford University Press, 1991), pp. 24-30,

use corrosion-resistant reactors and pipes. This requirement might be reduced by substituting a less corrosive chlorinating agent for HC1 or by replacing the production equipment as often as necessary. In order to improve the purity and stability of sulfur mustard in storage, corrosive byproducts can be removed by distillation or solvent extraction.

There are five U.S. producers of thiodiglycol and about eight foreign producers in five countries.[16] Most of these companies do not sell the chemical but use it internally in the manufacture of other products. In addition, about 100 firms worldwide purchase thiodiglycol for the synthesis of specialty chemicals and other industrial uses.[17] When Iraq began mustard-gas production in the early 1980s, it was unable to make thiodiglycol indigenously and ordered more than 1,000 tons from foreign sources.[18] In response to the threatened embargo on exports of thiodiglycol from Western countries, however, Iraq developed an indigenous production capability based on reacting ethylene oxide with hydrogen sulfide. Both of these ingredients are widely available. Hydrogen sulfide can be extracted from natural gas or crude oil, where it is often present as an impurity, or derived from elemental sulfur. Ethylene oxide is readily produced from ethylene, a major product of petroleum refining.

In sum, the production of mustard gas is relatively easy from a technical standpoint and could probably be concealed. While export controls on thiodiglycol might initially create a major hurdle for new proliferants, the effectiveness of controls will diminish as these countries acquire an indigenous capability to produce it. Furthermore, just because synthesis from thiodiglycol is the ‘‘best’ process does not mean that it will be used by a proliferant. Any of the other synthetic pathways could work just as well for a developing country and might be used to circumvent export controls.

| Nerve Agents

Nerve agents are supertoxic compounds that produce convulsions and rapid death by inactivating an enzyme (acetylcholinesterase) that is essential for the normal transmission of nerve impulses. The nerve agents belong to the class of organophosphorus chemicals, which contain a phosphorus atom surrounded by four chemical groups, one of which is a double-bonded oxygen. Although many organophosphorus compounds are highly toxic, only a few have physical properties that give them military utility as nerve agents.[19] The difference in toxicity between pesticides and nerve agents derives from the nature of the chemical groups surrounding the phosphorus atom. In general, nerve agents are 100 to 1,000 times more poisonous than organophosphorus pesticides.[20]

Two classes of nerve agents, designated G and V agents, were produced in large quantities in the 1950s and ’60s by the United States and the former Soviet Union. (See figure 2-3.)

The *G-series nerve agents are* known both by informal names and military code-names: tabun (GA), sarin (GB), GC, soman (GD), GE, and GF. This class of compounds was discovered in 1936 by Gerhard Schrader of the German firm IG

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[16] Leo Zeftel, personal communication, 1992; U.S. Department of Commerce, Bureau of Export Administration, Office of Foreign Availability, *Foreign Availability Review: 50 CW Precursor Chemicals (II)* (Washington, DC: Department of Commerce, Nov. 8, 1991), p. 54.

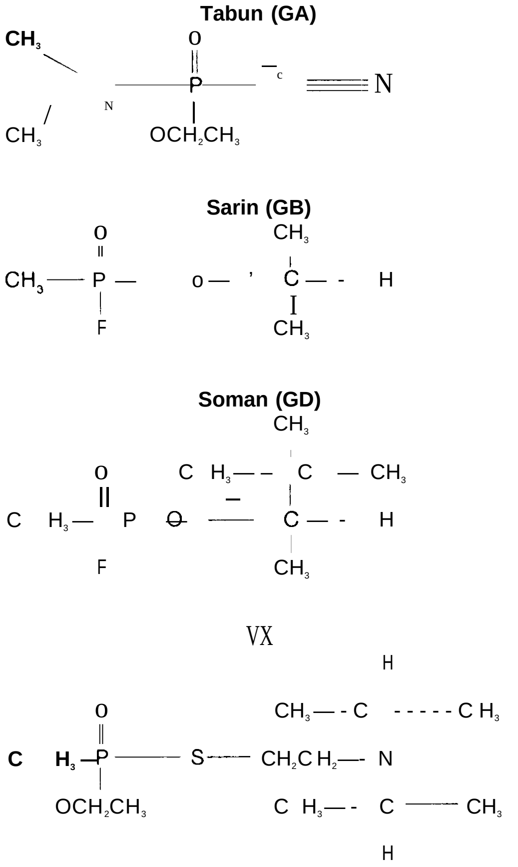
[17] Giovanni A. Snidle, ‘ ‘United States Efforts in Curbing Chemical Weapons Proliferation, ’ *World Military Expenditures and Arms Transfers 1989* (Washington, DC: U.S. Arms Control and Disarmament Agency, October 1990), p. 23.

[18] W. Seth Carus, *The Genie Unleashed: Iraq’s Chemical and Biological Weapons Program,* Policy Papers No. 14 (Washington, DC: The Washington Institute for Near East Policy, 1989), p. 13.

[19] Benjamin Witten, *The Search for Chemical Agents* (Aberdeen, MD: Edgewood Arsenal Special Technical Report, 1969).

[20] Alan R. Pittaway, “The Difficulty of Converting Pesticide Plants to CW Nerve Agent Manufacture, ” Task IV, Technical Report No. 7 (Kansas City, MC): Midwest Research Institute, Feb. 20, 1970), p. 1.

Figure 2-3-Nerve Agents



SOURCE: JAYCOR, *Noncompliance Scenarios: Means By Which Parties to the Chemical Weapons Convention Might Cheat*, Technical Report No. DNA-TR-91-193, January 1993, pp. B-2-B-5.

Farben during research on new pesticides. Although tabun is relatively easy to produce, it is not as toxic as the other G agents. After World War II, details of German research on the G agents were published, and sarin and soman emerged as preferred agents for military purposes.

All the various G agents act rapidly and produce casualties by inhalation, although they also penetrate the skin or eyes at high doses (particularly when evaporation is minimized and contact is prolonged by contamination of clothing).[21] Sarin evaporates faster than it penetrates the skin, but soman and GF are less volatile and pose more of a skin-contact hazard.

The *V-series nerve agents* include VE, VM, and VX, although only VX was weaponized by the United States. These agents were originally discovered in 1948 by British scientists engaged in research on new pesticides. Military development was then conducted by the United States and the Soviet Union, both of which began large-scale production of V agents in the 1960s.[22] VX is an oily liquid that may persist for weeks or longer in the environment. Although not volatile enough to pose a major inhalation hazard, it is readily absorbed through the skin. The lethal dose of VX on bare skin is about 10 milligrams for a 70 kilogram man.[23]

PRODUCTION OF NERVE AGENTS

From the standpoint of production processes, the nerve agents can be clustered into three groups: tabun; sarin/soman, and VX.

Tabun

The first militarized nerve agent and the simplest to produce, tabun (GA), is made from four precursor chemicals: phosphorus oxychloride ($POCl_3$), sodium cyanide, dimethylamine, and ethyl alcohol. Most of these ingredients are widely available. Ethanol and sodium cyanide are commodity chemicals that are manufactured and sold in vast quantities; dimethylamine and phosphorus oxychloride are produced by companies in several countries for commercial applications in the production of pharmaceuticals, pesticides, missile fuels, and gasoline additives.

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[21] Col. Michael A. Dunn and Frederick R. Sidell, "Progress in Medical Defense Against Nerve Agents," *Journal of the American Medical Association*, vol. *262, No. 5*, Aug. *4, 1989*, p. 649.

[22] Manuel Sanches et al., *Chemical Weapons Convention (CWC) Signatures Analysis* (Arlington, VA: System Planning Corp., Final Technical Report No. 1396, August 1991), p. 68.

[23] Witten, op. cit., footnote 19, pp. 92, 100.

The basic production process for tabun was developed by Germany during World War II and was later employed by Saddam Hussein's Iraq. Tabun synthesis does not require the use of corrosive starting materials and does not produce highly reactive intermediates. The two-step process involves mixing the ingredients and a carrier solvent in a reaction vessel equipped with a sodium-hydroxide scrubbing system to neutralize the gaseous hydrochloric acid (HC1) byproduct. A relatively simple air-tight enclosure is also needed to prevent the escape of toxic vapors. The ingredients must be added in the correct order, without heating, and the vessel cooled to keep the reaction from building up too much heat. Little or no distillation equipment is required, although the purity of tabun can be increased to more than 80 percent by removing the carrier solvent and the off-gasses by vacuum distillation.[24] In sum, tabun production is relatively easy because it does not include the difficult alkylation reaction needed to make the other nerve agents. The major technical hurdle in tabun synthesis is the cyanation reaction (in which a cyanide group is added to the central phosphorus), because of the difficulty of containing the toxic hydrogen cyanide HCN gas used as the reagent.

During World War II, Germany manufactured tabun in large quantities but never used it in combat. In early 1940, the Germans began construction of a huge tabun factory with the capacity to produce 3,000 tons of agent a month. Because of technical problems, however, it took the Germans over 2 years, until April 1942, to get the plant operational.[25] The Iraqis also had difficulties with the manufacture of tabun, although they managed to produce a material with about 40 percent purity that was used in the Iran-Iraq War.[26]

Sarin/soman

Sarin (GB) and soman (GD) are both made in a batch process with the same basic reaction steps, but they contain different alcohol ingredients: isopropyl alcohol for sarin and pinacolyl alcohol for soman. (The choice of alcohol changes the toxicity and volatility of the product but does not affect the difficulty of production.) Phosphorus trichloride (PCl_3) is the basic starting material for the synthesis of both agents and, depending on which of several alternative synthetic pathways is chosen, two to five steps are required to make the final product. The alternative syntheses all involve the same four reaction steps, which can be carried out in several different sequences.[27] During the 1950s, new production methods overcame the technical difficulties that had prevented the Germans from engaging in the large-scale production of sarin and soman during World War II. The introduction of these new methods enabled the U.S. sarin plant at Rocky Mountain Arsenal in Colorado to produce 10 tons of agent per day.

The synthesis of G agents entails three major technical hurdles. First, the production process involves the use of hot hydrochloric acid (HC1) and hydrogen fluoride (HF), both of which are extremely corrosive. The use of these compounds in reactors and pipes made of conventional steel

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[24] S. Black, B. Morel, and P, Zapf, "Verification of the Chemical Convention" *Nature,* vol., 351, June 13,1991, p. 516.

[25] Robert Harris and Jeremy Paxman, *A Higher Form of Killing: The Secret Story of Germ and Gas Warfare* (London: Chatto & Windus, 1982), pp. 55-56.

[26] Dee, op. cit., footnote 11.

[27] For example, the United States used the so-called "Di-Di" process to produce sarin. In this process, methylphosphonic dichloride (DC), or CH_3POCl_2, is partially reacted with hydrogen fluoride (HF) gas to make a roughly 50:50 mixture of DC and methylphosphonic difluoride (DF). The DC-DF mixture is then reacted with isopropyl alcohol. This reaction displaces chlorine atoms preferentially, resulting in the formation of sarin and hydrochloric acid (HCl) gas, which must be removed rapidly by distillation to avoid degradation of the nerve-agent product. (Pure DF is not used because the reaction with isopropyl alcohol would liberate HF gas, which is soluble in G agent and virtually impossible to degas, resulting in a highly corrosive mixture.)

results in corrosion measured in inches per year.[28] During World War II, the Germans lined their reactors with silver, which is resistant to HCl and HF. Today, corrosion-resistant reaction vessels and pipes are made of alloys containing 40 percent nickel, such as the commercial products Monel and Hastalloy.[29] Although it is possible to manufacture sarin and soman without corrosion-resistant reactors and pipes, the chance of major leaks is significantly increased compared with using corrosion-resistant equipment.

The second hurdle in the production of G agents is the alkylation reaction, in which a methyl group ($-CH_3$) or an ethyl group ($-CH_2CH_3$) is added to the central phosphorus to form a P-C bond. This step is rarely used in the production of commercial pesticides and is technically difficult.

The third hurdle is that if high-purity agent with a long shelf-life is required, the supertoxic final product must be distilled-an extremely hazardous operation. Distillation is not necessary if a country plans to produce nerve agents for immediate use rather than stockpiling them. During the Iran-Iraq War, for example, Iraq gave priority to speed, volume, and low cost of production over agent quality and shelf-life. As a result, the sarin in Iraqi chemical munitions was only about 60 to 65 percent pure to begin with and contained large quantities of hydrogen fluoride (HF), both because of the synthesis process used and the deliberate omission of the distillation step. Although the Iraqis could have distilled their sarin to remove the excess HF, they chose not to do so because the batches of agent were intended to be used within a few days. To retard the rate of deterioration, sarin-filled shells were stored in refrigerated igloos. Thus, whereas the distilled sarin produced by the United States in the early 1960s has retained a purity of more than 90 percent for three decades, the agent content of Iraqi sarin after 2 years of storage had generally degraded to less than 10 percent and in some cases below 1 percent.[30]

VX

The persistent nerve agent VX has a phosphorus-methyl ($P-CH_3$) bond and a phosphorus-sulfur bond but contains no fluorine. There are at least three practical routes to V-agents that might be used by proliferant countries. As with G agents, production of VX involves a difficult alkylation step.[31] Because the VX manufacturing process avoids the use of HF gas, however, it is less corrosive than the production of sarin and soman. Indeed, after the alkylation step has been completed, the rest of the synthesis is straightforward.

PRODUCTION HURDLES

In summary, the technologies required for the production of mustard and nerve agents have been known for more than 40 years and are within the capabilities of any moderately advanced chemical or pharmaceutical industry. The technical hurdles associated with nerve-agent production are not fundamentally different from those associated with commercial products such as organophosphorus pesticides. The most technically challenging aspects include:

- the cyanation reaction for tabun, which involves the containment of a highly toxic gas;

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[28] Stephen Black, Benoit Morel, and Peter Zapf, *Technical Aspects of the Chemical Weapons Convention: Interim Technical Report* (Pittsburgh, PA: Carnegie Mellon University, Program on International Peace and Security, 1991), p. 70.

[29] Although glass-lined reactors and pipes resist HCl corrosion, HF attacks glass and hence can only be used in metal reactors.

[30] United Nations Special Commission, "Second Report by the Executive Chairman of the Special Commission Established by the Secretary-General Pursuant to Paragraph 9 (b) (i) of Security Council Resolution 687 (1991)," UN Security Council document No. S/23268, Dec. 4, 1991, p. 5.

[31] The U.S. production method for VX, *known as the Newport* process, involved high-temperature methylation, in which phosphorus trichloride (PCl_3) is reacted with methane gas (CH_4) at a high temperature *(500* degrees C) to form au alkylated intermediate, with a yield of only about 15 percent,

- the alkylation step for sarin, soman, and VX, which requires the use of high temperatures and results in corrosive and dangerous byproducts such as hot hydrochloric acid;
- careful temperature control, including cooling of the reactor vessel during heat-producing reactions, and heating to complete reactions or to remove unwanted byproducts;
- intermediates that react explosively with water, requiring the use of heat-exchangers based on fluids or oils rather than water; and
- a distillation step if high-purity agent is required.

While some steps in the production of nerve agents are difficult and hazardous, they would probably represent more of a nuisance than a true obstacle to a determined proliferant. The final distillation step can also be avoided if a proliferant country seeks to manufacture low-purity agent for immediate use and is prepared to cut corners on safety, environmental protection, and the life-span of the production equipment. Indeed, the United States produced nerve agents very effectively with 1950s technology and without the stringent safety and environmental standards that would be required today. In an attempt to conceal a CW production effort, a proliferant country might also resort to less-well-known production processes that had earlier been discarded because of their high cost, inefficiency, hazards, or need for unusual precursors or catalysts.

costs

A sulfur-mustard production plant with air-handling capabilities might cost between $5 million and $10 million to build, In contrast, a more sophisticated G-agent production facility would cost between $30 and $50 million. Since waste-handling facilities would account for more than 50 percent of the cost of a G-agent plant, a ‘‘no-frills’ production facility that did away with waste handling might cost about $20 million.[32] Construction of a large-scale plant and equipment would be almost impossible for a developing country without outside assistance, but cost alone is unlikely to be the deciding factor for a determined proliferant.

Implications of New Technology

Given the well-understood production pathways of mustard and nerve agents and their record of use in warfare, a developing country that sought to acquire a CW capability would not need to develop and weaponize new agents. The development and production of novel CW agents would probably be undertaken only by nations with an advanced scientific-industrial base; even then, a major investment of time and resources would be required. During the 1930s, it took an advanced industrial country like Germany 6 years to put the first nerve agent, tabun, into production.[33]

Even so, the development of entirely new classes of CW agents remains a real possibility. In late 1992, a Russian chemist alleged that a military research institute in Moscow had developed a new binary nerve agent more potent than VX; he was subsequently arrested by the Russian Security Service for disclosing state secrets.[34] Another cause for concern is that some laboratories working on chemical defenses are studying the mode of action of nerve agents at the molecular level. Although the purpose of this research is to develop more effective antidotes, it could also assist in the development of novel

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[32] Dee, op. cit., footnote 11.

[33] Gordon M. Burck, ‘‘Chemical Weapons Production Technology and the Conversion of Civil Production,’’ *Arms Control,* vol. 11, No. 2, September 1990, p. 145.

[34] ‘‘Mirzayanov, Fedorov Detail Russian CW Production,’’ *Novoye Vremya* (Moscow), No. 44, October 1992, pp. 4-9 (translated in FBIS-SOV-92-213, Nov. 3, 1992, pp. 2-7). See also, Will Englund, ‘‘Ex-Soviet Scientist Says Gorbachev’s Regime Created New Nerve Gas in ‘91,” *Baltimore Sun,* Sept. 16, 1992, p. 3.

compounds more deadly than existing nerve agents.[35] A more potent agent would not necessarily translate into greater military effectiveness, however, unless the dissemination system were improved as well.

Some experts are also concerned that even though the Chemical Weapons Convention (CWC) bans the development of *any* toxic chemical for warfare purposes, some countries might seek to circumvent the CWC verification regime by modifying existing agents to avoid detection or by weaponizing a “second string” of known but less effective poisons. The carbamates, for example, are a class of toxic pesticides that resemble organophosphorus nerve agents in that they inactivate the enzyme acetylcholinesterase. To date, the carbamates have not been developed as CW agents because they have a number of operational drawbacks: they are relatively unstable, are solids at room temperature (posing less of an inhalation threat), and are relatively easy to treat or pretreat with antidotes.[36] Even so, such chemicals might become more attractive as an alternative to standard nerve agents. Also of potential concern as novel CW agents are toxins of biological origin, which might be produced in militarily significant quantities with biotechnological techniques. Some toxins are thousands of times more potent than nerve agents, although they also have operational limitations. (See next chapter.)

Another potential threat is the use of penetrant chemicals to defeat chemical defenses, such as “mask-breakers’ capable of saturating gas-mask filters made of activated charcoal.[37] Defensive equipment has long been modified to deal with certain small molecules of this type and is still being improved.[38] Although a variety of other means for penetrating masks and protective clothing have been examined over a period of many years, all of them have operational shortcomings.[39] Even so, penetrants remain a serious potential threat. If a new concept for penetrating CW defenses emerged that lacked the existing drawbacks, it could have a major impact on the overall military significance of chemical weapons. As one analyst has pointed out, the long-term danger is that “some future technological development might reverse the present ascendancy of the defense (i.e., antichemical protection) over the offense, thereby destroying a major incentive for deproliferation. "[40] Since such a technological breakthrough could trigger renewed competition in chemical weapons, measures to constrain research and development would be of major value in halting CW proliferation.

Precursor Chemicals for CW Agents

Chemicals **that serve as** starting materials in the synthesis of CW agents are known as ‘ ‘precursors. During the two world wars, the major powers produced CW agents from indigenous precursors. In World War I, for example, Germany manufactured chlorine and phosgene gas in huge volumes with existing chemical facilities.

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[35] **External Affairs and International Trade** cm@ **Verification Research Unit,** ***Verification Methods,*** *Handling,* ***and Assessment*** *of Unusual* ***Events*** *in Relation to Allegations* ***of the*** *Use* ***of Novel*** *Chemical Warfare Agents* **(Ottawa,** *Canada:* External Affairs, March 1990), p. 10.

[36] **There is,** however, **another** side to the coin. The reversibility of **carbamate poisoning (e.g., with atropine** treatment) would offer an advantage to the attacker in the **case** of accidental leaks or spills. Similarly, the relative instability of **carbamates would** result in less persistence in the **environment,** facilitating occupation of attacked territory.

[37] Walter J. **Stoessel,** Jr., chairman, et **al.,** *Report of the Chemical* ***Warfare Review*** *Commission* **(Washington, DC: U.S.** Government **Printing Office,** June **1985), p. 32.**

[38] **Telephone interview** with Tom **Dashiell, consultant,** U.S. **Arms** Control **and Disarmament** Agency, Feb. 9, 1993.

[39] **J. Perry Robinson, ed.,** ***The Chemical Industry and the*** *Projected Chemical Weapons Convention, Vol. Z: Proceedings* ***of a SIPRI/Pugwash*** *Conference (New* **York,** *NY:* Oxford University Press, 1986), p. 70.

[40] **Julian Perry Robinson,** “The Supply-Side Control of the Spread of Chemical Weapons,” **Jean-Francois Rioux,** ed., ***Limiting*** *the Proliferation of Weapons: The Role of Supply-Side Strategies* **(Ottawa,** *Canada:* Carleton **University** Press, 1992), p. *70.*

Table 2-l—Dual-Use Chemicals

Dual-use chemical	CW agent	Commercial product
Thiodiglycol	Sulfur mustard	Plastics, dyes, inks
Thionyl chloride	Sulfur mustard	Pesticides
Sodium sulfide	Sulfur mustard	Paper
Phosphorus oxychloride	Tabun	Insecticides
Dimethylamine	Tabun	Detergents
Sodium cyanide	Tabun	Dyes, pigments, gold recovery
Dimethyl methylphosphonate	G Agents	Fire retardants
Dimethyl hydrochloride	G Agents	Pharmaceuticals
Potassium bifluoride	G Agents	Ceramics
Diethyl phosphite	G Agents	Paint solvent

SOURCE: Giovanni A. Snidle, "United States Efforta in Curbing Chemical Weapons Proliferation," U.S. Arms Control and Disarmament Agency, *World Military Expenditures andArms Transfers 7939* (Washington, DC: U.S. Government Printing Office, October 1990), p. 23.

Today, however, the globalization of the chemical industry has led to large international flows of dual-use chemicals.

Many of the basic feedstock chemicals used in the production of nerve agents (e.g., ammonia, ethanol, isopropanol, sodium cyanide, yellow phosphorus, sulfur monochloride, hydrogen fluoride, and sulfur) are commodity chemicals that are used in commercial industry at the level of millions of tons per year and hence are impossible to control. Monitoring their sale would also be of little intelligence value because the imprecision of international-trade data would make it impractical to detect the diversion of militarily significant quantities. Hydrogen fluoride, for example, is used at many oil refineries and can be purchased commercially in large quantities; it is also easily derived from phosphate deposits, which usually contain fluorides.

Most of the key precursors for nerve-agent production also have legitimate industrial uses, but the fact that they are manufactured in much smaller volumes makes them somewhat easier to control These chemicals include phosphorus trichloride (with 40 producers worldwide), trimethyl phosphite (21 producers), and—for tabun only—phosphorus oxychloride (40 producers).[41] phosphorus oxychloride, for example, is used extensively in commercial products such as hydraulic fluids, insecticides, flame retardants, plastics, and silicon. Similarly, dimethyl methylphosphonate (DMMP), an intermediate in nerve-agent production, is produced as a flame retardant by 11 companies in the United States and 3 in Europe (Belgium, United Kingdom, and Switzerland) .42 (See table 2-l.)

Developing countries seeking a CW capability generally lack the ability to manufacture key precursor chemicals and must purchase them from foreign sources, typically at well above normal market rates. Because of this dependency, Western governments have attempted to slow CW proliferation by establishing a committee known as the Australia Group, which coordinates national export-control regulations to restrict the sale of key CW precursors to sus-

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[41] U.S. Department of Commerce, op. cit., footnote 16, pp. 39, 58, 36, respectively.

[42] Ibid., pp. 22-23. Lists of sources of CW precursors vary, since some lists include only those companies with an annual production volume greater than 4,500 kilograms or 5,000 pounds.

pected proliferants.[43] Nevertheless, the export controls coordinated by the Australia Group cannot prevent countries that are outside this body from selling precursor chemicals. Indeed, as Western countries have tightened CW-related controls, exports from developing nations such as India have increased. Of the 54 precursor chemicals whose exports are regulated by the Australia Group countries, Indian companies export about 15, only 4 of which are subject to Indian government export controls.[44]

Furthermore, to the extent that immediate precursors for mustard and nerve agents are controlled by the Australia Group, a proliferant might seek to circumvent such export controls in the following ways:

- Substituting an uncontrolled precursor chemical for one that is controlled. For example, although thionyl chloride is subject to export controls as a chlorinating agent for producing nerve agents, a proliferant could easily substitute some other chlorinating agent (e.g., phosgene, sulphuryl chloride) that is not on any export-control list. Thus, the technical means may exist to bypass any particular technology-transfer barrier.[45]
- Purchasing relatively small amounts of the same or different precursor chemicals from multiple sources, instead of obtaining large quantities from a single source. For example, a country might purchase several different types of chlorinating agent for the conversion of thiodiglycol to sulfur mustard. Such a purchasing strategy would reduce the visibility of CW production, although it would also increase the complexity of the production process.
- Producing more obscure (but still effective) CW agents whose precursors are still available. For example, production of the nerve agent soman (GD) requires pinacolyl alcohol, which has no commercial uses and whose export is restricted by the Australia Group. Because of this embargo, Iraqi military chemists chose instead to produce a 60:40 mixture of sax-in and GF (a less common nerve agent of intermediate persistence).[46] Sarin is made with isopropyl alcohol (ordinary rubbing alcohol), while GF is made with cyclohexyl alcohol (an industrial decreasing agent). Unlike pinacolyl alcohol, both isopropyl alcohol and cyclohexyl alcohol are common industrial chemicals that are not subject to export controls.
- "Back-integrating," or acquiring an indigenous capability to manufacture precursor chemicals from simpler compounds whose export is not controlled or that are available from domestic sources. For example, thiodiglycol, the immediate precursor of sulfur mustard, can be produced in a batch process by reacting ethylene oxide with hydrogen sulfide. Both of these ingredients can be derived from oil or natural gas. Before the Persian Gulf War, Iraq built a huge production line at its Basra petrochemicals complex that was capable of manufacturing 110,000 tons of ethylene per year.[47]

In the case of nerve agents, all of the key precursors can be made from the most basic starting materials; including phosphorus, chlorine, and fluorine. The production facilities needed to make these precursors from raw materials are not particularly large and could be

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[43] Julian Perry Robinson, "The Australia Group: A Description and Assessment," Hans Guenter Brauch et al., eds., *Controlling the Development and Spread of Military Technology* (Amsterdam: W University Press, 1992), pp. 157-176.

[44] Michael R. Gordon, "U.S. Accuses India on Chemical Arms," New York *Times*, Sept. 21, 1992, p. A7.

[45] Robinson, "The Supply-Side Control of the Spread of Chemical Weapons, " op. cit., footnote 40, p. 68.

[46] U.S. Department of Defense, *The Conduct of the Persian Gulf War: Final Report to Congress* (Washington, DC: Department of Defense, April 1992), p. 18.

[47] Kenneth R. Timmerman, *The Death Lobby: How the West Armed Iraq* (Boston: Houghton-Mifflin, 1991), p. 35.

embedded in an existing industrial complex, although large amounts of energy would be required. During the Iran-Iraq War, for example, the Australia Group made a concerted effort to prevent Iraq from obtaining supplies of phosphorus oxychloride ($POCl_3$), a key precursor of tabun. In response, Baghdad built a plant to manufacture phosphorus oxychloride indigenously, using raw phosphate ore from its huge phosphate mine at Akashat, so that it was no longer vulnerable to supplier embargoes of this precursor.[48]

Iraq also tried to apply back-integration to sarin production. In 1988, the Iraqi government contracted two West German companies to build three chemical plants at Al Fallujah, 60 miles west of Baghdad, for the conversion of elemental phosphorus and chlorine into phosphorus trichloride (PCl_3), a key sarin precursor.[49] Baghdad also planned to produce hydrogen fluoride (HF), another essential ingredient in sarin production, by extracting it from phosphate ore with sulfuric acid. By the time of the August 1990 invasion of Kuwait, Iraq was on its way to building an indigenous capability to produce all of the major precursors of tabun and sarin, although it ultimately did not achieve this objective.[50]

The Iraqi case suggests that a country with large deposits of phosphate ore, a well-developed petrochemical industry, plentiful energy supplies, and access to the necessary technical know-how can develop an indigenous capability to produce all the major precursors of mustard and nerve agents. This ‘ ‘back-integration’ strategy would enable such a country to circumvent any foreign export-control regime designed to deny it access to CW agent precursors. Nevertheless, developing a back-integration capability is a large and costly undertaking, and may therefore be beyond the means of all but the richest and most ambitious states of the developing world.

Containment and Waste Treatment

Because of the toxicity of CW agents, containment measures may be taken to ensure the safety of the plant workers and the nearby population. Such measures include air-quality detectors and alarms, special ventilation and air-scrubbing systems, protective suits and masks, and chemical showers for rapid decontamination. The safety and ventilation measures at the Iraq’s Al Muthanna CW production plant included measures comparable to U.S. procedures in the 1960s, when most of the U.S. chemical weapon stockpile was produced.[51]

For this reason, one should not use current U.S. safety and environmental standards as the norm when judging the likely proliferation paths of developing countries. If a ruthless government is willing to tolerate large numbers of injuries or deaths among production workers, CW agents can be manufactured in a very rudimentary facility with few, if any, systems in place to protect worker safety or the environment. In the former Soviet Union, for example, closed CW-agent production facilities were only introduced in the 1950s; before then the production process was entirely open to the atmosphere. According to a Russian scientist, production of blister agents during World War II took place under horrifying conditions:

> In Chapayevsk we sent many thousands of people “through the mill” during the war. Soldiers who had been deemed unfit worked at the plant. Production was completely open: mustard gas and lewisite were poured into shells from kettles and scoops! In the space of a few months the ‘‘workers in the rear’ became invalids and died. New people were brought into

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[48] Ibid., p. 52.

[49] Carus, op. cit., footnote 18, pp. 22-27.

[50] ‘‘News Chronology: August through November 1991,“ *Chemical Weapons Convention Bulletin, No. 14,* December 1991, p. 8.

[51] Dee, op. cit., footnote II.

> production. Once during the war a train bringing reinforcements was delayed for some reason, and the plant stopped work. There was simply no one there to work! In nearby villages and hamlets there is probably no family which has not had a relative die in chemical production.[52]

If a proliferant country is concerned about protecting its environment or population (or wishes to cover up telltale evidence of its CW activities), the treatment and disposal of wastes from CW agent production poses a technical challenge. The waste stream contains hot acids contaminated with lethal agents and a large quantity of phosphates. Cleaning out the production line also requires large quantities of decontamination fluid, which becomes mixed with chemical agent and must be chemically or thermally destroyed to dispose of it an environmentally sound manner. In the most modem plants, many spent or unused chemicals (e.g., DMMP, thionyl chloride) are recycled back into the production process. With the effective use of recycling, about one-half ton to 1 ton of waste is generated for each ton of nerve agent produced; without recycling, the ratio of waste to product is much higher.[53]

| Weaponization of CW Agents

The weaponization of CW agents involves three steps:

1. the use of chemical additives to stabilize or augment the effects of a CW agent;
2. the design and production of munitions for dispersal of agent; and
3. the filling, storage, and transport of munitions.

Each of these steps is discussed in detail below.

CHEMICAL ADDITIVES

The principal military requirements of a CW agent are that it be sufficiently toxic to produce large numbers of casualties, and thermally and mechanically stable enough so that it can survive explosive dissemination or passage through a spray device. Several chemicals may be added to CW agents to allow long-term storage or to enhance their military effects against personnel:

- *Stabilizers (e.g., amines)* prevent the degradation of CW agents exposed to hot temperatures or stored for long periods by absorbing acids released by chemical decomposition. Although CW agents filled into munitions do not require a long shelf-life if they are used immediately in combat, stockpiled munitions require stabilizers to prevent deterioration over a period of years.
- *Freezing-point depressants* lower the freezing point of liquid CW agents primarily mustard) to permit use under winter conditions.
- *Thickeners increase the* viscosity and persistence of liquid agents.
- *Carriers* increase the airborne concentration of an agent like sulfur mustard, which is not very volatile at normal temperatures. During World War II, Germany did research on the potential use of silica powder as a potential carrier for mustard agents. A large quantity of sulfur mustard can be absorbed onto the powder and dispersed as a dust cloud. Because it contains a higher concentration of agent, ‘‘dusty mustard’ produces more serious and rapid casualties than droplets of liquid agent.[54]

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[52] ‘‘Mirzayanov, Fedorov Detail Russian CW production” op. cit., footnote 34, p. 4.

[53] Crawford & Russell, Inc., *Selection and* Demonstration *of the Most Suitable Processor the Production of Methylphosphonic Dichloride* (Aberdeen Proving Ground, MD: U.S. Army Chemical Research, Development and Engineering Center, Dec. No. CRDEC-CR-87086, June 1987).

[54] J. Perry Robinson and Ralf Trapp, ‘‘~uction and Chemistry of Mustard Gas, ” S. J. Lundin, cd., *Verification of Dual-use Chemicals under the Chemical Weapons Convention: The Case of Thiodiglycol,* SIPRI Chemical & Biological Warfare Studies No, 13 (New York Oxford University Press, 1991), p. 8.

- *Antiagglomerants,* such as colloidal silica prevent caking of powdered agent.

Although stabilizers are added routinely to CW agents, thickeners and carriers are more difficult to use. Thickeners, for example, do not readily go into solution and may take several hours to dissolve. Countries that do not require agents with high effectiveness or a long shelf-life may simply choose not to use additives, thereby simplifying the production process.

FILLING OPERATIONS

In a CW agent production facility, the toxic material may flow directly from the production reactors to a munitions filling plant, where it is loaded into artillery shells, rockets, bombs, or spray tanks. Alternatively, the agent may be stored in bulk so that military missions can be considered when matching agents to munitions, or in the expectation that new delivery systems will be developed.

Because the filling operation is extremely hazardous, it is typically performed inside a sealed building with a controlled atmosphere; the filling machines themselves are totally enclosed and sealed from the external environment. The primary technical challenge is to seal the supertoxic liquid inside the munition without leakage and then to decontaminate the external surfaces. Iraq filled its unitary CW munitions on an enclosed, automated assembly line at the Al Muthanna production complex near Samarra. Such filling and sealing operations typically take about 2 to 3 minutes per projectile.[55]

A proliferant country might also fill CW munitions manually, although this operation would be labor-intensive and extremely dangerous. (Recall the quote above describing the manual filling of shells at a Soviet mustard plant during World War II.) During manual filling, a plant worker wearing a gas mask and protective clothing transfers the agent through a hose from a storage vessel to the munition, which must then be plugged and sealed without any vapor loss or spillage. In wartime, filled munitions would be transported from stockpiles to positions on the battlefield from which they would be used. Other preparatory activities, such as inserting fuses and bursters, would also be required.

MUNITIONS DESIGN

Chemical munitions are designed to convert a bulk payload of liquid or powdered agent into an *aerosol* of microscopic droplets or particles that can be readily absorbed by the lungs, or a *spray* of relatively large droplets that can be absorbed by the skin.[56] An aerosol consists of droplets between 1 and 7 microns (thousandths of a millimeter) in diameter, which remain suspended in the air for several hours and are readily inhaled deep into the lungs. In contrast, a spray capable of wetting and penetrating the skin consists of droplets at least 70 microns in diameter.[57]

A volatile agent like sarin is disseminated as a fine aerosol to create a short-term respiratory hazard. More persistent agents like sulfur mustard and VX are dispersed either as an aerosol (for respiratory attack) or as a coarse mist (for skin attack or ground contamination). After dissemination, nonvolatile agents may remain in puddles on the ground for weeks at a time, evaporating very slowly. The quantity of agent required to accomplish a particular military objective depends on the toxicity of the material involved and the efficiency of dissemination.

Many of the design specifications for chemical munitions can be found in the open patent literature, and suitable munitions production plants exist in many parts of the world. An aerosol or spray of CW agent may be disseminated by explosive, thermal, pneumatic, or mechanical means. The simplest device for deliver-

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[55] Dee, op. cit., footnote 11.

[56] J. H. Rothschild, *Tomorrow's Weapons: Chemical and Biological* (New York, NY: McGraw-Hill, 1964), p. 66.

[57] Edward M. Spires, *Chemical Weaponry: A Continuing Challenge* (New York, NY: St. Martin's Press, 1989), p. 21.

ing CW agents is a liquid spray tank mounted on an airplane or helicopter; such systems are commercially available for the dissemination of agricultural chemicals. To deliver an aerosol or spray of agent close enough to the ground to produce casualties, however, an aircraft must fly at low altitude and is thus vulnerable to air defenses, if they exist.

CW agents can also be delivered with a wide variety of munitions. During the Iran-Iraq War, for example, Iraq delivered mustard and tabun with artillery shells, aerial bombs, missiles, rockets, grenades, and bursting smoke munitions.[58] A bursting-type munition is packed with chemical agent and a high-explosive burster, a fuse, and a detonator; the use of more explosive produces a freer aerosol but may destroy much of the agent in the process. The fuse may be designed either to explode on impact with the ground or, using a proximity fuze, at an altitude of about 15 feet to enhance the formation of the aerosol cloud.[59] Sarin does not burn, but VX does and is therefore disseminated nonexplosively from a spray tank or by simple injection into the air stream from an aircraft or glide bomb.

Binary munitions

Chemical munitions can be either *unitary* or *binary in* design. Unitary munitions are filled with CW agent at a loading facility (often colocated with the production plant) before being stored and transported, so that only a fuse need be added before use. Binary munitions, in contrast, contain two separate canisters filled with relatively nontoxic precursor chemicals that must react to produce a lethal agent. The two components are either mixed together manually immediately before firing or are brought together automatically while the binary bomb or shell is in flight to the target. Contrary to general belief, the chemicals produced in binary weapons are not novel CW agents but rather well-known ones, such as sarin, soman, and VX. (For technical reasons, tabun cannot be produced in a binary system).

The United States developed three binary chemical munitions: a 155mm artillery shell to deliver sarin against enemy troop concentrations on the battlefield; the BIGEYE spray bomb to deliver VX against fixed targets deep behind enemy lines; and a warhead for the Multiple Launch Rocket System (MLRS) containing a mixture of intermediate-volatility agents.[60] The binary artillery shell is a liquid/liquid system: one of the two precursor chemicals is isopropyl alcohol (rubbing alcohol), while the other, methylphosphonic difluoride (DF), is less toxic than tear gas.[61] In contrast, the BIGEYE spray bomb is a solid/liquid system: after the bomb is released, a pyrotechnic gas cartridge mixes particulate sulfur with a liquid precursor code-named QL to form VX. After the reaction has occurred, the bomb glides across the target, dispersing VX in its wake as a spray.[62] The development of advanced binary munitions entails considerable engineering challenges, both to accommodate the two components in a ballistically sound package and to effect the necessary chemical reaction during the flight of the shell or bomb.

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[58] Harvey J. MacGeorge, ''Iraq's Secret Arsenal,'' Defense & *Foreign Affairs*, January/February 1991, p. 7; MacGeorge, ''The Growing Trend Toward Chemical and Biological Weapons Capability,'' *Defense and Foreign Affairs*, April 1991, p. 6.

[59] Burck and Flowerree, op. cit., footnote 14, p. 506-507.

[60] Dan Boyle, "AnEnd to Chemical Weapons: What Are the Chances?" *International Defense Review*, vol. 21, September 1988, p. 1088. Although the 155mm shell and the BIGEYE bomb were produced, the MLRS system was terminated in the final stages of development.

[61] In air, DF has an LD_{50} (lethal dose in 50 percent of a population) of 67,000 mg/min/m^3, compared with 63,000 mg/min/m^3 for CS (tear gas). DF and isopropyl alcohol are loaded into the munition in separate canisters; when the round is fired, the forces of acceleration rupture the wall between the canisters and allow the two reagents to mix. By the time the shell strikes the earth, the reaction is complete; the fuze detonates a burster charge, which disseminates a cloud of aerosolized sarin. Dee, op. cit, footnote 11.

[62] Dee, op. Cit., footnote 11.

Nevertheless, binary CW weapons do not necessarily require sophisticated munition designs, since the two precursor chemicals can be premixed manually on the ground immediately prior to use. Iraq, for example, developed crude binary nerve-agent bombs and missile warheads because its DF precursor was very impure, causing the sarin product to decompose rapidly. As a result, the Iraqis planned to mix the binary precursors at the last possible moment before firing. At the Al Muthanna CW production facility, Iraqi workers half-filled 250-kilogram aerial bombs and Scud missile warheads with a mixture of isopropyl and cyclohexyl alcohols, and stored the DF component separately in plastic jerry cans. The operational plan was that just before the bombs and missiles were prepared for launch, a soldier wearing a gas mask would open a plug in the bomb casing or warhead and pour in the contents of four jerry cans of DF; the ensuing reaction would result in a 60-40 mixture of sarin and GF (a more persistent nerve agent).[63]

Binary weapons offer advantages in terms of ease and safety of production, storage, and transport, and hence might be attractive to potential proliferants. Nevertheless, binary weapons create operational drawbacks on the battlefield. The two precursors must either be premixed by hand-a dangerous operation----or separate canisters containing the two ingredients must be placed inside each munition immediately before firing.

Cluster bombs

One way to increase the area coverage of an aerial bomb or missile warhead is by means of cluster munitions, in which the chemical payload is broken up into many small bomblets (submunitions) that are released at altitude and scatter over a large "footprint' on the ground. During World War II, the United States developed chemical cluster bombs that carried 100 bomblets, each containing 5 kg of mustard, Such weapons were designed to release the bomblets in a random pattern at an altitude of 1,000 feet; individual parachutes slowed the descent of the bomblets so they would not bury themselves in the ground.


UNITED NATIONS, H. ARVIDSSON

United Nations inspector sampling DF, a nerve agent precursor that had been dumped into a pit in Iraq. The Iraqis stored DF separately from their chemical munitions, intending to add it just before use to form the nerve agents sarin and GF.

MISSILE DELIVERY SYSTEMS

Ballistic missile systems such as the Soviet-designed Scud-B (with a range of 300 km) and FROG-7 (with a range of 67 km) can deliver warheads bulk-filled with chemical agent. Iraq developed bulk chemical warheads for its Al-Hussein modified Scud missiles (with an extended range of 500 to 600 km), although there is

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[63] Terry J. Gander, "Iraq--The Chemical Arsenal," *June's Intelligence Review,* vol. 4, No. 9, September 1992, p. 414.

UNITED NATIONS, SHANKAR KUNHAMBU

Iraqi worker preparing to open up for inspection a chemical warhead developed for Iraq's modified Scud missile.

no evidence that they were actually tested.[64] United Nations inspectors in Iraq were shown 30 CW missile warheads, of which 16 had unitary sarin warheads. The other 14 were of the "binary" type and were partially filled with a mixture of alcohols pending the addition of DF stored in jerry cans nearby.

During the 1950s, the United States also developed CW cluster warheads for a series of rockets and missiles, including the Honest John, Sergeant, Improved Honest John, and the developmental LANCE warhead. A cluster warhead, however, cannot cover an area large enough to ensure that a missile as inaccurate as a Scud will deliver chemical agent to a particular target. Moreover, the area covered by a cluster warhead is somewhat unpredictable, since it depends to a large extent on the terrain and weather in the target zone.

Cruise missiles and remotely piloted vehicles (RPVs) are also potential CW delivery systems. During World War II, the Germans considered filling the warhead of the V-1 flying bomb with phosgene gas instead of the normal 800kilograms of high explosive. They decided against this proposal, however, after calculating that high explosives would actually produce more casualties than gas.[65] Nevertheless, a cruise missile or long-range RPV fitted with a 500 kg spray tank would be a cheap and effective delivery system that could lay down a linear spray cloud of CW agent.

In sum, systems suitable for delivering CW agents are widely available, and even the development and production of crude (manually mixed) binary weapons does not require a sophisticated industrial base. These observations suggest that the weaponization step does not pose a major technical bottleneck to the acquisition of a CW capability.

INDICATORS OF CW PROLIFERATION ACTIVITIES

Verification of the international ban on chemical weapons will require the capability to detect militarily significant production of CW agents in a timely manner. Even a small production facility could manufacture militarily significant quantities of CW agent if it is operated for several years. Over a decade, a pilot-scale plant producing 10 tons of agent per year would accumulate 100 tons-a militarily significant quantity under certain contingencies.[66] Such long-term accumulation would, however, require distilling the agent to ensure a long shelf-life, thereby increasing complexity and cost; otherwise the total quantity of agent would be reduced by deterioration over the lo-year period. Increasing the number or scale of the production plants would reduce the length of time needed to accumulate a militarily significant stockpile.

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[64] Declan McHugh, ‘‘~w Conference,’’ *Trust and Verify, No. 35,* January 1992, p. 2.

[65] Harris and Paxman, op. cit., footnote 25, p. 59.

[66] Manuel L. Sanches et al., *Analysis of Signatures Associated with Noncompliance Scenarios,* Report No. DNA-TR-92-74 (Arlington, VA: System Planning Corp., January 19'93), p. 7.

Monitoring measures designed to detect illicit CW production may be *cooperative,* within the framework of the Chemical Weapons Convention (CWC), or *noncooperative,* based on intelligence agents, remote sensing, and covertly placed monitoring devices that are not part of a negotiated regime. The cooperative monitoring regime established by the CWC requires participating countries to submit declarations, which will then be checked through ‘‘routine’ onsite inspections; discrepancies may suggest illicit activities. To deter clandestine CW agent production, the treaty also provides for “challenge” inspections at government or private facilities, declared or undeclared. The advantage of the cooperative regime is that it permits direct access to production facilities, albeit in a tightly circumscribed manner. In contrast, unilateral intelligence-gathering efforts have the advantage that they are not constrained by agreed restrictions on data collection. The two approaches are not mutually exclusive and can be employed in a complementary manner.

Several potential indicators, or “signatures,” of CW development, production, and weaponization are discussed below. Although each signature taken in isolation is probably inadequate to prove the case, a “package” of signatures from various sources may be highly suggestive of a CW capability. Evaluating the effectiveness of the verification regime for the Chemical Weapons Convention must take into the account the specificity and sensitivity of these various signatures and how much confidence one might have in them. The following analysis does not attempt a full assessment of the CWC verification regime (e.g., detailed procedures for inspections) but focuses more narrowly on the utility of the various signatures that might be monitored.

A separate but related issue is the quality of the evidence needed to ‘ ‘prove’ to the international community that a country has violated its treaty obligations, and the consequences of detecting a violation. This issue of the standard of proof has been a long-standing problem of verification. Although there may be sufficient evidence to convince some countries that a violation has occurred-particularly if they are suspicious to begin with-the case may not be unassailable in the face of the accused party’s plausible denials. At the same time, the accusing party may not wish to release all of its supporting evidence to a larger audience because of the risk of compromising sensitive sources and methods of intelligence. The standard-of-proof problem has no simple solution and should be kept in mind during the following discussions of ‘signatures” of chemical weapon acquisition.

| Research and Development Signatures

The frost stage in the acquisition of a CW capability is laboratory research and development of offensive agents, although this step is not necessary if standard agents and known production processes are to be employed. The following step is pilot-scale production to work out problems in the manufacturing process. Because of the small scale of these operations, they can be very difficult to detect.

SCIENTIFIC PUBLICATIONS

One way of tracking a country’s research and development activities relevant to CW is to read its contributions to the chemical literature. The fact that leading academic chemists suddenly stop publishing may bean indicator of military censorship or the diversion of civil scientists into defense work. Publication tracking can also produce red herrings, however, since changes in scientific productivity may result from many factors. During World War II, for example, the Germans read great significance into the fact that references to new pesticides suddenly disappeared from U.S. scientific journals. German intelligence analysts deduced correctly that military censorship was responsible for the cut-off, but they wrongly assumed that the United States had independently discovered nerve agents. The Germans’ faulty intelligence assessment led them to fear U.S. retaliation in kind if they initiated the use of nerve agents, and was one of several factors that deterred them fiorn resorting to chemical warfare.[67]

While publication tracking might provide clues to technologically advanced CW developments, it would be much less useful in the case of a developing country like Iraq that is simply attempting to produce standard agents with known production processes. Such a country would employ mainly industrial. chemists and chemical engineers, who publish very little in the open literature. For this reason, publication tracking is likely to be of only secondary value in monitoring CW proliferation.

HUMAN INTELLIGENCE (AGENTS OR DEFECTORS)

Human agents, defectors, or even leaks to the press in more open societies can be of value in revealing the existence of secret chemical-warfare R&D activities. In October 1992, for example, Vil Mirzayanov, a Russian military chemist, gave interviews to the press in which he stated that scientists at the State Union Scientific Research Institute of Organic Chemistry and Technology in Moscow had developed a new binary nerve agent that, in terms of its combat characteristics, was "five to eight times superior' to the most toxic of the VX-type agents now in existence. Mirzayanov also alleged that a batch of between five and 10 metric tons of the new agent had been produced.[68] He was subsequently arrested by the Russian Security Ministry (the successor to the KGB) and charged with revealing state secrets.[69] Because human-intelligence reports--particularly those based on hearsay or indirect evidence—may be misleading, however, they typically need to be confirmed with other, more objective forms of evidence before being used to support final conclusions.

| External Production Signatures

Since so much of CW agent production involves dual-use technologies, it is necessary to distinguish clearly between illicit and legitimate production. Unfortunately, there are few, if any, specific, unambiguous external signatures of CW production. A number of potential indicators are discussed below.

PATTERNS OF MATERIAL AND EQUIPMENT IMPORTS

Developing countries seeking to acquire a CW capability are nearly always dependent on outside assistance, at least in the initial stages. During the 1980s, numerous companies from Western Europe and Japan sold chemical plants to proliferant countries, which then converted them into CW production facilities. Different suppliers provided the laboratories and production plants, sold chemical precursors, and furnished maintenance equipment. Iraq, for example, was able to purchase 7 turnkey chemical plants and to order thousands of catalogue parts on the international market, along with all the necessary precursor chemicals for the production of CW agents. Similarly, the Libyan CW plant at Rabta was designed by the West German firm Imhausen-Chemie and built by companies from ''nearly a dozen nations, East and West, ' according to Robert M. Gates, then deputy director of the National Security Council.[70]

Because of the initial reliance of proliferants on outside assistance, suspicious exports and imports of production equipment and chemical

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157 Harris and Paxman, op. cit., footnote 25, p. 64. For a discussion of other factors that convinced the Germans not to use chemical weapons, see Frederick J. Brown, *Chemical Warfare: A Study in Restraints* (Princeton, NJ: Princeton University Press, 1%8); and John Ellis van Courtland Moon, "Chemical Weapons and Deterrence: The World War II Experience," *International Security*, vol. 8, No. 4, spring 1984, pp. 3-35.

68 ''Mirzayanov, Fedorov Detail Russian CW Production,'' Op. Cit., footnote 34, p. 2.

69 Serge Schmemann, ''K.G.B.'s Successor Charges Scientist," *New* York *Times, Nov.* 1, 1992, p. 4.

70 William Tuohy, ''U.S. Pressing Allies on Libya Chemical Plant,'' *Los Angeles Times*, Jan. 3, 1989, p. 10.

precursors may indicate the acquisition of a CW production capability. For this reason, monitoring exports of materials considered critical for CW production, such as glass-lined pipes and corrosion-resistant alloys, could prove useful.[71] Since much of this equipment is dual-use, however, its acquisition is not necessarily proof of an intent to produce CW agents. Moreover, tracking such transactions is difficult because proliferants like Iraq and Libya take care to set up elaborate networks of 'front' companies, paper subsidiaries, and middlemen to hide their purchases.

Precursors of CW agents are also difficult to track. Unlike weapon-grade fissionable materials (e.g., highly enriched uranium and plutonium), which are produced in relatively small quantities and have quite restricted civil uses, most CW precursors have legitimate commercial applications and are traded internationally in volumes that make precise accounting impossible. A useful case study is that of thiodiglycol, the immediate precursor of sulfur mustard. Since a limited number of companies and countries manufacture this chemical, it was initially believed that calculating the agreement between its production and consumption, or *material balance,* might provide a way to detect diversions from legitimate commercial uses to illicit mustard production.

In 1989-91, a working group of the international scientists' organization Pugwash studied the feasibility of such a monitoring effort. They found that since thiodiglycol could be produced secretly or diverted from legitimate uses with relative ease, an effective control regime would require: 1) continuous monitoring of all chemical plants capable of producing it, and 2) establishing a materials balance between starting materials and products at all stages of its life-cycle. The Pugwash team concluded that such a monitoring system would be extremely difficult and costly to implement. Moreover, standard inaccuracies in data-gathering on feedstock chemicals could mask the diversion of significant quantities of thiodiglycol for the production of mustard agent, rendering mass-balance calculations of questionable utility .[72]

Tracking phosphorus-based compounds used to make nerve agents is even more difficult. Billions of pounds of these chemicals are bought and sold for commercial purposes, so that militarily significant quantities would be lost in the ''noise' of international trade. Because the production of many basic commodity chemicals is shifting from the industrialized countries to the developing world, some precursor chemicals are produced at multiple locations in several countries, greatly complicating the difficulty of material accounting. Moreover, given the long interval between order and delivery, it is difficult to account for materials in transit.

At the level of an individual plant, calculating the material balance between the feedstocks entering a plant and the products coming out is only possible to an accuracy of 2 to 3 percent—a margin of error too large to prevent a militarily significant diversion of precursors to CW agent production. Calculating a precise material balance would also require extensive access to a company's production records and might therefore jeopardize legitimate trade secrets. As a result, materials-balance calculations cannot provide a reliable indicator that precursor chemicals are being diverted to CW agent production.

Some analysts have suggested that the *ratios* of starting materials and catalysts needed for CW agent production might provide reliable signatures because they are distinctive from those used in commercial production. For example, a plant producing 10 tons of sarin per day would need large quantities of precursors and catalysts in

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[71] Robert Gillette, "Verification of Gas Plant a Murky Task,'' *Los Angeles Times,* Jan. 5, 1989, p. 5.

[72] Martin M. Kaplan et al., ''Summary and Conclusions, ' *Verification of Dual-Use Chemicals Under the Chemical Weapons Convention: The Case of Thiodiglycol,* S. J. Lundin, ed. (Oxford, England: SIPRI/Oxford University Press, 1991), pp. 124-136.

specific proportions. Nevertheless, many complex factors influence the quantities of precursor chemicals consumed by a chemical plant, including the stoichiometry of the reactions used for agent production, the number of production steps, and the yield of each step.[73] Some reactants might be used in excess to boost yield or to increase reaction rates, and feedstocks could be deliberately stockpiled to distort the calculated ratios. For these reasons, ratios of starting materials are unlikely to provide a reliable indicator of CW agent production.

The presence of key additives (e.g., stabilizers, thickeners, or freezing-point depressants) in association with precursor chemicals may be indicative of CW agent production. Because the use of additives is generally optional, however, their absence would not necessarily rule out illicit CW agent production.

ECONOMIC DISLOCATIONS

The clandestine diversion of a large commercial chemical plant (and associated precursor materials) to CW production might have a noticeable impact on the local economy in a small, underdeveloped country with relatively little economic activity. For example, temporarily ceasing civilian production might create observable shortages of consumer goods normally produced by the plant, such as pesticides or drugs. Whether such economic dislocations would be observable, however, depends on the extent to which the chemical plant was integrated into the local economy. In more industrialized countries such as India, South Korea, and Taiwan, such relatively small economic effects would be obscured by the ‘‘noise” of fluctuating output within the overall economy. Moreover, in some developing countries, chemical production is entirely for export, so that one would have to monitor foreign sales rather than domestic markets. A proliferant country might also stockpile a portion of its output for several months or years and use it to make up for shortfalls in normal production. As a result, economic dislocations are unlikely to be a reliable signature.

VISUAL SIGNATURES

Unlike nuclear weapon facilities, which are single-use, limited in number, and easy to identify, civilian chemical plants are two orders of magnitude more numerous, have multiple uses, and are configured in different ways depending on the chemical process. Moreover, there are no unique features or external markings that would distinguish a facility capable of CW agent production from an ordinary chemical plant.[74] A clandestine military production facility might be hidden underground or inside a mountain, or embedded within a legitimate chemical complex, making it essentially invisible from the air. Chemical munitions are small, impossible to distinguish visually from high-explosive shells, and easy to conceal, as are bulk chemical agents. Indeed, 100 tons of nerve agent—a militarily significant quantity in many conflict scenarios—would fit into a dozen trailer-trucks.[75] A proliferant country might therefore hide chemical weapons or bulk agent on railcars, in underground bunkers, or in inconspicuous buildings.

Despite these limitations, however, a pattern of anomalous visual indicators at a chemical facility might arouse suspicions that could be verified by other means. Indicators of CW production that might be visible in overhead imagery obtained by reconnaissance aircraft or satellites include:

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[73] Mark F. Mullen, Kenneth E. Apt, and William D. Stanbro, *Criteria for Monitoring a Chemical Arms Treaty: Implications for the Verification Regime* (Los Alamos, NM: Los Alamos National Laboratory, Center for National Security Studies, Report No. 13, December 1991), p. 8.

[74] Briefing by Manuel L. Sanches, System Planning Corp., Oct. 23, 1992.

[75] Kathleen C. Bailey, “Problems With a Chemical Weapon Ban,” *Orbis*, vol. 36, No. 2, spring 1992, p. 244.

- the construction of a large chemical plant that has not been reported in the chemical trade press;[76]
- siting of the plant in an extremely remote and isolated location;
- a high level of security surrounding the plant, such as multiple or electrified fences, air-defense batteries, and guard units;
- an extremely dispersed layout, with large distances between buildings to complicate attacks from the air;
- the proximity of the chemical plant to a metal-machining factory capable of fabricating munitions;
- the presence of tanker trucks associated with the transport of hazardous chemicals;
- a lack of steel drums or other packaging materials normally associated with the production of commercial chemicals;
- traffic movement at night or under guard;
- the death of vegetation, livestock, birds, or wild animals in the vicinity of a plant;
- a flurry of activity at a chemical facility suggestive of a major accident, yet no coverage of the event in the local media.

Box 2-A provides an example, taken from press accounts, of how visual signatures contributed to the identification of a CW production facility in Libya. The utility of these signatures depends, of course, on the individual proliferant's approach. Although the visual indicators cited above would have worked well for Iraq, they would have been unsuccessful in the case of a proliferant that embedded its CW production facilities within large commercial chemical complexes.

In addition to visual signatures, infrared reflections or emissions detected by specialized overhead sensors might, in principle, provide indications of CW production activity .77 For example, multispectral cameras might detect stressed or dying foliage around a production plant resulting from emissions of toxic chemicals. A thermal-infrared camera might also assist in monitoring a facility's operational status by revealing the intensity of heat emitted by various parts of the production line and smokestacks. Cool and hot buildings, pipelines, and tanks could be readily identified by infrared imaging, indicating which parts of the facility were active at any given time-although such evidence could be misleading.[78] Synthetic-aperture radar (SAR) imagery, which tends to highlight reflective surfaces, might also reveal details not evident in an optical photograph such as feed pipes, power lines, and vehicles parked around a facility .[79] SAR can also generate images of near-photographic quality at night and in bad weather.

Nevertheless, overhead reconnaissance has its limitations. In addition to the difficulty of distinguishing a CW production facility from an ordinary chemical plant in photographs, overhead imagery may be susceptible to deliberate efforts at camouflage, concealment, and deception (CC&D). The Libyans, for example, reportedly engaged in an effective deception campaign that initially convinced Western intelligence agencies that the Rabta CW production plant had been destroyed

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[76] In general, the trade press reports on the construction of all major legitimate chemical plants.

[77] For additional information on surveillance and remote sensing, see Us. Congress, Office of Technology Assessment, *Cooperative Aerial Surveillance in International Agreements*, OTA-ISC-480 (Washington, DC: U.S. Government Printing Office, July 1991) and U.S. Congress, Office of Technology Assessment, *The Future of Remote Sensing From Space: Civilian Satellite Systems and Applications,* OTA-ISC-558 (Washington, DC: U.S. Government Printing Office, July 1993).

[78] Amy Smithson and Michael Krepon, *Strengthening the Chemical Weapons Convention Through Aerial Inspections,* Occasional Paper *No. 4* (Washington, DC: Henry L. Stimson Center, April 1991), p. 15.

[79] Synthetic-aperture radar (Sri) creates a detailed terrain map by capturing the reflection of timed microwave pulses emitted by a moving transmitter, whose motion creates a synthetic antenna with an apparent diameter much greater than that of the actual transmitting antenna. This large effective antenna size allows much greater resolution than a stationary radar could achieve, permitting the creation of photograph-like images.

Box 2-A-How Libya's Secret CW Plant Was Detected

Press accounts provide an interesting illustration of how patient detective work by the U.S. intelligence community, compiling data from a wide variety of sources, provided strong circumstantial evidence that Libya was building a clandestine CW facility long before the plant started production.[1] (In summarizing these stories here, OTA is neither confirming nor challenging their accuracy.) The Rabta case therefore provides some useful lessons in the detection of covert CW proliferation by intelligence means.

In the early 1930s, reconnaissance-satellite photos of Libya revealed that a major construction project was under way in a hilly region about 35 miles southwest of the Libyan capital of Tripoli. Western intelligence reports also indicated that Ihsan Barbouti, an Iraqi-born businessman whose Frankfurt-based engineering firm had been linked to the construction of a CW plant in Iraq, was using front companies to ship chemical equipment, supplies, construction plans, and personnel to Libya. Barbouti's operation involved some 30 German companies, several Austrian engineers, and Swiss banks.[2]

The prime contractor was lmhausen-Chemie, a West German chemical firm that became involved with the Libyan project in 1985, at a time when it was in financial difficulties. Most of the equipment and supplies left European ports under false export documents, and in order to circumvent existing export controls, Barbouti used a complex commercial network involving front companies that transferred goods through ports in the Far East.[3] Construction at Rabta was carried out under tight security conditions by 1,300 low-wage laborers imported from Thailand.[4]

Meanwhile, satellites and high-altitude reconnaissance aircraft followed the progress of construction at the Rabta site. By 1938, the imagery suggested that the facility, which sprawled over several acres, was nearing completion. Libyan government officials adamantly insisted that the Rabta facility was a pharmaceutical plant, designated Pharma-150. Yet the factory was unusually large by the standards of the pharmaceutical industry and was ringed by high fences and 40-foot sand revetments-seemingly excessive security for an ordinary chemical plant.[5] Since the production facility was completely enclosed inside a warehouse-like structure, overhead photography revealed nothing about the process equipment inside, but the plant's oversized air-filtration system suggested that it was intended for the production of toxic chemicals.

Once the overhead imagery had aroused suspicions, Western countries sought to develop new sources of information among the foreign technicians and construction workers from more than a dozen European, Asian, and Middle East countries employed at the Rabta facility. These sources described plant equipment layout, and supplies, providing additional dues that the site might be intended for CW production. Intelligence analysts concluded that the complex comprised a large chemical agent production plant, a chemical arms storage building, and a metalworking plant built by Japan Steel Works.[6] The latter facility contained Japanese-made machine tools, officially intended for the production of irrigation pumps but also suitable for the production of artillery shells and gas cannisters.[7] Delivery of special steels used in bomb casings suggested to U.S. and British intelligence that

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[1] See Thomas C. Wiegele, *The Clandestine Building of Libya's Chemical Weapons Factory: A Study in International Collusion* (Carbondale, IL: Southern Illinois University Press, 1992).

[2] William C. Rempel and Robin Wright, "Libya Plant Found by Vigilance, Luck," *The* Los *Angeles Times*, Jan. 22, 1989, pp. 1,21.

[3] Timothy Aeppel, "Seeking Smoking Guns," *The Christian -rice Monitor*, Jan. 6, 1989, p. 1.

[4] William R. Doerner, "On Second Thought," *Time*, vol. 133, No. 4, Jan. 23, 1989, p. 31.

[5] Bill Gertz, "Satellites Spot Poison-Bomb Piant in Libya," *Washington Times*, Mar. 5,1991, p. A3.

[6] Bill Gertz, '12nd Chemical Arms Plant Spied in Libya," *The Washington Times*, June 18, 1990, p. A6.

[7] Robert Gilette, "Verification of Gas Plant A Murky Task" Los *Angeles Times*, Jan. 5, 1989, p. 11.

Libya was actually manufacturing chemical munitions?

The West German government obtained construction blueprints of the Rabta plant from the engineering firm Saltzgitter. These plans revealed some anomalous features suggestive of CW agent production. According to a German government report,

> The joint planning of chemical plants and the metal processing plant as well as security facilities not usually found in a pharmaceutical facility (airtight windows and doors, gas-tight walls between the production and the control unit, burn-off unit, corrosion-proof lining on pipes, and escape routes) make it possible to draw the conclusion that 'Pharma 150' is a chemical weapon Plant[9]

It was not until August 1988, however, that the CIA obtained more solid evidence that the Rabta plant was engaged in CW agent production. Following a partial test run of the production process, an accidental spill occurred as highly toxic wastes were being transferred for diaposal outside the plant. The resulting aloud of fumes killed a pack of wild desert dogs in the vicinity of the plant. Their bodies, detected by satellite, indicated that the plant was producing chemicals of warfare toxicity.[10]

The "smoking gun," however, reportedly came from communications intercepts. During the accident, panicked Libyan officials called Imhausen-Chemie-the West German firm that had designed the plant-for emergency advice. Since the Libyans placed the call over international phone lines, U.S. intelligence was able to intercept the conversation.[11] According to an account in Time magazine, "in a frantic effort to get advice on cleaning up and repairing the plant, Libyan officials spoke at length with Imhausen-Chemie personnel. Those conversations left no doubt that employees of the West German firm were just as aware as the Libyans that the plant was being used to produce toxic gas."[12]

On September 14,1988, the State Department went public with the fallowing statement: 'The U.S. now believes Libya has established a CW production capability and is on the verge of full-scale production of these weapons." CIA director William Webster provided further details in a speech on October 25, 1988 claiming that the Libyan plant was the largest chemical weapon facility the agency had detected anywhere in the developing world.[13] In August 1990, the intelligence community deduced that large-scale production of chemical agents at Rabta had begun after a photoreconnaissance satellite observed specialized trucks designed to transport CW agents picking up barrels of suspected agent at the plant.[14] In 1992, an intelligence official stated publicly that the Rabta facility had produced and stockpiled more than 100 metric tons of the nerve gas sarin and other CW agents.[15]

Nevertheless, the public case against Rabta-as reported in the news media-is circumstantial and will remain so until Libya signs and ratifies the Chemical Weapons Convention and permits intrusive inspections of the facility. According to a skeptical assessment, "Neither the charges that Libya is attempting to develop chemical weapons nor the allegations that Libyan forces have used them can be independently substantiated from the public

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[8] James Adams, *Engines of War: Merchants of Death and the New Arms Race* (New York, NY: Atlantic Monthly Press, 1990), p. 243.

[9] "Report Submitted by the Government of the Federal Republic of Germany to the German Bundestag on Feb. 15,1989, Concerning the Possible Involvement of Germans in the Establishment of a Chemical Weapon Facility in Libya," reprinted in U.S. Senate, Committee on Foreign Relations, *Chemical and Biological Weapons: The Urgent Need for Remedies*, 101st Congress, First Session, Jan. 24, Mar. 1, and May 9, 1989 (Washington, DC: Government Printing Office, 1989), p, 81.

[10] Rempel and Wright, op. dt., footnote 2, p. 21.

[11] Ibid, pp. 1, 21.

[12] Doerner, op. dt., footnote 4, p. 31.

[13] David B. Ottaway, "Behind the New Battle With Libya," The *Washington Post*, Jan. 8, 1989, p. C4.

[14] Gertz, op. cit., footnote 6, p. Al.

[15] Gordon C. Oehler, "Address to the Annual Soref Symposium of the Washington Institute fOr Near East Policy," Apr. 27, 1992, p. 4.

Box 2-A-How Libya's Secret CW Plant Was Detected-(Contfnued)

record, but there is sufficient circumstantial evidence to make Libya a strong suspect as a chemical **weapons** proliferator:’[16]

Moreover, although the detection and monitoring of the Rabta site was an intelligenoe success-story, it remains to some extent a special ease. Because Libya is a desert nation that relies heavily on **foreign expertise and labor, the** presence of foreigners **provided valuable sources of information. Denselypopulated and** industrialized countries suspected of having covert CW programs are harder to monitor because they can conceal them in a large and diverse array of chemical plants involved in production of pharmaceuticals, pesticides, and fertilizers.[17] Finally, even in the Rabta case, the inherent unreliabilityof circumstantial evidence underscores the importance of rigorous onsite inspection in verifying the Chemical Weapons Convention.

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[16] Gordon M. Burck and Charles C. Flowerree, *International Handbook on Chemical Weapons Proliferation* (New York, NY: Greenwood Press, 1991), p. 267.

[17] Rempel and Wright, op. dt., footnote 2, p. 21.

by fire on March 13, 1990.[80] When the French commercial Earth-resources satellite SPOT-1 photographed the Rabta facility on March 18, however, it looked fully intact.[81] According to press reports, only after several days did the U.S. intelligence community realize that the Libyans had created the illusion of a major fire at the plant by painting scorch marks on the roofs of buildings, burning several truckloads of old tires to produce black smoke, and. rushing ambulances to the area to make it appear that the plant had suffered severe damage.[82]

In sum, external visual signatures, such as those that might be observed through overhead photography, can provide clues of CW production activities but. are rarely conclusive and must be supplemented with evidence from onsite inspections. While it is possible to conclude from indirect or ambiguous signatures that something suspicious is going on, making a convincing case that a country has broken its solemn treaty commitments requires a higher standard of evidence.

| Internal Production Signatures

Under the CWC verification regime, external signatures obtained noncooperatively through overhead photography and remote-sensing will be supplemented with internal signatures obtained by authorized onsite inspections. Examples of some internal signatures are discussed below.

PRODUCTION PROCESS EQUIPMENT

As discussed above, the synthesis of nerve agents requires a few reactions that are rare in the production of pesticides: the cyanation reaction for the synthesis of tabun; the alkylation reaction for the synthesis of sarin, soman, and VX; and the fluorination reaction for the synthesis of sarin and soman.[83] Indeed, since alkylation is not required for the production of most organophosphorus pesticides, civil plants employ feedstocks con-

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So Michael R. Gordon, "U.S. Says Fire at Libya Arms Plant May Be a Hoax," *The New York Times*, Mar. 31, 1990, p. 3.

[81] "Small Fire, Much Smoke," *The Economist*, vol. 314, No. 648, Mar. 31, 1990, p. 42.

[82] Bill Gertz, "Satellites Spot Poison-Bomb Plant in Libya," *The Washington Times*, Mar. 5, 1991, p. 3.

[83] Burck, op. cit., footnote 33, p. 155.

[84] The phosphorus used in most pesticides is pentavalent rather* trivalent.

taining a different chemical form of phosphorus than is used to make nerve agents.[84]

Unfortunately, there is no “signature equipment for the manufacture of CW agents. Since CW agents can be and have been produced by a variety of standard organic-chemical processes, it is almost impossible to identify an individual piece of equipment that has been specifically designed or modified for this purpose. This fact makes it extremely difficult for all but the most trained eye to spot a CW production facility. The necessary equipment would tend to be standard rather than unique, consisting of chemical reaction vessels and “back-end’ processing equipment. Distillation columns, for example, are not necessarily a good indicator of illicit activity because they are also found in many legitimate chemical plants. They might also be omitted from a CW production facility if the proliferant does not require pure agent with a long shelf-life.

Still, a combination of subtle changes in plant design and layout might be indicative of illicit production, particularly if an analysis of the design suggests that it does not make engineering and economic sense for its declared commercial purpose. For example, unusual process steps such as alkylation might stand out if they are inconsistent with the plant’s pastor present mix of commercial products or are not being carried out on an appropriate scale. A plant designed to work with highly toxic materials might also have specialized pumps and valves with double seals and other safety measures. In such cases, a more intrusive inspection would be warranted to verify that the suspect facility is not engaged in CW production activities.

Another feature of a nerve-agent production plant that might help distinguish it from an ordinary pesticide plant is the means of heating and cooling the reaction vessels. Since chemical processes for nerve agents produce highly unstable intermediates that react explosively with water, steam-heating and water-cooling must be replaced with special heat-exchange fluids and heating oils that require the use of cooling towers rather than steam vents. A nerve-agent production plant would therefore lack the steam clouds that are a common feature of chemical plants.[85] Even so, this signature would not necessarily be unique to nerve-agent production, since many legitimate chemical plants use organic solvents or mineral oils as heating and cooling media rather than steam or water. Moreover, a shrewd proliferant seeking to avoid detection might deliberately install misleading steam-cloud generators!

In general, analysis of plant design and layout is most useful in the case of turnkey plants developed and exported by foreign companies, which tend to use distinctive design formats and templates. Indigenously designed chemical plants may have unique layouts that make it more difficult to draw inferences about their functions.

CORROSION-RESISTANT MATERIALS

Since the reactions needed to produce mustard and nerve agents are highly corrosive, along-term CW production facility might use corrosion-resistant pipes, valves, and reaction vessels made of special alloys with a high nickel content, such as Hastelloy. Unfortunately, there is currently no practical method to identify corrosion-resistant materials without taking physical samples or looking inside, particularly if a reactor or pipe is painted or wrapped in insulating material.[86] Moreover, the use of corrosion-resistant reactors and pipes is increasingly common in the civilian chemical industry. Since commercial manufacturers may wish to avoid replacing vessels and pipes on a regular basis, some advanced commercial plants build in an extra level of protection by installing Hastelloy or glass-lined reaction vessels to protect equipment and maintain product

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[85] Stockholm International peace Research Institute, *The Problem of Chemical and Biological Warfare, Vol. VI: TechnicalAspects of Early Warning and Verification* (Stockholm: Almqvist & Wiksell, 1975), p. 293.

[86] Sanches et al., op. Cit., footnote 66, p. 63.

purity. A proliferant country might also be able to acquire used corrosion-resistant equipment that still has a few years of life in it after the guaranteed 5 to 10 years have expired.[87]

Conversely, a proliferant engaged in the covert production of CW agents might choose deliberately not to use corrosion-resistant materials for the following reasons:

- such materials might not be available because of export controls;
- the use of such materials might reveal the intent to produce CW agents; or
- the near-term capital cost to extend the life of the equipment would not be justified, particularly if a country planned to produce only a limited stockpile of chemical weapons.

Although a stainless-steel reactor will be severely corroded by HF gas, it can still function for about a year. A proliferant might therefore be willing to live with the inconvenience of replacing equipment at shorter intervals and use ordinary construction materials in an attempt to conceal its activities. For this reason, the presence in a chemical plant of corrosion-resistant material does not necessarily indicate that C W agents are being produced, and its absence from a suspect facility may merely reflect the frequent replacement of standard equipment or a lack of plans for long-term agent production.

SAFETY AND POLLUTION-CONTROL EQUIPMENT

The toxicity of nerve agents is roughly 1,000 times greater than that of most organophosphorus pesticides. Nevertheless, only the last step in agent production poses a serious toxic hazard; in the case of both G and V agents, this is a very small part of the process. To prevent the release of deadly fumes into the environment, the final process step in a CW production plant would probably be carried out in a tightly sealed enclosure, operated at a negative pressure so that any leaks would result in air being drawn in rather than toxic gases escaping. Reaction vessels involved in this step might also be operated by remote control, requiring special piping and computer systems, and pumps might be equipped with double or triple seals to guard against leaks.[88]

A CW production plant might also have ventilation and emission-control systems that differ from those of a legitimate pesticide or pharmaceutical plant. In pesticide plants, fresh air often circulates continually through the plant and vents directly into the atmosphere. Although increasingly stringent environmental regulations are strengthening emission controls in developed countries, pesticide plants in developing countries are likely to be open to the environment.[89] Similarly, pharmaceutical plants generally shield products from contamination by maintaining the production area at a *higher air* pressure than the outside environment, so that all contaminants flow away from the production process. In contrast, in a CW agent plant the final production steps would probably be maintained at a *lower* pressure than the outside air so that the lethal vapors do not leak into the surrounding environment.

The hazards associated with production of nerve agents might also require the use of large activated-carbon filtration systems and scrubbers to remove all supertoxic chemicals from the exhaust air. The German firm of Noske-Haeser, for example, installed an expensive air-cleaning plant for the Iraqi chemical laboratory at Salman Pak Intelligence analysts concluded that the dimensions of the air-cleaning system were too large if the 10 laboratories were simply engaged in commercial research and development, partic-

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[87] Gordon Burck, EAI corporation personal communication, 1992.

[88] Burck, op. cit., footnote 13, p. 129.

[89] Peter M. Zapf, "Appendix A: The Chemistry of Organophosphate Nerve Agents," Benoit Morel and Kyle Olson, eds., Shadows *and Substance: The Chemical Weapons Convention* (Boulder, CO: Westview Press, 1993), p. 297.

ularly given the fact that the Iraqis did not normally care about environmental protection.[90] Thus, while plant emission controls would reduce chemical signatures outside the plant, the presence of scrubbers and other air-cleaning systems would provide a clue that toxic agents were being produced.

Still, while special containment measures may provide a telltale sign of CW agent production, they are by no means a foolproof signature. First, the pressurization of a facility can be reversed by changing the direction of air flow, perhaps in a deliberate attempt to deceive an inspection team, although this capability must be designed-in. Second, as the chemical industry has adapted to increasingly stringent environmental and occupational-safety laws, ordinary chemical plants have increasingly adopted sophisticated air-treatment systems and corrosion-resistant materials, blurring the distinction between CW-capable and commercial facilities. As a result, equipment designed for commercial purposes may provide adequate containment for CW-agent production.[91]

Conversely, a lack of stringent safety measures is not a foolproof indicator that a country is not producing CW agents, since a ruthless government that does not care about the welfare of workers might fail to take such basic precautions. Although the German Government argued that the chemical plant sold to Iraq by the Karl Kolb firm was not suitable for CW production because it lacked adequate safety equipment, the real reason for the lack of safety measures was Saddam Hussein's willingness to tolerate a high incidence of injuries and deaths among the plant staff. Iraqi officials later admitted to UN inspectors that there were about 100 accidents per year involving chemical agents, 10 of them major.[92]

Finally, the advent of binary chemical weapons means that it is no longer necessary to manufacture supertoxic agents to acquire a CW capability. Instead, a production plant could manufacture DF, the immediate precursor of the G agents, which is no more toxic than many commercial organophosphorus pesticides. Such a plant would not require high levels of containment and hence could be more easily disguised.

WASTE TREATMENT AND DISPOSAL

Chemical weapon producers have been known to dispose of their highly toxic wastes in an environmentally reckless manner. After World War II, the Soviet Union and other countries dumped large quantities of nerve and mustard agents at sea in metal barrels that have now corroded, posing a serious threat to the marine environment. The Soviets also dumped vast quantities of toxic wastes from CW agent production directly into rivers. In the aftermath of the Gulf War, Iraq destroyed large quantities of chemical munitions it had failed to declare by pouring the toxic agents into standing ponds or holes dug in the ground, and by open-air burning.[93]

Nevertheless, countries with greater concern about protecting the environment might equip a CW agent production plant with more extensive waste-treatment facilities than a typical commercial plant. Such facilities might include tanks for the storage of toxic wastes and a treatment unit to neutralize acid byproducts with alkaline chemicals and to detoxify and remove phosphorus compounds. After treatment, the neutralized wastes might be reduced by evaporation or incineration, and then disposed of in ways that might be observable. For example, *waste lagoons are* quite conspicuous because of their size and

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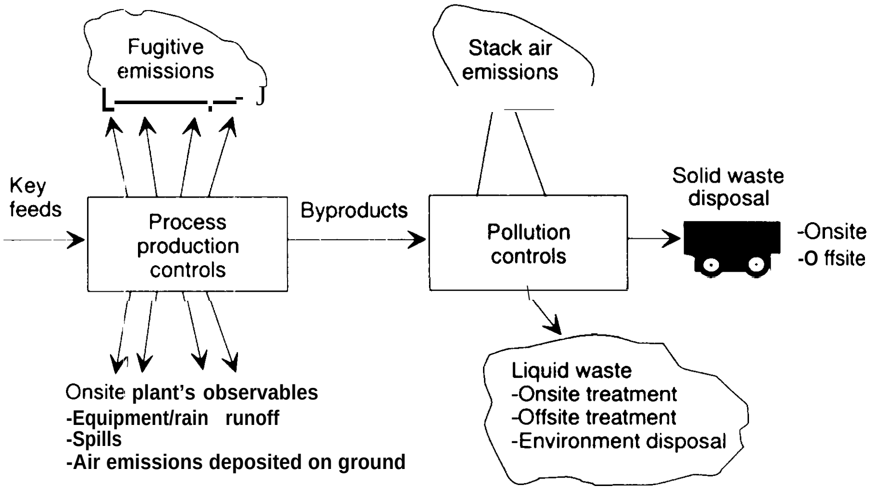
[90] "Report on German Technology in 'Diyala' Gas Lab," *Stern*, Feb. 7,1991, pp. 29-33; translated in FBIS-WEU-91-032-A, Feb. 15,1991, p. 9.

[91] Burck and Flowerree, op. Cit., footnote 14, p. 13.

[92] *Chemical Weapons Convention Bulletin,* op. cit., footnote 50, p. 16.

[93] Peter Grier, "UN Inspectors in Iraq Get Chemical Surprise, " *Christian Science Monitor,* June *23, 1992,* pp. 1,4.

Figure 2-4-Production Facility Observable



SOURCE: System Planning Corp., *Chemical Weapons* Convent/on *(CWC) Signatures Analysis,* Final Technical Report No. 1396, August 1991, p. 61.

because phosphates promote algal and bacterial growth, which would be visible in overhead photographs. (However, some legitimate chemical plants have lagoons situated near agricultural land, where fertilizer runoff may cause similar algal blooms during the summer months.) Another disposal method involves injection of toxic wastes into *deep underground wells. Since* deep wells are hard to dig and would have to be quite large, they might be difficult to conceal.[94] The waste well at the U.S. Rocky Mountain Arsenal, for example, was 12,000 feet below the surface.

CHEMICAL SIGNATURES

The goal in collecting and analyzing samples during on-site inspections of chemical plants and suspect facilities is to detect signatures of illicit CW production; at the same time, it is important to minimize the potential for false alarms and to limit the disruptive effects of sampling on the commercial chemical industry. Phosphorus-methyl (P-CH_3) bonds are characteristic of nerve agents, are rare in most organophosphorus pesticides, and are extremely resistant to degradation and hence persist for long periods in the environment. The phosphorus-fluorine bond found in sarin and soman is also unusual, and its detection in a commercial pesticide plant would warrant further investigation.

Chemical signatures may be detected from a variety of sources. (See figure 2-4.) Inspectors given on-site access to chemical facilities under the terms of the chemical Weapons Convention will be allowed to take wipe samples from the surfaces of process and pollution-control equipment, as well as liquid samples from the production process and the waste stream. Even if the reactors and pipes are flushed clean prior to an inspection, the production of CW agents would leave behind traces of agents, precursors, and byproducts that are absorbed into rubber seals and gaskets, which are too costly to replace frequently. The concrete floor of a plant also provides an absorbent matrix for leaked chemicals and is a potential reservoir of CW agent residues. Analyzing such samples with sensitive

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[94] Stockholm International Peace Research Institute, op. cit., footnote 85, p. 293

analytical techniques such as combined gas chromatography/mass spectrometry should therefore reveal the presence of telltale chemicals. (See app. 2-A.) Nevertheless, such sampling and analysis may be constrained by the amount of access provided during an onsite inspection.

Detecting Clandestine Production

Detection of clandestine CW agent production in a nondeclared facility would require noncooperative data collection by human agents or by covertly emplaced or remote sensors, which might then be used to cue a challenge inspection. While detection of a clandestine production facility would be difficult, some possible signatures are discussed below.

EFFLUENT ANALYSIS

A number of approaches rely on the monitoring of plant effluents to detect clandestine CW agent production at a distance. One such approach is to use computer atmospheric models to predict where gaseous plant emissions are most likely to be deposited on the ground, and to take soil samples from such locations for analysis. Because the atmospheric models are imperfect, however, the effluent sample may be too dilute to be identified.

Near-site monitoring techniques, such as laser spectroscopy, are also under development for detecting telltale chemicals in the exhaust plumes rising from chemical plant stacks without the need to obtain access to a plant site. Such technologies include both passive spectroscopic systems that detect and analyze radiant emissions at multiple wavelengths, and active systems that transmit laser radiation at selected wavelengths and then analyze the backscattered or emitted radiation. (See app. 2-A.) At present, near-site monitoring technology is not yet sufficiently sensitive or reliable for verification purposes. Part of the problem is that the quantity of gaseous emissions from a chemical production facility is very site-dependent and is a function of the plant's emission-control systems and the quality of its maintenance.

A third approach to detecting clandestine CW agent production is the analysis of liquid effluents. Since no chemical reaction is 100 percent complete, there are always some residual materials left over that may not be emitted as a gas and will emerge in the waste stream. All methods of CW production produce significant quantities of wastes, although the exact amounts depend on the choice of production process, the extent of recycling, and how rapidly the waste stream is sent to a treatment facility. Flushing out the production line with a decontaminating solvent or water also creates a liquid effluent that must be disposed of. Analyzing such chemical traces may therefore provide a means of detecting CW agent production without gaining access to the interior of a site. Nevertheless, effluent analysis has a number of limitations:

- A proliferant may simply store production wastes onsite or inject them into a deep well rather than releasing them into the environment. A proliferant might also create a phoney waste stream to mislead monitors, who would not be able to detect the real fate of the production wastes without access to the interior of the plant.
- Once the waste stream has passed through a treatment facility, its characteristic chemical components may be destroyed.

  Since a handful of commercial products (pesticides and fire retardants) break down to methylphosphonate, the same final degradation product as nerve agents, merely identifying this compound in the waste stream would not in itself provide conclusive evidence of a violation.
- If the plant effluent were discharged into a river, one would have to obtain water samples close to the source before the chemical signatures were diluted to undetectable levels.

For a detailed discussion of effluent analysis, see appendix 2-A.

BIOMARKERS IN PLANT WORKERS AND WILDLIFE

Yet another approach to monitoring makes use of the natural ecosystem around a chemical plant as a long-term collection mechanism. In recent years, occupational health specialists have identified a number of "biomarkers" associated with exposure to toxic chemicals such as pesticides. Living plants and organisms (including humans) tend to concentrate various trace chemicals in their tissues, so that measurable quantities can be detected in the higher members of the food chain living in the vicinity of a suspect facility. Entire small organisms (e.g., insects), samples of animal fur, urine, blood, or feces, or plant leaves, flowers, fruit, or roots, could be analyzed to identify chemical compounds not normally present in the local environment.[95] Such an approach might provide more comprehensive coverage than point detectors.

A related approach is to collect samples of tie, blood, skin, or hair from chemical plant workers and analyze them for telltale biomarkers of covert CW production. One might look either for metabolizes of sulfur mustard and nerve agents in body fluids such as blood and urine, or for ''adducts' of mustard or nerve agents bound to cellular DNA. (See app. 2-A.) In the United States, however, such monitoring might be considered a violation of Fourth Amendment protections against intrusive personal searches if it were conducted without a warrant, and other countries might simply refuse to allow it.

| Storage of Agents and Munitions

Although CW munitions are indistinguishable at a distance from conventional munitions, they may be stored in bunkers that have distinctive characteristics. In Iraq, CW storage bunkers were located inside ammunition-storage depots but were secured separately with fencing or barbed wire, set off in remote locations, and spaced far apart. Before the start of the Coalition bombing campaign during Operation Desert Storm, however, the Iraqis moved many of their chemical munitions out of the storage bunkers and buried them in the desert to protect them from attack. The Iraqis also constructed decoy bunkers intended to mislead enemy bombers. Thus, storage bunkers may not be a reliable signature of either the presence or the absence of a CW capability.

Of course, the discovery of stockpiled chemical munitions would provide a clear indication of a CW capability. Artillery shells and rockets containing CW agents, high explosives, or smoke rounds are identical in shape, however, and differ only by an external color code that could be easily painted over. Since chemical munitions are impossible to distinguish by visual inspection alone, a proliferant country might attempt to violate the Chemical Weapons Convention by painting chemical munitions to look like high-explosive shells and storing them in the same depot.

In order to characterize the contents of sealed munitions while avoiding the hazards of direct sampling, several nondestructive evaluation (NDE) methods are under development. One such method, known as Portable Isotope Neutron Spectroscopy (PINS), was developed by the Idaho National Engineering Laboratory. This technique involves irradiating a shell with neutrons, which interact with the chemical contents of the munition to produce g aroma rays that are unique for each chemical element. Nerve agents are rich in phosphorus and mustard agents in chlorine, while high explosives contain large quantities of nitrogen but no phosphorus, chlorine, or arsenic. As a result, the gamma emission spectra for CW agents and high explosives are easily distinguishable. Although the PINS technique has shown a 95 percent accuracy rate in tests on known chemical shells, its reliability under uncontrolled field conditions has not yet

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[95] Sylvia Talmage and Barbara Walton, ''SXI@ Mammals as Environmental Monitors," *Oak Ridge National Laboratory Review, vol. 25,* No. 1 (1992), pp. 55-57.

been demonstrated conclusively.[96] Several other NDE systems are also under development and have differing strengths and weaknesses.[97] For example, acoustic resonance spectroscopy uses sound waves to assay the contents of a shell. It has the advantage of being able to complete an assay in 10 seconds, but the disadvantage of requiring the acoustic signatures of known reference shells of the same type.

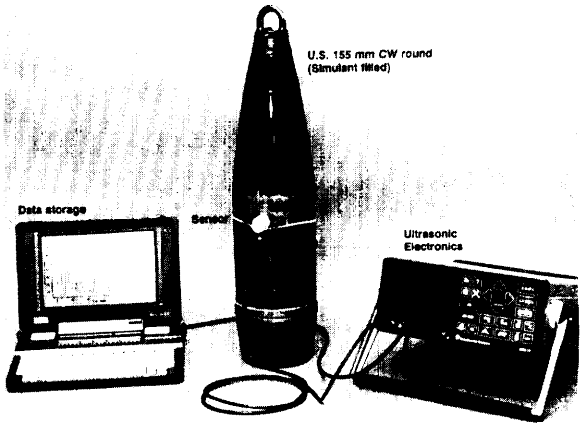
| Weaponization and Testing Signatures

Weaponization and testing of CW munitions may also provide signatures, although these, too, may be ambiguous.

VISUAL SIGNATURES

Test ranges for operational testing of chemical munitions and dual-use delivery systems such as artillery and missiles cannot be hidden underground or inside closed buildings, and hence may show up in overhead images. Such a test range generally consists of a support area containing administration and logistics and an experimental area containing a test grid and a large downwind sampling zone with an array of sampling poles .98 Nevertheless, an illegal test facility might well be camouflaged and the tests conducted at night or when reconnaissance satellites are out of range. Observing a test might require considerable luck.

Ground or aerial observations of military exercises involving chemical weapons might provide some clues to a country's intentions, but they are probably not a reliable signature. One problem is that it is very difficult to understand the purpose of a military exercise without knowing the scenario that the planners are ruining. Exercises that involve the firing of munitions to generate an aerosol might imply preparations for offensive CW use, but they could also pertain to the generation of smoke screens. Alternatively, a proliferant might conduct misleading field exercises for purposes of deception. Defensive and decontamination exercises might also be part of a broader offensive strategy. And although field testing is desirable, it is not an essential prerequisite for acquiring a CW capability.



Ultrasonic pulse echo apparatus to distinguish chemical munitions from conventional rounds. No echo is observed if the shell is empty; echoes will return at characteristic times lf the shell contains a solid, liquid, or powder.

