Letters to the Editor

U.S. Spent-Fuel Disposal Strategies and International Safeguards

I. INTRODUCTION

Domestic safeguards for fissile nuclear materials are universal, and a variety of international safeguards regimes are applicable, in most member states of the International Atomic Energy Agency (IAEA), to declared nuclear facilities dedicated to peaceful missions. The U.S. strategy to dispose of all spent nuclear fuels (SNFs) and high-level wastes (HLWs) in engineered geologic repositories has a sometimes-overlooked consequence, namely, the need to maintain domestic and international safeguards in perpetuity. The implication of this legal requirement is not adequately recognized by the nuclear industry. The Office of Civilian Radioactive Waste Management of the U.S. Department of Energy (DOE), which has the responsibility to accept and store the spent fuels in the long term either in surface facilities or in engineered geologic repositories, has yet to include safeguards issues in their "mission plan."

In 1992, an interagency effort was initiated by the Office of Arms Control and Nonproliferation of the DOE to develop a research and development program to safeguard U.S. spent fuels in an international safeguards regime. It is in this context that this Letter to the Editor examines the current spent-fuel management scenario, identifies nuclear material safeguards issues, and proposes safeguards concepts for the U.S. spent-fuel management system. Awareness within the United States about international safeguards relevant to the geologic disposal of spent fuels must increase, and desirable actions by U.S. industries and governmental agencies must be identified well before the geologic repositories for spent fuels become a reality.

There are several stages in the nuclear fuel cycle where materials usable in weapons (primarily, highly enriched uranium and plutonium) are available for diversion. This discussion, however, is limited to the potential diversion of spent fuels for clandestine plutonium recovery. This topic of nuclear proliferation via spent fuels has been totally ignored until recently because of the assumption that fissile and fertile materials from spent fuels would be reprocessed and used. In recent years, concerns about nuclear proliferation from spent fuels have increased as a result of proposals from poorer nations, primarily the People's Republic of China, to host spent-fuel storage facilities for a fee.[1] The proposed geologic repositories are now perceived as potential sources of large quantities of plutonium, uranium, and a variety of rare and strategically important elements, such as palladium, ruthenium, rhodium, and technetium.[2,3]

Current safeguards regimes for nuclear materials in reactor facilities and fuel fabrication facilities primarily depend on item verifications, where possible, and verifications of declared amounts of nuclear materials through independent estimates. Problems related to verifying the mushrooming number of SNFs are extremely difficult and will compound when spent fuels are consolidated.

Such problems are not peculiar or confined to spent fuels. For example, similar difficulties may arise when thousands of nuclear warheads are dismantled as a result of bilateral agreements between the United States and the republics of the former Soviet Union. Performing periodic verifications of stored dismantled weapons parts is equally challenging.

The concepts proposed here highlight safeguards elements necessary for a pragmatic safeguards system for SNF from nuclear power generation. The efforts required to initiate and maintain a verifiable international safeguards regime are examined in the context of a typical storage facility in the United States.

II. GENERIC FEATURES OF A SAFEGUARDS SYSTEM

The real and perceived risks of nuclear proliferation have led to various forms of domestic and international safeguards for nuclear materials. The desired result of effective application of IAEA safeguards is the assurance that nuclear materials are not being diverted from peaceful applications to nuclear weapons. This goal is different from that of domestic safeguards, which relies on the state's own physical protection and materials accounting measures. Effective verification of safeguards is essential to a credible nonproliferation regime; such a regime promotes confidence among states, helps strengthen their collective security, and plays a key role in preventing the proliferation of nuclear weapons. Therefore, international safeguards are an essential feature of all commercial nuclear industries, especially in the Post-Cold War era.

The primary objective of a safeguards system is to detect and deter diversion of nuclear materials for malevolent use. Generally speaking, safeguarding nuclear materials from diversion consists of two main elements—physical protection and materials accounting. An analogy exists with the banking industry, which also routinely uses security (vaults, guards, cameras, etc.) in conjunction with accounting, computerized recordkeeping, and outside auditors. The banking analogy is complicated by the role of nonnegligible measurement errors in the determination of fissile nuclear materials in a complex matrix, such as spent fuels.

The first element, physical security, is necessary to deter and prevent outsiders from simply taking what they want by force. Rogue nations and terrorist organizations will always have malevolent uses for special nuclear materials (SNMs). Although spent-fuel handling poses near-term safety hazards, those hazards alone may not discourage highly motivated adversaries; therefore, provisions to circumvent such hazards are necessary. It has been argued that Iraq, for example, gained valuable technical expertise from separating gram quantities of plutonium from spent fuels, even though the plutonium itself was of minimal use.[4] Diversions of large quantities of material would have still more ominous implications.

