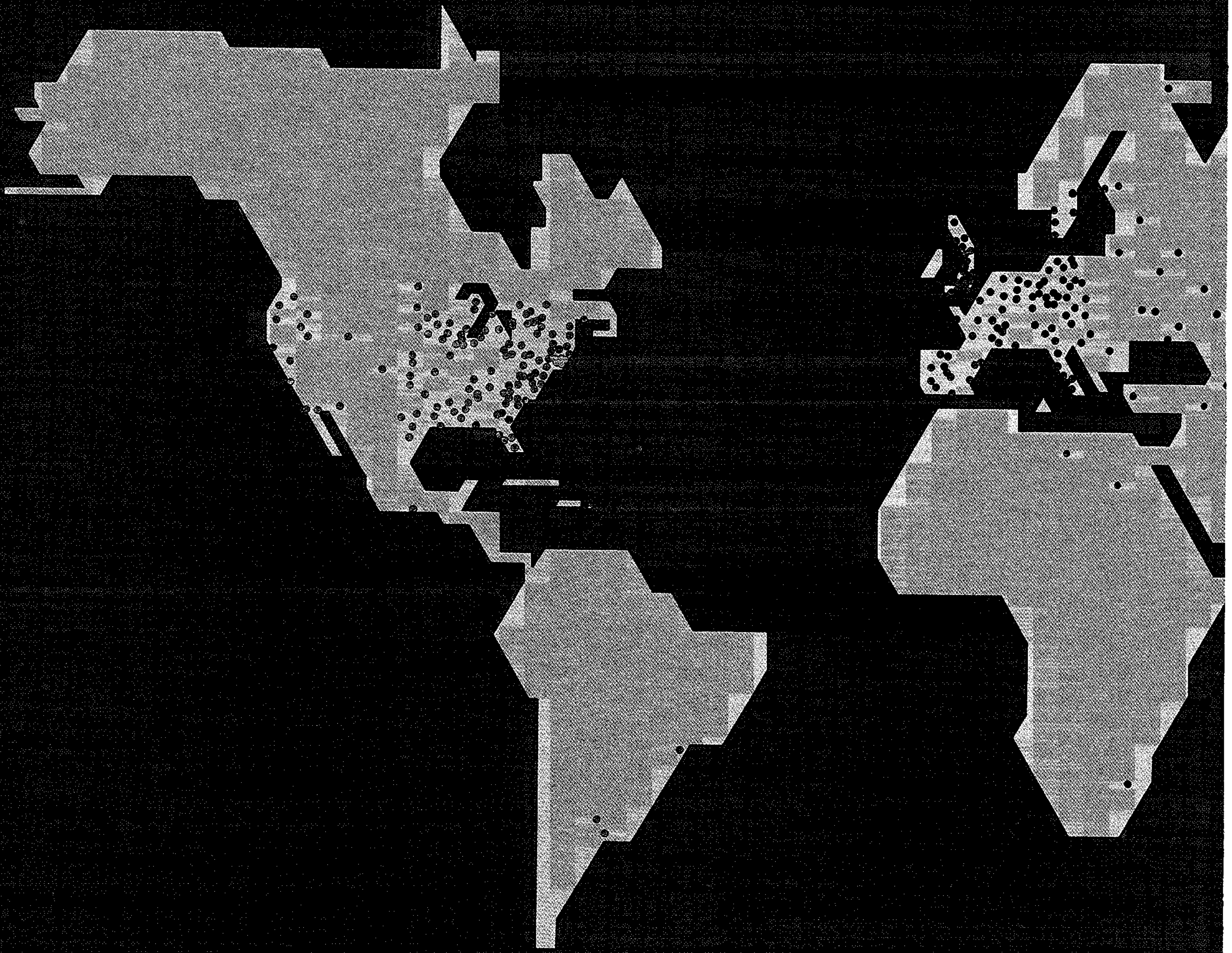
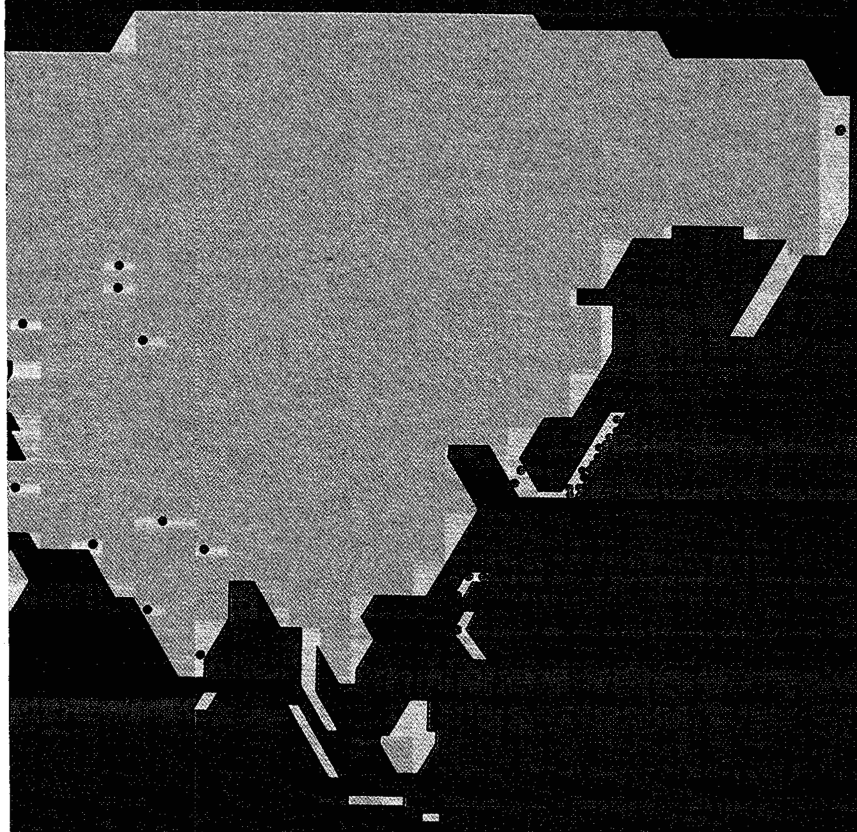
Nuclear Safeguards—



