Fig. 20. The Active Well Coincidence Counter including detector body, cart, and portable electronics for automated data collection and analyses.

plant instrumentation is field inspection using portable instrumentation. Equipment for this application must be lightweight, rugged, and simple to operate. A leading example of this instrumentation is the High-Level Neutron Coincidence Counter (HLNCC), which measures the effective ^{240}Pu content in bulk plutonium samples by coincidence counting the spontaneous fission neutrons from the plutonium.

To extend the same type of equipment to uranium assay applications, we use active neutron interrogation to induce the fission reactions because the spontaneous fission rate in ^{235}U is too small to be useful in the passive mode.

The basic principle of the AWCC is fast-neutron interrogation using a random neutron source (for example, AmLi) and counting the induced fission reactions using coincidence techniques to suppress the signal from the random interrogation source. The AWCC uses 42 ^{3}He detectors to count the induced fission neutrons. It also has two neutron sources of similar strength ($\sim 5 \times 10^4$ n/s), one in the lid and one in the bottom plug. The use of two neutron sources produces a rather uniform vertical response. Also, the CH_2 plugs act as neutron shields to reduce the background neutrons counted in the ^{3}He tubes from the AmLi sources. This shielding technique improves the induced signal-to-interrogation neutron background ratio by a factor of 10.

The AWCC has been designed to take advantage of the portable electronics package that was developed for the HLNCC. The electronics unit is interfaced directly to the HP-97 programmable calculator shown in Fig. 20. A microprocessor in the unit reads out the run time, total counts, real plus accidental counts, and accidental counts to the HP-97. The HP-97 reduces the data using the software package selected by the operator.

The unit is useful for measuring bulk UO_2 samples, high-enrichment uranium metals, LWR fuel pellets, and ^{233}U-Th fuel materials, which have very high gamma-ray backgrounds. By removing the AmLi source, the unit can measure ^{238}U and plutonium in the passive neutron coincidence mode. We recently have supplied the first AWCC system to the IAEA for field test and evaluation.

Status of Development and Implementation

Acceptable performance criteria for NDA techniques for safeguards, established well over a decade ago, include measurement times in the range from a few seconds to 1 hour and the following accuracies for the various material categories: 0.2-3.0% for uniform feed and product materials, 2-10% for recoverable scrap, and 5-30% for waste. We have achieved or exceeded these goals for many of the materials associated with the following fuel processes: uranium enrichment, uranium and plutonium fuel fabrication, and uranium and plutonium scrap recovery. The development of NDA methods and instruments has been greatest for measurements of scrap and waste, holdup, high-purity raw materials, and finished fuels—the material categories that were first identified as priority problems for NDA development.

Portable instruments and a number of stand-alone instruments for measuring containers of SNM were the first to be developed and tested in operating facilities. Some of these instruments then were adapted for on-line applications so that items or samples of plutonium material could be measured without being removed from the glove box containment.

Current research is focused on extending the range of applicability (to other compositions and concentrations) and improving accuracies of existing technologies, adapting techniques for in-