Quantitative data on SNM contents of spent fuels are necessary for reprocessing, as well as safeguards, purposes. Accounting based on such measurements allows the operating facility to track SNM within defined boundaries. Associated records are extremely useful in detecting diversion by those who are not in a position to falsify paperwork or corrupt a computerized data base. In addition, accounting records can help resolve innocent, common mistakes that arise.

Lastly, review of accounting data by external auditors is helpful. Just as insiders at banks have, at times, been successful in defeating internal security/accounting and embezzling funds, insiders at nuclear facilities have the potential to remove SNM without being detected internally. In safeguards, the IAEA plays the role of an outside auditor. The IAEA reviews the declared inventories and selects items on a sampling basis for independent measurement. It is unnecessary and prohibitively expensive to measure all items. Those independent measurements are then compared with values declared by the facility to verify the inventory.

Extension of these basic concepts to spent-fuel safeguards is by no means simple. Because no facilities for the final disposal of spent-fuel assemblies have been established, most of the spent fuels are (and will be) stored for long periods in engineered retrievable storage systems. One important safeguards consideration related to spent-fuel storage is the fact that spent fuel—or more precisely, the plutonium contained in spent fuel—becomes more accessible with increasing cooling time because of the decay of fission products. This means that the degree of radiological self-protection is decreasing, and the attractiveness for diversion is increasing.

III. SPENT-FUEL DISPOSAL STRATEGIES

Currently, there are two generic approaches to spent-fuel management. One involves permanent storage of spent fuel in geologic repositories, and the other involves reprocessing of spent fuels and recycling of uranium and plutonium in thermal and fast reactors. Nations that are committed to spent-fuel reprocessing include Argentina, Belgium, Bulgaria, China, Czechoslovakia, Finland, France, Germany, Hungary, India, Italy, Japan, the Netherlands, Switzerland, the U.K., and the former USSR (Ref. 5). Canada, Sweden, and the United States initially opted for permanent storage of spent fuels in geologic formations. Other nations with nuclear power programs are temporarily storing spent fuels in a variety of locations and will choose one of these options in the future.

Canada and Sweden considered final geologic disposal of spent fuels as an option based on the U.S. strategy for spent-fuel disposal. However, in 1989, Canada postponed a final decision on the disposition of spent fuels until the middle of the next century. In the meantime, Canada plans extensive dry storage for its Canada deuterium uranium (CANDU) fuels.

Sweden has actively pursued nuclear power termination and geologic disposal of spent fuel. However, Sweden is currently reevaluating its past declarations to terminate the nuclear power options and permanently dispose of spent fuels and has postponed all actions to implement an earlier decision to terminate all nuclear power generation by 1995. It may also adopt a more realistic position on spent-fuel disposal in the near future.

Taiwan and South Korea continue to express their desire to recycle plutonium from spent fuels in their commercial reactors. South Korea is now engaged in a joint program with Canada to develop a fuel cycle to use spent pressurized water reactor (PWR) fuels in CANDU reactors as a form of recycling fissile materials from spent light water reactor (LWR) fuels.[6]

IV. SAFEGUARDS FOR U.S. SPENT NUCLEAR FUELS

The U.S. spent-fuel management system is the largest in the world. It is slated for international safeguards as part of a U.S. voluntary offer of civilian nuclear facilities for international safeguards. This offer was made by President Johnson in 1967 as an inducement to other countries, especially the former West Germany and Japan, to sign the nuclear nonproliferation treaty. The U.S./IAEA Safeguards Agreement[7] was endorsed by the U.S. Senate and entered into force on December 9, 1980. To prescribe policies and responsibilities, the DOE and the U.S. Nuclear Regulatory Commission (NRC) have issued orders and regulations for compliance with this agreement.[8,9] Accordingly, there are nearly 200 nuclear facilities in the United States that have the potential to be under IAEA safeguards. These include all commercial reactors and fuel fabrication facilities and almost all research reactors, critical assemblies, and test reactors in the United States.

At the end of 1990, ~22 000 metric tonnes (Mt) of uranium in spent fuels had been discharged from commercial LWRs in the United States.[10] This quantity represents almost all the spent fuels (~77 000 assemblies) accumulated from U.S. nuclear power generation since 1968, including those from plants that have already been shut down and/or decommissioned. Of this total, ~8400 Mt (or 46 800 assemblies) are boiling water reactor fuels and 13 600 Mt (or 30 200 assemblies) are PWR fuels. It is estimated that this inventory will increase to 40 000 Mt by the year 2000 and to 85 000 Mt by the year 2035, when all presently operating reactors will have reached their design life of 40 yr (Ref. 11). Should additional plants come on line during the interim, the future inventories will be even larger.