PACIFIC NORTHWEST LABORATORIES

DIFFICULTIES OF DETECTION

The various signatures associated with the acquisition of a CW capability, along with potential detection methods and countermeasures, are summarized in table 2-2. Overall, the challenge of detecting and monitoring clandestine production of CW agents is a formidable one. None of the production signatures is a reliable indicator by itself, and even combinations of signatures may depend on making

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[96] Personal communication, A. J. Caffrey, senior scientist, Idaho National Engineering Laboratory, Aug. 23, 1993.

[97] In addition to PINS, other Non-Destructive Evaluation (NDE) methods currently under investigation include x-ray, acoustic resonance spectroscopy, ultrasonic pulse echo, laser acoustic spectroscopy, and ion-tube neutron spectroscopy. For a review of current NDE research and development, see the special issue of *Verification Technologies* devoted to this topic (U.S. Department of Energy, Office of Arms Control and Nonproliferation, *Verification Technologies,* First/Second Quarters 1992).

[98] Sanches et al., op. cit., footnote 66, pp. 53-54.

Table 2-2—Chemical Weapon Program Signatures and Concealment

Program stage	Signature	Detection methods	Concealment methods comment
Design and engineering	Scientific and technical publications (presence or absence)	Literature survey and analysis	1. Manage publication activities 2. Use widely available technical information rather than design new agents or techniques
Acquisition of raw materials	Patterns of feed material acquisition	Monitoring of open-source trade data; espionage	1. Shuffle, divert acquisitions; mix with legitimate uses 2. Develop clandestine networks 3. Produce known precursor chemicals indigenously 4. With chemical industry development, raw materials acquisitions increasingly lose their utility as a signature
Clandestine production plant	Security Measures	Overhead imaging or human intelligence (humint)	Conceal measures, or place plant within other secure facilities
	Effluents	Sampling of air, water, or soil near suspect plant--various forms of chemical analysis	1. Chemically alter effluents with decontaminating solvents or them with additives 2. Hide wastes or remove for off-site disposal
Converted or multipurpose production plant	Security Measures	Overhead imaging or humint	Conceal measures
	Effluents	Sampling of air, water, or soil near suspect plants-various forms of chemical analysis; laser remote sensing of emission plumes	1. Chemically alter or mask effluents 2. Remove wastes for offsite disposal

observations in the right place and at the right time. Major hurdles to detection include:

- the possibility of intermittent production in a small, pilot-scale facility;
- the low volatility of most of the compounds of interest (resulting in low atmospheric concentrations even insignificant leaks occur);
- masking and interference from legitimate chemicals produced at a typical multiple-use facility;
- the political and economic costs of challenge inspections, which will severely constrain the number of facilities that can be inspected;
- the difficulty of detecting production of binary agents, which are made from dual-use chemicals and widely available industrial alcohols.

Despite the difficulties of detecting clandestine CW production, however, the cooperative verification regime will be supplemented with national intelligence-gathering efforts that may provide indications of CW-related activities somewhere along the acquisition spectrum ranging from research through testing and the development of military doctrine. (As an illustration of the contribution of national intelligence efforts, Box 2-A recounts press reports describing how the United States tracked the Libyan CW production facility at Rabta.) These additional sources of information should increase the chances of detecting a clandestine CW program, and could

Program stage	Signature	Detection methods	Concealment methods comment
	Special safety and containment measures	Onsite inspection of suspect plants	1. Sacrifice worker safety 2. Modern chemical plants increasingly have these features
	Rare chemical processes (e.g., alkylation or cyanation)	Onsite inspection of suspect plants	Alternate weapons agent production with commercial production requiring same processes
	Corrosion-resistant reactors and other fittings	Onsite inspection of suspect plants; tracking of imports of such parts	1. Replace corrodible equipment as needed 2. Trend is toward use of such parts in legitimate commercial processes
	Tell-tale residues within plant	On-site chemical analysis of absorbent parts (or removal for off-site analysis)	1. Use decontaminating solvents 2. Practice quick replacement of such parts as rubber flanges and seals that might absorb residues
	Biomarkers in plant workers	Analysis of urine and blood samples	Prevent collection of samples unless specifically permitted by challenge inspection regime
Weapon assembly	Uniquely configured arsenals (e.g., distribution of storage bunkers)	Overhead imaging	Pattern facilities after conventional arsenals
Weapon testing	Uniquely configured test facilities	Overhead imaging	1. Make special features temporary 2. Test on overcast days, at night, or in absence of imaging devices

SOURCE: Office of Technology Assessment, 1993.

be used to trigger challenge inspections under the treaty regime.

ALTERNATIVE PROLIFERATION PATHWAYS

There are two basic approaches to acquiring an indigenous CW production capability:

- build a dedicated CW agent production plant (open or clandestine);
- convert existing chemical facilities (single-purpose or multipurpose) to CW agent production on a temporary or permanent basis.[99]

In the past, proliferant countries seeking a CW production capability have purchased turnkey plants from foreign suppliers. For example, both Libya and Iraq purchased entire chemical plants from German firms that were then converted to CW agent production. Increasingly, however, proliferants purchase parts and engineering know-how from a variety of sources and integrate them on their own. This new approach to acquisition makes it more difficult to halt CW proliferation through export controls.

Proliferant countries-particularly those that sign and ratify the Chemical Weapons Convention-

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~ A proliferant might also purchase bulk or weaponized CW agents from a state that already possesses them. This approach is likely to be at most temporary, however, since the purchasing state would remain dangerously dependent on the supplier.

are most likely to produce CW agents in a clandestine manner to avoid provoking international political and economic sanctions. Nevertheless, a country that has been threatened or attacked by a more powerful neighbor may seek to acquire a CW capability as quickly as possible. This scenario would be compatible with the manufacture of cheap, low-stability agents for near-term military use and might involve acquiring the capacity for rapid but not necessarily secret production in wartime. Such a‘ ‘breakout’ capability might either be built deliberately in peacetime or improved in response to a military crisis.

Building a Dedicated Plant

The advantage of building a clandestine CW plant on a new site is that it can be built in an isolated location, far from commercial chemical plants that might be subject to routine inspections under the Chemical Weapons Convention.[100] The number of plant personnel could be kept to a minimum for security reasons, and specialized construction and camouflage procedures could be used. On the other hand, siting a dedicated CW production facility in the midst of a large commercial industrial complex would have the advantage that the surrounding ‘‘noise” would drown out any telltale CW-related signatures. Moreover, the construction of a clandestine plant at an isolated site, if detected, would tend to draw attention to the facility.

Another strategy for a proliferant country would be to acquire one or more pilot-scale chemical plants and use them to accumulate, over a period of years, enough CW agent to be a potent strategic asset in certain regional conflicts.[101] Because of their small size, pilot-scale facilities would be easier to conceal. Nevertheless, stocks of agent produced over a long period of time would have to be of greater purity to ensure an adequate shelf-life. This requirement would in turn demand distillation and the use of stabilizers, complicating the production process.

Converting an Existing Plant

An alternative pathway to acquiring a CW capability would be to convert all or part of a declared commercial facility to CW agent production. Experts disagree over the speed with which a commercial plant could be converted. Former CIA director William Webster alleged that the Libyan Pharm-150 plant at Rabta was capable of CW agent production but that ‘‘within fewer than 24 hours, it would be relatively easy for the Libyans to make the site appear to be a pharmaceutical facility .’’[102] Reportedly, this potential for deception was one reason that the United States turned down an offer by Libyan leader Muhamar Khadafy to do a one-time onsite inspection of the plant.[103]

Some analysts challenge the assumption that it would be easy to convert a commercial chemical plant to the production of CW agents by simply changing valves or piping.[104] First, only a few types of chemical plants are suitable for conversion to production of nerve agents. Fertilizer plants use a different kind of phosphorus (phos-

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[100] Most commercial chemical plants in the developing world are located in populated areas. Even if a commercial plant is initially built in a remote location, the resulting employment opportunities and economic activity tend to attract large numbers of migrants to the immediate vicinity.

[101] Robert C. Gough, Sandia National Laboratory, personal Communication 1992.

[102] Testimony by William H. Webster, Director of Central Intelligence, in U.S. Senate, Committee on Governmental Affairs, *Global Spread of Chemical and Biological Weapons,* 101st Congress, 1st Session, Feb. 9, 1989 (Washington DC: U.S. Government Printing Office, 1990), p. 13.

[103] Tuohy, op. cit., footnote 70, P. 10.

[104] Much of the following analysis is based on research conducted by Alan R. Pittaway and the Midwest Research Institute in the late 1960s and early 1970s. See Midwest Research Institute, *The Difficulty of Converting Pesticide Plants to CW Nerve Agent Manufacture,* Technical Report No. *7* (Kansas City, MO: Midwest Research Institute, Feb. 20, 1970).

phate) chemistry, do not contain most of the necessary equipment for the chemical synthesis of nerve agents, and lack stringent safety and containment measures. Pharmaceutical plants share many precursors with CW agents, but the scale of drug production is generally much smaller than that of other specialty chemicals. Organophosphorus pesticide plants are most suitable for conversion to nerve-agent production, since the phosphorus chemistry is similar and much of the process equipment is of the type and capacity suitable for large-scale production of nerve agents.

In 1987, for example, the United States produced at least 5,000 pounds of each of 204 pesticides, of which 33 were organophosphorus compounds. Of the 33, six were alkylated, making them structurally similar to nerve agents and hence of greatest concern. Those six alkylated pesticides were produced at 24 plants owned by 17 companies.[105] In recent years, however, the trend in pesticide development—at least by countries not seeking to produce nerve agents—has been to move away from alkylated compounds to those with reduced mammalian toxicity. As a result, ever fewer pesticide plants today are equipped with processes that can be readily converted to nerve-agent production, although a proliferant could opt deliberately **for an old production method.**

In addition to pesticides, a handful of commercial organophosphorus compounds are structurally related to nerve agents, including flame retardants, plastics, and fuel additives. Volume of production for the most significant of these compounds, the fire retardant dimethyl methylphosphonate (DMMP), is on the order of 2,200 metric tons annually among four producers worldwide.[106] Thus, **the manufacture of** DMMP and related compounds could still be used as a cover for nerve-agent production.

The technical hurdles involved in converting a commercial plant to CW agent production are different depending on whether the commercial facility is single-purpose or multipurpose. Both pathways are discussed below.

SINGLE-PURPOSE PLANT

Single-purpose chemical plants are generally custom-designed and optimized for production of one product in vast quantities. As a result, converting such a plant to some other form of production can take months. The German pharmaceutical firm Bayer, for example, spent 2 years rebuilding a single-purpose facility so that it could produce two different but related chemicals. After this initial investment, the plant could alternate between the two products with a changeover time of 3 to 4 weeks.[107]

The differences in the chemical synthesis of commercial organophosphorus compounds and nerve agents mean that some of the processes and equipment are not easily convertible, but others are. For example, pesticide plants do not normally contain equipment for performing the cyanation reaction needed for tabun; the alkylation reaction needed for sarin, soman, and VX; or the fluorination reaction needed for sarin and soman. Thus, the presence of any of these process steps in a pesticide plant would warrant further investigation. Pesticide plants normally have distillation equipment that consists mainly of stripping columns, which are not adequate for distilling nerve agents like sarin or soman.[108] (Distillation is only needed, however, if a long

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[105] The six pesticides with a P-alkyl bond that were produced in the past in the United States were: 2-chloroethylphosphonic acid, Fonophos, Fosmine ammonium, Glyphosate and its isopropylamine salt, and Trichlorfon. Today, Fonophos is the only alkylated pesticide still produced in significant quantities. See Stanford Research Institute International, *Directory of Chemical Producers USA* (Menlo Park, CA: SRI International, 1988).

[106] Zapf, op. cit., footnote 89, p. 280.

[107] Burck, op. cit., footnote 33, p. 151.

[108] Ibid., p. 148.

shelf-life is required.) Moreover, pesticide plants do not normally use hydrogen fluoride-a key ingredient of sarin and soman-and generally use phosphorus oxychloride ($POCl_3$) or phosphorus pentasulfide (P_2S_5) as a starting material rather than phosphorus trichloride (PCl_3). Since phosphorus pentasulfide is not suitable for use in alkylation reactions, it cannot be utilized as a starting material for nerve-agent production.[109]

For these reasons, converting a pesticide plant to nerve-gas production would mean modifying the production process and stretching the operating conditions to obtain reasonable yields while still maintaining secrecy. According to one assessment, for example, ‘‘the conversion of a parathion plant to the production of G-agents would be extremely difficult, requiring substantial material changes and plant retooling. ‘‘[110] The modifications would involve rerouting pipes, valves, and mechanical seals to meet minimal operating requirements. For example, a proliferant might design a plant to produce an organophosphorus pesticide that lacks a phosphorus-carbon bond and then change the feed materials and process equipment to add a final alkylation step-either in a clandestine section of the main plant or at a separate location. It would also be possible to design a plant that could make nerve agents and then add on “bypass piping to permit the commercial production of pesticides and pharmaceuticals. Thus, in time of need, it would be easy to convert the plant back to nerve-agent production.

Conversion to nerve-agent production might also require upgrading safety, containment, and waste-disposal procedures, although as has been stated earlier, such signatures can be ambiguous. Converting a single-purpose pesticide plant to nerve-agent production would require at least several weeks and would involve the following steps: design of the modified production line, acquisition of the needed equipment, and construction, checkout, and pilot operation. The actual time requirements would depend on the experience of the plant personnel, the priority given the project, and willingness to cut corners on worker safety and environmental protection.

Conversion time might be reduced by cannibalizing equipment from other plants or by employing used equipment, but the lack of integrated safety systems would probably result in serious accidents and deplete the skilled workforce needed to run the plant. According to one analyst, ‘‘Unless the plant had been designed for convertibility in the first place, the first victims of the conversion would be the production workers.’[111] It would also be difficult or impossible to clean out the pipes, pumps, and reactors well enough after CW-agent production to deceive an onsite inspection. For all of these reasons, it would probably be simpler to build a dedicated CW agent production facility than to convert an existing single-purpose plant.[112]

MULTIPURPOSE PLANT

A multipurpose plant would be easier to convert to production of nerve agents than a single-purpose plant. Multipurpose plants are common in the specialty chemical industry, and they are also operated by subcontractors known as “toilers” or custom producers who make small batches of chemicals for larger companies that do not want to invest in special equipment for this purpose. For this reason, multipurpose plants are designed for maximum flexibility. Process units, heat exchangers, and storage facilities are connected by extra pipes that can be linked in various configurations to manufacture several different

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[109] **Pittaway,** op. cit., **footnote 20.**

[110] Zapf, op. cit., footnote 89, p. 292.

[111] **Robinson, ‘‘Chemical Weapons Proliferation,’’** op. cit., footnote **8,** p. *26.*

[112] *Alan* R. Pittaway, “An Approach to the Problem of **Inspecting** for **Organophosphorus** Chemical Munition Production, Transportation and Storage” (**Booz-Allen** Applied Research, Inc., August 1%8), p. 14.

chemicals over the course of a year.[113] The equipment is generally designed to handle highly corrosive chemicals. Some process equipment may be kept on pallets to minimize conversion time, and quick-cleaning features and sophisticated electronic controls permit rapid rearrangement of components. Because of the complexity of a multipurpose plant, its operation requires highly skilled engineers and other experienced personnel.

Today, modem multipurpose facilities capable of short-term, small-batch production are not the norm in developing countries, where the great majority of companies produce large volumes of a few commodity chemicals. As a result, there are few multipurpose plants in the developing world that could be reconfigured. Nevertheless, the trend in the worldwide chemical industry is to build more multipurpose plants as a means of adjusting to rapid changes in production technology. Such a plant might therefore have the equipment needed for nerve-agent manufacture distributed among its various production processes.

If a multipurpose plant were designed for rapid conversion from one chemical process to another, it might be possible to switch over in a few days with little chance of being detected. Even so, a plant specifically designed for rapid conversion from commercial to CW-agent production would be costly to build (on the order of $150 million), and would require a high level of technological know-how in plant design, engineering, and operation, and a skilled construction workforce. Design and construction would take about 4 years in most parts of the developing world.

A dual-use plant designed for rapid conversion would also require stringent cleaning measures for the final steps in the production process to prevent the contamination of commercial products-particularly pharmaceuticals-with deadly CW agents. Since seals on pumps and other material-handling equipment absorb chemicals from the production process, switching from production of one chemical to another requires removing the pumps and cleaning them off-line, a time-consuming process. In a rapidly convertible plant, however, the production line might be configured with modular pumps that could be removed quickly for cleaning and then replaced. Alternatively, two sets of pumps might be installed in parallel so that different chemicals could be produced on the same line without contaminating each other.[114] Nevertheless, a plant that has been specifically designed to facilitate rapid decontamination would probably be uneconomical for commercial production, and would therefore arouse suspicions on those grounds.

| Binary Agent Production

Some analysts have argued that binary weapons might accelerate CW proliferation by making chemical weapons inherently easier and safer to manufacture, store, transport, and use.115 Indeed, the relative lack of toxicity of the two precursors means that production plants require less stringent containment measures. In the 1950s, for example, the United States produced the binary precursors DF and QL in plants open to the outside air and with relatively few safety precautions. Illicit production of binaries is also more difficult to detect because the two chemical components have some legitimate commercial

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[113] "CMA's Olson Unravels Intricacies of Verifying a Chemical Arms Treaty," *Chemical and Engineering News,* vol. 67, No. 17, Apr. 24, 1989, p. 8.

[114] Interview with Kyle Olson, EAI Corp., 1992.

11S Brad Roberts, "Technical Impediments t. Proliferation and Binary Production," *Binary Weapons: Implications of the U.S. Chemical Stockpile Modernization for Chemical Weapons Proliferation,* Report by the Congressional Research Service prepared for the Subcommittee on International Security and Scientific Affairs of the Committee on Foreign Affairs, House of Representatives, Apr. 24, 1984 (Washington DC: Government Printing Office, 1984), p. 14.

uses. A binary sarin weapon, for example, would consist of two ingredients, DF and isopropanol, which react spontaneously to form the nerve agent. Yet dichlor-the immediate precursor of DF—has legitimate commercial uses in fire retardants, insecticides, and plastics, and isopropanol (rubbing alcohol) is a common industrial chemical. Manufacture of these compounds for legitimate uses could thus be used as a cover for the illicit production of nerve agents. Finally, binary weapons make it possible to use standard logistics channels and less rigorous security measures during production and transport, and they have a relatively long shelf-life.

I Trade-Offs

For a country seeking to develop a CW production capability, there are several major tradeoffs in the choice of proliferation pathway:

SIMPLICITY V. VISIBILITY

A proliferant faces a tradeoff between the use of a proven and relatively simple production process for CW agents (e.g., conversion of thiodiglycol to sulfur mustard) and the need to conceal its activities by using less well known precursors or procedures, thereby complicating the production process. Thus, a proliferant must balance the need for secrecy against the efficiency and cost of production.

SPEED V. VISIBILITY

If an aspiring proliferant faces a long-term adversary and seeks to acquire a strategic CW stockpile, it may seek to minimize visibility by investing the money and time needed to build a dedicated clandestine plant. If the threat is more immediate, however, it may choose to convert an existing commercial facility to CW agent production.

SAFETY V. VISIBILITY

A proliferant may seek to minimize the visibility of a CW production facility by jury-rigging it from used equipment or items purchased from multiple suppliers. The lack of an integrated plant design would result in more hazardous operation, however, increasing the occupational risks to the workforce and the contamination of the environment near the plant. A reckless government might even deliberately accept a greater risk to its workforce or population in order to acquire a CW capability more quickly or covertly, particularly if it were a party to the Chemical Weapons Convention.

SIMPLICITY V. SHELF-LIFE

The sophistication of the production technology required to manufacture agents depends on the urgency of a country's military requirements. If a country has no immediate need to use CW agents and plans to stockpile them for several years, the agents will require along shelf-life and must therefore be produced with high purity. If a country is producing nerve agents for immediate use in battle, however, it can afford to make a less pure product by eliminating the distillation step or the use of stabilizing additives.

AUTONOMY V. EFFICIENCY

Using an immediate precursor of a CW agent is obviously more efficient than using a starting material that is several steps removed from the final product. Thus, while back-integration of precursor chemicals reduces a proliferant's dependence on outside suppliers, it also results in greater overall complexity and cost, requires more workers to operate the plant, and results in a larger production complex to conceal and to decontaminate.

Appendix 2-A
Techniques for the Detection and Analysis of Chemical Signatures

The Chemical Weapons Convention (CWC) permits the collection and analysis of samples during onsite inspections. Although the details of the sampling process remain to be determined by a Preparatory Commission that is meeting in The Hague to negotiate the details of treaty implementation, several analytical techniques may be used to detect and monitor chemical signatures associated with the illicit production of CW agents. Such methods could be employed either during onsite inspections of declared chemical plants authorized by the CWC or for near-site monitoring from the perimeter of a facility or from an overflying aircraft. Clandestine CW production facilities would first have to be identified by intelligence assets and then subjected to a challenge inspection before chemical sampling could take place.

The future international inspectorate to be established under the CWC will require the establishment of accredited analytical laboratories that use certified testing procedures for identifying CW agents, precursors, and degradation products. During onsite visits, inspection teams will use specified instrumentation for performing in situ chemical analyses. To facilitate the development of such agreed instrumentation and procedures, the Government of Finland has sponsored since 1973 the development of suitable analytical techniques. In recent years, this program has included a series of international ''round-robin" experiments involving the analysis by laboratories in 15 countries of unknown samples spiked with nerve and mustard agents, precursors, and degradation products.[1] The participating countries have agreed that the presence of controlled compounds will be confirmed with at least two different instrumental methods of analysis, and that the analytical laboratories will implement stringent quality-control measures.

The difficulty of detecting CW agent signatures is site-dependent and is a function of the sophistication of a plant's emission-control and decontamination systems and the quality of its maintenance. According to one analysis, the verification challenge ranges in difficulty from the relatively simple task of detecting the production of treaty-controlled chemicals in a large, single-purpose, stand-alone facility with a rudimentary emission-control system to the much harder problem of detecting telltale signatures at a facility equipped with an advanced environmental

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[1] The participating countries in the Third Round-Robin Test were Australia, Canada, China, the Czech and Slovak Federated Republic, Finland, France, Germany, India, the Netherlands, Norway, the Russian Federation (two labs), Sweden, Switzerland, the United Kingdom, and the United States (two labs). See Marjatta Rautio, cd., *International Interlaboratory Comparison (Round-Robin) Test for the Verification of Chemical Disarmament. F.3. Testing of Procedures on Simulated Military Facility Samples* (Helsinki: Ministry of Foreign Affairs of Finland, 1992).

control system and embedded in a large multipurpose chemical complex.[2]

Since the analytical techniques described below can reveal a considerable amount of information regarding the operation of a chemical facility, verifying the CWC must balance the intrusiveness needed to detect treaty violations against the risk of compromising confidential business information unrelated to the treaty.[3] In order to minimize this risk chemical analyses for CWC verification will not involve an exhaustive characterization of samples but will focus instead on the search for a specific set of known chemicals associated with CW production. Screening for a set of known target compounds poses less of a threat to proprietary information than would a complete chemical analysis of the sample. If one or more suspect chemicals were detected in the waste stream, however, a more in-depth analysis might be warranted.

ONSITE INSPECTION TECHNIQUES

During the production of a CW agent, traces of various chemicals are released in vapor form from the plant's smokestacks and ventilation systems and are also absorbed by the seals and gaskets on pumps and other fittings, the agitator in the reaction vessel, and various rubber components and grease seals. Thus, during onsite inspections; of a chemical facility, inspectors might disassemble pumps and other pieces of equipment close to the production vessel, or take swipe samples from inside the machinery, which is not likely to be flushed clean by conventional decontamination methods.[4] In order to ensure that the samples do not degrade before being analyzed, inspectors must use proper sampling techniques (e.g., dry v. wet swipes). They must also determine whether actions have been taken to preclude access to) possible samples, such as painting over a stain on the floor.

CW agents and precursors break down in the environment through the action of ultraviolet radiation (photolysis), water (hydrolysis), and air (oxidation), resulting in a series of degradation byproducts. Environmental factors such as sunlight, weather, temperature, and soil type can influence the rate of degradation. Dilution is another key factor affecting detectability: chemicals in effluents discharged into a river, for example, may be diluted to undetectable levels a few hundred meters or so downstream from the outflow pipe.[5]

Determining g the presence or absence of known chemicals is generally performed with some variant of a gas *chromatograph/mass spectrometer (GC/MS), an* instrument that combines two analytical methods in tandem. First, the gas chromatography vaporizes the sample and passes it through a packed column or a hollow glass capillary tube lined with a fine polymer material. Various substances in the sample take different amounts of time to emerge from the tube, depending on their molecular weight and their attraction to the polymer lining. As they emerge from the chromatography, constituents of the sample are then introduced into a mass spectrometer, which breaks them up into a compound-specific set of molecular fragments and then measures their masses very precisely.

Sorting molecules first by their retention time in the chromatography and then by the masses of their constituent parts, GC/MS analysis can reliably identify each of several compounds in a sample. Such identification is usually performed automatically by a pattern-recognition algorithm, which tries to match the mass spectrum of each component against a computer database containing tens of thousands of reference spectra of known chemical compounds and comes up with one or more candidates with specified probabilities. For purposes of CWC verification, considerable effort has gone into compiling ''libraries" of GC/MS spectra for CW agents, precursors, and degradation products.

If the GC/MS instrument is calibrated correctly, it can confirm very reliably whether a given

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[2] James D. Barden et al., *Remote Sensing Technology and CW Arms* Control (Alexandria, VA: Kaman Sciences Corp., Report No. P650-1254G-1, Feb. 2, 1993), p. '7.

[3] For an in-depth discussion of this issue, see U.S. congress, Office of Technology Assessment, *The Chemical Weapons Convention: Effects on the U.S. Chemical Industry,* O'TA-BP-ISC-1O6 (Washington, DC: U.S. Government Printing Office, August 1993),

[4] "CMA's Olson Unravels Intricacies of Verifying a Chemical Arms Treaty," *Chemical and Engineering News,* vol. *67, No. 17,* Apr. 24, 1989, p. 9.

[5] Albert Verweij et al., "Chemical Warfare Agents: Verification of Compounds Containing the Phosphorus-Methyl Linkage in Waste Water," *Science, vol.* 204, May 11, 1979, p. 617.

chemical is present in a sample at remarkably low concentrations, even in complex mixtures. The device can detect substances in the parts per trillion range, although the more complicated the mixture is, the harder it is to reach such high sensitivities. If the sample is being tested for the presence of a known chemical, the detection limit will be much lower than for an unknown chemical. GC/MS is sensitive enough to detect nerve-agent degradation products in waste water even after extensive purification efforts. Empirical results also indicate that detectable traces of CW agents may persist for long periods after production. In one trial inspection, traces of a carbamate pesticide were found 2 months after production ended by analyzing wipe samples from equipment and waste samples, as well as air samples from warehouses and packaging lines.[6]

Nevertheless, the extremely low detection thresholds achieved in the laboratory may not be possible in the field. GC/MS may not be able to identify trace quantities of agent with a high probability in the complex environment of a multipurpose chemical plant, since other compounds unrelated to CW agent production may interfere with the analysis. In such cases, visual inspection of the plant could help pare down the list of possible candidate compounds to those it would be technically feasible to manufacture in that facility.

During an onsite inspection, special sample-preparation methods may be necessary. For example, a water-soluble chemical may have to be converted into a derivative that is volatile enough to pass through a gas chromatography. It may also be necessary to try to extract the target compounds from a more complex mixture or from an absorbent material such as concrete, although such custom extractions tend to be difficult, time-consuming, and expensive. Some nerve-agent precursors, for example, absorb tightly to concrete and are only released by strong acid treatment.

In addition to GC/MS, a gas chromatography can be combined with other types of detectors to perform specific analytic tasks. For example, *a flame photometric detector can* identify the presence of sulfur or phosphorus in a sample with high sensitivity, while an *electron-capture detector can* identify fluorine and phosphorus-containing compounds. GC/MS can be complemented with other methods of chemical analysis. For example, *high-performance liquid chromatography (HPLC) is* useful for separating polar, nonvolatile compounds, Bioassays such as the acetylcholinesterase-inhibition test can detect nerve agents at very low concentrations through their ability to inactivate the enzyme acetylcholinesterase involved in neuromuscular transmission. Antibody-based techniques, such as the *enzyme-linked immunosorbent assay (ELISA),* rely on the ability of monoclinal antibodies to detect trace quantities of target compounds with high sensitivity, although their specificity may be relatively poor. Monoclinal antibodies have been produced for most of the major CW agents.[7] Finally, research and development is under way on *biosensors, in* which binding of the target compound to specific antibodies or cellular receptor molecules triggers an optical, physical, or electrochemical change that can be converted into an electrical signal.

In the hypothetical case of a whole new class of CW agents whose spectra are not already stored in a computer database, one would have to use an analytical method that provides detailed structural information from which the identity of the molecule can be deduced. GC/MS can provide useful information about unknown compounds, such as their molecular weight and elemental composition. In addition, *nuclear magnetic resonance (NMR)* spectroscopy is often used in conjunction with other techniques such as infrared and Raman spectroscopy to derive a molecular structure for unknowns. Nevertheless, structure determination with NMR requires a fairly pure sample in the milligram range, many orders of magnitude greater than the minimum concentration at which a known compound can be detected with GC/MS.[8]

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[6] Gordon M. Burck, "Chemical Weapons Production Technology and the Conversion of Civil Production,'' *Arms Control, vol.* 11, No. 2, September 1990, p. 141.

[7] C. N. Lieske et rd., "Development of an Antibody that Binds Sulfur Mustard," *Proceedings of the 1991 Medical Defense Bioscience Review (Fort* Detrick, MD: U.S. Army Medical Research Institute of Chemical Defense, Aug. 7-8, 1991), pp. 131-134.

[8] Manuel Sanches et al., *Chemical Weapons Convention (CWC) Signatures Analysis* (Arlington, VA: System Planning Corp., Final Technical Report No. 1396, August 1991), p. 23.

Chemical Signatures

Sulfur mustard breaks down in the environment into thiodiglycol and two impurities, thioxane and dithiane, which can be identified as signatures of mustard production.[9] Most nerve agents (e.g., sarin, soman, and VX, but not tabun) contain a phosphorus-methyl ($P\text{-}CH_3$) bond that is difficult to break it remains intact after chemical treatment and can only be destroyed by aggressive treatments such as high-temperature incineration.[10] These nerve agents break down in the waste stream into methylphosphonate (which contains the phosphorus-methyl bond), whereas most organophosphorus pesticides are degraded to phosphoric acid. (See figure 2A-l.)

The durability of the phosphorus-methyl bond also means that it can be identified for long periods after being discharged into the environment. For this reason, the phosphorus-methyl linkage is thus a good signature of illicit nerve-agent production. For example, soil samples taken in late 1992 from bomb craters near a Kurdish village in northern Iraq by a team of forensic scientists and later analyzed with GC/MS were found to contain degradation products of sarin and mustard gas more than 4 years after the village was bombed by the Iraqi army in 1988. This finding suggests that traces of CW agents or their degradation products can be detected after persisting in the environment for long periods, provided that the samples are taken from a point of high initial contamination such as the center of a bomb crater.[11]

Chemical signatures associated with the production of CW agents could also be obtained from sampling the waste effluent stream of a production plant, although the samples would have to be collected before significant dilution occurred. At the same time, little additional data would probably be derived from visiting the plant's control room (where the relevant information could be hidden), sampling from the production line (which might interfere with production), or examining the plant's books (which could be forged).[12] In order to ensure that the waste stream was actually connected to the production line, however, the inspectors would have to be given unlimited access to the plant's waste-processing system.

I Problem of False Positives

Since GC/MS analysis is so sensitive, it is unlikely to yield "false negatives," that is, to conclude mistakenly that a sample contains no evidence of illicit production. However, the problem of 'false positives"—unfounded suspicions of noncompliance-is more troublesome, particularly with respect to early precursors and final degradation products. In the case of **nerve agents, false-positives can arise if the plant is manufacturing or using a legitimate compound that contains a phosphorus-methyl bond and thus breaks down into the same degradation product as a nerve agent.** Fortunately, only a handfull of commercial products contain a phosphorus-methyl bond, including the pesticide Mecarphon and the organophosphorus flame retardant dimethyl methylphosphonate (DMMP), which is also used as a plasticizer for vinyl plastic and an intermediate in the production of herbicides.

Worldwide production of DW is spread among 14 companies, 11 in the United States and 3 in Western Europe.[13] According to one assessment, "A challenged facility may claim it is producing a chemical closely related to a scheduled agent [CW agent or precursor] which would result in emissions overlapping those of the scheduled agent. As a result, some identified chemicals may not be sufficiently unique for

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[9] Sanches et al., *Analysis of Signatures Associated with Noncompliance Scenarios,* Report No. DNA-TR-92-74 (Arlington, VA: Systems Planning Corp., January 1993), p. 59.

[10] See U.S. Congress, Office of Technology Assessment, *Disposal of Chemical Weapons: Alternative Technologies—Background Paper,* OTA-BP-O-95 (Washington, DC: U.S. Government Printing Office, June 1992).

[11] Human Rights Watch, "Scientific First: Soil Samples Taken From Bomb Craters in Northern Iraq Reveal Nerve Gas-Even Four Years Later, " press release, Apr. 29, 1993; Lois Ember, "Chemical Weapons Residues Verify Iraqi Use on Kurds," *Chemical& Engineering News,* vol. 71, No. 18, May 3, 1993, pp. 8-9.

[12] Stephen Black, Benoit Morel, and Peter M. Zapf, "E laminating the Shadows: On-site Inspections and the Chemical Weapons Convention" Benoit Morel and Kyle Olson, eds., Shadows *and Substance: The Chemical Weapons Convention* (Boulder, CO: Westview, 1993), p. 193

[13] U.S. Department of Commerce, Bureau of Export Administration, Office of Foreign Availability, *Foreign Availability Review: 50 CW Precursor Chemicals (II) (Washington DC:* Department of Commerce, Nov. 8, 1991), p. 23.

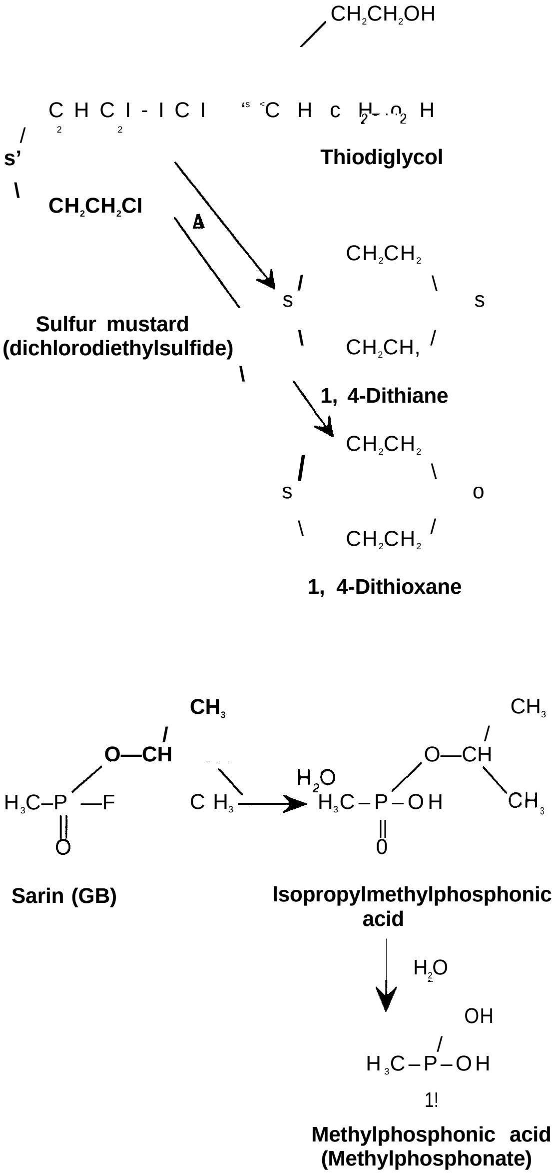
this particular plant. The same situation applies to illicit facilities embedded within larger related plants. ''[14]

Because methylphosphonate is resistant to further degradation, it tends to accumulate in the environment, Background levels have therefore been increasing gradually in the rivers, lakes, and streams of industrialized countries. For example, Albert Verweij and colleagues in the Netherlands detected significant levels of the compound in the waters of the Rhine and Meuse Rivers because of the upstream manufacture of DMMP.[15] Such environmental background levels may either generate false-positives (unless they had been previously measured) or, conversely, mask the actual effluents from nerve-agent production. For this reason, the detection of trace levels of methylphosphonate in the air, soil, or water near a chemical plant might not provide unequivocal evidence of nerve-agent production.

To solve **the problem of false positives, it would be essential to screen liquid and gaseous chemical-plant emissions for a specific set of target compounds. In** addition to the CW agents themselves and their degradation products, this list would include agent precursors and intermediate byproducts generated at various steps in the manufacturing process, and their respective degradation products. The major weaponized CW agents each have up to six different synthetic routes, requiring different sets of equipment and precursor chemicals. Thus, a suite of target compounds could provide evidence for each of these alternate production pathways. Identifying such suites of chemical compounds in the waste stream would reduce the likelihood of false-negatives and false-positives.

Detecting traces of nerve agents themselves clearly provides the best evidence of illicit production. If the actual agents cannot be found, the next best evidence is provided by primary degradation products and, if possible, both parts of the original agent molecule (e.g., the acid and amine components of VX). The detection of a secondary degradation product **such as methylphosphonate would not in itself constitute**

Figure 2-A-I-Chemical Warfare Agents and Degradation Products



SOURCE: *Chemical and Engineering News, vol. 71, No. 18,* May *3, 1993,* p. *8.*

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[14] Sanches et al., op. cit., footnote 9, p. 65.

[15] Verweij et al., op. cit., footnote 5, p. 617.

strong evidence of illicit production because it could also result from certain legitimate chemicals.[16] Nevertheless, if methylphosphonate is detected in the waste stream and plant officials seek to explain it away by claiming pesticide or DMMP production, the inspectors could ask for supporting evidence in the form of samples and written records.

Circumvention Scenarios

In addition to the problem of false-positives, there is the possibility of deliberate deception on the part of a determined proliferant. For example, a country engaged in clandestine CW-agent production might take special measures to mask or otherwise conceal the presence of telltale chemical signatures in the waste stream.[17] Indeed, a problem associated with sensors designed to detect trace quantities of chemicals is that they can easily be swamped by related signals. Examples of some possible deception strategies include:

- Pumping chemical wastes from the plant into underground storage tanks or wells, or into tanker trucks for disposal off-site.
- Setting up a phoney waste stream for sampling that is unconnected to the actual production line.
- Continually recycling the waste stream to reduce the quantities of byproducts released.
- Using a decontaminating solution that reacts with traces of illicit chemicals to form a product that may not be in the standard library of a GC/MS. This strategy has been termed “designer decontamination.”18 For example, the methyl phosphonate in the waste stream could be reacted with thionyl chloride and an alcohol to obtain a diester, which would not look anything like the original compound in a GC/MS analysis. Nevertheless, the use of an unusual decontaminating solution would be suspicious if’ nothing about the facility justified its presence; in addition, the sample could be hydrolyzed during the analysis to regenerate the methylphosphonate.
- Diluting the release of a telltale byproduct such as methylphosphonate in the waste stream so that it can no longer be detected. In practice, the effectiveness of this strategy would depend on the detection limits of the analytical instrument, which for GC/MS can reach parts per trillion. Thus, achieving the necessarily dilution to evade detection would require impractically large volumes of decontamination fluid.
- Flushing the production line with a decontaminating solution followed by a legitimate but closely related commercial product to mask any residues of agent. This scheme would only be possible if the plant were simultaneously producing a commercial compound containing a phosphorus-methyl bond, such as an alkylated pesticide (e.g., methyl-parathion) or DMMP. A sophisticated cheater, however, would almost certainly couple the two operations.
- Passing production wastes through an ion-exchange resin to remove methylphosphonate; such resins are expensive but reusable.
- Developing a novel agent that is not in the GC/MS database. Russian scientists, for example, have reportedly developed a new type of binary nerve agent.[19] Such a scenario is unlikely in most developing countries, however, since the development of an entirely new class of CW agents would require a costly investment in research, development, and testing. Modifications of existing CW agents might be detected by programming the instrument’s computer to recognize a family of related agents.

Some of these circumvention strategies might reduce the probability of detection. If, however, they were performed after notification of a challenge inspection, they might be carried out hastily and carelessly, resulting in spills or other accidents that would leave behind telltale traces of agent. The use of unusual decontamination strategies might also raise suspicions of a violation. Thus, such waste effluent

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[16] Marjatta Rautio, ed., *International Inter-Laboratory Comparison (Round-Robin) Test for the Verification of Chemical Disarmament. F.1. Testing of Existing Procedures* (Helsinki: Ministry of Foreign Affairs of Finland, 1990), p. 93.

[17] See Kathleen C. Bailey, “Problems With a Chemical Weapons Ban,'' *Orbis,* vol. 36, No. 2, spring 1992, pp. 239-251.

[18] Ibid., p. 241.

[19] ''Mirzayanov, Fedorov Detail Russian CW Production,'' *Novoye Vremya, No. 44,* October 1992, pp. 4-9 (translated in FBIS-SOV-92-213, Nov. 3, 1992, pp. 2-7),

sampling techniques would be most effective when used in conjunction with other forms of onsite inspection.

Searching for a suite of compounds (agents, precursors, and degradation products) on a target list would also help defeat circumvention efforts, since the *pattern* of chemical signatures emitted by a plant could not be masked as easily as a single chemical. Indeed, the likelihood of masking all of the target compounds associated with a given production process would be very low. Conversely, **whereas a secondary degradation product like methylphosphonate may give rise to false-positives, the probability of an error declines rapidly when the suspect chemical is found in conjunction with a suite of other target compounds in the same manufacturing process.**

In sum, it remains an open question whether a carefully planned and executed deception aimed at illicit production of CW agents would be detected. Nevertheless, cheaters would probably not be sure they could get away with the deception, and hence might be deterred from trying. **While one might theoretically conceive of a plant design that could circumvent detection, such a facility would probably differ significantly from existing commercial plants and might therefore arouse suspicion on those grounds.** According to one analysis:

> In a multipurpose plant. . . industry would invest significantly so that the interior of the actual production line could be easily cleaned in order to enable quick product change; this would not be the case for waste water channels, reactor ventilation systems, off-specification lines and so on, which would be connected either to purification stations or to equipment used to recycle certain chemicals. It is there inspections would look for traces of illicit production; if they were designed in such a way that they could easily and thoroughly be decontaminated, this would be an economically unfeasible and suspect effort by civil industry .[20]

NEAR-SITE AND REMOTE MONITORING TECHNIQUES

Near-site and remote monitoring of chemical signatures will probably be carried out openly within the negotiated terms of the Chemical Weapons Convention and covertly as an intelligence operation. Covert sensors, by definition, could not be openly discussed they would have to be made sufficiently reliable and rugged to permit long periods of unattended operation in a potentially hostile environment and cleverly disguised to prevent detection and tampering.[21]

Near-site monitoring can be either *real-time,* meaning that the concentration of a particular substance is monitored continuously, or *integrative,* meaning that only the average or the cumulative amount over a period of time is recorded. Integrative monitoring can be further subdivided into *active* and *passive* methodologies. Active-integrative systems pump air or water through a filter over a period of days or weeks to concentrate trace molecules for later analysis. In contrast, passive-integrative systems simply absorb and retain trace chemicals from the environment over a period of time, much like a sponge.

I Air-Sampling Systems

Active air-sampling could be conducted either with a system on the ground in the vicinity of a chemical plant, or based on an overflying aircraft.[22] **There are two types of gaseous emissions from a CW production plant: controlled smokestack emissions and "fugitive" emissions.** Stack emissions are planned releases from the production process that have been filtered by the plant's pollution-control system. Fugitive emissions are uncontrolled releases that have not passed through the pollution-control system, such as slow leaks from storage tanks, gaskets, and reactor pressure-release valves, or an accidental production-

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m J. Perry Robinson and Ralf Trapp, "Production and Chemistry Of Mustard Gas,'' S. J. Lundin, cd., Verification *of Dual-use Chemicals under the Chemical Weapons Convention: The Case of Thiodiglycol,* SIPRI *Chemical&* Biological Warfare Studies No. 13 (Oxford, England: Oxford University Press, 1991), p. 15.

[21] Franklin E. Walker, *Technical Means of Verifying Chemical Weapons Arms-Control Agreements* (Washington, DC: Foreign Policy Institute, Johns Hopkins University School of Advanced International Studies, May 1987), p.15.

[22] Ministry for Foreign Affairs of Finland, *Air Monitoring as a Means for Verification of Chemical Disarmament,* vols. I-III (Helsinki: Ministry for Foreign Affairs, 1985-1987).

line rupture. Since the chemicals involved in CW production are not particularly volatile, fugitive emissions would tend to stay closer to the ground, and might be detected through real-time sampling at locations near the production equipment. Moreover, fugitive emissions (e.g., from storage tanks or the waste-treatment system) may persist even after a plant has been temporarily shut down.

Air sampling involves collecting samples of air downwind from a chemical facility and analyzing them for CW agents, precursors, or byproducts; it can be either real-time or integrative. In one approach, atmospheric contaminants could be pumped through a tube packed with an absorbing substance (e.g., resin beads), concentrated for a period of time, and later driven off by flash heating in an inert-gas atmosphere and identified with GC/MS or high-performance liquid chromatography. Air-borne chemicals may also adhere to dust particles or and maybe transported in droplets of water vapor, raindrops,, or snowflakes.[23] In an experiment conducted in Finland, 4 kilograms of a nerve-agent simulant containing phosphorus were released into the atmosphere and subsequently identified in air samples collected 200 kilometers from the release site.[24] The U.S. Army is also developing atmospheric monitoring systems to protect the public from accidental leaks during the destruction of CW agent stockpiles.

In the treaty-verification context, detection sensi**tivities for air sampling are demanding for the following reasons:**

- Given the lethality of CW agents, production plants usually incorporate high-containment features that minimize emissions. The more modern the plant design, the lower the level of fugitive emissions and the more difficult detection becomes. Developing countries tend to impose less stringent safety practices, but the extent of fugitive emissions varies greatly from plant to plant. The trace amounts released into the atmosphere might not be concentrated enough to create an identifiable signal.
- The majority of materials involved in CW agent production that yield detectable signatures are not very volatile even if a leak occurs, compounding the sensitivity problem.
- When air samples are taken over longer ranges, weather patterns can complicate efforts to identify the source of detected emissions, since wind may shift the direction of the emission plume. Remote air sampling cannot pinpoint the source of a clandestine facility for challenge inspection unless the sampling is conducted for extensive periods or happens to coincide with the release of detectable emissions, and unless an atmospheric-transport model can trace the contaminants back to the facility of origin.
- Deliberate countermeasures might foil air-sampling efforts. A clever plant operator might be able to mask such releases, particularly if he had prior knowledge of the monitoring technologies. Alternatively, a cheater who was aware he was being monitored might control emissions or discontinue production while samples were being collected, or refuse permission for aerial overflights. Although fugitive emissions (e.g., from storage tanks) might continue in the absence of production, they might not be concentrated enough to be detectable.

Because of these factors, **even in those instances where detection has been accomplished by air sampling, the detection was made through extensive sampling grids during rather massive releases. This source is easy** to extinguish simply by stopping production.[25]

Optical Detection Systems

Another approach to the real-time detection and analysis of chemicals released deliberately or accidentally from a CW production facility is to use a remote spectroscopic system based on light scattering, absorption, or induced fluorescence. A combination of two or more of these techniques may be needed to produce

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[23] Amy Smithson and Michael Krepon, *Strengthening the Chemical Weapons Convention Through Aerial Inspections*, Occasional Paper No. 4 (Washington, DC: Henry L. Stimson Center, April 1991), p. 13.

[24] Ministry for Foreign Affairs of Finland, The Finnish *Research Project on the Verification of Chemical Disarmament* (Helsinki: Ministry for Foreign Affairs, 1989), p, 13.

[25] Raymond R. McGuire, Treaty Verification Program, Lawrence Livermore National Laboratory, personal communication, 1992.

reliable results.[26] Remote spectroscopy can either be "passive,' which analyzes electromagnetic radiation emitted by the sample or by background sources, or ''active, ' which irradiates the sample with a laser beam. For example, *fourier transform infrared spectroscopy (FTIR)* has been used to detect telltale chemical signatures in stack plumes or fugitive emissions at ground level or at higher altitudes. Broadband infrared has the potential to identify a wide variety of compounds simultaneously.

A closely related active laser sensing technique is known as lidar, for "light detection and ranging, " Whereas spectroscopes are generally broad-band techniques, lidar is laser-based and thus consists of a single or a few distinct wavelengths. (As lasers become tunable, however, this distinction may disappear). An advantage of laser-based systems is that the power is focused at a single wavelength rather than being spread among many, *Differential absorption lidar (DIAL)* uses two different wavelengths, one of which is absorbed by the target molecule and one that is not. The difference between the absorbed and unabsorbed signals is used to determine the target molecule's concentration. Another lidar technique, known as *Raman spectroscopy, involves* exciting a chemical with a monochromatic laser and measuring shifts in frequency that provide structural information. Water is not a strong Raman absorber and thus causes little interference.

Remote sensing of chemical-plant emissions maybe performed on stack plumes or fugitive emissions at ground level or at higher altitudes. In principle, the illuminating laser can be located on the ground or mounted on an aircraft, a remotely piloted vehicle, or even a satellite. To characterize the chemical emissions from a smokestack, the laser would be pointed either directly at the gaseous exhaust emitted from the stack or downwind along the effluent plume, and the returned light picked up by a detector. Fluorescence or absorption of light by the chemical compounds in the exhaust give rise to characteristic spectral bands.

"Closed-end" optical detection systems employ a mirror or separate detector to analyze the illuminating laser beam after it passes through the chemical plume. They are more sensitive than "open-ended" systems, which collect only light scattered back to a detector near the laser source. The FTIR detector, under development for the Environmental Protection Agency, is an example of a closed-end system. It emits a beam of infrared light across the plume, and a large mirror then reflects the beam back to the emitter/detector system, doubling the path length and thereby increasing the sensitivity. After being processed the resulting data yield the characteristic infrared absorption spectra for the chemical species of interest.[27]

The success of optical remote-sensing techniques depends on a number of variables, however, including:

- the concentration of the target compound(s) in the plant emissions, which may be a function of emission controls;
- the chemicals present in the background and their concentrations;
- the detection limits of the remote-sensing equipment.

Current-generation systems are not sufficiently sensitive to detect trace quantities of agent. For example, lidar technologies are capable of detecting CW agent in air at concentrations of 1 to 10 milligrams per cubic meter. In other words, they are several orders of magnitude less sensitive than existing analytical instruments used for onsite sampling, which have a detection limit of 1 to 10 micrograms per cubic meter.[28] Experience has shown that the probability of remotely detecting activities occurring within a manufacturing facility is nearly zero if samples are collected more than a few meters from the building. Waste effluent streams are an exception to this rule, but even here samples must be collected before significant

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[26] Kenneth E. Apt, Los Alamos National Laboratory, "Near-Site Monitoring for Compliance Assessment of the Chemical Weapons Convention" LACP-90-289, June 15, 1990.

[27] Robert Lentz et al., *Chemical Weapons (CW) Treaty Verification Technology* Research *and Development: program Interim Summary* (Aberdeen Proving Ground, MD: Chemical Research, Development & Engineering Center, Report No. CRDEC-CR-124, September 1991), p. 24.

[28] Manuel L, Sanches, et al., *Analysis of Signatures Associated With Noncompliance Scenarios*, Report No. DNA-TR-92-74 (Arlington, VA: System Planning Corp., January 1993), p. 96.

dilution occurs.[29] Moreover, chemical plants in developing countries do not now employ sophisticated environmental protection devices, but as such equipment becomes more widely available, plant emissions could be reduced significantly.

Potential countermeasures also exist to remote-sensing technologies. For example, a determined cheater might reduce emissions below the detection threshold, or release masking compounds that absorb infrared radiation at the same frequencies as do the target chemical species.

Sorbent Materials

One approach to passive-integrative monitoring involves the use of absorbent materials called "sorbents, ' which have a very large internal surface area. Airborne chemicals simply diffuse into the material and are irreversibly bound to it, although they can later be extracted for chemical analysis. Examples of sorbent materials include *diatoms* (porous, silica-based structures that are the microscopic skeletons of plankton), *zeolites* (long-chain polymers of silicon, oxygen, and aluminum), and *silica gels* that have been chemically modified to absorb organic chemicals but not water.

Conceivably, artificial rocks or gravel made of a sorbent material could be dispersed in the vicinity of a suspect facility. These sorbents would accumulate volatile chemicals from the air over an extended period of time, providing concentrated samples for laboratory analysis.[30] The drawbacks of passive-integrative systems are the lack of temporal information about the timing of effluent releases, plus the fact that chemical agents may degrade in the natural environment or within the absorbent material.

BIOMARKERS FOR CW AGENTS

Wartime or occupational exposure to CW agents can leave behind long-lasting traces in humans or other living organisms. These biochemical signatures, known as "biomarkers," might conceivably be monitored as a means of detecting illicit CW production or use. During the Iran-Iraq War, for example, chemical analysis of urine samples from Iranian soldiers attacked with sulfur mustard revealed elevated levels of the metabolize thiodiglycol in most of the victims. In some cases, however, the technique could not distinguish between control urines and samples of allegedly exposed soldiers. To solve this problem, scientists at the U.S. Army Medical Research Institute of Chemical Defense developed a more sensitive assay that involved chemically derivatizing thiodiglycol before conducting the analysis.[31] Using this method, levels Of urinary thiodiglycol in individuals moderately exposed to mustard gas were found to be greater than 10 nanograms per milliliter (10 parts per billion) for at least a week[32] Similar techniques have been developed for detecting the major metabolizes of nerve agents (methylphosphonate esters) in biological fluids by converting them into derivatives suitable for gas-chromatographic analysis.[33] The advantage of urinary metabolizes is that measuring them is much less invasive than taking blood samples; the drawback is that most organophosphorus compounds are cleared from the body within 48 hours of exposure.

Another biomarker technique involves measuring the activity of the enzyme acetylcholinesterase, which is specifically inhibited by nerve agents. While this enzyme is located primarily in nervous tissue, it is also present in the blood-both plasma and red blood

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[29] Raymond R. McGuire, op. cit., footnote 25.

[30] W, Earl, Los Alamos National Laboratory, "Specialized Sorbents," presentation at the Chemical Weapons Convention Verification Technology Research and Development Conference, Herndon, VA, Mar. 3, 1993.

[31] E. M. Jakubowski et al., "Quantification of Thiodiglycol in Urine by Electron Ionization Gas Chromatography-Mass Spectrometry," *Journal of Chromatography, Biomedical Applications,* vol. 528, 1990, pp. 184-190.

[32] E. M. Jakubowski et al., "Case Studies of Accidental Human Mustard Gas Exposure: Verification and Quantification By Monitoring Thiodyglycol Levels, " *Proceedings of the 1991 Medical Defense Bioscience Review (Fort Detrick, MD:* U.S. Army Medical Research Institute of Chemical Defense, Aug. 7-8, 1991), pp. 75-80.

[33] M. L. Shih et al., "Detection of Metabolizes of Toxic Alkylmethylphosphonates in Biological Samples, " *Biological Mass Spectrometry,* vol. 20, 1991, pp. 717-723.

cells—although its function there is unknown. It is possible to measure the activity of blood acetylcholinesterase compared with known normal values (preferably with earlier values from the same person or a set of normal values from several individuals); the effects of nerve-agent exposure on the activity of the enzyme are detectable for up to 3 weeks .34 Measurements can be made on small blood samples drawn from the fingertip. This technique has been used for routine health control of workers involved in production or spraying of organophosphorus pesticides, and it might also reveal the clandestine production of nerve agents at a suspect production or storage facility. Nevertheless, the assay would not be able to distinguish between the illicit production of nerve agents and the legitimate production of organophosphorus pesticides or fire retardants in the same plant. It would also be essential to know the background (pre-exposure) levels of acetylcholinesterase activity.

Yet another means of detecting exposure to CW **agents involves the detection of "adducts" resulting from the binding of toxic chemicals directly to molecules** of DNA or protein **in the body. Sulfur** mustard, for example, forms covalent bonds with nucleotide bases along the DNA strand that may persist for several days or weeks. The major DNA adduct produced by sulfur mustard is an alkyl group bound to the nucleotide guanine, which accounts for over 60 percent of the DNA damage caused by sulfur mustard.[35] The DNA molecules can be extracted from skin cells or peripheral white blood cells and analyzed. A group of Dutch scientists has also developed monoclinal antibodies to alkylated guanine, making it possible to use an immunoassay (ELISA) technique to detect adducts in DNA extracted from white blood cells. This method is sensitive enough to detect one DNA adduct among 10^8 unmodified nucleotides-a level of damage resulting from exposure to a small dose of sulfur mustard.[36]

Analysis of DNA adducts can reveal an individual's prior exposure to toxic chemicals, and has already been used to monitor occupational exposure to pesticides through both the air and the skin. This technique might also be used to detect clandestine production of CW agents by plant workers at suspect facilities, although there may be constitutional barriers to mandatory blood testing in some countries. Monitoring of DNA adducts also has some technical drawbacks. Only small quantities of adducts can be extracted from accessible tissue such as white blood cells, and DNA adducts tend to be removed by chemical and enzymatic processes and hence do not persist for long in the body, having a half-life of a few weeks.

Because of the transience of DNA adducts, several investigators have turned instead to protein adducts, **such as the alkylation of hemoglobin by sulfur mustard.** Experiments have shown that about 1,000 times more sulfur mustard binds to proteins than to DNA.[37] Moreover, hemoglobin has a relatively long lifespan (120 days), permitting the determination of cumulative exposure to toxic chemicals over a period of months.[38] Analysis of blood samples for hemoglobin adducts might therefore be the best way of detecting long-term exposure to CW agents in chemical-plant workers. Nevertheless, the concentrations of hemoglobin adducts are usually found at extremely low levels (femtomoles or picomoles per gram), requiring measures that are extremely sensitive and selective.[39] Such testing therefore entails complex tradeoffs among sensitivity, specificity, and cost.

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[34] S. J. Lundin, "The Inhibition of Cholinesterase Activity by Organophosphorus Compounds as a Means in an Inspection Procedure," in Stockhom International Peace Research Institute, *The Problem of Chemical and Biological Warfare, Vol. VI: Technical Aspects of Early Warning and Verification* (Stockholm: Almqvist & Wiksell, 1975), pp. 180-181.

[35] David B. Ludlum, Paula A. Ritchie, and Miasnig Hagopian, "Systemic Toxicity of Sulfur Mustard: A Predictive Test Based on the Measurement of DNA Adduct Formation in Peripheral Blood, " *Proceedings of the 1991 Medical Defense Bioscience Review (Fort Detrick, MD:* U.S. Army Medical Research Institute of Chemical Defense, Aug. 7-8, 1991), pp. 97-100.

[36] H. P. Benschop et al., "Immunochemical Diagnosis and Dosimetry of Exposure to Sulfur Mustard," *Proceedings of the 1991 Medical Defense Bioscience Review (Fort* Detrick, MD: U.S. Army Medical Research Institute of Chemical Defense, Aug. 7-8, 1991), pp. 67-74.

[37] Ibid., p. 72.

[38] Gary T. Vaughan and T. Mark Florence, "Biomonitoring of DNA-Damaging Toxina, " Dianne Watters et al., eds., *Toxins* and *Targets: Effects of Natural and Synthetic Poisons on Living Cells and Fragile Ecosystems* (Philadelphia PA: Harwood Academic Publishers, 1992), p. 172.

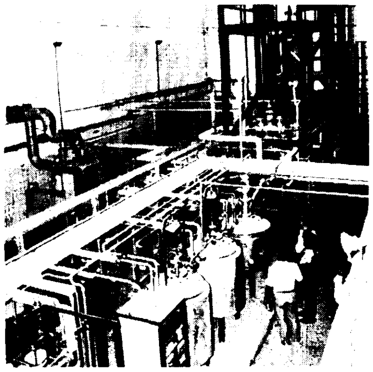
[39] Ibid., p. 172.

Technical Aspects of Biological Weapon Proliferation

3

Biological and toxin warfare (BTW) has been termed “public health in reverse” because it involves the deliberate use of disease and natural poisons to incapacitate or kill people. Potential BTW agents include Living microorganisms such as bacteria, rickettsiae, fungi, and viruses that cause infection resulting in incapacitation or death; and toxins, nonliving chemicals manufactured by bacteria, fungi, plants, and animals. Microbial pathogens require an incubation period of 24 hours to 6 weeks between infection and the appearance of symptoms. Toxins, in contrast, do not reproduce within the host; they act relatively quickly, causing incapacitation or death within several minutes or hours.

The devastation that could be brought about by the military use of biological agents is suggested by the fact that throughout history, the inadvertent spread of infectious disease during wartime has caused far more casualties than actual combat.[1] Such agents might also be targeted against domestic animals and staple or cash crops to deprive an enemy of food or to cause economic hardship. Even though biological warfare arouses general repugnance, has never been conducted on a large scale, and is banned by an international treaty, BTW agents were stockpiled during both world wars and continue to be developed as strategic weapons—“the poor man’s atomic bomb’’—by a small but growing number of countries.[2]



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[1] John P. Heggers, “Microbial Invasion—The Major Ally of War (Natural Biological Warfare),” *Military Medicine*, vol. 143, No. 6, June 1978, pp. 390-394.

[2] This study does not address the potential use of BTW agents by terrorist groups. For a discussion of this topic, see U.S. Congress, Office of Technology Assessment, Technology *Against Terrorism: The Federal Effort*, OTA-ISC-481 (Washington, DC: U.S. Government Printing Office, July 1991), pp. 21-22. See also Jessica Eve Stem, “Will Terrorists Turn to Poison?” *Orbis, vol. 37, No. 3,* summer 1993.

The Biological and Toxin Weapons Convention of 1972, signed and ratified by some 130 countries, bans the development, production, stockpiling, and transfer of BTW agents for warfare purposes. This treaty was weakened from the start, however, by the impossibility of banning research on BTW (agents, the fact that the development, production, and storage of BTW agents are permitted for defensive or peaceful purposes, and the absence of formal mechanisms for verification or enforcement.[3] It has also been alleged that key signatory states such as the former Soviet Union have systematically violated the treaty. According to a recent White House report, ‘‘the Russian offensive biological warfare program, inherited from the Soviet Union, violated the Biological Weapons Convention through at least March 1992. The Soviet offensive BW program was massive, and included production, weaponization, and stockpiling. ’

The biological disarmament regime has also come under growing pressure from the global spread of biotechnologies suitable for both civil and military applications, and from the revolution in genetic engineering, which has made it possible to manipulate the genetic characteristics encoded in the chemical structure of the DNA molecule. Soon after the publication in 1973 of techniques for cutting and splicing DNA molecules across species lines, a few concerned scientists worried that these powerful methods might be applied to develop new and more dangerous biological-warfare agents. Today, some defense planners believe that genetic engineering and other biotechnologies may eventually remove some of the military liabilities of BTW agents, increasing the attractiveness of these weapons to states of proliferation concern. It is not clear, however, that such techniques would significantly alter the military utility of BW agents compared with the numerous already known agents.

Given the perceived need to strengthen the Biological Weapons Convention (BWC), and the fact that the Chemical Weapons Convention (CWC) includes formal verification measures such as onsite inspections, a number of countries have proposed establishing a similar verification regime for the BWC. (See box 3-A, pp. 74-75. See also ch. 2 for discussion of procedures and technologies that might be used to detect the production of chemical weapons.) Nevertheless, verifying the nonproduction of biological weapons is inherently more difficult than for chemical weapons, for three reasons.

First, since BW agents are living microorganisms that reproduce inside the host, they are much more potent per unit weight. Thus, whereas CW agents must be stockpiled in the hundreds or thousands of tons to be militarily significant, a few kilograms of a BW agent such as anthrax bacteria could cause comparable levels of casualties. Such a small quantity of agent would be relatively easy to hide.

Second, whereas the production of CW agents requires certain distinctive precursor materials, reactions, and process equipment and leaves behind telltale chemical signatures, the production of BW agents involves materials and equipment that are almost entirely dual-use. As a result, it can be extremely difficult to distinguish illicit BW agent production from legitimate activities permitted under the BWC, such as the production of vaccines.

Third, because of the potency of BW agents and the exponential rate of microbial growth, a militarily significant quantity of BW agent could be produced in a matter of days in a small, easily

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[3] Some analysts worry that the Chemical Weapons Convention which was recently opened for signature and includes stringent verification measures, may create incentives for some proliferant countries to acquire biological rather than chemical arms-both because BTW agents can be produced in smaller, more concealable facilities, and because the Biological Weapons Convention currently lacks effective verification mechanisms.

[4] George Bush, “The President’s Report to Congress on Soviet Noncompliance With Arms Control Agreements, ” Jan. 14, 1993, p. 14.

concealed clandestine facility. All of these factors make the verification of compliance with the BWC a particularly challenging task.

This chapter provides technical background on the difficulty and detectability of BTW production and weaponization. The discussion covers the major technical hurdles involved in the acquisition of biological weapons and the associated ‘‘signatures’ that might be monitored to track their spread.

SUMMARY

Although biological and toxin weapons are often grouped together with chemical weapons, they differ in important ways. The most obvious difference is that whereas CW agents are man-made, nonliving poisons, biological agents are infectious microorganisms that reproduce within the host to cause an incapacitating or fatal illness. Toxins, being poisonous chemicals manufactured by living organisms, have characteristics of both chemical and biological agents.

Because of the ability of pathogenic microorganisms to multiply rapidly within the host, small quantities of a biological agent—if widely disseminated through the air-could inflict casualties over a very large area. Weight-for-weight, BTW agents are hundreds to thousands of times more potent than the most lethal chemical-warfare agents, making them true weapons of mass destruction with a potential for lethal mayhem that can exceed that of nuclear weapons. The lengthy incubation period of microbial pathogens places a major limitation on their battlefield utility, except in situations of attrition warfare, sabotage attacks against command and communications facilities deep behind enemy lines, or strikes against massed troops prior to their commitment to battle. Moreover, the delayed effects of biological weapons would not prevent their covert use against crops, livestock, or people as a means of crippling the economy and psychological morale of a targeted country.

Biological and toxin weapons potentially pose greater dangers than either chemical or nuclear weapons because BTW agents are so lethal on a pound-for-pound basis, their production requires a much smaller and cheaper industrial infrastructure, and the necessary technology and know-how are almost entirely dual-use and thus widely available. Despite the drawbacks of biological agents for tactical military use (e.g., delayed action, the dependence on meteorological conditions for their effectiveness, and the difficulty of precise targeting), they might be attractive as a strategic weapon-particularly for small, non-nuclear nations embroiled in regional conflicts or threatened by a nuclear-weapon state.

One technical hurdle to acquiring a militarily significant BTW capability is to ensure adequate containment and worker safety during production and weapon handling. It is also technically difficult to deliver biological agents to a target area so as to cause infection in a reliable and predictable manner. Although a supply of standard BTW agents for strategic attacks against wide-area civilian targets (e.g., cities) would be relatively easy to disseminate using crude delivery systems such as an agricultural sprayer, this means of delivery would be largely uncontrollable and subject to shifting atmospheric conditions. A more predictable-and hence more tactically useful-means of delivery against point targets on the battlefield would require extensive research, development, and testing. In particular, the integration of BTW agents into long-range delivery systems such as cluster bombs poses complex engineering hurdles-although these problems appear to have been solved for a few agents by the United States and the Soviet Union during the 1950s and 1960s.

There are no specific indicators, or “signatures,” that can differentiate unambiguously between the development of offensive BTW agents and work on defensive measures such as vaccines, since both activities require the same basic know-how and laboratory techniques at the R&D stage. Moreover, certain types of civilian facili-

Box 3-A—The Debate Over BWC Verification

The Biological and Toxin Weapons Convention (BWC) of 1972 bans agents and delivery systems of types and in quantities that have no justification for prophylactic, protective or other peaceful purposes," yet the treaty does not define permitted activities more precisely and lacks any formal mechanisms for verifying compliance. At the time the BWC was negotiated it was considered politically impossible to obtain international support for onsite inspections and other intrusive verification measures. Since 1972, however, the emergence of genetic engineering and other novel biotechnologies has led to renewed concern over the seriousness of the biological and toxin warfare threat. Given the dual-use nature of the agents and equipment the feasibility of effective verification has been widely debated.

At the Second Review Conference of the BWC in 1986, the participating countries sought to build confidence in the treaty regime through an annual exchange of information on permitted activities and facilities that could be potentially associated with biological and toxin warfare. Additional confidence-building measures were adopted at the Third Review Conference in 1991. None of these measures are legally binding, however, and less than half of the parties to the treaty have participated to any extent in the data exchanges. At the Third Review Conference, several countries supported the drafting of a legally binding verification protocol to supplement the BWC that, inter alia, would require each Party to declare all treaty-relevant biological research and production facilities. The declarations would be confirmed by routine onsite inspections, supplemented by challenge inspections of undeclared facilities.

Proponents of a verification protocol argued that while a BWC verification regime could not provide absolute confidence in a country's compliance, it would serve to deter the proliferation of biological and toxin weapons by:

- imposing a risk of discovery and increasing the cost and difficulty of a clandestine program;
- providing opportunities for parties to demonstrate compliance, and enhancing confidence in the compliance of others;
- decreasing the number of sites of proliferation concern;
- providing an opportunity to act on national intelligence information without public disclosure of sensitive sources and methods;
- creating a legal framework for the conduct of challenge inspections; and
- reinforcing the international legal norm against the acquisition and use of BTW agents.[1]

The Bush administration, however, opposed the negotiation of a formal verification protocol on three grounds:

- the BWC could not be verified effectively because biological production facilities are dud-useand lack distinctive "signatures";
- a negotiated regime could not be sufficiently intrusive to detect clandestine facilities, generating false confidence that a country was in compliance with the treaty when in fact it was not; and
- highly intrusive inspections by multinational teams could expose both government and commercial facilities to foreign espionage. In particular, the loss of valuable trade secrets could weaken the competitive edge of the U.S. biotechnology and pharmaceutical industries?

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[1] Federation of American Scientists, Working Group on Biological and Toxin Weapons Verification, "Progress in Identifying Effective and Acceptable Measures fora compliance Protocol tithe Biological Weapons convention," working paper, May 1993.

[2] Statement by Ambassador Ronald F. Lehman, II, Head of United States Delegation, Biological and Toxin Weapons Convention Third Review Conference, Sept. 10, 1991. Note that In signing the Chemical Weapons Convention (CWC), the U.S. Government has determined that the highly intrusive inspections mandated in that treaty do not pose an unacceptable risk to proprietary information or national security. However, the Inspections specified in the CWC to verify that chemical weapons are not being produced or stored wwid not necessarily be sufficient for the purposes of verifying the Biological Weapons Convention. Therefore, the fact that CWC Inspections have been judged worthwhile despite their potential for espionage does not automatically mean that proposed BWC inspections wwid be also be seen as acceptable. For a discussion of measures by which industry can protect itself from the ioss of proprietary information due to Chemical Weapons Convention declarations and inspections, see U.S. Congress, Office of Technology Assessment, *The Chemical Weapons Convention: Effects on the U.S. Chemical Industry*, OTA-BP-ISC-1O6 (Washington, DC: U.S. Government Printing Office, August 1993).

While the controversy over BWC verification has focused largely on technical issues, it is fundamentally a political debate over whether the burden of uncertainty associated with BWC verification would hamper more severely the verifier or the violator. Proponents of BWC verification argue that even imperfect monitoring measures would create a finite probability of detection that would have a significant deterrent effect on potential proliferants. Furthermore, a verification regime based on mandatory declarations of treaty-related sites and activities would deter the use of known facilities for BTW production, driving any violations into Clandestine facilities and thus making them more difficult and costly. Verification opponents counter, however, that an ineffective verification regime would create false confidence and hence would be worse than none at all.

There is also a semantic difference over the meaning of the term “verification.” The U.S. Government uses this word in a narrow technical sense to mean the ability to detect violations within a specified regime with a high degree of confidence. In contrast, proponents of verification see it as the cumulative result of many sources of information, only some of which would be explicitly contained in a negotiated regime. Indeed, verification proponents admit that no negotiated inspection regime could detect clandestine facilities with a high degree of confidence. Instead, they argue, a formal verification regime would provide a legal instrument to permit inspections of suspicious facilities that have been detected by covert intelligence means. While many countries could be deterred from violating the treaty by a low probability of detection, some determined proliferants would require more intrusive measures.

Despite the Bush administration’s opposition to a formal verification protocol for the BWC, it did agree to the establishment of an Ad Hoc Group of Government Experts to identify and evaluate various monitoring approaches from a scientific and technical standpoint. This verification experts (VEREX) group met twice in Geneva during 1992, from March 30 to April 10 and from November 23 to December 4. The focus of its activities was to prepare a list of 21 potential BTW verification technologies, divided into onsite and offsite categories. The onsite measures were exchange visits, inspections, and continuous monitoring; the offsite measures were information monitoring declarations, remote sensing, and inspections. Each of these verification measures was evaluated in terms of 6 criteria:

1. technical strengths and weaknesses, including the amount and quality of information provided;
2. ability to distinguish between prohibited and nonprohibited activities;
3. ability to resolve ambiguities about activities;
4. technology, material, manpower, and equipment requirements;
5. financial, legal, safety, and organizational implications; and
6. impact on scientific research, cooperation, industrial development, and other permitted activities, and implications for the protection of commercial proprietary information.[3]

To determine whether combining some measures would result in synergistic effects, a methodology was developed for assessing measures in combination. The results indicate **that the interaction of two or more measures may yield synergistic capabilities or limitations that are not present** when the measures are evaluated **in isolation.**

Between the first and second VEREX meetings, the U.S. position on BWC verification softened noticeably, and the new Clinton administration initiated a thorough review of its BTW nonproliferation policy. The VEREX group met again on May **24-** June 4, 1993 to evaluate the proposed verification measures. The group met a final time on September 13-24,1993 to prepare and adopt by consensus a final report to be forwarded to the States Parties to the BWC. This final report will provide the basis for a decision by a majority of the participating countries on whether to proceed with the negotiation of a legally binding verification protocol for **the BWC. If such a decision is made in the affirmative, a Preparatory Conference could take place in late 1994 followed by a Special** Conference in early 1995.

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[3] Conference on Disarmament, *Final Declaration of the Third Review Conference of the BWC*, Part II, document no. BWC/CONF.III/23, p. 17.

ties will inevitably have the capacity to engage in illegal military production activities. Since excessive secrecy might be indicative of offensive intent, however, greater opemmess and transparency would tend to build confidence in a country's defensive intentions.

Advances in biotechnology have made it possible to produce militarily significant quantities of pathogens and toxins rapidly and in small, easily concealable facilities, greatly complicating the task of detecting BTW programs with national technical means of surveillance. To monitor clandestine programs, it is necessary to integrate data from many sources, with a particular emphasis on human intelligence: (agents and defectors).

Even though much of the equipment used to produce BTW agents is dual-use, this is not necessarily true of the agents themselves. Most microbial agents produced for peaceful purposes have no military utility, while those that do are made in very few places and in small quantities. Legitimate applications of dangerous pathogens and toxins (e.g., vaccine production and the use of toxins to treat neurological disorders and for experimental anticancer therapy) are relatively few at present, and are largely confinied to sophisticated biomedical facilities not normally found in developing countries (with the exception of a few vaccine production plants). Moreover, given the fact that the biotechnology industry is still in its infancy around the globe, the background of legitimate activities is still relatively small.

The weaponization of BTW agents entails field testing of biological aerosols, munitions, and delivery systems, as well as troop exercises, which might be detectable by satellite or other technical means of verification. Nevertheless, testing of microbial aerosols might be conceded or carried out at night or under the cover of legitimate dual-use activities, such as the application of biopesticides.

Despite growing concern over the military implications of genetic engineering, this technology is unlikely to result in 'supergerms" significantly more lethal or controllable than existing BW agents or capable of eliminating many of the uncertainties associated with the use of microbial pathogens in warfare. At the same time, however, gene-splicing techniques might facilitate the weaponization of microorganisms and toxins and enhance their operational effectiveness by rendering them more stable during dissemination (e.g., more resistant to heat, ultraviolet radiation, and shear forces) and insusceptible to standard vaccines and antibiotics. Moreover, genetic engineering techniques could be used to develop and produce more effective protective vaccines for the attacking forces.

In the past, most plant and animal toxins had to be extracted from biological materials in a costly and labor-intensive operation, but the ability to ''clone' protein toxin genes in bacteria has made it possible to produce formerly rare toxins in kilogram quantities. For the forseeable future, however, toxin-warfare agents are unlikely to provide dramatic military advantages over existing chemical weapons, although their greater potency makes it easier to transport and deliver militarily significant quantities. While it is possible that bioregulators and other natural body chemicals (or synthetic analogues thereof) might be developed into powerful incapacitants, the nontrivial problem of delivering such agents in a militarily effective manner would first have to be solved.

BIOLOGICAL AND TOXIN AGENTS

Just because a microorganism causes a serious disease does not make it a potential warfare agent. Of the several hundred pathogenic microbes that directly or indirectly afflict humans, only about 30 have been considered as likely warfare agents.[5]

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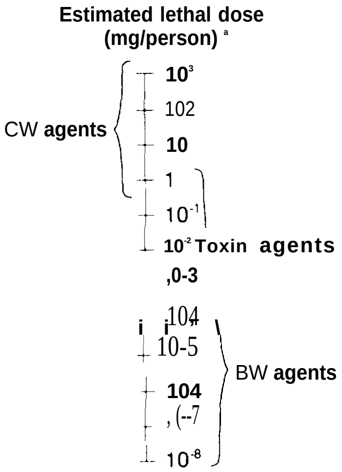
[5] Department of the Army, U.S. Army Medical Research and Development Command, *Final Programmatic Environmental Impact Statement: Biological Defense Research Program,* RCS DD-M (AR) 1327 (Fort Detrick, MD: USAMRDC, 1989), p. A7-2.

Desirable characteristics of a biological agent developed for military use include:

- *the* ability to *infect reliably in* small doses;
- *high virulence,* or capacity to cause acute illness resulting in incapacitation or death, without experiencing an undue loss of potency during production, storage, and transport;
- *a short incubation period* between infection and the onset of symptoms;
- *minimal contagiousness* of the disease from one individual to another, to avoid triggering an uncontrolled epidemic that could boomerang against the attacker's population;[6]
- *no widespread immunity-either* natural or acquired-to the disease in the population to be attacked;
- *insusceptibility to common medical treatments,* such as generally available antibiotics;
- *suitability for economic production in militarily* significant quantities from available raw materials;
- *ease of transport,* and *stability* under wartime field conditions of storage and delivery;
- *ease of dissemination (e.g.,* as an aerosol cloud transmitted through the air);
- *ability to survive environmental stresses* during dissemination (e.g., heat, light, desiccation, and shear forces) long enough to infect; and
- *availability of protection* against the agent for the attacking troops, such as a vaccine, antibiotics, and/or protective clothing and respirators.[7]

Figure 3-1—Toxicity of CBW Agents



a paper clip weighs about 500 mg

SOURCE: Office of Technology Assessment, 1993,

BTW agents differ widely in infectiousness, length of incubation period, and lethality (see figure 3-l). A variety of them, including bacteria, rickettsiae, viruses, and toxins, were weaponized during the U.S. offensive BTW program, which was terminated in 1969. Brief descriptions of some typical BTW agents follow.

Bacteria

Bacteria are single-cell organisms that are the causative agents of anthrax, brucellosis, tularemia, plague, and numerous other diseases. They vary considerably in infectivity and lethality. The bacterium that causes tularemia, for example, is highly infectious. Inhalation of as few as 10 organisms causes disease after an incubation period of 3 to 5 days; if not treated, tularemia results in deep-seated pneumonia from which 30

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[6] Some analysts have suggested that a country might deliberately develop contagious BW agents, which might be rendered insusceptible to any drugs that could be used to combat them. Japan, for example, developed plague-a highly contagious disease—as a BW agent during World War II. While contagious agents are commonly dismissed as too dangerous to use, they might convey a decisive military advantage on the attacker if (1) he could give an antidote or vaccine to his own population, (2) the agent was designed to attack crops or livestock specific to the target country, or (3) the agent could be delivered to a distant target by a long-range delivery system such as a ballistic missile. Although mass vaccination of the attacker's own population appears unlikely for logistical reasons, a ruthless aggressor-state might be willing to put its own population at risk.

[7] The effectiveness of defenses cannot be guaranteed, however. No vaccine is 100 percent effective, since even a strong immunity can be overwhelmed by inhaling a heavy dose of agent.

Box 3-B-Anthrax as a Biological-Warfare Agent

Anthrax, a severe illness caused by the bacterium *Bacillus anthracis,* is considered the prototypioal biological-warfare agent. In nature, anthrax is primarily a disease of cattle and sheep but can also infect humans. it can survive for long periods in soil in a dormant (spore) phase; after infection, it reverts to an active phase in which it mulitipiies rapidly in the body and secretes fatal toxins. Natural human infection can result either from skin contact with infected animals, ingestion of contaminated meat or inhalation of anthrax spores, usually from contaminated hides. Cases of pulmonary-and in some outbreaks gastrointestinal--anthrax are almost invariably fatal if not **treated immediately with antibiotics. Inhalation of aerosolized spores would be the primary route of infection if the bacteria were used deliberately as a biological-warfare agent. As extrapolated from animal studies, inhalation of about 1,000 spores or less can produce fatal pulmonary anthrax** in some members of an exposed **population,** while inhalation of about 8,000 spores-weighing about 0.08 microgram-is fatal within less than a week to a large proportion of those exposed.[1]

After inhalation into the lungs, anthrax spores travel to the lymph nodes of the chest, where they become active, multiplying and releasing three proteins-edema factor, lethal factor, and protective antigen. in specific combinations, these proteins function as potent toxins, enabling the bacteria to resist host defenses and to invade and damage host tissues via the bloodstream, resulting in uncontrollable hemorrhaging. in this manner, anthrax bacteria travel to the intestines and other areas, where they cause severe tissue damage. Initial signs of pulmonary anthrax infection include a high fever, labored breathing, choking cough, and vomiting; it is usually fatal within 4 days.[2] Although infections may respond to immediate antibiotic therapy, it is relatively easy to develop antibiotic-resistant anthrax strains.

in addition to its lethality, anthrax has other characteristics that make it an effective BW agent. First the disease is not contagious from one individual to another. As a result, anthrax would not spread far beyond the intended target or boomerang against the attacker's troops or civilian Population, assuming they do not enter a contaminated area Second, anthrax is easy to produce. The organism and its spores can be readily produced

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[1] **Testimony by Barry J. Erlick, Biological Weapons** Analyst, Department of the **Army, in** U.S. **Senate,** Committee on Governmental Affairs, ***Global Spread of Chemical and Biological Weapons:*** *Assessing Challenges and Responses,* **101st** Congress, First Session, Feb. 9, 1989 (Washington, DC: U.S. Government Printing **Office,** 1990), p. 32.

[2] **Philip J. Hilts, "U.S. and Russian Researchers Tie Anthrax Deaths to Soviets,"** ***New York Times,*** **Mar. 15, 1993, p. A6.**

to 60 percent of victims die within 30 days.[8] Brucellosis, another bacterial disease, has a low mortality rate-about 2 percent-but an enormous capacity to inflict casualties. Infection gives rise to fever and chills, headache, loss of appetite, mental depression, extreme fatigue, aching joints, and sweating.[9] The bacterial agent that has received the most attention is anthrax, whose pulmonary form is highly lethal. (See box 3-B,)

Under certain environmental conditions, anthrax bacteria will transform themselves into rugged spores that are stable under a wide range of conditions of temperature, pressure, and moisture. One gram of dried anthrax spores contains more than 10^{11} particles; since the lethal dose by inhalation in monkeys is between l@ and l@ spores, a gram of anthrax theoretically contains some 10 million lethal doses.

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[8] **Testimony by Barry J. Erlick,** Biological Weapons **Analyst,** Department of the Army, in U.S. Senate, **Committee** on **Governmental** Affairs, *Global Spread of **Chemical** and Biological Weapons: Assessing Challenges and **Responses,*** **101st Cong.,** 1st sess., Feb. 9, 1989 (Washington DC: U.S. Government Printing Office, 1990), p. 32,

[9] J. H. Rothschild, *Tomorrows Weapons: Chemical and Biological (New* **York, NY:** McGraw-Hill, **1964),** P. 212.

in the laboratory in almost unlimited quantities, and antibiotic-resistant strains have been developed with standard selection techniques.[3]

Third, when anthrax bacteria are incubated under particular conditions, they transform themselves into the rugged spore form, which has along shelf-life. Although most spores can be killed by boiling for 10 minutes, they can survive for up to 20 years or longer in soil and animal hides.[4] This spore-forming ability makes anthrax particularity well suited for delivery by missiles or bombs. The spores are stable when suspended in air, can survive explosive dissemination from a bomb or shell, and-unlike most pathogens-will live for several days if direct sunlight is avoided. Indeed, fieldtest data have shown that anthrax spores decay at a rate of less than 0.1 percent per minute, which is very slow for a microorganism.[5]

Nevertheless, anthrax has certain liabilities as a tactical weapon. First, at lower doses there is a wide spread in incubation times, ranging from a few days to several weeks, suggesting that the spore germinations that result in infection can be delayed for considerable periods.[6] This variability greatly reduces the predictability and hence the military utility of the agent. Second, anthrax spores are so persistent that they can contaminate an area for long periods, denying it both to defender and attacker. During World War II, for example, Britain detonated experimental anthrax bombs on Gruinard Island off the coast of Scotland, releasing spores that remained in the top 6 to 8 inches of soil for more than 40 years.[7] By infecting livestock, anthrax bacteria might also create new reservoirs of disease that could result in occasional outbreaks, making it impossible to use the affected area productively for long periods.[8] That might be the desired intent, however, were anthrax to be used as a strategic weapon.

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[3] World Health Organization, *Health Aspects of Chemical* and *Biological Weapons* (Geneva: WHO, 1970), p. 74.

[4] Donald Kaye and Robert G. Petersdorf, "Anthrax," Eugene Braunwald et al., eds., *Harrison's Principles of Internal Medicine,* 1 lth ed. (New York, NY: McGraw Hill, 1987), p. 557.

[5] World Health Organization, op. cit., footnote 3, p. 94.

[6] presentation by Matthew Meselson, Harvard University, at Seminar on Biological Weapons in the 1990s, sponsored by the Center for Strategic and International Studies, Washington, DC, Nov. 4, 1992.

[7] These explosive anthrax bombs were crude and inefficient in creating an aerosol cloud composed of small particles. Instead, the bombs compacted the spores into the ground. Effective BW munitions would not do this. William C. Patrick III, former program analysis officer, U.S. Army Medical Research Institute of Infectious Diseases, Fort Detrick, MD, personal communication, 1992.

[8] World Health Organization, op. cit., footnote 3, p. 75.

Rickettsiae

Rickettsiae are microorganisms that resemble bacteria in form and structure but differ in that they are intracellular parasites that can only reproduce inside animal cells. Examples of rickettsial diseases that might be used for biological warfare include typhus, Rocky Mountain spotted fever, Tsutsugamuchi disease, and Q fever. Rickettsiae have a wide variety of natural hosts, including mammals and arthropods such as ticks, fleas, and lice. If used as BW agents, however, they would probably be disseminated directly through the air.

Viruses

Viruses are intracellular parasites that are about 100 times smaller than bacteria. They can infect humans, crops, or domestic animals. Viruses consist of a strand of genetic material (DNA or RNA) surrounded by a protective coat that facilitates transmission from one cell to another. The Venezuelan equine encephalitis (VEE) virus causes a highly infectious disease that incapacitates but rarely kills. In contrast, some hemorrhagic fever viruses, such as Lassa or Ebola fever, are exceedingly virulent, killing 70 out of every 100 victims. The AIDS virus, despite its lethality, would not be an effective warfare agent because its mean incubation period of 10 years is too slow to give it any tactical or strategic value in warfare, and because it cannot be transmitted through the air.

Fungi

Fungi do not generally cause disease in healthy humans, although the fungus *Aspergillus,* which infects by inhalation, can cause serious opportunistic infections in people with a weakened immune system. A few other fungi, such as *Coccidioides immitis* and *Histoplasma capsulatum, also* infect naturally by inhalation and can cause severe pulmonary infections in susceptible individuals, but they have never been considered as potential BW agents. Fungal diseases are, however, devastating to plants and might be used to destroy staple crops and cause widespread hunger and economic hardship. Examples of plant fungal pathogens include rice blast, cereal rust, and potato blight, which can cause crop losses of 70 to 80 percent.

| Toxins

A toxin is a poisonous substance made by a living system, or a synthetic analogue of a naturally occurring poison. An enormous variety of toxins are manufactured by bacteria, fungi, marine organisms, plants, insects, spiders, and animals, and more than 400 have been characterized to date. Such toxins can exert their effects by three different routes of exposure-injection, ingestion, and inhalation-and their potency derives from their high specificity for cellular targets. For example, many toxins bind to specific sites in nerve membranes, disrupting the transmission of nerve impulses and causing fatal respiratory paralysis. Other toxins selectively block cellular protein synthesis or other vital physiological functions.

From a chemical standpoint, there are two categories of toxins: protein toxins, which consist of long folded chains of amino acids; and nonprotein toxins, which tend to be small but complex molecules.

PROTEIN TOXINS

Most bacterial toxins, including those associated with cholera, tetanus, diphtheria, and botulism, are large proteins. For example, various strains of *Staphylococcus* ***aureus,*** a major bacterial pathogen, secrete protein toxins that cause severe nausea, vomiting, and diarrhea lasting from 1 to 2 days. The United States developed one of these toxins, *Staphylococcus* enterotoxin B (SEB), as a warfare agent in the 1960s. Spray-dried SEB, when disseminated through the air in aerosol form, causes a chemical pneumonia that is more debilitating than the toxin's gastrointestinal effects when ingested; it can incapacitate exposed troops within hours, with recovery in 4 to 6 days.[10] Botulinal toxin, secreted by the soil bacterium *Clostridium botulinum,* is the most poisonous substance known. The fatal dose of botulinal toxin by injection or inhalation is about 1 nanogram (billionth of a gram) per kilogram, or about 70 nanograms for an adult male.11 The toxin is also relatively fast-acting, producing death between 1 and 3 days in 80 percent of victims. The U.N. inspections of Iraq after the Gulf War confirmed that the microbiological research facility at Salman Pak had done development work on botulinum toxin as a potential warfare agent. Nevertheless, attempts to weaponize botulinal toxin have in the past failed to prevent extensive loss of toxicity that accompanies dispersion.

Ricin, a plant toxin derived from castor beans, irreversibly blocks cellular protein synthesis and is lethal when inhaled in a dose of about 10 micrograms (millionths of a gram) .12 Castor

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[10] William C. Patrick III, former program analysis officer, U.S. Army Medical Research Institute for Infectious Diseases, Fort Detrick, MD, personal communication, 1993.

[11] D. M. Gill, "Bacterial Toxins: A Table of Lethal Amounts," *Microbiological Reviews,* March 1982, pp. 86-94.