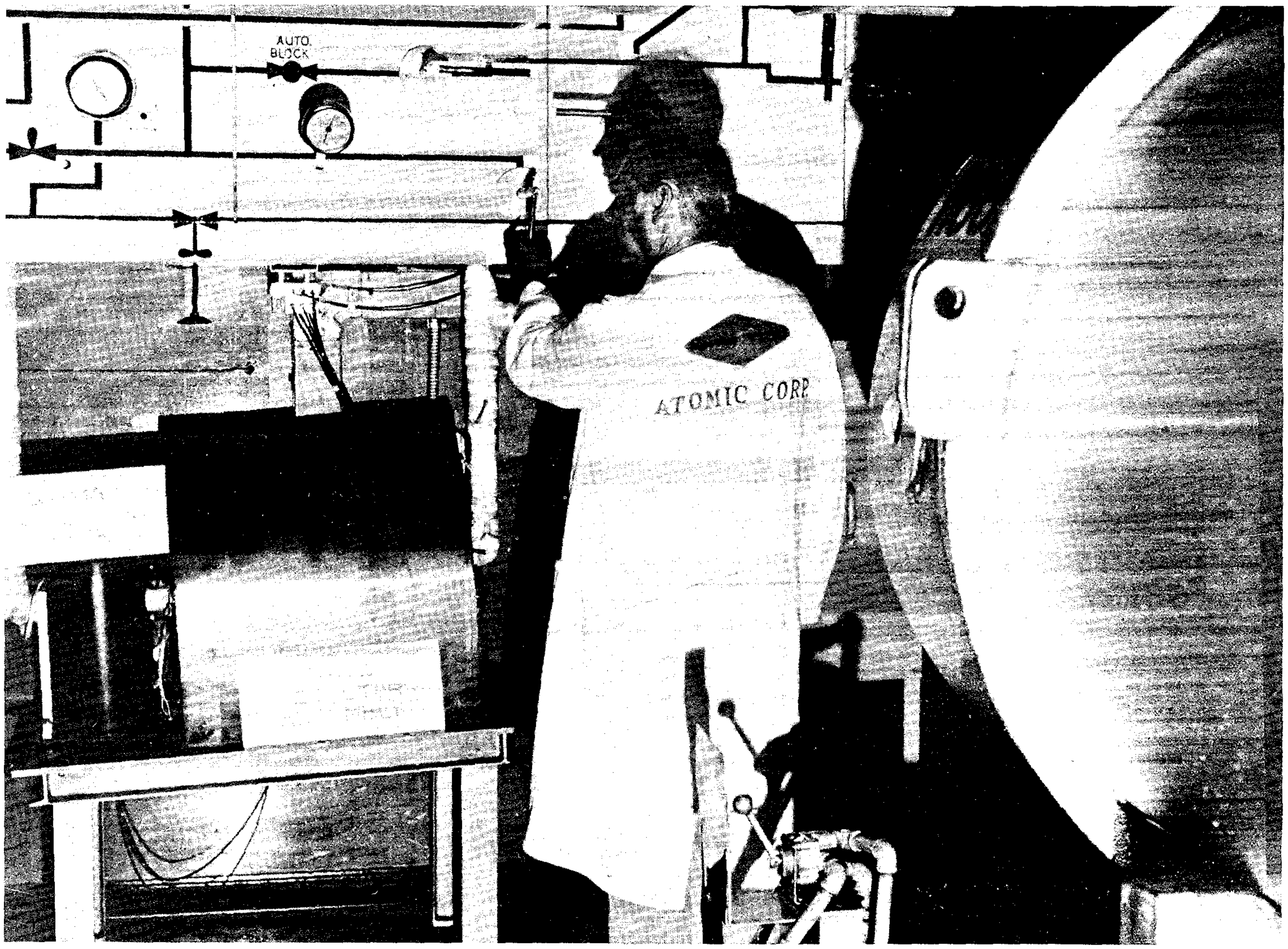

Fig. 21. In-line UF_6 enrichment monitor installation at the extended-range product-withdrawal station of the DOE/Goodyear Atomic gaseous diffusion plants. Passive gamma-ray and neutron instruments continuously measure ^{235}U and ^{234}U enrichments of liquid UF_6 to provide criticality safety and process controls.

line measurement and monitoring of bulk process materials, developing specialized instrumentation for inspectors and for containment and surveillance, developing methods to measure spent fuels and "hot" reprocessing materials, and finding techniques to measure advanced fuel materials such as mixed uranium-plutonium solids and solutions.