A Global Issue

by G. Robert Keepin



The location of nuclear power plants, operating, under construction, and planned. Of the 530 units worldwide, 341 are outside the United States; about 230 plants are in operation.

Since the dawn of the nuclear age man has experienced varying degrees of both optimism and apprehension about the use and misuse of nuclear energy. This awesome form of energy has provided both an abundant and beneficial source of energy and unprecedented capability for destruction. This basic duality is the driving force behind the unsettled, and still evolving, politics of nuclear energy.

Immediately after World War II, there was hope that placing all nuclear activities under international ownership and management would prevent the proliferation of nuclear weapons. In 1946, the Baruch plan proposed the creation of an international atomic development authority, to be entrusted with all phases of the development, use, inspection, and control of nuclear energy. The plan delineated the need for restraint in nuclear-weapon development and for international safeguards and penalties to prevent diversion of nuclear materials from civilian nuclear power programs. It also proposed that all nations forego the production and possession of nuclear weapons. Although many elements of the Baruch plan were eventually incorporated into international safeguards, in its time the plan was rejected and by 1952, three nations had produced nuclear weapons. Secrecy became the fundamental nuclear policy of the United States and other nations. By the early 1950s, many nations were seeking ways to acquire nuclear technology benefits and to develop their own nuclear energy programs. This activity had an inherent potential not only for peaceful uses but also for military applications. The situation clearly called for renewed attempts to arrive at some form of international understanding, consensus, and constraint.

President Eisenhower's 1953 proposal, the widely hailed "Atoms for Peace" program, marked a fundamental change in US nuclear policy. The program was designed to promote international cooperation in the peaceful uses of nuclear energy and, at the same time, to establish international controls to ensure that the products of this cooperation would not be diverted to military uses.

The Atoms for Peace program was adopted as part of the Atomic Energy Act of 1954. This federal legislation also authorized private ownership of nuclear materials and facilities in the United States and signalled the start of rapid development of nuclear power programs, both domestically and internationally. In 1955, the first United Nations Conference on the Peaceful Uses of Atomic Energy assembled in Geneva, Switzerland. Here, for the first time, scientists from the West and the East met to discuss the technical problems of nuclear energy.

I recall clearly that many of us in the US delegation to the Geneva Conference were filled with a sense of history, and some amazement too, at the open reporting of previously restricted information on fuel-cycle processes and plant operations. Nearly every day, after late-night meetings of the US delegation at the headquarters Hotel du Rhone, we saw new areas of cross-section and fission process data declassified and released to the public. During this historic and unprecedented conference, I could not help but remember my earlier days as a University of Chicago freshman. There, on the way to our freshman calisthenics class under the West Stands of the football stadium, we would occasionally pick up black dust on the soles of our tennis shoes as we passed a sealed-off, heavily guarded area posted with the following warning: US Government Metallurgical Project—Keep Out. As I was to learn years later, the black dust was graphite, the neutron slowing-down or "moderator" material used by Enrico Fermi and his coworkers to achieve the world's first self-sustaining fission chain reaction on December 2, 1942. To me, the unprecedented open spirit of international cooperation that marked the first Geneva Conference was in stark contrast to the wartime secrecy that had of necessity characterized nuclear activities just 13 years earlier in Chicago.

The International Atomic Energy Agency (IAEA), a cornerstone of the Atoms for Peace implementation, was created in 1957 to focus on the promotion and control of the peaceful uses of nuclear energy. From the standpoint of politics and economics, Eisenhower's Atoms for Peace program was more acceptable and far more feasible to implement than the Baruch plan because it did not call for international ownership and management of sensitive nuclear activities. Instead, it proposed a system of *nationally* owned and operated nuclear programs under *international* (IAEA) safeguards inspection and control. Two years before the creation of the IAEA the United States had begun implementing the Atoms for Peace program through "bilateral agreements." Under these agreements the United States provided other nations with nuclear reactors, enriched nuclear fuel, and technical assistance in the development of their civilian nuclear programs. In exchange, these nations accepted bilateral safeguards to ensure the peaceful use of the material and assistance. The United States administered and inspected these safeguards. Establishment of the IAEA in 1957 provided a more acceptable and effective framework for the administration of safeguards agreements than had been possible under the strictly bilateral agreements.

The IAEA's two basic objectives are simple and direct:

The Agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world. It shall ensure, so far as it is able, that assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose.

Throughout the 1960s, peaceful nuclear energy programs flourished in many countries because supplier nations, including the United States, offered an extremely attractive, long-term source of nuclear fuel, to discourage the development of other supply sources.