[12] G. A. Balint, "Ricin: The Toxic Protein of Castor Oil Seeds," *Toxicology,* vol. *2, 1974, p.* 80.

beans are widely cultivated as a source of castor oil, which has numerous legitimate industrial applications. The paste remaining after the oil has been pressed out contains about 5 percent ricin, which can be purified by biochemical means. During World War II, several countries studied ricin as a potential chemical-warfare agent, and the British developed and tested an experimental ricin weapon known as the "W bomb, " although it was not ultimately deployed.[13] In September 1978, the Bulgarian secret police (with technical assistance from the Soviet KGB) assassinated Georgi Markov, an exiled Bulgarian dissident living in London, by firing a tiny metal ball filled with ricin into his thigh from a pellet-gun concealed inside an umbrella; Markov died two days later.[14] According to published reports, Iran has acquired 120 tons of castor beans and is allegedly purifying ricin in pharmaceutical plants.[15]

NONPROTEIN TOXINS

Nonprotein toxins are small organic molecules that often have a complex chemical structure. They include tetrodotoxin @educed by a puffer fish), saxitoxin (made by marine algae known as dinoflagellates, which are taken up and concentrated by clams and mussels), ciguatoxin and microcystin (synthesized by microscopic algae), palytoxin (made by a soft red Hawaiian coral), and batrachotoxin (secreted by poisonous frogs indigenous to western Colombia). Typical characteristics of nonprotein toxins are high toxicity, the absence of antidotes, heat stability (unlike most protein toxins), resistance to other environmental factors, and speed of action. Saxitoxin, for example, produces initial symptoms within 30 seconds after ingestion and can cause labored breathing and paralysis in as little as 12 minutes. There is no known prophylaxis or therapy, and the lethal dose in 50 percent of those exposed maybe as low as 50 micrograms, a potency 1,000 times greater than the chemical nerve agent VX.[16]

Trichothecene mycotoxins are a family of about 100 poisonous compounds manufactured by certain strains of the mold *Fusarium* that grow on wheat, millet, and barley. When ingested by people or livestock, these toxins kill rapidly dividing cells such as those of the bone marrow, skin, and the lining of the gastrointestinal tract; they also block certain clotting factors in the blood, causing severe bleeding after injury. In aerosol form, about 35 milligrams of the trichothecene mycotoxin T-2 can kill a 75-kilogram man; unlike most other toxins, it is also absorbed through the skin. Although mycotoxins are significantly less potent than chemical-warfare agents such as VX, they are relatively easy to produce and are highly stable.

In 1982, the Reagan administration alleged that the Soviet Union and its allies were using a toxin-warfare agent in Southeast Asia known as "yellow rain" whose active ingredients were trichothecene mycotoxins.[17] The Soviets denied the allegations, and the United States was unable to provide convincing public evidence to back up its charges in the face of criticism on the part of

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[13] Stockholm International Peace Research Institute, *The Problem of Chemical and Biological Weapons, Vol. I: The Rise of CB Weapons* (Stockholm: Almqvist & Wiksell, 1971), p. 123.

[14] Robert Harris and Jeremy Paxman, *A Higher Form of Killing: The Secret Story of Gas and Germ Warfare* (London: Chatto & Windus, 1982), pp. 197-198; David Wise, ''Was Oswald a Spy, and Other Cold War Mysteries," New *York Times Magazine,* Dec. 6, 1992, p. 44.

[15] Douglas Wailer, "Sneaking in the Scuds, " *Newsweek,* June 22, 1992, p. 42.

[16] Erlick, op. cit., footnote *8,* p. 32, See also B.J. Benton and F.C.T. Chang, ''Reversal of Saxitoxin-Induced Cardio-Respiratory Failure by Burro IgG Antibody and Oxygen Therapy,' *Proceedings of the 1991 Medical Defense Bioscience Review (Fort* Detrick, *MD:* U.S. Army Medical Research Institute of Chemical Defense, Aug. 7-8, 1991), p. 176.

[17] U.S. Department of State, *Chemical Warfare in Southeast Asia and Afghanistan, Special* Report No. *98,* Mar. 22, 1982, P. 30.

many in the U.S. scientific community.[18] Following early reports of the presence of trichothecenes in samples from alleged attacks, the U.S. Army and the U.K. Ministry of Defense initiated large analytical studies but were unable to confirm the early findings.[19] Nonetheless, U.S. intelligence officials, based on all the: information available to the U.S. intelligence community, remain confident in the yellow rain allegations and have not retracted them.

Compared to microbial pathogens, toxins offer the following tactical advantages:

- The most toxic toxins (e.g., botulinal toxin) are exceedingly potent, so that small, easily transportable quantities would be militarily significant for certain missions.
- Toxins tend to deteriorate rapidly once released into the environment, whereas anthrax spores and persistent chemical agents can centaminate soil for months or years. For this reason, territory attacked with toxin agents could be occupied more rapidly by attacking forces.
- Toxins are well suited to covert warfare. Whereas chemical agents leave telltale degradation byproducts that persist for long periods in the environment, some toxin agents break down completely over a period of weeks or months, leaving no traces. Moreover, even fresh samples of toxin might not provide conclusive evidence of military use if the agent occurred naturally in the region where it was employed.

Despite these operational advantages, however, toxins have drawbacks for battlefield use:

- Protein toxins such as botulinal toxin decompose rapidly on exposure to sunlight, air, and heat, and thus would have to be used at night.
- Protein toxins may be inactivated by the mechanical shear forces caused by passage through an aerosol sprayer.[20] While low-molecular-weight toxins such as saxitoxin and trichothecene mycotoxins are more stable than protein toxins, they are less stable than chemical-warfare agents.
- Most toxins (with the exception of trichothecene mycotoxin T-2) do not penetrate the skin, nor would toxin lying on the ground create a vapor hazard.[21] Weaponization therefore requires the creation of a small-particle aerosol cloud, in which the toxin must remain airborne to be effective.
- The inhalation threat posed by protein toxins such as botulinal **toxin can be countered** effectively with modern gas masks (although a surprise or covert attack might expose personnel to lethal concentrations before they could don their masks).

For conventional battlefield use, toxins offer few military advantages over chemical nerve agents. Toxins would, however, probably be superior for small-scale clandestine operations.

ACQUIRING A BTW CAPABILITY

The acquisition of a militarily significant BTW capability would probably involve the following steps (see figure 3-2):

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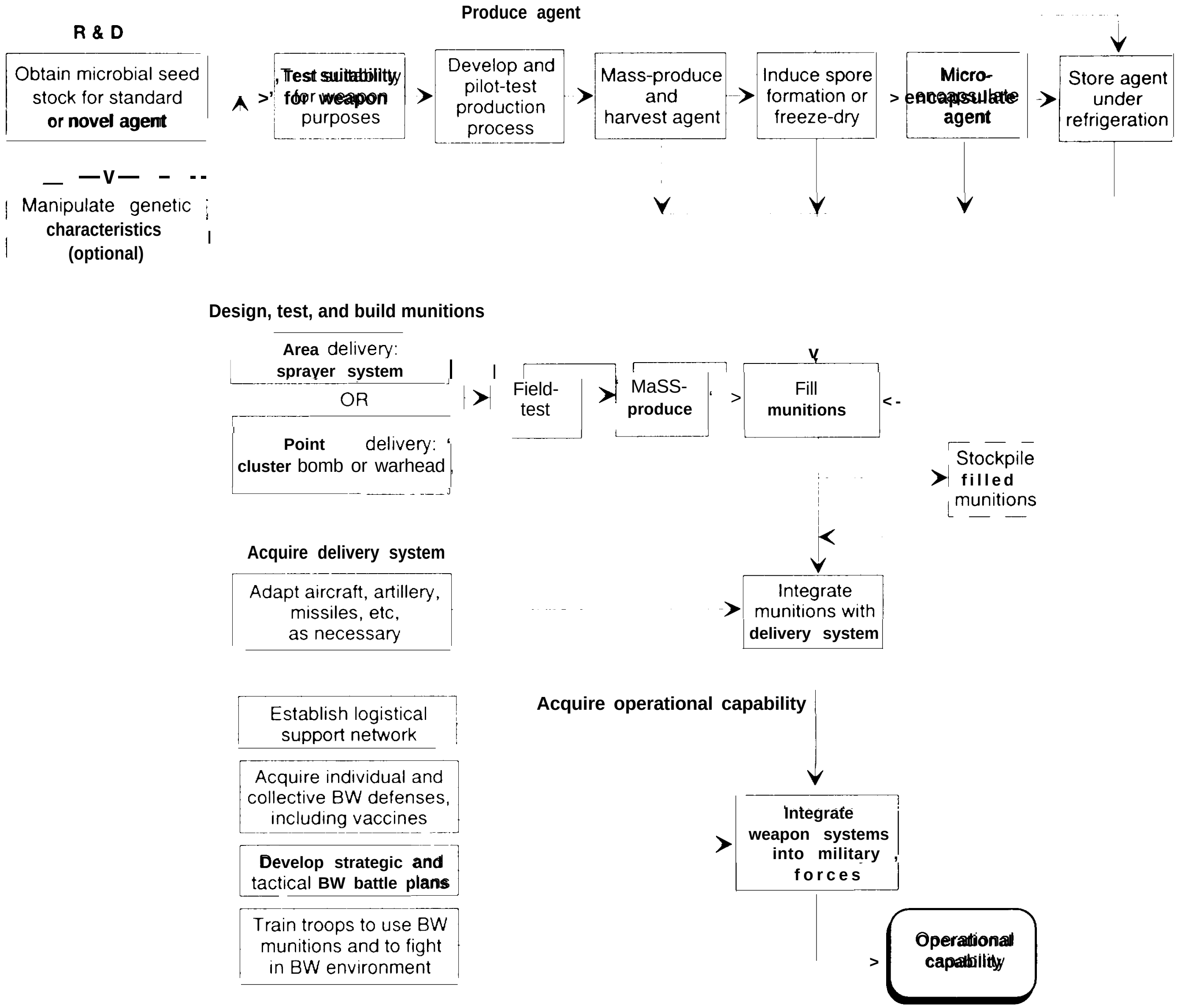
[18] Julian Robinson, Jeanne Guillemin, and Matthew Meselson, "Yellow Rain in Southeast Asia: The Story Collapses," Susan Wright, cd., Preventing a *Biological Arms Race* (Cambridge, MA: MIT Press, 1990), pp. 220-238. See also U.S. Senate, Committee on Foreign Relations, Subcommittee on Arms Control, Oceans, International Operations, and Environment, 98th Cong., 1st sess., *Yellow Rain: The Arms Control Implications,* Feb. 24, 1983 (Washington DC: U.S. Government Printing Office, 1983).

[19] Robinson et al., op. cit., footnote 18, pp. 228-229.

[20] A few protein toxins are quite stable: SEB in milk, for example, is not destroyed after boiling for 30 minutes. In addition, the stability of protein toxins can be increased through a technique known as microencapsulation (see production section below), David S. Huxsoll, former director, U.S. Army Medical Research Institute for Infectious Diseases, personal communication, 1992.

[21] Shirley Freeman, "Disease as a Weapon of War," *Pacific Research,* vol. 3, February 1990, p. 5.

Figure 3-2—Biological Weapon Acquisition



SOURCE: Office of Technology Assessment, 1993.

1. Establishment of one or more facilities and associated personnel with organizational and physical provisions for the conduct of work in secret;
2. Research on microbial pathogens and toxins, including the isolation or procurement of virulent or drug-resistant strains;
3. Pilot production of small quantities of agent in flasks or small fermenter systems;
4. Characterization and military assessment of the agent, including its stability, infectivity, course of infection, dosage, and the feasibility of aerosol dissemination;

5. Research, design, development, and testing of munitions and/or other dissemination equipment;
6. Scaled-up production of agent (possibly in several stages) and freeze-drying;
7. Stabilization of agent (e.g., through microencapsulation) and loading into spray tanks, munitions, or other delivery systems; and
8. Stockpiling of filled or unfilled munitions and delivery vehicles, possibly accompanied by troop training, exercises, and doctrinal development. (In some but not all cases, a country planning the offensive use of BTW agents would take measures to protect its own troops, such as immunization, the acquisition of respirators, and training in self-protective measures.)

The key steps in this acquisition sequence are examined below in terms of their technical difficulty.

| Research, Development, and Weaponization

Countries seeking a BTW capability are likely to start with the development of standard agents that have been weaponized in the past, such as anthrax, tularemia, and botulinum toxin. Nearly all proliferant states lack the sophisticated scientific and technological infrastructure needed to develop novel agents such as exotic viruses, whose military characteristics are poorly understood.

BTW agents are widely accessible. Pathogenic microorganisms are indigenous to many countries and can be cultured from infected wild animals (e.g., plague in rodents), living domestic animals or infected remains (e.g., Q fever in sheep, anthrax in cattle), soil in endemic areas (which may contain trace amounts of anthrax bacteria and other pathogens), and spoiled food. Certain biological supply houses also ship strains of microbial pathogens to scientists throughout the world. For example, American Type Culture Collection (ATCC), a nonprofit company in Rockville, MD, acts as a clearinghouse for research institutions around the world, shipping each year approximately 130,000 cultures of weakened (''attenuated”) pathogens to 60 nations.[22] While such attenuated strains are not virulent and hence could not be converted directly into biological weapons, they would be useful for BTW research and development and for preparing self-protective vaccines. Methods for culturing organisms and for inducing spore formation are also described in the open scientific literature, and standard microbiological procedures can be used to produce more virulent or antibiotic-resistant strains of microbial pathogens.

Once a proliferant had acquired BTW agents, they might be modified genetically through simple selection techniques to increase their virulence or effectiveness. For example, incubating microbial pathogens in the presence of standard antibiotics can induce the emergence of drug-resistant strains, which can then be subculture and mass-produced. Agent development would also involve “weaponization," or a thorough assessment of the agent military potential, including its stability, infectivity, course of infection, and effective dosage. This step would include the testing of candidate agents to determine their effectiveness, including the feasibility and reliability of aerosol dissemination. Such tests might be carried out either in a sealed aerosol chamber or in field studies of simulant microorganisms at a remote testing range.

THE DUAL-USE DILEMMA

A fundamental problem in countering the proliferation of biological and toxin weapons is the fact that much of the necessary know-how and technology is dual-use, with legitimate applications in the commercial fermentation and biotechnology industries. Many developing countries

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[22] Eric Nadler and Robert Windrew, ''Deadly Contagion,'' *The New Republic,* vol. 204, No. 5, Feb. 4, 1991, p. 18.

have acquired industrial microbiology plants for the production of fermented beverages, vaccines, antibiotics, ethanol (from corn or sugar cane), enzymes, yeast, vitamins, food colors and flavorings, amino acids, and single-cell protein as a supplement for animal feeds.[23] This global expansion of the civilian biotechnology industry, combined with the growing number of molecular biotechnologists trained in the West, has created much broader access to the expertise and equipment needed for the development of BTW agents. Sophisticated laboratories that might be used for the design of novel BW agents are inexpensive compared with nuclear weapon plants. Moreover, biotechnology is information-intensive rather than capital-intensive, and much of the relevant data are available in the published scientific literature. For these reasons, it is virtually impossible for industrialized states to prevent the diffusion of weapon-relevant information to states of proliferation concern.

It has been estimated that more than 100 countries have the capability-if not necessarily the intent-to develop at least crude biological weapons based on standard microbial and toxin agents.[24] In addition to the United States, Russia, Western Europe, and Japan, countries with an advanced commercial biotechnology infrastructure include Argentina, Brazil, Chile, Cuba, India, Israel, the People's Republic of China, Taiwan, and Thailand. Cuba, in particular, has an advanced biotechnology industry that exports vaccines and reagents to other Latin American countries.[25] While Iraq lags somewhat behind this group of countries, Baghdad established a national Center for Genetic Engineering and Biotechnology in the late 1980s, initially staffed with only four scientists.[26] As an increasing number of developing countries become involved in commercial biotechnology, they may be tempted to explore its military potential.

In addition, the legitimate use of toxins for medical therapy and biomedical research is increasingly widespread. Botulinal toxin, for example, is used to treat abnormal muscle spasms known as dystonias by selectively paralyzing the spastic muscles; it has also been applied cosmetically to smooth wrinkles.[27] Toxins such as ricin, when linked to antibodies that selectively target cancer cells, have shown promise in clinical trials as an anticancer therapy.[28] Furthermore, saxitoxin and other exotic toxins that bind specifically to channels or receptors in nerve-cell membranes are valuable research tools in neuroscience. The inherently dual-use nature of many pathogens and toxins makes the prevention of BTW-relevant research extremely difficult. Consumption of toxins for medical therapy and research has already expanded to the current level of hundreds of grams per year, and the anticipated further growth of such therapies will eventually blur the

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[23] For an overview, see U.S. Congress, Office of Technology Assessment, Biotechnology *in a Global Economy,* OTA-BA-494 (Washington, DC: U.S. Government Printing Office, October 1991).

[24] Testimony of Thomas Welch, Deputy Assistant Secretary of Defense (Chemical Matters), reported in *Defense Week,* May 9, 1988.

[25] Raymond A. Zilinskas, "Biological Warfare and the Third World," *Politics and the Life Sciences,* vol. 9, No. 1, August 1990, p. 61.

[26] Presentation by Raymond Zilinskas, Washington Strategy Seminar, Washington, DC, July 14, 1992.

[27] *Tom Waters,* 'The Fine Art of Making Poison,'' *Discover,* vol. 13, No. 8, August 1992, p. 32; and Anna Evangeli, ' 'Botulism Gives Faces New Lease of Life, " New *Scientist,* vol. 137, No. 1859, Feb. 6, 1993, p. 18. See also Fritz P. Gluckstein and Mark Hallet, *Clinical Use of Botulinum Toxin: January 1987 through September 1990, 318 Citations* (Washington DC: National Library of Medicine/U.S. Government Printing Office, 1990).

[28] David Fitzgerald and Ira Pastan, ''Targeted Toxin Therapy for the Treatment Of Cancer, " *Journal of the National Cancer Institute,* vol. 81, No. 19, October 1989, pp. 1455-1463; Andrew A. Hertler and Arthur E. Frankel, "Immunotoxins: A Clinical Review of Their Use in the Treatment of Malignancies," *Journal of Clinical Oncology,* vol. *7, No. 12,* December 1989, pp. 1932-1942; Lee H. Pai and Ira Pastan, ''Immunotoxin Therapy for Cancer,' *Journal of the American Medical Association,* vol. 269, No. 1, Jan. 6, 1993, pp. 78-81.

distinction between medically useful and militarily significant quantities of toxins.[29] The legitimate applications of toxins will therefore have to remain relatively open to preclude their use for illicit purposes.

Finally, the development of defenses against BTW attack-an activity explicitly permitted by the Biological Weapons Convention-draws on much of the same knowledge base needed to develop offensive BTW agents. Indeed, “threat assessment, an important aspect of some biological-defense programs, includes the evaluation of defenses under simulated warfare conditions and may be indistinguishable from the development of offensive BTW agents .[30] Furthermore, certain defensive activities may have offensive applications. According to one assessment, ‘‘the virulence of micro-organisms is studied both for its relevance to the field of natural infections and in order to produce living, attenuated vaccines. Such knowledge can obviously be used more or less directly to make a BW agent more virulent.”[31] For these reasons, biological-defense activities such as the development of vaccines may arouse concerns about offensive intentions unless they are conducted openly and in an unclassified environment..

In sum, research on potential BTW agents does not necessarily imply an offensive weapon program because much of the relevant knowledge is multiuse. This inherent ambiguity means that at the R&D stage, the only difference between offensive and defensive activities is one of *intent. The* policy dilemma is that progress in controlling infectious diseases requires the free and open flow of information, so that researchers can build on and validate the work of others; imposing controls on the publication of results with potential military implications would seriously impede legitimate scientific research worldwide. Nevertheless, openness may impose some limits on the misuse of biomedical research for malicious purposes.

Large-Scale Production

BTW agents would be relatively easy and inexpensive to produce for any nation that has a modestly sophisticated pharmaceutical or fermentation industry. Indeed, mass-production methods for growing pure cultures are widely used in the commercial production of yogurt, yeast, beer, antibiotics, and vaccines. Nearly all the equipment needed for the production of pathogens and toxins is dual-use and widely available on the international market, increasing the potential for concealing illicit activities under the cover of legitimate production. Whereas a typical vaccine production facility costs a minimum of $50 million, a much less elaborate industrial fermentation plant suitable for conversion to BTW agent production could be built for about $10 million.[32] In such a‘ ‘no-frills’ facility, bacteria could be grown in standard dairy tanks, brewery fermenters, or even in the fiberglass tanks used by gas stations.

In contrast to chemical-warfare (CW) agents, no specialized starting materials are required for the production of biological and toxin agents except for a small seed stock of a disease-producing organism. Nutrients such as fermentation medium, glucose, phosphates, peptone, and a protein source (e.g., casein, electrodialyzed whey, or beef bouillon) are widely available and are routinely imported by developing countries that have commercial fermentation industries. A state seeking a CW capability, in contrast, re-

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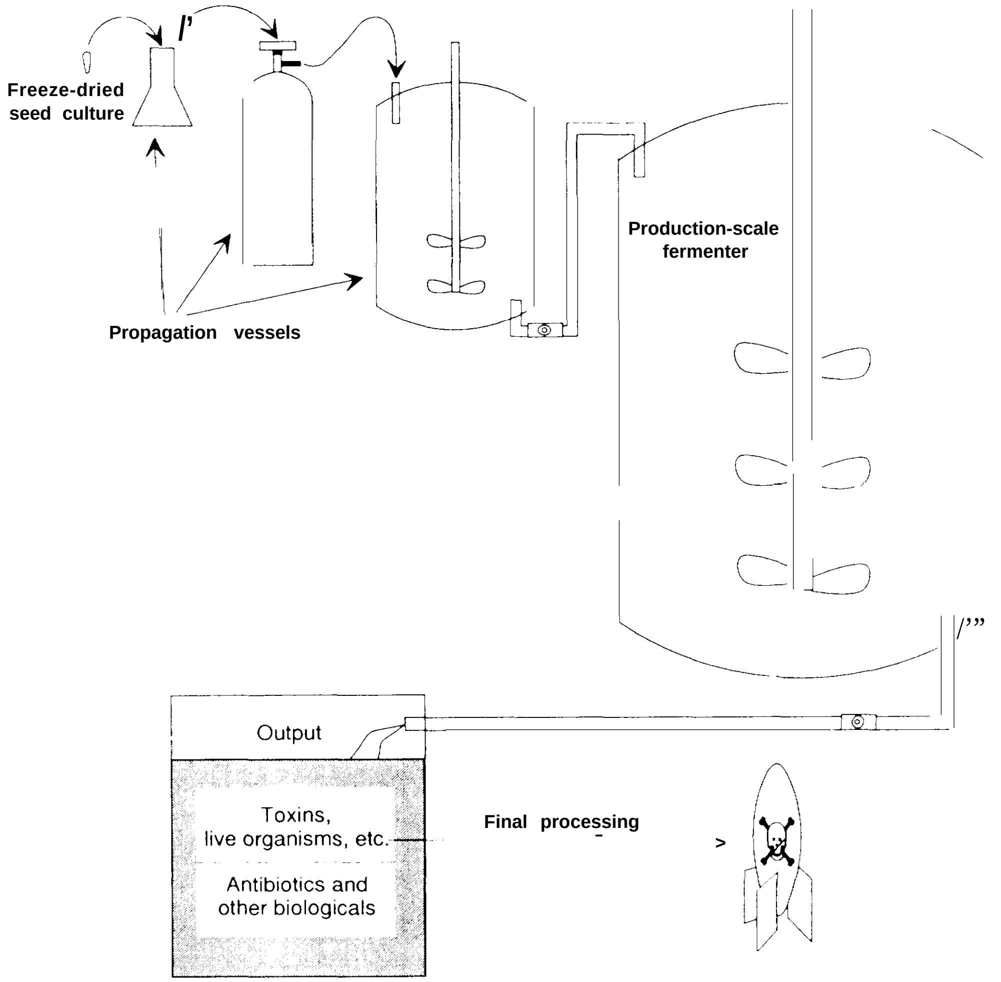
[29] & P. Zelicoff, Senior Member, Technical Staff, Sandia National Laboratories, personal communication, 1992.

[30] See Susan Wright and Stuart Kc@@ ‘‘The Problem of Interpreting the U.S. Biological Defense Research *program,’* Susan Wright, cd., *Preventing a Biological Arms Race* (Cambridge, MA: MIT Press, 1990), pp. 167-196.

[31] Stockholm International Peace Research Institute (SIPRI), *The Problem of Chemical and Biological Warfare, Vol. VI: Technical Aspects of Early Warning and Verification* (Stockholm: Almqvist & Wiksell, 1975), p. 24.

[32] Interview with Dr. Ron Thibeautot, Wyeth-Ayerst vaccine production plant, Marietta, pA, Oct. 22, 1992.

Figure 3-3-Production of Biological Agents by Fermentation



SOURCE: U.S. Senate, Committee on Governmental Affairs, Global *Spread of Chemical and Biological* Weapons, 101st Cong., 1st sess., Feb. 9, 1989 (S. Hrg. 101-794), p. 241.

quires hundreds or thousands of tons of unusual precursor chemicals that may be difficult to obtain.

PRODUCTION OF BACTERIAL AGENTS

A biological-warfare plant would contain fermenters and the means to sterilize and dispose of hazardous biological wastes on a large scale. A small vial of freeze-dried seed culture, grown in a fermenter in a nutrient medium kept at constant temperature, can result in kilograms of product (e.g., anthrax bacteria) in as little as 96 hours.[33] (See figure 3-3.) Microbial pathogens such as plague bacteria can also be cultivated in living animals, ranging from rats to horses.

Fermentation can be carried out on a batch basis or in a continuous culture from which organisms are constantly removed and an equal volume of new culture medium is added. An advantage of continuous culture is shorter turna-

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[33] Erlick, op. cit., foomote 8, p. 32.

round time, increasing the productivity of each fermenter. Indeed, if nutrients are supplied continuously and natural growth-inhibitors are removed as soon as they are formed, the bacterial culture can be maintained indefinitely in a phase in which it multiples exponentially. A continuous culture can therefore yield nearly 10 times as much product per volume of culture medium as the batch approach.[34] Nevertheless, batch culture has generally been used to cultivate BW agents in the past because continuous culture is technically more complex and sometimes results in a loss of potency. High levels of purity are not required for BW agents; 60 to 70 percent purity will suffice and is easy to obtain. The main technical hurdles in bacterial production are:

- the danger of infecting production workers;
- genetic mutations that may lead to a loss of agent potency; and
- the contamination of bacterial cultures with other microbes (e.g., bacterial viruses) that may kill them or interfere with their effects.

Although biological agents can be grown in ordinary laboratory flasks, an efficient production capability would require the use of specialized fermenters. Until fairly recently, large-scale production of bacteria for commercial or military purposes required tank-type bioreactors containing thousands of liters of culture, with mechanical stirring or a flow of air to oxygenate the culture medium. During World War II, for example, the Japanese Army ran a top-secret BTW facility in occupied Manchuria at which more than 3,000 workers grew kilogram quantities of pathogenic bacteria (including the agents of anthrax, brucellosis, plague, and typhus) in giant vats.[35]

Also during World War II, the United States and Britain planned to produce anthrax bacteria in large quantities for use in a strategic bombing campaign against Germany. In 1943, a pilot anthrax production plant became operational at Camp Detrick, MD, staffed with about 500 bacteriologists, lab assistants, chemical engineers, and skilled technicians.[36] Based on this experience, the decision was made to build a fill-scale plant at Vigo, Indiana, at a cost of $8 million, where 1,000 workers would manufacture more than 500,000 anthrax bombs a month (or, alternatively, 250,000 bombs filled with botulinal toxin). Since both agents store well, they could be stockpiled in large quantities. The Vigo plant was completed in early 1945 but never actually went into production.[37] Although it is far from certain the anthrax bombs would have worked as designed, it is possible that large areas of Germany could have been rendered uninhabitable for decades.

In 1950, the U.S. Congress voted $90 million to build another BTW plant called X-201 at a renovated arsenal near Pine Bluff, Arkansas. The new production facility had 10 stories, 3 of them underground, and was equipped with 10 fermenters for the mass-production of bacterial pathogens on short notice.[38] To give some idea of the scale involved, the Pine Bluff facility and its associated munitions-falling plant required a water supply of 2 million gallons per day, an electrical power supply of 5 megawatts, and an initial workforce of 858 people.[39] Production of BW

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[34] SIPRI, vol. VI, op. cit., footnote 31, p. 43.

[35] The Japanese BTW facility was code-named Unit 731. John W. Powell, "A Hidden Chapter in History," *Bulletin of the Atomic Scientists*, vol. 37, No. 8, October 1981, pp. 44-52. For a more detailed description, see Peter Williams and David Wallace, *Unit 731: Japan's Secret Biological Warfare in World War II* (New York, NY: Free Press, 1989).

[36] = and Paxman, op. cit., footnote 14, pp. 1(X L101.

[37] Ibid., p. 103.

[38] Ibid., p. 160.

[39] Matthew Meselson, Martin M. Kaplan, and Mark A. Mokulsky, "Verification of Biological and Toxin Weapons Disarmament," *Science & Global Security*, vol. 2, Nos. 2-3, 1991, p. 237.

agents on such a vast scale is far in excess of what a country would need to wreak enormous destruction on an adversary.

Over the past decade, technological advances associated with the commercial biotechnology industry have made it possible to produce large quantities of microorganisms in much smaller facilities. The introduction of computer-controlled, continuous-flow fermenters and compact ultrafiltration methods has vastly increased productivity, making it possible to reduce the size of a fermenter to about 1,000-fold less than conventional batch fermenters that give equivalent production.[40] Real-time sensors and feedback loops under microprocessor control have also optimized culture conditions, resulting in much higher yields and better quality products than in the past. The resulting increase in productivity has made it possible to reduce the amount of trained manpower needed to operate large-scale fermenters and to use smaller, more concealable production equipment. Of course, a developing country could produce many small-scale batches of BTW agents in laboratory glassware without the need for high-technology fermenters.

PRODUCTION OF VIRAL AND RICKETTSIAL AGENTS

Pathogenic viruses and rickettsiae are intracellular parasites that can only reproduce inside living cells. There are two approaches to cultivating these agents: in intact living tissue (e.g., chick embryos or mouse brains) or in isolated cells growing in tissue culture. The latter approach is technically simpler because it requires only flasks and nutrient medium, but certain viruses (e.g., influenza) do not grow well in tissue culture and must be cultivated in fertilized eggs. In 1962, Fort Detrick used more than 800,000 eggs for the cultivation of pathogenic viruses.[41]

Growing viruses and rickettsiae in cultured mammalian cells offers greater control but involves certain technical hurdles. The cells must adhere to a surface to grow and also require a complex culture medium based on blood serum obtained from horses and cows. Until recently, cultured mammalian cells were grown on the inner surface of rotating glass bottles, which limited the volume of production. Over the past decade, however, new methods for cultivating mammalian cells have been developed that permit higher concentrations of cells and greater recovery of product. For example, allowing the cells to grow on surface of beads suspended in culture medium has permitted the scaling-up of production. Yield has been improved further by replacing the beads with microcarriers, which have a porous internal structure into which animal cells can grow.[42]

Hollow-fiber technology offers an even more efficient method of growing anchorage-dependent mammalian cells in high concentrations for the cultivation of viruses or rickettsiae. The cells are grown on the outer surface of thin fibers that are immersed in the growth medium; air is pumped through the fibers and diffuses through the fiber wall to reach the cells.[43] Since a single hollow-fiber bioreactor is equivalent to several thousand one-liter roller bottles, it occu-

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[40] Government of Australia, ‘ ‘Impact of Recent Advances in Science and Technology on the Biological Weapons Convention’ Background *Document on New Scientific and Technological Developments Relevant to the Convention on the Prohibition of the Development, Production and Stockpiling of Bacteriological (Biological) and Toxin Weapons and on Their Destruction,* Third Review Conference of the BWC (Geneva, Switzerland), Document No. BWC/CONF.III/4, Aug. 26, 1991, p. 3.

[41] Seymour M. Hersh, *Chemical and* Biological *Warfare: America's Hidden Arsenal* (Indianapolis, IN: Bobbs-Merrill, 1%8), p. 78.

[42] S.B. Primrose, *Molecular* Biotechnology, 2d ed. (Oxford, England: Blackwell Scientific Publications, 1991), p. 116.

[43] Government of the U.S.S.R, “Selected Scientific and Technological Developments of Relevance to the BW Convention,” *Background Document on New Scientific and Technological Developments Relevant to the Convention on the Prohibition of the Development, Production and Stockpiling of Bacteriological (Biological) and Toxin Weapons and on Their Destruction, Third* Review Conference of the BWC, Geneva, Switzerland, Document No. BWC/CONF.III/4/Add.1, Sept. 10, 1991, p. Al 1.

pies less than one-twentieth the volume of the previous technology.[44] Advantages include economy and the high concentration and purity of the end-product, which reaches 98 percent on leaving the reactor. In sum, the new cell-culture techniques greatly simplify the production of viruses and rickettsiae and allow large-scale yields from very small facilities.

PRODUCTION OF TOXINS

The most efficient way to produce bacterial toxins is through fermentation. Botulinal toxin, for example, is derived from a culture of Clostrid*ium botulinum* bacteria, which multiply rapidly under the right conditions of temperature, acidity, and the absence of oxygen. It takes only about 3 days to grow up a dense culture of the bacterial cells, which extrude botulinal toxin into the surrounding culture medium. (Purification of the toxin is neither necessary nor desirable, since it tends to reduce stability.) During World War II, Japan's Unit 731 produced kilogram quantities of botulinal toxin in a fermenter approximately 10 feet high and 5 feet wide.[45] A crude preparation of toxin can be freeze-dried down to a solid cake, which is then milled into a fine powder suitable for dissemination through the air. The milling operation is exceedingly hazardous, however, and must be carried out under high-containment conditions. Plant toxins such as ricin, whose raw material is widely available, could easily be produced in the hundreds of kilograms.

With recombinant-DNA techniques, rare animal toxins—formerly available only in milligram amounts-can be prepared in significant quantities in microorganisms. Although these techniques are still largely restricted to the advanced industrial countries, they are spreading rapidly around the world. One method, known as the "cloning" of toxin genes, involves identifying DNA sequences in plants and animals that govern the production of protein toxins, transferring these genes to a suitable microbial host, and mass-producing the toxin in a fermenter. In this way, ordinary bacterial cells can be transformed into miniature toxin factories.[%] Production of animal toxins in bacteria involves certain technical hurdles, however. Bacteria typically produce and secrete toxins only under special conditions, which may not be met in an artificial environment; and bacteria may be unable to perform certain biochemical "processing" steps needed to convert a protein toxin to its active form.[47] For these reasons, it maybe necessary to clone plant and animal toxins in yeast or mammalian cells, a technically more challenging task.

Nonprotein toxins are considerably harder than protein toxins to produce in militarily significant quantities. Until recently, even small amounts of nonprotein toxins such as saxitoxin had to be extracted from large quantities of biological material with costly and labor-intensive purification methods. For example, 270 kilograms of toxin-containing clam siphons yielded less than 5 grams of saxitoxin.[48] Although some nonprotein toxins such as saxitoxin and tetrodotoxin can be synthesized in the test tube with multistep procedures, the overall yield is only

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[44] Government of the United States, "Technological Developments of Relevance to the Biological and Toxin Weapons Convention" *BackgroundDocument on New Scientific and Technological Developments Relevant to the Convention on the Prohibition of the Development, Production and Stockpiling of Bacteriological (Biological) and Toxin Weapons and on Their Destruction,* Third Review Conference of the BWC (Geneva, Switzerland), Document No, BWC/CONF.III/4, Aug. 26, 1991, p. 30.

[45] Williams and Wallace, op. cit., footnote 35, p. 124.

[46] Alan Wiseman, "The Organization of Production of Genetically-Engineered Proteins in Yeast," *Endeavor* (new series), vol. 16, No. 4, 1992, pp. 190-193,

[47] Richard Novick and Seth Shulman, "New Forms of Biological Warfare?' Susan Wright, cd., *Preventing A Biological Arms Race* (Cambridge, MA: MIT Press, 1990), p. 115.

[48] Edward J. Schantz et al., "Paralytic Shellfish Poison. IV. A Procedure for the Isolation and Purification of Poison from Toxic Clam and Mussel Tissues," *Journal of the American Chemical Society,* vol. 79, Oct. 5, 1957, pp. 5230-5235,

Table 3-I—Key Production Techniques for BTW Agents

Type of agent	Low-tech production	High-tech production
Bacteria	Batch fermentation, production in animals	Genetically engineered strains, continuous-flow fermentation
Rickettsiae and viruses	Cultivation in eggs, mouse brains, or tissue culture (roller bottles)	Culture in mammalian cells grown on beads, microcarriers, or hollow fibers
Protein toxins	Batch fermentation and purification of a bacterial toxin, or extraction of toxin from a plant or animal source	Cloning of toxin gene in microbial host, extraction
Nonprotein toxins	Extraction from plant or animal source	Cloning of a series of genes, each governing production of one of the enzymes needed to complete a step In the biosynthetic pathway

SOURCE: Office of Technology Assessment, 1993.

about 0.1 percent, making it unlikely that militarily significant quantities of toxin could be produced by chemical synthesis.[49] Biotechnological approaches are possible but technically challenging, involving the synthesis not of a single protein but of an entire series of enzymes, each necessary to catalyze one step in a complex series of reactions.[50]

Production techniques for the various types of BTW agents are summarized in table 3-1. With advanced fermentation techniques available today, a militarily significant supply of BTW agents could be produced over a period of several days, obviating the need for the long-term stockpiling of agents. As a result, a BTW production facility might remain largely quiescent in peacetime. After completing R&D, weaponization, and pilot-production tests on BTW agents, a proliferant could build production and storage facilities and either keep them mothballed or in use for legitimate commercial purposes. Clandestine production facilities might be kept in reserve, ready to be diverted to the rapid manufacture of BTW agents in the event a major conflict breaks out. Alternatively, a commercial production facility could be kept in operation and converted to BTW production in wartime. The advantage of the latter option is that it would be easier to retain the necessary trained staff and up-to-date equipment, albeit at some cost in secrecy.

CONTAINMENT MEASURES

Since working with pathogenic microorganisms is extremely hazardous, specialized physical-containment or ‘‘barrier’ measures are needed to protect plant workers and the surrounding population from infection. Great care must be taken to prevent BTW agents from escaping from a production facility and causing a devastating plague in the country producing the weapons.

In advanced industrial countries, work on highly infectious microbial agents is carried out in high-containment (Biosafety Level 3 or 4) facilities. In a BL3 facility, all personnel have been immunized against the infectious agents they work with. Since no vaccine is 100 percent effective, however, they also wear protective

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[49] Manuel L. Sanches et al., Chemical *Weapons Convention (CWC) Signatures Analysis (Ml* ington, VA: System Planning Corp, Final Technical Report No. 1396, August 1991), p. 89.

[50] Primrose, op. cit., footnote 42, p. 84.

clothing, goggles, and face masks. Microorganisms are manipulated in special biohazard safety cabinets maintained under “negative’ pressure (lower than the outside atmosphere), so that air flows into the work area. In addition to these primary barriers, secondary barriers to the spread of infectious materials include the use of high-efficiency particulate air filters and the incineration of exhaust.[51] Because viral particles are about a hundredth the size of bacteria, they are more difficult to contain with filters and other means. Moreover, spore-forming bacteria (e.g., the agents of anthrax and tetanus) foul the air-handling system with long-lived spores, which can easily contaminate other products. As a result, these bacteria are normally produced in separate facilities.[52]

A BL4 facility, the highest level of containment, is designed to isolate the human operator from the infectious agents. Since research on dangerous microbial pathogens requires handling much lesser quantities of” hazardous material than does production, it is generally performed in small BL4 enclosures inside a less stringent BL3 facility.[53] Such enclosures generally consist of sealed boxes with rubber-glove ports that provide absolute containment, and ‘hoodlines’ that make it possible to move hazardous cultures directly from a glove-box to an autoclave, which destroys the infectious microorganisms with superheated steam. In a larger BL4 research or production facility, the human workers are isolated from the microbes, rather than vice-versa. Each operator wears a self-contained “space suit” and is completely isolated from the surrounding room, which is contaminated with infectious agents. He or she enters the laboratory through an air-lock and hooks up to a supply of compressed air. The suit is kept under positive pressure so that if there is any loss of physical integrity, the leaking air will blow outwards, reducing the risk of infection.

A developing country seeking to develop biological weapons would probably use much less elaborate containment measures. During World War II, for example, the Japanese Army’s Unit 731 produced vast quantities of highly infectious agents, yet the workers were protected only by wearing rubberized suits, masks, surgical gloves, and rubber boots, and by receiving vaccinations against the agents they were working with. The United Nations inspections of Iraq after the 1991 Gulf War revealed that BTW researchers in that country’s BTW program used surprisingly rudimentary containment measures, at the level of a BL2 facility. Laboratory technicians were vaccinated against the infectious agents they worked with and used simple laboratory hoods, but they did not wear masks or protective clothing.

Commercially available containment systems used for vaccine production might be suitable for cultivating highly pathogenic organisms. To comply with environmental and occupational-health standards and to ensure the purity of products for human use, many pharmaceutical plants carry out the microbial production of antibiotics and other drugs in a “clean room” that is comparable to a formally designated BL4 facility. Clean rooms for drug production are normally kept Under positive pressure to keep contaminants out, whereas areas of a vaccine plant used for the culture of infectious microorganisms are kept under *negative* pressure to prevent the dangerous microbes from escaping. In principle, the direction of air flow could be reversed, albeit with some difficulty.

Methods for sterilizing equipment after use with hazardous microorganisms include physical measures such as dry heat or pressurized, superheated steam; ionizing radiation such as x-rays

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[51] Department of the Army, U.S. Army Medical Research and Development Coremand, op. cit., footnote 5, p. 7-15.

[52] Gary Ebert, vice president for operations, Connaught Laboratories (Swiftwater, PA), personal communication, 1992.

[53] Herbert Marcovich, “Verification of High-Containment Facilities,” S.J. Lundin, cd., *Views on Possible Verification Measures for the Biological Weapons Convention* (Oxford, England: SIPRI/Oxford University Press, 1991), p. 55.

and high-energy ultraviolet radiation; and chemical treatment with formaldehyde or bleach.[54] Sophisticated biotechnology plants often have self-sterilizing fermenters and process equipment, whether or not they are handling hazardous microorganisms. Such plants would therefore have an inherent capability to work with BTW agents.

Stabilization of BTW Agents

Once BTW agents have been produced, it is necessary to process them into a form that enhances their stability in storage and after dissemination, so that they remain viable long enough to infect. Since microbial pathogens are living organisms, they will eventually deteriorate and die unless their metabolism is slowed down or stopped. Such a process of suspended animation occurs naturally in the case of spore-forming microorganisms such as anthrax, which can survive for decades in the dormant spore form. Nonspore-forming microbes and most toxins, however, tend to break down rapidly in the environment if not protected. For this reason, BTW agents are generally most effective if disseminated within a few days after production. If rapid use is not feasible, the live agents must be converted into a more stable form so that they can survive the stresses of storage, transport, and dissemination.

FREEZE-DRYING

One method for enhancing the stability of BTW agents is rapid freezing and subsequent dehydration under a high vacuum, a process known as freeze-drying or *lyophilization. In* a few hours, a lyophilizer, a device mainly used in the pharmaceutical industry, reduces a solution of bacteria and a sugar stabilizer to a small cake of dried material that can then be milled into any desired state of freeness. Lyophilization avoids the need to maintain microorganisms in inconvenient and dangerous liquid suspensions during storage and transportation. It also makes possible a significant increase in agent potency by direct inhalation of particles of dried agent into the lungs.[55] This technique is also applicable to toxins; a fine dust of dried toxin, if inhaled, can be deadly in extremely small quantities.

If kept in cold storage, the desiccated organisms will remain viable for long periods, although they still deteriorate. For example, freeze-dried brucellosis bacteria can be stored for several months, and Q-fever rickettsiae for up to 8 years.[56] Lyophilization also extends the shelf-life of protein toxins: freeze-dried *Staphylococcus* enterotoxin B (SEB) can be stored for up to a year. Even so, the virulence and viability of lyophilized BTW agents decays over time: there is a loss of potency of a factor of 10 to 100 over a period of 1 to 5 years, so that much larger quantities of older agent are required to produce the same military effect.[57]

CHEMICAL ADDITIVES

The stability of a microbial aerosol can be increased by adding a variety of compounds to the spray material.[58] Moreover, antiagglomerants such as colloidal silica help prevent the clumping of freeze-dried microbial agents and toxins that have been milled into a fine powder. Agricultural research on biological pesticides, such as the insect-killing bacterium *Bacillus thuringiensis,* has provided much information on methods for stabilizing bacterial agents in the field. For example, new formulations of *B. thuringiensis* have been developed that extend the life of the

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[54] Department of Army, U.S. Army Medical Research and Development Coremand, op. cit., footnote 5, pp. A-132, A-13-3.

[55] Williams and Wallace, op. cit., footnote 35, p. 72.

[56] Rothschild, op. cit., footnote 9, pp. 206-219.

[57] SIPRI, vol. VI, op. cit., footnote 31, p. 50.

[58] Robert J. Goodlow and Federic A. Leonard, "Viability and Infectivity of Microorganisms in Experimental Airborne Infection," *Bacteriological Reviews,* vol. 25, 1%1, p. 185.

disseminated bacteria by means of ultraviolet protestants and other additives that ensure compatibility with existing agricultural sprayers.[59]

MICROENCAPSULATION

Another approach to stabilization, known as microencapsulation, emulates natural spore formation by coating droplets of pathogens or particles of toxin with a thin coat of gelatin, sodium alginate, cellulose, or some other protective material. (An industrial example of microencapsulation is the production of carbonless carbon paper, in which ink droplets are coated in this manner.) Microencapsulation can be performed with physical or chemical methods.[60]

Micromcapsulation production methods can be set up to generate particles of a selected size range (e.g., 5 to 10 microns).[61] The polymer coating protects the infectious agent against environmental stresses such as desiccation, sunlight, freezing, and the mechanical stresses of dissemination, and permits cold-storage of microbial pathogens for several months. Microcapsules can be charged electrostatically to reduce particle clumping during dissemination, or ultraviolet-light blocking pigments can be added to the microcapsule to protect microorganisms against degradation by sunlight. Once in the target environment, such as the interior of the lung, the polymer coating dissolves, releasing the agent. Microencapsulation can also be applied to toxins, making them more stable, predictable, and safer to handle.

Integration With Delivery Systems

A biological or toxin agent is of little military utility if it does not produce consistent and reliable effects and cannot be delivered to a target. BTW agents are all nonvolatile solids that would be disseminated either as a liquid slurry or a dry powder of freeze-dried organisms or toxin.[62] Possible delivery systems range in complexity and effectiveness from an agricultural sprayer mounted on a truck to a specialized cluster warhead carried on a ballistic missile. The difficulty of delivery-system development depends on the proliferant’s military objectives. It is not hard to spread BTW agents in an indiscriminate way for the purpose of producing large numbers of casualties over a wide area. It is much more difficult, however, to develop BTW munitions that have predictable or controllable military effects against point targets, such as troop concentrations on the battlefield.

Many pathogens infect man naturally by means of an intermediary organism (“vector’ ‘), such as a mosquito or tick.[63] Military microbiologists discovered during World War II, however, that BTW agents can be disseminated through the air, making it possible to infect large numbers of people simultaneously. Many microbial pathogens and toxins-even those normally transmitted by vectors or in food-can invade the body through the lungs, giving rise to foci of infection or traveling through the bloodstream to other parts of the body. The key to producing large-

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[59] Government of the United Kingdom, ‘‘General Developments Relevant to the BWC,’’ in *Background Document on New Scientific and Technological Developments Relevant to the Convention on the Prohibition of the Development, Production and Stockpiling of Bacteriological (Biological) and Toxin Weapons and on Their Destruction,* Third Review Conference of the BWC (Geneva, Switzerland), Document No. BWC/CONF.III/4, Aug. 26, 1991, p. 25.

[60] Arthur Osol et al., eds., Remington’s *Pharmaceutical Sciences, 15th* ed. (Easton, PA: Mack Publishing Co., 1975), P. 1604.

[61] A micron is a thousandth of a millimeter.

[62] C.V. Chester and G. P. Zimmerman, ‘‘Civil Defense Implications Of Biological Weapons,’’ *Journal of Civil Defense, vol. 17,* No. *6,* December 1984, p. 6.

[63] The disease vector *is* usually some type of arthropod: mosquitoes transmit yellow fever and dengue fever; fleas transmit plague; and ticks transmit tularemia and Q fever, During 1932-45, the Japanese BW facility known as Unit 731 set up flea “nurseries” for the production of 135 million plague-infested fleas every 4 months. As a delivery system, porcelain bombs were developed that could contain about 30,000 infected fleas. See Williams and Wallace, op. cit., footnote 35, p. 27.

scale respiratory infections is to generate a biological “aerosol”: a stable cloud of suspended microscopic droplets, each containing from one to thousands of bacterial or virus particles. (Fogs and smokes are examples of visible aerosols.) Biological aerosols can be produced with a relatively simple piece of machinery, analogous to a home vaporizer, that sprays a suspension of microorganisms through fine nozzles, converting about 85 percent of their starting material into droplets in the desired size range.[64] The concentration of organisms in the starting solution influences the distribution of organisms among the aerosol particles.[65]

Aerosol dissemination of many vector-borne diseases, such as yellow fever, Rocky Mountain spotted fever, tularemia, and tick-borne encephalitis, can produce atypical infections of the respiratory tract. Respiratory infection with such agents bypasses normal protective mechanisms such as local inflammatory processes and increases the virulence of pathogens that normally have a low lethality, such as Venezuelan equine encephalitis (VEE).[66] In the case of microbial pathogens that can be transmitted by different routes, such as anthrax bacteria, respiratory infection results in by far the most virulent form of the disease. For example, whereas untreated skin anthrax is fatal in only about 5 percent of cases, pulmonary anthrax is fatal in more than 90 percent of cases.[67]

Freeze-dried toxins can also be disseminated in the form of an aerosol. Recent studies have shown that saxitoxin and T-2 trichothecene mycotoxin are at least 10 times more toxic when administered by aerosol than by intravenous injection.[68] Because protein toxins are large organic molecules, however, they are susceptible to environmental stresses such as heat, oxidation, and shear forces. As a result, attempts to aerosolize toxins have encountered problems in maintainingg the stability of the agent before and after dissemination. It is also difficult to formulate protein toxins capable of penetrating the skin.

The primary challenge in weaponizing BTW agents for long-range delivery is to keep them alive long enough to infect enemy troops. The agent must be capable of withstanding the physical stresses involved in the dissemination process without losing activity. Technical hurdles involved in the design of self-dispensing biological weapons are as follows:

- the munition or delivery system must generate a cloud of aerosol particles with dimensions that allow them to be inhaled deep into the lungs of the target personnel;
- the agent must be physically stabilized so that it can survive the process of dissemination long enough to infect the target personnel;
- the agent must disseminated slowly to permit aerosolization while avoiding loss of viability or toxicity; and
- the overall size and shape of the aerosol cloud and the concentration of agent within it must be reasonably predictable, so that the dispersion pattern can be matched to the target.[69]

These technical hurdles are discussed below.

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[64] Milton Leitenberg, “Biological Weapons, ’ Scientist *and Citizen,* vol. 9, No. 7, August-September 1%7, p. 157.

[65] Goodlow and Leonard, op. cit., footnote 58, p.184.

[66] World Health Organization, *Health Aspects of Chemical and Biological Weapons* (Geneva: WHO, 1970), *p.* 61.

[67] Zelicoff, op. cit., footnote 29.

[68] Government of the U. S. S. R., “Selected Scientific and Technological Developments of Relevance to the BW Convention” op. cit., footnote 43, p. A lO.

[69] Stockholm International Peace Research Institute (SIPRI), *The Problem of Chemical and Biological Warfare, Vol. II: CB Weapons Today* (Stockholm: Almqvist & Wikell, 1973), pp. 72-73.

EFFECT OF PARTICLE SIZE

The particle size of an aerosol is critical to both its atmospheric stability and its military effectiveness. Whereas larger particles tend to settle out of the air, microscopic particles between one and five microns in diameter form a stable aerosol in which the particles remain airborne for a long time. The very low settling velocity of the particles will by itself keep a biological aerosol cloud suspended in the air for long periods. Such a cloud may therefore be transported by the wind over long distances. Moreover, losses resulting from fallout and washout are negligible and do not significantly reduce the concentration of an aerosol cloud. Particles less than 5 microns in diameter generally do not collide with smooth surfaces in their path but are carried over them by air currents. In contrast, transport over rough surfaces for distances of more than a kilometer can result in significant deposition.

Aerosolized BTW agents generally do not penetrate the skin and thus do not represent a significant contact hazard; instead, they infect individuals only if inhaled into the lungs.[70] Particle size is also critical for respiratory infection. Almost all particles larger than 5 microns in diameter are trapped in the phlegm and passages of the upper respiratory tract, while particles smaller than 1 micron diameter are exhaled without being retained in the deep lung tissue. Only particles between 1 and 5 microns in diameter are small enough to reach the tiny terminal air sacs (alveoli) of the lung, bypassing the body's natural filtering and defense mechanisms. In one set of experiments on the effect of particle size on respiratory infection, tularemia bacteria were administered to guinea pigs as an aerosol. When the aerosol. particles were 1 micron in diameter, only 3 bacterial cells per animal were needed to kill 50 percent of the guinea pigs, but when the particle size was increased to 7 microns, the number of bacteria per animal required to kill half of the guinea pigs rose to 6,500.[71]

PHYSICAL STABILIZATION

The use of mechanical devices to generate aerosols from a bulk storage tank places a variety of mechanical stresses on microorganisms, reducing the number of viable, infectious cells. Relatively few microbial pathogens can meet the stability requirements of bulk dissemination.[72] Those agents best suited for long-range attack can infect with a small number of microorganisms and are hardy enough to survive for a fairly long period floating in the air. Once released, however, the aerosol cloud "decays" over time as the microorganisms die as a result of exposure to oxygen, atmospheric pollutants, sunlight, and desiccation, resulting in a loss of viability (ability to survive and multiply) and virulence (ability to cause disease and injury). A BW agent disseminated into a given environment may also retain its viability while losing its virulence.[73]

Decay of an aerosol cloud occurs in two stages. Initial dissemination is followed by a period of very rapid cell death during the first several seconds after the cloud has been released. Indeed, producing a liquid aerosol by explosive dispersion or passage through a spray device may kill as many as 95 percent of the microorganisms. This initial stage is followed by a much slower rate of decay, so that the aerosol cloud may persist for long periods of time. A relative humidity of over 70 percent promotes microbial survival.[74] Large-particle clouds are more resistant to the lethal effects of solar radiation than small-particle

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[70] Ibid., p. 29.

[71] Maj. William D. Sawyer, "Airborne Infection," *Military Medicine,* February 1%3, pp. 90-92.

[72] SIPRI, vol. II, op. cit., footnote 69, p. 30.

[73] Group of Consultant Experts on Chemical and Bacteriological (Biological) Weapons, *Chemical and Bacteriological (Biological) Weapons and the Effects of Their Possible Use,* United Nations Report No. E.69.I.24 (New York NY: Ballantine Books, 1970), p. 13.

[74] Department of the Army, U.S. Army Medical Research and Development Command, op. cit., footnote 5, p. A7-16.

clouds, and dry disseminated aerosols are more resistant than wet aerosols.[75] As the plume disperses, long-lived particles (e.g., anthrax spores) may be deposited on the ground, where they may then adhere to large particles of surface soil and dust. If the surface is disturbed, either by the wind or by human activities, the spores can again be resuspended, potentially causing additional infections.[76] The inhalation hazard is much reduced, however, owing to the large particle size.

TYPES OF AEROSOL ATTACKS

There are two types of aerosol dissemination of BTW agents. “Area” attack involves releasing an aerosol cloud upwind and allowing it to drift over the target area. In contrast, “point” attack involves projecting the agent in a cannister that releases the agent immediately over the target.[77]

Area attack

A BTW weapon designed for area attack would disseminate its payload as an aerosol cloud containing a sufficient concentration of viable microorganisms to infect the targeted personnel with particles in the 1 to 5 micron size range. The simplest means of area delivery is with spray tanks mounted on manned aircraft, unmanned remotely piloted vehicles (RPVs), or cruise missiles, which can release a large quantity of agent over a controlled line of flight. A slow-flying aircraft such as a crop duster could discharge a line of agent that, as it travelled downwind, would reach the ground as a vast, elongated infective cloud. Such a linear cloud of agent, known as a ‘‘line source, can cover a larger area than a cloud released from a single spot, or ‘‘point source. ’

Air rushing past the spray tank can be used to force out its contents; alternatively, compressed air or carbon dioxide may be used to disseminate the agent. Aerosol generators might also be operated from offshore ships or submarines parallel to a coastline, producing an invisible cloud of BTW agents that could be carried by the prevailing winds over key coastal cities or military bases.[78] The discharge rate must be slow enough to generate a stable aerosol, yet slow-flying aircraft and RPVs are extremely vulnerable to air defenses.

Area attack with a biological aerosol depends heavily on atmospheric diffusion and wind currents to dilute and spread the agent over the area being attacked. The most stable atmospheric conditions occur on cold, clear nights or early in the morning, when the ground and the layer of air above it are cooler than the next higher 1ayer of air. This phenomenon, called an *inversion,* is ideal for the delivery of BTW agents because the stable interface of warm and cold air prevents the vertical mixing of the cloud and causes it to hug the ground, keeping the organisms at a low altitude where they can be inhaled. In contrast, bright sunlight causes atmospheric turbulence that breaks up the aerosol cloud, and also contains ultraviolet rays that kill many microorganisms. For these reasons, a BTW attack would be most likely to come at dusk or at night.[79]

The effectiveness of an area attack also requires detailed knowledge of the prevailing wind direction and speed. Under favorable wind conditions, an aerosol cloud could contaminate the air over large areas, but if the wind is erratic or excessively strong, the agent might fail to reach the target or might be dissipated too rapidly to be

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[75] Goodlow and Leonard, op. cit., footnote 58, p. 184.

[76] Ammon Birenzvige, *Inhalation Hazard from Reaerosolized Biological Agents: A Review,* Report No. CRDEC-TR-413 (Aberdeen Proving Ground, MD: Chemical Research, Development and Engineering Center, September 1992).

[77] SIPRI, vol. II, op. cit., footnote 69, p. 28.

[78] W. Seth Carus, *‘‘The Poor Man’s Atomic Bomb?’’: Biological Weapons in the Middle East,* Washington Institute Policy Papers No. 23 (Washington, DC: Washington Institute for Near East Policy, 1991), p. 11.

[79] Chester and Zimmerman, op. cit., footnote 62, p. 7.

effective. Assuming the target is nearby, the attackers will know the wind direction and can plan the attack at a favorable time. If the target is deep inside enemy territory, local meteorological conditions would be harder to assess without access to current weather data. Nevertheless, hundreds of airports worldwide broadcast wind direction, speed, cloud cover, and temperature every 3 hours according to World Meteorological Organization guidelines.

A remotely piloted vehicle or subsonic cruise missile flying at low altitude might reduce such problems by disseminating the toxic cloud close to the ground just upwind of the target—assuming, of course, that the attacker had the means of knowing which way the wind was blowing over the target area. In 1960, the U.S. Army began developing a drone aircraft that could be used to deliver chemical and biological weapons. The pilotless plane was designed to carry 200 pounds of germ agents as far as 115 miles.[80] Even relatively unsophisticated cruise missiles might be capable of generating line-source aerosols for off-target attacks.[81] For this reason, the simultaneous proliferation of biological weapons and cruise-missile capabilities may become a major security threat in the future.

Point attack

A point BTW attack would be performed with munitions delivered by artillery, rockets, missiles, or aircraft. Although the targeted personnel would be warned of the attack by the arrival of the munition, the rapid formation of a concentrated aerosol (within 15 to 30 seconds) means that many soldiers would inhale an incapacitating or lethal dose of agent before they had time to put on their gas masks properly, assuming they were available.[82] A point attack that dropped the agent directly over the targeted personnel would also be much less dependent on meteorological conditions, although it would require a much higher payload of munitions per area covered.

MUNITIONS FOR POINT ATTACK

Munitions developed for chemical-warfare agents are generally unsuited for biological warfare because of the lower stability of BTW agents and their susceptibility to environmental factors such as ultraviolet radiation and air pollution. There are two basic methods for disseminating BTW agents from a munition: *explosive* and *pressurized*. Whereas explosive dissemination produces an almost instantaneous build-up of aerosol concentration over the target, it destroys a large portion of the infectious agents and tends to produce drops that are considerably larger than the optimal droplet size for inhalation.[83] In contrast, pressurized munitions do not disperse agent as rapidly as explosive munitions but provide better control of particle size, are gentler on the microorganisms, and produce an aerosol cloud that is visible for a shorter period of time. One method of pressurized delivery is to force a liquid suspension of agent through a fine nozzle, which breaks up the material into droplets of the appropriate size.

A BTW bomb or warhead may either be filled with bulk agent or with numerous self-dispensing cluster-bomb units (CBUs). A cluster bomb has a casing that breaks open during delivery to scatter a large number of smaller submunitions over a wide area. The submunitions then fall to earth and are triggered to go off at an altitude of about 15 to 20 feet off the ground. Each of these bomblets generates a small aerosol cloud; these multiple point sources are then coalesced by air currents into a single large cloud. During World War II, the United States and Great Britain

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[80] Hersh, op. cit., footnote 41, p. 71.

[81] Carus, op. cit., footnote 78, pp. 10-11.

[82] Rothschild, op. cit., footnote 9, p. 76.

[83] Ibid., p. 60.

jointly developed a 500-pound bomb for the delivery of anthrax spores. Each bomb casing contained 106 four-pound bomblets designed to burst in midair, producing dense aerosols of spores. Twenty of these bomblets could cause a high fatality rate among humans and livestock over a one-square-mile area, and British war plans called for using as many as 40,000 anthrax bombs against six German cities.[84]

Nevertheless, the technical difficulty of dispensing submunitions should not be underestimated. Missile delivery would place severe environmental stresses on microbial agents, including freezing temperatures prevailing at high altitudes and friction-heating of the missile nosecone during reentry through the atmosphere, which could be fatal to microbes without sufficient insulation. The timing of agent dissemination would also be critical, since if it occurred at the wrong altitude, the agent would not form a militarily effective aerosol. Releasing the agent too high would cause it to dissipate before it could be inhaled by the targeted troops; releasing it too low would merely produce a puddle of toxic material on the ground. In sum, effective agent dissemination requires a series of mechanical steps to work perfectly, and atmospheric conditions to cooperate.

Other problems associated with weaponization include the hazards of loading munitions with agent, and corrosion and seepage from filled munitions. Despite these technical hurdles, however, effective biological munitions have been developed and deployed in the past. In 1951, the first anticrop cluster bombs were placed in production for the U.S. Air Force; each bomblet contained turkey feathers contaminated with cereal rust spores.[85] Also during the 1950s, the United States developed small, self-dispersing BTW bomblets for the Honest John missile.[86]

In conclusion, strategic BTW attacks against cities might be carried out with relatively simple off-target delivery systems, such as a spray tank carried by an aircraft. After dissemination, the aerosol cloud might behave in unexpected ways in response to changes in the wind and weather, potentially boomeranging against the attacker's own troops or population.[87] More controlled point attacks with BTW agents for military purposes would require the use of missiles or bombs, possibly equipped with cluster munitions, but such attacks would be technically more difficult to carry out.

Some analysts contend that the most probable use of BTW agents would be for covert warfare against crops, livestock, or human populations for purposes of economic destabilization. In this case, relatively small quantities of BTW agents might be introduced by human saboteurs directly into the air or water supply of a city or military installation.

INDICATORS OF BTW AGENT PRODUCTION

Detection and monitoring of BTW agent production is an extremely challenging task for the following reasons:

- All equipment and feedstock materials used to make BTW agents is dual-use and could be used for legitimate purposes in the biotechnology or pharmaceutical industries.
- Utilizing new biotechnologies, production could take place in facilities that are much smaller and less conspicuous than in the past,

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[84] Barton J. Berstein, "Churchill's Secret Biological Weapons," *Bulletin of the Atomic Scientists,* January/February 1987, pp. 4&50.

[85] SIPRI, vol. II, op. cit., footnote 69, p. 160.

[86] Rothschild, op. cit., footnote 9, p. 78.

[87] In 1942, during World War II, special Japanese troops spread diseases such as cholera, typhoid, plague, and anthrax in China. Subsequently, more than 10,000 Japanese soldiers fell ill after they overran a contaminated area, presumably because regular soldiers had not been informed about the use of biological weapons. Barend ter Haar, *The Future of Biological Weapons, The Washington Papers No. 151 (New* York, NY: Praeger, 1991), p. 5.

with no obvious signs to indicate illicit activity.

- Legitimate facilities might be diverted to the production of BTW agents in a relatively short time.
- Since microbial agents can be grown in an advanced fermenter from a few cells to many kilograms of agent over a period of days or weeks, it would not be necessary to maintain large stockpiles (although filled or empty munitions would need to be stored).

The extreme potency of BTW agents means that as little as a few kilograms can be militarily significant.

- BTW agents would be hard to distinguish from naturally occurring pathogens, particularly if the agents are endemic to the affected area.

There is an enormous variety of potential BTW agents, each requiring a specific detection method.[88]

According to a State Department official, “In many ways, recent progress in biological technology increases the ease of concealment of illicit manufacturing plants, particularly for biologically derived chemicals such as toxins. . . . Not only has the time from basic research to mass production decreased but the ability to create agents and toxins with more optimal weapon potential has increased. Simply put, the potential for undetected breakout from treaty constraints has increased significantly.”[89] Thus, while the characteristics of a given facility may be consistent with an offensive BTW program, the odds of finding a “smoking gun’’ -such as a munition filled with BTW agent—are quite low.

Despite these difficulties, however, a few factors constrain the detection problem. Microbial pathogens and toxins of military concern have relatively few civilian uses in scientific research and medical therapy, and such applications are generally confined to sophisticated biomedical research centers not often found in developing countries. As a result, there are some production and weaponization signatures that-if integrated effectively with national intelligence collection and declarations of activities and facilities relevant to the Biological and Toxin Weapons Convention-might provide strong circumstantial evidence of a clandestine BTW program.

| Research and Development Signatures

Many research and development activities related to BTW agents are inherently ambiguous in that they can support both defensive and offensive purposes. It is therefore essential to evaluate the evidence in the context of a country overall behavior and the openness and transparency of its nominally defensive program. Telltale indicators of a BTW program *might* include the existence of biological research facilities operated under military control, the large-scale production of vaccines in excess of legitimate domestic needs, or the purchase of dual-use biological materials and equipment. Analysts searching for indicators of foreign BTW activities should avoid “mirror-imaging’ ‘—the temptation to judge other countries by U.S. standards. Only by first understanding a country’s commercial standards for biological containment and good manufacturing practice is it possible to identify anomalies that do not fit this basic profile.[90]

SCIENTIFIC PUBLICATIONS

The collection and systematic analysis of scientific and technical information published by a country of proliferation concern can help to

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[88] Stephen S, Morse, ‘‘Strategies for Biological Weapons Verification” *Proceedings of the Arms Control and Verification Technology Conference,* Williamsburg, VA, June 1992 (Washington, DC: Defense Nuclear Agency, in press.)

[89] H. Allen Holmes, ‘‘Biological Weapons Proliferation,’’ *Department of State Bulletin,* vol. 89, July 1989, p. 43.

[90] Graham S. Pearson, ‘ ‘Biological Weapons: The British View,’ presentation at a Seminar on Biological Weapons in the 1990s, sponsored by the Center for Strategic and International Studies, Washington DC, Nov. 4, 1992.

monitor research trends, identify institutions and scientists associated with such research activities (including cooperation with foreign states), and identify gaps or abrupt halts in open research on particular topics that may be suggestive of military censorship. Although such literature analysis is unlikely to reveal BTW activities that have been deliberately concealed, it can raise questions about the capabilities and activities of various facilities and is useful when combined with other sources of information. For example, useful intelligence on Soviet BW activities was reportedly gleaned from clues picked up in the Soviet scientific literature. By tracking the award of academic honors and by noticing obvious gaps in a series of published papers, Western intelligence analysts could judge which fields of biological research Soviet military scientists had entered.[91] During the 1970s and '80s, for example, the Soviet literature contained a remarkably large number of publications on toxin research.[92]

Nevertheless, publication tracking is not a reliable indicator of a BTW program. First, it requires the existence of a preliminary scientific research effort before a country undertakes production of BTW agents. In the past, countries with offensive BTW programs, such as Japan, Germany, the United States, and the Soviet Union, launched a major scientific research effort in relevant areas of microbiology before they could develop biological weapons. Today, however, much of the basic science is already well understood, and explicit weapon-development programs could be undertaken with relatively little preliminary research.

Second, because many variables affect scientific productivity and publication rates, publication tracking can only provide a broad indication of a state's BTW activities. The scientific culture in many developing countries does not demand large numbers of publications, so there will be fewer to monitor. Finally, the biomedical databases available for tracking (e.g., MEDLINE) do not have representative numbers of scientific abstracts from the countries of greatest proliferation concern, particularly for papers not published in English.[93] For this reason, the number of abstracts in the database dealing with microbial and toxin agents may not correlate either positively or negatively with a country's BTW activities. For all these reasons, publication analysis is an unreliable-although potentially useful—indicator of BTW activity.

HUMAN INTELLIGENCE

Because of the limited value of technical collection systems such as satellites for monitoring BTW activities, human intelligence is vital in this area. For example, Vladimir Pasechnik, a Russian microbiologist with first-hand knowledge of the Soviet BTW program, defected to Britain in 1989 while attending a scientific conference in London and provided extensive information on Soviet BTW activities that was unobtainable by other means.[94] Human agents and defectors can also confirm suspicions about sites and activities based on other sources of intelligence. Nevertheless, the UNSCOM biological inspections of Iraq have shown that human intelligence can be unreliable or misleading if the individual reporting does not have direct knowledge or is unfamiliar with the technical details of what he is describing.[95]

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[91] Harris and Paxman, op. cit., footnote 14, p. 114.

[92] David B&r, ''Chemical and Biological Warfare Agents—A Fresh Approach,'' *Jane's Intelligence Review*, vol. 5, No. 1, January 1993, p. 44.

[93] Zelicoff, op. cit., footnote 29.

[94] Bill Gertz, "Defecting Russian Scientist Revealed Biological Arms Efforts,'' *The Washington Times,* July *4,* 1992, p. A4.

[95] Telephone interview with David Huxsoll, dean, School of Veterinary Medicine, Louisiana State University, Baton Rouge, LA, Aug. 17, 1992.

Weaponization and Testing Signatures

Weaponization involves the determination of whether a candidate BTW agent is militarily effective and how it would be used. These activities have no obvious civilian counterpart, and hence would be indicative of a clandestine BTW development program. Signatures associated with the testing of candidate BTW agents might be easier to detect than agent production signatures, and inspections focusing on weaponization activities would also be more acceptable to the biotechnology industry than production monitoring, since they would not compromise trade secrets.

Examples of weaponization and testing signatures that might be observable with overhead photography include field tests of aerosol dispersal patterns, tests of effectiveness against large animals, and the surreptitious burial of dead animals from weaponization tests .96 Other weaponization signatures would only be visible during an onsite inspection. For example, specialized aerosol test chambers might be used to study the behavior of biological aerosols in the environment or the detonation of BTW munitions. If such a test facility were found in a nominally civilian vaccine plant, it would be extremely suspicious. Indeed, the secret Soviet BW facility at the All-Union Research Institute of Applied Microbiology in Oblensk reportedly contained two such test chambers. The "aerosol-dissemination test chamber' consisted of a steel cube, roughly 50 feet on a side, in which experimental animals were tethered to the floor and exposed to BW aerosols released from ceiling vents. There was also a reinforced ''explosive-test chamber' in which the detonation of BW munitions was simulated.[97]

Although some analysts contend that weaponization could be carried out in enclosed, unobtrusive facilities, others argue that the integration of signatures from a variety of sources would make a militarily significant weaponization program difficult to hide. Nevertheless, there are a number of potential concealment strategies:

- Weaponization studies short of actual field tests could be performed inside production facilities.
- Open-air testing of BTW weapons would be difficult to detect if the test grid were masked, or if there were no distinctive delivery systems or advance indications of where to look. In addition, since many BTW agents are sensitive to sunlight, they would be tested at night.[98]
- Certain legitimate activities, such as the dissemination of biopesticides on crops, or the use of conventional smoke bombs, might be used as a cover for BTW weaponization testing.

A growing number of countries, for example, are replacing chemical pesticides with certain microorganisms that are natural insect-killers. Although over 100 bacteria, fungi, and viruses infect insects, only a very few are in commercial production. The most widely used is *Bacillus thuringiensis,* a bacterium that produces a crystalline protein toxic to insects and is applied to crops as an aerosol from agricultural sprayers.[99] Although B. *thuringiensis* does not have the characteristics of a BW agent and would be a poor simulant for weaponization studies, field tests with bacteria more closely resembling BW agents could be disguised as biopesticide application. Thus, if biopesticides are already in use in the

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96 Test ranges will likely be at remote locations. The former Soviet Union, for example, operated a BTW test site on isolated Vozrozhdeniye Island in the Aral Sea.

97 John Barry, ''Plarming a Plague?" Newsweek, Feb. 1, 1993, p. 40.

98 James Adams, Engines *of War: Merchants of Death and the New Arms Race (New* York, NY: Atlantic Monthly Press, 1990), P. 221.

99 primrose, op. cit., footnote 42, p. 76.

local agricultural sector, a covert proliferant could use them to test the open-air dissemination of microbial aerosols in preparation for germ warfare, and also to justify the acquisition of hardware needed to disperse the agent. Nevertheless, substantial field tests using grams or kilograms of micron-sized particles could be detected in samples taken at great distances downwind if the organism had distinctive DNA sequences and those doing the detection knew what to look for.

| Production Signatures

Production of BTW agents is nearly impossible to detect by visual inspection alone, although this approach may add some useful pieces to the puzzle.

EXTERNAL VISUAL SIGNATURES

BTW production facilities may sometimes be detected or monitored with overhead photography, although the evidence is nearly always ambiguous. For example, the Institute of Microbiology and Virology in the Russian city of Sverdlovsk, 850 miles east of Moscow, reportedly aroused the suspicions of U.S. intelligence analysts in the 1970s because of certain characteristics observed by satellite. Photointerpreters identified tall incinerator stacks, large cold-storage facilities, animal pens, sentries, and double barbed-wire fences. These features, not unlike those at the former U.S. offensive BTW facility at Fort Detrick, suggested that the Sverdlovsk facility might serve military purposes.[100] In Much 1980, the U.S. Government attributed a serious outbreak of pulmonary anthrax in Sverdlovsk the previous year to Soviet BW activities at the microbiology institute. Although Soviet officials denied the allegations at the time, in May 1992 Russian President Boris Yeltsin finally admitted that the anthrax epidemic had been caused by an accident at the military facility. Russian military spokesmen have insisted, however, that the anthrax work at Sverdlovsk was "defensive" in nature, and this question has yet to be resolved.[101]

Recent innovations in biotechnological production technology aimed at increasing productivity, cutting costs, and improving safety have further blurred distinctions important for verification, such as between a laboratory and a production facility. In the past, large batch fermenters and refrigerated storage vaults provided signatures of BTW production; today they are being replaced in advanced industrial countries with small, continuous-flow fermenters that can produce large quantities of highly infectious materials rapidly in a laboratory-scale facility. Such advances in production technology have greatly increased the difficulty of detection by reducing the size of plants needed to produce militarily significant quantities of BTW agents and the amount of time needed to break out of disarmed status. With the new production technologies, a clandestine BTW plant might be more easily camouflaged, buried underground, or hidden within a larger complex that produces legitimate commercial products.

Still, satellite or aerial photography might help to monitor sites judged suspicious on the basis of other sources of intelligence. The following signatures of BTW agent production might be detected or monitored with overhead imaging:

- "Excessive" secrecy and security surrounding a nominally civilian microbiological facility, such as a brewery, sugar refinery, infant-formula plant, or single-cell protein plant. Telltale security measures might include double or triple fencing, watch towers,

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[100] Elisa D. Harris, "Sverdlovsk and Yellow Rain: Two Cases of Soviet Noncompliance?" *International Security*, vol. 11, No. *4, spring 1987,* pp. *41-95.*

[101] See *Milton* Leitenberg, "A Return to Sverdlovsk: Allegations of Soviet Activities Related to Biological Weapons,' *Arms Control, vol.* 12, No. 2, September 1991 (published April 1992), pp. 161-190; and Milton Leitenberg, "Anthrax in Sverdlovsk: New Pieces to the Puzzle, " *Arms Control Today*, vol. *22, No. 3,* April 1992, pp. 10-13.

and air-defense missile batteries-although concealment, camouflage, and deception operations are possible.

- Elaborate microbiological production facilities inconsistent with the level of sophistication of other, clearly civilian plants.
- Facilities for housing large numbers of primates, horses, rats, mice, rabbits, sheep, goats, or chickens (for producing eggs), when such animals are not clearly associated with vaccine production.
- Changes in activity at nominally civilian production facilities.

PLANT DESIGN AND LAYOUT

Other signatures of BTW production would not be visible from outside a suspect facility, and thus could only be detected during an intrusive onsite inspection. The basic equipment in a BTW production facility would be much the same as that in a vaccine plant, including equipment and materials for microbial fermentation, cell culture, or egg incubation, followed by harvesting, purification, and lyophilization. Both a vaccine plant and a BTW production facility would require a source of pharmaceutical-grade distilled water to remove bacterial contaminants in tap water that would interfere with the growth of desired microbial agents. And both types of facilities would require autoclaves to sterilize the growth media and decontaminate the equipment after production.

It is also important to evaluate BTW-related activities in their socioeconomic context. In developed countries, civilian production facilities that utilize microorganisms, such as pharmaceutical plants and even breweries, now incorporate safety and environmental equipment that were once unique to BTW production facilities. This fact has made it easier to use commercial production as a cover for illicit military work, although the presence in a vaccine-production plant of processes that cannot be justified on technical or economic grounds may provide indicators of possible conversion or diversion to BTW production. Nevertheless, a clandestine BTW production facility could be so small that it could be easily hidden.

PHYSICAL CONTAINMENT

In developed countries, an important difference between a vaccine plant and a BTW production facility may be the level and type of physical containment measures that are employed. Three aspects of physical containment might be suggestive of a clandestine BTW program:

First, production of vaccines involves the use of living, attenuated microbial strains that are either further weakened to produce a live vaccine or killed immediately after cultivation. As a result, stringent containment measures are required only during the *initial phase* of vaccine production, which involves the cultivation of agents before they are attenuated or killed.[102] According to one assessment, “Extensive safety precautions during the whole production cycle for a vaccine are hardly defensible economically and would hence be suspect. ’ ’[103]

A second difference between a vaccine plant and a BTW production facility is the presence in the former of costly measures to protect the purity, sterility, and reproducibility of the products so that they are suitable for human use. Thus, an indicator of illicit BTW production in a pharmaceutical facility might be the *absence* of measures to purify the product and ensure its sterility.

Although BTW agents would probably be cultivated under *negative pressure* to prevent dangerous microbes from escaping from the plant, this would not be a reliable signature because negative pressure would also be needed

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[102] David L. Huxsoll, ~@ D. Parrott, and William C. Patrick III, “Medicine in Defense Against Biological Warfare,” *Journal of the American Medical Association,* vol. *262, No. 5,* Aug. 4, 1989, p. 679.

[103] SIPRI, vol. VI, op. cit., footnote 31, p. 45.

in a legitimate pharmaceutical plant that is producing live, attenuated vaccines. It would also be possible to reverse the pressurization of a facility before an inspection by changing the direction of flow of the faltered air, but only if the system were engineered for this purpose in advance. Moreover, governments engaged in the covert production of BTW agents would probably not hesitate to cut comers on containment and worker safety in order to avoid signaling their intentions.

In addition to the type and level of physical containment, several other potential signatures of clandestine BTW production might be detected during an onsite inspection.[104] The utility of such signatures is highly controversial, however, and each one is open to criticism. These signatures might include:

- Bad odors associated with microbial fermentation, since multiplying bacteria produce a variety of volatile and odiferous gases. However, odors do not travel far and are nonspecific.
- Seed stocks and cell lines inappropriate for declared activities such as production of vaccines or single-cell protein, or in amounts exceeding immediate research needs. However, such materials would probably not be declared and could be easily hidden.
- Activities related to microorganisms and toxins that cannot be explained by civilian needs, such as development of vaccines against rare, nonindigenous disease agents. However, such activities could be easily hidden.
- Production capacity greatly in excess of demand for the plant's legitimate products, such as vaccines. However, such excess capacity would not be required for a BTW capability.
- A discrepancy between a small quantity of output product (e.g., packaged vials of vaccine) and a large quantity of input materials (e.g., fermentation media). However, calculation of a precise material balance is probably impossible.
- Air compressors, air tanks, or lines for air-supplied protective suits as a means of enhancing physical containment. However, compressors are easily hidden.
- Facilities for rapid decontamination and cleaning of the production line, or evidence of recent large-scale decontamination operations, fumigation, or removal of materials or equipment. However, decontamination routinely occurs in pharmaceutical facilities.
- Large stockpiles of bleach (sodium hypochlorite or sodium hydroxide) for use as a decontaminating agent. However, such agents are also widely used in legitimate commercial facilities.
- Specialized equipment for the lyophilization, *milling,* or microencapsulation of BTW agents. However, lyophilization machines are ubiquitous in the pharmaceutical indusW.
- Refrigerated storage bunkers, freezers, or large quantities of liquid nitrogen for storing stockpiles of live or freeze-dried pathogens. However, since significant quantities of biological agents can be grown relatively quickly, long-term stockpiling of agents in refrigerated bunkers is unnecessary.
- Anomalous transport of microbial products or wastes off-site. However, microbial waste can be steam-sterilized.
- Incomplete or anomalous plant production records. However, a proliferant engaged in illicit production is unlikely to provide such records voluntarily. Records might also be

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[104] Federation of American Scientists, Working Group on Biological and Toxin Weapons Verification, ''A Legally Binding Compliance Regime for the Biological Weapons Convention: Refinement of Proposed Measures Through Trial Facility Visits," draft manuscript, March 1992, p. 12. See also SIPRI, vol. VI, op. cit., footnote 31, p. 35.

forged, although it is hard to do so convincingly.

Still, although the indicators listed above would not necessarily be associated with illicit production activities, a pattern of them might arouse suspicions.

BIOCHEMICAL SIGNATURES

BTW agents do not possess a single common chemical signature, such as the phosphorus-methyl bond characteristic of most nerve agents, but pathogenic microorganisms can be identified in minute quantities using sensitive immunological, biochemical, and genetic techniques. (See box 3-C, pp. 108-109.) Telltale traces of DNA from virulent strains of bacteria and viruses might be discovered in samples collected during an onsite inspection of a suspect site, even after the facility had undergone decontamination. Such traces might be indicative of previous research or production activities at the facility. Fermenters also generate large quantities of liquid wastes that might contain unusual metabolic byproducts and other telltale chemicals even after decontamination treatment.

Nevertheless, the fact that certain toxins and microbial pathogens have defensive or medical uses means that it can be difficult to distinguish legitimate from illicit BTW activities. Toxins also differ from chemical-warfare agents in that they do not leave persistent traces in the environment and are easily destroyed by autoclaving with superheated steam. The extent to which heat-neutralized protein toxins could be detected by immunological methods is unknown. Finally, the ability of modem analytical techniques to detect trace amounts of biological organisms could make legitimate biotechnology facilities reluctant to submit to such intrusive inspection for fear of losing proprietary information. Analytical instruments could probably be "blinded," however, to detect only the presence or absence of known BTW agents.

BIOMARKERS

Since the workforce in a BTW production facility would likely be immunized against the agents being produced, another approach to verification would be to determine whether the blood of workers in a suspect fermentation or vaccine facility contains antibodies against known BTW agents. Monitoring of immunization programs would involve taking blood samples from plant workers for onsite immunological analysis. Another approach would be to take blood samples from wild animals (e.g., rodents) in the vicinity of a suspect facility to detect possible exposure to unusual infectious agents.

Although most vaccine production plants require all workers to undergo initial and periodic blood collection and analysis, it would be difficult to negotiate a verification regime that requires such intrusive inspections. Furthermore, performing such tests as part of routine onsite inspections might violate U.S. constitutional protections against "unreasonable searches and seizures," since it would be difficult to protect confidential medical information unrelated to the purpose of the inspection. According to one legal scholar, "No treaty could empower inspectors to conduct random intrusive body searches for possible telltale evidence of radiation or biological weapons."[105] Another analyst argues, however, that biomedical sampling might be upheld by the courts on grounds of national security if there is a clear connection between the objectives of the regime and the analysis of biochemical indicators.[106]

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[105] David A, Koplow, "Arms Control Inspection: Constitutional Restrictions on Treaty Verification in the United States," *New York University Law Review, vol. 66,* May 1988, p. 355.

[106] Jerry R. Stockton, Edward A. Tanzman, and Barry Kellman, *Harmonizing the Chemical Weapons Convention With the United States Constitution* (McLean, VA: BDM International, Report No. DNA-TR-91-216, April 1992), p. 59.

Stockpile and Delivery System Signatures

Stockpiling of agent or loading into sprayers, munitions, or other delivery systems might be associated with a number of signatures. The following might be observable by aerial or satellite photography:

- cold storage of bulk BTW agents in refrigerated bunkers or igloos, although small quantities of stored agent would probably not be detected;
- storage depots for BTW-capable munitions and delivery systems in proximity to possible production facilities; and
- heavy trucks for the transport of empty or filled munitions in the vicinity of a biological production facility.

The remaining signatures could only be detected during an onsite inspection:

- inappropriate metal-working equipment or stock that might be used to fashion munitions;
- specialized equipment for filling BTW agents into munitions and warheads;
- breeding of insect vectors, or acquisition of equipment for disseminating biological agents and toxins as an aerosol cloud;
- munitions or parts thereof for disseminating BTW agents; and
- the training of troops in the tactical use of BTW agents.

Weapon Use Signatures

BTW agents might either be used deliberately or escape accidentally from a secret military research or production facility, as happened in the Soviet city of Sverdlovsk. It is therefore important to determine whether an outbreak of infectious disease in an area where it is not endemic is the result of clandestine biological warfare activities and, if possible, to identify its source. Field epidemiology can help investigate alleged cases of biological and toxin warfare.[107] Indeed, the Centers for Disease Control's Epidemic Intelligence Service was originally founded in 1951 out of concern that terrorists or foreign intelligence agencies might launch a covert BTW attack against the United States.[108]

As a first step, all of the likely natural causes of an epidemic must be investigated and excluded—a difficult task given the enormous variability of infectious diseases. Covert attacks aimed at economic sabotage are most likely to involve animal or plant pathogens. The best known case of a suspicious epidemic took place in 1981 in Cuba, which suffered a severe outbreak of dengue fever, a mosquito-borne viral illness. Of the estimated 350,000 people who developed the disease, approximately 10,000 suffered from severe (hemorrhagic) symptoms and 158 died, a mortality rate of 1.6 percent.[109] Cuban President Fidel Castro blamed the epidemic on covert U.S. biological warfare, which he alleged was being run by the Central Intelligence Agency. Epidemiological analysis indicated, however, that the outbreak was of natural origin. The Cuban epidemic occurred a few months after a major outbreak of hemorrhagic dengue fever in Southeast Asia. Epidemiologists determined that Cuban construction workers building a hotel in Hanoi, Vietnam, had become infected with the disease. After returning home to Cuba, they were bitten by

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[107] Peter Barss, ''Epidemic Field Investigation as Applied to Allegations of Chemical, Biological, or Toxin Warfare, " *Politics and the Life Sciences,* vol. 11, No. 1, February 1992, pp. 5-22.

[108] Stephen S. Morse, ''Epidemiological Surveillance for Investigating Chemical or Biological Warfare and for Improving Human Health,' ' *Politics and the Life Sciences,* vol. 11, No, 1, February 1992, pp. 28-29.

[109] Jay P. Sanford, ''Arbovirus Infections,' Eugene Braunwald et al., *Harrison 's Principles of Internal Medicine,* 1 1th ed. (New York, NY: McGraw-Hill, 1987), p. 727.

Box 3-C-Biochemical Detection of BTW Agents

Inspections of microbioiogical laboratories or production facilities for indications of BTW activities might involve the collection and analysis of samples to detect the presence of undeclared pathogens or toxins. Such samples might include wipes from equipment and air filters or liquid samples from the waste stream or the environment near the plant Alternatively, air filters might be used to screen large volumes of air inside, or even at a considerable distance from, a plant.

Immunological techniques. The fastest method for detecting pathogens is to use specic antibodies that have been labelled with a tag of some type, such as a fluorescent molecule or a radioactive atom. Such antibodies would bind to the pathogen with high specificity, providing nearly unambiguous evidence of its presence. Techniques for producing large quantities of "monocional" antibodies, all specific to a single marker protein on the surface of a microorganism, permit the detection and identification of minute quantities of bacterial and viral agents (and protein toxins) in Mood or environmental samples. Such immunological screening techniques include radioimmunoassay (RIA) and enzyme-linked immunosorbent assay (ELISA). A drawback of such assays is that they could not identify BTW agents that had been genetically modified to alter their immunological characteristics.

Bioassays. A pathogen or toxin can be detected by measuring its physiological effects on intact organisms or on isolated cell or enzyme systems. For example, many toxins work by specifically inhibiting the enzyme acetylcholinesterase involved in nerve transmission, thereby reducing its ability to break down the messenger chemical acetylcholine. Devices known as 'biosensors" are under development that use receptor molecules or enzymes immobilized on the surface of a chip to detect the binding of toxins or viral agents. One biosensor capable of detecting toxins, developed by engineers at Arthur D. Little, is moving into a manufacturing prototype.[1]

Genetic analysis. The advent of recombinant-DNA techniques has made it possible to identify minuscule quantities of microorganisms in complex samples.The first step is to prepare standards by isolating single-strand DNA sequences from specific microorganisms or synthesizing them chemically and labeling them with a radioactive isotope or a fluorescent dye. These labeled DNA fragments, known as "DNA probes," can pair up or "hybridize" with DNA in a sample if the sample contains DNA from the same microorganism. The advantage of DNA probes is their unique specificity, which enables them to identify a single type of pathogen even in complex mixtures.

Because of background noise, it can be difficult to detect probe/target hybrids when only a small number of microorganisms are present in the sample. This problem was solved in 19$5 with the development of a powerful new technique known as polymerase chain reaction (PCR), which can amplify a given DNA sequence as much as 1O^8 times. PCR therefore makes it posssible to use DNA probes to identify pathogens present in trace quantities-as few as tensor hundreds of microorganisms-without having to grow them into larger colonies over a period of days or weeks. Since PCR reagents are available in kit form, this technique has greatly speeded the diagnosis of infectious diseases, including potential BW agents such as anthrax bacteria.[2] PCR is also useful for analyzing biological samples in the field or during an onsite inspection of a suspect facility it has even detected killed bacteria in autoclaved samples?

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[1] Richard F. Taylor, Arthur D. Little Corp., "Portable, Real-Time Biosensors for Chemical Agent Verification," presentation at the Chemical Weapons Convention Verification Technology Research and Development Conference, Herndon, VA, Mar. 2-3,1993.

[2] Department of Defense, *Annual Report to Congress* on *the Research, Development, Test and Evaluation of the Chemical/Biological Defense Program for the Period October 1, 19$0 Through September 30, 7991,* RCS:DD-USDRE(A) 1085, p. 51. See also, M. Carl et al., "Detection of spores of *Bacillus anthracis* using the polymerase chain reaction," *Journal of Infectious Diseases,* vol. 185, 1992, pp. 1145-1148.

[3] T. Barry and F. Gannon, "Direct Genomic DNA Amplification From Autoclaved Infectious Microorganisms Using PCR Technology," *PCR Methods and Applications, VOL* 1, 1991, p. 75.

Nevertheless, PCR has some limitations. First, it is only suitable for identifying known organisms, since one must decide in advance which DNA sequences to use as probes. Second, because many pathogenic microbes (e.g., anthrax bacteria) are ubiquitous in the environment in trace amounts, a probe of sufficient sensitivity may find "prohibited" DNA everywhere! Third, the accuracy of PCR depends on both the length of the target DNA sequence and the length of the PCR "primers," which bind to the target DNA to initiate the amplification process. As one tests for shorter sequences (e.g., 100 instead of 1,000 DNA base-pairs), the sensitivity of the technique increases but its specificity declines, since several different microbial species may have identical short DNA sequences. For this reason, two levels of detection have been proposed, depending on the characteristics of the DNA probe. The first level would identify the group of pathogenic bacteria to which a suspect agent belongs by detecting a DNA sequence common to all species in that group; the second level would provide species-specific identification by using longer DNA probes specific to each microorganism targeted for detection.[5]

Genetic *fingerprinting*. Known technically as restriction-fragment length polymorphism (RFLP) analysis, this technique involves the use of special "restriction" enzymes that cut microbial DNA at specific sites. This treatment results in a pattern of DNA fragments of different sizes, which can be analyzed by separating the fragments on a gel. Genetic fingerprinting can also be done with RNA viruses. The result of this technique is a characteristic pattern of spots on the gel. Since different DNA sequences will result in a different pattern of spots, comparing such maps will reveal the extent to which two strains of a bacterium or virus differ genetically.