Ultimately, the best gauge of the success of these developments is the level of acceptance and implementation by the nuclear industry, regulatory agencies such as the US Nuclear Regulatory Commission, and for the international arena, the IAEA. In most operating nuclear facilities that process low-enriched uranium for use in commercial power reactors and high-enriched uranium and plutonium for defense programs and research reactors, the implementation of the NDA methods described here to complement or replace analytical chemistry measurements for safeguards and process control has been extremely gratifying. An example is the in-line UF_6 enrichment monitor at the DOE/Goodyear Atomic gaseous diffusion plant (Fig. 21), which serves principally for process control and criticality safety. Major exceptions are spent-fuel reprocessing plants, where the slowdown or postponement of reprocessing has in turn delayed the testing and implementation of promising measurement methods for the fission-product-contaminated

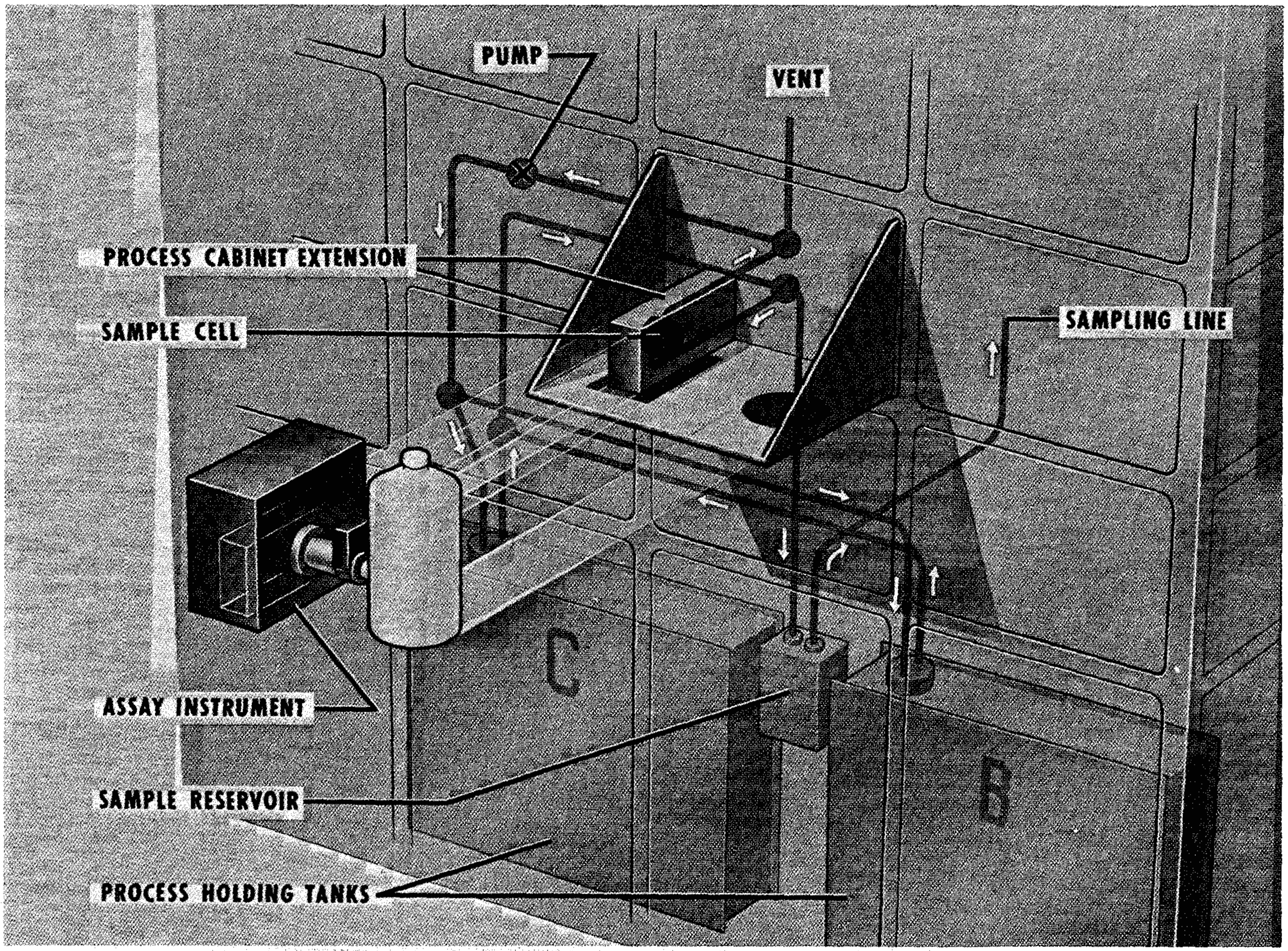

Fig. 22. The in-line absorption-edge densitometer for the Savannah River Reprocessing Plant. Plutonium product solution is pumped from holding tanks through a measurement cell, which is located inside an extension of the process line containment.

uranium and plutonium materials processed in these plants. A project is now under way to test an in-line K-edge densitometer (Fig. 22) for measuring plutonium concentration in the product solution line of the Savannah River spent-fuel reprocessing plant, which is operated for DOE national defense programs.

A typical nuclear facility now has an NDA counting room in which scrap and waste and samples from the process lines are measured for materials accounting, process control, and waste management. Portable NaI and germanium gamma-ray detectors and neutron counters are used routinely to measure holdup for inventories or investigate process anomalies. Fuel rod scanners are used in all light water reactor fuel fabrication facilities in the United States and most of those in