Independently of this peaceful development, France and the People's Republic of China developed and tested nuclear weapons during this period: France in 1960 and China in 1964. These events increased concerns about nuclear weapon proliferation—both the further build up within nuclear-weapon nations and the possession by new nations. In the mid-1960s, intensified efforts to reduce the risk of proliferation culminated in the 1970 Treaty on the Nonproliferation of Nuclear Weapons (NPT), drafted and signed by the United States and the Soviet Union. Nonnuclear-weapon nations that ratify this treaty give up the option to develop nuclear weapons and agree to submit all their nuclear activities to international (IAEA) inspection in exchange for the right to engage in peaceful nuclear activities with the cooperation of the nuclear-weapon nations.

One concept in international relations introduced by the NPT was unprecedented: participating nations committed themselves to international inspections within their boundaries, thereby yielding part of their national sovereignty to an international authority. During NPT negotiations, one concern of the nonnuclear-weapon nations was that applying international safeguards to their activities, and not to comparable activities in the nuclear-weapon nations, would work to their disadvantage in the competitive marketing of peaceful nuclear energy. This problem was partially resolved when the United States and the United Kingdom, by volunteering to place their peaceful nuclear facilities under IAEA safeguards, put both weapon and nonweapon nations on an equal footing. At present, 116 nations, including 3 having nuclear weapons, are parties to the NPT; and 61 nonnuclear-weapon nations have concluded the required safeguards agreements now in force with the IAEA.

The bases for international safeguards on proliferation and diversion of nuclear materials are the NPT, and the IAEA safeguards and inspection system. Other instruments and activities playing a role include the 1967 Treaty for the Prohibition of Nuclear Weapons in Latin America, known as the Treaty of Tlatelolco; the 1976 Nuclear Suppliers Agreements, the so-called "London Club"; and the Nuclear Non-Proliferation Act of 1978.

In the mid-1970s, a broad re-examination of the policies and practices underlying the NPT was undertaken. The re-examination stemmed in part from India's nuclear explosion in 1974 and in part from the concern that the worldwide growth of nuclear power and the reprocessing of spent fuel would make available large quantities of plutonium. Rightly or wrongly, many persons believe that the step from available plutonium to a nuclear weapon is relatively short. This belief leads in turn to the question of whether safeguards inspection and detection systems can provide "timely warning" of plutonium diversion in one nation quickly enough for the international community of nations to take necessary diplomatic actions, including possible sanctions. This line of reasoning resulted in the conclusion that an unacceptable risk of proliferation exists even if the safeguards system could detect diversion at the moment it occurs, and led to the new US position, announced by President Carter in April of 1977. The new position has deferred breeder reactor development, the reprocessing of spent fuel, and the so-called plutonium economy until after evaluation of alternative fuel cycles by the 66-nation International Nuclear Fuel Cycle Evaluation (INFCE) study. After 2 years of extensive effort, the final INFCE report was published in March 1980. Although there are many differences among the INFCE participating nations, a significant degree of consensus was reached on the future directions of nuclear energy. Recognizing the worldwide growth of nuclear energy, the INFCE final summary report calls for continued development of nuclear energy under strengthened nonproliferation measures, and for specific endorsement of plutonium, properly safeguarded, as an important fission energy resource for the future. It was further recognized that countries with large electrical power grids, limited uranium resources, and appropriate experience in nuclear technology will be employing the plutonium-burning fast breeder reactor; accordingly the INFCE report calls for placing the associated sensitive fuel-cycle materials under the most highly effective safeguards and nonproliferation measures.

LASL's Safeguards Program

The safeguards program began at the Los Alamos Scientific Laboratory (LASL) in 1966, at a time when nuclear power programs were expanding in the United States and several other industrial countries at an unparalled rate. After 2 years with the IAEA Headquarters Staff in Vienna, I became convinced of the coming importance—both politically and technically, of the worldwide nuclear safeguards problem. I returned to the United States in late 1965 equally convinced that LASL should launch a vigorous program to develop new nondestructive assay (NDA) techniques and instruments that would in time provide the technical basis for meeting the increasingly stringent safeguards requirements that were inevitable. Following a lengthy series of briefings, hearings, button-holing, and budget reviews with the Atomic Energy Commission (AEC) and the Congressional Joint Committee on Atomic Energy, the nation's first safeguards research and development program was funded and launched at LASL. The program began in a small laboratory at Pajarito Site; as the program grew, this was augmented a year later by the addition of a second, larger laboratory at Ten Site. Six months after the LASL program was launched, the AEC in Washington established the Office of Safeguards and Materials Management as well as a Division of Safeguards in the AEC Regulatory Branch. The Regulatory Branch is now the Nuclear Regulatory Commission (NRC).

Typical of new projects in their early stages, the new safeguards staff at LASL was highly enthusiastic and dedicated to the challenge before us. The LASL Safeguards program got off to a head start in the safeguards field with a commanding lead that I believe has been retained ever since. With the encouragement and cooperation of Dick Baker, Chemistry-Materials (CMB) Division Leader at the time, and the patient tolerance of Bill Maraman and his Plutonium Chemistry and Metallurgy Group, a special technical liaison committee was set up in 1967 between safeguards researchers and the CMB staff. The committee identified needed applications of newly developed NDA technology to materials measurement, accountability, and safeguards problems. Such problems were not uncommon in the materials processing, fabrication, and recovery operations carried out routinely at the CMB plutonium facility. Through the years, the close liaison between safeguards researchers and the CMB staff has contributed significantly to LASL's leadership position in US and international safeguards technology and to LASL's designation as the Department of Energy's (DOE) lead laboratory in safeguards material accountability and control research and development.