All microbial pathogens can be "fingerprinted" by analyzing their genetic material (DNA or RNA). Since there are always minor genetic differences among various strains of a pathogenic microorganism, it is very likely that a laboratory-developed strain is genetically distinct from an indigenous strain. Moreover, an indigenous strain that has been produced in large quantities is likely to be more genetically homogeneous than the causative agent of a natural epidemic. For many microbial pathogens, scientists have compiled a library of characterized strains t hat can be compared with any newly discovered strain. Thus, genetic fingerprinting often provides enough information to determine the source of a virus and whether it has been modified genetically in the laboratory. Trace amounts of genetic material can be amplified for further analysis using PCR.

Town analysis. For toxins, analytical techniques for detection and characterization include immunoassay, as well as analytical chemistry techniques such as combined gas chromatography/mass spectrometry (GC/MS), liquid chromatography, and others. Quadruple mass spectrometry is used to analyze protein toxins, as well as samples dissolved in water.[6] Very large biomolecules must be broken down into smaller components for analysis. To this end, a technique known as pyrolysis mass spectrometry involves heating complex materials in a controlled manner to generate characteristic chemical signatures that can then be analyzed by a mass spectrometer.[7] These signatures are compared with a large computer database of known chemical spectra to identify the compounds present Finally, if a pure sample of a protein toxin or peptide bioregulator is available, it may also be possible to identify it from its amino-acid sequence. Off-site detection of toxins is nearly impossible, however, because they lack volatility.

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[4] Moreover, a laboratory might detect a contaminant from past rather than current work, such as anthrax spores from earlier samples.

[5] Barbara J. Mann, *Detection of Biological Warfare Agents Using the Polymerase Chain Reaction* (Research Triangle Park, NC: Battelle Memorial Institute, September 1992), DTIC No. AD-A259391.

[6] External Affairs and International Trade Can-Verification Research Unit, *Verification: Development of a Portable Trichothecene Sensor Kit for the Detection of T-2 Mycotoxin in Human Blood Samples* (Ottawa: External Affairs, March 1987).

[7] Diane M. Kotras, "New Detection Approaches for Chemical and Biological Defense," *Army Research, Development and Acquisition Bulletin*, January-February 1989, p. 2.

mosquitoes, which then transmitted the disease to others.[110]

Another suspicious epidemic that still remains to be explained took place during the civil war in Rhodesia (now Zimbabwe) from 1978 to 1980. An unprecedented outbreak of cattle anthrax was almost entirely confined to the Tribal Trust Lands-the areas then assigned to Rhodesia's blacks and accounting for about 17 percent of the country's land area.[111] Since cattle were the primary source of wealth for black farmers, the epidemic led to the severe impoverishment of the ected rural populations. The outbreak of cattle thrax was accompanied by a secondary human idemic, which resulted in more than 10,000 infections and 182 human deaths. Since anthrax is not contagious from one individual to another, the explosive nature of the human epidemic was striking: the reported incidence of human anthrax cases during the 1979-80 period was more than 400 times the average incidence of the previous 29 years. Some epidemiologists believe that the losing Rhodesian government forces may have resorted to biological warfare with anthrax against cattle in order to impoverish the rural black population, as a desperate tactic in the final months of the civil war, and that humans were infected secondary to contact with infected animals or animal products.[112]

EPIDEMIOLOGICAL ANALYSIS

Distinguishing natural disease outbreaks from those produced deliberately requires careful investigation and knowledge of local diseases and endemic infections. There is at present no generally accepted methodology for investigating the possible use of BTW agents. But Dr. Jack Woodall, an epidemiologist with the World Health Organization in Geneva, has identified a number of characteristics of a disease outbreak **that** would suggest it was not of natural origin:[113]

- *The appearance of an endemic disease far outside its established range.* A natural disease outbreak might be distinguished from a BTW attack by determiningg whether its source is an agent endemic to the region. Although jet travel has made it easier for infectious agents to spread discontinuously from one continent to another, the progression of an epidemic typically involves gradual spread to contiguous regions or along transportation routes.
- *Appearance of a vector-borne disease in the absence of natural vectors or reservoir hosts.* Plague epidemics, for example, typically begin in rats and are spread to man by infected fleas. The initial form of the disease in humans is the bubonic form affecting the lymph nodes, which later converts into the more lethal and contagious pneumonic form. Thus, the sudden appearance of pneumonic plague in humans (1) in the absence of infected rats and fleas, and (2) without precursor cases of the bubonic form, would be suggestive of a covert BW attack.
- *Pulmonary disease in the absence of natural mechanisms for producing high-concentration biological aerosols. Since* many infectious diseases do not naturally infect the lungs, the anomalous appearance of a respi-

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[110] Telephone interview with Dr. Scott Halstead, Associate Director of the Health Sciences Division, Rockefeller Foundation, New York, *NY*, Aug. 6, 1992.

[111] See J.C.A. Davies, "A Major Epidemic of Anthrax in Zimbabwe, Part l," *Central African Journal of Medicine,* vol. 28, 1982, pp. 291-298; and J.C.A. Davies, "A Major Epidemic of Anthrax in Zimbabwe, Part 2," *Central African Journal of Medicine, vol. 29, 1983,* pp. 8-12.

[112] Meryl Nass, "Anthrax Epizootic in Zimbabwe, 1978-1980: Due to Deliberate Spread?" The *PSR Quarterly,* vol. 2, No.4, December 1992, pp. 198-209.

[113] John P. Woodall, "WHO Health and Epidemic Information as a Basis for Verification Activities Under the Biological Weapons Convention" S.J. Lundin, cd., *Views on Possible Verification Measures for the Biological Weapons Convention,* SIPRI *Chemical &* Biological Warfare Studies No. 12 (Oxford, England: Oxford University Press, 1991), pp. 59-70.

ratory form of such a disease might be indicative of a deliberate aerosol attack. Other human activities than deliberate military attack may generate infectious aerosols, however. The outbreak of Legionnaires' Disease at a hotel in Philadelphia, for example, was traced to a natural microbial contamination of the building's air-conditioning system.

- *Unusual epidemiological patterns that differ from natural disease outbreaks.* A deliberate BW attack by aerosol dissemination would infect a large number of exposed individuals simultaneously, causing a majority of them to develop symptoms at approximately the same time. Thus, instead of a gradual rise from a smaller number of precursor cases, there would be an "explosive' outbreak of disease in many thousands of people.[114]

While these characteristics are all plausible, the recent natural outbreak in New Mexico of ‘ ‘Navajo flu, ’ a virulent respiratory illness with greater than 30 percent mortality, meets nearly all of the criteria Woodall proposes. Hanta virus, now known to be the cause of the illness, had never before been known to occur among humans in the Western Hemisphere, Whereas all previous reported cases around the world were hemorrhagic fevers with shock and kidney failure, this recent outbreak took the form of a respiratory illness. Finally, the epidemiology of the disease was extremely unusual and confused investigators for months. This episode points out the difficulty of distinguishing a highly anomalous disease outbreak of natural origin from the deliberate or accidental release of biological-warfare agents.[115]

An important task of epidemiological analysis is to characterize the strains of disease-causing agents indigenous to the affected area, thereby making it possible to distinguish preexisting "background" strains from BW agents introduced from the outside. Even if it could be ascertained that a disease outbreak was of artificial origin, however, it might still not be clear who had initiated the attack. It might also be difficult to collect the necessary data if investigators were denied permission to visit the sites of the alleged attacks.

A current problem with depending on epidemiology to detect the use of BTW agents is that such skills are unlikely to be available in those regions of the world where biological warfare is most likely. In order to detect new infectious diseases such as AIDS before they reach epidemic proportions, the epidemiologist Donald A. Henderson has proposed the establishment of an international network of research centers to monitor the emergence and spread of new infectious diseases, linked to a global rapid-response system.[116] Beyond its obvious public-health benefits, such a global surveillance system would make it easier to distinguish artificially induced epidemics associated with the covert use of BTW agents from ordinary background noise. ‘‘[117] It would thereby help to deter biological warfare and also to identify false claims of BW, an important objective.

Table 3-2 summarizes the various potential signatures associated with BTW development,

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[114] Nevertheless, the anthrax epidemic in the Soviet town of Sverdlovsk (now Yekaterinburg) in 1979-now recognized to have been the result of an accidental release of anthrax spores from a Soviet military biological facility-was associated with a gradual increase in the number of cases over a period of several weeks, a pattern that appeared consistent with a natural epidemic. It is known, however, that at low levels of exposure, anthrax spores germinate at different rates in exposed primate hosts, resulting in highly variable incubation periods. Matthew Meselson, Harvard University, personal communication 1993.

[115] Zelicoff, Op. cit., footnote 29.

[116] Donald A. Henderson, "Surveillance Systems and Intergovernmental Cooperation" Stephen S. Morse, cd., *Emerging Viruses (New* York: Oxford University Press, 1992), pp. 283-289. See also Joshua Lederberg et al., *Emerging Infections: Microbial Threats to Health in the United States* (Washington, DC: National Academy Press, 1992), pp. 134-137.

[117] Mark L. Wheelis, "Strengthening Biological Weapons Control Through Global Epidemiological Surveillance, " *Politics and the Life Sciences,* vol. 11, No. 2, August 1992, pp. 179-189.

Table 3-2—Biological Weapon Program Signatures and Concealment

Program stage	Signature	Detection methods (examples)	Concealment methods, comment
Research & development	Scientific and technical publications (presence or absence)	Literature survey and analysis	1. Manage publication activities 2. Use widely available technical information rather than design new agents or techniques
	Nondeclaration of work with potential BTW agents or with pathogen aerosols	Human intelligence (humint), on-site inspections	Conceal undeclared activities
Clandestine production plant	Security measures	Overhead imaging or humint	Conceal measures, or place plant within other secure facilities
	Large numbers of eggs or laboratory animals for virus production	Humint	Use tissue culture rather than animals for production of viruses
	Storage depots for BTW-capable munitions	Overhead imaging or humint	Conceal depots underground (although facility building would be visible)
	imports of dual-use equipment (fermenters, lyophilizers, microencaipsulation systems)	Tracking of exports to suspected proliferants	1. Obtain equipment from multiple suppliers, or through intermediaries 2. Divert equipment from legitimate civil activities 3. Make equipment indigenously
Converted or multipurpose pharmaceutical plant	Security measures	Overhead imaging or humint	Conceal measures
	Residues of virulent microbial strains or genetically modified agents	Sampling of air, water, or soil in or near suspect plants; together with various forms of biochemical analysis (e.g., ELISA, bioassay, DNA probes, PCR)	1. Decontaminate production line with bleach or superheated steam and autoclave cultures 2. Remove wastes for off-site disposal 3. Claim that BTW agents are being used for defensive activities
	Special safety and containment measures	Onsite inspection of suspect plants	1. Sacrifice worker safety 2. Modern biotech plants increasingly have these features
	Processes or capacity that cannot be justified on technical or economic grounds	Onsite inspection of suspect plants	Such assessments are highly subjective
	Seed stocks, cell lines, and equipment (e.g., microencapsulation) inappropriate for declared activities	Onsite inspection and sampling	Claim that material and equipment is being used for legitimate medical applications, although possibilities may be limited
	Omission of costly measures to ensure purity and sterility of pharmaceuticals or to inactivate agent to make vaccine	Onsite inspection	Employ measures to simulate pharmaceutical production (costly)
	Facilities for rapid, large-scale decontamination	Onsite inspection	Use legitimate vaccine production activities as a cover

Program stage	Signature	Detection methods (examples)	Concealment methods, comment
	Evidence of immunization to BTW agents in plant workers or evidence of infection in people or animals nearby	Blind tests	Refuse permission to take blood sampils
Weaponization and testing	Uniquely configured arsenals (e.g. distribution of storage bunkers)	Overhead imaging	Pattern facilities after conventional arsenals
	Cold storage of BTW agents	Thermal infrared imagery Excess electrical capacity	1. Produce large quantities of agent shortly before use to minimize need for storage 2. Mask thermal-infrared emissions from refrigerators
	Specialized equipment for filling agents into munitions	Onsite inspection	Conceal filling operation at some remote location
	BTW testing facilities, such as small aerosol chambers	Onsite inspection, sampling and analysis	Carry out tests inside dosed buildings
	Field testing of aerosol generators and delivery systems	Overhead imaging, onsite inspection, sampling and analysis	1. Mask test grid 2. Use legitimate activity such as biopesticide dissemination as a cover for illicit activities, although high security might be a giveaway
	Large animals for aerosol testing		
	Field training of troops		
	Uniquely configured test facilities	Overhead imaging	1. Make special features temporary 2. Test on overcast days, at night, or in absence of overhead imaging systems
Weapon use	Anomalous characteristics of a disease outbreak (e.g., atypical agent, explosive disease spread, pulmonary disease in absence of natural respiratory	1. Field epidemiology 2. Genetic fingerprinting of disease agent	Use a disease agent indigenous to the area being attacked

SOURCE: Office of Technology Assessment, 1993.

production, weaponization, and use. Many of these indicators are nonspecific, since their presence could be associated with other, legitimate activities. Even so, a pattern of such signatures would be suggestive of a clandestine BTW program that could then be confirmed by other means.

MILITARY IMPLICATIONS OF GENETIC ENGINEERING

The past two decades have seen revolutionary advances in the ability to manipulate the genetic characteristics of living organisms at the molecular level. Genetic engineering involves identifying regions along the DNA molecules that encode desirable genetic characteristics and cutting and splicing these segments of DNA with enzyme tools to create "recombinant" strains. Since all living creatures contain DNA, it is also possible to combine genes across species lines to give an organism novel traits that do not occur in nature.

Novel Agents?

Techniques for the engineering of genes in bacteria and animal cells, and for the modification of proteins, have become widely available. Although advanced genetic-engineering capabilities are still rare in the developing world, gene-splicing "kits" containing the necessary equipment and reagents (e.g., restriction enzymes) can be easily obtained by mail order, and much of the necessary know-how is openly published in the scientific literature. Some analysts have speculated that gene-splicing technologies could be used to develop 'second-generation' BW agents with greater military utility by making the behavior of these agents in the environment more predictable.[118] Toxin genes and Virulence factors might also be transferred from one species of microorganism to another. According to John Birkner, a foreign technology analyst for the Defense Intelligence Agency, "recombinant-DNA techniques could open up a large number of possibilities. Normally harmless, nondisease-producing organisms could be modified to become highly toxic and produce effects for which an opponent has no known treatment. Other agents, now considered too unstable for storage or biological warfare applications, could be changed sufficiently to become effective. ' '[119]

Although it could theoretically add a toxin gene to a harmless bacterium to render it virulent, recombinant-DNA technology is unlikely to produce novel pathogens more devastating than the highly infective and lethal agents that already exist in nature. The reason is that any attempt to combine genes from unrelated organisms is likely to interfere with the highly developed and integrated pattern of genetic traits that give rise to pathogenic behavior. Since a whole constellation of genes must work together for a microorganism to cause disease, altering a few genes with recombinant-DNA techniques is unlikely to yield a novel pathogen significantly more deadly than natural disease agents.[120] It is therefore doubtful that genetic engineering could result in novel BW agents with greater potency than naturally occurring agents.

Increased Controllability of Microbial Agents

Nevertheless, the genetic modification of standard BTW agents might, however, overcome specific obstacles that currently limit their military utility. In particular, genetic engineering and modern biotechnologies can facilitate microbial production, improve storage and delivery, create antibiotic resistance, and enhance the controllability of existing pathogens. It is not clear, however, that these modifications would significantly alter the military utility of BW agents compared with the numerous already known agents.

SHORTER INCUBATION TIME

Modifying BW agents to act more rapidly would increase their tactical utility on the battlefield, although this is unlikely to be accomplished anytime soon.

ENVIRONMENTAL STABILITY

Genetic engineering might be able to increase the ability of microorganisms and toxins to withstand some of the stresses associated with storage and dissemination, for example, by inserting complexes of genes for resistance to inactivation by temperature, ultraviolet radiation, drying, and the shear forces associated with aerosol formation. Most of these traits are genetically complex, however, and are not well understood.

INCREASED VIRULENCE

Development of a system for the super-expression of toxin genes has made it possible to develop recombinant bacterial strains that pro-

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[118] Erhard Geissler, ''Implications of Genetic Engineering for Chemical and Biological Warfare,'' *World Armaments and Disarmament: SIPRI Yearbook 1984* (London: Taylor & Francis, 1984), pp. 421-451.

[119] John Birkner, cited in R. Jeffrey Smith, "The Dark Side of Biotechnology," Science, vol. 224, June 15, 1984, p. 1215.

[120] Jonathan B. Tucker, ''Gme: Wars, '' *Foreign Policy, No. 57,* winter 1984-85, p. 62.

duce 10 to 100 times more toxin than natural strains.

ANTIBIOTIC RESISTANCE

Inserting antibiotic-resistance genes into naturally infectious agents can make them resistant to one or more prophylactic or therapeutic drugs, rendering such defenses useless. At the same time, an attacker could immunize his troops against the modified agent, protecting them without the need for antibiotics. Reportedly, the Soviet Union launched a secret program in 1984 to develop a genetically engineered form of plague that was resistant to antibiotics.[121]

VACCINE PRODUCTION

Recombinant-DNA techniques make it easier and safer to produce specific vaccines to match novel agents, thus enabling the attacker to protect his own forces while denying a vaccine to the defender. In the past, the difficulty of producing effective protective vaccines was a major obstacle to acquiring an offensive BTW capability. Nevertheless, recombinant vaccines are not always effective because they represent one or a few antigens rather than the full set of antigens present in the actual pathogen.

CONTROLLED PERSISTENCE

Genetic engineering might result in more controllable BW agents through the manipulation of genes to program the survival of a bacterial population released into the environment. For example, it might be possible to program microorganisms genetically to survive only under a narrow set of environmental conditions. Alternatively, one might design regulatory sequences known as ‘‘conditional suicide genes, ’ which cause a microorganism to die off after a specified number of cell divisions.[122] By inserting such genes into pathogens, it might be possible to create a BW agent that would cause disease for a limited period of time and then spontaneously die off.

IMMUNOLOGICAL MODIFICATION

By means of gene transfers, it would be possible to modify the antigenic (antibody-inducing) proteins on the outer surface of a pathogenic virus or toxin, thereby rendering the modified agents insensitive to a preexisting host immunity or to standard vaccines and antitoxins. (Since most toxin antigens are located on the scaffolding of the molecule rather than near the site responsible for its toxic effects, it would be possible to alter the immunological characteristics of a toxin without changing its biological activity.) Further, since most diagnostic procedures for BTW agents rely on the detection of certain surface antigens with antibodies, modification of the antigens would make it harder to detect, identify, and counter the modified agents.

HOST SPECIFICITY

Some analysts have raised the grotesque possibility of making microbial pathogens more discriminate by designing ‘‘ethnic weapons’ that exploit differences in gene frequency between populations to selectively incapacitate or kill a selected ‘‘enemy’ population to a greater extent than a‘‘friendly’ population. Yet human populations are not uniform enough to be uniquely targeted by a given pathogen.[123]

* * *

These possibilities notwithstanding, the practical obstacles to developing more controllable BW agents remain enormous. Even if genetic engineering could produce recombinant pathogens that survived for a predetermined length of

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[121] Barry, op. cit., footnote 97, p. 41”

[122] Preparatory Committee for the Third Review Conference of the Parties to the BWC, *Background Document on New Scientific and Technological Developments Relevant to the Convention on the Prohibition of the Development, Production and Stockpiling of Bacteriological (Biological) and Toxin Weapons and on Their Destruction,* Document No. BWC/CONF.III/4, Aug. 26, 1991, p. 11.

[123] Novick and Shulman, op. cit., footnote 47, p. 114.

time in the environment, they would remain incalculable in their effects, since their dissemination would still rely on wind and weather, and mutations might change the behavior of a genetically modified agent after it had been released. Once released,, living pathogens might propagate, evolve, and develop ecological relationships with other living things in ways that cannot be entirely foreseen. Furthermore, genetically engineered pathogens would require extensive trials to verify that they would survive long enough to infect target personnel after being disseminated by a weapon system and exposed to the natural environment, in which most microorganisms are extremely fragile. Thus, testing in human subjects might be required to give a military planner confidence in genetically engineered biological agents.

Modified Toxins and Bioregulators

Another potential threat from the biotechnological revolution is the development of new toxin-warfare agents. Known protein toxins, such as botulinal and ricin, deteriorate in response to environmental factors such as temperature and ultraviolet radiation, and thus rapidly lose toxicity after dissemination. Although genetic engineering is unlikely to increase the potency of naturally available toxins, it might conceivably be applied to modify the chemical structure of toxins to:

- increase the stability of toxins so that they can better be disseminated as an aerosol;
- alter the antigenic structure of toxin molecules, rendering them insusceptible to existing antitoxins or antibody-based diagnostic techniques;
- develop "chimaeric" toxins (combinations of two different toxin molecules, such as ricin and diphtheria toxin) that are more capable of penetrating and killing target cells; and
- design novel peptide toxins (possibly consisting only of the biologically active region of a protein toxin) that are as poisonous as nerve agents but are small enough to penetrate the filters currently used in masks and protective garments.[124]

BIOREGULATORS

Recombinant-DNA research may also lead to the development of more effective incapacitants. With genetic engineering, even the body's own natural substances might be utilized as warfare agents. "Bioregulators' are small, physiologically active peptides (chains of amino acids smaller than proteins) that are normally present in the body in minute quantities and that orchestrate key physiological and psychological processes. They are active at very low concentrations and influence the full spectrum of life processes, both physiological and mental. Bioregulators govern, for example, hormone release, control of body temperature, sleep, mood, consciousness, and emotions. An important subgroup of the bioregulators are the opioid peptides, which can induce analgesia and euphoria. Since these naturally occurring peptides are active in the body in trace amounts, the application of larger quantities might induce euphoria, fear, fatigue, paralysis, hallucinations, or depression, giving them some potential as nonlethal incapacitating weapons.[125]

Bioregulators might be modified chemically to enhance their physiological activity, stability, or specificity. For example, the modification of the peptide hormone LHRH (leutenizing hormone

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[124] External Affairs and International Trade Canada, Verification Research Unit, *Novel Toxins and Bioregulators: The Emerging Scientific and Technological Issues Relating to Verification of the Biological and Toxin Weapons Convention (Ottawa:* External Affairs, September 1991), p. 47.

[125] Swedish National Defense Research Institute, *Genetic Engineering and Biological Weapons,* Report No. PB88-210869 (Umea, Sweden: National Defense Research Institute, November 1987; translated for the Office of International Affairs, National Technical Information Service, May 1988), p. 58.

Table 3-3—implications of Genetic Engineering for Biological and Toxin Warfare

Capability	Possible now	May be possible In 5 years	May be possible In 10 years, If ever
Shorter incubation time		X	
Temperature stability	X[a]		
UV stability		X[b]	
Drying/aeosol stability			X
Antibiotic resistance	X[c]		
Controlled persistence			X
Immunological modification	X[c]		
Host specificity			X
Cloning of toxin genes	X		
More stable toxins		X	
Novel toxins			X

[a] For certain protein toxins

[b] For bacteria

[c] In some cases, not all

SOURCE: Office of Technology Assessment, 1993.

releasing hormone) by substituting a single amino acid yielded a product 50 times more potent.[126] Even so, it would be difficult to disseminate peptides through the air in a militarily effective way. The ability of a peptide to diffuse across the mucosal membranes of the respiratory tract depends on its molecular size. Although attempts to deliver the small peptide hormone ADH (antidiuretic hormone) with a nasal aerosol have been successful, similar efforts with insulin have failed because of the molecule's relatively large size.[127]

The possible implications of genetic engineering for biological and toxin warfare are summarized in table 3-3. Although the potential for the misuse of genetic engineering to develop new and militarily more effective BTW agents currently appears limited, this emerging threat clearly deserves to be monitored carefully. *Advanced* genetic-engineering capabilities are still rare in the developing world, but most of the larger countries in the Middle East already have the technical capability to selectively breed microbial strains with enhanced virulence, survivability, and antibiotic resistance. In According to one analyst, "If you can identify the gene you want to move, it is possible to do so. '[129]

For at least the medium-term, BTW proliferants are likely to produce proven agents such as anthrax and botulin toxin, rather than invest large amounts of time and money on experimentation with genetically engineered microorganisms. Eventually, however, technologically sophisticated proliferants might try to modify standard agents to make them more stable during dissemination or more difficult to detect or to defend against.

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[126] Government of the United States, op. cit., footnote 44, p. 29.

[127] Zelicoff, Op. cit., footnote 29.

[128] Anthony H. Cordesman, *Weapons of Mass Destruction in the Middle East* (London: Brassey's (UK), 1991), p. 77.

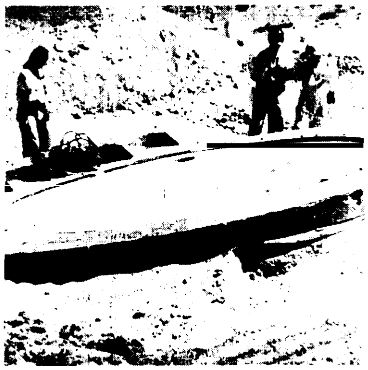
[129] Zelicoff, Op. cit., footnote 29.

Technical Aspects of Nuclear Proliferation

4

A wide variety of policy tools are available for combating nuclear proliferation, as described in the OTA Report *Proliferation of Weapons of Mass Destruction: Assessing the Risks.*[1] Since these measures depend at least in part on the technical prospects for monitoring and controlling nuclear proliferation, this chapter provides background on the difficulty and the detectability of nuclear weapon production. It describes the technical requirements for developing a nuclear weapon, identifying the steps that are the most difficult, time-consuming, or expensive, as well as those that are most amenable to external control. It also discusses detectable ''signatures' associated with each of these steps that might be used for monitoring or verification purposes.

To evaluate the proliferation risks posed by any particular country, however, or to determine which policies can most effectively reduce those risks, the technical hurdles described in general terms in this chapter must be considered in the context of the country's individual situation. In many cases, nontechnical considerations, rather than technical ones, may dominate not only whether a country decides to pursue nuclear weapons but also its likely success in doing so. These factors, which are highly country-dependent, include:



- the ability of a government to organize, manage, and carry through complex, long-term projects involving a large scientific and technological infrastructure, and to keep state secrets;
- a country's foreign business contacts, trade, and supply of hard currency; and

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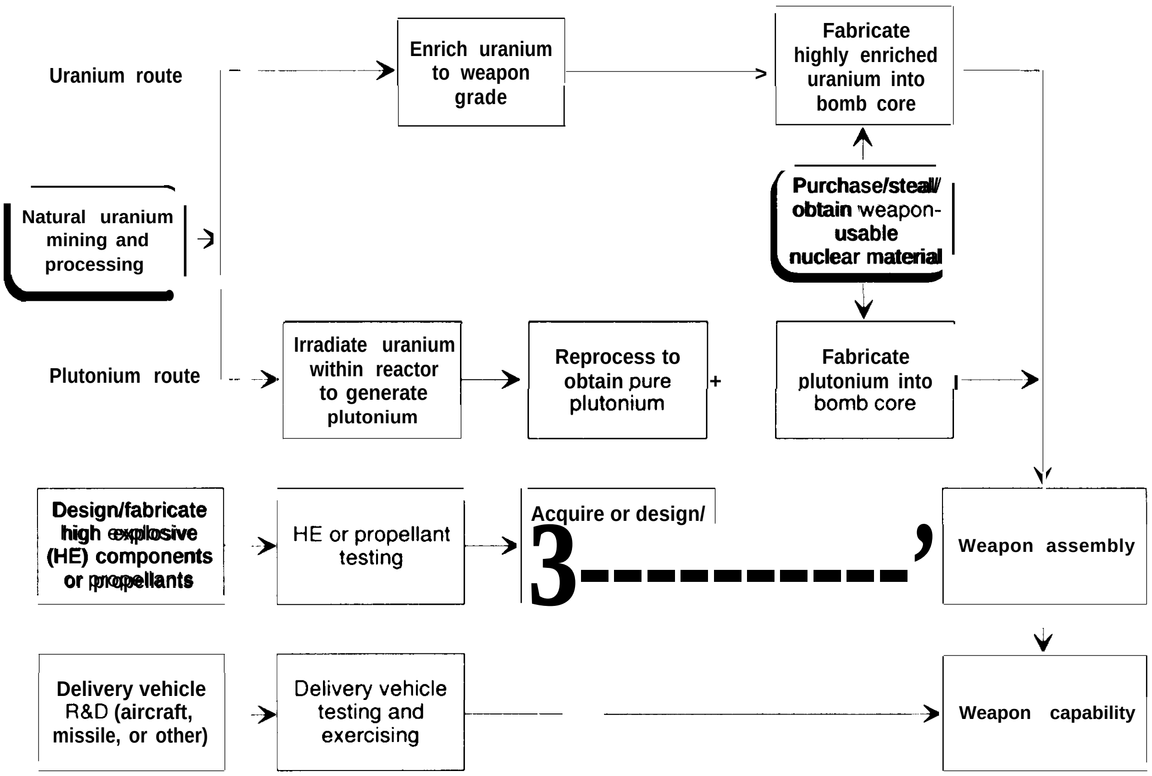
[1] U.S. Congress, Office of Technology Assessment, *Proliferation of Weapons of Mass Destruction: Assessing the Risks,* OTA-ISC-559 (Washington, DC: U.S. Government Printing Office, August 1993).

Figure 4-I—Technical Routes to a Nuclear Weapon Capability



SOURCE: Office of Technology Assessment, 1993.

- the domestic and international costs of getting caught, including possible diplomatic isolation and potential loss of trade, of technology transfer, or of foreign assistance.

Addressing such technical and nontechnical factors on a country-by-country basis, however, is beyond the scope of this report.

OVERVIEW AND FINDINGS

Manufacturing nuclear weapons, shown schematically in figure 4-1, is a complex and difficult process. It can be divided into three basic stages. The first, and most difficult, is the production of the special nuclear materials-plutonium, uranium-233, or enriched uranium-235—that are at the heart of a nuclear warhead. These materials can sustain nuclear chain reactions that release tremendous amounts of energy in a short period of time (see box 4-A for definitions of various nuclear materials). To manufacture highly enriched uranium-235 (HEU) for weapons, the uranium-235 isotope must be separated from the much more common uranium-238. A number of techniques can be used to enrich uranium, all of which to date involve complex and expensive facilities (see app. 4-B on enrichment technologies). Plutonium for weapons is derived from the naturally occurring uranium-238 isotope, which cannot be used directly in a nuclear weapon. However, irradiating uranium-238 in a nuclear reactor will convert part of it into plutonium-239, which can be used in nuclear weapons after it is separated from the unconverted uranium and other irradiation byproducts in a step called chemical reprocessing. Similarly, uranium-233 is

Box 4-A-Glossary of Nuclear Materials

Fertile material-an isotope that can be transformed into a fissile isotope by absorbing a neutron, such as when irradiated in a nuclear reactor. For instance, U-238 is a fertile (as well as fissionable, see below) material that tends to absorb slow neutrons, after which it decays into the fissile isotope Pu-239. Thorium-232 can similarly be transformed into U-233.

Fissile material-an isotope that readily undergoes fission (splits into two or more lighter elements, thereby releasing energy) after absorbing neutrons of any energy. Fissile materials can undergo self-sustaining nuclear chain reactions, in which the neutrons released in fission reactions will themselves induce additional fission reactions (most fissile materials emit two or more additional neutrons, on average, per fission). Important fissile isotopes are U- 233, U-235 and Pu-239. (Pu-241 is also fissile, but is normally created as a byproduct of Pu-239 production.)

Fissionable materitial isotope that undergoes fission only after absorbing neutrons above a certain energy. The most important fissionable material, U-238, emits less than one additional neutron, on average, per fission reaction; thus, although it can release additional energy when bombarded by neutrons of sufficient energy, it cannot sustain a nuclear chain reaction.

Highly enriched uranium (HEU)-uranium enriched in the isotope U-235 to 20 percent or more; often refers to enrichments above 80 percent, which are more useful for nuclear weapons. Uranium enriched to such levels will normally contain about 1 percent U-234, which is responsible for much of its radioactivity.

Low-enriched uranium (LEU)-uranium enriched in the isotope U-235 to less than 20 percent; often refers to enrichments of 2 to 5 percent, which are used to fuel t he most common type of commercial power nuclear reactor ("light-water reactors").

Mixed oxide fuel (MOX)-nuclear reactor fuel composed of plutonium and natural or low-enriched uranium in oxide form ($U0_2$ and PuO_2. The plutonium component plays the role of the fissile U-235 isotope in LEU fuel, thus reducing the need for uranium enrichment. For instance, MOX fuel with a plutonium concentration of about 3 to 5 percent can substitute **for a portion of the low- enriched uranium fuel** in most types of nuclear reactor. (LEU-fueled reactors also make and burn plutonium as they operate, such that by the time LEU fuel is considered to be "used up," it contains more plutonium than U-235.)

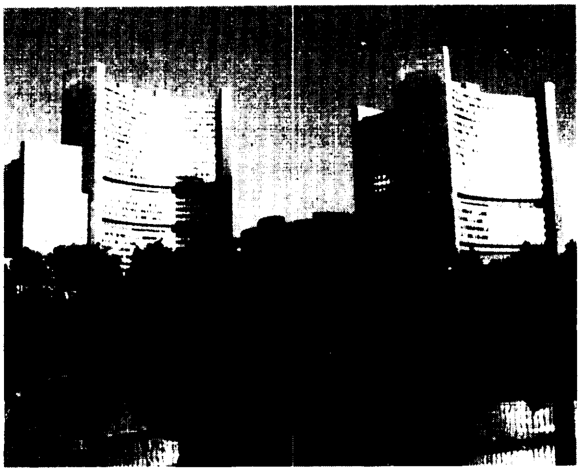
Natural uranium (Nat-U)-uranium of the isotopic concentration occurring in nature, in which about 0.7 percent is the isotope U-235, and 99.3 percent is U- 238. It also contains a trace of U-234.

Reactor-grade plutonium (RGPu)-plutonium that contains at least 20 percent of the nonfissile isotopes Pu-240 and Pu-242. RGPu is produced in most power reactors under normal operation, whereby fuel elements containing U-238 are exposed in the reactor to high neutron fluences for long periods of time (typically a year to a few years).

Weapon-grade plutonium (WGPu)-plutonium that typically contains 6 percent or less of the isotopes Pu-240 and Pu-242, isotopes that makes design of nuclear weapons increasingly more difficult. WGPU is created when U-238 is irradiated in a nuclear reactor for only a short period of time.

Yellowcake-uranium concentrate (with the isotopic ratio of natural uranium), which is produced from uranium ore through a process called "milling"; consists of about 80 percent U_3O_8; may also refer to U_3O_8 itself.

SOURCE: Office of Technology Assessment, 1993.


PETR PAVLICEK, IAEA

The Vienna International Center, housing the headquarters of the International Atomic Energy Agency.

produced by irradiating thorium in reactors (this path is not shown in figure 4-l). Neither the production of uranium-233 nor of plutonium requires enriched uranium.

To make the enriched uranium or plutonium into a weapon, various additional components must be added: chemical explosives (or in the case of gun-type weapons, propellants) to assemble the nuclear material into a super-critical mass that will sustain an explosive chain reaction; nonfissile materials to reflect neutrons and tamp the explosion; electronics to trigger the explosives; a neutron generator to start the nuclear detonation at an appropriate time; and associated command, control, and security circuitry (see app. 4-A on nuclear weapon design). In general, nuclear testing that involves a detonation of the resulting nuclear explosive device is not necessary for a competent designer to have high confidence that a relatively unsophisticated fission weapon will detonate, although nonnuclear testing of the chemical explosive system in an implosion-type weapon would be required. A gun-type weapon made with HEU would not even require chemical-explosive testing. Nevertheless, nuclear explosive testing would be much more important for a proliferant seeking to develop either very low-weight weapons, such as for delivery by missiles of limited payload, or thermonuclear weapons.

The third stage in developing a nuclear weapon capability is integrating the weapon with a delivery system and preparing for its use. Many of the states seeking nuclear weapons also seem to be developing ballistic missiles, and all already have combat aircraft. However, high-tech military systems are not required to deliver nuclear weapons; other military or civilian vehicles could also be used.

International Controls

IAEA SAFEGUARDS

International efforts to control proliferation have traditionally focused on production of nuclear weapon materials, since that is the most difficult and the most visible (short of nuclear testing) of the processes necessary to make nuclear weapons. The Nuclear Nonproliferation Treaty of 1968 (NPT) requires non-nuclear-weapon member states to place all their nuclear materials under *safeguards:* a system of materials accountancy, containment, and surveillance administered by the International Atomic Energy Agency (IAEA) and supported by regular onsite inspections at declared facilities. IAEA safeguards (see app. 4-C) are intended to detect, and thereby deter, the diversion of such materials from declared peaceful purposes to weapons. Under the NPT, safeguards must be imposed on all nuclear materials possessed by non-nuclear-weapon state (NNWS) parties, transferred between NNWS parties, or transferred from any party to any nonparty.[2] The Treaty also

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[2] The IAEA traditionally does not consider uranium ore or uranium concentrate to be ''nuclear material' for safeguards purposes until it is converted into a form suitable for further enrichment (e.g., uranium hexafluoride gas) or for fuel fabrication (e.g., oxide, metal, alloy, or carbide forms). IAEA safeguards also include an exception allowing declared nuclear material to be removed from safeguards for the purpose of military nonexplosive use, such as for submarine-propulsion reactors.

requires that no equipment ‘‘especially designed or prepared for the processing, use, or production” of nuclear material shall be transferred by an NPT member to any nonnuclear-weapon state, even one not party to the NPT, unless all nuclear material processed by that equipment is placed under safeguards. By mandating the adoption of IAEA safeguards, the NPT is intended to permit states to pursue peaceful nuclear programs without giving rise to fears of nuclear weapon development.

Safeguards are important for all nuclear facilities, but especially for those dealing with enrichment or reprocessing. Many of the commercial facilities that enrich uranium for use in power plants, if reconfigured for higher enrichments, would be able to make highly enriched uranium for hundreds of weapons or more per year.[3] Moreover, several countries reprocess spent fuel from nuclear reactors to recover the plutonium generated during reactor operation, and even pilot-scale reprocessing plants can produce enough plutonium for weapons. Civilian nuclear fuel cycles that include the use of plutonium and its attendant reprocessing facilities could—if not safeguarded, or if safeguards were violated—be used to produce plutonium for large numbers of weapons. The type of plutonium produced in commercial nuclear reactors under normal operation, called reactor-grade plutonium, is more difficult to make into a weapon than plutonium produced specifically for weapons.[4] Nevertheless, reactor-grade plutonium can be used to make nuclear weapons of significant (though probably much less predictable) yield, and any state possessing significant quantities of separated plutonium should be considered to have the material needed to fabricate nuclear components for nuclear explosive devices in a short period of times

IAEA safeguards are designed, and to date have served, to make it very difficult to divert ‘‘significant quantities’ of nuclear materials from safeguarded facilities. (The IAEA defines a ‘‘signtilcant quantity’ of fissile material as 8 kg of plutonium or 25 kg of highly enriched uranium-see app. 4-C.) Indeed, the construction and operation of nuclear power reactors and other commercial facilities so as to divert materials to a weapon program is neither the easiest nor the most efficient route to obtain nuclear weapon materials. Moreover, by using modern equipment and measurement techniques, safeguards methods have been significantly improved and in many cases are becoming more automated, more tamper-resistant, and less intrusive to plant operation. Commercial-scale bulk-handling facilities such as fuel-fabrication plants, uranium-enrichment plants, and reprocessing facilities, which process large quantities of nuclear material in often dilute and easily modifiable aggregate form rather than in accountable units such as fuel rods or reactor cores, are more difficult to safeguard than individual nuclear reactors. However, at present there are no large facilities of this

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[3] Almost all civilian power reactors use low-enriched uranium (LEU, see box 4-A), but the enrichment facilities that produce LEU might also be used to produce HEU. Reconfiguring some types of enrichment plants, such as gaseous diffusion plants, from producing LEU to producing HEU would be extremely time-consuming and virtually impossible to accomplish in a safeguarded facility without detection. On the other band, reconfiguring gas centrifuge plants could, in theory, be accomplished more easily. Institutional barriers, such as a state’s own system of control and perceived best interests, must supplement technical ones as deterrents to any such reconfiguration.

[4] The states that have been known to or have sought to produce nuclear weapons have made a determined effort to produce weapon-grade materials specifically for that purpose; no military nuclear weapon program is known to have relied on reactor-grade plutonium.

[5] See, for example, J. Carson Mark, Reactor-Grade *Plutonium's Explosive Properties* (Washington, DC: Nuclear Control Institute, August 1990).

type under fulltime IAEA safeguards in countries of particular proliferation concern.[6]

Still, IAEA safeguards have fundamental limitations. First, several suspect nuclear proliferant states are not signatories to the NPT and are not obligated to place all their nuclear facilities under safeguards. Second, safeguards cannot prevent an NPT member from amassing a stockpile of nuclear weapon materials under safeguards, withdrawing from the NPT, and asserting that its stockpile is no longer subject to safeguards. Third, while the NPT clearly obligates member states to declare *all* of their nuclear facilities and place them under safeguards, it does not provide a "hunting license" to verify the absence of undeclared facilities. The IAEA does have the power to request "special inspections" at declared or undeclared facilities, should it find reason to do so, but no such inspections of undeclared facilities (except in Iraq) have ever been carried out.[7] Therefore, the NPT and the IAEA have very little ability to forestall the development of nuclear weapons in states that are not NPT members, and only limited ability in NPT member states that are able to develop a secret nuclear infrastructure outside IAEA safeguards. Indeed, the covert, indigenous production of nuclear materials is now most likely a greater danger than the diversion of nuclear materials from safeguarded facilities. Some of the signatures that might reveal such a covert program are discussed in this chapter.

EXPORT CONTROLS

Export controls constitute the other primary means (besides IAEA safeguards) by which the international community can seek to prevent proliferant states from acquiring the technical capability to develop nuclear weapons. (Most other nonproliferation policies address the incentive, and not the capability, to develop nuclear weapons .8) One form of export controls is imposed by the NPT, which forbids the transfer of equipment designed to process nuclear materials unless it is placed under IAEA safeguards. The NPT also prohibits nuclear-weapon states from exporting goods or information that would assist in any way with the development by non-nuclear-weapon states of nuclear weapons.

If, despite the NPT, a state were able to import unsafeguarded nuclear material suitable for weapons—perhaps from the former Soviet Union or from a proliferant state already possessing enrichment or reprocessing facilities-it would obviate the need to produce its own weapon material. Such transfers would leapfrog the bulk of the international technical controls against proliferation. Transfers of low-enriched uranium are not nearly so dangerous, since they do not eliminate a proliferant state's need to develop complex enrichment facilities. However, if a proliferant already has such facilities, feeding them with LEU rather than natural uranium can easily more than double their capacity to produce weapon-grade uranium.

Jolted by India's "peaceful nuclear explosion' in 1974, several industrialized countries collec-

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[6] Note that only facilities under *full-time* safeguards are considered here, since those not safeguarded or safeguarded only part of the time (e.g., when safeguarded fuel is present) cannot be expected to be verifiably free from diversion at other times. (Argentina and India, for instance, have some nuclear facilities under part-time safeguards, and Kazakhstan has a fuel-fabrication plant not yet under safeguards, though it is moving toward accession to the NPT and thus to full-scope safeguards.) Brazil has a medium-size fuel-fabrication facility under IAEA safeguards and, with South Africa's accession to the NPT, that country's enrichment facilities are also being placed under full-scope safeguards. But neither state is considered a first-order proliferation threat at present.

[7] The IAEA's first attempt at requesting such a special inspection was directed at North Korea in early 1993 and was refused. Subsequently, the IAEA declared North Korea to be in violation of its safeguards agreement and referred the matter to the United Nations Security Council, which is addressing the issue. As of November 1993, the dispute was still under negotiation.

[8] Incentives and other policy tools, such as security guarantees, cooperation and development assistance, regional arms control, and threats of U.N. or other intervention, are introduced in ch. 3 of the OTA report *Proliferation of Weapons of Mass Destruction; Assessing the Risks,* op. cit., footnote 1.

tively decided to impose export controls that would extend beyond those required by the NPT. Forming the Nuclear Suppliers Group in 1975, these countries initially agreed to exercise restraint on the transfer of any goods or systems directly applicable to the production of nuclear weapon materials (e.g., nuclear reactors and reprocessing equipment for separating plutonium, or systems such as gas centrifuges or gaseous diffision systems for enriching uranium).[9] As a result, the export of most such systems today is tightly constrained. Together with the required imposition of IAEA safeguards, these controls have made it very difficult for would-be proliferant states to acquire "turn-key" systems to produce nuclear weapon materials. However, technologies for some older enrichment methods (e.g., the calutrons for electromagnetic separation, used by Iraq) and some components for not-yet-commercialized methods (e.g., lasers useful for research on some advanced separation techniques) have been more easily obtainable. Moreover, rather than importing complete systems to produce nuclear materials, some proliferant states now possess and others are attempting to build their own equipment, drawing on "dual-use' technologies such as high-voltage power supplies, high-strength alloys and carbon-fiber products, high-performance ion-exchange resins and liquid-liquid contacting equipment, precision machine tools, welding equipment, and specialized furnaces that also have legitimate civil (nonnuclear) applications. Spurred largely by Iraq's progress toward nuclear weapons as revealed after the Persian Gulf War of 1991, the 27 countries of the Nuclear Suppliers Group recently extended their controls to include a wide array of ''dual-use' technologies (see app. 4-D), thus closing many loopholes in previous nuclear export controls.

Computers are an important class of dual-use goods, having widespread applications in civil as well as weapon-related fields. Useful as they may be for nuclear weapon development, however, advanced high-performance computers (so-called '' supercomputers '' in the 1980s) are *by no means necessary* for design of first-generation fission weapons even in the absence of nuclear testing; placing strict limits on their exports would be of only secondary importance compared to limiting technologies for nuclear-materials production. Computers of lesser capability are more than adequate for first-time proliferants and are becoming increasingly difficult to control as their production spreads around the world. However, advanced computers are relatively more important for proliferants pursuing advanced nuclear weapons, including thermonuclear ones.

In addition to nuclear materials and weapon-related technology, expertise is a key ingredient in making nuclear weapons. Although specific details remain secret, basic *principles* of nuclear weapon design have been widely known for decades and cannot be controlled. Moreover, the progress made by successful nuclear proliferants shows that dedicated research programs can fill in the engineering details. First-time proliferants in the 1990s could and probably would build nuclear weapons considerably smaller and lighter than the first U.S. weapons. Nevertheless, "weaponizing" a nuclear warhead for reliable missile delivery or long-term shelf-life adds additional technical difficulties and could significantly increase the research and development efforts needed to field it. Should they offer their services, skilled weapon designers from the acknowledged nuclear powers could significantly accelerate the progress of a proliferant's nuclear program, primarily by steering it away from unworkable designs. They would also be particularly significant in the fields of isotope-separation

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[9] Not only are these export controls not mandated by the Nuclear Non-Proliferation Treaty, but many countries, particularly developing states, argue that they violate the NPT obligation upon industrialized states to participate in "the fullest possible exchange of equipment, materials and scientific and technological information for the peaceful uses of nuclear energy' (NPT, Article IV, Section 2).

techniques or plutonium production. Such individuals could fill critical gaps in a proliferant's knowledge or experience, adding greatly to the likelihood that its programs would succeed. They could also increase the range of sophistication of designs feasible without testing. Therefore, continuing to protect subtle weapon design details and preventing experienced weapon-system scientists and engineers from emigrating or selling their services to proliferant states will be important adjuncts to export-control policy.

| Difficulty and Detectability of Nuclear Proliferation

Producing nuclear weapon materials indigenously would require at least a modest technological infrastructure and hundreds of millions of dollars to carry out. The costs of a full-scale indigenous program, however, especially if clandestine and lacking outside nuclear-weapon expertise, can be as much as 10 to 50 times higher than for a program aimed at producing just one or two bombs and largely carried out in the open or with outside technical assistance. Prior to the Gulf War, Iraq spent many *billions* of dollars-over 20 times the cost of a minimal program-to pursue multiple uranium-enrichment technologies, to build complex and sometimes redundant facilities, to keep its program as secret as possible, and to begin to lay the foundation for a fairly substantial nuclear capability. Few countries of proliferation concern could match the resources that Iraq devoted to its nuclear weapon program. (Iran probably could, however, if it so chose.)

In the near term, low- and medium-level gas centrifuge technology may become increasingly attractive to potential proliferants, for reasons including the availability of information on early-model centrifuge design, the widespread use of and possible illicit access to know-how for more advanced centrifuge technology, and the relative ease both of hiding centrifuge facilities and using them to produce highly enriched uranium (HEU). The more advanced centrifuge technology, once obtained, could lead to small, efficient, and relatively inexpensive facilities that would be particularly difficult to detect remotely.

Because of their small size and potential for high enrichment in few stages, laser isotope enrichment techniques could prove to be difficult to detect and control if successfully developed in a clandestine program.[10] Nevertheless, except in the advanced industrial countries, constructing operational laser-enrichment facilities will remain very difficult. *(Industrial-scale* facilities remain difficult even for the advanced countries.) Therefore, it is unlikely for at least another decade that these technologies would play a significant role in nuclear programs of developing countries.

The published data and recent successes in Japan and France, respectively, with ion-exchange and solvent-extraction enrichment methods relying on conventional chemical-engineering processes, make these techniques potentially a more serious proliferation concern than they had previously been thought.

Aerodynamic enrichment techniques, which use carefully designed nozzles or high-speed gas flows to separate isotopes by mass, have been successfully developed by Germany and South Africa. Some aerodynamic techniques require fairly sophisticated technology to manufacture precision small-scale components, but are otherwise conceptually straightforward and are capable of producing HEU.[11] If strict controls are not maintained on these technologies, they could pose proliferation risks.

Gaseous diffusion technology, developed by each of the five declared nuclear powers, forms

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[10] Laser enrichment technologies use precisely tuned laser beams to selectively energize the uranium-235 isotope most useful for nuclear weapons and separate it from the more common uranium-238 isotope (see app. 4-B on enrichment technologies).

[11] A principal difficulty in constructing aerodynamic enrichment facilities, however, is obtaining pumps, seals, and compressors that are resistant to uranium hexafluoride.

the basis for much of the world's current enrichment capacity, but it has proven difficult for other countries to develop and does not appear to be as likely to be pursued by proliferant states as some other methods.

The process of acquiring or constructing the appropriate facilities and then producing nuclear weapon materials in them provides many signatures and the greatest opportunity for detecting a clandestine nuclear weapon program. The development and testing of nuclear weapon *components* provide significantly fewer observable indicators. Assembly and deployment of a small number of weapons themselves might similarly not be easily detected, although specialized preparations for aircraft or missile delivery might be more readily seen. Deploying large numbers of nuclear weapons, however, might call for new military doctrine and elaborate training, security, and support systems, thus increasing the number of people involved and the possibility that information about the program might be leaked. Sufficiently large nuclear tests (possibly at the kiloton level; certainly at the 10 kt level) would probably be detectable by various means, but they are not necessary for fielding first-generation fission weapons with reasonably assured yields.

Iraq and South Africa demonstrated that with enough effort and financial resources, a country can hide from international view both the size and specifics of its nuclear weapon program-though certainly not all evidence of its existence, Iraq, for example, though party to the NPT, clandestinely pursued an ambitious program outside of safeguards, while maintaining a massive internal organization and extensive and carefully developed channels of foreign technical assistance (many of which have now consequently been subject to more stringent controls). Therefore, although technology restrictions can retard proliferation, and verification procedures and monitoring technologies can help detect and thus deter proliferation, the primary barriers to proliferation of nuclear weapons in the long term remain institutional rather than technological. A state's perception of its own security and national interests, and whether it believes a nuclear weapon program would serve those interests or detract from them, play major roles in the decision process.

ACQUIRING NUCLEAR WEAPON CAPABILITY

For most of the nuclear age, purchasing or stealing nuclear weapons has been relatively easy to dismiss, since the nuclear powers controlled their weapons very tightly. However, the collapse of the Soviet Union for the first time has posed real concerns over the security of nuclear weapons themselves, as well as over weapon materials, components, design information, related technology, and expertise.[12] The following section addresses the potential diversion of Soviet nuclear weapons; it is followed by a discussion of the more traditional problem of preventing states from manufacturing their own nuclear weapons.

"Loose Nukes" in the Former Soviet Union

Various unconfirmed reports in the first months of 1992 in the European press and elsewhere claimed that Iran had purchased several tactical nuclear warheads or their components from one or more newly independent Islamic republics of the former Soviet Union.[13]

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[12] See, for example, Oleg Bukharin, *The Threat of Nuclear Terrorism and the Physical Security of Nuclear Installations and Materials in the Former Soviet Union,* Occasional Paper No. 2 (Monterey, CA: Center for Russian and Eurasian Studies, Monterey Institute of International Studies, August 1992).

[13] See, for example, Yossef Bodansky, "Iran Acquires Nuclear Weapons and Moves to Provide Cover to Syria," *Defense and Foreign Affairs Strategic Policy,* February *1992,* Special Section, pp. 1-4; and FBIS, WEU-92-054-A, Mar. 19, 1992 (about a report in the Mar. 15, 1992 issue of the German magazine *Stern).*

Since nuclear artillery shells, short-range rockets, aerial bombs, and other tactical weapons intended for battlefield use are readily portable, such reports are cause for concern. Nevertheless, senior Russian intelligence officials have claimed that they know where every one of their weapons is and that none is missing.[14] Furthermore, U.S. officials have said, without asserting that they know the whereabouts of every Soviet nuclear weapon, that they are not aware of any independent evidence corroborating such transfers.[15] Past attempts to purchase nuclear warheads, such as by Libya from China, have been reported, but never known to be successful.[16]

By mid-1992, according to Russian officials and later supported by CIA director R. James Woolsey in congressional. testimony,[17] all tactical nuclear weapons had been returned to Russia from non-Russian republics. However, since the political situation in Russia is far from settled, removing nuclear weapons from the other republics to Russia does not resolve questions concerning the weapons' security. Moreover, strategic weapons—the higher yield, bulkier weapons designed for intercontinental missile or bomber delivery-are still based in three non-Russian republics (Ukraine, Belarus, and Kazakhstan), raising questions over the: ultimate status of these republics as nuclear or non-nuclear powers.

Even if whole nuclear weapons were transferred to a non-weapon state, it is unlikely in most circumstances that they could be detonated in their present form. All strategic and many tactical weapons in the former Soviet Union are believed to be configured with "permissive action links" (PALs) or equivalent controls that preclude their direct detonation except upon introduction of a special code.[18] However, the level of sophistication of Soviet PALs is not known, and many—especially early models-may be comparatively rudimentary, not integral to the weapon, or entirely absent.[19] Such devices cannot be presumed to delay indefinitely a technically sophisticated individual or team that had prolonged access to the weapon.

Moreover, a smuggled weapon would constitute a serious danger even if it could not be detonated. First, disassembly by suitably trained individuals could provide valuable first-hand information on its design, materials, and components. Second, the weapon's nuclear materials might be recovered for use in another weapon. As such, transfer of any warhead to any nonweapon-state would be cause for serious concern, even if its immediate utility as a detonable device were low.

| Manufacturing Nuclear Weapons

Aspiring proliferants unable to purchase or steal nuclear weapons, or unwilling to rely on so limited an arsenal, would have to manufacture them on their own. The following sections

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[14] Paul Quinn-Judge, "In Republics, An Eye on Bombs, Scientists," *Boston Globe,* June 23, 1992, p. A14; and Mary Curtius, "U.S. Seeks to Stop Stockpile Leaks," *Boston Globe,* June *24, 1992,* p. *22.*

[15] See, for example, R. James Woolsey, Director of Central Intelligence, testimony before the Senate Committee on Governmental Affairs, Feb. 24, 1993.

[16] Leonard S. Spector with Jacqueline R. Smith, *Nuclear Ambitions: The Spread of Nuclear Weapons, 1989-1990* (Boulder, CO: Westview Press, 1990), pp. 175, 178, and references therein.

[17] Testimony of R. James Woolsey, Feb. 24, 1993, op. cit., footnote 15.

[18] Kurt M. Campbell et al., *Soviet* Nuclear Fission: *Control of the Nuclear Arsenal in a Disintegrating Soviet Union,* CSIA Studies in International Security, No. 1 (Cambridge, MA: Center for Science and International Affairs, Harvard University, November 1991), pp. 13-17. Although the first PALs used on U.S. weapons were simple mechanical combination locks, subsequent designs have become more sophisticated; many now include disabling devices that, upon attempts at unauthorized intrusion, can destroy critical warhead components, rendering the warhead undetonable. Warheads also traditionally include environmental sensing devices, which, although more easily bypassed than intrusion sensors in PALS, enable the warhead to detonate only after it undergoes the proper stockpile-to-target or launch sequence (e.g., changing barometric pressure, acceleration, etc.).

[19] Ibid., p. 15.

describe and analyze the various steps required to produce nuclear weapons, identfying the points at which international nonproliferation efforts might have the greatest leverage.

This chapter focuses on *covert* nuclear weapon programs. Since 1964, when China detonated its first nuclear device, no country has openly advertised developing a nuclear weapon capability, even though several states are suspected of having mounted nuclear weapon programs since then.[20] India, a non-NPT state, detonated a so-called ‘‘peaceful nuclear device’ in 1974, but denies having a nuclear weapon program. Evidently, international norms against nuclear proliferation (or the reactions of regional adversaries) have been sufficient to prevent emerging nuclear powers-even those not members of the NPT—from advertising their programs too openly.[21]

A successful proliferant must overcome a number of technical hurdles. Among them are: obtaining enough fissile material to form a super-critical mass for each of its nuclear weapons (thus permitting a chain reaction); arriving at a weapon design that will bring that mass together in a tiny fraction of a second, before the heat from early fissions blows the material apart; and designing a working device small and light enough to be carried by a given delivery vehicle. These hurdles represent *threshold requirements: unless* each one is adequately met, one ends up not with a less powerful weapon, but with a device that cannot produce any significant nuclear yield at all or cannot be delivered to a given target. Table 4-1 and figure 4-1 outline the steps required to produce and deploy nuclear weapons. Both the figure and the table show the two basic approaches for acquiring nuclear materials: enriching uranium to highly enriched levels, or irradiating uranium in a nuclear reactor followed by reprocessing to separate out the plutonium.[22] They also portray the weapon design, fabrication, and deployment stages.

SOURCES OF NUCLEAR MATERIALS

A potential proliferant has three options for acquiring fissile material needed for a nuclear weapon: purchase or theft, diversion from civilian nuclear activities in violation of IAEA safeguards, or indigenous production in unsafeguarded facilities. Each of these routes is prohibited to NPT non-nuclear-weapon states and to states that are parties to nuclear-free-zone treaties such as the Treaty of Tlatelolco; such states are prohibited from operating unsafeguarded nuclear facilities. Any unsafeguarded facilities that such states did operate would presumably be run covertly. Non-NPT states such as Israel, India, and Pakistan are under no treaty obligations to refrain from acquiring, producing, or selling fissile materials or to place all their nuclear production facilities under IAEA safeguards (some come under safeguards when processing safeguarded material supplied by NPT states), but they might well seek to keep unsafeguarded activities secret anyway.

Indigenous production of weapon-grade nuclear material requires a large, complex, and expensive set of specialized facilities, and the

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[20] Evidence Of a country's decision to ‘‘go nuclear’’ need not be dramatic, as it was with the inspections in Iraq following the 1991 Gulf War, with Mordecai Vanunu's revelations about Israel's nuclear program, or with India's “peaceful” detonation in 1974. Instead, evidence of a country's potential intent and capability can unfold slowly over tie. The latter has been the case with North Korea and@ and before they opened up their facilities to safeguards, with South Africa, Argentina, and Brazil. South Africa's program was subsequently also revealed in a more dramatic fashion by President F.W. de Klerk, when he announced in March 1993 that South Africa had assembled six nuclear weapons in the 1980s.

[21] Many nonproliferation specialists, however, worry that an open nuclear arms race may erupt between India and Pakistan, both of which are “threshold” states considered either to have nuclear weapons or to have the capability to construct them on short notice.

[22] Thorium can &SO be irradiated in nuclear reactors to produce the fissile isotope uranium-233, which can then be separated for use in nuclear weapons by chemical reprocessing similar to that for plutonium. However, thorium-based fuel cycle technology has not been developed to the point where it would present a likely proliferation route.

Table 4-I-Steps to Produce and Deploy Nuclear Weapons

Acquisition of nuclear weapon materials

- Mining of uranium-bearing ore
- Milling to extract uranium concentrate in the form of "yellowcake" (U_3O_8) or other uranates[a]
- Chemical processing to convert yellowcake into useful compounds (such as UO_2, UF_6, UF_4, UCl_4)

-Uranium-235 based weapons:

- Enrichment of uranium to high levels of uranium-235 (most often carried out using uranium hexafluoride, UF_6, or other uranium compounds)
- Conversion of enriched uranium product to uranium metal

---Plutonium-based weapons:

- Uranium fuel fabrication in the form of metal or oxide (using alloys, ceramics, zircalloy or aluminum cladding, etc.)
- Reactor construction and operation (typically requiring a graphite or heavy-water moderator[b], unless enriched uranium fuel were available)
- Reprocessing of spent fuel to extract plutonium product
- Conversion of plutonium product to plutonium metal

Weapon fabrication (plutonium or uranium weapons)

- Design and fabrication of fissile core
- Design and fabrication of nonnuclear components (chemical explosives, detonator, fuze, neutron initiator, reflector, etc.)
- Weapon assembly

Weapon testing and deployment

- Physics tests (hydrodynamic, hydronuclear, or nuclear—see text)
- Development of delivery system and integration with warhead
- Weapon transport and storage
- Possible development of doctrine and training for use

[a] U_3O_8 can also be purchased on the international market; transfers to or from NPT parties with safeguards agreements in force must be reported to the IAEA, but do not require inspections.

[b] The moderator in a nuclear reactor slows down the neutrons produced in fission reactions so that they can more efficiently induce subsequent fission reactions. Heavy-water and ultra-pure graphite are effective neutron moderators having very low neutron absorption, thus permitting reactors to operate on natural uranium.

SOURCE: Stephen M. Meyer, The *Dynamics of Nuclear Proliferation,* (Chicago, IL: Univ. of Chicago Press, 1984), p. 175; and OTA.

relevant facilities therefore represent principal "chokepoints" for controlling nuclear proliferation. Unless a state succeeded in importing or otherwise acquiring weapon-usable material directly, producing such material in dedicated facilities is likely to cost many times what it would cost to design and fabricate other nuclear weapon components. Moreover, the nonnuclear development work could be funded and carried out well in advance of the supply of suitable nuclear materials (as was the case in Iraq), and it is much harder to monitor and control than nuclear material production.

This section discusses various sources where nuclear materials might be stolen or diverted to weapon use; it is followed by a discussion of requirements for manufacturing such materials indigenously.

Diversion or Theft

Nuclear materials, some of which are relatively easy to convert into forms directly usable in nuclear weapons, are stored at and transported among hundreds of civilian nuclear facilities around the world. These stockpiles and transfers inevitably introduce some risk of theft or diversion, depending on the material and the level of its protection. Theft of weapon-grade nuclear materials would be more serious than that of material requiring substantial additional processing. If a particular stockpile were poorly safeguarded, diversion of material might not be detected before it had already been fabricated into a weapon. Such a clandestine diversion would probably constitute a greater danger than the hijacking of a shipment, which would certainly be noticed and might trigger military or other action to recover the stolen material or prevent its being used.

The low-enriched uranium (LEU) that fuels hundreds of nuclear power reactors worldwide cannot be used directly to make nuclear weapons. If used instead of natural uranium as a feedstock for a proliferant state's own uranium enrichment program, however, it can speed up considerably the production of highly enriched uranium for weapons. Furthermore, civilian nuclear reactors convert part of their uranium fuel into plutonium as they operate.[23] When separated from the unconsumed uranium fuel and the radioactive by-products produced during reactor operation—a step called *reprocessing—the* plutonium so obtained can be reused in nuclear reactors. However, it can also be used to make a weapon. By the year 2000, hundreds of tonnes of plutonium will have accumulated worldwide in civilian spent fuel, and with current plans, over 100 tonnes will have been separated and stored. This potential coupling between civil nuclear power and nuclear weapons is a fundamental reason for the International Atomic Energy Agency's system of nuclear safeguards (see app. 4-C).[24]

Due in part to IAEA safeguards, individual commercial power reactors are neither the most vulnerable nor the most fruitful sites for diverting nuclear materials. Several possible sources of nuclear materials described below pose greater risks of theft or diversion than do commercial nuclear power reactors. Similarly, facilities where nuclear materials are handled in *bulk* (enrichment, fuel-fabrication, and reprocessing plants) pose substantially greater diversion risks than do commercial power reactors, but are consequently inspected much more often. In any case, there are no large bulk-handling facilities under full-time safeguards in countries of current proliferation concern.[25]

REACTOR-GRADE PLUTONIUM AND NUCLEAR WEAPONS

Reactor-grade plutonium recovered from civilian reactors differs from weapon-grade plutonium in the relative proportions of various plutonium isotopes (see box 4-B). Reactor-grade plutonium has a higher rate of spontaneous fission reactions

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[23] Reactors containing significant amounts of uranium-238 produce plutonium at a rate of about 1 gram per day per megawatt-thermal (MW(t)) of reactor power, or about 10 kg per year for a 30-MW(t) reactor running 90% of the time. Note that commercial reactors are usually rated in terms of the *electrical* power they produce, in units of megawatts-electric (MW(e)), whereas research reactors and plutonium-production reactors are rated in terms of overall thermal power, MW(t). Since about two-thirds of the power used to generate electricity y becomes waste heat, a typical large commercial nuclear power plant that generates 1,000 MTV(e) would have a thermal power *of* about 3,000 MW(t).

[24] The 1977 OTA report *Nuclear Proliferation and Safeguards,* OTA-E-48 (Washington DC: U.S. Government Printing Office, June 1977), and appendices, vol. 2, parts 1 and 2, discusses the relationship between nuclear power, nuclear weapons, and international safeguards. The U.S. Department of Energy presented a detailed technical assessment of these relationships in Nuclear *Proliferation and Civilian Nuclear Power, Report of the Nonproliferation Alternative Systems Assessment Program* (NASAP), DOE/NE-0001/1, vols. 1-9, June 1980. Other references discussing nuclear safeguards include "Materials Management in an Internationally Safeguarded Fuels Reprocessing Plant," *Los Alamos Scientific Laboratory Report IA-8042,* vols. I-III (April, 1980); David Fischer and Paul Szasz, *Safeguarding the Atom: A Critical Appraisal* (London: SIPRI, Taylor and Francis, 1985), especially ch. 7 and apps. II and III; Lawrence Scheinman, *The International Atomic Energy Agency and World Nuclear Order* (Washington DC: Resources for the Future, 1987), especially chs. 4 and 5; *IAEA Bulletin,* for example, vol. 32, No. 1 (1990); and *Journal of Nuclear Materials Management,* for example, vol. 20, No. 2 (February 1992).

[25] India operates reprocessing facilities that are under safeguards only when reprocessing safeguarded uranium fuel. This leaves India, a non-NPT state, with the capability to separate plutonium for weapon use with this facility at other times. North Korea's alleged reprocessing facility at Yongbyon has been declared to the IAEA but has not yet been fully placed under safeguards. Brazil has a medium-sized fuel fabrication facility under IAEA safeguards, and South Africa's enrichment facilities have come under safeguards with its accession to the NPT, but neither state is considered a first-order proliferation threat at present.

than weapon-grade, generating neutrons that can initiate the nuclear chain reaction during weapon detonation sooner than would be optimal. As a result, using reactor-grade plutonium in a first-generation nuclear weapon can significantly reduce both the predictability and the expected yield of a weapon designed by a proliferant state.

None of the states that have either made nuclear weapons or attempted to do so appear to have selected anything but high-quality plutonium or uranium for their designs. Nevertheless, from a technical perspective, reactor-grade plutonium can be used to make nuclear weapons (see box 4-B), and any state possessing significant quantities of separated plutonium should be considered to have the material needed to fabricate nuclear components for nuclear explosive devices in a short period of time.

REPROCESSING PLANTS AND SEPARATED PLUTONIUM

Several hundred tonnes of weapon-grade plutonium will likely be recovered from dismantled U.S. and Russian warheads over the next decade and stored at facilities in those two countries.[26] In addition to this plutonium, large quantities of separated plutonium *from civilian* reactors around the world continue to accumulate and be stored at four principal reprocessing sites: La Hague and Marcoule in France, Sellafield in Britain, and Chelyabinsk in Russia.[27]

Reactor-grade plutonium separated from spent fuel can be used either in a new generation of civilian reactors designed especially to use plutonium fuel, or in conventional nuclear reactors, where it can substitute for the uranium-235 in some portion of the LEU fuel.[28] However, unless the utilization of separated plutonium increases dramatically, it is almost certain that the current surplus of over 70 tonnes of stored separated plutonium will increase by another 100 tonnes by the year 2000.[29] Eventually, most of the foreign-owned plutonium at the sites in France and the U.K. is contractually obliged to be returned to its countries of origin-most of whom are not nuclear weapon states[30]—thus significantly increasing the transport and handling of plutonium around the world. By the end of the century, an additional several hundred tonnes of unseparated plutonium worldwide will also have accumulated in spent reactor fuel.[31]

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[26] See U.S. Congress, Office of Technology Assessment, *Dismantling the Bomb and Managing the Nuclear Materials*, OTA-O-572 (Washington DC: U.S. Government Printing Office, September 1993). Safeguarding the storage and ultimate disposition of nuclear materials from dismantled weapons in the former Soviet Union is a high U.S. priority and is the subject of intense ongoing discussions with Russia.

[27] Small commercial reprocessing facilities are also operating at Tokai-mura in Japan and Tarapur in India, and have operated in the past in the United States (West Valley, New York), Germany (Karlsruhe), and Belgium @roch6mic-Mel). India is building an additional facility at Kalpakkam, possibly to begin operation in 1993-94, and Japan is planning to finish constructing a major reprocessing facility at Rokkasho-mura by about 2005. Reprocessing facilities for separating Russian *military* plutonium are located at two additional sites: Tomsk-7 and Krasnoyarsk. See Frans Berkhout et al., "Disposition of Separated Plutonium,'' *Science & Global Security*, vol. 3, No. 1, 1992, table 2, p. 7.

[28] Plutonium for use in conventional nuclear reactors is usually combined with natural or low-enriched uranium in their oxide forms (UO_2 and PuO_2) to make mixed-oxide fuel or MOX. MOX having a plutonium concentration of about 3 to 5% of the uranium concentration can be used to replace about a third of the fuel rods in some types of conventional light-water reactor. Fast breeder reactors (FBRs) fueled primarily by plutonium are currently being developed by Japan, China, and Kazakhstan. France (which has shut down its Superphénix breeder reactor) and the U.K. are no longer as actively involved with breeder development as they had been in the past.

[29] Prior t. 1991, about 120 tomes of civilian RGPu had been separated worldwide at the four facilities mentioned, of which 37 tonnes had been recycled in advanced liquid-metal reactors (mostly in demonstration breeder reactors) and another 12 tonnes as MOX fuel for conventional light water reactors (LWRs). From 1991 through 2000, another 190 tomes are contracted to be separated, primarily at reprocessing plants in Great Britain, France, and Japan, of which only about 70-80 tonnes are expected to be recycled in reactors.

[30] These countries include Belgium, Finland, Germany, Italy, Japan, Netherlands, and Switzerland.

[31] Frans Berkhout, Anatoli Diakov, Harold Feiveson, Marvin Miller, and Frank von Hippel, ' 'Plutonium: True Separation Anxiety,'' *Bulletin of the Atomic Scientists*, vol. 48, No. 9, November 1992, pp. 28-34.

Box 4-B—Reactor-Grade Plutonium

Plutonium produced in a reactor continues to be exposed to neutrons until the fuel is removed from the reactor. This prolonged exposure results **in the buildup of other plutonium isotopes (atomic numbers 238,240,241, 242) in addition to plutonium-239.[1] The even isotopes of plutonium have a** high probability of spontaneous fission and thus neutron emission, plus several other deleterious neutronic effects in weapons. By current U.S. definition, reactor-grade plutonium contains at least 20 percent even (non-fissile) isotopes, whereas weapon-grade contains 6 percent or less.

Because the non-239 plutonium isotopes are more radioactive and emit more spontaneous neutrons, they make the design of a plutonium weapon more difficult (virtually lmpossible at high concentrations of Pu-238). The problems are at least two-fold. From the perspective of bomb performance, **if too much plutonium-240 or -242 is** present its spontaneous neutrons have a high probability of starting the chain reaction too soon, thus substantially reducing the yield. Second, reactor-grade plutonium generates 6 to 10 times more heat per unit mass than does weapon-grade plutonium,[2] and an IAEA significant quantity of RGPu (8 kg) would generate well over 100 watts of heat.[3]

Nevertheless, the critical mass of RGPu is only about 25 percent higher than that of weapon grade, and nuclear explosive devices can be designed that use it.[4] Plutonium with a nonfissile concentration (plutonium 240 plus 242) as high as 50 percent-as might be recovered from very high burn-up LEU fuel or MOX fuel-can also be used to make explosive devices having kiloton yields?

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[1] Although 65 percent of the neutrons captured by plutonium-239 cause it to fission, the remaining 35 percent are absorbed to create plutonium-240. Other higher isotopes are formed similarly. Reactor-grade plutonium normally continues to be exposed in a reactor for up to a few years. Weapon-grade plutonium is produced from uranium-238 that ls exposed for only a relatively short the, possibly on the order of weeks.

[2] Plutonium recovered from spent LEU or MOX fuel after 10 years of storage generates 14 to 24 W/kg-Pu, whereas weapon-grade plutonium generates only 2.4 W/kg-Pu. *Plutonium Fuel: An Assessment* (Paris: OECD/NEA, 1989), tables 9,128, as cited in Frans Berkhout, Anatoli Diakov, Harold Feiveson, Helen Hunt, Edwin Lyman, Marvin Miller, and Frank von Hippel, "Disposition of Separated Plutonium," *S&me& Global Security, vol.* 3, No. 1,1992, p. 10.

[3] If this much RGPu were left surrounded with high explosive of low thermal conductivity, such as in an implosion device, it could generate temperatures above 200 "C, depending on the design.

[4] See J. Carson Mark, Reactor-Grade *Plutonium's Explosive Properties* (Washington, DC: Nuclear Control institute, August 1990).

[5] Alex DeVolpi, "Fissile Materials and Nuclear Weapons Proliferation," *Ann. Rev. Nucl. Part. Sci.*, vol. 36, p. 108 (table 4), In addition, based on declassified information, Maj. Gen. Edward B. Giller, deputy assistant administrator for national security for the U.S. Energy Research and Development Administration, stated in September 1977 that the U.S. detonated a nuclear device in 1962 using low-grade plutonium typical of that produced by civilian power plants (Robert Gillette, "Impure Plutonium Used In '62 A-Test," *&s Angeles Times, Sept.* 16, 1977, p. A3), thus providing experimental confirmation that such material could be used to build an atomic weapon. (Neither the isotopic composition of the plutonium used nor any yield information was released; at the time, reactor-grade plutonium was defined to contain greater than 8 percent of the isotopes Pu-240 and Pu-242.) See atso Paul Leventhal, "Weapons-Usable Nuclear Materials: Eliminate Them?" In *Director's Series on Proliferation*, Kathleen C. Bailey, cd., Lawrence Livermore National Laboratory, UCRL-LR-1 14070-1, June 7,1893, p. 34.

Box 4-C-Japanese Shipments of Separated Plutonium

After two decades of shipping spent fuel to Europe for reprocessing and storage, Japan has now begun a major program to ship back large quantities of separated plutonium from its LWR spent-fuel. Shoe the United States originally supplied this fuel, it has the right under the revised 1987 U.S.-Japan Nuclear Cooperation Agreement to approve or reject the final security plans for the shipments. Current plans call for up to30 or40 tonnes of separated plutonium to be returned to Japan by the year 2000, using four or five shipments per year.

Since the early 1980s, shipments of plutonium by sea have required extraordinary security arrangements. Even so, a 1988 Pentagon study stated that "...even if the most careful precautions are observed, no one could guarantee the safety of the cargo from a security incident, such as an attack on the vessel by small, fast craft, especially if armed with modern antiship missiles."[1] However, unless the attackers were able to board the ship and carry away the plutonium before it sank or before additional security forces arrived or could pursue them, this may not be a very credible diversion scenario. Similarly, scenarios to commandeer the ship and evade the inevitable pursuit do not seem very credible. Therefore, at least from a security standpoint, fears over Japanese shipments of plutonium may be exaggerated. Nevertheless, if such shipments become commonplace, the potential risk of such an attack may increase.[2]

[1] "Transportation Alternatives for the Secure Transfer of Plutonium from Europe to Japan," *Sea Transportation Alternatives,* U.S. Dept. of Defense, Mar. 7,1988.

[2] See, for example, David E. Sanger, "Japan's Plan to Import Plutonium Arouses Fear that Fuel Could Be Hijacked," *New York Times,* Nov. 25, 1991, p. D8.

Except for the few countries with unsafeguarded reprocessing facilities (Israel, India, and possibly North Korea[32]), obtaining plutonium for weapon purposes would require its diversion at the foreign reprocessing facility and subsequent illegal transfer to the target country, or diversion from safeguards within the country to which it had been returned (see box 4-C). Such steps would be legally risky and perhaps very costly to attempt in secret, but they remain a possibility.

MATERIAL LEAKAGE FROM FORMER SOVIET REPUBLICS

If security and control of the former Soviet nuclear weapon establishment breaks down, the diversion of nuclear materials maybe more likely than the smuggling of intact weapons. Weapon material can be shipped in much smaller and lighter quantities than can complete weapons, and in forms that (unlike weapons) are not discrete, countable units. Significant amounts of nuclear material could conceivably escape without detection by accounting procedures-specially at bulk-handling facilities. Indeed, numerous allegations that former Soviet weapon materials have been offered on the black market have already appeared in the press.[33] So far, the U.S. Central Intelligence Agency reports that it has not been able to verify *any* transfer of weapon-grade materials in significant quantities, and its director has testified that 'most reports of transfers appear to be scams, hoaxes, or exaggerations. ' However, it is impossible to be certain that *all are.*[34]

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[32] North Korea has suspended its announced intention to withdraw from the Nuclear Non-Proliferation Treaty and is therefore still bound by its safeguards agreement with the IAEA, but has not yet resolved its dispute with the IAEA concerning the conditions of this agreement. The IAEA has therefore been unable to confirm North Korea's adherence to safeguards.

[33] See, for example, Marc Fisher, ''Germany Reports a Surge in Nuclear Smuggling Cases,' *Washington Post,* Oct. 10, 1992, p. A27.

[34] Testimony of R. James Woolsey, Feb. 24, 1993, op. cit., footnote 15.

The reports of nuclear smuggling out of the former Soviet Union, even though most are probably hoaxes, illustrate an important new aspect of the proliferation problem. First, they add substantial amounts of ‘‘noise’ to the system, making it more difficult to distinguish real proliferation threats from false ones. Second, by their very existence, they demonstrate the willing complicity of supply-side middlemen with covert channels in the former Soviet Union, The potential for nuclear smuggling has thus become an important issue.

In addition to the threat of diversion of ex-Soviet weapon material from stockpiles that are nominally under Russian military control, other material might be available from civil nuclear facilities within Russia, or from active or mothballed facilities in other republics.[35] As an NPT nuclear-weapon state, Russia is not subject to mandatory safeguards at any of its nuclear facilities, and several of the former Soviet republics have not yet joined the NPT[36]

The issues presented by Russian plutonium from dismantled weapons are quite different from those surrounding Russian weapon HEU. The United States is negotiating the purchase of 500 tonnes of Russian HEU over the next 20 years for use in commercial power reactors. (The HEU would be blended down to LEU in Russia before the material was transferred.) No comparable purchases are envisioned for weapon-grade plutonium, making it possible that Russia would choose to recycle its excess plutonium as MOX in its own power reactors or to keep as many as 10,000 to 20,000 plutonium pits (the nuclear weapon cores that contain the fissile material) in long-term retrievable storage.[37] Both the plutonium and the HEU could conceivably end up in the wrong hands unless adequate measures are taken to regulate their transport, storage, and ultimate disposition. Procedures are required to minimize and safeguard stockpiles of both plutonium and HEU, to use them in commercial fuel or, in the case of plutonium, to dispose of it in safe and acceptable ways, all while taking into account strong economic pressures and potential political instability.

HEU FROM RESEARCH REACTORS

Over 100 of the approximately 325 total worldwide research and test reactors are fueled with highly enriched uranium (HEU enriched to more than 20 percent uranium-235), for which the total HEU inventory is about 4,000 kg. Most of this HEU inventory is in the form of 90 to 93 percent uranium-235. Thirty-six HEU-fueled research and test reactors are in the United States, some 2 dozen are in Russia and other former Soviet republics, and the remainder are located in about 34 additional countries. Approximately 40 of these foreign reactors (not including those in the former Soviet Union) are rated at over 1 MW(t), and many contain several kilograms of HEU fuel.[38]

The United States is one of the principal suppliers of research-reactor fuel, exporting 100 to 150 kg HEU annually. To reduce the proliferation risks posed by HEU reactors, the United States has developed and tested several types of compatible high-density LEU fuels that can be substituted for HEU fuels in research reactors. All but 3 of the ca. 40 foreign HEU-fueled research reactors larger than 1 MW(t) could be converted to LEU fuels developed so far, but only about 10

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[35] William C. Potter, Eve E. Cohen, and Edward V. Kayukov, *Nuclear Profiles of the Soviet Successor States, Monograph No. 1* (Monterey, CA: Program for Nonproliferation Studies, Monterey Institute of International Studies, May 1993); and Oleg Bukharin, *The Threat of Nuclear Terrorism*. . . . op. cit., footnote 12, pp. 4-5.

[36] As of November 1993, only Armenia, Azerbaijan, Belarus, Estonia, Latvia, Lithuania, Russia, and Uzbekistan had joined the NPT.

[37] See U.S. Congress, Office of Technology Assessment, *Dismantling the Bomb and Managing the Nuclear* Materials, op. Cit., footnote 26,

[38] Milton M. Hoenig, ‘ ‘Eliminating Bomb-Grade Uranium Fuel from Research Reactors,” *Nuclear Control Institute,* January 1991, p. 3; and Oleg Bukharin, *The Threat of Nuclear Terrorism*. . ., op. cit., footnote 12, p. 5.

VADIM MOUCHKIN, IAEA

(a) During a U.N. inspection in October 1991, IAEA inspectors examine the bomb damage to the IRT-5000 research reactor at Al-Tuwaitha.

VADIM MOUCHKIN, IAEA

(b) The Tammuz-2 reactor was also damaged by coalition bombing during Operation Desert Storm. Both reactors had been fueled by highly enriched uranium.

have plans to do so. Only a handful of other research reactors have been converted so far. (Reactors operating at less than 1 MW(t) generally have lifetime cores, providing little incentive to convert.)[39]

Although all the HEU used in non-nuclear-weapon-state reactors is obtained from suppliers that require it to be placed under IAEA safeguards, a nation or terrorist group would have little difficulty in recovering HEU metal from fresh fuel if it were seized from storage at the reactor site or in transit.[40] Even if the fuel were lightly irradiated, e.g., for a few hours per week at less than 100 kW (e.g., in a typical university research reactor), the small quantities of radioactive fission products it would contain would not prevent recovery of the uranium, especially after waiting a few days or weeks for the fuel's activity to decay to lower levels.[41]

Most research-reactor fuel, however, has been irradiated for longer than this, making it much more radioactive and difficult to handle. Theft of such fuel (though likely to be regarded as a very serious incident), would also be an unlikely means of acquiring a nuclear *arsenal, since* quantities are limited in any one location and, in most reactors, are significantly less than what is needed for a weapon. Although crossing the nuclear threshold by obtaining material for even one bomb poses a significant danger, it is not as serious a threat as assembling a production line for making nuclear weapons in quantity. For these reasons, the proliferation concerns involving diversion or theft of HEU research-reactor fuel are legitimate, but limited in scale.[42]

Indigenous Production of Materials

The **alternative to stealing,** diverting, or purchasing weapon-grade nuclear materials is manu-

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[39] Hoenig, ' 'Eliminating Bomb-Grade Uranium Fuel. . .," ibid., p. 3; see also Armando Travelli, "The RERTR Program: A Status Report," Argonne National Laboratory, Oct. 2, 1992,

[40] For instance, even before Iraq was discovered to have a massive nuclear weapon program, there was concern that it might have diverted for nuclear weapon use the 12,3 kg of 93% HEU originally supplied by France for its 40 MW(t) Osirak reactor or the 13.6 kg of Soviet-supplied 80% enriched fuel. (See footnote 5 in box 4-D.)

[41] Hoenig, ' 'Eliminating Bomb Oracle Uranium Fuel. . .,'' op. cit., footnote 38, p. 3.

[42] Research reactors can also be used to produce plutonium, however, which is also a concern. See below.

facturing them indigenously. Many different approaches to producing nuclear materials are available, depending on what nuclear materials a proliferant starts with, what access it has to dual-use or nuclear-specific technologies, and what cost it is willing to bear to acquire proscribed technologies on the black market. Various approaches also place specific demands on a proliferant's technology base, infrastructure, and expertise, and pose different operational difficulties and risks of detection once acquired.

International nonproliferation policies have made it quite difficult to use turn-key imported facilities to produce weapon-grade materials. The Nuclear Non-Proliferation Treaty prohibits NPT parties from exporting major nuclear facilities—especially those for uranium enrichment or reprocessing-unless they are placed under IAEA safeguards. (Those goods requiring the imposition of safeguards have been placed on a multilaterally agreed ''trigger list.") In April 1992, all 27 members of the Nuclear Suppliers Group (NSG) further agreed to require full-scope safeguards-the imposition of IAEA safeguards not only on the transferred facility but also on all other nuclear facilities in the recipient country—as condition of any significant new nuclear exports to nonweapon states. NSG countries also adopted stringent licensing and export policies for a new list of 65 categories of *dual-use* items (see app. 4-D). However, several nations experienced in nuclear technology-including Argentina, Brazil, China, India, and Ukraine-are not members of the NSG, though at least Argentina has stated that it would abide by the original 1977 NSG export guidelines.

Material production could involve obtaining LEU and enriching it further to produce HEU, or it could require creating the entire nuclear fuel cycle indigenously, starting with uranium ore and ending up with plutonium (see table 4-l).

ACQUISITION OF NATURAL URANIUM

Production of either weapon-grade uranium or plutonium starts with uranium ore, followed by a number of processing stages that are described below. As the materials approach weapon grade, their processing facilities become more specialized, and international controls on their use and shipment become more stringent.

Uranium ore, which is commonly mined along with other mineral-bearing ores and contains only about 1 part in 500 of uranium, is not subject to safeguards. Similarly, milling facilities that extract the uranium concentrate known as "yellowcake" (U_30_8) from ore are not safeguarded. (The *amounts* of yellowcake exported or imported by NPT states having formal safeguards agreements in force must be reported to the IAEA, but such transfers are not verified by inspections. In the past, various countries have reportedly attempted to acquire yellowcake clandestinely.[43]) Mining and milling processes suitable for extracting uranium concentrate are standard in the mining industry. Many countries that are or had been of proliferation concern have large indigenous deposits of uranium-bearing ore and already operate mines and milling facilities.[44]

Yellowcake effectively becomes subject to safeguards inspections only after it is introduced into a declared conversion plant that produces a form of uranium suitable for further enrichment (e.g., uranium hexafluoride) or for fuel fabrication

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[43] For example, Israel is widely believed to have orchestrated the disappearance in November 1968 of 200 tom of yellowcake that was being shipped from Antwerp to Genoa (Spector, *Nuclear Ambitions*, op. cit., footnote 16, p. 155). Between 1978 and 1980, Pakistan is believed to have acquired from Libya quantities of up to 100 tons of yellowcake that Libya had originally purchased from Niger. (John J. Fialka, "West concerned by Signs of Libyan-Pakistan A-Effort, " *Washington Star, Nov. 25, 1979;* and Spector, *Nuclear Ambitions*, op. cit., footnote 16, p. 176.) Although Libya had been a member of the NPT since 1975, it was not required to report its imports or exports of yellowcake until it concluded a formal safeguards agreement with the IAEA in 1980.

[44] See *Uranium Resources, Production, and Demand*, a Joint Report of the OECD Nuclear Energy Agency and the IAEA (Paris: OECD, 1986), and other references cited in Spector, *Nuclear Ambitions*, op. cit., footnote 16.

(e.g., oxide, metal, alloy, or carbide). Such further processing typically uses specialized facilities that would trigger the application of IAEA safeguards if imported; to evade safeguards at this stage, a proliferant would have to construct a clandestine conversion facility with uncontrolled goods. Doing so would add expense and effort but would probably not introduce particular roadblocks.[45]

PLUTONIUM PRODUCTION AND REPROCESSING FACILITIES

A key step in pursuing the plutonium route is obtaining a source of irradiated uranium, either by diverting spent fuel from a safeguarded reactor or by irradiating uranium in a dedicated plutonium-production reactor. The reactors most commonly used commercially, called "light-water reactors, ' are difficult to divert fuel from clandestinely, since their fuel rods are readily accounted for (if safeguarded), and since shutting such reactors down for refueling creates an observable event (even when unsafeguarded). Moreover, they require enriched uranium to operate, which is much more difficult to obtain outside of safeguards than is natural uranium.

Rather than divert fuel from a safeguarded reactor, a proliferant might build a dedicated plutonium-production reactor fueled by natural uranium. The section below discuses costs for two possibilities: a small (30 MW thermal output) reactor based on a widely available design that could produce sufficient plutonium for 1 or 2 weapons per year, and a larger (400 MW thermal) reactor that could produce some 10 to 20 weapons-worth of plutonium annually. Such production reactors would be based on reactor technologies better suited to plutonium production than is the light-water design, but these alternate technologies typically require specialized materials such as heavy water or ultra-pure graphite which, if imported, would trigger the imposition of safeguards.[46] AS is also discussed below, the construction and operation of a nuclear reactor produces a number of indicators or signatures that might reveal its existence (see section on monitoring).

The combination of a nuclear reactor and reprocessing plant offers a potentially less technologically advanced route to weapon-usable *material than* many methods of uranium enrichment. Israel and India, for instance, operate unsafeguarded reactors and reprocessing facilities that, in part, were built indigenously, and North Korea has built and operated similar facilities that were initially outside of safeguards.[47]

Extracting plutonium from spent fuel utilizes chemical processes that, in theory, have been within the grasp of most middle industrial powers for some time (see table 4-2). The principal difficulties in building a reprocessing plant stem from the intense radioactivity of the spent fuel to be reprocessed. Remote-handling equipment, radiation shielding, and other specialized equipment must be built and maintained to protect plant workers. Although most of the chemicals used in a reprocessing plant are available commercially, much of the needed equipment is export-controlled, and many countries would be unable to build such facilities without foreign technical assistance. Large facilities have notoriously taken a very long time to construct, and for technical as

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[45] Fuel fabrication and cladding, for example, might be done in a common metalworking shop.

[46] Molecules of heavy water have their two hydrogen atoms replaced by deuterium atoms, an isotope of hydrogen having an extra neutron in the nucleus. Although present in small quantities in naturally occurring water, heavy water is a controlled nuclear-related material once concentrated. Heavy-water and ultra-pure graphite are effective neutron moderators having very low neutron absorption thus permitting reactors to operate on natural uranium; both materials are on the IAEA "trigger list' of nuclear goods that cannot be exported by an NPT-member state without the imposition of safeguards. However, it may be possible to manufacture such graphite indigenously or to obtain nonreactor-grade graphite commercially that could be used in reactors (possibly after additional purification) without triggering safeguards.