Belgium, France, Germany, Italy, and Japan to quality-assure all fuel rods. Some facilities, such as the plutonium plants operated at LASL and Rocky Flats for defense programs and the General Electric/Wilmington light water reactor fuel fabrication plant, have installed near-real-time material accounting systems that use NDA instruments for measurement or verification of material movement throughout the plant.

We are equally gratified by the acceptance of NDA technology by regulatory agencies, both as a part of safeguards systems for plants and for independent

TABLE V
INSTRUMENTATION DEVELOPED BY LASL FOR IAEA APPLICATIONS

Instrument	Principle	Applications
SAM-II	Passive gamma-ray enrichment meter	UF_6 cylinders, UO_2 powder, fuel pellets and rods
Segmented gamma scanner	Transmission-corrected gamma-ray measurements	UO_2, PuO_2 scrap and waste
HLNCC	Passive neutron coincidence counting	Pu metal, PuO_2 powder, MOX fuel
AWCC	Active neutron interrogation and coincidence counting	U metal, UO_2 powder, U-Al alloy
Coincidence collar	Active neutron interrogation	PWR, BWR, and HWR fuel assemblies
K-edge densitometer	Active gamma-ray transmission	Pu and U solutions reprocessing plants
Reactor power monitor	Passive neutron	LWR reactor power monitor
Spent-fuel verification instruments	Cerenkov glow, passive gamma-ray, passive neutron	LWR and HWR spent fuel assemblies in storage pools

inspector verifications. Through the US program of technical assistance to the IAEA, we have developed a number of key NDA instruments and applications for international inspection of nuclear plants, and have provided inspectors with training, manuals, calibration, and implementation assistance. Table V lists instrumentation we have developed for IAEA applications. One technique helps to verify relative burnup and cooling time of spent reactor fuel assemblies to infer the resulting plutonium inventory (Figs. 23 and 24). E. Dowdy has pioneered a convenient method using the Cerenkov glow for confirming that the spent-fuel assemblies stored in an underwater array as shown in Fig. 23 are