Today, the LASL safeguards program encompasses all aspects of the design, development, testing, and in-plant evaluation of new techniques, instrumentation, and integrated systems for safeguarding fissionable materials in all types of civilian and national defense nuclear facilities. These activities involve over 150 staff and support persons mainly concentrated in 7 technical groups: Safeguards Technology, International Safeguards and Training; Detection, Surveillance, Verification and Recovery; Safeguards Subsystems Development and Evaluation; Integrated Safeguards Systems and Technology Transfer; International Safeguards; Analytical Chemistry; and Computer and Telecommunications Security.

Safeguards Objectives—Domestic and International

From the beginning of the US nuclear program, nuclear materials and facilities—in both civilian power and defense-related activities—have been recognized as potential targets for theft, diversion, extortion, and sabotage. Accordingly, a substantial national program of safeguards and security was established early on and has been operational ever since. The goal of the national system is to protect nuclear material in facilities and in transit from subnational threats, such as overt attack by an armed group; from diversion, theft, or other unauthorized activity by facility employees; or from a combination of these "external" and "internal" threats. An external threat—for example, an overt attack by 4 to 8 adversaries armed with automatic weapons, the hijacking of a shipment, or sabotage—is countered by physical protection measures. The more subtle internal threat—covert diversion or theft of nuclear materials—is countered by materials accountability and control systems together with appropriate containment and surveillance measures.

In practice, an integrated system of materials accountability and control together with physical protection is structured to provide, for a given facility, a high-confidence, defense-in-depth safeguards and security system. The record speaks well for the effectiveness of US operational safeguards and security. According to a 1980 Rand Corporation document on threat analysis:

No nuclear installations in the United States have been attacked, seized, or sabotaged in a manner that caused public risk by release of radioactive materials. No nuclear weapons have been stolen or illegally detonated. No nuclear materials have been diverted or taken by force from installations or while in transit and used for blackmail or made into bombs. No radioactive matter has been maliciously released, endangering public safety.

The document also states that, although threats have been made to use nuclear materials, all but one proved to be hoaxes. In the one exception low-enriched uranium was removed from a facility, but was recovered within 3 days, and the thief was apprehended. A few cases of minor sabotage have occurred in the United States and occasional incidents of sabotage or attempted sabotage at nuclear facilities in other countries have been reported in the international press.

Physical protection measures include fences, alarms, the prohibition of unauthorized vehicles, random searches of packages or containers entering secured areas, written records of visitors, DOE clearance requirements, portal monitors to detect illicit movement of nuclear material, dual communications systems for protective force personnel, and response force procedures. Operational procedures, such as the two-man rule, requiring the presence of two cleared persons for access to nuclear materials; special training in emergency procedures; and drills and operational tests of system effectiveness, further support and strengthen the physical protection measures.

NRC regulations for civilian facilities and DOE regulations for government facilities implement material accountability and control in the United States. Under these regulations, measurement and control of special nuclear materials (SNM), such as plutonium and ^{235}U, are typically required to be better than 1%. The control requirement for reactor fuel fabrication plants, for example, is to within 0.5% of plant throughput. For plutonium and highly enriched uranium (enriched to 20% or more in ^{235}U), physical inventories are typically required at bimonthly intervals and/or semiannual intervals. Physical inventories are based on measurements of all material categories including difficult-to-measure scrap and waste, but excluding certain categories of sealed containers and storage vaults. In addition, control and accountability procedures and records must be independently reviewed and audited by NRC or DOE at established intervals.

The concept of "graded" safeguards, used in both domestic and international systems, provides the greatest amount of control and protection to the most sensitive nuclear materials. In the US system, nuclear materials are divided into three categories depending on how difficult it is to convert the material into weapons-usable form. Thus plutonium, highly enriched uranium, and ^{233}U, in the form of metal or pure compounds, such as oxides or carbides, are designated Category I materials; these require the highest priority and most stringent safeguards. Scrap, residues, and mixtures that must be processed, transmuted, or enriched to become usable in an explosive device are designated Category II or III materials, depending on the amount of SNM involved.

In contrast to national safeguards systems, which are designed to counter subnational adversaries, international systems are designed to verify that governments have not used nuclear activities as a source of material for clandestine nuclear weapon programs. The objectives as well as the technical requirements and methods used in the two systems are quite different in some important respects. International safeguards systems are aimed at detecting the diversion of nuclear material to unauthorized purposes and at deterring such diversion by the risk of early detection. While a national safeguards system has the authority and capability to physically protect facilities and material and to recover diverted material, the international (IAEA) system is neither intended to, nor able to, *prevent* diversion. Its main objective is to *detect* discrepancies in inventories and to *deter* diversion by providing a *timely warning* intended to *trigger* international reaction, including possible sanctions.

IAEA safeguards objectives and requirements contain two important quantitative expressions: *significant quantity* and *conversion time.* A significant quantity is the approximate amount of nuclear material, including allowance for loss, deemed necessary to construct an explosive device. Conversion time is the estimated minimum time required to produce the nuclear components of an explosive device. For materials in direct weapon-usable form, such as the metallic state, the IAEA has defined the significant quantity of plutonium and ^{233}U as 8 kilograms and the significant quantity of highly enriched uranium as 25 kilograms. Designated significant quantities are of course larger for low-enriched uranium and for materials in less directly usable forms. Similarly, IAEA has adopted estimated conversion times for different material categories. For example, conversion times for plutonium, ^{233}U, or highly enriched uranium in the metallic form are taken as the order of days (7-10 days), whereas conversion times of oxides or other pure compounds of plutonium, ^{233}U, or highly enriched uranium are taken as the order of weeks (1-3 weeks). The IAEA timely warning criterion requires that the *detection time,* defined as the maximum elapsed time between an indicated diversion and its detection by IAEA safeguards, be less than the estimated minimum conversion time.