[47] Spector, *Nuclear Ambitions,* op. cit., footnote 16, pp. 86, 139, 172 In the 1960s, however, India benefited from shared U.S. technology and Israel obtained significant technical assistance from France.

Table 4-2—Reprocessing Programs and Capability Outside the Declared Nuclear Weapon States

Country	Reprocessing facility	Dates of operation	Capacity (actual or projected) [t HM/yr][a]	Safeguards?
Japan	Tokai-mura	1981 -present		yes
	Rokkasho-mura	2005?	[800]	yes
Germany	Karlsruhe	1971-1990	35	yes
Belgium	Eurochemic-Mol	1966-1974	30	yes
Israel	Dimona	1966? -	[50-100]?	no
India	Trombay	1966-1974; [1983-present]?	30	no
	Tarapur	1982-present	100	partly
	Kalpakkam	1 993/94	[200]?	no
Pakistan	Chashma	construction ended 1978?	[100]	NA
	Rawalpindi	not operating?	[5]?	no
North Korea	Yongbyon	[1992]?	pilot-scale?	[yes][b]
Iraq	Tuwaitha	1989-1991 (destroyed)	lab-scale	(violation)
South Africa	Pelindaba	[1987-?]	pilot-scale?	yes[c]
Argentina	Ezeiza	suspended 1990	[5]	partly
Brazil	Resende	suspended 1980s	[3]	yes
South Korea	NA	abandoned 70s	NA	
Taiwan	NA	abandoned 70s	NA	

[a] Tonnes heavy metal per year. Items in [brackets] or with question marks represent estimates or substantial uncertainty, respectively.

[b] Although North Korea became a member of the NPT in 1985, its safeguards agreement with the IAEA was not signed until 1992, and the implementation of this agreement was still under negotiation as of November 1993.

[c] Prior to South Africa's joining the NPT in 1991, this facility was only under safeguards when safeguarded fuel was present. Since then, it has come under full-scope safeguards.

SOURCE: Adapted from David Albright, Frans Berkhout, and William Walker, *World Inventory of Plutonium and Highly Enriched Uranium, 1992* (Oxford: Oxford University Press/SIPRI, 1993), p. 90; and Leonard S. Spector and Jacqueline R. Smith, *Nuclear Ambitions: The Spread of Nuclear Weapons, 1989-1990* (Boulder, CO: Westview Press, 1990).

well as economic and political reasons, even the smaller ones are sometimes abandoned before completion.[48] Furthermore, the IAEA and U.N. involvement and the ongoing negotiations with North Korea aimed at resolving the dispute over its nuclear facilities have demonstrated the kind of pressure that can be brought to bear on countries harboring suspect facilities when their existence is known.

France, the U. K., and Japan, which each operate commercial reprocessing facilities, are not current nuclear proliferation concerns.[49] France and the U.K. are already nuclear weapon states, and Japan, as a non-nuclear-weapon NPT

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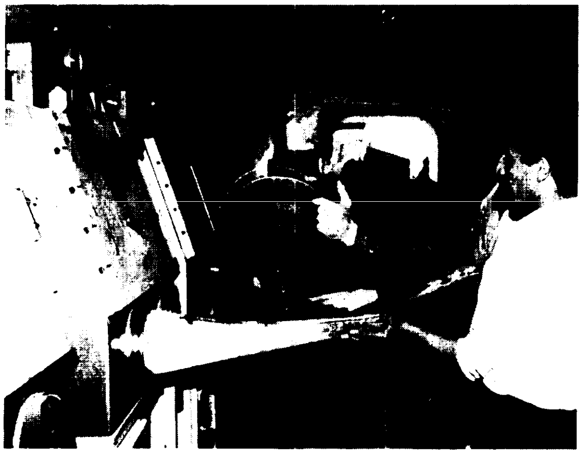
[48] For example, construction on a large reprocessing facility was begun in Pakistan in the late 1970s with French assistance, but may have been abandoned sometime following France's termination of its involvement in 1978. In 1990, Argentina also indefinitely suspended its work on building a small reprocessing plant at Ezeiza. See Spector, *Nuclear Ambitions*, op. cit., footnote 16, pp. 115, 239.

[49] India, on the other hand, operates a medium-size reprocessing facility at Tarapur that is not under full-time safeguards, thus allowing it the option of producing weapon materials free of international legal constraints if it so chose. Russia continues to operate three reprocessing plants, but in the past has not segregated civilian from military operation. States that once reprocessed civilian spent fuel but have discontinued doing so include Germany, Belgium, and the United States.



Under IAEA supervision in October 1991, Iraqi workers pour concrete into glove boxes at Al Tuwaitha to prevent their future use. Glove boxes are used to *protect workers from radioactive materials such as plutonium,*

member, has all its facilities under full-scope IAEA safeguards. Even so, material-accountancy at large spent-fuel reprocessing plants involves inherent uncertainties that are not necessarily less than an IAEA-defined significant quantity of nuclear material.

In addition, plutonium fuel-fabrication facilities are also now operating in France, the U.K., Japan, Belgium, and Germany, and another one may soon be constructed in Chelyabinsk, Russia. Plutonium and uranium recycling policies in these countries, however, are still undergoing revision and may not be finalized for some years (see table 4-3).

URANIUM ENRICHMENT TECHNOLOGIES

Table 4-4 compares various enrichment technologies according to several factors that a proliferant country would have to consider before choosing to pursue a particular enrichment method. (See app. 4-B for descriptions of these enrichment technologies.) In addition to various characteristics of each method, a proliferant's choice will depend strongly upon its own technical infrastructure, expertise, and access to foreign technical assistance. For instance, Argentina's experience in metallurgy was likely an important factor in its decision to pursue gaseous diffusion, and Pakistan's theft of Dutch centrifuge designs was undoubtable influential in its decision to pursue that approach.

Table 4-5 concentrates on technical attributes of each process, comparing various enrichment techniques in terms of efficiency and separation factor per stage (and thus the number of stages required to enrich uranium to, say, 90 percent U-235). Each *stage* of an enrichment plant takes an input source of uranium, or ‘‘ feed,’ and produces two outputs: one with a greater concentration of uranium-235 than the feed (the “product”), and the other depleted in uranium-235 (the “tails”). The *separation factor* indicates how much enrichment each stage provides. (It is defined as the ratio of the relative isotopic abundance of uranium-235 in the product to that in the tails.) Some approaches, such as electromagnetic separation, achieve very high degrees of separation per stage, and very few stages are needed to obtain highly enriched uranium. Others, however, only marginally enrich the product in each stage, and up to thousands of stages are needed to obtain HEU.

For enrichment approaches in which each stage provides only marginal enrichment and thus many successive stages are required, the stages are connected into *cascades.* Each stage (usually consisting of many individual elements working in parallel) feeds its product to the stage operating at the next higher level of enrichment and its tails to the next lower.

Table 4-5 also gives estimates for the amount of electricity per unit enrichment capacity required for each approach, with enrichment capac-

Table 4-3-Plutonium and Uranium Recycle Policies in Europe and Japan

Country	Plutonium recycle	Reprocessed uranium recycle	LWR-MOX program
Belgium	Yes?	?	MOX fabricator. Plans to load two reactors with MOX, beginning mid- 1990s.
France	Yes	Yes[a]	MOX fabricator. First phase (eight reactors) to be loaded with MOX by 1993.16 reactors to be loaded by late 1990s,
Germany	Yes	Tested with MOX	MOX fabricator. Leader in MOX experience. 18 reactors to be loaded with MOX.[b]
Italy	No’	No	No operating reactors.
Japan	Yes	?	MOX fabricator. Demonstration program (two reactors) planned for 1994-1997. Commercial program due to start in 1995, rising to 12 LWRs loaded with MOX by 2003.
Netherlands	Yes[d]	No	MOX R&D at Dodewaard was suspended as of 1992.
Russia	Expected	Yes	Uranium separated from VVER-reactor fuel is recycled in graphite-moderated (RBMK) reactors.
Spain	No	No	No.
Switzerland	Yes	?	Has loaded two reactors with MOX.
United Kingdom	No	Yes	Plans to become a MOX fabricator,

[a] Official French policy is to recycle uranium recovered from rep recessed spent fuel, either by re-enriching It or by using it as the matrix for LWR-MOX fuel fabrication. However, the low price of natural uranium has meant that the Electricité de France has shown little practical interest in uranium recycle.

[b] As of 1992, only 10 reactors had been awarded licenses to load MOX fuel, and MOX had been loaded at 7 of them.

[c] A small MOX test program ran at Garigliano in the 1970s. Most Italian separated plutonium has been used to fuel France’s fast breeder reactor, Superphénix.

[d] A small MOX test program ran at Dodewaard in the 197& and 1980s. Dutch separated plutonium has been used in the Superphenix and Kalkar fast reactor cares.

SOURCE: Frans Berkhout et al., “Disposition of Separated Plutonium,” *Science & Global* Security, vol. 3, No. 1, 1992, p. 14.

ity measured in terms of ‘separative work units, or SWUs.[50]

Most of the sensitive technologies and components used for uranium enrichment fall under strict export controls, both in the United States and abroad, and are therefore very difficult to obtain on the open market. Nevertheless, some have escaped these controls, mainly due to lax enforcement and variability of regulations among supplier countries. For example, security leaks in the URENCO consortium-a uranium enrichment enterprise established by the British, Ger-

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[50] SWUs measure the decrease in entropy, or conversely the increase in order, resulting when a given isotopic mixture is split into two mixtures of greater and lesser concentrations. (Combining two pure substances--say pure uranium-235 and pure uranium-238-results in a mixture that is more disordered than its original constituents. Reversing that process by separating an isotopic mixture into its constituent parts therefore increases its order.)

Although the exact formula relating the number of SWUS to the concentration of uranium-235 in the feed, product, and tails is complicated, a rough approximation for the SWUs needed to produce a given amount of 3% or higher enriched product from natural uranium (with typical tail depletions of about 0.3%) is about 120-200 times the number of kilograms uranium-235 contained in that product. The low end of this range applies to final enrichments from 3 to 5%, the high end for those from 20 to 97% (see Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation* (London: Taylor & Francis, Ltd., 1983), pp. 96-98, esp. formulas 5.2 and 5.6). For example, producing 1 kg of 3%, 20%, *or* 90% enriched product from natural uranium (with 0.3% tails) would require 3.4, 38, and 193 SWUS (and 7.5, 50, and 225 kg of natural uranium), respectively.

Table 4-4-Relative Ease of Developing Various Enrichment Technologies for Weapon Programs

	Diff	Cent	Aero	Chem	EMIS	IC/PC	AVLIS	MLIS	LAP
Availability factors:									
Technology/know-how widespread	+	++	+/-	+1-	++		+1-		
Components attainable	+/-	+/-	+	+[a]	++		·		·
Operational factors:									
Convertible LEU to HEU		++	+	+	++	+	++?	+?	·
Minimal training required	+	+	+	+	+	-.	..	-.	..
Uses standard UF_6 feed	+	+						+	+
Low maintenance requirements	+	+	+	+	--		..		
Detectability factors:									
Small plant size	+1-	+		+	+1-	+	+	+	-
Short equilibrium time	--	+		--	+	+	++	+	?
Low power consumption	--	+	..	+1-	.-	+	+?	+	+
Commercially justifiable		++		?	--	?	?	?	?
Overall proliferation concern:[b]	+/-	++	+/-	+	+	.-		+/-	

KEY:

+/++ Indicate favorable/very favorable factor from the perspective of a potential proliferant.
-/- indicate unfavorable/very unfavorable factor.
? indicates insufficient information.

Diff - Gaseous diffusion
Cent = Gas centrifuge
Aero = Aerodynamic methods (Becker nozzle or Helikon processes)
Chem = Chemical exchange (Japanese Asahi or French Chemex processes)
EMIS = Electromagnetic Isotope Separation (e.g., calutrons)
IC = ion Cyclotron Resonance
PC - Plasma Centrifuge
AVLIS - Atomic Vapor Laser Isotope Separation
MLIS = Molecular Laser Isotope Separation
LAP = Laser-Assisted Process (e.g., Chemical Reaction by Isotopic Selective Laser Activation, or CRISLA)

[a] The ion-exchange resin developed and used in Japan by the Asahi Chemical Co. is proprietary and would be difficult to duplicate, even if samples could be obtained. However, a number of research programs around the world are developing fast equilibrium-time resins that might be useful for future chemical enrichment applications. it has also been reported that Ukraine produces an ion-exchange resin similar to that used in Japan's Asahi process (William C. Potter, Monterey Institute of International Studies, private communication, November 1992).

[b] Overall Proliferation concern should be taken only as a very rough indicator, since it is *strong/y country-dependent.* In arriving at this overall rating, "availability" and "operational" factors were each given twice the weight of the "detectability" factors, but for countries with an advanced technology base or skills suited to a particular technology, the relative weighting might be very different.

SOURCE: Allan S, Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation* (London: Taylor & Frands, Ltd., 1983), p. 19; Marvin Miller and George Rathjens, "Advanced Technologies and Nuclear Proliferation," in Robert H. Bruce, ad., *Nuclear Proliferation: South Asia and the Middle East,* Monograph No. 2 (Perth, Australia: Indian Ocean Center for Peace Studies, 1992), pp. 107-123; and OTA (see app. 4-B on enrichment technologies).

Table 4-5—Efficiency of Uranium Enrichment Technologies[a]

	Separation factor or enrichment factor[b]	No. of stages for 90% HEU[c]	kWh/SWU	kW for 4,000 SWU/yr
Gaseous diffusion	1.004-1.0045	3,500-4,000	2,500	1,200
Gas centrifuge	1.2-1 .5[d]	40-90	100-200	50-100
Aerodynamic				
Helikon/UCOR	1.030	540	4,000	2,000
Becker nozzle	1.015	1100	3,600	1,800
Chemical				
French Chemex	1.002-1.003	5,000-8,000’	600	300
Japanese Asahi	1.001-1.0013	12,000-1 6,000’	150	75
Electromagnetic [b]				
EMIS (calutron)	20-40	2-3	20,000 -30,000[f]	10,000-15,000
ion cyclotron resonance/ Plasma centrifuge	- [3-10]	[4-8]	[200-600]	[100-300]
Laser processes				
AVLIS	- [5-1 5]	[a few]	[100-200]	[50-100]
MLIS	- [3-1 o?]	[under 10?]	[200-250]	[100-125]
LAP (CRISLA)	~` [1.5][g]	- [20]	[tens?]	[low]

a Estimates in [brackets] are uncertain and may not be achievable on an industrial scale.

b For electromagnetic and laser processes, estimates are for the *enrichment* factor, not the separation factor. “Separation factor” is defined as the ratio of the relative (^{235}U-to-^{238}U) enrichment of the product to that of the tails in any one stage of a cascade, and is the figure given for diffusion, centrifuge, aerodynamic and chemical processes. “Enrichment factor” is the ratio of relative enrichment of the product to that of the *feed*, which is more relevant to processes whose separation per stage is high enough that a many-stage cascade is not required, and in which the “cut” (the ratio of the total amount of material in the product to that in the tails) is therefore not as relevant. The separation factor for a given process is always larger than its enrichment factor, but only slightly larger when the cut is much less than 50%, as it may be in some laser processes.

c Assumes tails with 0.3% ^{235}U content.

d The given range applies t. modern centrifuges and is dependent on their length, rotational speed, and other factors. The earliest centrifuges operated at subcritical peripheral speeds of 250 m/see and had separation factors of only 1.026. See Manson Benedict and Thomas H. Pig ford, *Nuclear Chemical Engineering, 2nd ed. (New York,* NY: McGraw-Hill, 1989), chapter 12.

e For chemical processes, a single physical item (e.g., an ion exchanger or pulse column) can contain tens or hundreds of effective “stages, ” so that these large numbers can be misleading.

f This figure is sometimes given as 3,000-4,000 (e.g., see Krass et al., below, p. 189), which would apply only to significantly improved calutrons that used multiple beams, permanent magnets, or other refinements. The figure given in the table is based on U.S. “Alpha” machines used during the Manhattan Project, which produced *only* about 1/3 gram uranium-235 per machine per day in about a 20% enriched product, and used more than 50kW per machine to power the electromagnets, pumps, and ion beams.

9 Estimate from Marvin Miller; derived from preliminary 1986 data of Isotope Technology, a small west-coast firm promoting the CRISLA process.

SOURCE: Adapted by OTA from U.S. Department of Energy, *Nuclear Proliferation and Civilian Nuclear Power, Report of the Nonproliferation Alternative Systems Assessment Program* (NASAP), “Volume II: Proliferation Resistance,” DOE/NE-0001/2, June 1980, p. 3-7; Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation* (London: Taylor & Francis, Ltd., 1983), p. 188; and Marvin Miller, “Atomic Vapor Laser isotope Separation,” FY1989 Arms Control Impact Statements, (Washington, DC: U.S. Government Printing Office, April 1988), p. 142.

man, and Dutch governments-have contributed to the proliferation of its centrifuge design technology.

Some components of very old technologies, such as electromagnetic isotope separators (EMIS, also known as "calutrons' '), and of very new technologies-some of which have still not been developed to a commercial scale by even the most advanced industrialized countries-have not been subject to export controls.[51] For example, magnets and beam sources for EMIS, and some lasers that could be used for laser isotope-separation techniques, have such widespread commercial applications that they have not been controlled in the past.[52]

Although gaseous diffusion dominated Western commercial enrichment for over three decades, it is now being overtaken by gas centrifuge technology. Neither technique has yet been used outside the five acknowledged nuclear powers to produce HEU on a large scale. However, the proliferation potential of centrifuges has won considerable attention both because of Iraq's pursuit of the technology before the Gulf War and because of Pakistan's success at building its own modem gas centrifuge plant with the help of blueprints and purchase orders stolen from the Dutch factory of the URENCO consortium.[53]

Detailed information on older centrifuge technology, in fact, is available in published documents.[54] However, these comparatively rudimentary designs are at least 25 times less efficient in terms of energy use and separation capacity than modem designs, whose manufacturing processes, design parameters, and operating characteristics remain classified. Older designs therefore cannot lead to facilities nearly as compact and efficient as those using modem technology. However, it is now becoming known that the former Soviet Union began developing gas-centrifuge technology on a massive scale in the 1950s and has advanced to fifth-generation designs. Russia continues to operate four major gas-centrifuge enrichment plants-though since 1987 these have only produced LEU for reactors—with a total capacity of about 10 million "separative work units" (SWUs), about half the world's total for this technology.[55]

Conversion of an existing facility

Large commercial enrichment facilities producing LEU for nuclear power plants, if reconfigured for higher enrichments, would

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[51] In 1961, the U.S. declassified the technology for electromagnetic and aerodynamic enrichment techniques, and for gaseous diffusion except for its diffusion barriers and pump seals. Germany found little difficulty in sharing the technology it had developed for the Becker nozzle aerodynamic process with South Africa, which in turn went on to develop on an industrial scale a different version of the process called Helikon, or ''stationary-wall" centrifuges. Although designs are also available in the open literature for early gas centrifuges, *modern* centrifuge technology remains classified both in the U.S. and by the URENCO consortium.

[52] Note, however, that the new Nuclear Suppliers Guidelines for dual-use items, once implemented, will tighten export controls on many of these technologies (see app. 4-D).

[53] Shyam Bhatia, Nuclear Rivals in *the Middle East* (London: Routledge, 1988), p. 8; James Adams, *Engines of War: Merchants of Death and the New Arms Race (New York, NY:* Atlantic Monthly Press, 1990), pp. 200-203; and Spector, *Nuclear Ambitions,* op. cit., footnote 16, pp. 90,97. Illicit efforts by proliferant states to obtain goods and technology have continued, as witnessed by the July 7, 1992 conviction in Philadelphia of Pakistani General Inam al-Haq for conspiring to illegally export maraging steel-350 (a material needed to construct gas centrifuges).

[54] See, for example, Gernot Zippe, *The Development of Short-bowl Ultracentrifuges,* University of Virginia Report No. EP-4420-101-60U, submitted to Physics Branch, division of Research, U.S. Atomic Energy Commission, Washington, DC, July 1960, referenced in Krass et al., *Uranium Enrichment. . . .* op. cit., footnote 50.

[55] See Mark Hibbs, *Nuclear Fuel,* Oct. *26,* 1992, *p. 3;* Oleg Bukharin , *The Threat of Nuclear Terrorism. . . .* op cit., footnote 12, August 1992, p. 4; and David Albright, Frans Berkhout, and William Walker, *World Inventory of Plutonium and Highly Enriched Uranium, 1992* (Oxford: Oxford University Press/SIPRI, 1993), pp. 54-56. According to these sources, all Russian centrifuge plants employ subcritical, aluminum-rotor centrifuges with annual throughput believed to be only around 5 SWU per machine,

have the enrichment capacity to make HEU for tens of weapons annually from the same amount of uranium source material required each year to fuel just one commercial-size nuclear power plant. Furthermore, each such enrichment facility typically supplies fuel for many tens of power reactors annually.[56]

If the enrichment technology is capable of doing so, upgrading 3 percent enriched uranium to 90 percent enriched uranium requires only about as much energy and enrichment effort as was required to enrich the 3 percent uranium in the first place. Although a cascade to enrich a *small* amount of LEU to weapon-grade levels would require several times as many *stages* as an LEU facility, each stage could be built with many fewer or much smaller elements, and it would cost only a fraction that of a large enrichment facility. Therefore, if they could avoid detection by safeguards (which would be difficult), those few countries already possessing commercial enrichment facilities could easily produce substantial amounts of nuclear weapon material by reconnecting part of a facility to produce 90 percent enriched material, by secretly adding additional enrichment stages, or by diverting some 3 percent enriched material to another (clandestine) facility.[57]

A covert facility fed by a small amount of diverted LEU, in theory, could be quite small and difficult to detect, although safeguards are designed to detect the diversion of the LEU. (See the following section.) The difficulty of reconfiguring an existing facility without detection, as opposed to building a new one, however, depends upon the type of enrichment technology used. Converting a large gaseous diffusion or chemical-exchange plant without detection from low to higher enrichments would be extremely difficult. Doing so would require either a complex reconnection of cascade elements, the addition of thousands of additional stages, or the reintroduction of enriched material into the original feed point.[58] Given the size of commercial facilities, it could take from months to over a year to re-establish steady-state plant operation after such a change, during which the change would almost certainly be detected.

Centrifuge cascades, on the other hand, can relatively easily be made to produce higher enrichments-either by adjusting the feed rates, by reintroducing higher enriched material into the feed, or by reconfiguring the cascade itself.[59] Since centrifuge-cascade equilibrium times are on the order of minutes to tens of minutes, such a change in enrichment levels could be accom-

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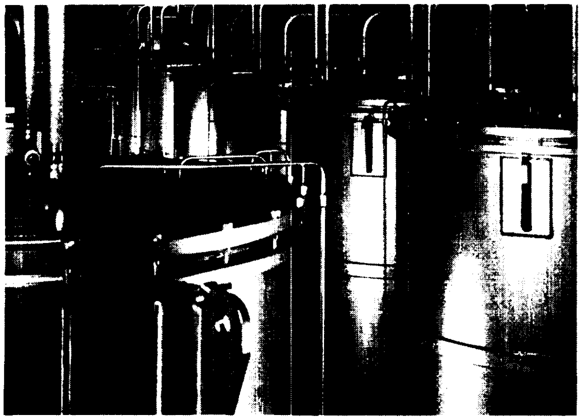
[56] That a commercial nuclear reactor requires far more fissile material than a nuclear weapon can be seen by comparing their energy outputs. A 1,000 MW(e) nuclear power plant, which generates heat through fission at a rate of about 3,000 MW, releases the energy equivalent of about 60 kilotons of TNT each day.

Alternatively, starting with natural uranium, less than 5,000 SWUs of enrichment effort are needed to produce an IAEA significant quantity (25 kg) of highly enriched (90 percent) uranium. In contrast, over 100,OOO SWUs are required to produce the approximately 30 tons of 3% enriched uranium consumed each year in a large commercial reactor, and commercial enrichment facilities have capacities of millions of SWUs per year.

[57] The only non-nuclear-weapon states actively involved in commercial enrichment for nuclear power are (see table 4-7) Japan, South Africa, and those countries participating in two consortia: URENCO and Eurodif. URENCO, established in 1971 by the U. K., W. Germany, and the Netherlands, operates several large centrifuge-based enrichment plants, Eurodif, a private commercial collaboration involving France, Italy, Belgium, Spain, and Iran that began soon thereafter, operates a large gaseous diffusion plant (10.8 million SWU/yr) at Tricastin in France. (Iran has been excluded from active participation since the 1979 revolution.)

[58] Especially for chemical-enrichment methods, which employ liquid phases, reconfiguration fOr HEU could also require Smaller elements to avoid the possibility of criticality accidents.

[59] Adjusting the feed rates can increase the enrichment of the product up to some maximum for a given cascade, called the “total reflux’ enrichment level. If normal operation of a given cascade produces 370 enriched product, then operating near total reflux could produce around 12% enrichments. Krass et al., *Uranium Enrichment. . . .* op. cit., footnote 50, p. 116. MLIS and the South African Helikon techniques might also offer advantages for producing HEU, but MLIS is still in the developmental stages, and the Helikon method currently utilizes an inflexible architecture. (See table 4-4 and table 4-5.)



PNC

Part of a gas-centrifuge cascade operated by Japan's Power Reactor and Nuclear Fuel Development Corporation (PNC). As required by the NPT all of Japan's nuclear facilities come under IAEA safeguards and are regularly inspected.

plished much more rapidly than for gaseous diffusion plants, whose: equilibrium times are weeks to months.

It is unlikely that operators of existing safeguarded centrifuge facilities would reconfigure or operate them clandestinely to produce HEU. Nevertheless, such a reconfiguration or modified operation is certainly possible and might even elude detection if them were a several-month period between safeguards inspections and if the alteration could somehow be made to look to the plant's containment and surveillance system like routine maintenance. Any such reconfiguration would require the collusion of many plant operators to keep it secret, however, providing a further deterrent.[60]

Building a dedicated facility

Table 4-6 lists the specialized requirements for the different enrichment approaches that could be taken by a potential proliferant who wished to build a dedicated uranium enrichment facility, indicating which are currently subject to export controls. Table 4-7 presents the status of each of the enrichment approaches in a number of countries. Many states have conducted R&D into a number of different approaches, with 10 non-nuclear-weapons states apparently having built pilot plants or production capability utilizing at least one of these enrichment methods. In India, Pakistan, and Iraq, those facilities have not been safeguarded, and in Brazil, Argentina, and South Africa, they have only recently been placed under safeguards.

The smallest, most easily hidden enrichment facilities would be based on energy-efficient processes that achieved high levels of enrichment in just a few stages. For example, laser and possibly plasma separation processes would be quite valuable to a proliferant state seeking a covert enrichment facility. However, energy efficiency and high separation per stage are usually directly related to technical complexity, and these advanced techniques will probably remain relatively inaccessible to developing countries for some time. Despite more than two decades of development work on these techniques, the most technologically advanced countries in the world have only recently taken laser separation techniques beyond the laboratory-scale demonstration stage.[61]

Aerodynamic methods such as the Becker Nozzle and Helikon process (see app. 4-B) have higher separation factors than gaseous diffusion, enabling them to reach high enrichments with fewer stages and smaller facilities. With no moving parts other than the compressors and pumps, they are operationally less complex than

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[60] Moreover, as a result of the early 1980s Hexapartite Safeguards Project addressing safeguards for centrifuge enrichment facilities, countries operating the principal centrifuge facilities in Europe and Japan have agreed to the principle of limited frequency unannounced access (LFUA) as one way of further reducing the possibility of any such reconfiguration. The Hexapartite project involved Australia, Germany, Japan, the Netherlands, the United States, and the United Kingdom, as well as the IAEA and Euratom.

[61] South Africa's Atomic Energy Corp., Ltd. plans to test a prototype molecular-laser-isotope-separation (MLIS) uranium enrichment-unit sometime in 1994, Note that this is in contrast to the AVLIS process currently being developed in the U. S., France, and the U.K. France announced in April 1992 that it had successfully produced 10 grams of low-enriched uranium using laser enrichment.

Table 4-6-Special Requirements for Uranium Enrichment Technologies

	Feed Material	Critical Equipment/Technology”
Gaseous diffusion	UF_6 gas	UF_6 processing equipment (corrosion-resistant)”; diffusion barrier”; specialized compressors/pumps/seals*; large heat exchangers.
Gas centrifuge	UF_6 gas	All components”: maraging steel (or other high strength-to-weight materials); endcaps; rotors; bellows; center post tubes; specialized ring magnets, magnetic suspension assemblies, and bottom bearings; scoops; baffles; outer casing; drive systems such as inverters; desublimers; high temperature furnaces; UF_6 processing equipment (corrosion-resistant). Also: vacuum/molecular diffusion pumps.
Aerodynamic	4% UF_6 plus 96% H_2 (mixture)	UF_6 processing equipment (corrosion-resistant)”; jet-nozzle units’ for Becker process, or vortex unit* for Helikon process (which uses a *2%/98%* gas mixture); compressors/pumps/seals (corrosion-resistant)”.
Chemical	U compounds	Proprietary ion-exchange resin” and exchange catalysts* (for Asahi process), or organic solvents and avoidance of catalytic elements (for Chemex process).
EM IS (calutron)	ucl_4[b]	Large electromagnets; high-voltage power equipment; stable, high-current ion source; collectors; vacuum/molecular diffusion pumps; $UC1_4$ processing equipment; and uranium recycling plant.
Ion cyclotron	U metal	Superconducting magnets; large solenoids; ion source; liquid helium; radiofrequency power supplies.
Plasma centrifuge	U metal	(Same as ion cyclotron method, but excluding radiofrequency power supplies)
AVLIS	U metal	High-power, pulsed dye laser; copper-vapor laser; vacuum pump; uranium vaporization equipment (such as electron-beam heater); high-voltage collector power supply; refractory materials.
MLIS/LAP (CRISLA)	UF_6 gas	High-power pulsed $C0_2$ laser; CF_4, CO, or excimer lasers (16 mm I R and/or UV); UF6carrier-gas mixture; UF_6 processing equipment (corrosion-resistant)”.
Thermal diffusion	liquid UF_6	UF_6 processing equipment (corrosion-resistant)”.

a Those items marked with asterisks (*) have been regulated by export controls for many years. Many of the remaining items (subject to certain threshold specifications) will come under the new NSG dual-use export-control guidelines, once implemented by NSG countries (see app. 4-D). Note, however, that while such controls may impose significant barriers to acquisition, they do not make it impossible.

b Higher efficiency liquid metal ion sources might also be used. See V.E. Krohn, and G.R. Ringo, "Ion Sources of High Brightness Using Liquid Metal," *Appl. Phys.* Letters, vol. 27 (1975), p. 479; and Oswald F. Schuette, "Electromagnetic Separation of Isotopes," U.S. Congress, Office of Technology Assessment, *Nuclear Proliferation and Safeguards,* OTA-E-48 (Washington DC: U.S. Government Printing Office, June 1977), app. vol. 2, Part 2-VI-c, pp. 93-108,

SOURCE: Adapted by OTA from Sean Tyson, "Uranium Enrichment Technologies: Proliferation Implications," *Eye on Supply* (Monterey, CA: Monterey Institute for International Studies), No. 5, fall 1991, pp. 77-86,

Table 4-7-Status of Uranium Enrichment Technologies by Country[a]

	Diff	Cent	Aero[b]	Chem[c]	EMIS	IC	PC	LIS	AVLIS	MLIS	LAP
Declared nuclear weapon states:											
Us.	3	2	1	1	3	1	1		2	1	1
Russia	3	3		1	2				1		
France	3	1		2		1			1		
U.K.	3	3							1		
China	3	2		1	1						1
Nonnuclear-weapon states under safeguards with at least pilot-scale enrichment facilities:											
Argentina	2							1			
Brazil		2	2	1					1		
Germany	2	3	2						1	1	
Italy	2	1						1			
Japan	1	3		2					1	1	1
Netherlands	2	3							1		
South Africa		1	3							1	
Countries outside the NPT or otherwise of proliferation concern:											
India		2						1			
Iran	1				1			1			
Iraq	1	1	1	1	2						
Israel		1									
Pakistan		2									
NPT parties (under safeguards) with only R&D-level enrichment programs:											
Australia		1		1			1	1			
Belgium	I							1			
Canada										1	
South Korea								1			
Romania								1			
Spain	1							1			

a Entries indicate the highest level of development achieved by a given country baaed on unclassified sources. Some processes may have been discontinued by some countries.

b South Africa has developed the Helikon aerodynamic process to industrial scale; Germany, Brazil, and the United States have focused on the Becker nozzle.

c Japan and France have developed the Asahi ion-exchange and Chemex solvent-extraction chemical processes, respectively. The specifics of other countries' chemical-enrichment research programs are not known.

KEY:

1 = R&D
2- Pilot Plant: facility with enrichment capacity of leas than 100,000 SWU/yr.
3 = Industrial Capability: facility with capacity of 100,000 SWU/yr or more.
LIS = Laser isotope separation techniques, general (AVLIS, MLIS, or LAP) (See key to table 4-4 for other abbreviations.)

SOURCE: Adapted by OTAfrom David Albright, Frans Berkhout, and William Walker, *World Inventory of Plutonium and Highly Enriched Uranium, 7992*, (Oxford: Oxford University Press/SIPRI, 1993); Sean Tyson, "Uranium Enrichment Technologies: Proliferation Implications," *Eye on Supply* (Monterey, CA: Monterey Institute for International Studies), No. 5, fall 1991, pp. 87-88; Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation* (London: Taylor & Frands, Ltd., 1983), p. 34.

centrifuges or laser processes.[62] Though not as energy efficient as centrifuges, aerodynamic methods can significantly enhance their production rates by using low-enriched uranium feed and can be used to produce very high enrichments.[63] They may therefore be a proliferation concern. However, complex small-scale manufacturing technology is required to fabricate critical aerodynamic components for the Becker nozzle technology, and the Helikon process is proprietary. Therefore, countries without very sophisticated technical capabilities would have to import such components (in violation of export controls).

Although key aspects are proprietary, chemical separation techniques such as the Japanese-developed ion-resin process and the French solvent extraction method are based on conventional chemical-engineering technology that in general is available to a great many countries around the world (see ch. 2). This enrichment approach could therefore prove difficult to control if the specific processes and materials involved were reproduced by a proliferant state.

Gaseous diffusion was the primary enrichment technique used by each of the five acknowledged nuclear powers. Classification by the United States of diffusion-barrier and compressor technology thus was not able to prevent its independent development by the other nuclear weapon states, even as early as the 1950s and 1960s.[64] Since then, however, the only other country that appears to have had some success at developing gaseous diffusion on its own is Argentina.[65] Since considerable engineering and materials expertise are required to design barriers and large corrosion-resistant compressors, the less-industrially advanced countries would still find it difficult to construct gaseous diffusion facilities.[66] Moreover, diffusion facilities are large and energy inefficient, making them virtually impossible to hide from detection on a commercial scale.

FROM NUCLEAR MATERIALS TO NUCLEAR WEAPONS

Knowledge and Expertise

Although successfully designing a nuclear explosive device requires individuals with expertise in metallurgy, chemistry, physics, electronics, and explosives, the required technology dates back to the 1940s, and the basic concepts of nuclear bombs have been widely known for some time. Much of the relevant physics for a workable design is available in published sources. As the Iraqis and others have discovered, many unclassified or declassified documents can also be obtained that make designing a weapon considerably easier than it was for the first nuclear powers (see box 4-D).[67] The first gun-type weapon ever

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[62] The Helikon process was largely developed internally in South Africa after it purchased rights to the related Becker Nozzle technology from Germany. Brazil also invested in the Becker technology in the late 70s. See Spector, *Nuclear Ambitions,* op. cit., footnote 16, pp. 243, 270.

62 The Helikon process was largely developed internally in South Africa after it purchased rights to the related Becker Nozzle technology from Germany. Brazil also invested in the Becker technology in the late 70s. See Spector, *Nuclear Ambitions,* op. cit., footnote 16, pp. 243, 270.

[63] Electromagnetic isotope separation also has these three attributes.

[64] See Albright *et al., World Inventory . . .,* op. cit., footnote 55, pp. 49-66.

[65] Ibid., pp. 180-181.

[66] Iraq, for instance, reportedly worked on gaseous diffusion for 6 years before abandoning it in favor of other methods. Jay C. Davis and David Kay, "Iraq's Secret Nuclear Weapon Program, " *Physics Today,* July 1992, p. 22.

[67] For instance, many basic physical principles of nuclear weapons (though not the implosion concept) are discussed in Robert Serber, *The Los Alamos Primer: First Lectures on How to Build an Atomic Bomb* (Berkeley, CA: Univ. of California Press, 1992). Serber's lectures were first given at Los Alamos at the start of the Manhattan Project in April 1943. Lecture notes were transcribed at the time and then declassified in 1965. The Iraqis legally obtained copies of many such documents from the West, such as declassified documents on lithium-6, a material useful for more advanced nuclear weapons. David Kay, head of several IAEA nuclear inspections in Iraq, private communication, Jan. 8, 1992.

Box 4-D-Iraq's Design Effort and Enrichment Approaches

Before the Gulf War, Iraqi scientists had progressed through several design iterations for a fission weapon based on an implosion design (one that is much more difficult to develop than the alternative, gun-type design-see app. 4-A). Still at the early stages of completing a design, they had successfully overcome some but certainly not all of the obstacles to a workable device.[1] Using HEU, a completed device based on the latest Iraqi design reportedly might have weighed from about a tonne to somewhat more than a tonne.[2] The Iraqis also possessed flash x-ray photography equipment and high-speed streak cameras? both useful in the R&D phase for studying the timing and compression achieved by a nuclear implosion design.

How close Iraq was to completing a bomb is still open to debate. At the request of the IAEA, a group of nuclear weapon designers from the United States, Britain, France, and Russia met in April 1992 to assess the progress of Iraq's nuclear program prior to the Persian Gulf War, based on documents that had been obtained through subsequent inspections. These designers reportedly concluded that bottlenecks in the program could have delayed completion of a working bomb for at least 3 years, assuming Iraq had continued its multifaceted strategy and design approach.[4] However, several experts familiar with the inspections believe that lraq could also probably

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[1] See Peter Zimmerman, "Iraq's Nuclear Achievements: Components, Sources, and Stature," Congressional Research Service report 93-323F, Feb. 18, 1993, pp. 18-22 and esp. app. 4-B, which reprints the *Al-Atheer Plant Progress Report for the Period 1 January 1990 to 31 May 7990,* Annex to the Sixth Inspection Report, U.N. Security Council S/23122, Oct. 8, 1991 (English), app. 4-B, pp. 23-24. Al Atheer was the principal site for weaponization research, development, and experimentation, similar to some of the roles played by Los Atamos during the Manhattan Project. The sixth inspection included the famous incident in which inspectors were detained for 4 days in a parking lot in downtown Baghdad near Petrochemical-3 (PC-3) headquarters.

[2] See, for example, Zimmerman, op. at., footnote 1, p. 19; and Colin Norman, "Iraq's Bomb Program: A Smoking Gun Emerges," *Science, vol.* 254, Nov. 1, 1991, pp. 644-645.

[3] David Kay, head of several IAEA nuclear inspections in Iraq, private communication, Dec. 1,1992. See also *Al-Atheer Plant Progress Report for the Period 1 January 1990 to 31 May 1990,* op. dt., footnote 2, pp. 23-24.

[4] Paul Lewis, "U.N. Experts *Now* Say Baghdad Was Far From Making an A-Bomb Before Gulf War," *New York Times,* May 20,1992, p. A6. See also, David Atbright and Mark Hibbs, "Iraq's Quest for the Nuclear Grail: What Can We Learn?," *Arms Control Today,* vol. 22, No. 6 (July/Aug 1992), p. 7.

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designed (the Hiroshima weapon), in fact, was based on such a sure--fire technique that no nuclear test was deemed necessary before it was used in warfare. (See app. 4-A for discussion of nuclear weapon designs.)

Nevertheless, knowledge must be supplemented by industrial infrastructure and the resources to carry a nuclear weapon program to completion. The technologies for building cars and propeller-driven airplanes date back to early in this century, but many countries still cannot build them indigenously.

The following section discusses some of the key areas of technical expertise required to construct weapons once the materials have been acquired.

COMPUTER SIMULATION AND DESIGN CODES

High-performance computers are not now, and never were, an essential technology for designing fairly sophisticated nuclear weapons. Various types of weapon designs were developed by the United States (as well as perhaps each of the other declared nuclear powers) without *any* kind of electronic computer.[68]

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[68] With only very primitive computers, Chinese designers reportedly studied 1,000 physical prototypes of the bomb before designing their first nuclear weapon. John W. Lewis and Xue Litai, *China Builds the Bomb* (Stanford, CA: Stanford University Press, 1988), p. 155.

have produced a workable device in as little as 6 to 24 months, had they decided to seize foreign-supplied HEU from under safeguards and focus their efforts on a crash program to produce a device in the shortest possible amount of time.[5]

In addition to extensive development of the electromagnetic isotope separation technique (EM IS, also called calutrons) and preliminary work on centrifuge enrichment technology and materials acquisition,[6] Iraq had also been pursuing chemical enrichment including both the ion-resin process developed by the Japanese and the liquid-liquid solvent extraction process developed by the French (see app. 4-B). At the time of the Gulf War, most Western analysts-with the notable exception of the French-believed that the chemical enrichment facility at Tuwaitha "Building 90" was not yet operable. Subsequent inspections by the IAEA, under auspices of the U.N. Security Council Resolution 687, found lab-scale experiments in chemical enrichment, but no evidence of success or any plans for a production plant. Since the French technology is both proprietary and subject to export controls, the Iraqis reportedly resorted to clever negotiation tactics to garner considerable amounts of design information on the process, ostensibly with the goal of licensing the technology at some point in the future. Their techniques reportedly included pressing for more and more technical details during a contract negotiation and then breaking off discussions just before closing a deal.[7]

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[5] In April 1991, Iraq's inventory of safeguarded highly enriched uranium included *unirradiated* fuel in the amounts of 13.6 kg of Soviet-supplied 80%-enriched HEU plus under 0.5 kg (out of the original 12.3 kg) of French-supplied 93% HEU; plus *partially irradiated* fuel in the amounts of 3.6 kg of 80% and 11.8 kg of 93%. Additional 80%-enriched HEU was listed as *irradiated* (fissile material would have been difficult to extract quickly from the irradiated fuel). Johan Molander, U.N. Special Commission, quoted in "Iraq's Bomb Program: A Smoking Gun Emerges," op. cit., footnote 2, p. 254.

[6] These aspects of the Iraqi program have all subsequently been described in some depth in published articles and reports. See, for example, Zimmerman, "Iraq's Nuclear Achievements. . .," op. cit., footnote 1.

[7] David Kay, presentation at the National Institute of Standards and Technology (N IST), Gaithersburg, MD, May 15, 1992.

Moreover, most of the U.S. nuclear weapons developed through the mid- 1970s were designed with computers no more capable than a typical 1990 engineering workstation—i.e., 1,000 to 100,000 times less powerful than modem high-performance computers, which now perform well in excess of 1,000 MFLOPS (million floating-point operations per second);[69] these weapons included high-efficiency primaries and the first thermonuclear weapon (1950-55); small-diameter primaries and nuclear artillery (1955 - 60); small strategic warheads (1960-65); the warhead for the Spartan antiballistic missile (1965-70); and weapons with tailored outputs (1970-75).[70] Of course, U.S. designers had the benefit of an extensive series of nuclear tests, which allowed them to validate both the weapons themselves and the computer programs that helped design them.[71]

Records obtained during the sixth IAEA inspection in Iraq show that the Iraqis had developed or acquired a number of computer codes for

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[69] A typical " supercomputer" of the mid- 1980s, such as the CRAY X-MP, had a speed of about 100 MFLOPS. Jack Worlton, Laboratory Fellow, Los Alamos National Laboratory, "Some Myths about High-Performance Computers and Their Role in the Design of Nuclear Weapons," Worlton & Associates, Technical Report No. 32, June 22, 1990.

[70] U.S. Department of Energy, "The Need for Supercomputers in Nuclear Weapons Design, " January 1986 (declassified), as cited in Worlton, ibid.

[71] Advanced Computation] power in the United States has also greatly facilitated miniaturizing nuclear weapons (i.e., achieving higher yield-to-weight ratios) and minimizing the amount of nuclear material they use. Moreover, it has promoted the development of 'safer' (less likely to detonate or disperse plutonium accidentally) and "cleaner" (for example, thermonuclear) weapons, and weapons that are designed to be reliable after being deployed for several decades.

use in their nuclear weapon design effort. These codes, found by IAEA inspectors, had been running on IBM PS/2 desktop computers;[72] such machines are capable of assisting with the design of first-generation nuclear weapons.

Since minicomputers, professional workstations, and other advanced computers roughly double in performance every 1 to 2 years, many types of computer become available worldwide not long after they are introduced, as they fall behind the rapidly advancing state of the art. Companies not subject to U.S.-style export controls—for example, in Israel, Brazil, India, and Bulgaria-are now developing and assembling indigenous high-perform ance computers comparable to or exceeding the best U.S. computers of just 5 or 6 years ago. A proliferant could also increase his computational power without violating export controls by installing accelerator boards for low-end to mid-range computers or by dedicating a relatively high-level machine (which is usually shared by many users simultaneously) to a single design effort.[73]

Therefore, top-of-the-line computers and numerical codes are certainly not a prerequisite to a successful nuclear weapon program, though their import may serve as an *indicator* of such and thereby provide valuable intelligence information. Given the utility of widely available computers to a weapon designer, even very strict export controls on top-model computers would probably do little to slow the development of a first-generation weapon program. Computational power would be relatively more important for programs pursuing advanced nuclear weapons, including thermonuclear ones.

NUCLEAR TESTING AND WEAPON FABRICATION

Although extensive testing of the implosion system and other weapon components would normally be essential before settling on a nuclear implosion design, *nuclear* testing (at full or nearly full yield) would not be required to field fission weapons, even for a new nuclear proliferant (see box 4-E). Both "hydrodynamic" tests of implosion characteristics (using a nonfissile core) and "hydronuclear" tests with extremely low nuclear yield can be used to lessen the need for full-scale nuclear tests in determining the adequacy of an implosion design.[74] Gun-type devices have even less demanding test requirements. If a proliferant state with competent designers decided in advance that no nuclear tests were to be carried out, it could pursue designs for fission weapons in the absence of those tests that would have a high probability of producing significant yields. Testing would be much more important, however, for a proliferant to develop either very low-weight nuclear weapons or thermonuclear weapons.

Weapon fabrication would also probably not present major technical hurdles to a proliferant. Assembly of a gun-type weapon is relatively straightforward. Implosion-designs would require lathes, other machine tools, and possibly isostatic presses to fabricate explosive lenses and other components, but there may be several suppliers of these dual-use items and various ways to import them. Little of the equipment for final assembly of a weapon is sufficiently specialized to be easily controllable by export laws. Some of the machine tools might be amenable to export monitoring, however, and may therefore serve as preliminary indicators of a program (see 'signatures' section below).

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[72] *Al-Atheer Plant Progress Report for the Period 1 January 1990 to 31 May 1990,* Annex to the Sixth Inspection Report, U.N. Security Council S/23122, Oct. 8,1991 (English), p. 14, reprinted as app. B of Peter Zimmerman, ''Iraq's Nuclear Achievements: Components, Sources, and Stature,' Congressional Research Service report 93-323F, Feb. 18, 1993. See also p. 20 of main text.

[73] Worlton, "some M@ about High-Performance Computers. . .," op. cit., footnote 69.

[74] See, for example, Robert N. Thorn and Donald R. Westervelt, ''Hydronuclear Experiments,'' Los Alamos National Laboratory Report LA-10902-MS, February, 1987.

Box 4-E – Utility of Tests at Various Yields

The decision to test a nuclear weapon must weigh the benefits of validating the design against the risks and political implications of the test's being detected. Tests with substantial nuclear yields can provide important information about a weapon design, but they are likely to be detected. Certain aspects of nuclear bomb design can be validated even at very low explosive yields. The following TNT-equivalent-ranges illustrate possible uses for such tests:[1]

No nuclear yield: With proper diagnostics, scientists can study implosion techniques, compression efficiency, and neutron initiator performance by substituting nonfissile material for HEU or plutonium.

Less than 1 ***kilogram (kg)*** nuclear yield; So-called "hydronuclear tests" at these yieids were carried out by Los Alamos during the testing moratorium of 1958-1961 to study certain characteristics of nuclear warhead designs.

1 *to a few kilotons* (/d): Fission weapons of both gun-type and implosion designs can be tested at full or almost full yields in this range. in addition, tests involving boosted-fission designs may be carried out within this yield range (see **app. 4-A).**

150 kt: The Threshold Test Ban Treaty of 1974 between the U. S., U. K., and former Soviet Union forbids testing at greater than 150 kt yields. However, advanced nuclear powers can probably design thermonuclear warheads with up to multimegaton yields without testing above the 150- kt threshold.

Atmospheric tests: Above-ground tests can be used to measure electromagnetic pulse, radiation, blast, fallout, and cratering phenomena that are much harder, or impossible, to study with underground tests.

if a proliferant state decides not to carry out nuclear tests with appreciable nuclear yields, it could probably still design reliabie first- generation gun-type or implosion fission weapons with yields similar to the Hiroshima or Nagasaki bombs, With a small number of tests at yields of a few to 10 kt, it may also make progress toward developing more compact or efficient weapons, possibly incorporating boosting. Atmospheric tests are highly visible, but they are not required to verify the basic function of nuclear explosives.

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[1] See, **for example, Ray E. Kidder, "Militarily Significant Nuclear Explosive Yields,"** *Federation of American* ***Scientists Public*** *Merest* ***Report,*** *vol. 37, No. 7,* **September 1985; and Dan Fenstermacher, "The Effects of Nuclear Test-ban Regimes on Third-generation-weapon Innovation,"** ***Science & Global Security,*** **vol. 1, Nos. 3-4 (1990), p. 193.**

EXPERIENCE FROM CIVILIAN NUCLEAR PROGRAMS

The infrastructure and experience gained from civilian nuclear research and nuclear power programs would be of substantial benefit to a nuclear weapon program. Up to a certain point in developing a civilian nuclear fuel cycle, its technology is virtually identical to that used for producing fissile materials for weapons. Relevant experience would include the ability to handle radioactive materials, familiarity with chemical processes for fuel fabrication and with materials having specific chemical or nuclear properties, and the design and operation of reactors and electronic control systems. Although this kind of experience is not unique to the operation of reactors--and is neither necessary nor sufficient to produce a weapon—it would provide a technology base upon which a nuclear weapon program could draw. Furthermore, the infrastructure supporting nuclear power generation and its associated fuel cycle can provide cover for elements of a weapon program, even in a country subject to IAEA safeguards.

RECRUITMENT, FOREIGN TRAINING, AND INDIGENOUS EDUCATION

The principles of nuclear weapons can be discovered without any prior design experience by any competent group of theoretical and experimental physicists and engineers. Although the specifics of designing, analyzing, testing, and producing a nuclear explosive device are certainly not taught in graduate schools, nuclear engineering and physics curricula inevitably provide a basic foundation for work in the area of nuclear weapon design. Indeed, students from many countries each year go abroad for instruction in such fields at top universities.

A country wishing to pursue nuclear weapons can also adopt its design methodology to the expertise at hand. Given scientists with only limited confidence in their design ability, such a state might choose to develop a very conservative implosion design that was not highly dependent on the quality of compression, or a gun-type weapon using HEU that, while bulkier and requiring more fissile material, would be much easier to build. First-hand design experience would be essential only to develop more sophisticated concepts, such as advanced or boosted fission weapons, high yield-to-weight weapons, or second-generation (thermonuclear) weapons.

Nevertheless, the assistance of outside experts with specific knowledge of nuclear design can significantly accelerate a program by avoiding ‘(dead-ends?’ that could waste valuable time and resources. Countries such as Iran, North Korea, Algeria, and Libya may well require a very long time if they were to start up a Manhattan-Project-like program, without access to experienced weapon designers. If too much time or money is required, then the risks of being discovered by outsiders (or even by internal political opposition) would increase, and a country may simply decide to abandon its program or not pursue it in the first place.

At least one case is already known, however, of one country’s nuclear design information being used by another country’s nuclear program. Yuli Khariton, the physicist who led the effort to develop the first Soviet nuclear weapon, recently admitted that the Soviets had obtained the design of the frost U.S. plutonium weapon shortly after it was used on Nagasaki. He claimed that this enabled the Soviets to carry out their first nuclear test 2 years ahead of schedule-in 1949 instead of 1951. He said that it was not until 1951 that they detonated a device based on their own design.[75] There have also been various unconfined reports of Chinese nuclear design information being used by Pakistan.[76]

According to the U.S. State Department, dozens of key Russian scientists would likely be able to direct critical aspects of a weapon program in a developing country, and perhaps 1 or 2 thousand technicians possess highly useful technical skills.[77] Several dozen nuclear scientists from the former Soviet Union (though probably not weapon designers) have reported been working in Iran, with dozens more entering other Middle Eastern countries.[78] Russian and Western specialists, however, say that so far they have no hard evidence that any attempt at recruiting actual nuclear weapon designers has been successful.[79]

In any case, the expertise needed to produce weapon-usable material *and* to make it into a deliverable weapon spans a wide range of disciplines and requires the right mix of individuals. Recruiting any given nuclear weapon specialist

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[75] Serge Schmemann, ‘‘1st Soviet A-Bomb Built from U.S. Data, Russian Says, “ New *York Times*, Jan. 14, 1993, p. A12. Khariton claimed that the design was obtained with the help of spy Klaus Fuchs soon after the U.S. bombs were dropped on Hiroshima and Nagasaki in August 1945.

[76] See, for example, Hedrick Smith, ‘‘A Bomb Ticks in Pakistan,’’ New *York Times Magazine,* Mar. 6, 1988, p. 38.

[77] ‘‘Redirecting the Soviet Weapons Establishment: An Interview with Ambassador Robert L. Gallucci,’’ *Arms Control Today*, Vol. 22, No. 3, June, 1992, pp. 3-6.

[78] Interview with David h-vi, director general of Israel’s Defense Ministry, in Ethan Bronner, ‘‘Israel Fears a Flow of Lethal Expertise to the Middle East,” *Boston Globe,* June 22, 1992, p. Al.

[79] Paul Quinn-Judge, “In Republics, An Eye on Bombs, Scientists,” *Boston Globe,* June *23, 1992,* p. A14.

could have significant or only marginal utility, and would depend strongly on the particular needs of a country at the time.

I costs

REQUIRED INFRASTRUCTURE

To develop nuclear weapons indigenously, a government must make a serious and long-term political commitment, must allocate significant amounts of resources and expertise, and must construct large facilities. (The required steps are summarized for uranium- and plutonium-based weapons in figure 4-1 and table 4-l). Since nuclear programs can vary tremendously, depending on a country's choices about paths, organization, secrecy, and goals, absolute costs are difficult to estimate. For instance, the path chosen by a country would strongly depend on its technical and industrial infrastructure, Moreover, the costs of developing the special nuclear materials cannot be directly compared with the costs of commercial enrichment facilities or spent-fuel reprocessing plants for nuclear power reactors, since facilities to produce only enough material for one or a few weapons per year can be tens of times more expensive per unit material processed than commercial facilities, but hundreds of times smaller. Steps to keep a program *clandestine can also* add considerably to the overall cost.

The Iraqi program, which appears to have been aimed at a small *arsenal* rather than a single weapon, took multiple paths and pursued its goals under tight secrecy. Starting in 1981, after the Israeli bombing of the Osirak reactor, Iraq apparently devoted its effort to producing enriched uranium instead of plutonium and began building complex research and production facilities (including twin sites for EMIS separation). Such a program can easily absorb much more money—*perhaps as much as* 10 *to* **50** *times more—than the* baseline plutonium-based program described below, and can run upwards of $10 billion.[80] Even then, it cannot be *assured* of success or of remaining secret. If nothing else, Iraq's program showed that there is a vast difference in cost between the cheapest direct route to nuclear weapons and a clandestine route taken by a country with little nuclear-weapon relevant experience, but relatively lofty nuclear ambitions.[81]

WEAPON MATERIALS DOMINATE THE COST

In general, the acquisition of sufficient quantities of weapon-grade materials presents not only the greatest technological hurdle, but also the greatest financial burden to the would-be proliferant. In the unlikely case that the government of a country without prior enrichment or reprocessing capability were to initiate a nuclear weapon program overtly, it could probably build a small production reactor and reprocessing plant more cheaply than it could produce equipment to enrich uranium. To remain hidden, however, a plutonium-based weapon program may have to take difficult and expensive measures. For instance, a proliferant might be driven to build a production reactor underground and to try to disguise its heat emissions to avoid being detected by infrared surveillance. If a country had no reason to reprocess spent fuel for commercial purposes, the discovery of a reprocessing facility would probably indicate weapons intent, so that steps might be called for to hide such a facility as well, or at least to keep it from being inspected.[82]

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[80] For comparison, the Manhattan District project spent $1.9 billion in 1940s dollars (which translates to about $10 billion in 1992 dollars): 50% to Oak Ridge for uranium enrichment 20% to Hanford for plutonium production and about 4% to weapon-related R&D at Los Alamos. See, for example, Zimmerman, op. cit., footnote **72, p. 4.**

[81] See also Thomas W. Graham, ' 'The Economics of Producing Nuclear Weapons in Nth counties, ' *Strategies for Managing Nuclear Proliferation: Economic and Political Issues* (Lexington, *MA:* Lexington Books, 1983), pp. 9-27.

[82] For instance, North Korea's claim that the facility at Yongbyon is for peaceful radiochemistry research (including separation Of plutonium) is particularly questionable, since that country's nuclear power industry is still in its infancy and could not be expected to derive benefits from plutonium recycling anytime soon.

Table 4-8-Nominal Costs for an Overt Small-Scale Plutonium-Based Weapon Program (in millions of 1992$)

Capital Costs of Construction:	
Uranium Mining Site (55,000 t ore/yr):	1.5-15
Milling Plant (100 t U_3O_8/yr):	8-9
Conversion Plant (85 t uranium-metal/yr):	12-14
Fuel Fabrication Plant (85 t natural-uranium-fuel/yr):	6-10
30-MWt Production Reactor: **(Brookhaven-type, air-cooled, graphite moderated, aluminum-dad natural uranium fuel; lower cost is for "stripped down" facility with little shielding)**	35-100
PUREX Reprocessing Plant:[a] **(85 t heavy metal/yr, very low burn-up fuel, batch processing, recovering about 10 kg plutonium/yr; low estimate is for rudimentary facility with little radiation shielding)**	12-36
RDT&E costs for the above facilitles:[b] **(10% - 15% of the capital costs)**	10-30
Start-up costs for the above facilities: (20°/0 - 25% of the **capital costs)**	15-45
Design and manufacture of the first nuclear weapons: **(includes capital costs of the weapon laboratory, RDT&E of the design phase, and nonnuclear components; 20-25% of the total cost of plutonium production (all above costs))**	20-65
Total cost of first plutonium-based weapon:	**$120-$300 million**

[a] PUREX stands for plutonium-uranium redox extraction process, a widely used method whereby uranium and plutonium are removed from spent fuel through a series of chemical processes.

[b] Research, development, testing, and engineering. This and the "design and manufacture" costs are based on early British and French nuclear weapon experience. Figures are adjusted to account for assumed cost reductions in RDT&E that resulted from "international nuclear learning" that took place most rapidly between about 1955 and 1960.

SOURCE: Adapted from Stephen M. Meyer, *The Dynamics of Nuclear Proliferation* (Chicago, IL: Univ. of Chicago Press, 1964), pp. 194-203.

A minimum-cost plutonium program

One detailed study has estimated that facilities sufficient to produce about one nuclear-weapon's worth of plutonium per year could be built for as little as $120 to $300 million (in 1992$), if the state building it did not try to keep it secret (see table 4-8).[83] This estimate includes the necessary uranium mining and processing facilities, a small production reactor to produce the plutonium, and a primitive reprocessing plant to recover it. Since few if any countries are likely to initiate such a program openly, this number is unrealistically low, but it can serve as a point of comparison for more detailed country-specific assessments.

According to this study, a country that has deposits of uranium ore could setup mining and ore processing (called "milling") facilities that would be sufficient to fuel a small production reactor in roughly 2 years, and without major expense or difficulty. Fuel fabrication, in theory, could be done in a common metalworking shop, although typically it has required imported facilities. The production reactor itself could be based on the Brookhaven Graphite Research Reactor, a 1955 design that has long been described in

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[83] Stephen M. Meyer, *The Dynamics of Nuclear Proliferation* (Chicago, IL: Univ. of Chicago Press, 1984), pp. 194-203. Also see the earlier cost-estimate studies done by the United Nations in 1%8 and by the U.S. Energy Research and Development Administration (ERDA) in 1976, as discussed in Graham, ''The Economics of Producing Nuclear Weapons in Nth Countries, ' op. cit., footnote 81.

unclassified U.S. Atomic Energy Commission documents. It is rated at 30 MW thermal output and if devoted to plutonium production, could produce enough for at least one nuclear weapon a year. (If a state seeking to build such a reactor could not do so indigenously, it could be forced to import specialized reactor components such as ultra-pure graphite. Such imports from an NPT state would trigger safeguards.)

Data regarding the design, construction, and operation of reprocessing facilities were also declassified and distributed through the 1955 Geneva conference on the peaceful uses of atomic energy. However, despite using chemical processes similar to those in standard industrial procedures, the reprocessing plant could be the most difficult step in this approach, due to the radiological hazard it would pose to plant workers. Nevertheless, radiation risks can be minimized (and the quality of the plutonium for weapon use improved) by irradiating the fuel to levels that are extremely low compared to those attained by commercial reactors—say, a few hundred megawatt-days per tonne of fuel (MWd/t), as opposed to 10,000 to 33,000. A small reprocessing facility could probably be built over the course of 3 to 4 years.

The total number of competent, experienced engineers needed over the course of several years to direct the construction of a Brookhaven-type graphite-moderated reactor and an associated reprocessing plant has been estimated to be about 10 to 20, together with a workforce of several hundred.[84] Cost estimates for the entire program (adjusted to 1992 dollars), including mining, milling, and fuel-fabrication facilities, are itemized in table 4-8. Many developing countries with a modest technical infrastructure could construct such facilities, and the cost of obtaining the trained specialists would constitute only a small fraction of the total weapon-program costs.

Reports in the open literature indicate that two countries have pursued unsafeguarded production reactors of approximately the size assumed here, although their cost data are not known. North Korea recently declared that one of its two operating reactors at Yongbyon is rated at 5 MW(e), but many Western analysts believe it is a 30 to 50 MW(t) production reactor.[85] Unofficial reports have alleged that Pakistan may have begun building a similarly rated (50 MW(t)) reactor in the mid-to-late 1980s.[86]

A more ambitious program aimed at indigenous construction of a 400-MW(t) production reactor and 10 to 20 weapons per year would require either a fairly high level of industrialization or a considerable nuclear technology base upon which to build. The only known *unsafeguarded* reactors with roughly this output (outside the five declared nuclear weapon states) are the five 220-MW(e) heavy -water reactors (HWRs) operating in India, and possibly Israel's Dimona HWR, believed by most to have operated at 40 to 70 MW(t),[87] but by some at up to 150 MW(t).[88] India has five other indigenous HWRs under construction, and North Korea has recently declared that is it constructing two power reactors with approximately this power rating-a graphite power reactor at Yongbyon rated at 50 MW(e) (in addition to two smaller reactors already in operation there), which would give it a thermal output of 150 to 200 MW(t), and a larger reactor at Taechon projected to have a power rating of 200

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[84] Meyer, ibid.

[85] See testimony of R. James Woolsey, Feb. 24, 1993, op. cit., footnote 15; and Spector, *Nuclear Ambitions,* op.cit., footnote 16, pp.128, 139.

[86] See Spector, Nuclear *Ambitions*, op. cit., footnote 16, p. 116.

[87] Ibid., pp. 83-4, 172.

[88] "Revealed: The Secrets of Israel's Nuclear Arsenal, *Sunday Times* (London), Oct. 5, 1986, p. Al.

MW(e) (roughly 600 MW(t)) once completed.[89] By one estimate, a reactor of several hundred MW(t) would normally take 5 to 7 years to complete, would require an overall capital investment in the range $400 to $1,000 million (1992$), and would require about 50 to 75 engineers supported by roughly 150 to 200 technicians for its design and construction.[90] Others estimate that practical difficulties normally encountered in constructing such facilities could increase these figures by up to 100 percent.[91]

Costs for small-scale uranium enrichment

Costs for a dedicated (and possibly clandestine) enrichment facility are extremely difficult to estimate, both because the procurement route and choice of technology are much more uncertain than for an indigenously built reactor and reprocessing plant, and because experience and openly published data relevant to enrichment facilities tend to be associated with very large commercial plants built for the nuclear power industry. (The cost can be much cheaper per unit enrichment capacity for large plants,) Nevertheless, a nominal idea of costs can be derived from smaller commercial facilities. Excluding research and development, the total cost for constructing a centrifuge facility capable of producing 300 kg HEU per year-12 times the IAEA significant quantity-might run from $100 to $500 million (in 1992$).[92] A smaller facility to produce about 15 kg of HEU per year based on calutron (EMIS) technology has been estimated to cost a minimum of $200 million.[93] If a small amount of additional enrichment capacity-say, enough for 30, rather than 300, kg of HEU per year-were to be built by a country already knowledgeable about the manufacture and operation of centrifuges, the costs could conceivably be much lower, perhaps only $2 to $5 million. The costs of building and operating such a facility in secret at a clandestine location, however, might increase this figure substantially.

| Implications of New Materials-Production Technologies

URANIUM ENRICHMENT TECHNOLOGIES

Although France, Japan, and the United States have made substantial progress in the last 10 years developing laser enrichment processes, successfully integrating laser or other advanced technologies into a facility capable of producing kilogram-quantities of HEU will probably remain beyond the reach of the developing countries for some time. Even in the most technologically advanced countries, these methods have tended to require a lengthy development period, and the quantities of material produced in the early stages has been very small. In contrast, technologies such as aerodynamic methods and centrifuges may offer potential proliferants a more attractive mix of characteristics. As evidenced by South Africa and Pakistan, these techniques appear capable of being developed successfully by countries having either a substantial technology base or access to sensitive design data.

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[89] Choe Jong Sun, spokesman for North Korean Ministry of Atomic Energy Industry, in interview with Leonard S. Spector, May 3, 1992, Pyongyang, as posted on Nuclear Nonproliferation Network.

[90] Meyer, The *Dynamics of Nuclear proliferation, Op. cit.,* footnote 83.

[91] George Anzelon, associate division leader of Z-Division, Lawrence Livermore National Laboratory, private communication Aug. 16, 1993.

[92] U.S. Congress, Office of Technology Assessment, *Nuclear Proliferation and Safeguards,* op. cit., footnote 24, p. 180.

[93] Oswald F. Schuette, ''Electromagnetic Separation of Isotopes, '' in OTA, *Nuclear Proliferation and Safeguards,* op. cit., footnote 24, vol. II, Part 2-VI, p. 105; costs have been converted to 1992 dollars.

TECHNOLOGIES AFFECTING PLUTONIUM FUEL CYCLES

Plutonium isotopic purification

The longer that reactor fuel containing uranium-238 is irradiated in a reactor, the higher will be its proportion of undesirable isotopes in the plutonium that is created, making it less desirable for nuclear weapons than pure plutonium-239. (See app. 4-A and the discussion earlier in this chapter on the use of reactor-grade plutonium in nuclear weapons.) Just as uranium-235 can be separated from uranium-238 to obtain bomb-grade material, so can plutonium-239 be separated from these other plutonium isotopes. Laser isotope separation (LIS) techniques, for instance, although not originally developed for that purpose, might be used.[94] Plutonium-239, in theory, could also be ‘‘enriched’ using centrifuges, EMIS, or even gaseous diffusion methods, though developing conversion facilities to produce the requisite plutonium compounds would be a major undertaking rife with its own set of problems.

Liquid-metal fast breeder reactors (LMFBRs)

Development of LMFBRs (reactors that are capable of breeding plutonium at a faster rate than they consume it) has progressed much less rapidly than was predicted in the 1970s. The principal breeder reactor programs have been located in Japan, France, and the former Soviet Union (mainly in Kazakhstan).[95] But France suspended operation of its 1,200-MW(e) production-scale FBR, called Superphenix, in 1990, and Germany and the U.K appear to be abandoning their efforts to develop breeders.

LMFBRs introduce safeguard concerns far beyond those faced with the light-water reactors (LWRs) most commonly used for power generation. Whereas reprocessing can be forgone for LWRs, it is integral to a breeder's fuel cycle. Fresh LMFBR fuel contains a considerably larger fraction of plutonium than does even the plutonium-containing MOX fuel intended for use in commercial LWRs. (LMFBRs such as Superphenix contain about 5 tonnes of plutonium in their cores.) Moreover, a considerable amount of the plutonium produced in an LMFBR under normal operation will be weapon-grade, whereas commercial light-water reactors produce much lower quality (reactor-grade) plutonium unless shut down and refueled much more frequently than economical operation would warrant.

Integral Fast Reactor (IFR) fuel cycle

In the future, new plutonium fuel cycles could also be developed and commercialized. One such concept, which has been under development by Argonne National Laboratory in the United States for many years, is called the Integral Fast Reactor (IFR),[96] The IFR was originally developed to reduce the amount of nuclear waste generated by reactors by "burning" more of the longest lived radioactive byproducts than can be consumed by conventional nuclear reactors. The reprocessing approach used in an IFR fuel cycle would produce plutonium-containing fuel that is considerably more radioactive than that resulting from the traditional PUREX process, thus being less attractive for diversion to a weapon program. To handle it efficiently, reprocessing would occur at

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[94] In the 1980s, the U.S. Department of Energy's plans for a laser isotope separation facility to be built in Idaho included separating plutonium isotopes. Although economically unattractive compared with more direct methods of obtaining nuclear weapon materials, the possibility of using LIS to enrich plutonium has added somewhat to the concern over the Japanese and South African development of pilot I-IS plants. Although both countries already operate reprocessing facilities and have legitimate needs for enriched uranium for nuclear power, the purification of separated plutonium would provide an additional path for producing weapon-grade plutonium.

[95] Kazakhstan's 335-MW(t) fast breeder (BN-350) dates from Soviet efforts over the past 10 to 20 years and is designed to use 20 to 25% enriched uranium as well as MOX fuel. Potter et al., op. cit., footnote 35, p. 9.

[96] Charles E, Till and Yoon I. Chang, ‘‘The Integral Fast Reactor,’ *Advances in Nuclear Science and Technology,* vol. 20 (1988), pp. 127-154.

the reactor site itself, in hot cells as close as 100 feet to the reactor.[97]

The proliferation concerns with the IFR fuel cycle, as with other fuel cycles involving reprocessing, center on the accountability requirements to assure nondiversion of nuclear material at any stage. Since the hot-cell area is small and has relatively few access points compared to the PUREX process, it would be more difficult for subnational groups to divert material from an IFR. However, because the IFR concept would require a closed-cycle inert-gas environment involving highly radioactive materials at high temperatures, effective materials-accountancy may be difficult to implement. Instead, safeguards will have to rely much more heavily on containment and surveillance measures (see app. 4-Con IAEA safeguards and the civilian nuclear fuel cycle). Although the prospect of IFRs substituting for conventional LWRs in the United States or even for liquid-metal breeder reactors in France or Japan does not appear to be likely for several decades, the long-term proliferation and safeguards implications of sharing IFR reactor technology with other countries is yet to be fully addressed .98

| Weaponization-Going Beyond the “Physics Package”

MINIATURIZATION

A nuclear device deliverable by aircraft or missiles at long range must meet certain size and weight constraints. The bombs used in World War II, called “Little Boy” and “Fat Man,” each weighed in excess of 4,000 kg, which would have made them virtually impossible to deliver by any ballistic missile deployed in the Third World today, and problematic for over half these countries’ combat aircraft, including the F-16, Mirage F-1, MiG-23, -27, and -29. (Chapter 5 discusses delivery systems suitable for nuclear weapons as well as chemical or biological weapons, and provides more detail on the capabilities of aircraft and missiles available to states of proliferation concern.)

A nuclear proliferant today could probably construct a much lighter bomb than the first U.S. bombs. Many experts believe that even the 500-kg payload limit originally set by the Missile Technology Control Regime (and since eliminated at the beginning of 1993) may no longer be appropriate for first-generation nuclear weapons. U.S. 8-inch and 155-mm nuclear artillery shells produced in the late 50s and early 60s suggest that compact and relatively lightweight warheads can indeed be designed. Although the design of these warheads drew on the experience gained from hundreds of nuclear tests, they may still have relevance to current proliferation concerns for several reasons. First, explosives technology and light-weight electronics have advanced dramatically since the 1950s. Second, other forms of testing, such as “hydronuclear tests” with extremely low nuclear yields (see discussion below) may allow at least the more technologically advanced proliferant countries to reduce amounts of materials in their weapon designs to levels well below those of the first U.S. weapons. Third, at least some knowledge of more advanced weapon designs (even if from three decades ago) maybe difficult to keep out of the hands of proliferants. Finally, even straightforward modifications to the designs of the first U.S. weapons could reduce their size considerably, albeit with some yield penalty, with no greater required sophistication. The mere fact that the United States has built low-weight nuclear weapons indicates that they *can* be built, considerably increasing a proliferant’s motivation to attempt to recreate such a

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[97] The IFR can use more radioactive nuclear fuel because it is less sensitive than many other types of nuclear reactor to fuel impurities that absorb neutrons.

[98] See, for example, R.G. Wymer et al., ‘‘An Assessment of the Proliferation Potential and International Implications of the Integral Fast Reactor,” prepared by Martin Marietta Energy Systems, Inc. for the U.S. Dept. of Energy and the U.S. Dept. of State, May 1992.

design. Their existence also offers the possibility that such designs might be stolen, particularly if the Soviet Union and other nuclear weapon states have developed low-weight warheads as well.

ANTI-AGING

Unless assembled immediately prior to use, warheads would have to be storable over some period of time to be militarily useful. To make warheads that were reliable after years of storage, many features might need refinement, including nondegrading high explosives, purer grades of plutonium[99] or, with weapon designs that use tritium gas for additional yield, a replaceable tritium supply. Anticorrosive materials might be required at various points within the weapon, in addition to metallurgically stabilized nuclear material. Some of these refinements might require substantially more research than what would be needed for a crude frost-generation weapon. Frequently recycling the nuclear material, reassembling the weapon, and inspecting the nonnuclear components could ameliorate these problems, but such measures introduce considerable logistical problems of their own.

REENTRY VEHICLES AND FUZING

As mentioned above, missile delivery would place constraints on a warhead's size and weight. For Scud-type missiles, which do not employ a separating reentry vehicle, these constraints are not severe. However, if a narrow cone-shaped reentry vehicle were deemed necessary to achieve desirable aerodynamic properties, it would have to be internally balanced to avoid wobbling or tumbling.[100] Such reentry vehicles would constrain the configuration of a warhead's high explosives and detonators, possibly requiring a more sophisticated design that a proliferant might wish to test in order to have high confidence in its performance.[101] It might also be desirable to incorporate radar altitude-fuzing, to avoid the added difficulty of designing weapons to detonate on impact, or *salvage fuzing* (detonation upon being attacked by an interceptor) to defeat missile defenses. These features would likely require flight testing of the reentry vehicle under realistic conditions before fielding it and would thus increase a program's visibility as well as its technical hurdles.

SIGNATURES OF NUCLEAR PROLIFERATION ACTIVITIES

The IAEA safeguards system provides a means of monitoring and inspecting peaceful nuclear activities in a great number of countries. In addition, however, individual countries may wish to monitor the potential for other countries to develop nuclear weapons—both to evaluate and deal with the security threat that such programs could pose and to assess the effectiveness of and possible improvements to nonproliferation policies. Every stage of nuclear weapon development, from material production to deployment, can generate signatures that provide some indication of a weapon program's existence or status, although only a few of them point fairly unambiguously to a nuclear weapon program.

This section surveys potential signatures of a nuclear weapon program without attempting to fully assess the capability to monitor nuclear proliferation or verify compliance with the NPT; such would require evaluating the capability to observe these signatures, identify them, and piece

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[99] Plutonium-241, an unwanted plutonium isotope, decays into americium-241, which is much more radioactive than plutonium. As it builds up within a weapon, that weapon becomes more difficult to work with and its characteristics can change. Higher grades of plutonium have less plutonium-241, thus reducing these problems.

[100] Although the principal reason that the acknowledged nuclear powers have attempted to prevent their missile warheads from tumbling or wobbling during reentry is to attain higher *accuracy,* a tumbling warhead's violent motions and potential lack of adequate heat shielding could also affect *reliability.*

[101] Testing would also be much more important if a proliferant were seeking to develop very low-weight warheads to accommodate limited payload capacities of certain types of ballistic or cruise missile.

them together with other sources of information to arrive at timely conclusions regarding particular states' activities.

Materials Acquisition

URANIUM OR PLUTONIUM DIVERSION FROM SAFEGUARDED FACILITIES

Under the mandate of the NPT, IAEA safeguards focus narrowly on a specific goal-timely detection of diversion of *significant? quantities* of fissile nuclear materials from facilities declared to be peaceful in purpose (see app. 4-C on safeguards). The detection of such diversion, or the discovery of unsafeguarded nuclear facilities in a state that had committed to place all its facilities under safeguards, would generate strong suspicions of a nuclear weapon program.

Safeguards primarily operate indirectly, by verifying that all nuclear materials are accounted for. (They are supplemented at certain types of facility by *containment and surveillance* techniques, which in principle could detect some types of diversion directly.[102]) *Material accountancy* seeks to verify the correctness of a plant's own operating records, much as an audit of a financial institution verifies its bookkeeping. Over the past 15 years, material accountancy techniques have improved significantly. Safeguards also make extensive use of automated equipment for measuring controlled items and for supporting containment and surveillance techniques.

In addition to evidence of diversion acquired through material accountancy or containment and surveillance, certain *behaviors* might also raise doubts about a safeguarded country's intent to comply with its nonproliferation agreements. Behaviors detectable through normal safeguards inspections could include: stalling tactics (e.g., unsubstantiated complaints about individual inspectors or repeated exclusion of inspectors with certain nationalities)[103]; barring inspectors' access to certain areas or facilities for suspicious reasons; having substantial or repeated *material-unaccounted-for* (MUF)[104]; or keeping inconsistent records. If detected by other means, construction of undeclared 'pilot facilities that appeared to be destined to contain nuclear material would also raise suspicions, as would refusal of an IAEA request for a special inspection at such a facility.[105]

URANIUM ENRICHMENT

If operated on a large enough scale (perhaps 10 bombs-worth per year), an energy-inefficient enrichment technology such as EMIS or gaseous diffusion might be detectable by its heat emission. At Iraq's A1-Tarmiya facility, for instance, heat rejection into the air or, as appears to have been planned, into the Tigris river, might well have been observable once operation had begun.[106] However, at lesser production rates or with more

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[102] Containment and surveillance equipment includes unattended video cameras, motion detectors, closed-circuit TV systems, and various types of seals.

[103] Under IAEA safeguards, a country has the right to reject inspectors of whatever nationalities it chooses (Or, for that matter, fOr any other reason), a right that is regularly exercised. For example, between 1976 and 1981 (the year that Israel attacked the Iraq's Osirak reactor), Iraq allowed only Soviet and Hungarian nationals to perform safeguards inspections on its territory. Testimony of Roger Richter, former IAEA inspector in Iraq, cited in J. Aroesty, K.A. Wolf, E.C. River, *Domestic Implementation of a Chemical Weapons Treaty,* Rand Report R-3745-ACQ (Santa Monica, CA: RAND Corp., Oct. 1989), p. 55,

[104] "Material-unaccounted-for" is a safeguards term describing differences between measured and expected values in material accountancy. MUF can result from normal measurement or calibration errors, or can indicate a possible diversion of materials.

[105] See, for example, George Bunn, *Does the NPT Require its Non-Nuclear Weapon Parties to Permit Inspection by the IAEA of Nuclear Activities That Have Not Been Reported to the IAEA?* (Stanford, CA: Center for International Security and Arms Control, Stanford University, April 1992).

[106] Anthony Fainberg, *Strengthening IAEA Safeguards: Lessons from Iraq* (Stanford, CA: Center for International Security Arms Control, Stanford University, April 1993), p. 21.

efficient technologies (e.g., centrifuges, or EMIS techniques that employed permanent magnets and lower beam-voltages), heat signatures would be less evident. Heat emission is a nonspecific signature, however, that would be most useful for monitoring the startup and shutdown patterns of known facilities; it would have to be combined with other indicators to determine whether a given unknown facility were nuclear-related.

A potential sign of a clandestine enrichment or other nuclear facility could be unexplained special security or military reinforcements around an industrial site. These arrangements might be visible from overhead or from the ground.

At close enough range, other signatures would become observable. For example, even a very small centrifuge plant might emit detectable acoustic or radiofrequency noise, and the pulsed lasers used for laser isotope separation emit characteristic electromagnetic signals at kilohertz frequencies that might be detected, Samples of substances taken from either declared or suspect facilities could also indicate their potential for producing weapon materials. For example, UCL$_4$ or other uranium chloride combinations could indicate EMIS or Chemex enrichment technology, and UF$_6$, UF$_4$, HF, or uranium metal could indicate other uranium enrichment techniques (see app. 4-B).[107] Analysis of environmental samples containing depleted or enriched uranium in water or soil would also provide very important signatures.

Patterns of foreign procurement of essential materials and parts, such as newer high-strength materials or maraging steel (a very high-tensile-strength steel used to manufacture some types of gas centrifuge), or large iron electromagnets, high-voltage power supplies, and large vacuum systems (for EMIS), might also help to indicate a county's intentions.

PLUTONIUM PRODUCTION

An indigenous uranium mining industry might provide early indication of a clandestine uranium or plutonium-based weapon program and is a sure indicator of at least the possibility. For the plutonium path, natural uranium could fuel a graphite- or heavy-water moderated plutonium-production reactor. A sizable research program involving breeder-reactors or the production of heavy water or ultra-pure carbon and graphite products might also be cause for concern, especially if such programs were not easily justifiable on other accounts.

Small research or power reactors with high neutron flux and significant amounts of uranium-238 in their cores can also be used to produce plutonium. However, a 40 to 50 MW(t) undeclared reactor (enough to produce plutonium for at least one bomb per year) should be easily discernible to overhead infrared sensors, at least if it is built above ground and located away from heavy industrial areas (such a location might be chosen for security and safety reasons anyway).[108] Insections of *safeguarded* **reactors,** especially if carried out at more random intervals, might detect unnecessary placement of uranium-238 in or around the core, augmenting the rate of plutonium production. Similarly, inspections of CANDU-style reactors (a heavy-water-moderated reactor that can be refueled online) or of frequently shut-down LWRs should call attention to very low-bum-up fuel cycles, from which the plutonium produced is predominantly plutonium-239, the isotope best suited for weapons.

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[107] Note, however, that the specific compounds UCl$_4$ and UF$_6$ would not likely be found in the atmosphere, Skim they react very quickly with water to form other compounds. The existence of UF$_4$ might also be evidenced by the particular processing equipment required to reduce it to metallic form.

[108] If the heat were discharged into a modest-sized river, a resulting rise in temperature on the order of 0.1 °C or more (depending on flow-rate, mixing, etc.) would be detectable in the far-infrared. Alternatively, heat from the cooling towers might also be detectable. See Fainberg, *Strengthening IAEA Safeguards,* op. cit., footnote 106, p. 21..

SPENT-FUEL REPROCESSING

In general, the plutonium-production route, which involves reprocessing of spent reactor-fuel to extract plutonium, would be easier to detect than would be a small-scale clandestine uranium-enrichment facility.[109] Plutonium and uranium from spent fuel (as well as enriched uranium from research reactor cores), is reclaimed by chopping up and dissolving the fuel elements in acid, subjecting the solution to solvent-extraction and ion-exchange processes, and chemically converting the plutonium and uranium in the resulting liquids to metallic or oxide forms. Methods for doing this, including the most common one, known as PUREX, involve various well-understood chemical processes that use characteristic groups of materials.

Detection of these materials, either by environmental sampling or by impactions, could indicate reprocessing activity.[110] Some chemicals might also be observed through export monitoring; for example, high-purity calcium and magnesium, which are used in the metal-conversion step, are included in the Nuclear Supplier Group's new list of sensitive dual-use items to be subjected to export controls (see app. 4-D).

Release of noble gases

In addition to the characteristic chemicals used in the PUREX process, effluents from reprocessing plants will contain telltale radioactive fission products, including radioactive isotopes of the noble gases xenon and krypton-especially krypton-85—and possibly argon.[111] Measurements made at the U.S. reprocessing facility at the Savannah River Plant in South Carolina have suggested that krypton-85 may be detectable, even from small facilities, at ranges of 10 kilometers or more.[112]

Isotopic content of plutonium

Analysis of plutonium samples or effluents from reprocessing could provide further evidence of *weapon intent* by revealing the fuel's irradiation level. For most types of reactor, a very low fuel-irradiation level would be a strong indicator of weapon activity. In addition, isotopic correlation techniques-which compare the isotopic ratios of different samples of plutonium-can provide sensitive indicators of plutonium production history or material diverted from one facility to another.[113]

Weapon Design and Intent

ACTIVITIES OF SCIENTISTS

The effort required to develop nuclear weapons can have a significant effect on the movement, publications, and quests for information of a country's leading scientists. Although publications on nuclear materials and reactors would be expected in connection with legitimate safeguarded activities, a sudden decline in these publications might be suspicious. Scientists directed to pursue a weapon program might begin seeking out specialized computer codes (especially adapted to high pressure and high temperature regimes) or attending a greater number of technical conferences in the areas of optical instrumentation, reactor-core neutronics, or high-explosives and shock-wave hydrodynamics. They

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[109] *Any* unsafeguarded experimentation with reprocessing by an NPT nonnuclear-weapon state would be suspicious, and reprocessing activity has traditionally been a cause for concern in any nonnuclear-weapon states, whether party to the NPT or not.

[110] Various acids, organic and inorganic solvents, and other chemicals are used in the PUREX process, as well as uranium and plutonium that would be present at each step. See, for example, Richard R. Paternoster, ''Nuclear Weapon Proliferation Indicators and Observable,' Los Alamos National Laboratory, LA-12430-MS/UC-700 (December 1992).

[111] Frank von Hippel and Barbara Levi, '' Controlling Nuclear Weapons at the Source: Verification of a Cutoff in the Production of Plutonium and Highly Enriched Uranium for Nuclear Weapons, " Kosta Tsipis et *al.*, Arms Control Verification: *The Technologies That* Make it *Possible* (Washington DC: Pergarnon-Brassey 's, 1986), pp. 351-53.

[112] Ibid.

[113] Alex DeVolpi, Argonne National Laboratory, private communication, Dec. 14, 1992.

might also begin purchasing large numbers of declassified documents from foreign weapon laboratories. (Such documents were indeed found among those seized in Iraq.) A sudden recall of trained scientists from other countries would be another observable, as would attempts to recruit foreign weapon scientists.[114] Sending large numbers of graduate students abroad to study technical fields related to nuclear weapon design *might* be associated with a weapon program. However, such a signature would be very ambiguous, since at the graduate level, most such fields have widespread application.

DECLARATIONS OF LEADERS

Public statements by high officials can also shed light on a nation's intentions, though they must be interpreted *within* a given political context. For instance, statements from Iraq before the 1991 Persian Gulf War and from Iran after that war could be interpreted to indicate a desire for weapons of mass destruction:

> . . . it behooves us to declare clearly that if Israel attacks and strikes, we will strike powerfully. If it uses weapons of mass destruction against our nation, we will use against it the weapons of mass destruction in our possession.[115]
>
> Since Israel continues to posses nuclear weapons, we, the Muslims, must cooperate to produce an atom bomb, regardless of U.N. attempts to prevent proliferation.[116]

NUCLEAR AND HIGH-EXPLOSIVE TESTING[117]

Implosion physics

Repeated high explosive (HE) tests are generally required before a workable implosion-type nuclear weapon can be designed.[118] Explosive tests to study either the HE alone or its ability to propel metal objects would usually require electronic or optical instrumentation. For observers at close enough range, some indicators of high-explosive testing activity are the following:[119]

- expansion of facilities or personnel at or near an existing ordnance plant;
- purchase or production of explosives more energetic than pure TNT, such as RDX, HMX, or PETN, any of which could be mixed with TNT;
- equipment for compacting or melting and casting HE, perhaps modified from what would be used at a standard ammunition loading plant;
- alternatively, for different types of explosives, isostatic or hydrostatic presses, weighing many tons and likely remotely controlled (some antitank shaped-charges are also made using such presses);
- precision, possibly template or computer-numerically controlled, two-axis machining facilities for HE, especially if suited for machining curved contours and surrounded by blast-protection shielding;

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[114] Reports in the press have claimed that Iran recently appealed to emigre nuclear engineers to return home, ostensibly to work on civilian applications of nuclear power.

[115] Speech by Saddam Hussein at the opening of the Arabs ummit conference in Baghdad, May 28, 1990, translated in FBIS-NEA, May 29, 1990, p. 5.

[116] Iranian Vice President Ataollah Mohajerani, Oct. 25, 1991, at an Islamic conference in Tehran, quoted in George J. Church, "Who Else will Have the Bomb?" *Time,* Dec. 16, 1991, p. 47.

[117] This and the following section draw heavily on material found in paternoster, "Nuclear Weapon Proliferation Indicators and Observable,' op. cit., footnote 110.

[118] In order to improve the symmetry and effectiveness of the implosion, multiple experiments would be called for, including measurement of the resulting core density.

[119] Paternoster, "Nuclear Weapon Proliferation Indicators and Observables,'' op. cit., footnote 110, pp. 7-9.

- waste and scrap from the above operations, possibly including effluent waste-water systems involving filters or catch basins; pronounced red coloration in waste water caused by dissolved TNT; solid scrap periodically destroyed by burning or detonation; and
- instrumented firing stations and control bunkers for HE or HE-metal tests using charges weighing up to hundreds of pounds.[120]

Test-firing of HE-metal systems containing uranium would be indicated by the following:

- bright streamers radiating from the test (caused by burning fragments of uranium) visible to the eye;
- local debris or dust that contained uranium; and
- nearby fire-extinguishing equipment, portable radiation monitoring equipment, or permanent air-sampling radiation-monitors.

Since highly dense (but nonfissile) uranium-238 is widely used in certain types of antitank weapon, these indicators could also stem from advanced nonnuclear munition programs. Therefore, most or all of these could be associated with conventional munitions production and do not give unambiguous evidence of nuclear weapon development. However, *spherically symmetric* implosions would be more likely connected with a nuclear program.

Gun-type weapon development

Gun-type weapons generally require highly enriched uranium surrounded by neutron-reflecting material such as natural uranium, tungsten alloy, or beryllium metal or oxide (ceramic). A development program might use hundreds of pounds of beryllium or thousands of pounds of uranium or tungsten for the neutron reflector alone. Unusually high importation of some of these items by certain countries might suggest weapon-development activity. In addition,

- ground cover at the detonation test-site may be cleared in only one direction, since the debris from tests-and especially burning uranium streamers if natural uranium were used as a mockup for HEU-would be concentrated in a cone coaxial with the direction of projectile firing (however, a test program for *nonfissioning* shaped charges or kinetic-energy rounds could also have such a configuration);
- special fast-acting very-high-pressure gauges might be used to record the pressures in the gun breech; and
- distinct acoustic features might be observable.

NUCLEAR LABORATORY EXPERIMENTS

Observers who had access to suspicious laboratories might detect the following signatures:

- Criticality tests—weapon designers using near-critical fissile assemblies may wish to measure criticality with closed-circuit television and neutron counters in remotely operated (possibly underground) experiments. However, experiments can also be performed at the bench-top level, not needing elaborate equipment, and much of the relevant data is already available in the open literature. Moreover, similar facilities are also used for agricultural and biological neutron-irradiation research. Any kind of criticality accident at a suspect site, however, would be a strong indicator of weapon-design activity, since other applications would be ununlikely to work with near-critical assemblies.
- Neutron background measurements—for gun-type devices, neutron-flux measurements would be required to assure that background neutron counts were sufficiently low. Such measurements might be indicated by a room containing neutron detectors that was shielded from external sources of neutrons, for exam-

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[120] Instrumentation could involve a few dozen high-speed oscilloscopes, high-speed rotating mirror 'streak' cameras; electronic-image-converter or high-speed framing cameras; and pulsed x-ray generators.

ple with water- or polyethylene-filled walls. Such facilities might also be used to test neutron initiators.