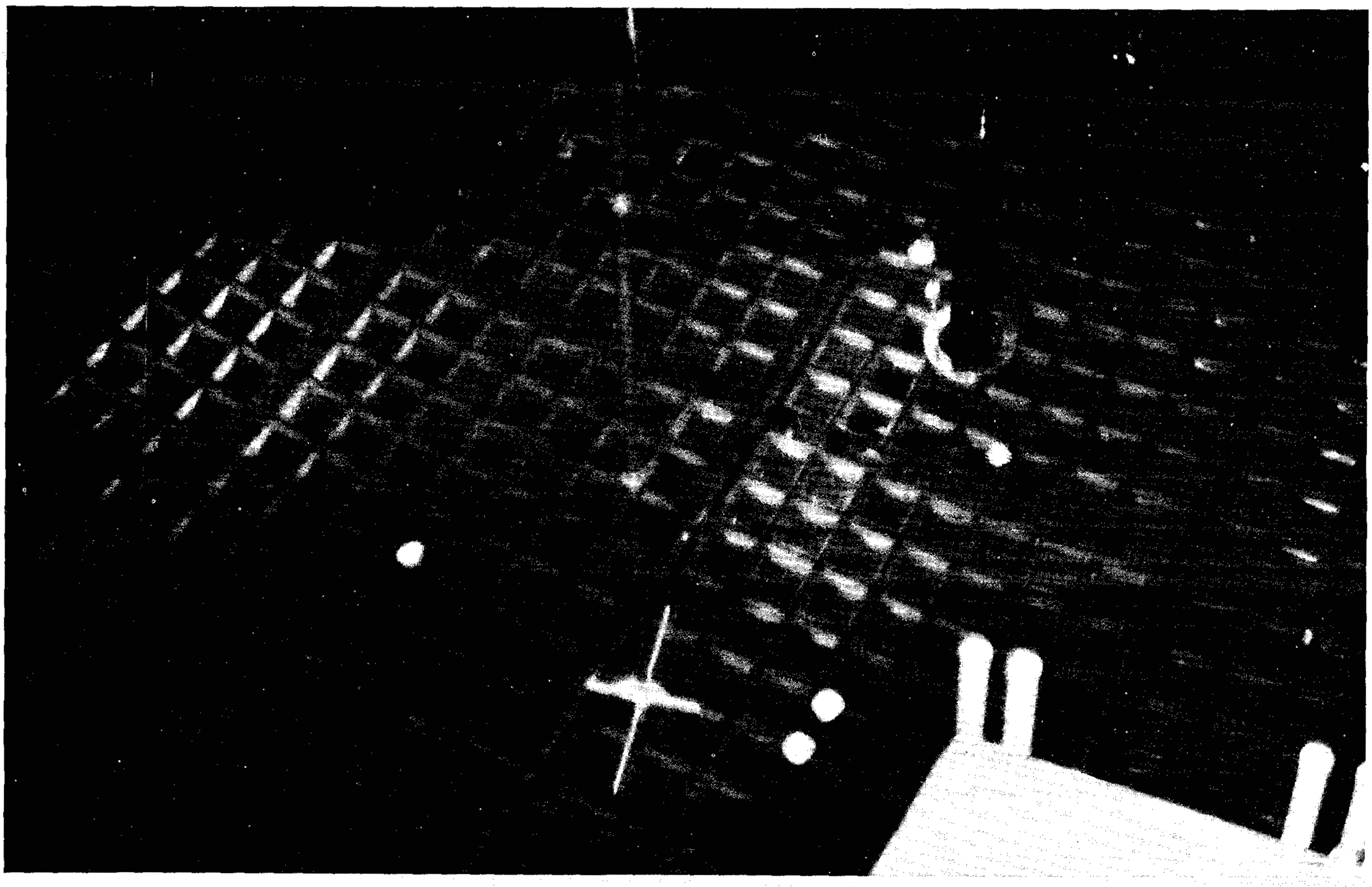

Fig. 23. A light water reactor fuel element storage array under about 10 m of water in a spent-fuel storage pool. One fuel element is raised about one-half its length through the ring ion and fission chamber (see Fig. 24) to measure the gamma-ray and neutron emissions.