In general, international safeguards criteria and requirements are not as stringent as the corresponding national safeguards and security requirements; this is due to the distinctly different objectives of national and international safeguards. In a national system, diversion of a relatively small amount of SNM, such as a threat to disperse 100 grams of plutonium, would be a matter of immediate concern. Thus, performance goals for a national system would typically include the detection of relatively small quantities of SNM in minutes or hours. Likewise, an alarm indicating unauthorized entry into a nuclear facility should bring armed guards to the scene within minutes. The IAEA, on the other hand, does not have the task of prevention or interception of such malevolent acts, or even the detection of such small target amounts of materials in such short times. Instead, the international safeguards system inspector must detect the larger IAEA significant quantities and, depending on the type of material, IAEA detection times may be days, weeks, or months rather than minutes or hours.

Like the record of the US system, the record of the IAEA international safeguards system is indeed reassuring. Thus far, there has been no diversion of nuclear material under IAEA safeguards, and the likelihood of future diversions can reasonably be expected to remain small, in part because of the ongoing operation, and continuous upgrading, of the IAEA system. The IAEA currently carries out some 800 inspections annually in well over 300 facilities around the world having an aggregate of some 70 tons of plutonium, over 10,000 tons of enriched uranium, and 30,000 tons of natural uranium. If one divides the annual IAEA safeguards budget by the kilowatt hours of electricity generated annually in all nuclear power plants, the result is roughly $0.00002 per kilowatt hour—or about 0.1% of the nominal cost of electricity.

Safeguarding the Nuclear Power Fuel Cycle

According to a recently completed 5-year study by the US National Academy of Sciences (the so-called "CONAES report"), the only choice the United States has to meet large-scale electricity demands for the next 30 years or more is to burn coal and build and operate nuclear power plants. This study of nuclear and alternative energy systems further concluded that nuclear-generated electricity may be the nation's only choice for the 20-year period beginning in 1990. Around that time, operation of coal-burning plants may be curtailed sharply by the future strong demand for coal as a valuable source of synthetic liquid and gas fuels, and by the threat that carbon dioxide accumulation from coal combustion could alter climatic conditions through the heat-trapping *greenhouse effect.*

The CONAES report addressed US domestic energy needs. Similar conclusions on the international level were reached independently by the 66-nation INFCE study, which addressed worldwide nuclear energy needs and fuel-cycle alternatives on a worldwide basis. The INFCE report calls for con-