- Development of neutron initiators-neutron initiators produce a pulse of neutrons to initiate the nuclear chain reaction at the optimum moment (see app. 4-A). They use either alpha-particle-emitting radioactive substances or small particle accelerators containing radioactive tritium gas,[121] Therefore, import or production of alpha-emitting materials, tritium, or the special facilities to handle them (similar to those used for spent-fuel reprocessing) could indicate weapon development. However, small accelerator-based neutron sources are produced commercially for oil-well logging and laboratory use, so that they do not necessarily indicate a weapon program.
- Special tests—Since neutron initiation is so important to the proper detonation of a nuclear device, tests involving actual HE with very small (sub-critical) amounts of nuclear material would likely be carried out as well. These might be conducted in shallow underground chambers designed for neutron shielding. (A series of such tests, called ‘ ‘hydronuclear experiments,’ was conducted by the United States during the testing moratorium of 1958 -61.) Some of the surface equipment associated with these tests might also be telling.[122]

WEAPON FABRICATION

Final assembly of nuclear weapons can take place at small facilities. Indicators of such facilities could include special security arrangements and structures designed to handle accidental detonation of high explosives. These signs, however, could also indicate conventional military facilities.

Import patterns of dual-use items might again provide indicators of intent to fabricate weapons. During their inspections of weapon facilities in Iraq, the IAEA found items such as computer-numerically controlled (CNC) machinery, two-axis lathes, vacuum furnaces, and isostatic presses that had been imported through a vast network of foreign suppliers and front companies (see box 4-F). Since this equipment has a variety of industrial and nonnuclear military uses, it would be very difficult to determine its exact connection to a nuclear program simply by knowing the quantities being imported. Nevertheless, if sufficient monitoring could be implemented to detect and analyze *changes or unusual patterns* of import, or if reliable accounts of these items' ultimate end-use could be kept, tracking some subset of duaI-use equipment might provide an indication of weapon development. The import of a suite of multiuse items would provide more important information than that of individual items.

Effluents and solid waste from a suspected weapon-fabrication site might include characteristic substances associated with working plutonium metal ‘‘buttons’ into raw shapes before machining, such as tantalum, magnesium oxide, aluminum, graphite, calcium fluoride, plutonium, and plutonium oxide.[123]

NUCLEAR TESTING

Visible signs of nuclear tests

The Integrated Operational Nuclear Detection System (IONDS) aboard the Global Positioning System (GPS) satellites is designed to detect the

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[121] Tritium, a radioactive isotope of hydrogen produced mainly in nuclear reactors dedicated to that purpose, is a key element in advanced (boosted or thermonuclear) weapons as well as in accelerator-based neutron initiators. It is not subject to safeguards, however.

[122] See Robert N. Thorn and Donald R. Westervelt, op. cit., footnote 74; and Paternoster, ‘‘Nuclear Weapon Proliferation Indicators and Observable,” op. cit., footnote 110, pp. 16.

[123] John E. Dougherty, ‘‘A Summary of Indicators of Nth Country Weapon Development Programs, ’ Los Alamos Scientific Laboratory, Report LA-6904-MS, January 1978, p. 4.

Box 4-F-Iraq's Attempts to Conceal or Suppress Signatures

IAEA


IAEA inspector David Kay talks with Iraqi military authorities after they deny access to sites at Falluja in June 1991 in defiance of UN. Security Council Resolution 687.

Iraq successfully concealed both the size and level of progress of its nuclear program.[1] Four months after the June 1981 bombing by Israel of Iraq's Osirak reactor, Jaffar Dhia Jaffar (deputy minister of industry, head of reactor physics at Tuwaitha and now believed to have been the head of Iraq's nuclear weapon program) reportedly convinced Saddam Hussein that remaining in the NPT while embarking on a clandestine nuclear weapon program would present no serious difficulties.[2] Over the next decade, a nuclear program code-named Petrochemical-3 employed over 20,000 employees-7,000 of them scientists and engineers--at an estimated cost of $7 to $10 billion. This program included at least two major enrichment programs (EMIS and centrifuges, plus preliminary work with chemical enrichment), direct foreign technical assistance, and massive foreign procurement-much but not all of which fell within the domain of legal dual-use items. For example, so as not to arouse suspicion, the calutron program imported large iron-pole magnets(4.5 meters in diameter) from a European foundry in crude, unfinished form; such iron forgings were finished to specification in Iraq. The Iraqis obtained the design for buildings at the Ash-Sharqat nuclear facility that were planned to house calutrons by duplicating the Yugoslav-built Tarmiya site.[3]

Iraq did indeed have a major petrochemical industry, which helped provide cover for its nuclear-weapon-program purchases. However, at least three other factors also helped shield its foreign procurement of nuclear-related dual-use items from drawing too much attention. First, tensions among IAEA member states in the Middle East following the Israeli bombing of the Osirak reactor made it harder for the IAEA to be as proactive with respect to Iraq as it might otherwise have been.[4] Second, Iraq's war with Iran could arguably have been placing heavy demands on certain technologies that needed replenishment through imports. And finally, the United States

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[1] Much of the material in this box is based on discussions with David Kay, head of several IAEA nuclear inspections in Iraq carried out under the auspices of U.N. Resolution 687, and his presentation at the National Institute of Standards and Technology (NIST), Gaithersburg, MD, May 15, 1992.

[2] David Kay, presentation at NIST, May 15, 1892, op. dt., footnote 1; from his discussion with Jaffar during one of the early IAEA inspections in 1991.

[3] Jay C. Davis and David Kay, "Iraq's Secret Nuclear Weapon Program," *Physics Today*, July 1992, pp. 21-27.

[4] Osirak was not yet operating at the time of the attack, but had already been placed under IAEA safeguards, which would have increased in scope once the reactor became operational. Furthermore, French technicians had been present at the reactor since 1978, and were scheduled to remain for years.

and other Western nations' tilt toward Iraq in the Iran-Iraq war gave Iraq many "green lights" for importing technologies that might otherwise have caused more concern?

The Iraqis also apparently had some success at foiling western National Technical Means (NTM) of verification. The Tarmiya site, for instance, which housed the main EMIS facility, had no security fence and no visible electrical capacity; only later did inspectors discover that it was powered by a 30-kV underground electrical feed from a 150 MWe substation several kilometers away. Tarmiya was also situated within a large military security zone, thereby needing no additional perimeter security or military defenses at the site.[6] At this same site, the Iraqis built a multimillion-dollar "chemical wash" facility for recovering uranium from refurbished calutron components. This facility was reportedly as sophisticated and clean as any in the West, and triple-filtered so as not to release any trace of effluents into the atmosphere that might have led to its detection once it began operation.

[5] For instance, electron-beam welding machines were being imported under the justification of repairing tanks and jet engines. This explanation was accepted by western countries, despite the utility these machines had for certain nuclear technologies. A U.S. company also reportedly sold Iraq a sophisticated milling machine without its export-restricted laser-alignment module, but then suggested that the latter be purchased from the company's German subsidiary, where less-stringent export controls were in effect. David Kay, presentation at NIST, op. cit., footnote 1, May 15, 1992.

[6] That the Tarmiya facility Indeed housed a substantial piece of the Iraqi nuclear program was only confirmed after the Gulf War in the early summer of 1991, when the movement thereof large saucer-like objects (just prior to the first IAEA inspection of the site) led to the positive identification of the Iraqi calutron program. cf. Davis and Kay, "Iraq's Secret Nuclear Weapons Program," op. cit., footnote 3, p. 24.

characteristic double flash of light from aboveground nuclear tests anywhere in the world. Other kinds of satellite imagery might also be used to detect chilling equipment or surface changes associated with underground tests, possibly even changes caused by the shock waves from the test itself.[124]

Seismic signatures

If a country chooses to use underground nuclear explosive tests to further a weapon program, seismic disturbances would provide another telling signature. Nuclear tests with explosive yields above 10 kt in almost any region of the world would be very difficult to hide from existing seismic networks and other national technical means of verification.[125] Similarly, tests with yields down to about 1 kt would likely be detectable if there were a comprehensive worldwide network of seismic *stations* coordinated for the task.[126]

Much work has been done to analyze evasion techniques and the potential use of seismic waves to distinguish low-yield nuclear tests from earthquakes and chemical explosions. One evasion method is called "decoupling,' whereby explo-

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[124] For instance, the locations of nuclear explosion under Degelen Mountain in the Soviet Kazakhstan test site have been shown to be clearly visible through color changes associated with the shock-wave-caused spallation of rocks from the mountain above them. William Leith and David W. Simpson, "Monitoring Underground Nuclear Tests," in *Commercial Observation Satellites and International Security*, Michael Krepon, Peter Zimmerman, Leonard Spector, and Mary Umberger, eds., (New York, NY: St. Martin's Press, 1990), p. 115.

[125] U.S. Congress, Office of Technology Assessment, *Seismic Verification of Nuclear Testing Treaties, OTA-ISC-361 (Washington* DC: *U.S. Gov*ernment Printing Office, May 1988), p. 13,

[126] Ibid. For instance, with a system of tens of seismic stations distributed in and around the U.S. and former Soviet Union, nuclear tests in those countries with no attempt to muffle the seismic signals could be detected and identified down to 0.1-0,5 kt; similar coverage in the southern hemisphere or worldwide would require a corresponding worldwide seismic network. *Decoupled* explosions, or ones conducted in a large cavity to reduce the seismic waves they cause, could similarly be detected and identified down to yields of several kt to 10 kt. Also see Prof. Lynn Sykes, Lament-Doherty Geological Observatory, Columbia University, presentation at the conference sponsored by the IRIS Consortium, *The Proliferation of Nuclear Weapons and the Role of Underground Testing,* Princeton University, Nov. 12, 1992.

sions are carried out in large underground cavities.[127] However, preparations for decoupled tests might be observed by the amount of excavation required.[128] Another scheme involves hiding the signal of a nuclear test in the aftershocks of an earthquake. However, the seismic signals of earthquakes are known to differ in detectable ways from those of nuclear explosions, and exploiting them might require delaying a test detonation for weeks or longer, poised to explode within seconds of a suitable earthquake.[129] Successful evasion scenarios for nuclear tests, therefore, appear not to be very credible, especially for a nation with limited resources or experience in such areas.

Atmospheric releases from underground tests

Underground nuclear tests, even at sub-kiloton yields, generate radioactive gases at extremely high temperatures and pressures. Even under the best of circumstances, some of the radioactivity produced by underground explosions may still escape into the atmosphere through seepage or especially through controlled purges or ‘‘drill-back’ sampling to gather further data about the explosion. In the worst case, a massive ‘venting’ of the underground test would produce a plume of gas containing millions of curies of radioactive debris rising thousands of meters into the air.[130] Even if a country has considerable underground testing experience, massive releases can still occur; the ‘‘Des Moines’ test at the Nevada Test Site on June 13, 1962—-a test carried out in a tunnel about 200 meters into the side of a mountain-unexpectedly vented such an enormous cloud of debris (11,000,000 curies) that it reportedly caused a near-panic among test-site workers who rushed to drive away from a mountain-size radioactive cloud that formed above the test site and began blowing toward them.[131] Prior to this test, the United States had already accumulated experience from several dozen shaft or tunnel tests carried out at the Nevada Test Site in 1958 and 1961-62. If a clandestine test site in another country were suspected, and if timely access could be gained near the site, radioactive products could be monitored by aerial or ground sampling. Small amounts of specific gases produced by underground tests might also be detected at close range by exploiting their light-scattering properties when illuminated by lasers.

Nuclear-test-site preparation

Regardless of whether a country chooses to test a nuclear device at full yield or at reduced yields, a suitable underground site would be highly desirable. Since underground tests can be contained quite effectively when carried out properly, test-preparation activities would often be more observable than would atmospheric releases from tests themselves. **Drilling rigs,** sections of one-meter-diameter or larger pipe, mining operations, or road construction in new remote locations could all indicate such preparations and could probably be observed by reconnaissance satellites. (Determining that such activities actually do pertain to nuclear testing, however, may prove more difficult.) Contacts with foreign firms having experi-

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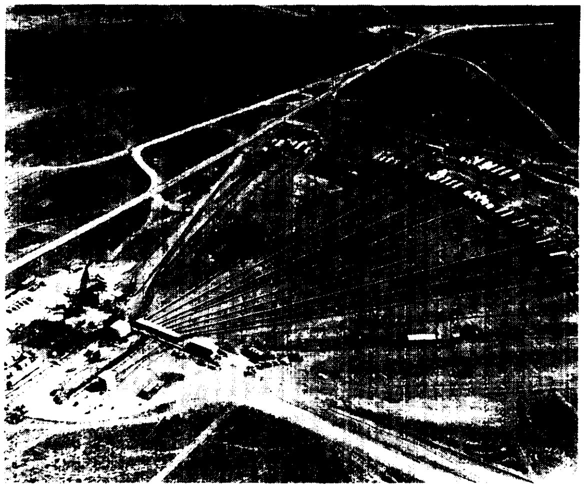
[127] The possibility remains that decoupled tests below 1 to 2 kt would not be readily identifiable as nuclear tests, even if they could be monitored and detected by an enlarged worldwide seismic network. OTA, *Seismic Verification of Nuclear Testing Treaties,* op. cit., footnote 125, p. 14.

[128] The diameter of the cavity needed to decouple a 1-kt detonation in rock, for instance, is roughly 40 meters, and it sales as the one-third power of the yield, OTA, *Seismic Verification of Nuclear Testing Treaties,* op. cit., footnote 125, p. 100.

[129] Distinguishing between earthquakes and nuclear tests depends somewhat on the strength of their seismic signals; fOr nuclear tests with yields below about 1 kt, discrimination can become very difficult.

[130] U.S. Congress, Office of Technology Assessment, *The Containment of Underground Nuclear Explosions,* OTA-ISC-414 (Washington, *DC:* U.S. Government Printing Office, October 1989), p. 4, 33.

[131] Jim Carothers, Office of History and Historical Records, Lawrence Livermore National Laboratory, presentation at the IRIS conference, Nov. 12, 1992, op. cit., footnote 126.


LAWRENCE RADIATION LABORATORY, LIVERMORE

Nevada test site location in 1966 prior to an underground nuclear test, Large drilling equipment, cranes, heavy electrical cables, and roads could all provide visual indicators of such a test site.

ence in large-hole drilling technology (for instance, through experience with nuclear testing programs in the United States or elsewhere) might also be indicators. Electronic data-acquisition systems, which are widely available around the world, would require extensive cabling systems suitable for transmitting diagnostic signals and might also be visible.

Deployment, Storage, and Maintenance of Nuclear Weapons

A country interested in possessing not just one or two but a small arsenal of nuclear weapons would have to make preparations for their storage, maintenance, handling, and deployment. Observable might include construction of maximum-security storage facilities or operational exercises reflecting the special requirements for handling nuclear weapons. Aircraft training runs for delivering nuclear weapons might exhibit unique flight profiles designed to give the pilot time to escape the effects of the blast. Military doctrine governing use of nuclear weapons would have to be developed and integrated into the command structure of appropriate forces. A greater number of people might thus learn of the weapons' existence, adding to the chance that human sources might reveal it.

The difficulty of producing fissile materials, however, limits the rate at which a proliferant could field nuclear weapons. If only a very small number of weapons were at hand, they might be reserved for strategic rather than battlefield use, thus reducing the need to conduct military exercises that anticipated combat in a nuclear environment. Furthermore, the weapons might be stored unassembled and their components kept at various locations. They might also be kept under the control of a small military or quasi-military unit outside of the regular military forces. It therefore might be very difficult to detect a nuclear force still in its infancy solely by relying only on observable changes in deployment, storage facilities, or military operations. Materials production would still provide the greatest opportunities for detecting such a program.

Appendix 4-A

Components, Design, and Effects of Nuclear Weapons

A nuclear weapon is a device that releases large amounts of explosive energy through extremely rapidly occurring nuclear reactions. Nuclear fission reactions occur when a heavy atomic nucleus is split into two or more smaller nuclei, usually as the result of a bombarding neutron but sometimes occurring spontaneously; fusion occurs when lightweight nuclei are joined, typically under conditions of extreme temperature and pressure. Nuclear weapons utilize either fission or a combination of fission and fusion.

A nuclear explosive device is normally made up of a core of fissile material that is formed into a ‘‘super-critical mass’ (see below) by chemical high explosives (HE) or propellants. The HE is exploded by detonators timed electronically by a “fuzing” system, which may use altitude sensors or other means of control. The nuclear chain-reaction is normally started by an “initiator” that injects a burst of neutrons into the fissile core at an appropriate moment.[1]

Fission devices are made with highly enriched uranium-235 or with plutonium-239, which is produced in nuclear reactors through neutron bombardment of uranium-238,[2] Uranium-233, which is produced in reactors fueled by thorium-232, can also be used to construct a fission device.

In fission weapons, energy is released through an explosive chain reaction that occurs when neutron-bombarded nuclei split and subsequently emit additional neutrons.[3] These additional neutrons sustain and multiply the process in succeeding fission reactions or ‘‘generations. The minimum mass of fissile material that can sustain a nuclear chain reaction is called a *critical mass* and depends on the density, shape, and type of fissile material, as well as the effectiveness of any surrounding material (called a ***reflector or tamper)*** at reflecting neutrons back into the fissioning mass. Critical masses in spherical geometry for weapon-grade materials are as follows:[4]

	Uranium-235	Plutonium-239
Bare sphere:.	56 kg	11 kg
Thick U Tamper.	15 kg	5 @

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[1] At a presentation at the South African Embassy, Washington, DC, on July 23, 1993, Waldo Stumpf, chief executive officer of the Atomic Energy Corporation of South Africa, Ltd., stated that South Africa designed a gun-type weapon using HEU that employed no neutron initiator.

[2] Uranium-235 is the only naturally occurring isotope that is ‘‘fissile,’’ “i.e., able to be fissioned by neutrons of any speed. Its concentration in natural uranium (most of which is uranium-238) is only about 0.71940.

[3] The amount of energy ultimately released is given by Einstein’s relation $E=mc^2$, where c is the speed of light and m is difference in mass between the original nucleus and that of all the pieces into which it is spit.

[4] Robert Serber, *The Los Alamos Primer: First Lectures on How to Build an Atomic Bomb* (Berkeley, CA: Univ. of California Press, 1992), p. 33.

U.S. DEPARTMENT OF ENERGY

The "mushroom cloud" of hot gases and radioactive debris caused by a nuclear detonation near the ground can rise upwards of tens of thousands of feet and spread dangerous radioactive fallout far downwind.

Significant quantities of nuclear materials have been defined by the International Atomic Energy Agency (IAEA), which is charged with ensuring that these materials not be diverted from peaceful uses into weapons (see app. 4-C and table 4C-3 on significant quantities). These thresholds, which the IAEA considers sufficient for processing into a weapon, are 8 kg of plutonium (total element) or 25 kg of the isotope uranium-235 in highly enriched form (uranium containing 20 percent or more of the isotope uraniurn-235).[5] A first-generation fission weapon developed by a state without much experience at nuclear weapon design would most likely have a yield in the range of 1 to 50 kilotons.[6]

Two basic designs to assemble a supercritical mass of fissile material are *gun-assembly* and *implosion. In the* gun-assembly technique, a propellant charge propels two or more subcritical masses into a single supercritical mass inside a high-strength gun-barrel-like container. Compared with the implosion approach, this method assembles the masses relatively slowly and at normal densities; it is practical only with highly enriched uranium. (If plutonium—even weapon-grade-were used in a gun-assembly design, neutrons released from *spontaneous* fission of its even-numbered isotopes would likely trigger the nuclear chain reaction too soon, resulting in a ''fizzle' of dramatically reduced yield. See box 4-B on reactor-grade plutonium in main text.)

In the implosion technique, which operates much more rapidly, a shell of chemical high-explosive surrounding the nuclear material is designed (for example, by being detonated nearly simultaneously at multiple points) to rapidly and uniformly compress the nuclear material to form a supercritical mass. This approach will work for both uranium and plutonium and, unlike the gun-assembly technique, creates higher than normal densities. Since critical mass decreases rapidly as density increases (scaling as the inverse square of the density), the implosion technique can make do with substantially less nuclear material than the gun-assembly method.

In both types of designs, a surrounding *tamper* may help keep the nuclear material assembled for a longer time before it blows itself apart, thus increasing the yield. The tamper often doubles as a neutron reflector. In a fission weapon, the timing of the initiation of the chain reaction is important and must be carefully designed for the weapon to have a predictable yield. A neutron generator emits a burst of neutrons to initiate the chain reaction at the proper moment—near the point of maximum compression in an implosion design or of full assembly in the gun-barrel design.

Using these approaches, a substantial fraction of a weapon's fissile material would probably be blown

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[5] If one could assemble 8 kg of plutonium into a sphere, it would have a diameter of about 9.2 cm, somewhat bigger than a baseball; 25 kg of uranium would have a radius about 1.5 times larger.

[6] A kiloton (kt) is defined as 4.18 x 10^{12} joules, which is approximately the energy released in the explosion of a thousand tons of TNT.

apart before it fissioned. To fission more of a given amount of fissile material, a small amount of material that can undergo fusion, deuterium and tritium (D-T) gas, can be placed inside the core of a fission device. Here, just as the fission chain reaction gets underway, the D-T gas undergoes fusion, releasing an intense burst of high-energy neutrons (along with a small amount of fusion energy as well) that fissions the surrounding material more completely. This approach, called *boosting,* is used in most modem nuclear weapons to maintain their yields while greatly decreasing their overall size and weight.

Fusion (or ''thermonuclear' weapons derive a significant amount of their total energy from fusion reactions. The intense temperatures and pressures generated by a fission explosion overcome the strong electrical repulsion that would otherwise keep the positively charged nuclei of the fusion fuel from reacting. In general, the x-rays from a fission "primary" heat and compress material surrounding a "secondary" fusion stage.[7] Such bombs, in theory, can be designed with arbitrarily large yields: the Soviet Union once tested a device with a yield of about 59 megatons.

EFFECTS OF NUCLEAR WEAPONS

The massive amounts of energy released by both fission and fusion explosives generate blast, heat, and radiation. Blast effects include shock waves, overpressure, and intense winds. Heat is released in the form of infrared and visible radiation which, for large-yield weapons detonated under the right conditions, can cause firestorms in cities well beyond the region of heavy blast damage.[8] Radiation effects include the prompt bursts of gamma rays and neutrons, the production of radioactive fission products and, if the explosion's fireball touches the ground, significant amounts of fallout of radioactive materials formed from or condensed upon soil that is swept up into the mushroom cloud.[9] Taking into account all of these effects except fallout, the *effective lethal radius*[10] for a l-kt fission weapon is approximately 0.7 km (area 1.5 km^2), for a 20-kt fission weapon 1.8 km (area 10 km^2), and for a l-Mt hydrogen bomb 7-13 km (area 150-600 km^2), depending on the occurrence of firestorms.[11]

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[7] The secondary usually contains solid lithium-6 deuteride. (Lithium-6 creates tritium when bombarded by neutrons produced during the detonation.) As in fission weapons, the liberated energy is reflected in the change in total mass during the reaction.

[8] William Daugherty, Barbara Levi, and Frank von Hippel, "The Consequences of 'Limited' Nuclear Attacks on the United States," *International Security,* vol. 10, No, 4, spring 1986, p. 15.

[9] A nuclear weapon detonated at high altitude can also generate a powerful pulse of radio waves (called "electromagnetic pulse' '), which can wreak havoc on some types of electronic equipment, but would not pose a direct human health risk.

[10] Here, *effective lethal radius* describes a circular area around ground zero for which the number of people residing in the circle (assuming uniform population density) is the same as the total number of people that would be killed under normal conditions by the immediate effects of the explosion. Alternatively, it describes the radius at which the fatality rate, given a typical amount of shielding for an urban area, is approximately 50%.

[11] See, for example, Dietrich Schroeer, *Science,* Technology, *and the Nuclear Arms Race (New* York, NY: John Wiley & Sons, 1984), p. 47 (figure 2.9).

Appendix 4-B

Enrichment Technologies

This appendix describes several approaches by which the uranium-235 isotope used in nuclear weapons can be separated from the more common uranium-238. Enrichment plants based on these approaches generally consist of a number of individual *stages*, each of which takes an input source of uranium, or "feed,' and produces two outputs: one with a greater concentration of uranium-235 than the feed (the "product"), and the other depleted in uranium-235 (the "tails"). The *separation factor* indicates how much enrichment each stage provides. (It is defined as the relative isotopic abundance of uranium-235 of the product divided by that of the tails.)

Tables 4-4 through 4-7 in the main text summarize and compare attributes of various enrichment approaches. The descriptions below are illustrative, but by no means exhaustive, of the isotopic enrichment methods known to have been supported by substantial research or development programs. Not included are many completely different techniques that have been proposed, some of which have undergone preliminary research.[1]

URANIUM AND ITS PROPERTIES

Several different chemical compounds of uranium are used in enrichment processes, all of which are difficult to handle. Although calutrons used by the United States during World War 11 and by Iraq in the late 1980s utilized UCl_4 feed to make ion beams, the most important feed material for enrichment is UF_6, a colorless solid at room temperature that sublimes at 56.5 "C. UF_6 is used in gaseous diffusion, centrifuge, aerodynamic, MLIS and, in its liquid state, thermal diffusion processes. It is highly corrosive to many metals and generally requires special nickel or aluminum alloys to process it. It also reacts violently with water and with many organic compounds such as oils and lubricants, so that handling systems must be extremely clean and free of leaks. Chemex processes (see below) normally use simple uranium compounds in hydrochloric acid solution.

In its elemental form, uranium is a silvery-white metal which, when finely divided in air, ignites spontaneously and, when in its atomic vapor state, is highly corrosive to many materials. AVLIS and plasma processes use atomic uranium. The ion beam

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[1] Examples of some of the others can be found in **Allan** S. **Krass** et al., *Uranium Enrichment and Nuclear Weapon Proliferation* (London: Taylor & Francis, Ltd., 1983), pp. 171-2, 186-7, and references therein.

used in EMIS, though produced from UCI_4, is also elemental uranium.

THERMAL DIFFUSION

The uranium compound UF_6 in its liquid state is subjected to strong temperature differences to separate the heavier (uranium-238) isotope from the lighter one (uranium-235). The United States developed this process before WWII using concentric tubes, cooled on the outside wall by water and heated on the inside by steam; in the region between the tubes, the lighter isotope very slowly tended to concentrate near the inner wall and rise, whereby it was removed. The separation factor is no more than about 1.0003, and only very low enrichments are possible.[2] In 1944, 2,100 such tubes-each almost 15 m high-produced enrichments of only about 0.9 percent uranium-235 (starting from natural uranium with about 0.71 percent uranium-235) to feed the U.S. calutron program.[3] Thermal diffusion is not known to have been used on any significant scale since World War II.

GASEOUS DIFFUSION

UF_6 in its gaseous state is forced through a suitable porous barrier that preferentially passes the lighter molecules containing uranium-235, which travel on average a little faster and diffuse through the barrier slightly more efficiently. Gaseous diffusion is a proven technology, but requires an enormous amount of electricity to operate its pumps and compressors. Moreover, to produce significant quantities of enriched material, cascades must have thousands of stages, each stage having many elements or chambers. A cascade requires up to weeks between start-up and the point when it first produces appreciable amounts of enriched uranium (and months or longer to reach equilibrium). Therefore, ‘batch recycling ‘—the process of reintroducing an enriched product as new feed stock into a cascade designed to produce LEU from natural uranium-is a relatively unattractive means of achieving higher enrichments. The U.S. gaseous diffusion plant at Oak Ridge made only a small contribution to the uranium enrichment effort during World War II, but the diffusion technology soon came to dominate the field.

GAS CENTRIFUGE

Precision high-speed rotors containing UF_6 gas spin within vacuum chambers. Heavier isotopes concentrate preferentially near the rotor’s wall and are made to convect upwards, where they can be scooped out. New high-strength lightweight materials, such as carbon- or glass-fiber bonded with resins allow modem centrifuges to spin at extremely high speeds.[4] Cascade equilibrium times are measured in minutes to tens of minutes. This technology is widely used in several countries in Europe and in Japan, and has also been developed in the United States.

Attractive for proliferation in almost every respect (economical, efficient, widely dispersed proven technology, easily capable of high-enrichment, etc.), modern centrifuge technology is classified and is constrained by strict export controls.[5] Even so, Japan, Pakistan, India, and Brazil have each been able to build gas centrifuge cascades, and Iraq and South Africa had purchased many components in spite of export controls. All of these have been URENCO-type modern centrifuges, which are at least 20 times more productive than those designed by Gemot Zippe in the Soviet Union in the late 1940s. By the late 1950s, the Soviet Union adopted Zippe’s basic design and went on to develop centrifuge technology to a production scale. (In 1942-43 during the Manhattan Project, the United States also considered using early-design centrifuges, but rejected them because of mechanical problems.)

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[2] Separation factor is defined as ratio of the relative (uranium-235 to uranium-238) enrichment of the product stream to that of the tails or waste stream in any one stage of a cascade.

[3] See Richard H. Rhodes, *The Making of the Atomic Bomb* (New York, NY: Simon & Schuster, 1986), pp. 552-4; and Manson Benedict and Thomas H. Pigford, *Nuclear Chemical Engineering, 2nd ed.* (New York, NY: McGraw-Hill, 1989), pp. 498-508. Even this small enrichment made a useful contribution to the productivity of the calutrons.

[4] Aluminurn and titanium rotors are only strong enough to run at moderate speeds; *maraging* steel—a particularly strong low-carbon alloy, typically consisting of at least 10% nickel plus cobalt, molybdenum, and other alloying agents-allows moderately high speeds. See Krass *et al., Uranium Enrichment. . . .* op. cit., footnote 1, pp. 132.

[5] Designs for low speed (subcritical) aluminurn-alloy centrifuges of the type developed by Gernot Zippe up to 1960, however, are an exception and are not classified.

AERODYNAMIC PROCESSES

A carrier-gas and isotope mixture is forced at high speed through a curved nozzle or vortex, allowing centrifugal force to concentrate the heavier isotopes nearer the outer portion of the flow where they can then be separated by a skimmer. Due to low separation factor (intermediate between gaseous diffusion and centrifuges) and high energy consumption, aerodynamic processes are economically not very attractive, but could be configured in modular cascades in a relatively small facility for a weapon program.

CHEMICAL EXCHANGE PROCESSES

Low-energy, low-maintenance chemical-exchange separation methods are based on chemical reactions that exhibit a slight preference for one uranium isotope over the other. Two methods known to have been developed to date are the Japanese Asahi ion-exchange process, which requires a proprietary resin, and the French solvent-extraction (Chemex) process. Both use special chemicals in the liquid state.[6] The Asahi process requires a specific catalyst and is limited by the mixing times of the reagents and the reticulated resin, but with the catalyst present the chemical exchange operates very rapidly. The French process does not require an exchange catalyst and is limited only by the mixing dynamics, but it must avoid impurities that can catalyze unwanted reactions. Because of the very low separation factor, up to thousands of stages can be required even to reach LEU; however, since a single physical item (e.g., an ion exchanger or pulse column) can contain tens or hundreds of effective "stages," these large numbers can be misleading. Both processes have been put through pilot-plant operations that have produced the expected enrichments at costs that would be economical on a commercial scale.[7]

In part because LEU made with chemical separation might permit other enrichment approaches to reach high enrichments more readily than they would if fed with natural uranium, France has offered to sell its Chemex process to countries only on the condition that they not pursue any other enrichment paths.

LASER PROCESSES

These methods include Atomic Vapor Laser Isotope Separation (AVLIS), Molecular-vapor Laser Isotope Separation (MLIS), and Laser-Assisted Processes (LAP) such as "Chemical Reaction by Isotopic Selective Activation" (CRISLA). All utilize small differences in the frequencies of light that atoms or molecules of different isotopic masses will absorb. Laser processes in general must induce several atomic or molecular interactions (excitations, ionizations, or chemical reactions) in succession, requiring several lasers to act in concert. Laser frequencies must be tuned very precisely-usually to an accuracy of about 1 part in 1,000,000.[8] Maintaining such precise tuning at high power levels is one of several key technical obstacles faced by laser processes.

AVLIS, as developed at the Lawrence Livermore Laboratory, uses laser radiation to selectively strip an electron off atoms of uranium-235, but not uranium-238, in a uranium metal vapor at high temperatures and low density. MLIS uses tuned laser light analogous to AVLIS to selectively excite an electron in ^{235}UFG (but not ^{238}UF molecules and then to remove one fluorine atom. CRISLA's inventors claim that they have a proprietary compound that functions as an intermediary, selectively reacting with laser-excited $^{235}UF_6$ molecules. (This has not been independently confirmed, however.) Although MLIS and CRISLA reaction rates are both hindered by unwanted molecular collisions competing with desirable laser-excitation processes, the CRISLA process may have the added complexity of needing a particular collisional excitation to win out over the others.

Laser processes are still in development, and tests so far have been conducted only in the laboratory or in small pilot-plants. Because of their potential to produce high enrichments in a single step and their low energy use, they could eventually prove to be very efficient. Some of the equipment associated with laser processes is not subject to export controls and could probably also be developed-at least on a laboratory scale-by countries such as Israel, India, and Brazil.

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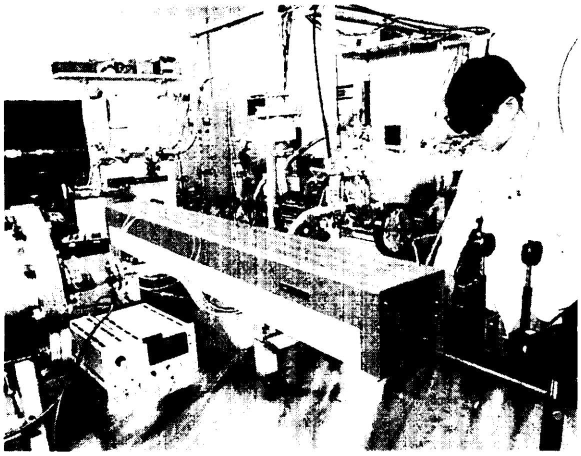
[6] If high enrichment levels are to be produced, great care must be taken to avoid the formation of a critical mass of material anywhere within the facility. Criticality with liquid and solid-phase methods is much more of a concern than with methods using gaseous forms of uranium.

[7] John M. Googin, senior staff consultant, Martin Marietta Energy Systems, Inc., private communication, Aug. 11, 1993.

[8] AVLIS uses pumped dye lasers, MLIS uses $C0_2$ infrared lasers and possibly xenon-chloride excimer lasers operating in the ultraviolet, and CRISLA uses CO infrared lasers.

PNC



Laser *equipment that could be used for research and development of laser isotope separation (LIS) techniques. LIS methods are among several advanced technologies that may eventually lead to more efficient ways of enriching uranium.*

Nevertheless, the required laser and material-flow technologies-especially at the scale needed for commercial operation—are highly sophisticated, and their integration poses a number of very serious difficulties.[9] However, in early 1992 the South African Atomic Energy Corporation announced that it was planning to begin operating one unit of a MLIS pilot enrichment facility in 1994, and a similar pilot-scale facility is being built in Japan. An AVLIS pilot plant is also under construction in the U.K.

ELECTROMAGNETIC PROCESSES

This group of technologies includes EMIS (calutrons), ion cyclotron resonance, and plasma centrifuge methods. Although theoretically as capable as laser processes at producing high enrichments with a small number of stages, these are — with the exception of the calutron—still in the experimental stage. All would require frequent maintenance, since the enriched product accumulates in collectors that can only be accessed when the system is turned off and partially disassembled. They also require a precisely controlled high-voltage vacuum-ion source (now subject to export controls under the 1992 Nuclear Suppliers Group dual-use guidelines) and strong, uniform electromagnets. (Ions are atoms with an electron removed, giving them a positive net electrical charge.) Ions of different masses are separated by exploiting the different curvatures of the paths they take when traveling through magnetic fields. Electromagnetic methods are also useful for separating plutonium isotopes, a task otherwise practical only through laser or centrifuge techniques.[10]

| Calutrons

Calutrons send high-voltage ions through a half-circle of rotation in a strong magnetic field inside a large disk-shaped vacuum chamber. They are very energy-inefficient, costly, bulky, and require a great deal of maintenance. Developed and used by the United States during World War II, their design was declassified decades ago.

Since higher separation factors require lower beam densities, up to several hundred calutrons could be required to produce enough HEU for a single bomb per year. However, use of even slightly enriched feed dramatically increases a calutron's production rate, thereby reducing the number of units needed. The Iraqi enrichment program relied primarily on calutrons.

| Ion Cyclotron Resonance

Ion cyclotron resonances techniques rely on the roughly 1 percent difference in frequency at which ions of different uranium isotopes orbit in a magnetic field. This difference allows precisely tuned radio waves to selectively energize one isotope over the other. The selected ions will absorb radio energy and orbit in ever larger spirals, eventually colliding with a downstream set of collector plates. Other isotopes are not affected, and most will pass through the gap in the plates. Key difficulties are that the process requires extremely

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[9] For instance, between 1973 and 1990, the U.S. Department of Energy invested almost $1 billion in AVLIS development, but produced only kilogram quantities of 1% enriched uranium. In 1990 it had planned to build a 100,000-250,000 SWU/yr pilot plant that might have begun operation in 1992, but the idea has now been practically abandoned.

[10] The plutonium isotopes of interest are closer in mass than uranium isotopes and hence harder to separate.


LOS ALAMOS NATIONAL LABORATORY

Iraqi electromagnetic isotope separation (EMIS) equipment, here being uncovered by IAEA and United Nations inspectors, had been hidden in the desert following the Persian Gulf War.

uniform magnetic fields, usually calling for superconducting magnets, and a suitable electromagnetic signal or wave. In large machines, producing ions from metallic uranium can also be problematic. This enrichment process has been demonstrated with modest size units, but is not projected to become commercially competitive.

| Plasma Centrifuge Separation

Plasma centrifuge separation, in contrast to ion cyclotron resonance, requires an ionized gas (or *plasma)* to be created that is dense enough to undergo frequent internal collisions. If injected perpendicular to a magnetic field, such a plasma will forma ring and rotate. As the isotopes to to equalize in velocity, the heavier isotopes will tend to concentrate toward the outer portion of the ring where they can be removed (analogous to gas centrifuges). This is probably the least developed of the electromagnetic methods, and may use substantially more energy and achieve a lower enrichment factor than ion cyclotron resonance. It may also suffer from instabilities and other operational difficulties.

Appendix 4-C

Safeguards and the Civilian Nuclear Fuel Cycle

As of the end of 1992, there were 424 commercial nuclear power reactors in operation in 29 countries, producing 330 GW of electricity (see table 4C-1).[1] About 75 percent of these are light-water reactors (LWRs) fueled by low-enriched uranium (LEU) containing 3 to 4 percent uranium-235. Most of the remainder are fueled by natural uranium and are moderated by either heavy water (CANDU-type reactors) or graphite.[2] Some LWRs in France, Germany, and Switzerland have now been loaded with mixed plutonium-uranium oxide (MOX) fuel, which replaces about a third of their cores. (Japan and Belgium also have plans to fuel LWRs with MOX.) Several breeder reactors fueled by plutonium have also been built, but the majority of them have been shut down in recent years.

The low-enriched or unenriched fuel supplying almost all of these reactors is not a direct proliferation threat. However, all nuclear reactors are theoretical sources of material for nuclear weapons, since plutonium is produced in reactors fueled by uranium, and the fresh low-enriched fuel used in LWRs would be considerably easier than natural uranium to transform into HEU.[3] *If not adequately safeguarded, the* fuel cycle and facilities associated with power reactors provide a number of points from which relevant materials could be diverted.

So far, no nuclear facilities under full-time IAEA safeguards are known to have produced fissile material used in nuclear explosives. The five nuclear weapon states have each used dedicated facilities to make weapon materials. The several states thought to have prepared weapon-usable material outside or in violation of safeguards commitments have primarily used either small reactors coupled with unsafeguarded pilot reprocessing plants (e.g., India, Israel, and North

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[1] These figures do not include 72 reactors under construction in these plus another three countries, or any research reactors—of which there are about 325 in over 50 countries. Half of these research reactors are in the five nuclear weapon states. The number of power and research reactors has remained nearly constant since the middle 1980s, with slightly more reactors having been decommissioned or shut down since that time than brought online.

[2] The moderator in a nuclear reactor slows down the neutrons produced in fission reactions so that they can more efficiently induce subsequent fission reactions.

[3] Uranium-233 (another weapon-usable material) is produced in reactors that contain thorium, but few reactors based on a thorium fuel-cycle have ever been built.

Table 4C-1-Nuclear Power and Research Reactors Around the World

	Power reactors in operation”			Power reactors under construction.		
	No. units	Total MW(e)	%electric power	No. units	Total MW(e)	Research reactors[c]
Argentina.	*2*	935	19.1 %	1	692	5
Belgium.	7	5,484	59.3%	—	—	5
Brazil..	1	626	0.6%	1	1,245	4
Bulgaria	6	3,538	34.00/0	—	—	1
Canada.	21	14,874	16.4%	1	881	14
China.	1	288	NA	2	1,812	12
Cuba.	—	—	—	2	816	0
Czech Republic.	4	1,632	28.7%	2	1,784	2
Finland.	4	2,310	33.3%	—	—	1
France.	56	57,688	72.7%	5	7,125	20
Germany.	21	22,559	27.6%		—	25
Hungary.	4	1,729	48.4%	—	—	3
India, ...	9	1,593	1.8%	5	1,010	6
Iran. ., ...	—	—	—	2	2,392	2
Japan.	44	34,238	23.8%	9	8,125	18
Kazakhstan, ...	1	335	NA	—	—	3
Korea, Rep. of.	9	7,220	47.5940	*3*	2,550	3
Lithuania.	2	2,760	NA	1	1,380	—
Mexico.	1	654	3.6%	1	654	4
Netherlands.	2	504	4.9%			2
Pakistan.	1	125	0.8%	—	—	2
Romania.	—	—	—	5	3,155	2
Russian Federation. . .	28	18,893	11.8940	18	14,175	20
South Africa.	2	1,842	5.9%	—	—	1
Slovak Republic.	4	1,632	28.7%	4	1,552	2
Slovenia	1	632	34.6%	—	—	0
Spain.	9	7,101	35.970			0
Sweden.	12	10,002	51 .6%			2
Switzerland.	5	2,952	*40.0%*	—	—	4
United Kingdom.	37	12,066	*20.6%*	1	1,188	11
Ukraine.	15	13,020	NA	6	5,700	2
Us..	109	98,796	21.770	3	3,480	92
World total:.	424’[9]	330,918[e]	NA	72	59,716	~326

NA = not available

a Data, which reflect the status as of the end of 1992 as reported by the IAEA, are preliminary and subject to change.

b percentages are for 1991, except for Russia and Slovenia, where preliminary 1992 data are used.

c Research reactors in operation as of May 1991. Total includes one research reactor in operation under the Commission of European Communities, five in Taiwan, plusthefollowing (in countries that have no power reactors) :Algeria (1); Australia (2); Austria (3); Bangladesh (1); Chile (2); Colombia (l); Denmark (2); Egypt (l); Estonia (2); Greece (2); Indonesia (3); Iraq (2); Israel (2); Italy (6); Jamaica (1); Latvia (l); Libya (l); Malaysia(l); North Korea (2); Norway (2); Peru (2); Philippines (1); Poland (3); Portugal (1); Thailand (1); Turkey (2); Uzbekistan (1); Venezuela (1); Vietnam (1); and Zaire (1).

d Represents the average 1991 value for the Czech and Slovak Republics

e The total includes Taiwan, where six reactors totalling 4,890 MWe are in operation, accounting for 37.80A of the total electricity generated there in 1992.

SOURCE: *IAEA Bulletin, vol. 35,* No. 1, March 1993 and vol. 33, No. 3, September 1991; and William C. Potter, Nuclear *Profiles of the Soviet* Successor *States* (Monterey, CA: Monterey Institute of International Studies, May 1993).

Table 4C-2—Number of Installations Under IAEA Safeguards or Containing Safeguarded Material as of Dec. 31, 1992

Type of installation[a]	INFCIRC/153b (Corr.)	INFCIRC/66[c] (Rev. 2)	In NWS[d]	Total
Power reactors.	182	17	2	201
Research reactors and critical assemblies.	145	22	2	*169*
Conversion plants, ...	7	3	0	10
Fuel fabrication plants.	34	9	1	44
Reprocessing plants.	5	1	0	6
Enrichment plants.	5	1	1	7
Separate storage facilities.	36	6	5	47
Other facilities.	57	4	0	61
Subtotals.	471	63	11	545
Other locations.	468	32	0	500
Nonnuclear installations.	0	3	0	*3*
Totals.	939	98	11	1048

a For some types of installation, predominantly reactors and so-called "other locations, " several installations can be located at a single site or facility.
b Covering safeguards agreements pursuant to NPT and/or Treaty of Tlatelolco; excludes locations in Iraq.
c Excluding installations in nuclear-weapon States; including installations in Taiwan, China.
d Nuclear-weapon States.

SOURCE: IAEA, *The Annual Report for 7992,* GC(XXXVII)/1060 (Vienna, Austria: International Atomic Energy Agency, July 1993), p. 149.

Korea) or unsafeguarded pilot enrichment plants (e.g., Pakistan, South Africa, and Iraq).[4]

The reason for the apparent preference for dedicated or unsafeguarded weapon facilities is straightforward: the construction and operation of nuclear power reactors and other commercial facilities so as to divert materials to a weapon program is neither the easiest nor the most efficient route to obtain nuclear weapon materials. First, more than 150 states have joined the NPT as nonnuclear-weapon states, which obligates all with nuclear facilities to sign and implement so-called *safeguard* agreements with the IAEA to provide assurance of *nondiversion* of nuclear materials. (As of Dec. 31, 1992, the IAEA had 188 safeguards agreements in force with 110 states plus Taiwan.[5] See table 4C-2.) Second, the vast majority of the material in the commercial nuclear fuel cycle is not directly suitable

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[4] See, for example, David Fischer and Paul Szasz, *Safeguarding the Atom: A CriticalAppraisal* (London: SIPRI, Taylor and Francis, 1985), p. 52; and Leonard S. Spector with Jacqueline R. Smith, *Nuclear Ambitions: The Spread of Nuclear Weapons, 1989-1990* (Boulder, CO: WestView Press, 1990).

[5] The 45 parties to the Nuclear Non-Proliferation Treaty with safeguards in force base their agreements on the IAEA document INFCIRC/153(Corrected)—' 'The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons. " The 10 non-NPT states with safeguards in force base their agreements on INFCIRC/66/ Revision.2 —"The Agency's Safeguards System" (1965, as provisionally extended in 1966 and 1968). (The term ''INFCIRC'' comes from ''Infomnation Circular. ' In addition, some safeguards were applied in the five nuclear weapons states under voluntary agreements.

Some important non-NPT states have accepted IAEA safeguards (INFCIRC/66) on certain facilities, but rarely do these cover key nuclear facilities from a proliferation perspective. In order for the IAEA to determine nondiversion for a State as a whole, it must have *all* nuclear materials in a country's fuel cycle under safeguards, a situation called fill-scope *safeguards.*

PETR PAVLICEK, IAEA

IAEA Board room showing participants at an international advisory committee meeting. Membership in the IAEA since 1957 has grown to over 100 States.

for weapons and requires difficult additional steps, such as conversion, further enrichment, or reprocessing, to make it so. For instance, all handling of commercial spent fuel requires extensive shielding to protect workers from lethal doses of radioactivity. Furthermore, reprocessing of that fuel yields reactor-grade plutonium, which is less desirable than other fissile materials for making weapons. Finally, operating large commercial facilities in the obviously uneconomic way that would be required to maximize their ability to produce weapon material-such as with frequent fuel changes-would draw considerable attention whether safeguarded or not.

IAEA SAFEGUARDS

IAEA safeguards are a system of procedures for nuclear material accountancy, control, and verification that are implemented through agreements between the IAEA and individual countries. These procedures involve: record-keeping at facilities; reporting requirements for material transfers and inventories; standardized measurements and assays; containment and surveillance methods (using seals, cameras, and other recording devices); and regular onsite inspections by the IAEA. The objective of safeguards is the timely detection of diversion (or verification of nondiversion) of a *significant quantity* of nuclear materials from *declared peaceful* activities to nuclear explosive purposes (see tables 4C-3 and 4C-4). Except for the **possibility of so-called "special" inspections-which had not been used at any undeclared location prior to the Persian Gulf War—safeguards agreements require only that declared (peaceful) activities be verified as being peaceful, and that the materials they involve be accounted for; they do not require verification of the absence of nondeclared (possibly weapon) activities (though such activities, if discovered, would be a violation).** Furthermore, even strict adherence to safeguards cannot predict future intent.

NPT safeguards focus on nuclear materials themselves and not on other facilities that potentially *could*

Table 4C-3--IAEA Significant Quantities of Nuclear Materials

	Material	Significant quantity	Safeguards apply to?
Direct-use material:	Pu[b]	8 kg	Total mass of element
	U-233	8 kg	Total mass of isotope
	U (with U-2352 20%)	25 kg	Mass of U-235 contained
Indirect-use material:	U (with U-235 < 200/0)'	75 kg	Mass of U-235 contained
	Thorium	20 tonnes	Total mass of element

a Plus rules for mixtures, where appropriate.

b For plutonium containing less than 80% Pu-238.

c Including natural and depleted uranium.

SOURCE: *IAEA Safeguards Glossary, 1987 Edition,* IAEA/SG/INF/1 (Rev. 1), (Vienna, Austria: International Atomic Energy Agency, December 1987), p. 24.

Table 4C-4-Estimated Material Conversion Time for Finished Plutonium- or Uranium-Metal Components

Conversion time	Beginning material form
Order of days (7-10):	Pu, HEU, or U-233 metal
Order of weeks (1-3)[a]:	PuO_2, $Pu(NO^-_3)_4$, or other pure Pu compounds; HEU or U-233 oxide or other pure U compounds; MOX or other nonirradiated pure mixtures containing Pu and U (U-233 + U-2352 20%); or Pu, HEU, and/or U-233 in scrap or other miscellaneous impure compounds
Order of months (1 -3):	Pu, HEU, or U-233 in irradiated fuel
Order of one year:	U containing < 20% U-235 and U-233; or Thorium

a This range is not determined by any single factor, but the pure Pu and U compounds will tend to be at the lower end of the range and the mixtures and scrap at the higher end.

SOURCE: *IAEA Safeguards Glossary, 1987 Edition,* IAEA/SG/INF/1 (Rev, 1), (Vienna, Austria: International Atomic Energy Agency, December 1987), p. 24.

be used to process them.[6] Materials are safeguarded at many stages in the fuel cycle: conversion (where uranium concentrate or plutonium, if it has been separated for use in fuel, may be cast into its fluoride, oxide, metal, alloy, nitride, or carbide forms); enrichment; fuel fabrication; reactor operation; spent-fuel storage; and reprocessing. The earliest phases of the fuel cycle, however, are not subject to safeguards. These phases involve mining the raw uranium-containing ore and "milling" it to convert it into natural-uranium concentrate (U_3O_8) called *yellowcake (see* figure 4C-1).

Few countries operate facilities that represent all stages of the fuel cycle, and some may have only a single nuclear research reactor supplied and fueled by another country. Nevertheless, unsafeguarded facilities could, in theory, be operated clandestinely along with safeguarded ones at any of these stages. Under safeguards agreements for non-NPT countries (INFCIRC/66), only certain facilities and materials are subject to safeguards; these states can legally operate other, undeclared facilities, and process undeclared material obtained from either their own uranium deposits or from other non-NPT states, outside of safeguards.

In nonweapon-state NPT parties, however, the requisite INFCIRC/153 safeguards agreements do not permit *any* nuclear facilities to be undeclared, even if they were to use only indigenously produced materials. Furthermore, in only one circumstance-which has never occurred-may such a state be permitted to transfer safeguarded material to a nonsafeguarded nuclear facility.[7]

The safeguards process consists of three stages (see figure 4C-2):

- *examination by the IAEA of state-provided information,* which covers design of facilities, inventories, and receipts for transfers and shipments of materials;
- *collection of information by IAEA inspectors,* either to verify material inventories, operating records, or design information or, in special circumstances, to clarify unusual findings; and
- *evaluation by the IAEA* of this information for completeness and accuracy.[8]

Taking into account each country and facility under safeguards, the IAEA annually produces a Safeguards Implementation Report (SIR) that contains qualitative judgments on whether safeguards goals have been fulfilled. However, these reports are not made available except to the IAEA Board of Governors and member governments.

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[6] Facilities that are built *with the express purpose of eventually containing nuclear materials,* however, must be declared.

[7] This exception covers the temporary removal of a declared amount of material from safeguards to a *declared (nonnuclear weapon) military* facility, such as for submarine propulsion reactors.

[8] See, for example, *IAEA Safeguards: An introduction (Vienna:* International Atomic Energy Agency, 1981), p. 19. Any discrepancy of nuclear materials between the recorded (book) inventory and the physical inventory determined by inspections is called *material unaccounted for* (MUF). When MUF exceeds the amount attributable to measurement uncertainties, the possibility of diversion exists and must be resolved, For an extensive discussion of safeguards concepts and methodologies, see also Fischer and Szasz, *Safeguarding the Atom,* op. cit., footnote 4; and Lawrence Scheinman, *The International Atomic Energy Agency and World Nuclear Order* (Washington, DC: Resources for the Future, 1987), especially chapters 4 and 5.

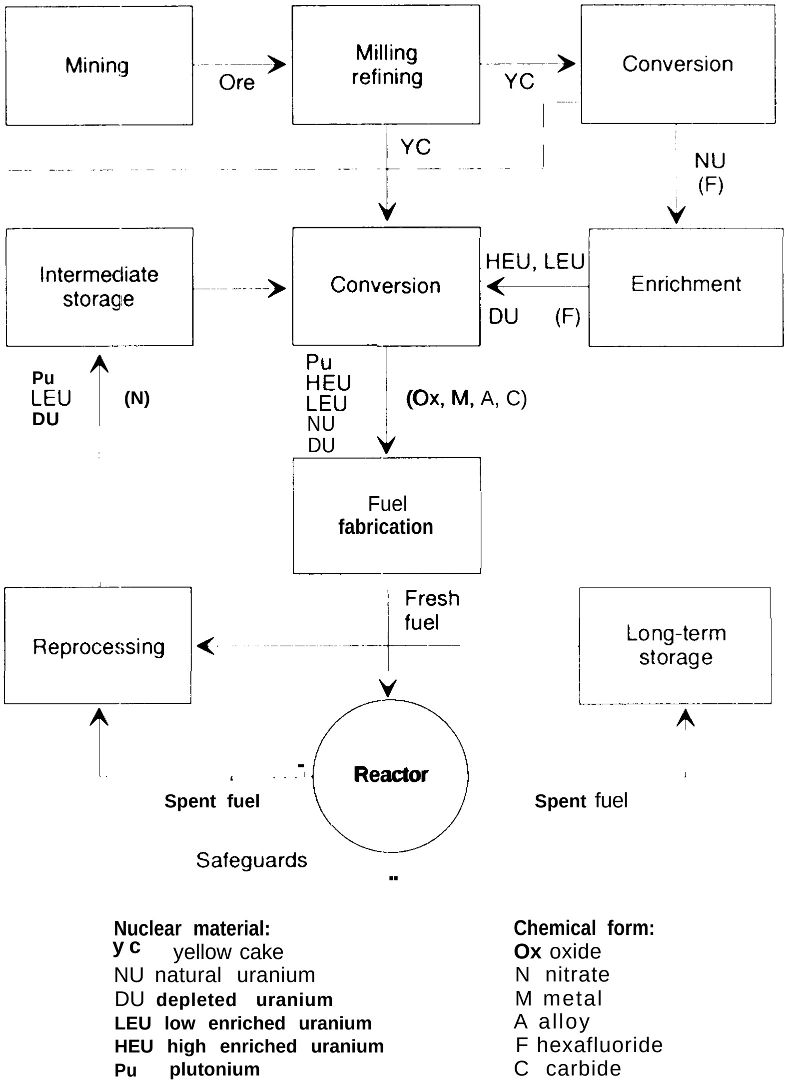


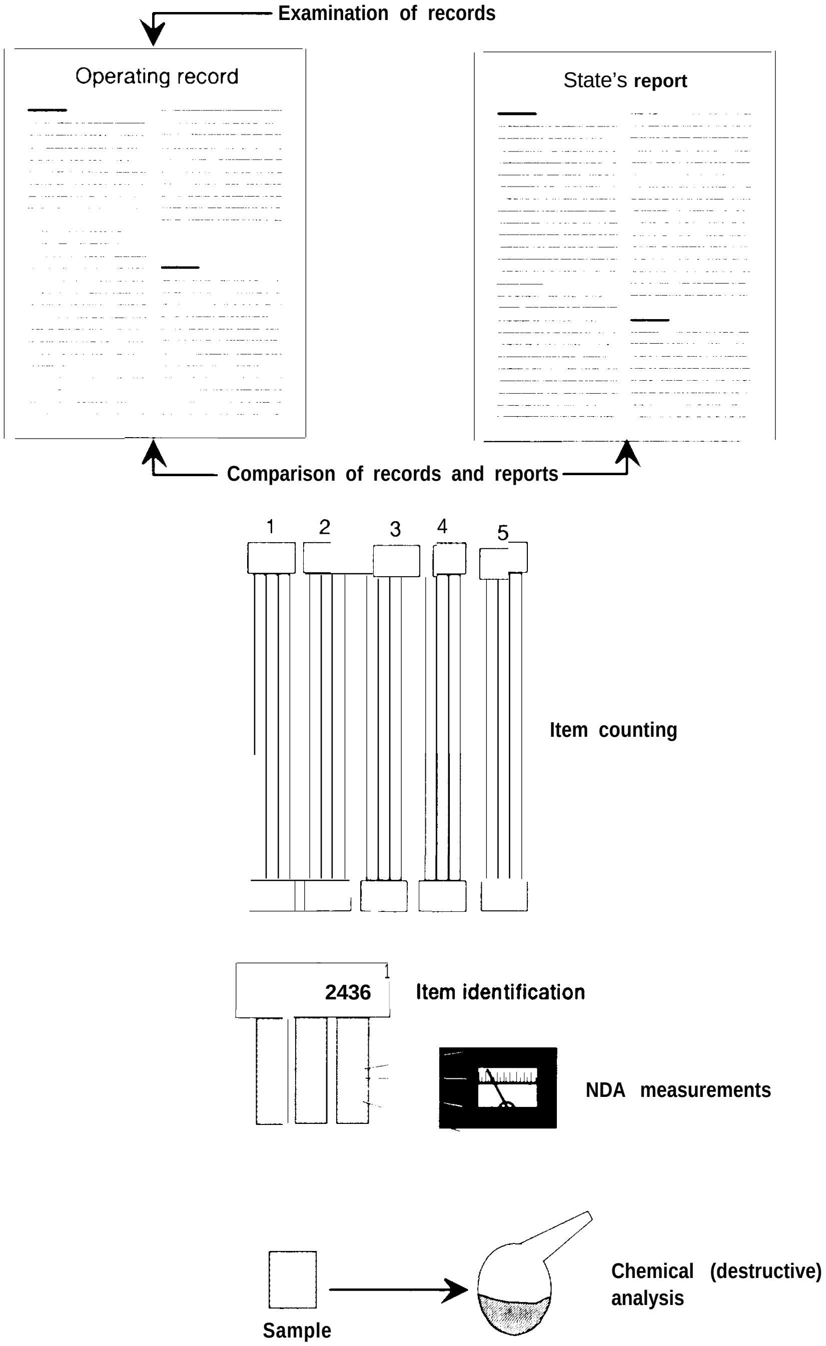
Figure 4-Cl-Simplified **Flow Diagram of the Nuclear Fuel Cycle**

SOURCE: *IAEA Safeguards: An Introduction,* **IAEA/SG/INF/3 (Vienna: International Atomic Energy Agency, 1981), p. 17.**

Before Iraq was shown to have violated safeguards, no safeguards disputes had ever been referred to the U.N. Security Council. Since then, the possibility of Security Council action has been raised with respect to compelling North Korea to allow inspections of two sites suspected of containing nuclear waste. Despite its NPT obligations eventually to do so, North Korea also had still not shut down one of its reactors (as of the summer of 1993) so as to allow IAEA inspectors to examine its core. Such inspections are necessary to determine whether North Korea has ever produced significant quantities of plutonium.

For reactors and fuel storage areas, material accountancy consists of identifying and counting fuel rods and assemblies and verifying their composition using nondestructive assays (NDA). LWR fuel assemblies are enclosed in the reactor vessel in such a way that the reactor must be shut down to change fuel

Figure 4-C2-Verification Activities of IAEA Inspectors or of the Safeguards Analytical Laboratory



(NDA=nondestructive assay)

SOURCE: *IAEA Safeguards; An /introduction,* IAEA/SG/INF/3 (Vienna: International Atomic Energy Agency, 1981), p. 23.

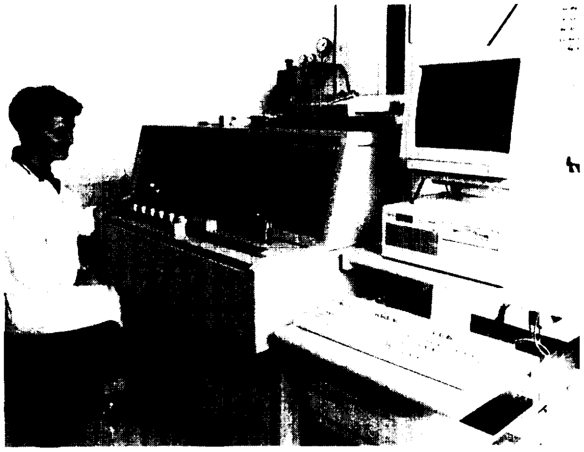

IAEA

IAEA safeguards inspectors (center) checking fresh fuel elements at a nuclear power plant. At such facilities, safeguards focus on item identification and material accountancy, in part by verifying the records of plant operators.

elements. This shutdown is time-consuming and observable and makes the design and implementation of safeguards for LWRs particularly simple.

CANDU-type heavy-water- moderated natural-uranium reactors, and Soviet RBMK-type graphite-moderated reactors, however, are refueled by inserting new fuel rods while simultaneously removing old ones—a process that does not require shutting down the reactor. Safeguarding such reactors requires much more frequent inspections as well as specialized equipment (e.g., automated bundle counters) to inventory the replacement of fuel elements. Furthermore, since heavy water reactors (HWRs) can be refueled much more inexpensively and easily than other types of reactor, fuel can be cycled through them quickly. Such reactors are therefore better suited than many others to produce weapon-grade plutonium[9] (see box 4-A in main text).

Once plutonium is separated, it represents much more of a proliferation hazard than when it is bound up within radioactive spent fuel. If reprocessing is done at a distant site, or separated plutonium is subsequently transferred to a MOX fuel-fabrication facility or back to the country of origin, the transport of spent fuel and especially of separated plutonium represent vulnerable points in the fuel cycle for diversion or theft.


IAEA

X-ray fluorescence spectrometer, which supports one of the techniques used by the MEA to analyze samples taken during nuclear inspections.

At "bulk-handling" facilities (such as those for enrichment, fuel fabrication, and reprocessing), samples of material from within *material balance areas* must periodically be removed and taken to an IAEA laboratory to determine their composition. The uncertainties in measurement at large bulk-handling facilities are necessarily much larger than those **involving the discrete items most often associated with reactors and their fuel.** (Consequently, the IAEA inspects bulk-handling facilities much more often, sometimes stationing permanent resident inspectors at these sites. Almost 50 percent of the total inspection effort is expended at bulk-handling facilities, even though these represent only about 7 percent of the total number of installations under safeguards.[10])

Technologies for implementing safeguards improved dramatically during the 1980s, and with these improvements have come greater transparency and confidence that the international fuel cycle is not being used to aid proliferation. The IAEA has incorporated computerized inspection reporting systems and has improved various methods for taking measurements and implementing containment and surveillance tech-

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[9] An unsafeguarded Canadian research HWR supplied the plutonium for the device India exploded in 1974, and a French-supplied HWR has been the source of unsafeguarded plutonium in Israel. Similar but *safeguarded* HWRs had been involved in suspect activities in South Korea and Taiwan before the U.S. persuaded these two NPT countries in the 1970s to abandon their reprocessing efforts.

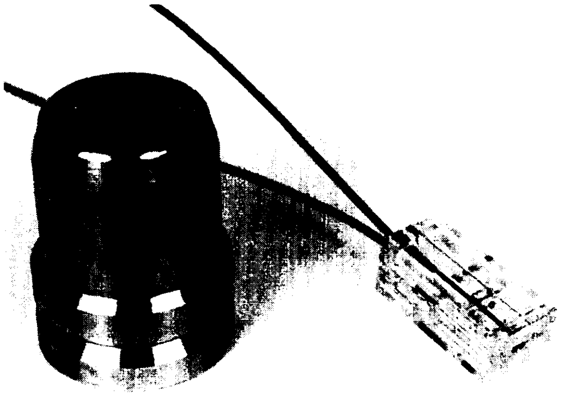
[10] V. Schuricht and J. Larrimore, ‘‘Safeguarding Nuclear Fuel Cycle Facilities,’ *IAEA Bulletin*, vol. 30, No. 1 (1988), p. 11.

niques (see figure 4C-3), including methods for film processing, verification of seals, and analysis of gamma spectrometric data. New tamper-resistant surveillance television and recording systems have been installed in an increasing number of facilities.[11]

A number of improvements in IAEA safeguards and procedures have also been adopted since the 1991 Persian Gulf War. These include establishing earlier reporting requirements for nuclear plant-design information; taking steps toward more universal reporting of exports, imports, and inventories of nuclear materials and equipment; reaffirming the right to conduct special inspections; and accommodating the use of more diverse sources of information.

Nevertheless, the IAEA safeguards system has inherent limitations with respect to forestalling potential nuclear weapon programs, some of which are the following:

- it does not cover all states, or even all facilities and items that could be used by a nuclear weapon program in those states that are covered (for example, it makes no attempt to cover research and development on nonnuclear components of nuclear weapons);
- it does not prohibit states from acquiring stockpiles of weapon-usable material (plutonium and HEU), or the means to produce them, provided that stocks and facilities are declared and for peaceful purposes (the IAEA, in fact, is charged with assisting member states in the development of their nuclear fuel cycles);
- it suffers from inherent uncertainties at bulk-handling facilities;
- its access to sources of information remains limited;
- it lacks an effective means of enforcement; and
- it is subject to diplomatic and political pressures to treat all states equally, making it difficult to select some as being of particular proliferation concern or to subject them to closer scrutiny. The bulk of the IAEA safeguards budget today is spent on facilities in Japan, Germany, and Canada, which are not regarded as countries of current proliferation concern.



IAEA

Two seals, known as COBRA and ARC, used by the IAEA to provide assurance that containers or other inspected items have not been tampered with between inspections.

Policy options to strengthen IAEA safeguards and other aspects of the nuclear nonproliferation regime have been discussed in a number of recent articles[12] and will also be addressed in a subsequent OTA report on nonproliferation policies.

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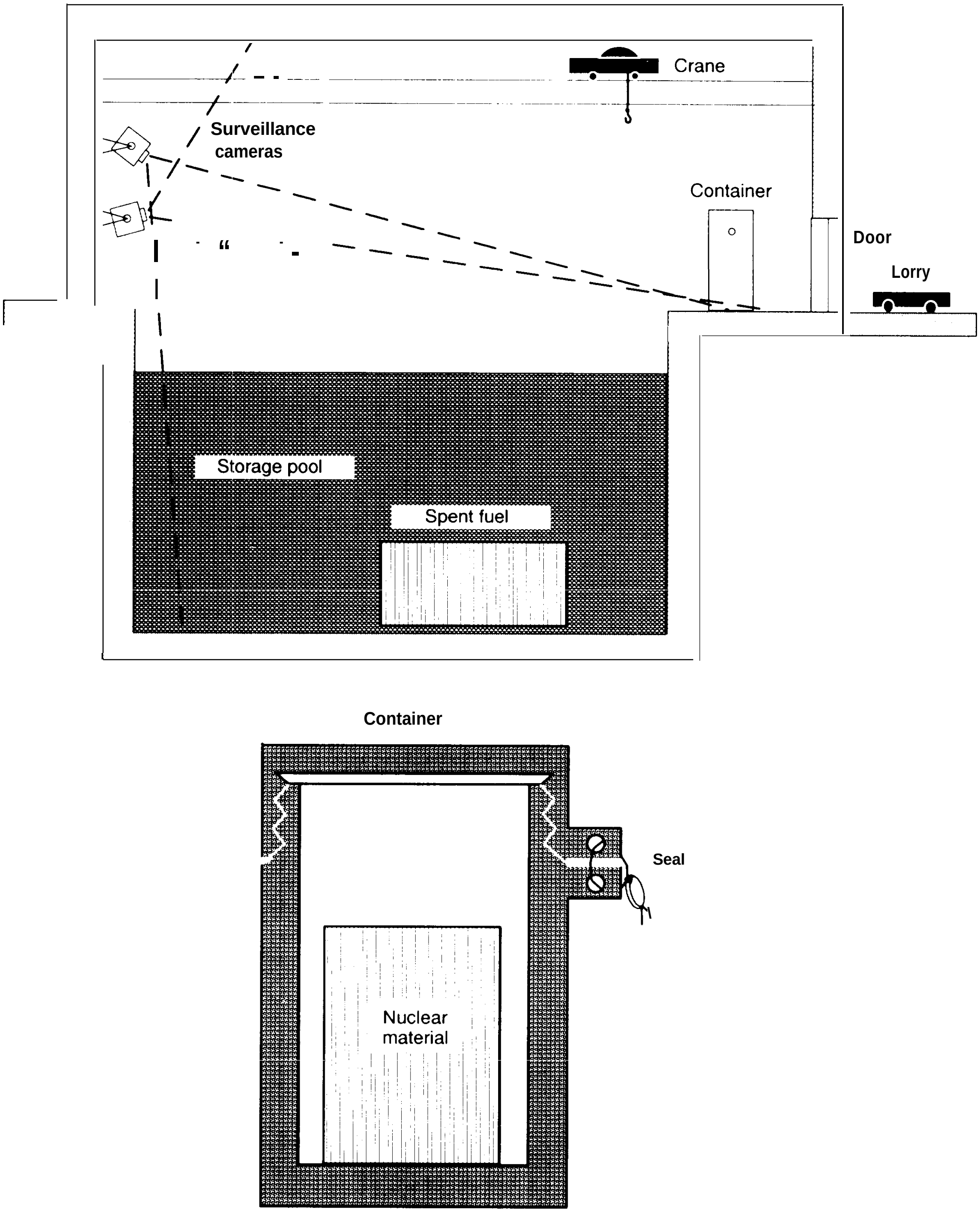
[11] Other equipment that has been improved over the last decade includes bundle counters for reactor that are refueled while online, and various equipment for measuring composition and amounts of nuclear material, for example, portable multichannel analyzers, K-edge densitometers, electromanometers, Cherenkov viewing devices, and neutron coincidence counters.

[12] See, for example, Lawrence Scheinman, "Nuclear Safeguards and Non-Proliferation in a Changing World Order," *Security Dialogue*, vol. 23, No. 4, 1992, pp. 37-50, and *Assuring the Nuclear Non-Proliferation Safeguards System (Washington DC: The* Atlantic Council, October 1992); three articles in *Disarmament, vol. XV, No. 2,* April 1992: Hans Blix, "IAEA Safeguards: New Challenges, " pp. 33-46; Ryukichi Imai, ''NPT Safeguards Today and Tomorrow, ' pp. 47-57; and Lawrence Scheinman, ''Safeguards: New Threats and New Expectations, ' pp. 58-76; and David Fischer, Ben Sanders, Lawrence Scheinman, and George Bunn, *A New Nuclear Triad: The Non-Proliferation of Nuclear Weapons, International Verification and the IAEA,* PPNN Study No. 3 (Southampton U.K.: Programme for Promoting Nuclear Nonproliferation, September 1992).

Figure 4-C3-Typical Containment and Surveillance (C/S) Measures Applied by the IAEA



SOURCE: *IAEA Safeguards: An Introduction*, IAEA/SG/INF/3 (Vienna: International Atomic Energy Agency, 1981), pp. 24-25,

Appendix 4-D

Dual-Use Export Controls

Meeting in Warsaw from March 31 to April 3, 1992, the 27 members of the Nuclear Suppliers Group[1] approved a broad new set of export control guidelines pertaining to the transfer of nuclear dual-use items. They agreed that each of the NSG member countries would implement the guidelines by the end of 1992[2] and would adopt a common policy requiring the application of full-scope IAEA safeguards as a condition of any significant new nuclear exports to nonnuclear weapon states.[3] The new guidelines include a technical Annex specifying 65 categories of nuclear-related dual-use equipment, materials, and technologies that are to be controlled, and establish procedures governing their transfer.

GUIDELINES AND LICENSING PROCEDURES

The new guidelines stipulate the following:

1. Licenses shall be required for the transfer of any item in the Annex to any destination by any participating country;
2. Transfers shall not be authorized:
   - if they are for use in a nonnuclear-weapon state in a nuclear explosive activity (including work on components or subsystems) or in an unsafeguarded nuclear fuel-cycle activity;
   - if there is an unacceptable risk of diversion to such an activity; or
   - if the transfers are contrary to the objective of averting the proliferation of nuclear weapons.
3. In judging whether these conditions are met, factors that should be taken into account include, but are not limited to:
   - an evaluation of the appropriateness of the end-use and of the material for that end use;
   - a country's past compliance history with safeguards and dual-use tech-transfer obligations;
   - whether governmental actions, statements and policies have been supportive of nuclear nonproliferation; and

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[1] The 27 NSG states were: Australia; Austria; Belgium*; Bulgaria; Canada*; Czech and Slovak Federal Republics*; Denmark; Finland; France*; Germany*; Greece; Hungary; Ireland; Italy*; Japan*; Luxembourg; Netherlands*; Norway; Poland*; Portugal; Romania; Russia*; Spain; Sweden*; Switzerland*; United Kingdom*; and United States.* (Countries with asterisks have been members of the Nuclear Suppliers Group since it was formed in 1977.)

[2] The guidelines are published in IAEA INFCIRC/254/Rev. I/Part 2, *Nuclear Related Dual-Use Transfers*, July 1992.

[3] See, for example, Roland Timerbaev, ''A Major Milestone in Controlling Nuclear Exports, " *Eye on Supply, No. 6,* spring 1992, pp. 58-65.

- whether the recipient has been involved in the past in clandestine or illegal procurement activities.

4. Before granting a License, a supplier shall be required to obtain a *statement of end-use and end-use location,* as well as a written assurance that the proposed transfer or any replica thereof will not be used in any nuclear explosive or unsafeguarded activity.
5. Supplier states shall be required to cooperate and consult with each other on licensing procedures, to report any *denials* of licenses, and to *refrain from licensing items whose export was previously denied by another supplier state.* (Exceptions and re-evaluations are allowed, however, with appropriate consultation,)

In sum, it is presumed that countries with insufficient nonproliferation credentials-even if party to the NPT—will be denied these dual-use goods.

ITEMS TO BE CONTROLLED

| Industrial Equipment

Combination spin-forming and flow-forming machines
- 2-axis, that can be fitted with numerical control units

Numerically controlled machine tools, control units, and software
- especially multi-axis ''contour-control' machining devices
- *except* that the precision and capability of these items must exceed a detailed set of technical specifications

High-precision (order of 1 micron) dimensional and contour inspection systems
- especially those capable of linear-angular inspection of hemishells

Vacuum or controlled-environment induction furnaces
- operating above 850 "C;
- *except if* for semiconductor wafer-processing

Isostatic presses
- capable of 700 atmospheres pressure with 6-inch or larger chambers

Robotic equipment (grippers and active tooling for ends of robot arms)


VADIM MOUCHKIN, IAEA

Portion of a remote manipulator that was destroyed in Iraq during an IAEA inspection in October 1991. Such manipulators can be used inside "hot cells" to handle radioactive material.

- able to safely handle high explosives or operate in radioactive environments and capable of variable/ Programmable movements
- *except if* for applications such as automobile paint-spraying booths

Vibration test equipment
- using digital control; 20-2,000 Hz; imparting forces of50kN(11,250 lbs) or more

Melting and casting furnaces-arc remelt, electron beam, and plasma
- generating temperatures above 1,200 degrees C in vacuum or controlled environments

Materials

Aluminum alloys (of specified strength)
- in tubes or solid forms having outside diameters greater than 75 mm

Beryllium metal and alloys
- *except* beryllium metal windows for x-ray machines or beryllium oxides specifically designed as substrates for electronic circuits

Bismuth (of at least 99.99% purity)

Boron or its compounds (isotonically enriched in boron-10)

Calcium (high purity)

Chlorine trifluoride

Crucibles made of materials resistant to liquid actinide metals

Carbon or glass "fibrous and filamentary" materials of high-strength
- especially when in the form of tubes with 75-400 mm inside diameter

Hafnium and its compounds

Lithium isotonically enriched in lithium-6
- *except* lithium-6 incorporated in thermoluminescent dosimeters

Magnesium (high purity)

Maraging steel (of specified strength)
- *except* forms in which no linear dimension exceeds 75 mm

Radium-226
- *except* radium contained in medical applicators

Titanium alloys (of specified strength)
- in tubes or solid forms, with outside diameter greater than 75 mm

Tungsten and its compounds
- in amounts greater than 20 kg and having hollow cylindrical symmetry with inside diameter between 100 mm and 300 mm
- *except* parts specifically designed for use as weights or garoma-ray collimators

Zirconium and its alloys
- *except in* the form of foil of thickness less than 0.1 mm

Uranium Isotope Separation Equipment and Components

Electrolytic cells for fluorine production (capable of 250 g of fluorine per hour)

Centrifuge rotor-fabrication andbellows-forming equipment

Centrifugal multiplane balancing machines (with specific characteristics)

Filament winding machines

Frequency changers (converters) or generators
- with specific characteristics, and operating from 600-2,000 Hz
- *except if specifically* designed for certain types of motors

Lasers, laser amplifiers, and oscillators
- copper-vapor and argon-ion lasers with 40 W average power
- high-pulse-rate lasers (tunable dye lasers, high-power carbon-dioxide lasers and excimer lasers)
- *except* continuous-wave or long-pulse-length industrial-strength CO_2 lasers for cutting and welding

Mass spectrometers and mass spectrometer ion sources , especially when lined with materials resistant to UF_6
- certain exceptions apply, however

Pressure measuring instruments, corrosion-resistant

Valves (special corrosion-resistant types using aluminum or nickel alloy)

Superconducting solenoidal electromagnets
- high magnetic field (greater than 2 tesla)
- with inner diameter greater than 300 mm and highly-uniform magnetic field
- *except if* specifically designed for medical nuclear magnetic resonance (NMR) imaging systems

Vacuum pumps (of specified size and capacity)

Direct current high-power supplies (100 V, 500 amps; e.g., for EMIS magnets)

High-voltage direct-current power supplies (20,000 V, 1 amp; e.g., for EMIS ion sources)

Electromagnetic isotope separators (EMIS)
- with ion sources capable of 50 mA or more

Heavy-Water Production-Plant-Related Equipment (other than trigger list items)

Specialized packings for water separation

Specialized pumps for potassium amide/liquid ammonia

Water-hydrogen sulfide exchange tray columns

Hydrogen-cryogenic distillation columns

Ammonia converters or synthesis reactors

Implosion Systems Development Equipment

Flash x-ray equipment
  - *except* if designed for electron microscopy or for medical purposes

Multistage light-gas guns/high-velocity guns (capable of 2 km,sec velocities)

Mechanical rotating mirror cameras (with recording rates above 225,000 fiarnes/see)

Electronic streak and framing cameras and tubes (with 50-ns resolution)

Specialized instrumentation for hydrodynamic experiments
  - velocity interferometers for measuring 1 km/see in under 10 microseconds
  - pressure transducers for 100 kilobars

Explosives and Related Equipment

Detonators and multipoint initiation systems
  - electrically driven detonators (e.g., exploding bridge wires) capable of nearly simultaneous (2,5 microseconds) initiation over an explosive surface greater than 5,000 mm^2

Electronic components for firing sets
  - switching devices or triggered spark-gaps (e.g., gas krytron tubes or vacuum sprytron tubes with 2500 V, 100 A, and delays of less than 10 microseconds)
  - capacitors (kilovolt-level, low inductance)

Specialized firing sets and equivalent high-current pulsers (for controlled detonators)

High explosives relevant to nuclear weapons (e.g., HMX, RDX, TATB, HNS, or any explosive with detonation velocity greater than 8,000 rn/see)

Nuclear Testing Equipment and Components

Fast oscilloscopes (with 1 ns sampling or 1 GHz bandwidth)

Photomultiplier tubes (with large photocathodes and 1 ns time-scales)

Pulse generators (high speed; 0.5 ns rise-times)

Other

Neutron generator systems (for inducing tritium-deuterium nuclear reaction)

General nuclear-material and nuclear-reactor related equipment
  - remote manipulators (used for radiochemical separation in “hot cells”)
  - radiation shielding windows (e.g., with lead glass, 100 mm thick)
  - radiation-hardened TV cameras (able to withstand 50,000 grays)

Tritium, tritium compounds, and mixtures (containing more than 40 Ci of tritium)

Tritium facilities, or plants and components thereof (including refrigeration units capable of -250 “C)

Platinized carbon catalysts (for isotope exchange to recover tritium from heavy water, or to produce heavy water)

Helium-3
  - *except* devices containing less than 1 g

Alpha-emitting radionuclides or their compounds (having alpha half-lives between 10 days and 200 years)
  - *except* devices containing less than 100 mCi of alpha activity

STRENGTHS OF THE GUIDELINES

- A wide range of dual-use technologies and materials is subject to strict export controls. Implementation of these controls should create significant obstacles for a nuclear weapon program attempting to import the specified items.
- A large number of countries have pledged to abide by these guidelines by adopting them into their own export control laws and have agreed not to undermine control actions taken by others.
- Factors to be taken into account before export licenses are granted are not limited to a recipient country’s being party to the NPT; these factors include past behavior and general compliance with nonproliferation goals.

POTENTIAL LIMITATIONS OF THE GUIDELINES

- Specific technical qualifiers and thresholds apply to the majority of controlled items on the list. A key questions is how effective each threshold is at determining the equipment's utility in a less-sophisticated or less-ambitions nuclear-weapon program -could dual-use items falling just short of the specifications still be helpful, and if so, how easily could they be obtained from NSG or non-NSG countries?
- The procedures only require reporting of license *denials. This* precludes routine active monitoring of trade, for example, to look for suspicious patterns of imports. However, the NSG has agreed to hold annual consultations for purposes including discussion on a voluntary basis of proposed and authorized transfers of these dual-use items.
- There is no provision for *inspecting the* end-use application, although individual countries may carry out such inspections on their own. (Inspections are periodically carried out, for example, by the Office of Export Enforcement of the U.S. Commerce Department.) This is primarily due to the expense and impracticality, both financial and political, of devising a comprehensive inspection regime for dual-use exports. If the guidelines are applied stringently, however, then export licenses for suspect proliferants will largely be denied, reducing the need for end-use inspections.

The Proliferation of Delivery Systems

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A country seeking to acquire weapons of mass destruction will probably desire some means to deliver them. Delivery vehicles may be based on very simple or very complex technologies. Under the appropriate circumstances, for instance, trucks, small boats, civil aircraft, larger cargo planes, or ships could be used to deliver or threaten to deliver at least a few weapons to nearby or more distant targets. Any organization that can smuggle large quantities of illegal drugs could probably also deliver weapons of mass destruction via similar means, and the source of the delivery might not be known. Such low technology means might be chosen even if higher technology alternatives existed. If the weapons are intended for close-in battlefield use, delivery vehicles with ranges well under 100 km may suffice. Strategic targets in some regional conflicts are only a few hundred kilometers from a nation's borders. (A fixed-direction launch system, such as the Supergun being developed in Iraq, might also be used in these circumstances.) Deterrence or retaliation against more distant countries, however, might require delivery ranges of many thousands of kilometers.

This chapter focuses on "high end" delivery systems—ballistic missiles, cruise missiles, and combat aircraft-for the following reasons:

- simpler systems, such as cars and trucks, boats, civil aircraft, and artillery systems are not amenable to international control. No nonproliferation policy could possibly prevent countries with weapons of mass destruction from utilizing such vehicles;
- there is a high degree of overlap among the countries pursuing weapons of mass destruction and those possessing, developing or seeking to acquire missiles and highly capable combat aircraft; and

modem delivery systems enable a country to do more damage to a greater number and variety of targets, with greater reliability, and potentially at longer range, than do low technology alternatives. Ballistic and cruise missiles in particular may have added psychological effects, since they can be harder to defend against, or even to detect, than manned aircraft.

Combat aircraft are already widely distributed around the world. Every country currently suspected of having or seeking weapons of mass destruction also has military aircraft that could be adapted to deliver such weapons. This chapter nevertheless examinesthes the proliferation of advanced aircraft for three reasons:

- such a review indicates how and why combat aircraft are already so widespread and what capabilities they offer;
- states seeking ballistic and cruise missiles do so in the context of widespread aircraft proliferation; and
- since advanced aircraft have proliferated more by transfers than by indigenous production, there is the possibility of limiting the proliferation of still more advanced systems.[1]

Even though owners of weapons of mass destruction may possess combat aircraft, there are reasons outlined below why they might prefer to use missiles. Unlike aircraft, however, ballistic and cruise missiles are subject to international supplier controls through the Missile Technology Control Regime.

This chapter begins with a comparison of the utilities of these three types of system for delivering weapons of mass destruction. Subsequent sections discuss the technological factors affecting the relative ease or difficulty of acquiring each type of capability, either through purchase, co-development, or indigenous design and production. These sections also indicate the types of observable indicators, or signatures, that if detected might reveal attempts to develop, build, or deploy each system.

SUMMARY

Effectiveness of Advanced Delivery Systems

Although combat aircraft, ballistic missiles, and cruise missiles are not necessary to deliver weapons of mass destruction, each type of vehicle is capable of doing so and each has particular strengths. A state with the resources, ability, and inclination to acquire delivery systems specifically for use with weapons of mass destruction has to consider the availability of candidate systems, the type of weapon to be delivered, the targets to be struck, and the purposes of planned attacks or threats of attack. Characteristics affecting the suitability of delivery vehicles to particular missions include range, payload amount and type, ability to evade or penetrate defenses, vulnerability to preemptive attack (pre-launch survivability), cost, and infrastructure requirements.

For delivering a nuclear warhead, the likelihood of successful delivery somewhere in the vicinity of the target (the combination of pre-launch survivability, reliability, and defense penetration) is more important than factors such as accuracy, cost, or excess payload capacity. By this measure, even though missiles are more likely to penetrate defenses, the reliability of piloted aircraft may sometimes count for more. Given their destructive potential, nuclear weapons need not be delivered with great accuracy (even a demonstration explosion on the proliferant nation's own territory or in the ocean could have great effect in some situations); neither would a nuclear delivery system have to carry

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[1] Competition in advanced weaponry is part of the context in which some countries seek weapons of mass destruction some analysts believe that limiting the spread of **advanced** combat aircraft is an important goal whether they would play a direct role in the delivery of weapons of mass destruction or not.

payloads much beyond the weight of a single nuclear weapon.

To the extent that cost matters in delivering a nuclear weapon, it is probably the total cost of acquiring a delivery capability-not the cost per ton of payload—that is relevant. Here, missiles (ballistic or cruise) have a strong advantage, since they are generally considerably cheaper than advanced aircraft.

Aircraft and cruise missiles are better suited than ballistic missiles to deliver chemical and biological agents over an extended area. Size of payload matters in chemical and in typical large-area biological attacks, since the damage that can be inflicted depends directly on the amount of agent that can be delivered.[2] In this respect, the typically larger payload capacity of manned aircraft would give them a strong advantage over both cruise and ballistic missiles.

Since known biological and chemical weapons are cheaper to develop than are nuclear weapons, the cost of their delivery system is a much larger fraction of the total cost, and hence a more important criterion, than in the nuclear case. To attack military targets with chemical weapons, the cost per ton of delivered payload would probably be important to the attacker. With their larger payloads and their reusability, aircraft are typically cheaper than missiles by this measure. Depending on how biological weapons were used (e.g., once for shock value, or repeatedly for genocide) either the cost of one sortie or the cost per ton of payload could be more important. Aircraft have a strong advantage for attacks against military targets, if the targets are mobile or located in unknown positions. Ballistic missiles, on the other hand, would have an advantage if the targets were particularly well defended.

| Availability of Delivery Systems

Unlike weapons of mass destruction, whose trade is heavily constrained by treaties and international norms, delivery systems such as aircraft and short range antiship cruise missiles are widely traded internationally. The United States and other Western industrialized countries have tried to delegitimize the sale of longer range ballistic and cruise missiles by creating the Missile Technology Control Regime (MTCR). When formed in 1987, the MTCR was intended to limit the risks of nuclear proliferation by controlling technology transfers relevant to nuclear weapon delivery other than by manned aircraft. To this end, the MTCR established export guidelines that, when adopted by complying nations, would prohibit them from selling ballistic or cruise missiles with ranges over 300 km and payloads over 500 kg to nonmembers.[3]

The Persian Gulf War and the recent emergence of potential secondary suppliers of missiles have helped convince a number of additional countries to participate in the MTCR. Beginning with seven original members in 1987, the MTCR has grown to 23 full members, with Argentina and Hungary now in the process of becoming full members. Another four countries (China, Israel, South Africa, and Russia) have agreed to abide by the MTCR's export restrictions (see table 5-l). On January 7, 1993, MTCR member states further tightened up the export restrictions, agreeing to a "strong presumption to deny' transfers of 300-km ballistic or cruise missiles regardless of their payload, and of any missiles-regardless of range

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[2] For attacks on cities, optimally distributed biological agents measuring in the tens of kilograms could theoretically inflict casualties comparable to a nuclear weapon. If contagious biological agents were used, damage would be less directly related to amount of agent distributed; however, contagious agents have serious operational drawbacks (see ch. 3). For comparisons of nuclear, chemical, and biological weapon effects, see ch. 2 of U.S. Congress, Office of Technology Assessment, *Proliferation of Weapons of Mass Destruction: Assessing the Risks,* OTA-ISC-559 (Washington, DC: U.S. Government Printing Office, August 1993).

[3] As applied to missiles or unmanned aerial vehicles, the MTCR prohibits the transfer of *complete systems*, *components* that could be used to make complete systems, and *technology involved in the production* of components or of complete systems. Each participating nation controls export of these items through its own national system of export controls, and the controls are coordinated among MTCR members.

Table 5-1—MTCR Countries

- 7 original members (1987):
  - Canada, France, Federal Republic of Germany, Italy, Japan, United Kingdom, United States
- 16 additional full members (as of Mar. 25, 1993):
  - Australia, Austria, Belgium, Denmark, Finland, Greece, Iceland, Ireland, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland
- Countries that have pledged to abide by MTCR provisions, but are not full members:
  - Argentina (pledged May 1991; in process of becoming full member, March 1993)
  - China (pledged November 1991)
  - Hungary (in process of becoming full member, March 1 993)
  - Israel (agreed October 3, 1991 to abide with MTCR provisions by the end of 1992; applying for membership, March 1993)
  - Romania (applying for membership, as of March 1993)
  - South Africa (has pledged to join, but date unspecified)
  - Soviet Union/Russia (pledged 1990/June 1991, respectively)

SOURCE: Adapted from Australian Department of Foreign Affairs and Trade, press release, Mar. 11, 1993; and *Arms Control Reporter, 1993* (Cambridge, MA: Institute for Defense and Disarmament Studies, 1993), section 706.

or payload—if the seller has reason to believe they would be destined to carry weapons of mass destruction.

| Technological Barriers to Delivery-System Proliferation

According to published sources, ballistic missiles with ranges from 300 to 600 km are already possessed or being developed by over a dozen countries outside of the five declared nuclear powers. In general, the acquisition by additional countries of more advanced missile technologies-those allowing ranges in excess of 1,000 km or accuracies much better than roughly 0.3 per cent of range-cm be slowed but not stopped by multilateral export controlls. It is unlikely that any country (other than China and the former Soviet republics that already possess intercontinental ballistic missiles) would pose a direct ballistic missile threat to the United States within the next 10 years. However, as the Persian Gulf War and the ongoing nuclear tensions involving North Korea have emphasized, important U.S. allies and overseas interests can already be put at risk by existing missiles in a number of countries.