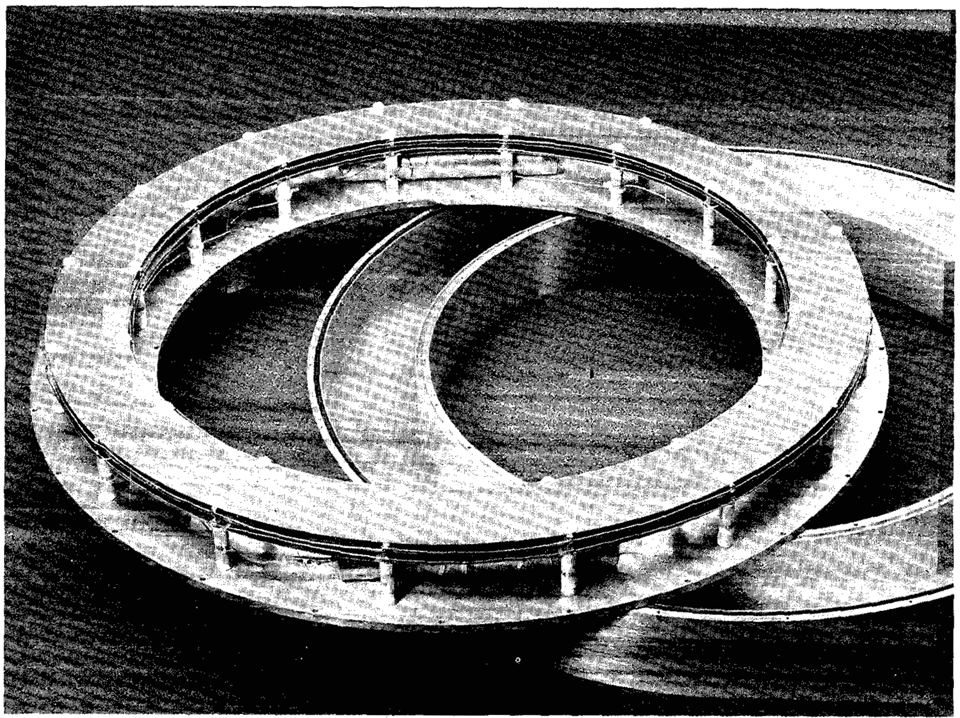

Fig. 24. Ring detector containing ion and fission chambers to measure intense gamma-ray and neutron emissions from spent-fuel assemblies to help verify burnup and cooling time in the fuel.

highly radioactive. Inspectors can turn off the overhead lights and measure the intensity of the Cerenkov glow, which is proportional to the activity level in the spent-fuel assembly. This approach is rapid and requires no instrumentation to be put in the contaminated water of the pool.

Challenges of the Future

While great progress has been made in filling the voids in safeguards measurement technology with NDA methods, the implementation of new technology has been confined largely to retrofitting existing facilities and conventional safeguards procedures. We have introduced high technology for measurements and accounting into plants that were designed both for manual operations and to rely on administrative controls and chemical assay for safeguards accounting. Implementation of NDA-based vehicle and personnel monitors has enhanced the containment and surveillance elements of safeguards for existing facilities.

Heretofore, the development of instruments has been focused on the need to measure uranium and plutonium generated in fabrication processes that keep these elements isolated from one another and are free of fission product contamination.

Current studies and conceptual process and facility designs involve both reprocessing and coprocessed uranium and plutonium fuels. These material forms and compositions pose a whole new set of measurement problems, which we have only begun to address. In the international arena, the fact that fuel reprocessing and development of the breeder are proceeding now makes solving the associated measurement and accounting problems an urgent need. Some of the materials for which NDA measurement techniques should be developed, tested, and evaluated are: leached spent-fuel hulls and other "hot" scrap and waste, mixed uranium and plutonium solutions with the various levels of fission product contamination characteristic of reprocessing, "cold" mixed plutonium and uranium solutions and solids characteristic of co-converson (from nitrate to oxide), and final breeder and (perhaps plutonium recycle) fuels. Futhermore, until commercial (LWR) spent fuels are reprocessed, they must be stored at the reactor sites or at special away-from-reactor (AFR) facilities. The spent fuels should be verified and measured quantitatively, if possible, to establish their economic value and to control batch make-up for future reprocessing, as well as for safeguards.