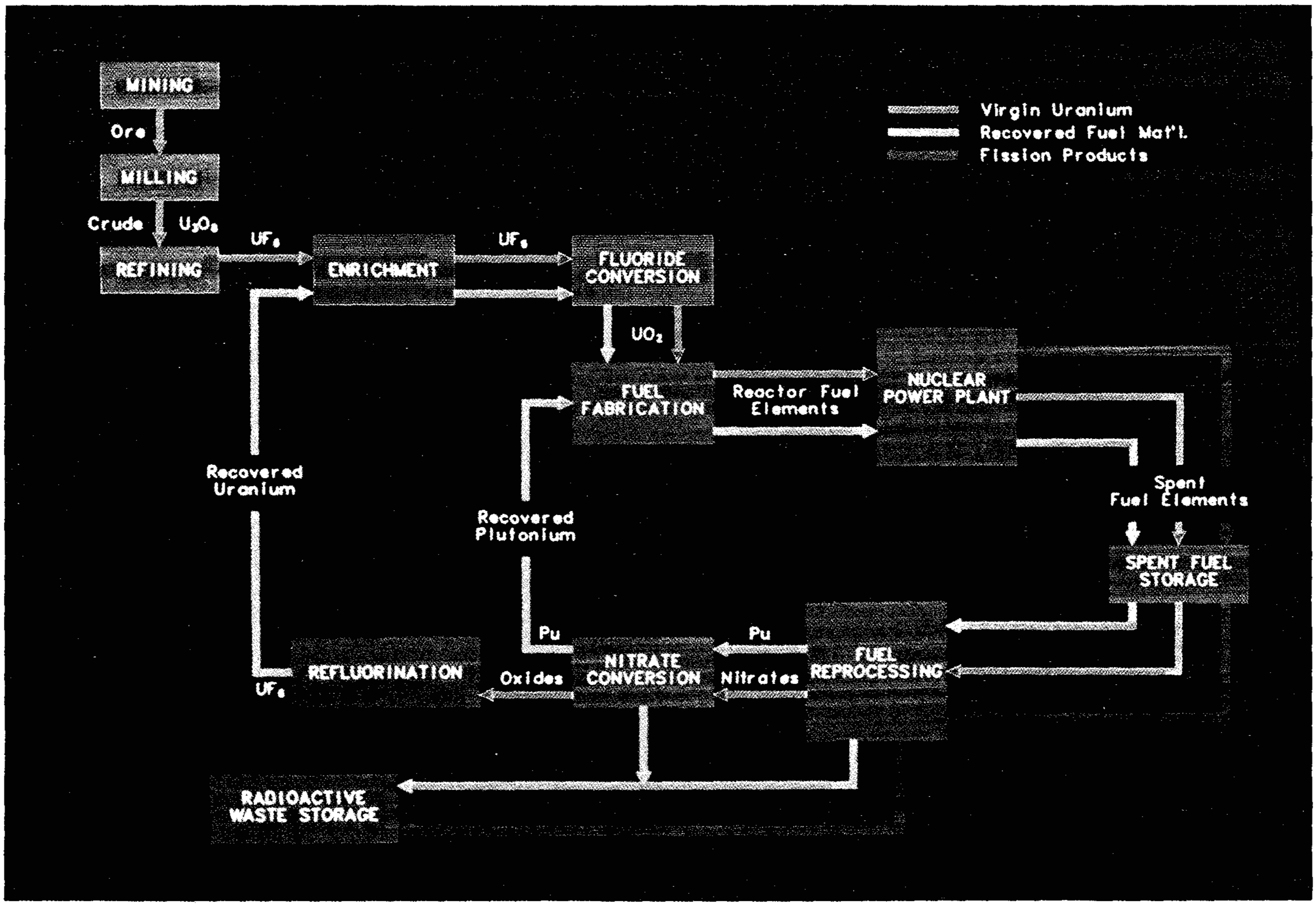


Fig. 1. Power Reactor Fuel Cycle. Uranium ore is mined, milled, and refined, and the resulting U_3O_8 *is converted to* UF_6 *for enrichment to approximately 3%* ^{235}U*. Reactor fuel, fabricated from virgin, enriched uranium, or mixtures of uranium and plutonium, provides power in the reactor. Spent-fuel elements are stored at reactor sites or at specially designed away-from-reactor storage facilities. In a "once-through" fuel cycle, the spent fuel is stored permanently, and the remaining* ^{235}U *and the plutonium formed as a by-product of power generation are not used. In a complete fuel cycle, the uranium and plutonium are recovered from the spent fuel and recycled to provide raw materials for new, "mixed-oxide" fuel elements. Safeguards efforts are concentrated on preventing diversion of separated plutonium between the fuel reprocessing and fuel fabrication steps.*

tinued development of nuclear power and endorsement of plutonium-based nuclear energy systems, including commercial development of the fast breeder reactor in appropriate countries, in order to avoid a projected shortage of uranium fuel by the end of this century. The INFCE report urged that technical safeguards against proliferation be applied in "a consistent and predictable" (reasonably standardized) way that would not discourage the peaceful development of nuclear energy by creating doubts and uncertainties about the future availability of fuel supplies.

Despite numerous problems and difficulties, nuclear energy is rapidly becoming a major energy source in an increasing number of countries. It currently supplies over 10% of all electric power generated in the United States and 20% or more of total electric power in some industrialized countries, such as Belgium, Sweden, and Switzerland. Some of the more advanced developing countries, such as India and South Korea, have significant and growing nuclear power programs, while many other developing countries are actively seeking to acquire this new source of energy. Recent projections indicate that nuclear power plants will supply nearly one-quarter of the world's electrical energy by approximately the year 2000. As IAEA Director General Sigvard Eklund noted at a recent LASL colloquium, the driving force behind the worldwide growth of nuclear energy is not difficult to understand when viewed against the background of economic, political, and supply-assurance problems associated with the world's shrinking supply of hydrocarbon fuels. With the growing demands for fossil fuel, the cost of oil, for example, has risen by a factor of 5 or 6 in nearly as many years.

Hand in hand with the promise of nuclear energy come some challenging, and recently much publicized, problems and concerns. The accident at Three Mile Island near Harrisburg, Pennsylvania, in 1979, focused worldwide attention on the problems of nuclear reactor safety. TMI also has had