Cruise missiles or other unmanned aerial vehicles that exceed the MTCR thresholds are not widespread outside of the United States and the former Soviet Union, but a number of systems with ranges of 50 to 200 km are available for purchase. In addition, technologies for guidance, propulsion, and airframes have recently made major advances and are becoming considerably more accessible to many Third World countries—particularly with the export of more advanced short range systems and the spread of aircraft production technology and co-licensing arrangements. Since very few countries have been able to develop *indigenous* aircraft industries capable of manufacturing jet engines, it should be possible in principle to control the spread of the most sophisticated engines and propulsion systems. However, the highest performance engines are not required for simple cruise missiles, and engines with lesser capabilities are becoming increasingly available on international markets.

The availability of satellite navigation services, such as the U.S. Global Positioning System (GPS), the Russian Glonass system, and possible future commercial equivalents, essentially eliminates guidance as a hurdle for weapon delivery by manned or unmanned aircraft. GPS receivers are inexpensive and commercially available. Although exportable models do not operate at sufficiently high altitudes and speeds to provide much help for guiding ballistic missiles (and even custom-made receivers operating during the entire boost phase would have very limited utility for improving ballistic missile accuracy), such receivers could be used with manned or unmanned aircraft to provide unprecedented navigational accuracy anywhere in the world. Even the least accurate form of GPS broadcasts would be sufficiently accurate for aircraft delivery of weapons of mass destruction.

| Delivery System Signatures and Monitoring

Most long range delivery system programs are hard to hide. Test launches of ballistic missiles can be readily detected, and intermediate and long range missiles require a lengthy development period and extensive flight testing at each phase, making an overall program particularly difficult to keep secret. Far from being hidden, civil space-launch programs-which inherently can provide knowledge useful to a military program—are usually considered a source of national prestige and are proudly advertised. In particular, the two most important aspects of missile capability for weapons of mass destruction-range and payload-can usually be inferred from monitoring such a space-launch program. (Guidance technology and accuracy would be more difficult to determine, but are less important for weapons of mass destruction.) Nevertheless, once deployed on camouflaged mobile launchers, missiles can be exceedingly difficult to track and account for.

Since combat aircraft are widely accepted as integral to the military forces of a great number of countries, there is no reason to hide their existence. But the act of modifying aircraft to carry weapons of mass destruction, or training pilots to deliver such weapons, might be very difficult to detect without intrusive inspections.

Of the three types of delivery system discussed in this chapter, development and testing of cruise missiles will be the hardest to detect. Several types of civilian-use unmanned aerial vehicles are also being developed and marketed, and without actual inspections it will be very difficult to discern whether such vehicles have been converted to have military capability. Monitoring delivery systems capable of carrying weapons of mass destruction will have the most success with ballistic missiles and highly capable aircraft.

EFFECTIVENESS OF DELIVERY SYSTEMS

The delivery capability required to use weapons of mass destruction varies enormously, depending on the weapon and the mission. A simple, covert means of delivery, such as smuggling, could be sufficient for a single nuclear or biological weapon, whereas a great many aircraft would be required to deliver hundreds of tons of chemical munitions in a coordinated attack against defended sites.

The following discussion examines the characteristics that affect the ability of combat aircraft, cruise missiles, and ballistic missiles to deliver weapons of mass destruction against relatively inaccessible targets.[4] These characteristics include range, payload, accuracy, cost, defense penetration, and reliability. Although a wide variety of systems have been or could be developed to deliver weapons of mass destruction (see table 5-2), the delivery systems discussed in this chapter have unique capabilities and thus pose particular dangers to potential victims. Unlike mines or clandestinely placed bombs, they do not require that the attacker be able to gain direct access to the target, and they can deliver weapons in far less time than would be required to smuggle them to a target. Unlike artillery shells, rockets, or mortars, they can reach distant military targets and population centers as well as tactical or battlefield targets. Unlike torpedoes, they are suitable for use against land as well as sea targets. Unlike civil vehicles such as commercial aircraft or ships, they have some ability to penetrate defenses.

The choice of delivery system will depend on the political or military circumstances envisioned as well as on the systems' individual capabilities. In at least one instance of known nuclear proliferation, for instance, delivery-system capabilities may have been all but irrelevant. In a speech to the South African parliament in which it was revealed that South Africa had assembled six nuclear

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[4] Much of the following discussion draws on Stanford University, Center for International Security and Arms Control, Assessing *Ballistic Missile Proliferation and Its Control* (Stanford, CA: Stanford University, November 1991), pp. 25-56.

Table 5-2—Actual and Possible Methods of Delivery

Weapon	Nuclear	Biological	Chemical
Aerial bomb	✓	✓	✓
Bomb submunitions		✓	✓
Aerial spray tank		✓	✓
Ballistic missile, nonseparating reentry vehicle	✓	✓	✓
Ballistic missile, separating reentry vehicle	✓	**(poss.)**	**(poss,)**
Artillery shell	✓	✓	✓
Rocket shell	✓	✓	✓
Mortar shell	✓		✓
Cruise missile warhead	✓	(poss)	(poss,)
Mine (land)	✓		✓
Mine (sea)	✓		
Antialrcraft missile warhead	✓		
Torpedo	✓		
Transportable clandestine bomb	✓	(poss,)	(poss)

Actual cases ✓

Theoretical possibility: (Poss)

SOURCE: U.S. Congress, Office of Technology Assessment, *Prolieration of Weapons of Mass Destruction:* Assessing the Risks, OTA-ISC-559 (Washington, DC: U.S. Government Printing Office, August 1993), p. 50.

weapons in the 1980s, President F.W. de Klerk said that

> The strategy was that if the situation in Southern Africa were to deteriorate seriously, a confidential indication of the deterrent capability would be given to one or more of the major powers, for example the United States, in an attempt to persuade them to intervene. It was never the intention to use the devices, and from the outset the emphasis was on deterrences

Perhaps most importantly, however, choice of delivery systems will depend on a state's ability to develop or acquire, adapt, and maintain them. These factors are discussed in detail later in this chapter.

Range

The importance of a delivery system's range is highly specific to the regional context. Seoul, South Korea, for example, is less than 50 km from the North Korean border. Major cities and military installations in Israel, Syria, and Jordan are located within a few hundred kilometers of each other, putting them within reach not only of each other's strike aircraft but also short range ballistic missiles.[6] Distances between key points in other pairs of Middle Eastern countries are somewhat larger; Jerusalem, Israel is about 350 km from the closest point inside Iraq, with Baghdad, Iraq the same distance from Saudi Arabian territory. Tehran, Iran is at least 525 km from the Iraqi border, which was one of the principal motiva-

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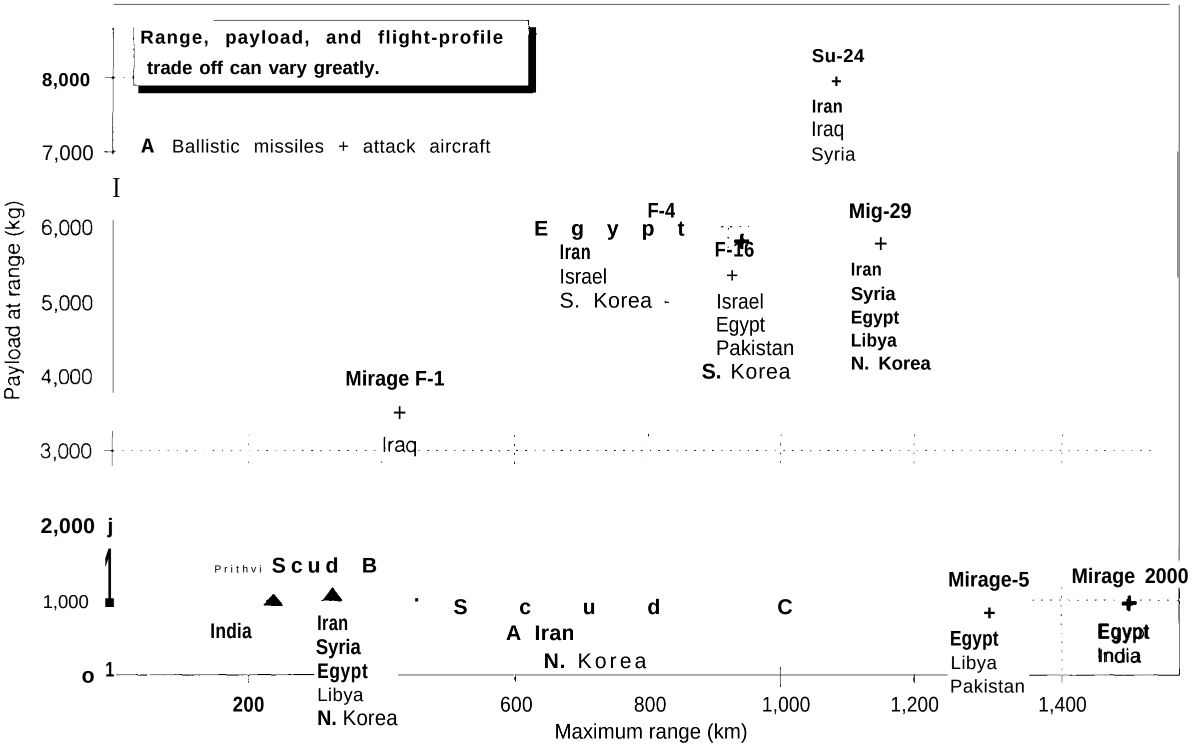
[5] President F.W. de Klerk, speech on the Nuclear Nonproliferation Treaty to a joint session of the South African Parliament, March 24, 1993, as quoted in ***Arms Control*** *Today, vol. 23, No. 3,* Aprit 1993, p. 28.

[6] The widely proliferated Scud missile, for instance, has a range of 300 km with a payload of about 1,000 kg.

Figure 5-l—Range and **Payload of Selected Aircraft and Missiles Operated by Potential Proliferants**



SOURCE: U.S. Congress, Office of Technology Assessment, *Proliferation of Weapons of* Mass *Destruction: Assessing the Risks, OTA-ISC-559* (Washington, DC: U.S. Government Printing Office, August 1993), p. 68

tions for Iraq to extend the range of its Scud-B missiles to about 600 km during the Iran-Iraq war.[7] Distances between the Korean peninsula and Japan, and between the nearest major cities in India and Pakistan, fall into the 600 to 1,200 km range. At ranges of a few thousand kilometers, U.S. allies and out-of-theater powers in Europe and Asia could be targeted from the Middle East, South Asia, or elsewhere.

As figure 5-1 shows, most combat aircraft in countries of proliferation concern have ranges far exceeding those of most ballistic and cruise missiles in those same countries. Moreover, the ranges of some aircraft can be extended by in-flight refueling. The need for greater geographical reach may also motivate the development or acquisition of longer range missiles, or the adaptation of cruise missiles for use from air or sea-based platforms. (The effective reach of such cruise missiles would be extended by the range of their carrier.) A full assessment of the military utility of cruise missiles must consider their use in conjunction with aircraft, surface ships, or submarines.

I Payload Amount and Type

Combat aircraft generally can carry much greater payload than can either ballistic or cruise missiles. Combat aircraft available to proliferant states typically have payload capacities from

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[7] The Iraqi extended-range Scuds were subsequently able to reach cities in Israel and Saudi Arabia during the Persian Gulf War of 1991.

2,000 to 4,000 kg, ranging all the way to 10,000 kg, whereas missile payloads tend to run from 500 to 1,000 kg (see fig. 5-l.). Cruise missiles available to proliferant nations typically carry much smaller warheads than do large ballistic missiles, although there is no reason why larger cruise missiles could not be developed. Indeed, large cruise missiles are in some ways easier to build than smaller ones, albeit also easier to intercept.

Without very sophisticated technology, ballistic missiles are not well suited for delivering chemical or biological weapons to broad-area targets. Such targets are most effectively covered with an aerosol spray delivered at slow speeds and low altitudes upwind from the target, a delivery profile much better suited to cruise missiles or aircraft. Nevertheless, by the 1960s the United States had developed submunitions for ballistic missiles that would spread chemical and biological agents more efficiently than would release at a single impact point.

For nuclear weapon delivery, both ballistic and cruise missiles have the advantage of not needing to provide an escape route for the pilot. In general, high-flying aircraft are more vulnerable to air defense than low-flying ones. However, delivering nuclear weapons with low-flying aircraft requires either a pilot willing to sacrifice himself with his plane, a time-delay fuse, or a lofted delivery profile in which the bomb is released on a high, arcing trajectory that provides enough time for the pilot to fly out of the area.

| Accuracy

Like range and payload, the accuracy with which a weapon of mass destruction must be delivered depends on the type of weapon and the target. Most of the ballistic missiles so far deployed in countries of proliferation concern have ranges less than 1,000 km and are unable to deliver weapons with accuracies much better than 1,000 meters. In the absence of weapons of mass destruction or large numbers of missiles, ballistic missiles this inaccurate have little military utility; they are better suited to wage terror campaigns against civilian populations or perhaps to badger large military installations.

It is not yet clear what accuracies will be achieved by the several countries developing or having already deployed missiles of greater than 1,000-km range. Depending on the level of technology, inaccuracies could range from hundreds of meters to many kilometers. Inaccuracies at the upper end of this range could be enough to limit the *military* effectiveness of even some types of weapons of mass destruction (though probably not their political impact).

Combat aircraft with sophisticated weapon-delivery systems and well trained pilots, on the other hand, can deliver munitions with accuracies of 5 to 15 meters, far better than is needed to deliver weapons of mass destruction to wide-area targets. Cruise missiles that are guided to their target on command from a remote operator can also attain accuracies much better than crude ballistic missiles. New guidance technologies make it possible even for autonomously operated cruise missiles to attain about 100-meter accuracies.

I Costs and Infrastructure Requirements

Since the total expense of producing nuclear materials and developing and building a nuclear weapon far exceeds that of any delivery system described here, it is not likely that cost considerations will play a very important role in selection of a nuclear delivery system.

Nevertheless, the cost of maintaining a modern air force could affect a state's ability to deliver large-scale chemical attacks, for instance. A typical estimate for the cost of a single advanced strike aircraft, including pilot training and several years of operations and support, but excluding the infrastructure investment, is $40 million. (The marginal cost of a Scud or SS-21 ballistic missile, similarly including operations and support but excluding launcher and other infrastructure expenses, costs only on the order of $1 million.[8]) In addition to their high unit cost, however, advanced strike aircraft require an extensive support infrastructure including maintenance facilities, spare parts, and highly trained personnel.

Given that a country has sufficient technical capability, it could build and maintain cruise missiles much more cheaply than piloted aircraft. Cruise missiles need only fly once, and they do not incur the expense of training pilots, nor the structural requirements of carrying them along, keeping them alive, and ensuring their safe return. Not counting sunk development and production costs, each additional U.S. *Tomahawk* sea-launched cruise missile costs about $1.5 million.[9] U.S. defense engineers estimate that it should be possible to build an equivalent missile for less than $250,000 by substituting low-cost satellite navigation receivers for the *Tomahawk's* sophisticated radar and optical pattern-recognition guidance systems.[10]

In general, however, cost comparisons of delivery systems for weapons of mass destruction are likely to be only marginally important. A proliferant country will probably make do with the delivery systems it already has or can most easily acquire or modify. Prices of delivery-system acquisition are also difficult to estimate, since they could vary drastically if systems are dumped on world markets by hard-currency-starved counties or if effective embargoes are implemented on sales, so as to drive up prices on the black market.

Defense Penetration

The high speed and steep angle at which ballistic missiles strike a target make them considerably harder to defend against than either piloted or unpiloted aircraft. The Patriot system, originally designed as an antiaircraft weapon, showed only a limited capability to intercept Scud missiles during the Persian Gulf War of 1991.[11] Furthermore, defending against missile attack would be considerably harder if missile warheads were fused to detonate on interception, or if each warhead dispersed many submunitions before coming into range of the defense.

Many developing countries possess air-defense systems capable of destroying traditional (non-stealthy) strike aircraft that attempt to attack defended sites. The effectiveness of such defenses would depend strongly on the sophistication and scale of the attack. Evidence from recent air engagements indicates that properly equipped and maintained strike aircraft-operated in conjunction with defense-suppression techniques (e.g., electronic countermeasures and attacks on air defense batteries)-can penetrate sophisticated defenses with losses of at most a few percent over the course of a campaign.[12] Although many Third World air forces would not be able to mount such a sophisticated and sustained air campaign, those pursuing weapons of mass destruction, with few exceptions, each have relatively advanced combat aircraft that might be used with sufficient effectiveness even against defended areas.

Whether an extensive air campaign would be necessary would depend on the context. A single nuclear weapon can destroy a city, and a relatively

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[8] Stanford, *Assessing Ballistic Missile Proliferation,* op. cit., footnote 4, p. 45.

[9] Steve Fetter, ''Ballistic Missiles and Weapons of Mass Destruction: What is the Threat? What Should be Done?" *International Security,* vol. 16, No, 1, Summer 1991,p. 11.

[10] As cited in ibid.

[11] Although early claims of Patriot success rates were clearly too Optimistic, the system's Overall performance against Scud attacks may never be known exactly. See, for example, Theodore A. Postol, ''Lessons of the Gulf War Experience with Patriot,'' *International Security,* vol. 16, No. 3, Winter 1991/92, pp. 161-171; and Robert M. Stein and Theodore A. Postol, "Correspondence: Patriot Experience in the Gulf War, " *International Security,* vol. 17, No. 1, Summer 1992, pp. 199-240.

[12] See, for example, John R. Harvey, "Regional Ballistic Missiles and Advanced Strike Aircraft,'' *International Security,* vol. 17, No. 2, Fall 1992, p. 59.

small amount of properly delivered biological agent could kill tens of thousands of people. Therefore, if a state is willing to tolerate higher losses of airplanes, pilots, and weapons—and if it is able to persuade its pilots to fly in spite of those risks-it may well be able to deliver weapons of mass destruction by air even against well-defended sites. Of course, this option was apparently not available to Iraq in the 1991 Persian Gulf War, since its air force was so mismatched with that of the coalition forces that its leaders decided not even to mount a serious aerial counterattack.

Cruise missiles can be effective at attacking defended targets, relying on their ability to execute low-altitude, circuitous approaches. They may also be air-launched and accompanied by aircraft in a defense-suppression role, making even short range cruise missiles particularly suited to attacking defended targets. Even if cruise missiles were detected, they can fly at altitudes below the reach of many medium or long range surface-to-air missiles, leaving only antiaircraft artillery or short range surface-to-air missiles to shoot them down,

Reliability and Survivability

Since they are single-shot systems, ballistic and cruise missiles are generally less reliable than manned aircraft, which are designed with pilot safety and multiple sorties in mind.[13] The types of redundant systems used to provide safety on aircraft are harder to provide for ballistic or cruise missiles, since a missile's range is more sensitive to changes in payload. Moreover, aircraft are generally tested in the design process more thoroughly than ballistic or cruise missiles, and more mission-critical systems in an airplane can be tested prior to use than in a ballistic missile. (For example, a solid rocket motor cannot be tested without being used up, and most liquid-fueled motors are only designed for a single fining.) Aircraft also tend! to fail gracefully and can usually return to base if problems are encountered.

Nevertheless, a state with a nuclear arsenal of only a few very expensive weapons may well pay the price-in cost and performance-of making its missiles more reliable. (This would likely involve a substantial engineering effort, precluding use of an "off-the-shelf' missile designed to less demanding requirements.) But even a reliable missile would likely be less forgiving of failure when it did happen than would an airplane. In the event an airplane fails to take off successfully, its weapon and its mission can usually be recovered—an important consideration in the case of a nuclear weapon whose completion may have cost a state a noticeable fraction of its gross national product for many years. Warheads are less likely to survive launch failures when mounted on cruise or ballistic missiles.

The *pre-launch* survivability of ballistic and cruise missiles is likely to be higher than that of airplanes, however, since they are smaller, can more readily be hidden, and do not need to be located near runways or landing strips. During Operation Desert Storm the coalition air forces pinned down or destroyed much of the Iraqi air force, but they may not have actually destroyed a single Scud missile or mobile launcher. Once located, however, missiles are more vulnerable than aircraft, which can flee or protect themselves.

Command and Control

Political leaders may find missiles (certainly ballistic missiles, but perhaps cruise missiles as well) to be more ''controllable" than piloted aircraft in that the infrastructure required to launch missiles is significantly smaller than that needed to sustain air operations. Launch orders need pass through fewer levels of command, and fewer people are in a position to block them. Perhaps most fundamentally, an unpiloted missile

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[13] Reliability here is defined as the probability of successful flight given that pre-flight or pre-launch checks have been passed.

cannot question its launch order. Ground-launched cruise missiles could have infrastructures more the size of those for ballistic missiles than those for piloted aircraft. Although deploying air- or sea-launched cruise missiles would require the participation of an air force or navy, with its attendant logistical and command structures, the launching platform could remain out of range of enemy forces. Thus, its logistical infrastructure might still be considerably less than that required to penetrate enemy airspace using manned aircraft.

| Achieving Tactical Surprise

Intercontinental ballistic missiles (ICBMs) can reach targets a quarter of the way around the globe in about 30 minutes. Tactical missiles complete their flight in even less time. Even though missiles traveling over ranges of a few hundred kilometers can be detected by early-warning radars or space-based infrared sensors early in their flight, they travel so fast that there is still very little warning of their arrival. Iraqi Scuds took about seven minutes to reach Israel, traveling at up to eight times the speed of sound, and the Israelis had about five minutes' warning of their arrival.[14] Combat aircraft could cover the same distance in about a half-hour. However, when hugging the ground over routes that mask their approach, they could hide from search radars and arrive on target with about as little warning as ballistic missiles.[15] Cruise missiles in general are harder to detect than aircraft because they are smaller, quieter, and operate at lower skin and engine temperatures. However, to take as much advantage from terrain masking as some aircraft can, they would require advanced guidance systems and accurate geographical information for planning flight routes.

| Target Acquisition

In *the* absence of remote, near-real-time reconnaissance capabilities, which are beyond the capabilities of most states, neither ballistic nor cruise missiles are suitable for use against mobile targets. Piloted aircraft would be the only available choice for such missions-and even then, only for some of them. As noted above, for example, even a determined coalition air-campaign had great difficulty locating and attacking Iraqi Scud launchers. Delivering chemical or biological weapons against moving military formations would call for pilot judgment, as might tactical uses of nuclear weapons. Attacking cities or fixed military bases with any of these weapons, however, would not demand precise target-acquisition capabilities.

Piloted aircraft have a clear advantage for military missions in which it is important to ascertain quickly that the weapon has been delivered to a target and detonated. Ballistic missiles do not provide any such indication, nor do autonomously guided cruise missiles. A cruise missile that was guided to its target via data link to a remote operator could send information (e.g., video imagery) indicating whether or not it arrived at its intended target. But this information would not necessarily indicate whether the warhead detonated, much less whether the target was destroyed.[16]

BALLISTIC MISSILES

| Classification of Missiles

A "ballistic missile" is a rocket-powered delivery vehicle that has some form of guidance system, that is primarily intended for use against ground targets, and that travels a large portion of its flight in a ballistic (free-fall) trajectory. Ballistic missile flight profiles are usually de-

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[14] Postol, "Lessons of the Gulf War Experience with Patriot, " op. cit., footnote 11, pp. 161-171.

[15] Stanford, *Assessing* Ballistic *Missile Proliferation,* op. Cit., footnote 4, p. 43.

[16] Aircraft pilots, too, can have difficulty making accurate bomb damage assessments. Despite its sophisticated reconnaissance systems, U.S. bomb damage assessments during the Persian Gulf War were still incomplete and delayed.

Table 5-3-Space-Launch Vehicles and Ballistic Missiles With Ranges Over 100 km in Non-MTCR Countries

Producing country[a]	Missile designation	Status[b]	Range [km]	Payload [kg]	Accuracy CEP [m]	Fuel/ stages	Comment[c]	imported missiies[d]
Countries with indigenous missile programs:								
Former Soviet Union[d]	**SS-21 (Scarab)**	**s**	**120**	**450**	**240-300**	**solid/1**	**1976 IOC**	
	Scud-B (SS-1)	**s**	**300**	**1,000**	**500-900**	**liquid/1**	**1962 Ioc**	
China[d]	**M-1 1**	**s?**	**300**	**500**	**300?”**	**solid/2**	**1990 Ioc?**	
	M-9	**D**	**600**	**500**	**300-600**	**solid/l**	**—**	
	DF-3A (CSS-2)	**s**	**2,500-3,000**	**2,000**	**2,500**	**liquicVl**	**1971 Ioc**	
Israel	**Jericho 1**	**s**	**480-650**	**250-500**	**smali?**	**solid/2?**	**w/France; 1973 IOC**	Lance[f]
	Jericho ii	**s**	1,500	**650-I,000?**	**?**	**solid/2**	**w/France; 1990 IOC**	
	Jericho IIB	**T**	**2,500**	**700?**	**?**	**solid/2**	**—**	
	Shavit	**s**	**2,500/7,500**	**750/150**	**NA**	**solid/3**	**SLV; w/France; 1988 IOC**	
India	**Prithvi**	**T**	**150/250**	**1 ,ooo/5oo**	**250?**	**liquid**	**1992 IOC?**	
	Agni	**T**	**2,500**	**1,000**	**2,500?**	**solid-liq/2**	**w/France, FRG; 1989 test**	
	"ICBM”	**P**	**5,000**	**?**	**Smaii?**	NA	**—**	
	SLV-3	**s**	**800**	**100**	**NA**	**solid/4?**	**SLV; 1980 IOC**	
	ASLV	**T**	**4,000**	**150-500?**	**NA**	**solid/4**	**SLV; w/France, FRG**	
	PSLV	**T**	**8,000**	**1,000**	**NA**	**liq-solid/4**	**SLV**	
	GSLV	**P**	**14,000**	**2,500**	**NA**	**cryo/solid**	**SLV**	
Taiwan	**Ching Feng**	**s-?**	**100-130**	**275-400?**	**?**	**liquid/1**	**like Lance; w/Israel; 1983 IOC**	
	hen Ma	**D-?**	**950**	**500?**	**?**	**solid**	**“Sky Horse”; canceled?**	
	name unknown	**D?**	**[950]?**	**?**	**NA**	**solid?/3?**	**SLV**	
North Korea (DPRK)	**Scud-B**	**s**	**340**	1,000	**$\lesssim$1,000**	**liquid/1**	**w/USSR, Egypt?**	**FROG-P;**
	Scud-C	**s?**	**600**	**500-700**	**'?**	**liquid/1**	**w/China**	**Scud-B (via Egypt)**
	Nodong-1	**T?**	1,000	**1 ,Ooo?**	**?**	**liquid/1 ?**	**w/China**	
South Korea	**NHK-1**	**s-?**	**180**	**500**	**?**	**solid**	**w/U. S.; 1978 IOC**	
	Korean SSM	**T**	**260**	**?**	**?**	**solid/2**	**·**	
	name unknown	**D-**	**[4,000]**	**?**	**NA**		**SLV; development began 1987**	

(Continued on next page)

Table 5-3-Space-Launch Vehicles and Ballistic **Missiles** With Ranges Over 100 **km in** Non-MTCR Countries—(Continued)

Producing country.	Missile designation	Status[b]	Range [km]	Payload [kg]	Accuracy CEP [m]	Fuel/ stages	CommenF	Imported missiles[d]
Brazil	Orbita MB/EE	D?	150	500	?	solid/1	1991 IOC?	
	Avibras SS-300	T-	300	1,000	?	liquid/1	suspended; 1991 IOC?;	
	MB/EE-350	D.?	350	500	?	solid	MB/EE's in abeyance	
	(MB/EE)?-600	D-?	600	500	?	solid	—	
	MB/EE-1000	D-7	1,000	?	?	solid	—	
	SS-looo	D-?	1,200	?	?	solid	SS-series in abeyance	
	IRBM	P?	3,000	?	?	solid	—	
	Sonda 3	s	80	135	NA	solid	SR; w/FRG	
	Sonda 4	S?	950	500	NA	solid	SR; w/FRG, France	
	VLS (Avibras)	D?	[10,000]	160-500?	NA	solid?/4	SLV; w/FRG	
Argentina	Alacran	D	200	100-500?	?	Solid/1	consortium; 1989 test	
	Condor II	D-	900	500	900?	solid/2	canceled 1991; SLV plans?	
South Africa	Arniston	T	500-1,500	500-1,000?	?	solid	w/Israel (Jericho 11?); '89	
	RSA-4	D	[10,000]	500	NA	solid/3	test SLV; test planned 1996	
Iraq (before Gulf War)	Fahd 300/600	D	300/600	?	?	solid/1	—	FROG-7; Scud-B
	A1-Husayn	s	600	150-500?	3,000	liquid/1	modified Scud-B; 1988 IOC	
	A1-Hijarah/Abbas	s?	750-900	1 00-300?	3,000	liquid/1	modified Scud-B; 1990 IOC?	
	Tammuz-1 (A1-Abid)	D	2,000	750?	?	liquid/3?	SLV?; w/USSR; December 1989test;clustered booster?	
Iran	Mushak-120	s	120	500	?	solid/1	w/China; 1990 IOC?	Scud-B&C (from DPRK); M-9 (negotiations); Nodong-1 (negotiations)
	Mushak-200	D	200	500?	?	solid/1	w/China	
	Scud-B	S?	300	1,000	1,000	liquid?/1	w/DPRK; 1984 IOC?	
	"Iran-700"	D?	700	?	600?	?	—	
	Tondar-68	D	1,000	400?	?	solid	w/China	

(Continued on next page)

Table 5-3-Space-Launch Vehicles and Ballistic Missiles With Ranges Over 100 km in Non-MTCR Countries-(Continued)

Producing country[a]	Missile designation	Status[b]	Range [km]	Payload [kg]	Accuracy CEP [m]	Fuel/ stages	Comment[c]	Imported missiles[d]
Pakistan	**Hatf II**	**T**	**300**	**500**	?	**solici/2?**	**w/France, China; 1988 test**	**M-1 1 (under negotiation)**
	Hatf III	**D?**	**600**	**500-1,000**	?	**solid/1 ?**	**w/China; staiied?**	
	Suparco	**s**	**[300]**	**?**	NA	**soiid/2?**	**SR; w/France; China?**	
	name unknown	**P**	**[1 ,200]**	**?**	NA	**soiid/3?**	**SLV**	
Egypt	**Scud-B**	**D7**	**300**	**1,000**	**1,000**	**liquid/1**	—	**FROG-7;**
	Scud-100	**D**	**600**	**500**	**?**	**iiquid/1**	**w/DPRK**	**Scud-B**
	Vector (Badr-2000/Condor II)	**D-?**	**<1 ,200”**	**450**	**750-900?**	**solid/2**	**w/Argentina Iraq**	
Libya	**Ai-Fatah (also “Otrag/ittisalt”)**	**D?**	**450-900**	**500?**	**?**	**liquid**	w/FRG?, **Brazil?; possibly in abeyance**	**FROG-7; Scud-B; SS-217; M-9 (negotiations)**

Countries that have only imported missiles:

Saudi Arabia:	**DF-3A (from China, 1987-1988)**
Syria	FROG-7, SS-21, **Scud-B (from USSR); Scud-C (from DPRK); M-9 (negotiations with China)**
Yemen:	**FROG-7; SS-21 ; Scud-B**
Afghanistan:	**Scud-B**
Algeria:	**FROG-7; Scud-B?**
Cuba:	**FROG-7**

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[a] Countries listed were not full members of the MTCR as of March 1993. (At that time, however, Argentina was becoming a full member.)

[b] S: in service. T: testing. D: under development. S-/T-/D-: in abeyance/suspended/abandoned. P: planned.

[c] IOC: initial operational capability. SLV: space-launch vehicle. SR: sounding rocket. NA: not applicable/available.

[d] All Scud-Bs listed as *imported* were obtained from the former Soviet Union except Iran’s, which were obtained from North Korea.

[e] The missiles listed for China and the former Soviet Union (which have both pledged to abide by the MTCR export provisions but are not full members) include only those known or suspected to have been exported to other countries.

[f] U.S. Lance (1972 IOC): liquid-fueled, 133-km range, 275-kg payload, 150- m CEP, and can carry cluster munitions. Soviet FROG-7 (1965 IOC): *unguided,* solid-fueled, 6&km range, 450-kg paytoad (perhaps 100 km with lighter payload), 400-m CEP.

The following countries are also able to or have already produced the following short-range missiles (under 100 km):

Argentina (Condor 1-95 km/365 kg, SR?, abandoned?); Brazil (Astros-II/SS-60 artillery rocket); Egypt (Sakr-80—solid, unguided, copy of FROG-7); India (MBRS); Indonesia (RX-250-2-stage sounding rocket, with France; MAR); Iran (Oghab—solid, unguided, 40 km; Nazeat—90 km/150 kg, solid, with China); Iraq (Ababil 50/100; Sajil-60 or Brazil’s Astros-II/SS-60 artillery rocket; Laith-90); Israel (MAR-290/350-solid artillery rockets, up to 90 km/330 kg); South Korea (U.S. Honest John—solid, unguided, 40 km); Pakistan (Hatf-I, with France); Taiwan (U.S. Honest John).

SOURCES: W. Seth Carus, *Ballistic Missiles in Modern Conflict* (New York: Praeger, 1991), pp. 85-90; *Arms Control Today,* April 1992, pp. 28-29; U.S. Dept. of Defense, *Conduct of the Persian Gulf War: Final Report to Congress,* Pursuant to Title V of the Persian Gulf Conflict Supplemental Authorization and Personnel Benefits Act of 1991 (Public Law 102-25), April 1992, p. 16; John W. Lewis and Hua Di, “China’s Ballistic Missile Programs,” *International Security,* vol. 17, *No.* 2, fall 1992, p. 11; Janne Nolan, Testimony before the Subcommittee on Arms Control, International Security and science, House Foreign Affairs Committee, Mar. 3, 1992; Duncan Lennox, ad., Jane’s *Strategic Weapons Systems* (Surrey, U. K.: Jane’s Information Group, 1990), Issues O-7, 1990-Jan. 7, 1992, and Jane’s *Defense Weekly,* Jan. 11, 1992, p. 50, June 6, 1992, p. 996, and Jan. 23, 1993, p. 18; Aaron Karp, “Ballistic Missile Proliferation,” *World Armaments and Disarmament: SIPRI Yearbook 1991* (New York: Oxford University Press, 1991); and U.S. Arms Control and Disarmament Agency, *World Military Expenditures and Arms Transfers, 1988/89,* pp. 18-19.

scribed in terms of three phases: the boost phase, in which the propulsion system generates thrust; the midcourse phase, in which the missile coasts in an arc under the influence of gravity; and the terminal phase, in which the missile experiences strong decelerating forces during its descent into the atmosphere. Missiles with ranges under 300 km remain in the atmosphere for their entire trajectory (and travel slower than longer range missiles), thus reducing the abruptness of the reentry transition.[17] In this chapter, all ranges refer ‘minimum-energy trajectories, ’ which maximize the range available to a given missile.[18]

Although *unguided rockets,* such as the Soviet FROG-5, the U.S. *Honest John,* and the Iranian *Oghab* rockets, maybe useful in some battlefield situations, they will not be considered here, primarily because their ranges are generally much less than 100 km even with small payloads. Similarly, rocket-assisted artillery, surface-to-air, air-to-air, and air-to-surface missiles are not included in this analysis.

A functional ballistic missile must (i) employ a propulsion system to provide thrust (ii) have a guidance and control system to direct its thrust (iii) carry a useful payload, and (iv) be supported by some sort of launcher, e.g., a freed gantry, a mobile truck-mounted erector-launcher, or a silo. The missile and its payload must be designed to withstand the mechanical and thermal stresses involved in launch and final approach to a target. For missiles with ranges substantially greater than about 400 km, the final approach involves reentering the atmosphere from space at very high speeds, causing intense heating, deceleration, and the possibility of strong lateral forces. The difficulty of designing missiles for a given payload therefore increases dramatically with range and level of accuracy.

Missiles are characterized in terms of several key parameters. The most fundamental of these are the missile’s range and payload, Payload is defined as the mass of the warhead(s) or other useful material (not counting the empty booster canister, for instance) that the missile can deliver at a given range. Within certain limits, payload can be traded off against range. (The same is true for aircraft and cruise missiles.) Accuracy refers to the likelihood that the payload will be delivered to within a certain distance of an intended target. There are both systematic and random contributions to inaccuracy, but in many cases the random errors are more important. Random errors are quantified by the Circular Error Probable (CEP), which defines the radius of a circle on the ground into which half of a large number of identical missiles launched along the same intended trajectory would fall.[19] Missiles are also characterized in terms of their number of propulsion stages, or sequentially firing boosters.

I Status of Missile Proliferation

Table 5-3 illustrates the existing or developing missile programs in countries that were not full members of the MTCR as of March 1993, as reported in public sources. (For China and the former Soviet Union, only missiles known or suspected to have been exported to other countries are included.) Since the sources for this table contain substantial variance and uncer-

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[17] The limit of the tangible atmosphere occurs at approximately 100 km altitude (below which the lighter and heavier air molecules are nearly uniformly mixed). At 100 km altitude, air density and pressure are roughly one millionth of their values at the Earth’s surface.

[18] Shorter ranges result when missiles are launched at angles either closer to the horizontal or closer to the vertical than the minimum-energy launch angle. Such trajectories are called ‘‘depressed’ or “lofted.”

[19] CEP does not take into account either launch failures or the systematic errors associated with mis-aiming the missile in the first place, called the ‘‘bias. ’ The CEP is also a median, rather than a mean; it does not predict how@ outside the circle the other half of the missiles will land. (For instance, some of Iraqi Scuds fired toward Israel during the Persian Gulf War landed quite far from intended targets or in the Mediterranean Sea.) Furthermore, in practice the expected miss-distance is usually elongated in the downrange direction, leading to an elliptical rather than circular error pattern. Therefore, even ignoring the bias, the CEP gives only a rough indication of the likelihood that a missile will hit an intended target.

Table 5-4-Ballistic Missile Production Capabilities

Category	Description	Countries
Advanced	Able to design and produce missiles comparable to those produced in the United States in the mid-1960s (e.g., ICBM-range ballistic missiles and space-launch vehicles)[a]	India Israei, and possibly Taiwan
Intermediate	Able to reverse-engineer, introduce changes to, and manufacture Scud-ilke missiles, and to make solid-propellant short-range missiles	Brazil, North Korea South Korea, and possibly Argentina and South Africa
Incipient	*some* capability to modify existing Scuds, but little else	Egypt, Iran, Iraq (before the Persian Gulf War), and Pakistan
No *indigenous capability*	*No* missile design or manufacturing capability, but have imported missiles with ranges above 100 km	Afghanistan, Libya, Saudi Arabia, Syria, Yemen, and possibly Algeria and Cuba

a Comparable *capability*, however, refers primarily to the design and assembly capability of large solid-propellant motors, and does not imply U.S. levels of manufacturing *capacity*.

SOURCE: Stanford University, Center for International Security and Arms Control, *Assessing Ballistic Missile Proliferation and Its Control* (Stanford, CA: Stanford University, November 1991), p. 153.

tainties in reporting the status or specifications of some missile programs, a range of estimates is indicated where appropriate.

Table 5-3 shows that 13 non-MTCR countries (not counting China and the former Soviet Union) may have indigenous missile-development programs for ballistic missiles exceeding 100 km in range. Only two of these, however—Israel and India-have demonstrated capability sufficient for indigenous design and production of multi-stage missiles.[20] Another six countries have imported missiles but have virtually no capability to develop or manufacture them. Most of the imported missiles have come from the former Soviet Union-Scud-Bs, FROG-7s, and some SS-21s—and many of them were obtained more than a decade ago. More recently, however, China has exported 2,500-km range DF-3s and possibly M-9s and M-lls, and North Korea has exported Scud-Cs. According to one analysis, the 19 countries mentioned above fall roughly into four categories, which are described in table 5-4.[21]

Indigenous capability is only one factor affecting missile proliferation. In the past, countries have been able to enhance their missile capabilities substantially from what they could have done

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[20] Taiwan also has relatively advanced aerospace industrial *capability,* but its ballistic-missile and space-launch programs (other than work on satellite vehicles themselves) have largely been on hold for many years.

[21] These categorizations, as well as the framework for evaluating indigenous capability, were developed in the Stanford report, *Assessing Ballistic Missile Proliferation,* op. cit., footnote 4, p. 153. Study methodology for that report included preparing detailed profiles for 17 subject proliferant countries that surveyed national, geographical, economic, and regime parameters, current conflicts and recent history, military posture, and the record of ballistic: missile acquisition. See *Ballistic Missile Proliferation Study Country Profiles,* Center for International Security and Arms Control (CISAC), Stanford University, July 1990 (unpublished). The study participants also examined technical features of missiles deployed or under development in the subject countries, along with key technologies needed for indigenous production. Many of the study participants have close ties to missile and aircraft development and production in both private industry and government. Principal authors (affiliated with CISAC unless indicated otherwise) were John Barker (Graham& James), Michael Elleman (CISAC and Lockheed), John Harvey, and Uzi Rubin. Other study participants were: Ronald Beaver, David Bernstein, Hua Di, Phil Farley, Lewis Franklin (CISAC and TRW, Inc.), Susan Lindheim, Michael McFaul, and William Perry.

on their own by importing missiles or advanced components, or by participating in joint ventures (e.g., between Argentina, Egypt, and Iraq to develop the *Condor* II *missile).* However, since the MTCR has restricted many of the outside sources of cooperation and assistance on missile development, indigenous capability has become more important for most countries of proliferation concern.

To understand the problem of missile proliferation more fully, trends in these capabilities must also be taken into account. According to at least two estimates, most of the countries in the top three categories of capability *could* advance upward in the list by about one category during the next decade, placing Israel, India, Taiwan, South Korea, Brazil, and possibly North Korea and South Africa in the "Advanced" category, and Pakistan, Iran, Argentina, and Egypt in the "Intermediate" category.[22] Assuming continuation of constraints imposed by U.N. Resolution 687 on Iraq's weapon programs, Iraq would be the only country remaining in the ''Incipient' category.

If countries are willing to dedicate sufficient resources to their missile programs, most of these advances in capability could occur even under a well-functioning MTCR. MTCR constraints, however, can significantly increase development costs, helping to convince leaders that the benefits are not worth the expense. The ballistic-missile programs in Brazil and South Africa for instance, may well *not* advance significantly, in part because of increased costs. (Brazil's diminishing export market and the decline in the threat that South Africa perceives itself to face may also be playing a large role.) Furthermore, largely because of diplomatic efforts by the United States since the 1970s, Taiwan and South Korea do not appear to be aggressively pursuing either ballistic-missile or space-launch programs at the present time, although they would have the technological *capability* to do so if they chose.

Even if such advances did take place, a large gap would remain between the capabilities of most of these nations and what would be needed to strike the United States. According to then-CIA Director Robert Gates, "Only China and the Commonwealth of Independent States have the missile capability to reach U.S. territory directly. We do not expect increased risk to U.S. territory from the special weapons of other countries-in a conventional military sense-for at least another decade. . . .' '[23] Among the handful of countries with both the technological capability and the resources to develop long range ballistic missiles over the next decade, few if any would likely have the intent to target the United States.

Missile Propulsion Technologies

The engineering fundamentals of rocket propulsion systems are well documented in standard texts.[24] In theory, there are few secrets involved in basic missile design. In practice, however, considerable expertise is required to integrate the various aspects of a ballistic missile into a militarily useful device.

Two kinds of chemical propulsion technologies—solid and liquid fuel-are widely used in ballistic missiles. Both rely on burning a fuel at high temperatures and expelling the hot combustion gases out the back of the engine. Whereas aircraft and many cruise missiles use oxygen in the atmosphere to burn the fuel they carry, ballistic missiles are unable to do so and must

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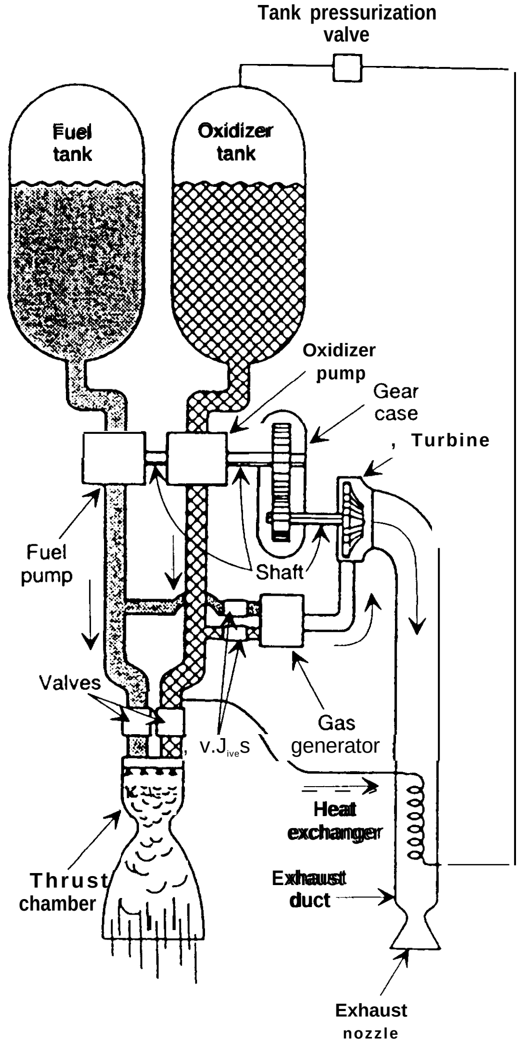
[22] Stanford, Assessing *Ballistic Missile Proliferation,* op. cit., footnote 4, p. 154; and *Ballistic Missile Proliferation: An Emerging Threat* (Arlington, VA: System Planning Corp., 1992) p. 28, Some reports indicate that Iran may have already moved into the "intermediate" category with indigenous production or assembly of Scud-B missiles. See, for example, Joseph S. Bermudez, Jr., ' 'Ballistic Missiles in the Third World—Iran's Medium Range Missiles, ' *Jane's Intelligence Review,* April 1992, pp. 147-152.

[23] Testimony of then CIA director Robert Gates, before the Senate Committee on Governmental Affairs, Jan. 15, 1992, p. 3.

[24] See, for example, George P. Sutton and Donald M. Ross, *Rocket Propulsion Elements: An Introduction to the Engineering of Rockets, 6th edition (New York:* John Wiley and Sons, 1992).

carry their own oxidizer.[25] In liquid-fueled boosters, the oxidizer is usually kept separate fromthe fuel and mixed with it only in the final combustion chamber. In solid ‘boosters, the oxidizer is contained in the propellant mixture. Regardless of the fuel type, however, ballistic missiles generally reach much higher speeds than other kinds of delivery vehicles with comparable payloads. Even 100-km range missiles, which remain in the atmosphere, typically strike their targets at approximately the speed of sound (330 rn/see, or 740 mph), and 1,000-km missile warheads are only slowed by the atmosphere from 3 km/see to about 1 km/sec (2,200 mph).[26]

Figure 5-2-Schematic Diagram of a Liquid-Propellant Rocket Engine



SOURCE: George P. Sutton and Donald M. Ross, *Rocket Propulsion Elements,* 5th edition (New York, NY: John Wiley and Sons, 1986). Copyright @ 1986 by John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.

LIQUID-FUELED PROPULSION

A country that operates chemical processing facilities would likely also be able to manufacture fuel and at least crude components for short range liquid-fueled missiles such as Scuds. Although many liquid fuels are physically hazardous due to their corrosive, explosive, carcinogenic, and toxic properties, several types are already in use by about a dozen developing countries.[27]

Liquid-fueled engines more powerful than those found in Scuds, however, are correspondingly harder to build (figure 5-2 shows a schematic diagram of a liquid-fueled engine). Substantially greater experience is required in the design and manufacture of their components, including precision valves, injectors, pumps, turbines, and combustion chambers-many of which would call for numerically controlled machine tools or highly skilled machinists to fabricate. The added difficulties include: the design and fabrication of larger components with

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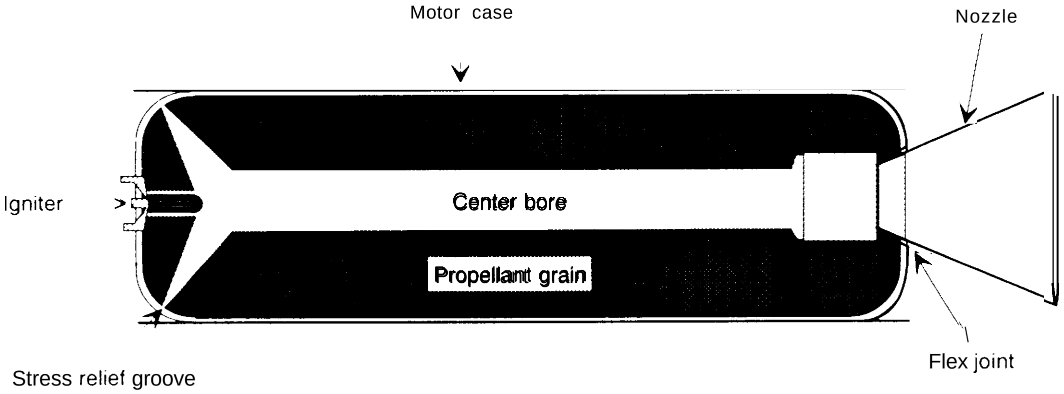
[25] Ballistic missiles carry their own oxidizers both to help reach the speeds needed for long range ballistic trajectories and because oxygen becomes too scarce at high altitudes. Propulsion systems that scoop up external air (called “air breathers’ ’)-except for more sophisticated technologies, such as high-speed ramjets and scramjets—are much more limited in the speeds they can achieve. Note, however, that short range air-launched cruise missiles, for example, can also be rocket-powered and can be designed to achieve supersonic speeds as well.

[26] See Juergen Altmann, *SDI for Europe? Technical Aspects of Anti-Tactical Ballistic Missile Defenses,* Peace Research Institute Frankfurt, Research Report 3/1988, September 1988, pp. 27-28.

[27] Commonly used fuels include hydrazine and unsymmetrical dimethyl hydrazine (UDMH), which are burned using the oxidizers nitrogen tetroxide or inhibited red fuming nitric acid (IRFNA). Scuds, for instance, use UDMH and IRFNA. Readily available liquid fuels that can also be used in rockets include gasoline, kerosene, ethyl alcohol, and liquid ammonia.

Figure 5-3—Schematic Diagram of a Solid-Propellant Rocket Engine



SOURCE: Center for International Security and Arms Control, Stanford University, ***Assessing Ballistic Missile Proliferation and Its*** Corrfro/(Stanford, CA: Stanford University, November 1991), p. 136. Reprinted by permission of Stanford University.

tighter tolerances; greater cooling requirements for engine parts exposed to high-temperature combustion gases; and more rigorous requirements for combustion stability, in order to avoid dangerous flow oscillations during thrust.

Moreover, to avoid gross inaccuracies, liquid-fueled engines capable of delivering sufficient thrust to deliver a 500 kg payload more than 1,000 to 1,500 km must employ a much more complex system of valves, pressurizers, flow-control meters, and actuators than are needed for less powerful engines, to control and terminate the thrust precisely. If lesser quality components are substituted, for example, from (dual-use) chemical-manufacturing or petrochemical-industry equipment, their poor performance might require development of a post-boost vehicle—a final stage capable of course corrections-to achieve even modest (several-kilometer) accuracies.[28] This would present an entirely new set of design problems.

In order to design these larger engines, many well-trained and experienced combustion scientists, chemical engineers, heat transfer specialists, and experts in fluid mechanics and mechanical design would be required, along with a well-funded, multiyear research and development program. Because of the similarity between some aircraft and missile components and the types of machining required to produce or maintain them, experience with aircraft maintenance facilities and especially with production, assembly, and rebuilding of jet engines might be very helpful in this regard.[29]

SOLID-FUELED PROPULSION

Although conceptually simpler than liquid-fueled missiles and involving almost no moving parts, solid-fueled missiles require years of practical experience to design and develop successfully, to learn how to manufacture safely, and to make accurate (figure 5-3 shows a schematic diagram of a solid-fueled booster). In addition to the advantage many proliferant countries have by already possessing liquid-fueled Scuds or their variants, the technology behind liquid-fueled engines can more easily be ''reverse engineered' than can solid-fueled boosters. Taking apart

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[28] For example, a valve that shut off 0.25 seconds too late at bum-out (when a 1,000-km range missile might be accelerating at 100 m/sec^2) would lead to a velocity error of 25 m/see and about a 17-km overshoot at the target. (Range is roughly proportional to the bum-out velocity squared, and bum-out velocity is about 3 Ian/see at 1,000-km range.)

[29] Stanford, *Assessing Ballistic Missile Proliferation,* op. Cit., footnote 4, p. 135.

someone else's solid missiles reveals little about the processes by which they were put together. The performance of liquid engines can be studied in detail by refueling and retesting them on static test stands, including partial throttle or early termination of thrust if problems develop during a test. The performance of solid motors, on the other hand, is heavily dependent on the way the solid fuel is cast into the particular missile, and once fired, it is almost impossible to stop the burning fuel in the middle of the test. If a solid motor fails on the test stand, there may be no recoverable data from which to try and correct the problem, and it might not even be clear if the problem was generic to the design or specific to the missile being tested. Even replicating the failure mode of such a test can be exceedingly difficult.[30] When launched, solid-fueled motors also require sophisticated thrust-termination mechanisms or computer-controlled maneuvers to use up excess propellant while remaining fixed on a given target; their burning fuel cannot be shut off simply by closing a valve.[31]

Since solid-fueled motors can be transported and stored with the propellant intact, and readied for launch much more quickly than their liquid-fueled counterparts, they offer operational and tactical advantages over liquid-fueled missiles. Many solid propellants from the 1950s and 1960s are well understood both theoretically and practically, and enough has been published about them to make this information easily available. Once the practical aspects of manufacturing solid-fueled missiles are mastered, far fewer components need be assembled, and production is consequently more straightforward. Hence, about a half dozen countries appear to be focusing their missile development programs primarily on solid-fueled technology.

Indigenous manufacture of steel motor *cases,* while requiring well-trained metallurgists and a moderately sophisticated steel treatment facility for rolling, forming, and welding chambers, would not present much difficulty for countries with metallurgical experience from manufacturing ships, oil pipelines, or oil-drilling equipment.[32] Very large chambers for intermediate-or long range missiles would require more sophisticated metal-working capabilities than typically found in these industries, however, because of the high temperatures and pressures they would have to withstand.[33]

The most challenging aspect of manufacturing solid-propellant motors involves safely preparing, ing, and casting the entire propellant—called the "grain"—into the missile case. For small motors and short range missiles, this is relatively simple. But as the motor size increases, preparing and casting a uniformly structured, well-bonded propellant grain can become problematic.

Preparing the mixture itself is not significantly harder than other chemical processes involving explosives. The oxidizer crystals must be ground to the proper size in a controlled environment and then carefully analyzed for impurities that could upset subsequent manufacturing steps or burning characteristics. The propellant ingredients consist of relatively dense solid particles suspended in a much-less dense liquid plastic material called a "matrix." To improve their structural, manufacturing, and burning properties, solid-propellant grains employ mixtures of crystalline oxidizers and powdered metal fuel in a plastic matrix that

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[30] C. Robert Dietz, senior missile designer (retired), Lockheed Missiles and Space Co., private communication, Dec. 8, 1992.

[31] The forward thrust of solid-fueled boosters can be cutoff by blowing out thrust-termination ports at the top of the booster, but this technique is relatively sensitive to error. Some missiles, such as the Indian Agni missile and certain space-launch vehicles, employ a combination of solid and liquid boosters to exploit the relative advantages of each.

[32] Stanford, Assessing *Ballistic Missile Proliferation,* op. Cit., footnote 4, p. 135.

[33] Some motor cases are fabricated out of fiber-reinforced composite materials, a technology currently available to moderately advanced industrial countries. The United States was employing woven spun fiberglass in the third stage of the Minuteman II missiles by the early 1%0s.

usually contains precise amounts of curing agents, catalysts, plasticizers, burn-rate modifiers, and processing aids. These ingredients must be combined in a specially designed large batch mixer to achieve uniformity of the propellant, a task that can be likened to producing a uniform mixture of sand and honey. Mixing is inherently dangerous, however, since accidents can cause large fries or explosions; a mixing blade that scrapes any surface can cause sparks that would ignite the fuel.

The mixture must then quickly be cast into the missile case and allowed to harden and cure. Extreme care must be taken during casting to ensure proper bonding of the propellant grain to the case wall and to avoid the formation of cracks or voids. Such imperfections can expose additional surface areas within the propellant, causing it to burn erratically or reach the wall prematurely, resulting in catastrophic failure of the motor. In addition, the larger the motor, the more susceptible solid propellants are to the formation of cracks due to repeated changes in temperature.

Proper grain design is also important. Its hollow cross-sectional shape determines the amount of surface area burning at any time, thus influencing the rate of burn, the internal pressure, and thus the motor's thrust. Design trade-offs must be made between minimizing the change in chamber pressure during the burn, on the one hand, and avoiding excessively rapid acceleration at the end of the bum when the missile is lightest, on the other; too much of one or the other would put undue stress on the missile casing. During boost, the grain must also withstand extremely high temperatures, pressures, and stresses of acceleration. As solid motors become larger, their engineering and fabrication therefore become increasingly more difficult.

To verify their integrity and proper structure, solid motors are inspected after their manufacture by nondestructive methods such as x-rays, ultrasound, and thermal imaging. (The equipment required for manufacturing a typical advanced solid motor is given in table 5-5.) Skipping these inspections would exact a price in terms of lower reliability.

H. ARVIDSSON, UNITED NATIONS

Blades of a highly specialized Iraqi solid-fuel rocket propellant mixer being destroyed under the authority of U.N. Security Council Resolution 687 during an inspection in 1992. Such mixers are used to prepare the fuel before casting it into the missile housing.

| Obtaining Missile Technology

PURCHASE

Until the 1980s, the majority of ballistic missiles sold or traded were related to the original liquid-fueled Soviet Scud-B, with at least eight developing countries obtaining Soviet Scuds directly-Afghanistan, Egypt, Iraq, Libya, North Korea, Syria, and North and South Yemen (which have since united).[34] Notably, all of the indigenous missile programs in the developing world that did *not* receive Scud missiles from the Soviet Union appear to have primarily (though not exclusively) pursued solid-fuel technology for their more advanced programs. These include Argentina, Brazil, India, Iran, Israel, South Korea

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[34] Several of these—Syria, Yemen, and possibly Libya—also obtained the more accurate (but shorter range) solid-fueled SS-21. See table 5-3 and sources therein.

Table 5-5-Typical Equipment for Processing Composite Solid Propellants

Process	Typical equipment
Reducing oxidizer crystal size and blending	Hammer mills; micropulverizers; fluid energy mills; sieves, screens, rotary dryers
Mixing	Automatic 2-or 3-bladed rotary vertical mixers
Casting	Coated mandrels; bells; spouts
Fabricating fiber-reinforced cases or nozzles	Automatic filament-winding machine
Inspecting to detect voids or unbended areas	X-ray or ultrasound equipment; thermal imaging; manipulators
Transferring components within the plant	Special vehicles or trailers for semi-finished motors and mixed-propellant slurry

SOURCE: Adapted from Tom Morgan, former group leader for counterproliferation and delivery vehicle systems, Lawrence Livermore National Laboratory, presentation at SDIO Missile Proliferation Conference, System Planning Corporation, Rosslyn, VA, Apr. 4-10, 1992.

Pakistan, South Africa, and Taiwan. No Soviet Scud recipients appear to have successfully developed solid-fueled missiles with anywhere near comparable range to their liquid-fueled missiles, except possibly Egypt.[35]

Although the Soviet Union was the main supplier of ballistic missiles to the Third World, some secondary suppliers and traders of missiles and missile technology have emerged.[36] These include: North Korea, which received Soviet-built Scuds from Egypt, sold indigenously built Scud-Bs and Scud-Cs to Iran and Syria, and appears to be in the process of selling 1,000-km *Nodong I missiles* to Iran as well; Libya, which trans-shipped Soviet-built Scud-Bs to Iran and North Korea; Israel, which reportedly transferred Lance missiles to Taiwan and Jericho missile technology to South Africa; Argentina, Egypt, and Iraq, who banded together in an unsuccessful effort to develop the *Condor II missile;* Brazil, which in the past has engaged in attempts to develop and sell missiles to a number of countries, including Libya and Iraq; and China.[37]

North Korean and Chinese behavior regarding missile sales have been particularly troubling to the West, since both have long resisted calls to exercise restraint. China has maintained that the sale of missiles does not qualitatively differ from sales by the West of high-technology jet fighters to countries in the same regions. Nevertheless, by the end of 1991 China had agreed in principle to abide by the provisions of the MTCR and largely accepted the West's judgment that both its M-9 and M- 11 missiles exceeded the MTCR's 300-km/500-kg threshold.[38]

Before this apparent change in policy, Chinese missile sales and technical assistance had added noticeably to missile capabilities in the Middle East and elsewhere. In 1988, China sold to Saudi Arabia about 30 to 50 liquid-fueled 3,000-km DF-3A missiles (called CSS-2 by the United States). These missiles have the longest range by far of any sold to a Third World country.

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[35] In addition to producing the solid-fueled Sakr-80 (a copy of the Soviet FROG-7, an unguided missile with range less than 100 km), Egypt participated in the now-abandoned consortium with Argentina and Iraq to develop the two-stage solid-fueled *Condor II* missile with approximately 1,000-km range.

[36] In the past, the United States supplied *Lance* and *Honest John* missiles to Israel and South Korea, respectively, but since the 1970s has transferred missiles only to NATO allies, and even these have had significant restrictions attached. The 1987 INF Treaty further constrained both U.S. and Soviet missile transfers. In 1991, Russia pledged to abide by the MTCR guidelines.

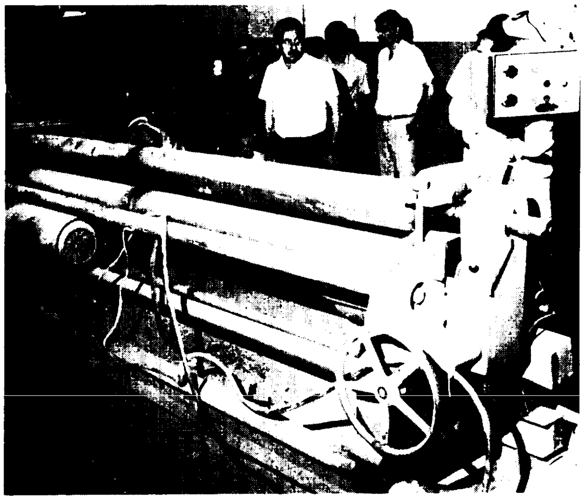
[37] -Pies in this paragraph taken from W. Seth Carus, *Ballistic Missiles in Modern Conflict* (New York: Praeger, 1991), PP. 14.18, and 21; and Douglas Jehl, "Iran is Reported Acquiring Missiles,' New *York Times*, April 8, 1993, p. A9.

[38] The pledge by China to abide by the MTCR was made at the end of 1991 during a trip by then-Secretary of State James A. Baker, III. During congressional testimony in February 1992, Baker said tbat China's pledge was "a very substantial and significant step forward, if they will adhere to their commitment. If they don't. . sanctions [on high-sped computers and satellite parts] will go right back on. " In August, 1993, the United States found that China had in fact violated its commitment to observe MTCR constraints, and announced that sanctions-yet to be determined—would be imposed. (See Stephen A. Holmes, ''U.S. Determines China Violated Pact on Missiles,' New *York Times*, Aug. 2s, 1993, p. 1).

Although the DF-3's accuracy is among the worst in the Middle East (CEP of over 2 km), these missiles have placed the entire Middle East and parts of the former Soviet Union within reach of Saudi Arabia. Chinese technical assistance has also played a significant role in the missile programs of North Korea, Iran, Brazil, and Pakistan.

According to various reports, certain German firms in the past have also provided technical assistance to missile programs in Argentina, Brazil, Egypt, India, Iraq, and Libya, and French and Italian firms have helped with aspects of programs in Argentina, Egypt, India, and Paki-Stan.[39]

More recently, however, several countries that had exported missile technology have been curtailing their assistance to foreign missile programs, and some are even becoming members of the MTCR. For instance, with the demise of its *Condor* || missile program, Argentina agreed to abide by the provisions of the MTCR in May, 1991, as did the Soviet Union one month later. As of March 1993, Argentina was in the process of becoming a full member of the MTCR, and Brazil may be considering joining. Each of these countries has had a history of either supplying missiles to developing countries or collaborating in missile programs with them. The only state said by the United States to be exporting MTCR-covered missiles today is North Korea. However, in light of China's reported export of M-11 missile launchers to Pakistan in 1991 and the more recent U.S. finding that China has violated its MTCR commitments, it remains to be seen whether or how well China will uphold the export constraints dictated by the MTCR.[40]


1. ARVIDSSON, UNITED NATIONS

A metal-rolling mill+me example of the type of multipurpose equipment that can be associated with ballistic missile production. This and other missile-related equipment in Iraq were destroyed under U.N. auspices in 1992.

EXPERTISE REQUIRED FOR INDIGENOUS DEVELOPMENT

Short range missiles

Reproducing, reverse engineering, modifying, and launching short range missiles does not require a particularly complex or expensive infrastructure. Many countries that would have great difficulty assembling a well-trained group of technical, operational, and tactical specialists needed to field an effective air force could still deploy a significant missile force.[41] (See box 5-A.)

The V-2 missile, designed and used extensively by the Germans during World War II, provides a baseline against which more sophisticated ballistic missiles can be compared. The V-2 was the frost operational version of a class of ballistic missiles that led to the Soviet-designed

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[39] See, for example, Carus, *Ballistic Missiles in Modern Conflict* op. cit., footnote 37, pp. 22-23.

[40] See, for example, Jim Mann, "Ctia Said to Sell Pakistan Dangerous New Missiles, ' *Los Angeles Times,* Dec. 4, 1992, p. Al; and Ann Devroy and R. Jeffrey Smith, "U.S. Evidence 'Suggests' China Breaks with Arms Pact," ***Washington Post, May 18, 1993,*** p. A9.

[41] Edward N. Luttwak, foreword to Carus, *Ballistic Missiles in Modern Conflict,* Op. cit., footnote 37, p. vii.

Box 5-A-Iraq's Missile Programs

Of those countries that have imported Scud missiles in the past, only North Korea and Iraq appear to have been successful at modifying and extending their range. North Korea has reportedly done so by a process called "reverse engineering": disassembling the missiles, learning how to manufacture or modify their parts, and manufacturing new missiles.[1] Iraq extended the range of its Scuds by taking sections from one missile's fuel and oxidizer tanks and splicing them into other missiles. In this way, three missiles were cannibalized to make two longer range ones.[2]

By mid-1990, Iraq possessed the Soviet-supplied *d-B missile (300-km range, 1-km CEP) @us two indigenous variants-the Al-Husayn(600-km range, 3-km CEP) and the Al-Hijarah(75O-km range, unknown CEP, also called Al-Abbas-ali capable of carrying conventional or chemical warheads. *Al-Husayn* and Al-Hijarah missiles, each about two meters longer than the original 1 l-meter Scud-Bs, were launched toward targets in Israel and Saudi Arabia during the PersianGulf War. From their launcher complexes, these missiles were capable of reaching Tel Aviv, Haifa, and Israel's nuclear facility at Dimona in the Negev desert.[3]

Despite the existence of a missile manufacturing center, however, it is likely that Iraq would still have required foreign assistance to fabricate precision missile components such as fuel-injector plates, turbo pumps, and guidance systems.[4] Since Iraq is known to have been importing many components and receiving foreign technical assistance for its missile (as well as other weapon) programs, it is uncertain whether it could have manufactured even a Scud-type missile completely on its own at the time of the Persian Gulf War.

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[1] Joseph S. Bermudez, Jr., "Ballistic Ambitions Ascendant: North Korea's Ballistic Missile Programme is a Threat to be Reckoned With," *Jane's Defence Weekly*, Apr. 10,1993, p. 20-22. Although Egypt and Libya have also both worked on developing 300 to 700 km one-stage liquid-fueled missiles, and Egypt was involved in the *Condor* //program, nothing isknowntohavebeen fietded so farfromtheseprograms. See, for example, Bermudez, "Ballistic Missile Development in Egypt," *Jane's Intelligence Review*, October 1992, pp. 452-458.

[2] W. Seth Carus and Joseph S. Bermudez Jr., "Iraq's 'Al-Husayn' Missile Programmed," *Jane's Soviet Intelligence Review, vol.* 2, No. 5, May, 1980, p. 205. Liquid-fueled missiles lend themselves to this technique, since the engines do not haveto change appreciably to accommodate larger amounts of propellant and longerburn-times.

[3] U.S. Dept. of Defense, *Conduct of the Persian Gulf War: Final Report to Congress,* Pursuant to Title V of the Persian Gulf Conflict Supplemental Authorization and Personnel Benefits Act of 1991 (Pub! lc Law 102-25), April 1992, p. 16. Note that many sources call the second modification of the Scud-B the *Al-Abbas,* and claim a range of 900 km. Such a discrepancy could easily be explained by a difference in payload.

[4] Tom Morgan, former group leader for counterproliferation and delivery vehicle systems, Lawrence Livermore National Laboratory, private communication, Dec. 20,1992.

Scud. Its characteristics are summarized in table 5-6.

As missile range increases from under 1,000 km to 2,500 to 5,000 km, there are generally at least two principal hurdles: manufacturing the larger propulsion systems needed to achieve the higher velocities required for longer range, and designing missiles with more than one stage.[42] Ensuring stable fuel combustion and flight characteristics while in the atmosphere also become more complex. *Expertise* is therefore a key ingredient in developing long range missiles—especially having access to engineers and technicians skilled in the areas of subsystem integration, testing, and production methods (see table 5-7 for one estimate of the personnel and time required) According to one experienced U.S. missile designer, a considerable amount of 'art" is always involved, especially for more sophisticated designs. Specifications and documentation can-

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[42] Additional design problems are caused by heating of the missile skin, the internal components, the propellant, and the reentry vehicle as a result of air friction at higher velocities.

H. ARVIDSSON, UNITED NATIONS

*View from the **muzzle end (top)** of the Iraqi ''supergun,'' **which Iraq installed and tested at Jabal Harmayn, some 200 kilometers north** of Baghdad.*

Using the experience gained from modifying Scuds, Iraq had also built and launched a prototype of a crude space-launch vehicle named the Al-Abid, and claimed that it had developed a 2,000-km range ballistic missile named *Tammuz* using similar technology.[5] Iraq's "Project Babylon"-not a missile itself, but a program to develop a specialized 1,000 mm-bore launcher or "Supergun"-was partially impeded by a British customs seizure of parts and by the murder of Gerald Bull, its principal designer. The supergun was being designed to fire guided rockets with conventional, chemical, or possibly nuclear warheads hundreds of miles.[6] A 350-mm research prototype had been completed and test- fired from a site about 120 miles north of Baghdad.[7]

[5] The prototype missile appeared to have three stages. The first consisted of engines in an indigenously built airframe (e.g., possibly clustered boosters). The second and third stages used for testing were inert, but were included for their weight and aerodynamic effects. See, for example, U.S. Dept. of Defense, *Conduct of the Persian Gulf War,* op. cit., footnote 3, p. 20.

[6] U.S. Dept. of Defense, *Conduct of the Persian Gulf War,* op. cit., footnote 3, p, 20. Note, however, that if such a missile launcher was intended to use guided rockets, much of its advantage would be lost (since the projectile's ultimate accuracy would still depend on its onboard guidance system), while it would subject the entire projectile to extreme accelerations not experienced in normal missile trajectories. The" Super Gun" may have indeed been better suited for placing small payloads into orbit, a task requiring less accuracy than attacking ground targets. C. Robert Dietz, senior missile designer (retired), Lockheed Missiles and Space Co., private communication, Dec. 8, 1992. See also, Brigadier K.A. Timbers, "Iraq: Supergun—A Complex Matter," *Army Quarterly and Defense Journal, vol. 22, April 1992,* p. 149.

[7] U.S. Dept. of Defense, *Conduct of the Persian Gulf War,* op. Cit., footnote 3, p. 20.

not **substitute** for first-hand experience in ballistic-missile design and manufacture.[43]

Nevertheless, foreign expertise in missile development has been widely available in the past. Countries such as Germany and Italy, even though members of the MTCR, had not sought until recently to restrict individual citizens from assisting with missile projects in developing countries.[44] Germany had not applied its export regulations to weapon systems co-produced with a foreign firm, or to *dual-use* components, technologies, or manufacturing capabilities. Although recent changes in German export control law now forbid this type of assistance, the breakup of the Soviet Union may lead to additional new sources of expertise.[45]

Before the advent of the MTCR, other major powers also engaged in a variety of cooperative

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[43] C. Robert Dietz, senior missile designer (retired), Lockheed Missiles and Space CO., private communication, Dec. 8, 1992.

[44] U.S. General Accounting Office, *U.S. Efforts* t. *Control the Transfer of Nuclear-Capable Missile Technology,* Report to Sen. DeConcini (NSIAD-90-176, June 1, 1990), p. 17.

[45] One incident in October 1992 illustrating these potential risks involved Russian authorities stopping 60 Russian engineers and technicians from departing to North Korea, reportedly to help with the latter's missile programs.

Table 5-6-Characteristics of the German V-2 Missile

Range	240-300 km
Warhead	1,000 kg high-explosive (conventional) warhead
Weight	12,900 kg fully fueled (twice that of the Scud); 4,000 kg empty
Maximum altitude	80 km
Impact velocity	0.8 km/sec
Propellant	Bi-propellant liquid-alcohol and hydrogen peroxide
Guidance and control	Gyroscopes for determining direction and velocity;[a] rotating vanes at ends of missile fins and rotating heat-resistant vanes in exhaust jet
First tested	1942, by Germany
World War II usage	2,000 missiles against Britain, resulting in 1,500 deaths 3,500 total missiles against cities in England and on the continent

[a] Experiments were also carried out, but no operational missiles produced, using radio-controlled guidance.

SOURCE: Gregory Kennedy, *Vengeance Weapon 2: The V-2 Guided Missile* (Washington, DC: The Smithsonian Institute, 1983), pp. 70-73.

efforts to develop Third World missile technology, including:[46]

- In the late 1960s and early 1970s, France provided sounding-rocket technologies and granted licensed production rights to India and Pakistan, in part to subsidize France's own space-launch development costs; the French also assisted with missile-development programs in Argentina, Brazil, and Indonesia.
- In the 1970s, the United States assisted South Korea in the construction of a Nike-Hercules surface-to-air missile manufacturing facility, whose product was later modified by the Koreans for surface-to-surface use. The United States also assisted India and Brazil in developing their sounding rocket programs.
- In the 1980s, Chinese missile experts travelled to Argentina and Brazil to provide technical assistance for their missile programs, as well as to promote sales of Chinese intermediate range missile technologies.

In the past, missile technology has also been transferred through sales and technical assistance among secondary suppliers themselves. Examples of such transfers were provided in the previous section. The foreign training of key individuals, too, has played a key role in missile programs. For example, according to William H. Webster, then Director of the CIA, "In the mid-1960s, the United States accepted a young Indian scientist, Dr. Kalam, into a training program at the Wallops Island Rocketry Center. This scientist returned to India, and, with the knowledge gained from his work on the civilian space program, Dr. Kalam became the chief designer of India's Prithvi and Agni ballistic missiles. "[47]

Hence, the proliferation of missile expertise and technology for at least short range systems was advanced by a variety of paths during the 1980s, helping facilitate its acquisition by several emerging missile powers. However, with the advent of the MTCR, many of the mechanisms by which this technology transfer had occurred have been constrained. (See box 5-B.)

Reentry vehicles

As ranges increase beyond 1,000 to 2,000 km, a ballistic-missile warhead must be afforded greater thermal protection to survive the heat

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[46] See, for example, Stanford, *Assessing Ballistic Missile Proliferation*, *Op. Cit.*, footnote 4, pp. 94-99.

[47] Testimony of William H. Webster, Director of Central Intelligence, in U.S. Senate, Committee on Governmental Affairs, *Nuclear and Missile Proliferation*, 101st Congress, 1st Session, May 18, 1989, S. Hrg. 101-562 (Washington DC: U.S. Government Printing Office, 1990), p. 12.

Table 5-7—Notional Personnel Requirements for Ballistic Missile Development

Design task	Personnel/time requirement
Design first-generation liquid-fueled missiles (similar to Scuds)	5 to 10 well-trained and experienced combustion scientists, chemical engineers, heat transfer specialists, and experts in fluid mechanics and mechanical design, in a well-funded, multiyear research and development program
Develop simple flight-control systems tailored to a particular missile (for instance, rotating vanes mounted in the path of the exhaust gas)	About 20 mechanical, electrical, and manufacturing engineers and technicians, and about 5 to 10 specialists to develop the guidance computer and software
Manufacture Scud-like or longer range liquid-fueled missiles	30 to 50 experienced machinists and technicians
Indigenously design, develop, and produce first-generation (Scud-like) ballistic missiles from scratch, starting from only a rudimentary industrial infrastructure	Total of 300 to 600 well-coordinated and experienced engineers, technicians, and manufacturing personnel
Learn how to manufacture solid-fueled rocket motors of 1,500-km range or more	A team of at least 5 to 10 specialists with many years of propellant-processing experience, to master the largely empirical mixing and casting techniques
Carry out a thorough program of flight testing	Roughly 100 or more experienced personnel and up to a dozen or more tests, plus specialized instrumentation, radars, data acquisition systems, and test ranges
Develop and produce a longer range, more advanced ballistic missile—if a relatively sophisticated industrial infrastructure were already in place	As few as 3 to 10 missile designers with hands-on experience could train local specialists within about 5 to 10 years

SOURCE: Adapted from Stanford University, Center for International Security and Arms Control, *Assessing Ballistic Missile Proliferation and Its* Control (Stanford, CA: Stanford University, November 1991), pp. 135,138, 140-141, 145, 147.

generated by reentry into the atmosphere.[48] In general, such protective packaging-called a reentry vehicle (RV)-is coated with material that gradually burns off and carries away heat in a process called ablation, thereby protecting the warhead inside. However, asymmetric ablation can cause an RV to steer itself far off course. Developing ablatively coated RVs that erode smoothly and predictably would be very difficult for most developing nations and, in any case, would require extensive flight testing.[49]

To protect a warhead during its passage through the atmosphere, it is also possible to use a blunt reentry vehicle. Manned space capsules are examples of blunt RVs designed to dissipate reentry heat and protect astronauts. Blunt RVs

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[48] There is one application using a nuclear weapon that requires neither accurate delivery nor a reentry vehicle. A nuclear weapon detonated at high altitude can generate a powerful pulse of radio waves (called ‘‘electromagnetic pulse’ ‘), which can wreak havoc on some types of electronic equipment. However, this would not pose the kind of direct human health risk normally associated with weapons of mass destruction.

[49] Stanford, *Assessing Ballistic Missile Proliferation*, op. cit., footnote 4, p. 143. Typical materials used in ablative nosetips include fiberglass, carbon-phenolic, and carbon-carbon composites.

Box 5-B-Technology Transfer and the Condor II Program

Although ballistic missiles rely on a number of multiuse technologies, some key technologies have characteristics uniquely identifiable with missile or space-launch-vehicie development programs. Such items include the hardware and software used in missile guidance systems,[1] special composite materials, largs specially designed soiid-propellant mixers and casting apparatus, and rocket-motor static test stands. Restricting trade in the suite of technologies most useful to developing missiles therefore provides some measure of control over missile proliferation. Nevertheless, control of missile proliferation by restricting trade in certain materials and technologies is Inherently more difficult than similarly controlling nuclear proliferation, since there are more potential suppliers of missile technologies and fewer of the relevant technologies are uniquely military in nature.

The cancellation in 1991 of the Argentina-based Condor II program, heralded as one of the successes of the MTCR regime, points broadly to the inherent difficulties involved in developing missiles with longer rangethanthe Scud. The 1,000-km -stage, solid-fueled Condor // missile, whose development may have been partly motivated by Argentina's defeat in the Falklands War, was to have been the product of a consortium between Argentina and Egypt, with financial assistance from Iraq. Each of the three states had previously developed or improved the performance of short range missiles such as the Scud, with varying degrees of success. However, despite attempts to recruit technical assistance and to import goods from a number of firms in Europe and the United States, the Condor II project ultimately proved unable to acquire many of the technologies needed for a complete system. in 1988, under pressure from the United States and constrained by the MTCR's newly imposed export restrictions, the consortium began to dissolve. By 1990 the program had ground to a standstill in all three countries.

Egypt's involvement in the project sheds light on the extent of foreign assistance that was sought.[2] Before the Condor II project, Egypt had advanced little beyond modifying Scuds and making the 80-km unguided missile called the Sakr-80. However, in gearing up for the more ambitious Condor //, an organization known as the CONSEN Group[3] arranged on behalf of Egypt for a number of well established European firms to provide key components:

Messerschmitt-Boeikow-Biohm (MBB) of Germany-guidance systems and general missile technology
MAN of West Germany--wheeled transporter-erector-launchers
Sagem of France -inertial navigation systems
SNIA-BPD of Italy-rocket motors and solid-fuel technology
Additional contractors, such as Bofors of Sweden, and Wegmann of West Germany.

The long list of companies and technologies that Egypt and Argentina attempted to involve in efforts to advance the levelofthe Coondor II missile in the l980s attests to the complexity of such an undertaking. From 1963 to 1988, an Egyptian by the name of Abdel Kader Helmy (who became a naturalized American citizen in October 1987) conducted on behalf of Egypt an ambitious program to acquire missile-related technology and components

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[1] For instance, missile guidance and control requirements are much more stringent than the simple position and velocity information available from widely used airline and shipping navigation systems.

[2] Much of the following is taken from Joseph S. Bermudez, Jr., "Ballistic Missile Development in Egypt," *Jane's Intelligence Review*, October 1992, pp. 456-45S. See also James Adams, *Engines of War: Merchants of Death and the* New Arms Race (New York, NY: Atlantic Monthly Press, 1990), pp. 257-267.

[3] The two most important companies in the CONSEN Group for Egypt% participation in the *Condor* project were iFAT Corp. Ltd., of Zug, Switzerland (responsive for the financial aspects) and CONSEN S.A.M., located in Monaco (responsible for contracting). Underthe direction of Egypt% Minister of Defense, an office tooordinatethe *Condor* //project was established in Salzburg, Austria, co-located with the offices of the CONSEN Group.

illegally from the United States. Helmy and his co-conspirators either exported or intended to export a wide variety of missile-related items to assist Egypt's programs for both the Scud and Condor//, including'!

- A fully instrumented test-stand for analyzing rocket motors of up to **20 tons thrust**
- **Strap-down inertial** guidance systems for the Con&//, and software for their optimization
- Fuel-air explosive warheads for the Condor //[5]
- Carbon-carbon and ceramic-composite materials to be used **in** *Condor //* nose cones
- Various chemicals for composite solkf-propellant rocket motors:
  - 18,000 lbs. of militarygrade aluminum powder
  - 11,000 lbs. of the synthetic rubber HTPB (hydroxyl-terminated polybutadiene)
  - 500 lbs. of EPON from the Miller-Stephenson Co., used in the aerospace industry for gluing composite fabrics to surfaces
  - Epoxy-hardeners from the Hemkel Co.
  - 40 lbs. of MAPO (tris-2-methyl aziridinyl phophine oxide), a soiid-propellant additive, from Arsynco co.
  - HMDI (hexamethylene diisocyanate), a curing agent for HTPB
- 21,200 lbs. of maraging steel intended for the motor casing of the first stage and connecting segments
- 185 yds. of Rayon-based ablative carbon fabric from the HITCO Co. for heat-shiefds to protect Condor //payload covers
- 436 lbs. of MX-4926, an ablative carbon-phenolic fabric from the Fiberite Co., essential for manufacturing the flexible nozzles the Condor // was to use for maneuverability
- Microwave rocket telemetry antennas from Vega Precision Laboratories

The majority of these efforts failed, however, and Helmy and a number of his collaborators were eventually arrested in June 1986. The loss of a U.S. conduit for missile technology imposed a staggering blow to the Egyptian component of the Condor //projct. Within months, both Egypt and Iraq had ended their involvementwith project.

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[4] Bermudez, "Ballistic Missile Development in Egypt," op. cit., footnote 2, p. 457.

[5] A prior attemptin1984 by the Egyptian Ministry of Defense to import components for fuel-air explosives 'ad been blocked by the U.S. State Department and Customs Service because the parts were on the Munitions Control List.

were also used with early U.S. ICBMs such as the Atlas. Exotic ablative materials are not nearly so important for blunt RVs, since air resistance quickly decelerates them to speeds slow enough for ordinary materials to withstand the heat generated during reentry. However, in employing blunt RVs, accuracy is lost both from self-steering and from atmospheric winds having a relatively larger effect on a slower moving RV. Their use could easily result in a loss of several kilometers or more in accuracy.

Long range missiles and ICBMs

Although several systems have been developed for categorizing ballistic missiles with ranges greater than 300 km, the U.S. Department of Defense classification system provides a useful reference:

- Short range ballistic missiles (SRBMs) have ranges up to 1,100 km, or 600 nautical miles (nmi),
- Medium range missiles (MRBMs) have ranges from 1,100 to 2,750 km (600 to 1,500 nmi),
- Intermediate range ballistic missiles (IRBMs) travel from 2,750 to 5,550 km (1,500 to 3,000 nmi),[50] and
- Intercontinental range ballistic missiles (ICBMs) can reach from 5,550 to 14,800km (3,000 to 8,000 nmi).

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[50] The Intermediate range Nuclear Forces (INF) Treaty categorized all surface-to-surface ballistic and cruise missiles with ranges between 500 and 5,500 km as "Intermediate Range".

With nominal payloads of roughly 500 to 1,000 kg, SRBMs are generally single-stage, meaning that they have a single set of (possibly clustered) rocket motors that is carried throughout the flight, even after its fuel is expended.[51] Multistage rockets, in contrast, are powered by successive sets of rocket motors, each of which is jettisoned when its fuel burns out. IRBMs and ICBMS are almost always multistage.[52] MRBMs are an intermediate case, typically consisting of either one or two stages.

Making the transition from a short range ballistic missile capability to being able to design and produce ICBMs involves a number of substantial technological hurdles. Iraq increased the range of imported Scuds from 300 km to between 600 and 900 km by cannibalizing and rejoining sections from different missiles to create longer ones, while simultaneously reducing the payload. But such methods would not work to create ICBMs.[53]

Developing accurate and reliable ICBMs—which would almost always be multistage-presents inherently new and drastically more complex difficulties than simply extending the range of Scuds. The following factors make the engineering and design of long range missiles difficult.[54]

Staging. Proper mating of the stages and getting them to detach and fire at precisely the right moment adds considerable complexity to the design. (Once the missile leaves the atmosphere, the missile can easily begin to tumble at the stage transition, because aerodynamic forces cannot be utilized to stabilize it.) Staging also increases the difficulty in designing the missile's flight control systems, while it generally decreases reliability, accuracy, and mobility.

As a partial alternative to staging, strap-on clusters of boosters can be and have been used to increase the range, possibly at considerably less expense than developing larger boosters. However, in addition to stability and reliability problems caused by using boosters not originally designed to be clustered, the potential increase in range would remain quite limited. In most cases, staging would still be required to reach ICBM ranges.[55]

Structure and Materials. To withstand the large forces caused by their greater launch-weight and stresses in the atmosphere, longer range missiles must incorporate stronger materials than

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[51] To generate enough thrust to lift a heavy missile, the (fret) stage must expel propellant gases at a tremendously high rate, requiring a large and thus heavy motor. But since the motor must be accelerated along with the rest of the missile, its own mass limits the speed it can achieve. (The same limits apply to strap-on boosters.) Only by abandoning a fret-stage spent motor and then firing a subsequent stage can a missile easily achieve the velocities necessary for ranges in excess of a few thousand kilometers.

[52] One exception is the U.S. Atlas missile, first tested in the early 1950s and deployed in the late 1950s, which achieved 10,000-km range with essentially one stage. Although it generated additional thrust by burning fuel after the first-stage-firing was complete, it did not release the first stage motor or housing. Fueled by kerosene and liquid oxygen, the Atlas used such a thin walled canister on its main stage that it could not reliably support its own weight in launch position until it had been properly loaded with fuel and pressurized.

[53] Increasing the size of the fuel tanks on a given stage can only go so far toward increasing a missile's range, since the overall missile weight, including the additional fuel, would at some point become greater than the missile's thrust, thus inhibiting liftoff. Moreover, adding length or weight can cause undesirable and sometimes unstable flight characteristics by altering the aerodynamic stresses, causing the missile to bend and flex, and changing the moment of inertia.

[54] See also, Lora Lumpe, Lisbeth Gronlund, and David C. Wright, 'Third World Missiles Fall Short,'' *Bulletin of the Atomic Scientists*, vol. 48, No. 2, March 1992, p. 36.

[55] Potential problems with strapped-together boosters include stability of the flight-control system, interference between the exhaust plumes, excess heat generation, and thrust cut-off errors that can lead to large inaccuracies, One analyst has estimated that by strapping together *Al-Abbas* extended range Scud missiles to carry a single 350-kg payload, one could achieve the following ranges: 1 booster—700 km; 3 boosters, dropping first two at burn out—1,500 km; 5 boosters, dropping first four at bum out—2,200 km; 7 boosters, dropping first four, then two, at respective bum outs-5,100 km. James R. Howe, Rockwell International, Space Systems Division, "Emerging Long Range Threat to CONUS," briefing packet, December 1992. Note that this last example is essentially a three-stage missile, but still does not achieve ICBM ranges.

those used in the Scud, usually requiring advanced composites or alloys.

Fuel-fraction. Only about 75 per cent of a rocket engine's weight can be propellant if materials and technologies comparable to those used in the Soviet Scud missile are employed. The greater the fuel fraction, the greater the range; therefore, a low fuel-fraction puts limits on the range a missile can achieve even if multistage. (Modern ICBMs achieve up to about 90 per cent propellant in each stage.)

Reentry vehicles. ICBMs reenter the atmosphere at higher speeds than shorter range missiles, making it considerably more difficult to protect their warheads from atmospheric heating.

Accuracy. Longer range missiles typically have correspondingly longer boost times which, for the same guidance system, would result in larger errors in burn-out velocity. These guidance errors then accumulate over longer flight times, increasing a missile's miss-distance. More accurate guidance and control systems are therefore required.

SPACE-LAUNCH CAPABILITIES AS A ROUTE TO BALLISTIC MISSILES

Instead of developing ballistic missiles directly or reverse-engineering short range missiles, a country might also try to attract foreign assistance in developing a space-launch capability.[56] At least five nations besides the United States and the former Soviet Union now have indigenous space-launch capabilities: China, France (whose Ariane launchers have been developed and operated in conjunction with the European Space Agency), Japan, India, and Israel. Brazil and Pakistan are also developing space-launch or sounding-rocket programs. Much of the technology used in sounding rockets and space-launch vehicles is directly applicable to surface-to-surface missiles. Hence, countries such as Brazil, India, and Pakistan have used civilian programs and foreign assistance to build expertise needed to design and build their own military systems. Israel's civilian and military programs are also undoubtable linked; the Shavit space-launch vehicle is widely reported to be a version of the *Jericho II* missile.[57] Although the space-launch or sounding-rocket programs of South Korea, Taiwan, and Indonesia do not appear to have progressed significantly in recent years, these programs have also received foreign technology assistance.

Some analysts have concluded that there are no longer any valid economic reasons for new countries to develop space-launch vehicles, and hence that the United States should not provide technical assistance to these programs.[58] However, this argument may give too little weight to the possible prestige value or hopes of technology transfer that could result from developing a space-launch capability. It also minimizes the reluctance nations may have to depend on other nations for space-launch services. Countries may also be motivated to develop the capability to launch satellites for military communications or reconnaissance-goals that are not civilian but fall short of developing offensive weapon-delivery systems.