Concerns are increasing about safeguards for uranium enrichment, the front end of the fuel cycle, as advanced isotope separation processes based on centrifuges, lasers, or plasma devices are implemented. Because of their inherently large isotope separation factors, fewer separation stages are required to produce high-enriched uranium than are needed for classical gaseous diffusion separators. Hence the advanced isotope separation techniques could be more easily used for covert production of bomb materials by the facility operator. New safeguards measurement problems associated with these advanced methods must be addressed.

Process lines in future facilities will use advanced processing and control technology, including remote operation and maintenance, to minimize personnel radiation exposure, assure material containment, and handle high throughput efficiently. Almost certainly more, not less, measurement instrumentation will be needed in process lines. The instruments must function very reliably, even in such high-radiation environments as reprocessing canyons, because of the restricted access. Individual measurement stations must be designed to meet the well-ordered requirements of cost-effective integrated, automated systems of materials accounting and control. At present, LASL and the Hanford Engineering Development Laboratory are planning NDA instrumentation to be incorporated at DOE's new Fuel Materials Examination Facility at Richland in an automated mixed uranium and plutonium oxide fuel fabrication line. With the DOE/ORNL Consolidated Fuel Reprocessing Program, LASL also is working on the conceptual safeguards design for an advanced fuel-reprocessing plant.

Implementation of advanced automated materials accounting and control systems may constitute an enigma for safeguards inspectors. The question is how an inspector can independently verify that a large complex integrated system has been operated as declared. Providing system integrity with sufficient transparency for verification will undoubtedly bring changes in the design of individual instruments and their measurement controls. Inspectors will need improved portable instruments to confirm the results of the large in-plant systems.

Safeguards technology, like waste management, was once viewed by many scientists and planners as a supportive, ancillary factor in the development of nuclear power for the generation of electricity. These factors, together with reactor safety, have now become dominant in the determination of the future of nuclear energy. Thus levels of activity in future safeguards instrumentation development just described will depend to a large extent on the acceptance and use of nuclear energy, which in turn will be strongly influenced by public perception of the safety of reactors, the capabilities for safeguarding these fuels for peaceful uses, and safe management of the associated nuclear waste materials. In this chicken-and-egg cycle, we hope that the significant advances in safeguards technology, as well as in reactor safety and waste management, will be given due consideration.

THE AUTHORS

Howard O. Menlove, Group Leader of the International Safeguards Group, has worked with the Nuclear Safeguards Program at LASL for 12 years. He has been active in research and development of advanced techniques for nondestructive assay of fissionable materials. At present, his work is in inspector instrumentation development and implementation, nondestructive assay standards and calibration, spent-fuel verification techniques, training, and technology transfer. Before joining LASL, he had considerable experience in neutron and fission physics and in gamma-ray spectroscopy. After earning his Ph.D. in nuclear engineering at Stanford University, he spent a year at the Kernforschungszentrum in Karlsruhe, FRG, supported by a Fullbright Award.

Roddy B. Walton earned his bachelor of science degree in physics at Texas A&M University, and his Ph.D. in nuclear physics at the University of Wisconsin in 1957. From 1959 to 1967, he was with the General Atomic Company, where he was involved in electron linac instrumentation and experiments in neutron thermalization, neutron capture cross sections, delayed gamma rays from fission, and photonuclear reactions. In 1967, he joined LASL, and has been working in development and implementation of methods for the measurement of fissionable materials for the nuclear safeguards program. He has been instrumental in the initiation of new projects, including the Mobile Nondestructive Assay Laboratory and its operation in the field, DYMAC (dynamic materials accounting), and systems analysis. He is a Fellow of the American Nuclear Society.