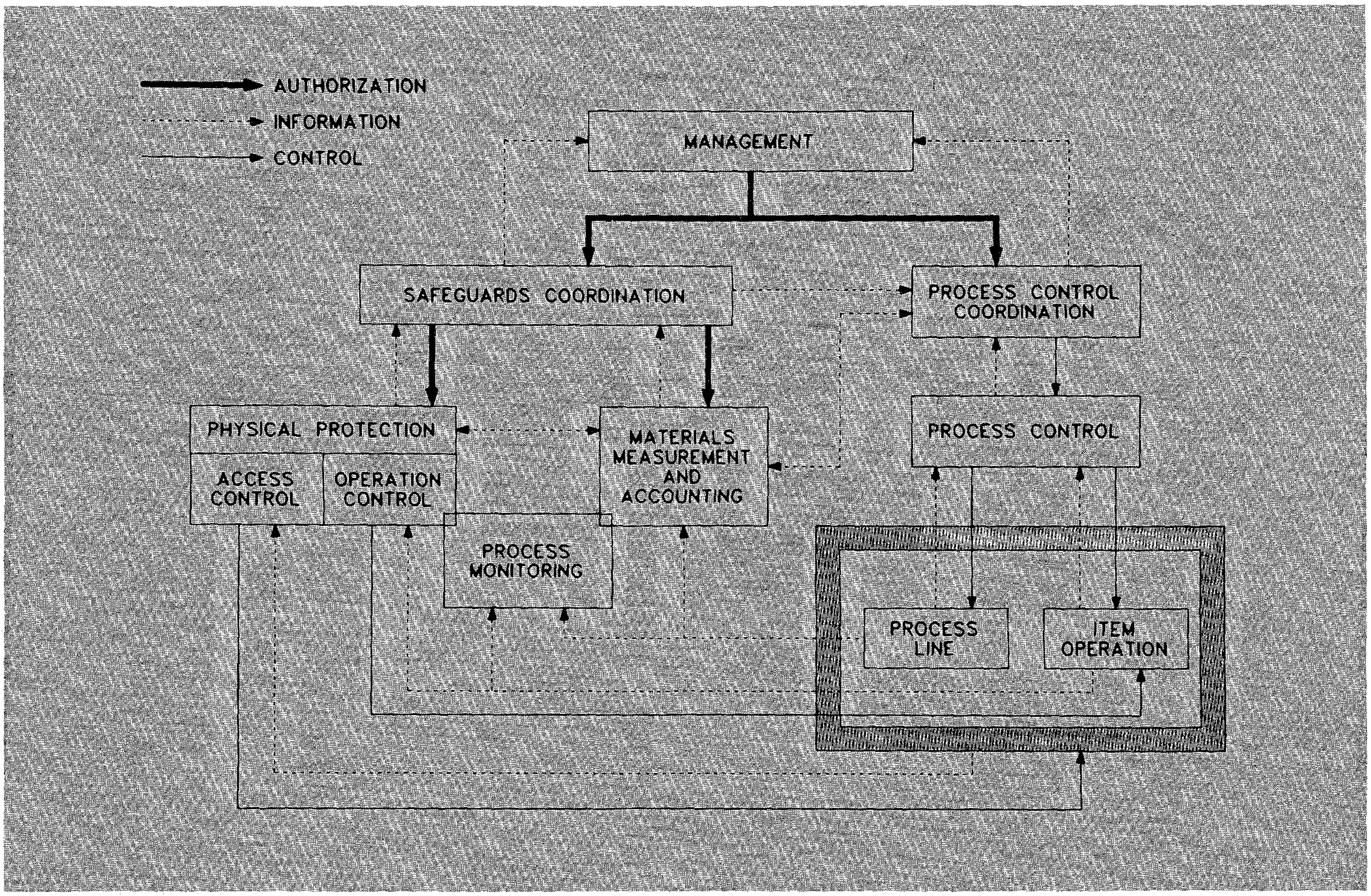


Fig. 2. Structure of the Safeguards System. The functional relationships among the elements of a safeguards system and the normally required management and process control elements of a nuclear fuel cycle facility are indicated by the arrows. Process and item operations are contained within a physical protection barrier (dark outline box) that is part of the physical protection and materials control components of the safeguards system. Materials control is provided by monitoring both the process line and the item operations; the item operations also are controlled. Materials measurements and accounting data are derived from measurements of nuclear materials in process operations. Coordination of each of the components of the safeguards system provides facility safeguards status information to both management and process control coordination.

implications for nuclear energy generally, bringing increased attention to the problems of nuclear waste, weapons proliferation, and nuclear material safeguards. Full realization of nuclear power's great potential for meeting world energy needs will clearly depend on how effectively such problems are addressed, including how effectively nuclear safeguards can be implemented on both the national and the international levels.

During their *lifetime,* nuclear reactor fuel materials undergo a variety of physical and chemical processes in various plants and facilities collectively known as the nuclear fuel cycle (Fig. 1). To maintain strict accountability and control of sensitive fissionable materials throughout the nuclear fuel cycle, we must be able to take a rapid and accurate inventory of these materials in each facility at any given time. This requirement is especially important if a diversion, theft, extortion, or blackmail threat should occur. We must be able to ascertain quantitatively what, where, and how much material is present in any facility at any time. Even more to the point, we must be able to ascertain how much material may be missing from a facility at any time.

Unique Role of Measurement and Accounting Systems

Effective safeguards (Fig. 2) depend on a combination of three basic components: (1) physical protection, (2) materials measurement and accounting, and (3) materials control, including process monitoring. Each component is necessary for a fully effective overall safeguards and security system, but only the materials measurement and accounting component can determine the amount and location of material in a plant at any given time. This capability for determining nuclear material inventories with adequate sensitivity and timeliness provides an overall quantitative check on the combined effectiveness of all other safeguards and security measures at a facility.

Under DOE sponsorship, LASL has developed and demonstrated new automated chemical analysis and NDA instruments that can measure the various forms of nuclear materials rapidly and accurately and thereby provide the high degree of incisiveness required of modern materials measurement and accounting systems. In the application of analytical chemistry methods for safeguards and accountability, it is extremely important to obtain analysis samples that are truly representative of the material being measured. Reliable inventory confirmation further requires precise and accurate analyses of the amounts and isotopic compositions of fissionable materials (uranium, plutonium, and thorium) in widely diverse physical and chemical forms, including pure products, reactor fuels having complex chemical compositions, and numerous types of scrap. Multiphase scrap and materials containing highly refractory components are particularly difficult to dissolve and analyze, while characteristically heterogeneous solid-waste materials in general are simply not amenable to meaningful assay by conventional sampling and chemical analysis techniques.

Major objectives of the LASL analytical chemistry safeguards program are (1) development of fast, effective dissolution techniques and analytical methods for uranium, plutonium, and thorium determinations; (2) design and construction of automated analyzers for these determinations; (3) evaluation of mass spectrometric measurements of uranium and plutonium isotopic distribution; (4) preparation of well-characterized plutonium standard reference materials for distribution by the National Bureau of Standards and for use in DOE safeguards standards intercomparison programs; (5) preparation of plutonium and uranium reference materials for calibration of NDA instrumentation used in the dynamic materials accountability (DYMAC) system at the LASL plutonium processing facility; and (6) participation in an interlaboratory program devoted to measurement of plutonium isotope half-lives.