Space-launch vehicles differ substantially from ballistic missiles intended for ground targets in their requirements for accurate guidance and reentry technology. Space payloads do not require reentry vehicles and rarely require extremely precise orbits, meaning that space-launch vehicles need not have as sophisticated guidance systems as long range ballistic missiles. Boost-

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[56] The material in this paragraph is primarily taken from Carus, *Ballistic Missiles in Modern Conflict, Op. cit.,* footnote 37, pp. 13, 24-25.

[57] Some analysts believe that the Shavit space-launch vehicle incorporates technology that the Israelis could use to build an ICBM (with useful weapon payloads and accuracy) with range in excess of 5,000 km. See, for example, Steven E. Gray, "Israeli Missile Capabilities: A Few Numbers to Think About," Lawrence Livermore National Laboratory, unpublished memorandum, Oct. 7, 1988.

[58] See, for example, Brian G. Chow, Emerging *National Space-Launch Programs: Economics and Safeguards*, RAND Report No. R-4179-USDP, January, 1993.

phase inaccuracies resulting in errors of tens of kilometers at apogee may be easily tolerable when placing a satellite in orbit, but they can be significant for surface targets even with weapons of mass destruction. Moreover, space-launch vehicles are usually launched from specific locations and can take weeks or months, if needed, to prepare for launch. Ballistic missiles, on the other hand, are much more useful *militarily if they can* be launched on short notice and are not restricted to freed launch-sites.

Still, ballistic missile technologies such as large boosters and high-quality guidance systems could be tested and developed under the guise of a well-developed space-launch program. A country that has demonstrated the capability to develop space-launch vehicles should therefore be considered capable of developing ballistic missiles as well.

COSTS OF MISSILE PROGRAMS

Short range missiles, such as Scud-Bs or SS-21s originally from the former Soviet Union, cost as little as $1 million apiece to produce.[59] At the other extreme is the Saudi purchase of DF-3 missiles from China, which reportedly cost $2 billion for 30 to 50 missiles and their associated launchers.[60] Even if the missiles in this purchase accounted for only half of the total cost, they would still cost over $20 million apiece. Together with launchers, this begins to approach the unit cost of acquiring advanced strike aircraft.

Producing missiles *indigenously can also* be extremely expensive. Press reports have indicated that the Saad-16 missile-development complex being built in northern Iraq (reportedly with the help of several West German companies) may have cost Iraq $200 million.[61] Estimates suggest that it would have cost Argentina $3.2 billion to develop and produce 400 *Condor II missiles,* and development costs alone may have been destined to exceed $1 billion.[62] Without financial assistance from other states, such costs would remain prohibitive for many of the countries of proliferation concern.

I Weaponization and Deployment

NAVIGATION, GUIDANCE, AND CONTROL SYSTEMS

As missile range is extended beyond a few thousand kilometers, the inaccuracies of less-sophisticated missile systems could begin to exceed several-kilometer CEPs,[63] which could affect targeting plans even for weapons of mass destruction. However, for most scenarios involving a proliferant country using or threatening to use a nuclear weapon, or even a terror attack with chemical weapons against another country's territory, it would matter little whether its missiles' CEPs were measured in meters or kilometers.

Guiding a missile to its target requires knowing precisely its orientation, position, and velocity—at least throughout its boost phase-and the ability to control its thrust to compensate for unexpected deviations in trajectory. (It also requires knowing precisely the locations of the launcher and target.) Guidance systems used by most ballistic missiles rely on *inertial* navigation systems to provide boost-phase information. Standard designs consist of gyroscopes, whose spinning components resist change in their orientation and thus provide a freed reference frame, and accelerometers, which in principle utilize weights

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[59] Stanford, *Assessing Ballistic Missile proliferation, Op.* Cit., footnote 4, P. 45.

[60] Ibid., p. 95.

[61] See Carus, *Ballistic Missiles in Modern Conflict,* op. cit., footnote 37, p. 22.

[62] Ibid., p. 64.

[63] For example, the 2,500-km range Chinese CSS-2 (DF-3) missile has a CEP of about 2.5 km, and the Iraqi *Al-Hijarah/Abbas* missile, an extended range Scud with a range of only 900 km has been estimated to have a CEP of over 3 km (2 to 3 miles). See, for example, *World Military Expenditures and Arms Transfers, 1988 (Washington DC: Arms* Control and Disarmament Agency, 1989), pp. 18-19.

attached to precisely calibrated springs. Well before the advent of computers, Germany devised an inertial guidance system for the V-2 missile that combined gyroscopes with electrical capacitors and electro-mechanical actuators to send flight-control information to the missile fins. Compact computers, however, are now used in essentially all modern inertial guidance systems.[64]

Adapting inertial navigation systems originally intended for aircraft or ships for use in missiles is problematic for several reasons. First, they may be too heavy or too large. Second, their performance may be degraded by a missile's high acceleration. And third, it may be impossible to align their orientation precisely enough to achieve the accuracy needed for missile guidance. Similarly, straightforward application of NAVSTAR Global Positioning System (GPS) information would be inadequate for keeping a missile oriented precisely enough during boost-phase for good flight control, and would only be useful if late boost-phase corrections or a post-boost vehicle were used to correct for any trajectory errors measured by GPS. (GPS is discussed in more detail in the cruise missile section below.)

Furthermore, in order to make use of navigation information, the guidance system (which computes the missile's position and orientation) must be connected to the missile's flight-control system, which adjusts the missile's trajectory during the boost-phase. Accuracies (due to boost-phase errors alone) better than about 0.3 per cent of range[65] can only be achieved with modem computer-controlled guidance packages that incorporate precise knowledge of the missile's response-times and steering forces. Precise understanding of the behavior of flight-control systems is required to avoid unstable flight maneuvers and over- or under-steering the missile. Slight flexing of the missile during boost can also be difficult to compensate for, even with sophisticated control systems.

U.N. PHOTO, H. ARVIDSSON

United Nations Special Commission inspector examining the tail section of an Iraqi modified Scud *missile, showing its heat-resistant vanes mounted in the exhaust path and its rotating tail fins.*

Advanced computer algorithms coupled with extensive flight testing can be very helpful in understanding and overcoming the biases of guidance system hardware. Coupling the guidance and flight control systems, however, has proven to be a major problem for many missile programs in developing countries, including those in Argentina and Brazil.[66] More advanced flight control systems relying on gimballed engines for liquid-fueled motors, or high-temperature flexible joints at the nozzle exit-cones of solid boosters, would also be difficult for developing countries to master in the short run.

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[64] In addition, the United States and other countries with advanced avionics industries have developed ring-laser gyroscopes for use as guidance systems in both missiles and advanced combat aircraft such as the F-16. These not only provide greater accuracy, but, since they have far fewer moving parts, can be readied for launch much more quickly than traditional gyroscopes.

[65] Expressing accuracy as a percentage of range is only a very approximate description of the effects Of error factors. Since these errors contribute indifferent and often nonlinear ways to miss-distances at the target, such percentages are used only for convenience and are not meant to imply a direct proportional relationship between accuracy and range.

[66] See, for example, Andrew Slade, "Condor Project in Disarray, " *Jane's Defense Weekly,* Feb. 17, 1990, p. 295.

Moreover, boost-phase guidance errors are only one contribution to the inaccuracy of ballistic missiles. For all but the shortest range missiles, the midcourse and reentry phases can contribute significant and sometimes unpredictable errors, resulting from:

- reentry vehicles steering off course, in much the same way that skydivers steer with their arms and legs (steering and lift forces can be caused by the RV's oscillating or tumbling when it first encounters the atmosphere, or by unexpected rates of RV ablation);[67]
- barometric pressure and weather over the target; and
- unmodeled anomalies in the earth's gravitational field.

In sum, accurate and reliable guidance, control, and reentry-vehicle systems for large, multistage ballistic missiles require integrating a set of critical technologies that would appear to be particularly difficult for developing countries to master. To the extent that reliable delivery of a weapon within several kilometers of its target matters, these difficulties provide an important barrier to the proliferation of long range missiles in developing countries. Barring direct purchase, progress toward long range missiles will come in measured steps at best, and sudden breakthroughs are unlikely.

MOBILITY AND SURVIVABILITY

Most missiles deployed in Third World countries can be launched from mobile wheeled or tracked vehicles known as transporter-erector-launchers (TELs). (Even ICBMs, such as the Russian single-warhead SS-25 and the U.S. Peacekeeper, can be put on mobile launchers and hidden.) Such launchers can be very difficult to locate and track and can be stored in secure locations, making them less vulnerable to preemptive attack. Syria reportedly stores its TELs in specially constructed, fortified tunnels, and Saudi Arabia may protect its DF-3 missiles by storing them in a chosen group of bunkers that are based on a design China uses to protect its strategic missiles.[68] In the Persian Gulf War, the mobility of the Scud launchers proved to be much more of a problem for the allied forces than had been anticipated. Even with the combined benefits of massive air superiority, the most advanced reconnaissance and targeting systems available, and hundreds of sorties flown each night, an extensive air-power survey carried out for the U.S. Air Force has found that although a few mobile Scud launchers may have been destroyed by coalition aircraft or by special operations forces during the war, there is no hard evidence that coalition air attacks destroyed ***any*** Iraqi Scud missiles or mobile launchers.[69]

Mobility comes at some cost, however. While it adds flexibility in choosing a launch site, it could require developing a reprogrammable flight-control system to adjust missile trajectories.[70] Long range missiles are significantly harder to make mobile than shorter range ones; many roads, bridges, and tunnels may not be capable of handling the weight and size of a long range missile, and off-road transportation would proba-

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[67] Reentry errors have been reduced in the United States and other countries with advanced missile programs, however, by extensive testing, computer modeling, use of techniques such as spinning the RV after properly aligning its axis, and using exotic materials to optimize nose-tip ablation.

[68] Carus, *Ballistic Missiles in Modern Conflict,* op. cit., footnote 37, p. 42.

[69] Eliot A. Cohen, *Gulf War Air Power Survey* (Washington, DC: School of Advanced International Studies, Johns Hopkins Univ., draft April 28, 1993), ch. 3, pp. 23,31-32. See also, Julie Bird, "Gulf Airstrikes Left Scuds Intact," *Defense News,* vol. 8, No. 19, May 17-23, 1993, p. 26.

[70] Reprogrammable flight-control systems would not be essential, however, since one could always keep a missile's range fixed by restricting its launch to an arc centered on a fixed target; for liquid-fueled missiles, one could compensate for the differences in range by adjusting the propellant level before launch.

bly be quite slow.[71] Nevertheless, any country with experience in manufacturing large heavy-duty vehicles, railroad cars, and construction equipment such as cranes, should be able to construct at least primitive mobile launchers for short range missiles. Therefore, mobile launchers would not present a major hurdle for an emerging missile power.

OVERCOMING DEFENSES

To date, the only use of ballistic missile defenses in wartime occurred during the Persian Gulf War, in which Patriot defense batteries were rapidly deployed to Israel and Saudi Arabia to counter Iraqi Scuds.[72] Over the six weeks of the war, 81 Scuds were reportedly launched by Iraq, 43 of which were targeted on military facilities and populated areas in Saudi Arabia, with the remainder against Israeli cities, About 47 Scuds were engaged by Patriot missiles. Claims made by the U.S. Army and Raytheon, the manufacturer of Patriot, over Patriot's success rate were initially quite optimistic. However, these claims generated much controversy and have since been revised downward several times .73

Few if any lessons from the Patriot-Scud engagements can be applied to the problem of missile defense in general, since both offensive and defensive systems will continue to evolve. Nevertheless, it was instructive that one of the simplest and indeed lowest technology forms of "penetration aid" probably played a role in reducing the effectiveness of Patriot. The Scud rocket casing, which remained with the warhead until late in reentry, tended to break up in the lower atmosphere, creating a much more difficult target for the Patriot to intercept. According to an engineer from the Raytheon Company who has had nearly two decades of involvement with the Patriot system,

> Due to design changes and poor workmanship when the Scuds were modified, they broke apart in midair and created the combined effects of stealth, maneuvering reentry vehicles (RVs), decoys and fragments, and reduced warhead vulnerability. All were unanticipated and added to the difficulty of defeating these TBMs [tactical ballistic missiles]. The inference of those who claim that because these TBMs were crude they were easy to defeat is incorrect.[74]

Simple measures might therefore be adequate against a defense system not designed to discriminate decoys, To protect against mid-course interceptors or associated radars, decoys could be rather primitive; dispersing bundles of radar-reflecting wire known as chaff might suffice. However, penetrating advanced terminal defenses might require more realistic decoys having aerodynamic properties similar to those of the warhead. Deploying such decoys would impose significant weight penalties.

Development work is now vigorously being carried out in the United States and in Israel on a variety of improved antitactical ballistic missile systems (ATBMs), including, for example, next-generation Patriots (called the PAC-3), a theater

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[71] Unless great care is taken to dampen shocks and vibrations, transporting medium- and long range *solid-propellant* missiles may also *damage the* fuel grain, resulting in loss of reliability.

[72] Several missile-defense systems had previously been developed by the United States and Soviet Union (and deployed, in the latter case), but all of these had used nuclear warheads, and none had been used in wartime.

[73] See, for example, U.S. Congress, House Committee on Government Operations, Subcommittee on Legislation and National Security, *Performance of the Patriot Missile in the Persian Gulf War,* 102nd Congress, 2nd Session, Apr. 7, 1992; and U.S. Congress, General Accounting Office, *Operation Desert Storm: Data Does Not Exist to Conclusively Say How Well Patriot Performed,* NSIAD-92-340 (Washington, D. C.: U.S. General Accounting Office, Sept. 22, 1992). See also Representative John Conyers, Jr., "The Patriot *Myth:* Caveat Emptor,'' *Arms Control Today,* vol. 22, No. 9, November 1992, pp. 3-10; Theodore A. Postol, ''Lessons of the Gulf War Experience with Patriot, " *International Security,* vol. 16, No. 3, Winter 1991/92, pp. 119-171; and Robert M. Stein and Theodore A. Postol, "Correspondence: Patriot Experience in the Gulf War, " *International Security,* vol. 17, No. 1, Summer 1992, pp. 199-240.

[74] Robert M. Stein, Manager of Advanced Air Defense Programs for the Raytheon Company, ''Patriot ATBM Experience in the Gulf War, ' article sent to subscribers of *International Security,* Jan. 9, 1992.

high-altitude area defense interceptor (called THAAD), and Israeli *Arrow* interceptors. Although one or more of these systems or others may eventually provide some level of regional defense against ballistic missiles carrying *conventional* weapons, even very small leakage rates against missiles carrying weapons of mass destruction could have devastating consequences. The potential effectiveness of defenses against the latter type of threat is therefore highly speculative at the present time.

COMMAND, CONTROL, HANDLING, AND SAFETY REQUIREMENTS

As was stated earlier, the infrastructure required to support a missile capability is smaller than that needed to sustain an effective air force. During the Iran-Iraq war, for instance, Iran was unable to acquire manned combat aircraft, but did manage to obtain and launch missiles under the control of the Islamic Revolutionary Guard, a force without a particularly high level of technical expertise.[75] Furthermore, targeting requirements at least for weapons of mass destruction would not present much of a problem, since published maps or commercially available satellite imagery would probably suffice in most cases.

Without its own reconnaissance aircraft or satellites, however, a country using missiles to deliver weapons of mass destruction may not know whether they landed anywhere near their intended targets, and might have to rely on news reports or spies to know the extent of the destruction it had caused. (For this reason, Israeli military censors restricted reporting during the Persian Gulf War about Iraqi Scud strikes in Israel.)[76]

Great care must be taken in transporting liquid rocket fuel or fielding mobile missiles to avoid accidents that could lead to explosions. However, transporting weapons of mass destruction would also warrant strict safety and security measures, so that the incremental safety requirements for handling the missiles would probably not add significant additional obstacles.

TESTING REQUIREMENTS

Ensuring the reliability of the complex thermodynamic, aerodynamic, and electro-mechanical systems involved in ballistic missiles requires extensive testing, both at the subsystem level and in full-scale tests. The engines can be tested in specialized static test stands on the ground, but missile guidance, control, and overall reliability assessments require flight tests. For instance, it is reported that after the initial flight test of China's frost medium range missile (the 1,200-km, single-stage, liquid-fueled CSS-1) failed in 1962, seventeen ground tests were performed before a series of three more flight tests (all successful) were carried out in 1964.[77] A thorough program of flight testing would involve specialized instrumentation, radars, data acquisition systems, and test ranges. If the intended payload were very expensive, such as a nuclear weapon, a high level of reliability would probably be desired, making short-cuts in missile flight-testing unwise and unlikely. Still, even well-developed and thoroughly tested missile systems are often still considered to be only about 80 to 90 per cent reliable .78

If a missile is to carry and disperse decoys and other penetration aids to help it overcome defenses, an additional development and testing

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[75] Carus, *Ballistic Missiles in Modern Conflict, op. Cit.,* footnote 37, p. 30.

[76] See, for example, "Missile Fired at Israel, ''New *York Times*, Feb. 1, 1991, p. 11. Also, during World War II, the British used double agents to carry false information to the Germans about the impact points of V-1 and V-2 missile attacks on London. See David Irving, *The Mare's Nest* (Boston: Little, Brown and Company, 1964), pp. 250-251.

[77] Phillip S. Clark, "Chinese Launch Vehicles-' Chang Zheng l', " *Jane's Intelligence Review,* November 1991, p. 508.

[78] See U.S. Congress, Office of Technology Assessment, *Access to Space: The Future of U.S. Space Transportation Systems*, OTA-ISC-415 (Washington DC: U.S. Government Printing Office, April 1990), p. 22.

program might be needed to develop them. Depending on the sophistication of the defenses, however, such a program to develop penetration aids would probably not be nearly as complex as developing the missiles and reentry vehicles themselves.

IMPLICATIONS OF GPS AND NEW GUIDANCE TECHNOLOGIES

One way a country might try to improve navigational accuracy is through incorporating Global Positioning System (GPS) data into a missile's guidance system (see section on Cruise Missiles, below, for a discussion of GPS capabilities). However, this presents two inherent difficulties. First, to comply with MTCR guidelines, GPS receivers for commercial or export sales must shut themselves down if they compute that they are traveling faster than 515 m/see or are at an altitude above 18 km. Since even 300-km-range Scud missiles reach speeds of more than 1,500 m/see and altitudes around 30 km before burnout, commercial GPS receivers would be of little use either in boost-phase or beyond. Nevertheless, if a country could manufacture its own GPS receivers, or obtain the underlying electronic processor chips from elsewhere, this part of the problem could be avoided.

The other problem with using GPS systems for missile guidance, however, is common to all missile systems: accurate navigational information must be translated into effective flight control. GPS could be of great help with rapid and accurate initialization of the missile's position before launch, and to some extent with determining true north, both of which could be important contributions. But GPS information alone would probably not help reduce the remaining uncertainty from inertial guidance-system measurements in the missile's *orientation* at the moment of thrust termination, when the missile is moving and accelerating most rapidly. Even during the boost phase itself, it is would be technically complex to transform GPS position and velocity information via the flight control system into useful adjustments in the missile trajectory, especially given the slow rate at which most GPS receivers update their readings. During boost phase, therefore, employing GPS data would probably not be of much help in producing more accurate missiles.

In theory, a post-boost vehicle could use GPS navigational data to greater advantage in making leisurely mid-course corrections outside the atmosphere. But a post-boost vehicle represents an additional missile stage with its own propellant, thrusters, and computational power; and it would pose an additional obstacle for emerging missile powers.

Terminal guidance, or steering a warhead to a precise aim point after it has reentered the atmosphere, has been employed on some advanced U.S. missiles (the *Pershing II*, for instance), but it would be exceptionally challenging for an emerging missile power to develop.

In sum, designing and producing reliable and reasonably accurate ballistic missiles of over 1,000-km range would be difficult but not impossible for many developing states. There may be increasing numbers of scientists from the former Soviet Union and elsewhere willing to assist in these efforts. Without dedicated resources and some outside technical assistance, however, a program would be lengthened substantially and likely encounter frequent setbacks. As missile range and size are increased, almost all aspects of missile development (e.g., combustion chambers, casting of solid propellants, multiple staging, guidance and control systems, reentry vehicles, and even transporters) become increasingly complex and technologically demanding. Consequently, achieving accuracy and reliability for such systems requires more time and expense and cannot be assumed to follow on the heels of first-generation missile deployment.

| Monitoring Ballistic Missile Programs

Intelligence capabilities for discovering or tracking missile transfers have been far from perfect. It was reportedly largely by accident that U.S. intelligence sources discovered the Saudi purchase of Chinese DF-3 missiles, and then at least two years after the fact.[79] It has also been reported that the United States was unaware of the extent to which Iraq had successfully extended the range of its Scud missiles during the 1988 Iran-Iraq ''War of the Cities.' '[80]

Missile development programs also draw on many dual-use goods that have legitimate industrial applications, making them difficult to control and monitor. These include forging, rolling, and other large metal-working equipment that could be used in manufacturing large motor cases, as well as computers and certain types of precision computer-controlled equipment.[81]

Nevertheless, production facilities for large missiles and especially for solid-fueled boosters might have distinctive characteristics that could facilitate their identification and monitoring. These features might be associated with their size or their capability to withstand accidental detonations.[82] Accidental explosions themselves might also be possible to monitor. Furthermore, for the vast majority of developing countries, development of longer range missiles would require that significant amounts of specialized hardware, materials, or technical assistance be imported, thus providing other governments a possible means to monitor the program's progress. It is therefore much more difficult to develop longer range missiles in secret than it is to secretly import medium range missiles or extend the range of short range missiles.

FLIGHT TESTING OF BALLISTIC MISSILES

By their bright exhaust plumes and unique flight profiles, flight tests of missile systems will continue to be easily monitored remotely. Static ground tests might also be visible. Static tests of individual missile stages and flight-tests at reduced range can partially disguise capabilities and make it difficult in the early stages of a program to determine its intent. But the step-wise progress and extensive test programs required to develop *long range* systems provide a lengthy window for observation.

MISSILE DEPLOYMENT

If a country wanted to convince its neighbors that it was indeed pursuing space-launch capabilities and not developing ballistic missiles, it might suggest that other countries inspect its missile production facilities. A plant that had the manufacturing capacity to turn out only one or two boosters per year would be less likely to be used for offensive missile production than one capable of mass-producing boosters by the dozen. Such a country might also allow others to inspect its payloads or observe its space launches at close range. However, not all countries would allow such transparency in their space-launch programs. Furthermore, such inspections could only verify that a given production facility, launch, or series of launches had a nonthreatening objective; they could not prove that the *capability* for developing a ballistic-missile delivery system was absent.

Like other delivery systems and weapons of mass destruction themselves, monitoring ballistic missiles can be more problematic once they are deployed than during their development and production. The best opportunity for monitoring

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[79] See David Ottaway, ''Saudis Hid Acquisition of Missiles, " *Washington Post*, March 29, 1988, p. A13; and Jim_ "U.S. Caught Napping by Sine-Saudi Missile Deal," Los Angeles Times, May 4, 1988.

[80] Carus, *Ballistic* Missiles *in Modern Conflict,* op. cit., footnote 37, P. 62.

[81] Stanford, Assessing Ballistic Missile *Proliferation,* op. cit., footnote 4, p. 6.

[82] For example, the one-stage Chinese DF-3A missile (range of about 3,000 km with a 1,100-kg payload) weighs 65,000 kg; the U.S. MX ICBM (1 1,000 km with 3,800 kg) weighs 90,000 kg. See, for example, *The Military Balance 1988-1989,* (London: International Institute for Strategic Studies, 1988).

the status of missile programs (other than openly displayed space-launch systems) is clearly afforded by the development and testing phase.

Summary—Ballistic Missile Proliferation

According to published sources, ballistic missiles with ranges from 300 to 600 km are already possessed or being developed by well over a dozen countries outside of the five declared nuclear powers. Their spread was greatly facilitated by the export in the 1970s and 1980s of Scud-B missiles from the Soviet Union. With the advent of the MTCR and an increasing number of countries abiding by its constraints on missile trade, the potential number of non-Third World suppliers of missiles has declined markedly. However, at the same time, additional countries have learned to copy, modify, extend the range of, and produce their own missiles, and a small number have developed long range systems—often in conjunction with space-launch programs and foreign technical assistance.

In general, the acquisition by developing countries of more advanced missile technologies-those allowing ranges in excess of 1,000 km or accuracies much better than roughly 0.3 per cent of range-can be slowed but not stopped by multilateral export controls. Those emerging missile powers that might have the intent to strike at the United States (e.g., Iran, Iraq, North Korea, Libya) will not be able to field long range missiles or ICBMs over the next 10 years, and those that could develop the capability (e.g., Israel, India, Taiwan) are not likely to have the intent. It is therefore unlikely that any country (other than China and the former Soviet republics that already possess intercontinental ballistic missiles or ICBMs) would pose a direct ballistic missile threat to the United States within the next 10 years.

Nevertheless, given the continuing export behavior of North Korea and possibly China, the potential for collaboration between emerging missile powers, and the possibility of missile experts becoming available from the former Soviet Union or from financially troubled companies in other non-MTCR countries, expertise in both short-and long range missile systems may continue to spread. Countries may continue to seek ballistic missiles for a number of reasons, including their prestige, their psychological value as terror weapons, the opportunities they provide for generating hard currency, technology transfer from space-launch programs, or even a shortage of trained pilots and infrastructure to support an air force. These motivations, combined with the fact that designing and manufacturing ballistic missiles in general requires considerably less sophistication than does producing jet engines for modem combat aircraft, will continue to make missile technology attractive for a number of countries of proliferation concern.

COMBAT AIRCRAFT

The potential use of combat aircraft for delivering weapons of mass destruction poses a number of complex issues. Advanced fighters and strike aircraft can carry out a wide variety of missions—e.g., air defense, close air support of ground troops, and striking targets inside enemy territory—and are widely accepted as legitimate military instruments.[83] However, some also provide the capability to deliver weapons of mass destruction, a mission not viewed with the same degree of acceptance. It is difficult or impossible to allow the former set of capabilities while preventing the latter, since almost any combat aircraft with an attachment point for ordnance or for other equipment can be modified to accommodate and deliver nonconventional weapons. Moreover, many potential proliferant states either possess or can buy combat aircraft far superior to available missiles in terms of payload, accuracy, range, and other characteristics. In most cases, the range,

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[83] The U.N. Charter explicitly recognizes the right of a nation to self-defense. Possession of combat aircraft fOr that purpose is thus not illegal under international law.

accuracy, and payload capabilities of combat aircraft already possessed by developing countries far exceed those of' their ballistic or cruise missiles, and many more countries have aircraft than have missiles.[84]

The relative numbers and capability of military aircraft in countries of proliferation concern vary greatly (see table 5-8). For example, the Israeli air force, which includes 63 F-15, 209 F-16,95 Kfir C2/C7, and 112 F-4E aircraft,[85] has a vastly greater capability in wartime for large-scale ordnance delivery at long range, and in the presence of hostile defenses, than is possessed by most developing countries. For some countries, however, capability is determined more by the availability of pilots, technicians, or even spare parts, than it is by numbers of aircraft. The training given pilots and the doctrine they employ is also very significant. Although variations in air-force size, readiness, and even pilot skill might not matter much for delivering a single nuclear weapon to an undefended target or a large city, the overall capability of a proliferant's air force could affect its ability to deliver large quantities of chemical weapons by air, or to engage in a protracted conventional air war that might eventually escalate to use of weapons of mass destruction.

Outside NATO and the former Warsaw Pact, most nations with large air forces and advanced combat aircraft also tend to have, or are thought to have, programs for the development of nuclear, chemical or biological weapons.[86] As can be seen from table 5-8, 7 of the top 10 non-NATO nonformer Soviet Bloc countries with the largest air forces are thought to have active programs in weapons of mass destruction (those not believed to have such programs are Japan, Sweden, and Yugoslavia); of those with the top 25 air forces, 11 have active programs and another four are thought to have had programs in the 1980s that are now being reversed. Furthermore, of all the developing nations believed to be engaged in the development of weapons of mass destruction, only one, Myanmar (formerly Burma), has less than 150 combat aircraft. (Figure 5-4 illustrates the overlapping nature of programs for the development of weapons of mass destruction in various counties.)

Trade in Weapon-Capable Aircraft

The proliferation of combat aircraft is already more widespread and intractable than that of ballistic missiles. Although some ***dual-use*** technologies useful in the development of ballistic missiles are still actively traded, trade in missiles themselves has always caused concern and has been subject to multilateral export controls since the MTCR was established in 1987. Nations are increasingly willing to take diplomatic or economic measures to contain the spread of ballistic missiles, forcing commerce in missiles-when it has taken place-to be carried out clandestinely.

In sharp contrast, most nations with advanced arms industries actively support the efforts of their aerospace companies to make international sales. The international market for fighters, interceptors, and strike aircraft is extremely competitive. In the middle 1980s, for example, when the U.S. Congress blocked the sale of F-15 fighter aircraft to Saudi Arabia, the Saudis turned to a U.K. firm, British Aerospace, and bought more

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[84] This analysis focuses on combat aircraft in countries believed to have *programs* for developing weapons Of mass destruction (other than the five acknowledged nuclear powers in the case of nuclear weapons) or that have ballistic missile programs but are not full members of the MTCR. These countries are almost exclusively in the developing world. (See ch. 2 of U.S. Congress, Office of Technology Assessment *Proliferation of Weapons of Mass Destruction: Assessing the Risks,* op. cit., footnote *2,* for the methodology used in identifying mass-destruction weapon programs in these countries.)

[85] International Institute for Strategic Studies, *The Military Balance 1992-1993* (London: Massey's, 1992).

[86] During the period over which most of the aircraft discussed in this section were acquired, NATO and former Warsaw Pact states were covered by a nuclear umbrella and other security guarantees resulting from their NATO and Soviet Bloc alliances. The close ties these states had to superpower allies armed with weapons of mass destruction lessened their own motivations to develop such weapons.

Table 5-8-Combat Aircraft and Mass-Destruction Weapon Programs in Non-NATO and Non-former Warsaw Pact Countries

Country[a]	FGA[b]	Fighter[b]	Bomber	Total[b]	WMD/M[c]	Example
China.	600	4600	630	5830	(N)BCM	Q-5(MiG-19)
North Korea.	346	376-387	81?	814?	NBCM	MiG-29
India.	400	327	9	736	NM	Mirage-2000
Israel.	169	479	0	648	NBCM	F-15/16
Syria.	170	302-463	0	633	BCM	MiG-29
Taiwan. ... , ... ,	512	0	0	512	BC	F-5
Japan. ....,.,..	94-198	280	0	478	none	F-15
Egypt. . . . .,,.,..,	113-149	295-323	0	472	CM	F-16
Sweden	97-237	214	0	451	none	JA-37
Yugoslavia	213-283	126	0	409	none	MiG-29
South Korea.	265	128	0	393	M?	F-16
Libya, ...	128	238	5	371	BCM	Mirage F-l
Pakistan	126-150	214	0	364		F-16
Iraq.	130	180	6	316	[NBCM]	MiG-29
Saudi Arabia.	97-152	102-132	0	284	M	F-15C/D
Iran. ... , ...	130	132	0	262	NBCM	F-14
South Africa	116-245	14	0	259	[N]M?	Mirage F-l
Algeria.	57	185	0	242	N?M?	MiG-23
Afghanistan.	110	80-123	0	233	M	MiG-23
Switzerland.	87	137	0	224	none	Mirage III
Brazil.	200	18	0	218	[N]M	F-5
Singapore	107-149	38	0	187	none	F-16
Vietnam.	60	125	0	185	c	Su-17
Cuba. ....,.	20	140	0	160	none	MiG-29
Argentina	16-89	66	0	155	[NM]	SuperEntendard

Key: FGA = fighter/ground-attack aircraft

Fighter -combat aircraft optimized for air-to-air mission

Bomber = aircraft optimized for delivering large payloads of bombs at relatively long range, possibly with internal bomb bay, and lacking air-combat capability

[a] Countries with less than 150 combat aircraft are not listed. The only such country that is frequently reported to have a mass-destruction weapon program is Myanmar (Burma), which is suspected of having chemical warfare capability and is reported to have 12 fighter aircraft.

[b] Higher numbers include combat-capable trainer aircraft, which are also included in totals.

[c] WMD/M - weapon of mass destruction or missile program:

N = frequently reported as having or trying to acquire nuclear weapons

B = frequently reported as having offensive biological warfare program

C = frequently reported as having offensive chemical warfare capability

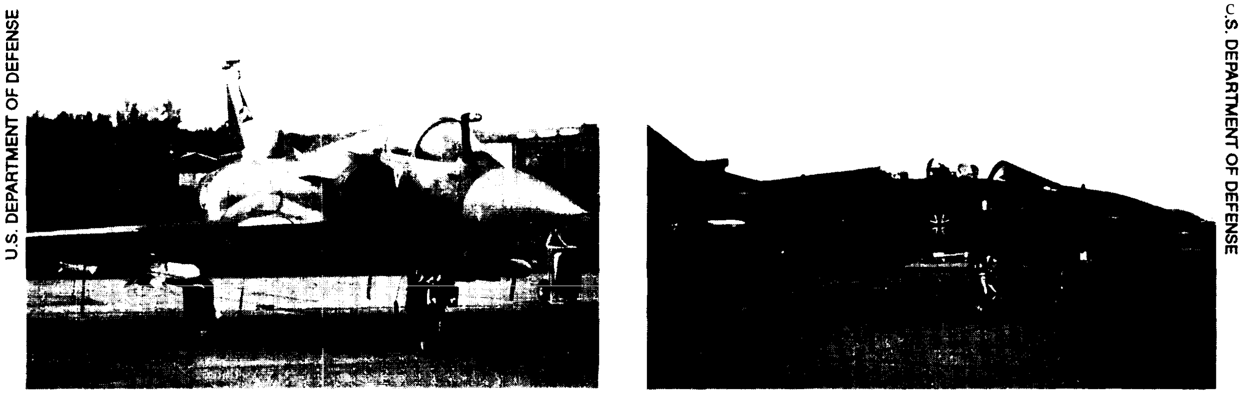
M = suspected of having or developing ballistic missiles with range of at least 300 km, and not full member of the MTCR as of March 1993

[ ] = program in reversal or no longer considered a proliferant threat

States are listed here as having nuclear, chemical, and biological weapon programs if they are commonly cited in the public literature as having such programs, as reviewed in ch. 2 of U.S. Congress, Office of Technology Assessment, *Proliferation of Weapons of Mass Destruction: Assessing the Risks*, OTA-ISC-559 (Washington, DC: U.S. Government Printing Office, August 1993). See also figure 5-4, drawn from the same source. (Since China is a nuclear-weapon state under the Nuclear Non-Proliferation Treaty, it is not considered a "nuclear proliferant" here.) States are listed as having missiles if they are listed in table 5-3 as having indigenous missile programs or imported missiles.

[d] Federal Republic of Yugoslavia (Serbia-Montenegro)

SOURCE: Office of Technology Assessment. Based on information drawn from International Institute for strategic Studies, *The Military Balance 1992-1993* (London: International Institute for Strategic Studies, 1992).



U.S. DEPARTMENT OF DEFENSE

U.S. DEPARTMENT OF DEFENSE

(a) Mirage-2000

(b) Tornado

U.S. NAVY

GENERAL DYNAMICS CORP.

(c) *Kfir*

(d) F-16

Advanced combat aircraft such as (a) the French Mirage-2000, (b) the German/British/Italian Tornado, (c) *the Israeli Kfir, and (d) the U.S. F-16 are operated by a number of countries around the world, some of which are thought to have programs to develop weapons of mass destruction.*

than 100 comparable Tornado IDS aircraft.[87] In a few instances, political or regional considerations have made it difficult for countries to obtain advanced combat aircraft, but most have been able to do so.[88]

Moreover, as developing nations have continued to purchase advanced combat aircraft, they have increasingly demanded transfer or licensing of underlying production technologies as part of

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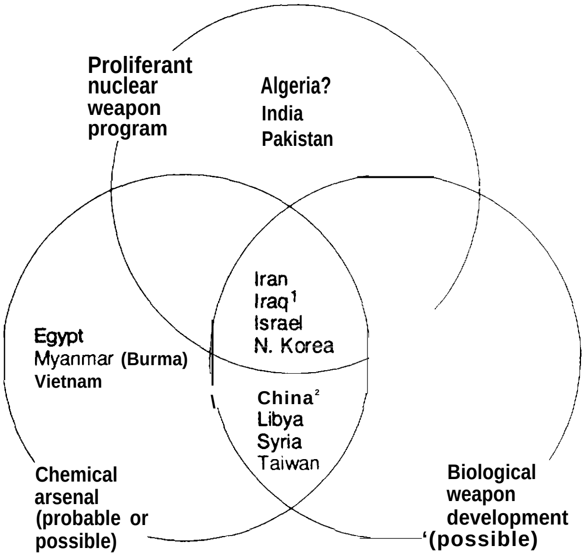
[87] The Tornado aircraft includes technology and components developed and manufactured in Britain, Germany, and Italy. It has considerably less air-combat capability than the F-15.

[88] For example, Iranian F-14 aircraft played only a small role in delivering conventional ordnance during the Iran-Iraq war, largely because the United States had cut off spare parts, training, and maintenance support following the Islamic revolution in 1979. On the other hand, even under the Pressler Amendment, which cut off aid (including military aid) to Pakistan after the President could no longer certify that it did not possess a nuclear weapon, commercial sales of military equipment supporting that country's air force appear to have continued. See, for example, "Shipments to Pakistan Under Investigation," *Washington Post, Mar.* 7, 1992, p. A1.

GENERAL DYNAMICS CORP.

The General Dynamics F-16 fighter, here being assembled at the U.S. Fort Worth facility, is flown by 17 air forces around the world. Licensed co-production facilities have been built in Belgium, Turkey, and the Netherlands.

Figure 5-4-Suspected Weapon of Mass Destruction Programs



Shaded area: also has Scud-type or longer range ballistic missile

[1] Iraqi programs reversed by U.N.

[2] China is an acknowledged nuclear-weapon state.

SOURCE: U.S. Congress, Office of Technology Assessment, *Proliferation of Weapons of Mass Destruction: Assessing the Risks,* OTA-ISC-559 (Wash., DC: U.S. Government Printing Office, August 1993), p. 66.

the transaction.[89] These licensed production arrangements help build up and extend the defense industrial infrastructure of recipient nations. Such transfers are often accomplished through complicated sales agreements, for example, in which the recipient nation buys a few copies of an advanced fighter off-the-shelf, assembles a second batch under license, and-to the extent that its industrial base can absorb and produce the technologies and components in question—manufactures the rest indigenously. In such transfers, highly sophisticated and classified subsystems are often withheld by the seller or provided in a downgraded version as an assembled component.

Over the past several years, trade in advanced combat aircraft has been brisk. During 1987-1992, the 20 developing countries having the largest air forces ordered a total of over 1,600 aircraft (see table 5-9). Of those aircraft, over two-thirds were ordered by proliferant nations that either now possess or are thought to be developing weapons of mass destruction (WMD), or were thought to be developing them at the time of the orders.

As these data suggest, proliferation of WMD-capable aircraft is embedded in the economic competition among firms of several different nations. The most common reasons cited in Europe and the United States to export advanced combat aircraft are that foreign military sales are necessary both to maintain existing production facilities and to fund R&D within the firm for

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[89] On the subject of licensed production of major weapon systems, see U.S. Congress, Office of Technology Assessment, *Global Arms Trade,* OTA-ISC-460 (Washington, DC: U.S. Government Printing Office, June 1991), pp. 6-9. Selected licensed production agreements in the 1980s include: U.S. F-16 fighter (to Turkey and to South Korea); French-German Alpha Jet (to Egypt); Brazilian EMB-312 Tucano trainer (to Egypt); Anglo-French Jaguar fighter (to India); Soviet MiG-27 fighter (to India); and U.S. F-5E Tiger-2 fighter (to Taiwan). Selected licensed production agreements in the 1970s included: French Mirage F- 1 fighter (to South Africa); Soviet MiG-21 fighter (to India); and Soviet MiG-19 fighter (to North Korea). See, for example, *SIPRI* Yearbook (New York: Oxford University Press, various years).

Table 5-9-Combat Aircraft Ordered 1987-1992 by Countries of Proliferation Concern[a]

Country[a]	Total	WMD/M[b]	No.	Type of Aircraft	Supplier[c]	Year
China	**76**	**(N)BCM**	**12**	**SU-24 Fencer**	**USSR**	**1990**
			24	**SU-27 Flanker**	"	**1991**
			40	**MiG-29**	"	**1991**
North Korea	**195**	**NBCM**	**20**	**SU-25 Frogfoot**	**USSR**	**1987**
			25	**MiG-29**	"	**1987**
			150	**MiG-21 MF**	USSR	**1988**
India	**40**	**NM**	**15**	**MiG-29**	"	**1988**
			15	**Jaguar**	France/U.K.	**1988**
			10	**Sea Harrier**	U.K.	**1989**
Israel	**90**	**NBCM**	**5**	**F-15D Eagle[d]**	**Us.**	**1988**
			30	**F-16C**	"	**1988**
			30	**F-16D**	"	**1988**
			15	**F-1 5A Eagle**	"	**1990**
			10	**F-1 5A Eagle**	"	**1991**
Syria	**8+**	BCM	**7**	**SU-24 Fencer**	USSR	**1988**
			8	**MiG-25 Foxhound**	"	**1989**
Taiwan	250	BC	**34**	**Kfir-C7**	Israel	**1991**
			6	**Kfir-TC7**	Israel	**1991**
			150	**F-1 6**	**Us.**	**1992**
			60	**Mirage 2000-5**	**France**	**1992**
Egypt	**123**	CM	**42**	**F-16C**	**Us.**	**1987**
			4	**F-16D**	"	**1987**
			1	**F-1 6D**	"	**1988**
			20	**Mirage-2000**	**France**	**1988**
			10	**L-39 Albatros[d]**	*Libya*	**1980**
			46	**F-16C**	**Us.**	**1991**
South Korea	**357**	**M?**	**24**	**F-4D Phantom**	**Us.**	**1987**
			4	**F-1 6D**	"	**1988**
			24	**F-4E Phantom**	"	**1988**
			12	**RF-4C Phantom**	"	**1988**
			24	**F-4E Phantom**	"	**1989**
			120	**F/A-18 Hornet**	"	**1989**
			20	**Hawk[d]**	**U.K.**	**1990**
			9	**RF-4C Phantom**	**Us.**	**1990**
			120	**F-1 6C**	"	**1991**
Libya	**15**	BCM	**15**	**Su-24 Fencer**	**USSR**	**1988**
Pakistan	**196**	**NM**	**11**	**F-1 6A**	**Us.**	**1988**
			75	**F-7**	**China**	**1989**
			60	**F-1 6A**	**Us.**	**1989**
			50	**Mirage-30**	*Australia*	**1990**
Iraq	**52**	**[NBCM]**	**36**	**Mirage F-1 C**	**France**	**1987**
			16	**Mirage F-1 C**	**France**	**1989**
Saudi Arabia	**176**	**M**	**12**	**F-15C Eagle**	**Us.**	**1987**
			420	**Hawk-200**	**U.K.**	**1988**
			60	**Hawk-1 00**	**U.K.**	**1990**
			12	**F-15D Eagle**	**U.S.**	**1990**
			72	**F-15XP**	**Us.**	**1992**
Iran	**1 30+**	**NBCM**	?	**MiG-21 F**	*E. Germany*	**1988**
			15	**EMB-312 Tucano[d]**	*Egypt*	**1988**
			?	**MiG-29**	**USSR**	**1990**

Country[a]	Total	WMD/M[b]	No.	Type of Aircraft	Supplier[c]	Year
South Africa	**7**	**[N]M?**	**7**	**PC-7[d]**	**Switzerland**	**1989**
Algeria	?	**N?M?**	?	**MiG-29**	**USSR**	**1988**
Afghanistan	0	M				
Brazil	**43**	**[N]M**	11	**S2F-1**	**Canada**	**1987**
			23	**F-5E Tiger II**	**Us.**	1988
			3	**F-5F Tiger II[d]**	**Us.**	**1988**
			6	**Mirage-3E**	France	**1988**
Vietnam	0	c				
Argentina	0	**[NM]**				

a See notes to Table 5-8 for explanation of countries listed.
b See key to Table 5-8.
c Supplier countries in italics are not the original producers of the aircraft.
d Trainer

SOURCE: Office of Technology Assessment. Based on information from *SIPRI Yearbooks,* 1988-92 (New York, NY: Oxford University Press, various years) and selected newspaper reports.

future production. Proponents of combat aircraft exports also assert that in the absence of exports, the balance-of-payments deficit would rise and tens of thousands of domestic aerospace workers would lose their jobs. Incentives for former Soviet republics to export military hardware, in the face of severe economic hardship and shortages of hard currency, are even stronger.

In addition to reasons of economics and alliance politics, however, trade in combat aircraft is driven by their utility in a wide range of military roles, including air defense, close-air support, reconnaissance, antiship, and tactical missions. Arms exporters assert that friendly states require combat aircraft to defend themselves. Such trade is also facilitated by the lack of any legal restrictions. Since military aerospace is a multibillion dollar sector in international trade, it will be extremely difficult to slow proliferation of combat aircraft. Establishing meaningful limits would require that major exporting nations adopt a strict multilateral control regime that did not recognize the right of participating nations to make unilateral sales or transfer production technology. Given these economic, political, and military realities, most analysts believe that a regime significantly curtailing trade in aircraft is unlikely to develop anytime soon.[90]

| Capabilities of Aircraft for Delivering Weapons of Mass Destruction

Existing aircraft inventories in both advanced and developing nations, and the diffusion of production capacity, indicate that most countries pursuing weapons of mass destruction already have relatively modem combat aircraft capable-after suitable modification-of delivering them to a variety of targets. While these states may be less able to carry out sustained *conventional air* combat, their current aircraft inventories are probably able to deliver weapons of mass destruction, with the possible exceptions of large-scale chemical weapon delivery (which would require a large number of missions) or penetrating the most heavily defended targets. Table 5-10 illustrates some of the capabilities of combat aircraft that have been exported to or are currently possessed by proliferant states.

In considering the requirements for effective delivery of multiple strikes (e.g., for waging

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[90] Nevertheless, antagonistic nations or alliances of nations could eventually agree among themselves to reduce inventories of combat aircraft, as was done through the Conventional Armed Forces in Europe (CFE) Treaty.

Table 5-10-Capabilities of Selected Combat Aircraft

Aircraft designation and country of origin	Payload [kg]	Combat Radius~ [km]	Generation[b]	Speed[c]
Brazil				
T-27	500	460 (est.)	3.5	low
China				
J-8 (Soviet derivative)	300?	400 (est.)	2	high
J-7 (MiG-21 derivative)	300	600	2	high
J-6 (MiG-19 derivative)	500	350 (est.)	1.5	reed-hi
J-5 (MiG-17 derivative)	200 (est.)	250 (est.)	1	medium
H-5 (II-28 derivative)	1,000	600 (est.)	1	medium
	3,000	275 (est.)		
H-6 (Tu-16 derivative)	9,000	1,200 (est.)	1	medium
Q-5 (MiG-19 derivative)	1,000	600	1.5	high
France				
Mirage-2000	1,000	370 (est.)	4	high
Mirage F-1	3,500	425	3	high
	500	1,390		
Mirage-5	907	1,300	2.5	high
Mirage Ill	907	1,200	2	high
Super Etendard	1,500	850 (est.)	3	high
France/Germany				
Alpha Jet	1,100	1,075	2.5	medium
France/U.K. Jaguar	4,000	1,408	3	high
India				
Ajeet (British Gnat derivative)	1,000	204	2	medium
Israel				
Kfir C2/C7	1,200	1,186	3	high
Dagger	(see French Mirage-5)			
South Africa				
Impala I/n (Italian Aermacchi MB-326 derivative)	1,800	130	2.5	low
	90	648		
Chettah	(see French Mirage-5)			
Taiwan				
AT-3	1,900	900 (est.)	2.5	medium
U.K.				
Buccaneer	3,000	900	2	medium
Sea Harrier	1,000	370	3	medium
U.K./Germany/Italy				
Tornado IDS	6,500	1,390	4	high
Us.				
F-16 Falcon	1,400	1,200	4	high
F-15 Eagle	11,000	1,270 (F-15E)	4	high
F-1 4 Tomcat	5,000	805 (est.)	4	high
F-4 Phantom	7,250	1,100	3	high
F-5 Tiger	730	890	2.5	high
F-104 Starfighter	1,500	312 (est.)	2	high
A-4 Skyhawk	4,600	600 (est.)	2	medium

Aircraft designation and country of origin	Payload [kg]	Combat Radius[a] [km]	Generation[b]	Speed[c]
USSR				
MiG-29 Fulcrum	1,400	475	4	high
	1,000	370		
MiG-27 Flogger D	2,000	700 (est.)	3	high
MiG-23 Flogger	2,000	700	3	high
MiG-21 Fishbed	500	740	2	high
SU-25 Frogfoot	4,400	250 (est.)	3.5	medium
SU-24 Fencer	3,000	1,050	3	high
Su-1 7/20/22	1,000	630	2.5	high
SU-7 Fitter	1,000	300 (est.)	2	medium
Tu-22/26 Blinder	12,000	4,000	3	high
Tu-16 Badger	3,790	3,100	1	medium

a Assumes un-refueled high-low-high flight profile carrying specified payload. However, since fuel, payload, range, and speed can be traded against one another, range and payload figures are subject to considerable variability.

b *Generation* designates the following approximate levels of technology: 1 = 1950s; 2 = 1960s; 3 = 1970s; 4 = 1980s. U.S. aircraft of the mid-1970s, however, receive a rating of generation 4.

c *Speed*: low - subsonic, generally propeller driven; medium - near transonic, to barely supersonic in ideal conditions; high = supersonic capability, e.g., roughly Mach 1.2 and above

SOURCE: Office of Technology Assessment. Based, in part, on information drawn from Jane's *All the World's Aircraft, 1978-1991* (Surrey, U. K.: Jane's Information Group Limited, various years).

large-scale chemical warfare), however, additional factors must be taken into account. First, a significant number of aircraft possessed by most developing countries would probably not be combat-ready. Some may have been disassembled to supply spare parts. Others may be in warehouses or in need of repair, and some will likely have crashed,

Second, combat aircraft vary widely in performance and quality in terms of such factors as reliability, serviceability, logistics, pilot ergonomics, thrust-to-weight ratio, turning radius and transient maneuver performance, and electronic countermeasures, Quality factors could affect the ability of aircraft to carry out certain types of missions, especially when facing opposing fighter-interceptors or other significant air defenses.[91] Moreover, as was demonstrated in Iraq, a superior air power might quickly become involved and effectively suppress even one of the larger air forces deployed in the developing world.

Third, few developing countries have expertise in mission planning, rapid turn-around, or accurate weapon delivery. Many developing countries would have difficulty maintaining a skilled core of pilots who are both able and willing to fly missions to deliver weapons of mass destruction. Capabilities for aircraft delivery of weapons at ranges more than 1,000 to 2,000 km are also very limited outside the major industrial powers. Long range delivery might be facilitated by long range bombers, aerial refueling, aircraft carriers, or forward bases. But few proliferant countries, if any, are expected to be able to incorporate these technologies into their air forces anytime soon.

In sum, any of the countries listed in table 5-8 could probably use their air forces to deliver at least a single nuclear weapon (if they possessed one) in a regional context, at ranges between 500 and 1,500 km, and under a wide variety of conditions. Many could mount a small-scale, but nevertheless effective biological or perhaps even

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[91] Air defense capability can also be supplied by other countries. For example, the United States supplied Israel with AWACS coverage and the Patriot system during the Persian Gulf War.

a chemical strike.[92] If additional nations embark on programs for the development of weapons of mass destruction, it is likely that many of them would already have the capability to deliver such weapons using aircraft. Nevertheless, the ability of several of these countries' air forces—like those of existing proliferants-may be questionable in terms of conducting sustained warfare, delivering large quantities of chemical weapons, or maintaining an attack in the event of third-party intervention.

Summary–Proliferation of WMD-Capable Aircraft

Combat aircraft with the range and payload sufficient to deliver nuclear, chemical, and biological weapons, though possibly requiring some modification, are possessed by almost all countries of proliferation concern. In terms of payloads deliverable at specified ranges, the capabilities of air forces of virtually all of these countries far surpass those of their missiles. Furthermore, there are no internationally binding restrictions on aircraft trade, which, in many cases, continues to be motivated by economic and foreign policy concerns.

Although the complex set of required technologies and expertise make it extremely difficult for countries of proliferation concern to design and manufacture advanced aircraft without external assistance, licensed production arrangements have increasingly spread manufacturing technologies to many parts of the world. Licensed co-production or assembly of Western or former Soviet supersonic aircraft is taking place in China, India, Israel, South Africa, South Korea, and Taiwan. Developing countries that have manufactured components or complete subsonic aircraft with some ground-attack capability include Argentina, Brazil, Chile, and an Arab consortium based in Egypt with the participation of Saudi Arabia, Qatar, and the United Arab Emirates.[93]

Because aircraft and missiles have different relative strengths-particularly in their ability to penetrate defenses—the two systems are not fully interchangeable.[94] Piloted aircraft have significant advantages over other delivery systems in terms of range, payload, accuracy, reliability, damage-assessment capability, and dispersal of chemical or biological agents. They can be used effectively under most circumstances, usually even in the presence of significant air defenses.[95] On the other hand, the unit price of a ballistic or cruise missile is considerably less than that of a piloted airplane, and missile delivery offers both military and psychological advantages, especially for a country wishing to deliver a single nuclear weapon to a heavily defended area.

CRUISE MISSILES AND UNMANNED AERIAL VEHICLES

The Intermediate Range Nuclear Forces (INF) Treaty defines a cruise missile as "an unmanned, self-propelled vehicle that sustains flight through the use of aerodynamic lift over most of its flight path,' and that is intended as a ''weapon-delivery" vehicle. Very short range cruise missiles can be rocket-powered, but longer range ones generally use small jet engines. Unmanned aerial vehicles (UAV) are usually slower moving air-breathing platforms (e.g., using jet or propel-

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[92] Lack of spare parts can degrade air-force combat *readiness,* but such degradation would not be as important for scenarios involving delivery of a very small number of nuclear or biological weapons.

[93] See, for example, Mark Lambert, ed., *Jane's All the World' s Aircraft: 1990-1991* (Surrey, U.K.: Jane' sInformation Group Limited, 1990); and James G. Roche, Northrop Corp., ''Tactical Aircraft, Ballistic and Cruise Missile Proliferation in the Developing World, " paper presented at the AAAS conference Advanced< *Weaponry in the Developing World,* Washington, DC, June 12, 1992.

[94] See John R. Harvey, ''Regional Ballistic Missiles and Advanced Strike Aircraft: Comparing Military Effectiveness," *International Security, vol. 17, No. 2.,* Fall 1992, pp. 41-83.

[95] For a more detailed analysis of air defense, see Arthur Charo, *Continental Air Defense: A Neglected Dimension of Strategic Defense* (Cambridge, MA: Center for Science and International Affairs, Harvard University, 1990).

ler engines) that are associated with reconnaissance, surveillance, target, or harassment missions rather than weapon delivery. (Any aircraft can theoretically be made into a UAV by incorporating an autopilot, but the term usually refers to systems initially designed for unmanned operation.) Both cruise missiles and UAVs are treated here as having potential for delivering weapons of mass destruction. Although cruise-missile payloads are generally less than those of ballistic missiles and much less than aircraft, the ability of some modern cruise missiles to fly at very low altitudes and slow speeds makes them particularly well suited for delivering chemical and biological weapons.

Indigenous Development

In the past, indigenous development of guidance and propulsion systems for long range cruise missiles presented almost insurmountable barriers for developing countries, In recent years, however, near-revolutionary advances in satellite navigation, long-distance communications, composite materials, and light-weight turbojet and turbofan engines have greatly facilitated cruise-missile development in a growing number of countries. Developing sophisticated, light-weight jet-engine technology remains a significant obstacle for most Third World countries, Nevertheless, crude pulse-jet technology was successfully employed by the Germans in the V-1 "BuzzBomb" as early as World War II, achieving ranges and payloads comparable to the V-2 and Scud missiles.[96] Furthermore, although the MTCR guidelines have restricted export since 1987 of complete systems and dedicated components for systems exceeding the 300 km/500 kg threshold, relatively sophisticated ready-made components from (unrestricted) short range antiship cruise missiles (ASCMs) and UAVs have been readily available for some time.[97] Trade in these components-m any of which have civilian utility—is making the manufacture of longer range systems considerably easier than in the past. Indigenous cruise-missile design and production has therefore become far more difficult to control. Moreover, cruise missiles and UAVs can be much smaller than other aircraft, and many of them can fly at low altitudes and evade radar, thus making them exceedingly difficult to detect.

As of the beginning of 1993, there were only 11 known cruise missile systems in service that exceeded the 1987 threshold of 300 km/500 kg, three in the United States and eight in Russia.[98] The U.S. Air Launched Cruise Missile (ALCM), *Tomahawk,* and Advanced Cruise Missile (ACM) have ranges of 2,500 to 3,000 km when nuclear-armed and over 1,000 km when armed with a conventional payload of 450 kg. Some Russian cruise missiles have 400 to 600-km ranges with 1,000-kg payload; others have about 3,000 km range with 300-kg payload. China and India are believed to have active development programs for cruise missile with ranges of about 600 km, but unknown payloads.

A growing number of countries already have development programs or the ability to manufacture cruise missiles with shorter range than those described above. The five acknowledged nuclear powers have all designed and built advanced jet-powered missiles capable of being further developed to give ranges in excess of 300 km *at supersonic speeds.* Israel, Italy, Japan, Sweden, and Taiwan have all developed subsonic turbojet-

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[96] See Anthony L. Kay, *Buzz Bomb* (Boylston, MA: Monogram Aviation Publications, 1977).

[97] The new MTCR guidelines adopted on January 7, 1993 prohibit the transfer of any ballistic or cruise missiles with range over 300 km, regardless of payload, and any such missiles—regardless of range or payload-if the supplier has reason to believe they may be destined to carry weapons of mass destruction. This would presumably restrict sales by MTCR members of any cruise missiles to suspected proliferant countries (see figure 5-4).

[98] Data in this and the following paragraph is from Duncan Lennox, ''Missile Race Continues, ' *Jane's Defence Weekly,* Jan. 23, 1993, p. 20.

powered missiles capable of flying well beyond 300 km. Brazil, Germany, Iraq, and North Korea also appear to have potential cruise missile programs developing a variety of systems, most of shorter range. In addition, Russia exhibited several cruise missile designs in 1992 that could be developed for export, or even remanufactured by other countries to begin programs of their own.[99]

GUIDANCE SYSTEMS

Command guidance

Short range, radio-controlled command guidance systems are relatively simple to design. The Soviets have used command guidance from airplanes, and the United States has developed several such systems. (The Germans also experimented with radio-controlled command guidance in the V-2 ballistic missile.) Several short range ASCMs have also been equipped with TV terminal guidance. Such systems include Israel’s Gabriel II, Taiwan’s version of the same, called the Hsiung Feng I, and the U.S. Standoff Land Attack Missile (SLAM). However, the range of a command-guided system. is limited by that of the communication link. If a radio link is used, it is susceptible to jamming. And while launch from aircraft can extend the effective range of command-guided missiles, an escort aircraft must then remain within communication range of the missile.

Inertial guidance

Inertial guidance systems are one of the most mature navigation technologies used in ballistic and cruise missiles. They use gyroscopes and accelerometers to determine the missile’s orientation and its motion along a particular heading. All gyroscopes are subject to drift error, however, which accumulates guidance inaccuracy over time. Standard high-quality commercial aircraft systems, for example, have errors leading to CEPs on the order of 2 km per hour of flight.[100] (The MTCR prohibits exporting cruise-missile navigation systems that have accuracies better than 10 km on a 300-km course, unless part of manned aircraft.) To compensate for the drift error, systems can utilize externally supplied information to update inertial navigation systems.

TERCOM

Since the 1970s, the United States has been using an advanced guidance system known as TERCOM (Terrain Contour Matching) for guidance of long range cruise missiles. It operates by comparing the altitude profile of the ground under portions of the missile’s flight path with terrain maps stored in its computer database. TERCOM’s guidance computer makes course corrections based on differences between measured and expected altitude data. Between updates, the missile’s flight is usually controlled by an inertial guidance system.[101] However, since TERCOM relies on terrain variation, it is useless for guidance over water, and ill-suited to flat plains or deserts. Furthermore, because TERCOM requires accurate pre-determined terrain maps along the approach to a target-usually requiring advanced satellite techniques to produce—

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[99] Ibid., pp. 19, 21. Note that U.N. Security Council Resolution 687 prohibits Iraq from maintaining or developing missiles with ranges exceeding 150 km.

[100] See, for example, ‘‘Sagem Shifting to Systems Integration to Expand Role as Avionics Supplier,’ *Aviation Week & Space Technology,* May 11, **1992, p. 50.** Ring-laser and fiber-optic gyroscopes (the latter still under development) are capable of substantially greater accuracy, but their manufacture is limited to countries with the most advanced electronics industries.

[101] Details of the TERCOM *system are* given in John Toomay, ‘“lkchrdcal characteristics, ‘‘ in Richard Betts, cd., *Cruise Missiles: Technology, Strategy, Politics* (Washington, DC: The Brookings Institution, 1981), pp. 36-9. Conventionally-armed versions of the U.S. cruise missiles have a supplementary terminal guidance system known as Digital Scene Matching Area Correlation (DSMAC), which compares a visual image of the target with one stored in the missile’s computer memory.

developing nations have had little means by which to exploit this technology.[102]

NAVSTAR Global Positioning System

Provided a target's coordinates are known in advance, cruise missiles could use satellite navigation such as GPS (see box 5-C) to fly to a target by any route desired. Circuitous routes using a series of waypoints might be chosen, for instance, to avoid heavily defended areas.

Although the MTCR guidelines prohibit export of any GPS receivers that operate above 18 km altitude and 515 rn/see, or those *designed or modified for use in* ballistic missiles or cruise missile with ranges beyond 300 km, many exportable GPS receivers would still be cruise-missile *capable.* Moreover, export restrictions do not apply to GPS receivers for use in aircraft, and the electronic circuitry required to process GPS signals would not be difficult for many countries to duplicate or otherwise obtain.

A number of methods (e.g., differential GPS) have been developed to improve on the accuracy of the GPS signal available to civilian users, but these methods would not be necessary for delivering weapons of mass destruction.[103] For attacks with weapons of mass destruction against second-echelon forces massing behind front lines, or against ''soft' civilian targets or population centers, even the worst-case 100-m accuracy provided by the degraded commercial signal would be sufficient to result essentially in a direct hit.

The air- or ship-launched U.S. Harpoon *antiship cruise missile was first produced in 1977 and has been sold to 19 U.S. allies including Egypt, Iran, Pakistan, South Korea, and Saudi Arabia.*

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PROPULSION AND AIRFRAME TECHNOLOGY

Cruise-missile propulsion systems, like guidance systems, are also much more widely available than in the past. Unlike combat aircraft, whose weight and expense mandates large reusable engines, cruise missiles can use much smaller turbojet or turbofan engines. Such engines are now manufactured in over 20 countries.[104] Despite Russia's agreeing to abide by the Missile Technology Control Regime, the former Soviet Union may be a particularly good source of this technology, since the republics have yet to setup

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[102] Even if high-quality Stereographic images could be purchased from commercial satellite photographic services such as the French SPOT or U.S. Landsat, it is unlikely that sufficient altitude resolution could be obtained for use with TERCOM systems. At most, this imagery might help with terminal guidance if there were distinctive terrain features in the neighborhood of the target and if the cruise missile could be equipped with a radar altimeter.

[103] The GPS signal available to commercial users, known as the "Course Acquisition (C/A)" code, contains errors that have been intentionally introduced to degrade accuracy. Differential GPS uses a receiver whose location is accurately known to calculate these errors. This information can then be used to correct the positions of other receivers viewing the same GPS satellites. This method can be used to obtain dramatic improvements even relative to the accuracy available to military users, called the "P-code." Lee Alexander, "Differential GPS in Operation Desert Storm, " *GPS World, vol.* 3, No. 6, June 1992, p. 37. As such, it could be particularly useful in aiming ballistic missiles accurately toward their targets prior to launch, if other methods of doing so were not available. Other techniques for improving on the C/A code have also been developed.

[104] See Mark Lambert, cd., *Jane's All the World's Aircraft, 1990-91,* op. cit., footnote 93. Although small Jet engines are becoming more widely available, they are not required; even old propeller-piston engines could be used in some applications.

Box 5-C-Satellite Navigation Systems and GPS

Space-based navigation systems began their development in the United States and former Soviet Union in the early 1970s, and for a variety of applications can now offer precise navigation services at low cost. The most developed system is the U.S. NAVSTAR Global Positioning System (GPS), which will soon provide accurate position (latitude, longitude, and altitude)and velocity information to receivers anywhere in the world. The full GPS constellation will include 21 satellites plus three spares, and is scheduled to be operational by 1995.[1]

Using four atomic clocks, each GPS satellite continuously broadcasts its position relative to the center of the Earth along with the precise time. Using this data a receiver can compute its distance from each of the GPS satellites it can observe, and therefore its own position by triangulation. Receivers must have access to a minimum of three simultaneous satellite broadcasts to obtain latitude and longitude information; a fourth satellite is needed to add altitude information.[2] GPS offers the advantages of being unlimitedly range, cheaper than TERCOM, and more accurate than inertial navigation systems by themselves (GPS would normally be combined with an inertial navigation system).[3]

To deny use of GPS's full capabilities to adversaries, GPS satellites broadcast two signals-one intended for use only by authorized U.S. military receivers, known as P-code (Precision Service), and the other for civilian users, known as C/A-code (Coarse/Acquisition). P-code offers position information accurate to within approximately 10 to 15 meters. The accuracy of C/A-code varies depending on how the United States operates the system, but can be in the neighborhood of 30 to 40 meters. Since even 40 meter accuracy is more than the United States wants to provide adversaries during a crisis, the C/A signal can be degraded by a technique known as "Selective Availability," which introduces intentional errors into the code limiting it to 100-m accuracy.[4] Even so, this would be sufficiently accurate for most purposes involving weapons of mass destruction.

Since navigational data of the quality delivered by GPS has very high commercial value, an extensive market in GPS receivers has grown to meet commercial demand. Off-the-shelf GPS receivers are available for less than

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[1] As of December 1992, 19 satellites were deployed.

[2] Artur Knoth, "GPS Technology and Third World Missiles," *International Defense Review,* vol. 25, May 1992, p. 413. One more satellite signal is required than the number of coordinates sought, since the receiver must also calculate and remove the effects of its own clock error.

[3] For example, the U.S. Defense Department, which has developed and maintains GPS, will use the satellite system to supplement missile guidance in the new U.S. Standoff Land Attack Missile (SLAM), a variant of the Harpoon anti-ship cruise missile, and in planned upgrades to the land-attack version of the Tomahawk sea-launched wise missiles. See Eric Arnett, "The Most Serious Challenge of the 1990s? Cruise Missiles in the Developing World," in W. Thomas Wander and Eric Arnett, eds., *The Proliferation of Advanced Weaponry: Technology, Motivations, and Responses* (Washington, DC: American Association for the Advancement of Science, 1992). The French company Sagem will offer a plug-in upgrade to its inertial navigation systems to provide navigational updates from a 12-channel GPS receiver. It will also offer the Integrated GPS/Inertial system for sale. See "Sagem Shifting to Systems Integration to Expand Role as Avionics Supplier," *Aviation Week & Space Technology,* May 11,1992, p. 50; and Clifford Bed, "World In a Box: Air Navigation Leaps Forward," *International Defense Review, vol.* 25, May 1992, pp. 417-418.

[4] Note, however, that the quoted GPS accuracies pertain to the 95% confidence level, so that 100-m "accuracy" here could translate roughly into a 40 to 50-m CEP (50% confidence level). Sources on empirical GPS signal accuracy include Philip Klass, "Inmarsat Decision Pushes GPS to Forefront of Civil Nav-Sat Field," *Aviation Week & Space Technology,* Jan. 14, 1991, p. 34; Bruce D. Nordwall, "Flight Tests Highlight New GPS Uses, Emphasize Need for GPS/Glonass System," *Aviation Week & Space Technology,* Dec. *2,1991,* pp. 71-73; and Paul M. Eng, "Who Knows Where You Are? The Satellite Knows," Business *Week,* Feb. 10, 1992, pp. 120-121. To prevent unauthorized access to the P-code, the GPS system is capable of encrypting it, producing what is called the Y-code.

$500, and relatively expensive, multichannel sets that provide more frequent updates sell for less than $5,000.[5] Receiver prices are likely to continue to drop.

The U.S. Government recognizing the system's civil application, has promised to provide the C/A-code signal free of charge for a period of at least 10 years. Commercial users are also exerting considerable pressure on the U.S. Department of Defense to cease degrading the C/A signal. This pressure is likely to mount, particularly if GPS is widely adopted for use in international air-traffic control.[6]

Two other systems may offer navigational data in the future that can supplement that provided by GPS. The Soviet Union has begun to deploy a system somewhat comparable to GPS called Glonass (Global Navigation Satellite System), and the international satellite agency Inmarsat plans to add GPS-like signals to its third generation of satellites.[7] Combining data received from the three systems would allow increased accuracy and reliability y, including the capability for real-time verification of the integrity of individual satellite signals.[8]

The Glonass system, which would provide the same accuracy to all users, advertises plus-or-minus 17-m accuracy 50 per cent of the time, comparable to P-code GPS accuracy.[9] However, only about 8 of the first 32 *Glonass* satellites deployed are still in operation, and given the political situation in Russia, the system's fate is uncertain.[10]

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[5] Inexpensive single-channel receivers, more appropriate for boaters than for aircraft, must switch sequentially among four GPS satellites in order to compute position; multichannel receivers allow reception from more than one satellite at a time, which improves accuracy and update-speed. Receivers with 6 channels are widely available, and 12 channels can aiso be obtained. See Gordon West, "Navigation," *Motor Boating & Sailing,* voi. 168, No. 4, October 1991, pp. 65-77; and Jeff Hum, *GPS: A Guide to the Next Utility* (Sunnyvale, CA: Trimble Navigation, 1989).

[6] See Philip J. Klass, "FAA Steps Up Program to introduce GPS as instrument Approach Aid," *Aviation Week & Space Technology,* Aug. 17, 1992, p. 38.

[7] See, for example, Klass, "Inmarsat Decision. . .", op. dt., footnote 4, p. 34. One reason for Inmarsat's decision to provide satellite navigation is concern that the United States may not continue to provide GPS services.

[8] Simultaneous access to five broadcasting satellites is sufficient to detect whether one of the satellites is malfunctioning, but six signals are needed to identify which one is in error. When the GPS constellation is complete, however, there should be enough satellites at any time in one's line-of-sight that this should not present a problem. See Bruce D. Nordwall, "Flight Tests Highlight New GPS Uses, Emphasize Need for GPS/Glonass System," *Aviation Week & Space Technology, Dec. 2, 1991,* p. 71.

[9] Artur Knoth, "GPS Technology and Third World Missiles," Op. dt, footnote 2, P. 414.

[10] Klass, "Inmarsat Decision. . .", op, cit., footnote 4, p. 35.

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an effective system of export controls.[105] Moreover, Ukraine, which holds a substantial fraction of the former Soviet Union's military aerospace industry,[106] has not yet agreed to abide by MTCR constraints, Antiship cruise missiles (ASCMs) purchased from Russia or elsewhere could also provide a proliferant country with engines suitable to power its own airframes up to perhaps a few hundred kilometers. ASCMs are widely available and, due to their short range, are generally exempt even from the new MTCR restrictions.

Nevertheless, very small, lightweight, and fuel-efficient engines, which are particularly important for longer range or stealthy cruise missiles, are still very difficult for proliferant countries to acquire.

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[105] See, for example, William C. Potter, "Exports and Experts: Proliferation Risks from the New Commonwealth,'' *Arms Control To&y,* vol. 22, No. 1, July/August 1992, pp. 32-37; and Jeffrey M, Lenorovitz, ''Russian Engine Firms Strive to Realign, ' *Aviation Week & Space Technology,* March 30, 1992, pp. 38-9.

[106] See, for example, Central Intelligence Agency, Directorate of Intelligence, "The Defense Industries of the Newly Independent States of Eurasia, " OSE 93-10001, January 1993, p. 7.

Airframes are probably the easiest part of cruise missiles to produce indigenously. Unlike combat aircraft, cruise missiles need only fly once, lessening the requirements for fatigue-resistant materials. They are also smaller, mostly subsonic, and need only accelerate modestly, thus avoiding the need for the type of high-strength or specialized materials typically found in ballistic missiles and reentry vehicles.[107] Unless high-speed maneuvers are required, cruise missiles and UAVs can more easily use light-weight or even radar-absorbent materials that would not ordinarily stand up to great aerodynamic stresses.[108] And since they require no cockpit or features to protect a pilot, they can be built much more cheaply and with smaller radar cross-sections than can piloted aircraft.

In sum, any country that supports an aerospace industry or has a modest industrial infrastructure should be able to integrate commercially available GPS receivers, turbojet engines taken from imported ASCMs, and indigenously built composite airframes to build its own cruise missiles. If launched from manned aircraft, the effective range of such cruise missiles could be increased substantially. Harder, though, would be to build cruise missiles with ranges far exceeding 300 km (carrying 500 to 1,000-kg payloads) or long range cruise missiles with low-observable (stealthy) technology.

OPERATIONAL FACTORS

To remain undetected by air defenses, cruise missiles can be made to fly at very low altitudes, exploiting the natural radar cover offered by reflections off trees, buildings, hills and other features of the terrain.[109] (Other techniques for increasing the probability of penetrating defenses include stealth technologies, supersonic speeds, or high-altitude approaches that might be detected but not easily engaged by air defense systems. U.S. and Soviet systems have incorporated a number of these techniques.) Low flight, however, increases the risks of crashing and sacrifices fuel efficiency.[110] Look-ahead radars and maneuverability can lessen the risk of crashes, but their weight will decrease a cruise missile's range, and their signal may help defenses locate them. These also require fairly sophisticated guidance and control technologies.

Early generation land-attack cruise missiles were particularly vulnerable to defenses, as demonstrated by the largely unsuccessful attempt by Egypt to use them against Israel in the Yom Kippur War of 1973. To saturate air defenses and increase the probability of key weapons getting through, a state may therefore wish to accompany a few cruise missiles carrying weapons of mass destruction with a large number of decoys. But such tactics would only be needed when attacking defended areas. The number of cruise missiles needed for guaranteed penetration would thus be highly scenario-dependent.[111]

The GPS system was designed to operate with completely passive receivers, obviating the need to send any signal back to the satellites. Receivers can therefore operate undetected. However, since GPS radio signals can be weak even compared with background noise levels, in theory they can

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[107] This advantage is less salient in cruise missiles designed for underwater launch from submarines, because the stresses inherent in changing pressure environments during flight require stronger materials.

[108] Sir Michael Armitage, *Unmanned Aircraft, Brassey's Air Power, Volume 3* (London: Brassey's Defense Publishers, 1988), p. 121.

[109] See William E. Dean, *How Low Can an Unmanned Aerial Vehicle Fly?*, RAND Paper P-7680-RGS (Santa Monica, CA: RAND Graduate School, October, 1990).

[110] The air-breathing engines used in most cruise missiles function more efficiently at higher altitudes, where the less dense air reduces both the drag on the airframe and the quantity of fuel necessary for efficient combustion.

[111] See, for example, Charo, *Continental Air Defense*, op. cit., footnote 95.

be jammed, at least for short periods of time.[112] (Between GPS updates, or if jammed, a cruise missile would have to fly using an inertial system.) Although all GPS satellites broadcast on the same frequency, each Glonass satellite broadcasts at its own frequency, and Inmarsat satellites will provide still more frequencies,[113] thus making it difficult to jam the entire future suite of satellite navigation signals. Furthermore, an incoming cruise missile must be detected ahead of time in order for jamming attempts to be activated.

At least for short range missile guidance, fiber-optic technology may also take on an increasing role in the future. The United States and Brazil have developed systems that connect antitank and antihelicopter missiles to controllers at distances up to 15 km. These systems use fiber-optic cables that spin off the end of a reel when the missile is launched.[114] Although optic cables can transmit signals over hundreds of kilometers without serious distortion, in practice these systems would probably be limited to about 100 km or less.[115] At such ranges, much simpler command-guidance systems are also available.

| Availability of Cruise Missiles and UAVs

No *land attack* cruise missiles are known to have been exported by the principal exporters of cruise missiles (the five acknowledged nuclear powers and Italy), and there is little reason to believe that these will be exported in the future.[116] Furthermore, no potential proliferant state is publicly known to have developed or acquired cruise missiles for the purpose of delivering weapons of mass destruction. Still, acquisition by such countries cannot be ruled out. Many of the components and technologies for producing cruise missiles fall outside of MTCR constraints, or can be obtained by converting civil systems, cannibalizing readily available ASCMs, or purchasing cruise missiles from non-MTCR suppliers.

ANTISHIP CRUISE MISSILES

The effectiveness of ASCMs frost gained notoriety in 1967, when Soviet-built Styx antiship missiles launched by Egypt sank the Israeli destroyer *Eilat.* More recently, incidents involving ASCMs drew worldwide attention when French-built *Exocet missiles* destroyed the HMS *Sheffield in the 1982* Falklands War and damaged the USS *Stark in 1987 in the* Persian Gulf.

Although only 11 countries have designed and produced ASCMs indigenously, ASCMs can

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[112] The ability to jam GPS signals is still the subject of some debate. Directional antennas designed to receive GPS signals from above may be less susceptible to jamming. Edward R. Harshberger, Long *Range Conventional Missiles: Issues for Near-Term Development, RAND* Note N-3328-RGSD (Santa Monica, CA: RAND Graduate School, 1991), p. 105. Furthermore, the nature of the signals broadcast by GPS satellites should make it possible using special signal-processing techniques to distinguish even very weak broadcasts from background noise or from powerful jamming signals, making GPS "a very hardy system." Jeff Hurn, *GPS: A Guide to the Next Utility (Sunnyvale,* CA: Trimble Navigation, 1989), p. 8.

[113] Philip Klass, "Inmarsat Decision Pushes GPS to Forefront of Civil Nav-Sat Field," *Aviation Week & Space Technology,* January 14,1991, p. 34.

[114] The U.S. Navy is also experimenting with air-launched, fiber optically-guided antiship cruise missiles. "U.S. Navy Tests Fiber-Optic Data Links for Air-Launched Weapons," *Aviation Week & Space Technology,* June 12, 1989, pp. 275-8.

[115] Hughes representatives indicated in a statement quoted in "U.S. Navy Tests Fiber-Optic Data. . .," ibid., that a 100-km range is near the limit for these systems. See also Carl White, "Light Fantastic: Fiber Optics: The Core of High-Tech Programs," *Sea Power, vol.* 34, *Mar@* 1991, p. 28.

[116] W.Seth Carus, *Cruise Missile Proliferation in the 1990s* (Washington, DC: Center for Strategic and International Studies, 1992), p. *32.*

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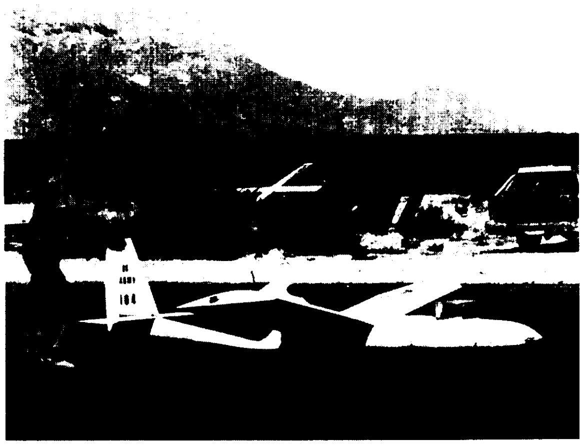
First produced around 1980, the Chinese Silkworm *liquid-fueled rocket-powered antiship cruise missile has been exported to Egypt, Iran, Iraq, and Pakistan, and is coproduced under license in North Korea.*



WARREN WEAVER, U.S. ARMY

A remotely piloted vehicle ready for testing at White Sands Missile Range, NM. This ground-controlled fixed wing vehicle with a cruising speed of 60 knots is designed to carry sensors. It is not a weapon system and is not designed to penetrate defenses. However, similar vehicles might be adaptable for weapon purposes, for example, for biological attacks against undefended targets.

readily be purchased.[117] They have consequently proliferated even more widely than ballistic missiles, with over 40 Third World countries now operating them.[118] Three systems in Particular have been widely exported: the Chinese *Silkworm* (95 km/510 kg); the Soviet Styx (80 km/500 kg); and the French *Exocet* (65 km/165 kg). Other systems exported to Third World countries include the British *Sea Eagle,* Israeli *Gabriel I/II,* Italian *Otomat,* and U.S. *Harpoon (see* table 5-11). Of these, the *Otomat* and *Harpoon* have the longest ranges, at 180 km and 220 km, respectively, but still fall short of the MTCR threshold.

Many ASCMs rely on active radar or infrared homing devices for terminal guidance against ships on the open ocean, which stand out readily from their surroundings. As such, ASCMs would not be very useful for land attacks except against distinctive short range targets. To give ASCMs a true land-attack capability, their homing systems would have to be replaced or supplemented by another type of guidance.[119]

Nevertheless, most ASCMs also use a rudimentary inertial-guidance system to navigate into the vicinity of a target that would be transferable

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[117] The 11 countries with indigenous cruise-missiles are the five declared nuclear powers plus Germany, Israel, Italy, Japan, Norway, and Sweden. Six other countries either currently manufacture ASCMs based on another country's design or have their own systems under development: Brazil, India, Iraq, North Korea, South Africa, and Taiwan. Cams, *Cruise Missile Proliferation in the 1990s,* ibid., pp. 34, 126-133 (table B-4); and Duncan Lennox and Arthur Rees, eds., *Jane's Air-Launched Weapons (Surrey, UK:* Jane's Information Group, 1990), Issues 8 and 9.

[118] Carus, *Cruise Missile Proliferation in the 1990s,* op. cit., footnote 116, p. 34. Even though many ASCMs cost more than a half million dollars apiece, there has been considerable interest among Third World countries in purchasing ASCMs.

[119] The United States developed the Standoff Land Attack Missile (SLAM) by replacing the seeker of the Harpoon ASCM with a television terminal guidance system. Other countries that would likely be able to replace a traditional ASCM seeker with TV guidance include Israel, India, South Africa, Taiwan, and possibly South Korea. Carus, *Cruise Missile Proliferation in the 1990s,* op. cit., footnote 116, p. 131.

Table 5-1 I—Selected Cruise Missiles and their Characteristics

Designation	Range [km]	Payload [kg]	Comment
ASCM Systems not exceeding the 1987 MTCR threshold of 300 k&500 kg:			
British Sea Eagle	110	230	1985; turbojet; exported to Germany, India
Chinese HY-2 (Soviet SS-N-2 derivative)	95	510	+1980; "Silkworm"; liquid-fuel rocket-powered; exported to Egypt, Iran, Iraq, Pakistan, and co-produced under license in DPRK
Chinese HY-4	135	500	late 1980s; turbojet
French Exocet	65	165	1979; solid-rocket powered; widely sold; operated by over 25 countries
German Kormoran 2	55+	220	1993; air-launched, rocket powered; operated only by Germany and Italy
Israeli Gabriel Mk-II	40	180	1976; solid-rocket powered; licensed variants produced in Taiwan and South Africa; exported to Chile, Ecuador, Kenya Singapore, Thailand
Israeli Gabriel Mk-IV	200	1 50+	1993?; turbojet (under development)
Italian Otomat Mk-II	180	210	1984; turbojet; European consortium; exported to Egypt, Iraq, Kenya, Libya, Nigeria, Peru, Saudi Arabia, and Venezuela
Japanese SSM-1	150	250	1988; turbojet; land-, ship-, or submarine-launched
Norwegian Penguin Mk-III	40+	120	1987; solid-rocket powered; exported to Greece, Turkey, Sweden, and United States
Soviet SS-N-2C	80	500	1962; "Styx"; liquid-rocket powered; exported to Algeria, Angola, Cuba Egypt, Ethiopia, Finland, India, North Korea, Libya, Somalia, Syria, Vietnam, Yemen, Yugoslavia; licensed production in Iraq
Soviet AS-5	230	1000	1966; liquid-rocket powered; "Kelt"; past exports to Egypt and Iraq; may exceed MTCR limits; land-attack and ASCM capability
Swedish RBS-15	70-150	250	1989; turbojet; exported to Finland, and possibly to Yugoslavia
Taiwanese Hsiung Feng-2	80-180	75?	1993?; turbofan?; (pre-production development)
U.S. Harpoon	120-220	220	1977; turbojet; air- and sea-launch platforms; sold to 19 U.S. allies including Egypt, Iran, Pakistan, South Korea, and Saudi Arabia; land-attack version (SLAM) has shorter range and television terminal guidance
Selected longer range cruise missiles (restricted from export by MTCR guidelines):			
Soviet SS-N-3	460	1000	1963; turbojet; "Shaddock"; strategic/anti-ship; launched from land, surface ships, and surfaced submarines; sold to Syria and Yugoslavia
Soviet AS-6	560	1000	1973; solid-rocket powered; "Kingfish"; Mach 3.5; land-attack capability; can be nuclear-armed
Soviet SS-N-21	3000	300	1987; turbofan; "Sampson"; nuclear-armed
U.S. Tomahawk	480-1250	450	1983; turbofan; HE warhead; 2500-km range with 300-kg payload
U.S. ACM	3000	?	1992; nuclear-armed; stealthy; air-launched

SOURCE: W.Seth Carus, *Cruise Missile Proliferation in the 1990s* (Washington, DC: Center for Strategic and International Studies, 1992); *Jane's A/rLaunched* Weapons, Issue 09, and *Jane's Strategic Weapons Systems,* Issue 07 (Surrey, U.K.: Jane's Information Group Limited, 1992); and James G. Roche, Northrop Corp., "Tactical Aircraft, Ballistic and Cruise Missile Proliferation in the Developing World, " paper presented at the AAAS conference *Advanced Weaponry in the Developing World,* Washington, DC, June 12, 1992.

to other platforms and missions. Systems such as the Israeli Gabriel II, which has been exported to several Third World countries (see table 5-1 1), use TV-terminal guidance and can therefore be used against land targets. Furthermore, typical ASCM payloads of 100 to 500 kg (sufficient for many types of high-explosive armor-piercing warheads) would be sufficient to carry biological agents or modest amounts of chemical agent. Soviet export models and some ASCMs copied by other countries have payloads of 500 to as much as 1,000 kg, which may be sufficient to carry proliferant nuclear warheads.[120]

UNMANNED AERIAL VEHICLES

An alternative to developing or modifying cruise missiles would be to purchase commercially available unmanned aerial vehicles (UAVs). Modern over-land UAVs are used in a wide variety of roles around the world, and could be purchased under the guise of surveillance for fighting drug trafficking,, forest fires, or illegal immigration. A state could then disassemble them for parts or mod@ them for weapon-delivery.[121] UAVs or "target drones" could also be made from expendable auto-piloted aircraft programmed for one-way missions.

UAVs offer many of the characteristics of cruise missiles.[122] However, most of them do not have suitable payload or range to be useful for carrying weapons of mass destruction. For instance, many are intended for short range reconnaissance missions, carrying sensor-payloads of 20 to 40 kg to ranges of less than 100 km.[123] Others are designed as target or harassment drones or for long endurance flight, but with payloads well under 100 kg. Nevertheless, longer range systems able to carry several hundred kilograms to ranges of several hundred kilometers have been designed in recent years by a number of companies.[124]

One example is the Teledyne-Ryan Model 350, built under contract in the United States as a surveillance platform. This UAV has a wingspan and length of only 3.2 m and 5 m, respectively, making it hard for enemy air defenses to detect.[125] Its turbojet engine can achieve speeds of Mach 0.9 and carry a 146-kg payload to a range of 1,500 km and back. It is based on an earlier model (Model 324, or "Scarab") sold to the Egyptian armed forces in 1988 for reconnaissance purposes.[126] Although the Scarab can carry 113 kg to a range of 1,000 km and back, it could not carry payloads exceeding the 500 kg MTCR threshold without substantial redesign and in-field modification. Its

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[120] Both the United States and the former Soviet Union have produced *nuclear-armed* ASCMs for their own fleets, but each has now committed to removing them.

[121] The most successful combat use of UAVs by developing countries was in the 1982 Israeli action against Syrian air defenses in the Bekaa Wiley in Lebanon. There, Israeli- and U.S.-designed UAVs were used for both reconnaissance and harassment. UAVs caused Syrian SAM air-defense batteries to trigger their fire control radar, leaving the SAMS open to Israeli anti-radiation missiles without exposing Israeli aircraft to the air defenses. The Syrians lost 19 out of 20 SAM batteries and 86 combat aircraft, while Israel lost one combat aircraft. Sir Michael Armitage, *Unmanned Aircraft, Brassey's Air Power, Volume 3,* op. cit., footnote 108, pp. 85-6.

[122] For training, in fact, some UAVs are specifically designed to mimic the characteristics of cruise missiles. Don Flamm, "Defense Technology: Unmanned Aerial Vehicles," *Asian Defense Journal,* August, 1991, p. 27.

[123] See, for ~-pie, E.R. Hooton and Kenneth Munson, eds., *Jane's Battlefield Surveillance Systems, 3rd edition, 1991-92* (Surrey, UK: Jane's Information Group, 1991).

[124] Stefan Geisenheyner, "Current Developments in Unmanned Aerial Vehicles," *Armada International,* vol. 14, October/November, 1990, pp. 78-80.

[125] Technical data for the Model 350 is taken *from Jane' s Battlefield Surveillance Systems,* op. cit., footnote 123, p. 229; and Geisenheyner, "Current Developments in Unmanned Aerial Vehicles," op. cit., footnote 124, pp. 80-3.

[126] The Scarab is built almost entirely of low radar-cross-section Kevlar-epoxy composites and can be programmed for long range guidance using a satellite navigation system and up to 100 waypoints. Don Flamm, 'Defense Technology: Unmanned Aerial Vehicles,' op. cit., footnote 122, p. 28.

export to Egypt was only approved by the United States subject to a U.S.-Egypt bilateral agreement *restricting* its use to reconnaissance within Egypt, forbidding modification, and giving the United States the right to inspect the inventory on short notice.[127]

Other examples of UAVs that could be given ground-attack capabilities include indigenously produced target drones or small RPVs built by Argentina, India, Iran, and Iraq.[128] Many of these have payloads well under 100 kg, however.

| Monitoring Cruise Missile Acquisition

Given the number of options available for their acquisition, cruise missiles will be extremely difficult to monitor in the developing world. Some cruise-missile related technologies-for example, GPS receivers—have so many legitimate uses that commercial sales receive little notice. Even UAV systems that require export notification or licensing have both civilian and military uses completely unrelated to the delivery of weapons of mass destruction, and whose promotion may well be in the interest of the exporting nation.

Indigenous production or cannibalization of ASCMs to acquire cruise missiles would be difficult to detect.[129] Although flight tests would certainly be required, cruise missiles have few readily identifiable inflight observables; they expel only modest amounts of heat and remain well within the atmosphere. Low-flying cruise missiles are difficult to detect even in wartime, when airspace is carefully monitored, illustrating the difficulty of detecting covert tests. The proliferation of at least short range cruise missiles could therefore prove to be an intractable problem over the next decade or so. Fortunately, longer range land-attack systems are not yet available to proliferant countries and are still amenable to some measure of control through the MTCR.

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[127] Major Patrick Michelson, Egypt country director, Office of the Secretary of Defense, private communication, June 2, 1993.

[128] Roche, "Tactical Aircraft. . .," op. cit., footnote 93, p. 11.

[129] See, for example, U.S. Congress, Office of Technology Assessment, *Monitoring Limits on Sea-Launched Cruise Missiles*, OTA-ISC-513 (Washington+ DC: U.S. Government Printing Office, September 1992), pp. 11,21.

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