An example of newly developed automated chemical analysis instrumentation is LASL's automated controlled-potential plutonium analyzer, which determines low-milligram amounts of plutonium with high (0.1%) precision at an average rate of one sample per 30 minutes. The combination of high measurement precision and a specially developed high tolerance for impurity elements makes this relatively low cost analyzer directly applicable to the analysis of a wide variety of nuclear materials.

Because representative sampling of some types of scrap and particularly of heterogeneous solid waste is a particularly plaguing problem, it is not surprising that in the early days of the LASL safeguards program one of the first CMB-identified requirements was for NDA instruments to measure scrap and waste materials. The inherently rapid NDA methods also offered the capability for measuring essentially every individual contained unit of feed or product material. For example, in the assay of reactor fuels, NDA techniques made it possible to measure the total fissionable material loading of each individual reactor fuel rod and to certify, on a routine production basis, the pellet-to-pellet uniformity of uranium fuel loading. Such certification of uniform loading is an important quality control factor in avoiding "hot spots" in the fissioning fuel, and thereby also an important factor in reactor safety. Other "spin-off" benefits of modern nondestructive and destructive measurement techniques developed for safeguards include better in-plant process control, quality assurance, operational safety, and more efficient management of recycle and waste materials.

Major goals for acceptable performance of NDA instruments were set forth in the period from 1965 to 1970, concurrent with steadily increasing pressures to rigorously quantify and reduce uncertainties in measured nuclear material inventories. Characteristic measurement times for individual items were usually under 10 minutes and desired accuracies for the various material categories were 0.2-3.0% for well-characterized, uniform feed and product materials; 2-10% for recoverable scrap materials; and 5-30% for poorly characterized nuclear waste.

Fissionable nuclide characteristics exploited for "passive" assay are the gamma-ray, neutron, and alpha-heat emissions accompanying the natural radioactive decay of the nuclides. Supplementing passive NDA techniques, "active" assay methods use external neutron sources to induce fissions in a sample; the fissions are then measured by counting fission neutrons or gamma rays. Gamma-ray and x-ray densitometry also provides rapid, accurate determination of the concentrations of uranium, plutonium, and thorium in typical solutions and solids.* The principal neutron and photon measurement techniques and instruments currently in use or being developed for measuring fuel-cycle materials are summarized in Tables I and II. Calorimetry, a technique based on the measurement of radioactive decay heat of contained materials, also has been implemented widely for measurement of plutonium.

Advanced Materials Accountancy and Control

In conventional safeguards practice, the accountability of nuclear materials within a facility and the detection of unauthorized removals have relied almost exclusively on discrete-item counting (as opposed to the more difficult task of measuring bulk process materials) and on material-balance accounting following periodic shutdown, cleanout, and

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**See "Nondestructive Assay for Nuclear Safeguards," in this issue.*

TABLE I
GAMMA- AND X-RAY ASSAY SYSTEMS

Instrument or Technique	Operating Principle	Application
Segmented gamma scanner[a]	Passive gamma-ray analysis; transmission of external source gammas used for attenuation correction	Quantitative assay of ^{239}Pu, ^{235}U in scrap and waste
MEGAS[a]	High-sensitivity passive x- and gamma-ray detection	Screening of low-density transuranic waste at the 10 nCi/g fiducial
Gamma-ray spectroscopy[b]	Passive gamma-ray analysis with Ge or NaI detectors; sometimes augmented by measurement of transmission of external source photons	Assay of U, Pu; Pu isotopic analysis; U enrichment
X-ray edge densitometry[b]	Photon transmission in the region of L_{III}- or K-edges	Elemental concentrations of Th, U, Pu
XRF[b]	X-ray fluorescence	Elemental analysis of Th, U, Pu

[a] Well developed for many fuel cycle applications; instruments commercially available.

[b] Developed for some fuel cycle applications and being evaluated for others.

physical inventory. The classical materials balance usually is drawn around the entire facility or a major portion of the process. It is formed by adding all measured receipts to the initial measured inventory and subtracting from this sum all measured removals and the final measured inventory. During routine production, material control is vested largely in administrative and process controls, augmented by secure storage for discrete items and sealed containers.

Although periodic shutdown-cleanout operations will always be important in determining the amount of bulk nuclear material holdup in process equipment, pipes, pumps, traps, and filters, the use of this procedure alone has inherent limitations in sensitivity and timeliness. Sensitivity is limited by measurement uncertainties that might obscure the diversion of relatively large quantities of SNM in a large throughput plant. Timeliness is limited by the practical difficulties, the expense, and hence the infrequency of process shutdown, cleanout, and physical inventory; thus a loss of material could remain undiscovered until the next physical inventory.

Recently developed NDA technology, state-of-the-art conventional (destructive) measurement methods, and special inplant sensors, combined with computer and data-base management technology, provide the necessary technical basis for much more effective methods of safeguarding nuclear facilities. For example, the greater sensitivity and timeliness requirements on SNM control now being imposed by DOE and NRC can be achieved by subdividing a nuclear facility into discrete accounting envelopes, called unit processes, and drawing individual material balances around them. A unit process is chosen on the basis of process logic, the time material resides within the unit process, and the ability to perform quantitative measurements and draw a material balance. Thus, by subdividing a facility into unit processes and measuring all material flows across unit process boundaries, the