The 1990 inventory of spent nuclear fuels in the United States represents fuels from two types of LWRs owned and operated by 54 utilities. These fuels were manufactured by 10 vendors and represent 88 different fuel designs. Present inventories of SNFs were discharged from more than 120 commercial reactors and have a wide range of burnup values. The complexities of geometry, configuration, and burnup of spent fuels and the geographic distributions of spent fuels in 37 states and at 74 locations make SNM content verifications by the IAEA challenging and resource intensive.

Because of the limited resources of the IAEA, only a few facilities in the United States are now chosen for IAEA safeguards at any one time, and this list of facilities is changed periodically by the IAEA in consultation with the United States. In applying safeguards at U.S. nuclear facilities, the IAEA employs the same scheme as it does for facilities located in non-nuclear-weapon states.

It is extremely challenging to design a safeguards system for the anticipated inventory of spent fuels. Equally, it would be a highly resource-intensive effort for the IAEA to verify the distributed inventory of spent fuels and the inventory placed in a geologic repository with a storage capacity for 66 000 Mt of fuels. The latter has a 25-yr operational phase and a 50-yr retrievable phase as required by law. The current schedule for the opening of the first geologic repository for spent fuels and HLWs in the United States is the year 2010 (Ref. 11).

V. DOMESTIC AND INTERNATIONAL SAFEGUARDS

Spent fuels now in the United States are in the custody of nuclear utilities and are under domestic safeguards required by the NRC. Currently, the NRC does not require accounting and verification for SNM in spent-fuel assemblies in storage locations. The NRC only verifies the existence of a viable domestic safeguards system for spent fuels at reactor sites and at storage locations.

In the international safeguards arena, material accountancy is considered the primary measure for nuclear material safeguards, and carefully scheduled independent verification of the accountancy system and inventories is extremely important in detecting diversions. The requirements include verification of declared inventories and the ability of safeguards systems to detect the loss of one significant quantity of SNM (presently defined as 8 kg of contained plutonium) within a 3-month period. This latter requirement, impractical though it may be, would put enormous pressure on the U.S. spent-fuel management system if international safeguards were applied to all spent fuels in U.S. inventory.

VI. U.S. SPENT-FUEL MANAGEMENT SYSTEM

The Nuclear Waste Policy Act[12] of 1982 and the Nuclear Waste Policy Act Amendments[13] of 1987 are the congressional mandates for all U.S. programs for the disposal of SNFs and HLWs. Neither piece of legislation addresses the long-term international safeguards for spent fuels in geologic repositories.

The key elements of current U.S. strategy for spent-fuel disposal are shown in Fig. 1. Current strategy for the first geologic repository also includes the placement of some of the vitrified HLWs from defense programs (not shown in Fig. 1). Spent-fuel assemblies will be packaged in appropriate containers and will be placed in engineered facilities within a geologic repository.

Current plans for spent-fuel disposal include various options for packaging and transporting items from reactors to the geologic repository. Almost all activities leading to the final disposal of spent fuels affect long-term safeguards. Accounting for fissionable materials in various spent-fuel-derived waste forms, such as intact spent-fuel assemblies, canistered spent-fuel assemblies, consolidated rods, and non-fuel-bearing materials, are required by the NRC to satisfy the needs of domestic safeguards.

IAEA safeguards additionally require periodic verification of the declared SNM values by direct measurements or by item accounting. Independent verification capability will be considerably more intrusive if rods are consolidated. According to an independent study by the Electric Power Research Institute,[14] "a substantial burden will be imposed on the utility if a requirement for independent verification of SNM contents of SNF containers (after rod consolidation) is forthcoming, as might be anticipated if the facility is selected for IAEA safeguards." Another detailed, site-specific study (for the Yucca Mountain Site repository) of consolidation of spent fuels has demonstrated the undesirability of consolidation.[15,16]

As part of the research and development for spent-fuel management, several prototypical rod consolidation demonstration programs have been funded, and a selected few have completed hot demonstrations. The next phase is to develop facilities and equipment for large throughput operations. These efforts to consolidate and store spent fuels will make the safeguards implementation efforts all the more complex and expensive.

Spent-fuel consolidation is promoted as a means of conserving storage space and transportation costs. However, the radiation exposure penalty associated with this approach and the safeguards consequences are extremely undesirable. The pros and cons of rod consolidation were reexamined by the DOE. They concluded that the ongoing consolidation efforts by utilities are not consistent with the waste management system requirements and that spent-fuel preparation for disposal should be performed in the federal waste management system rather than at reactor sites. The DOE has, however, reserved the option to reevaluate the desirability of consolidation during the advanced conceptual design of the repository and the waste package.[17]

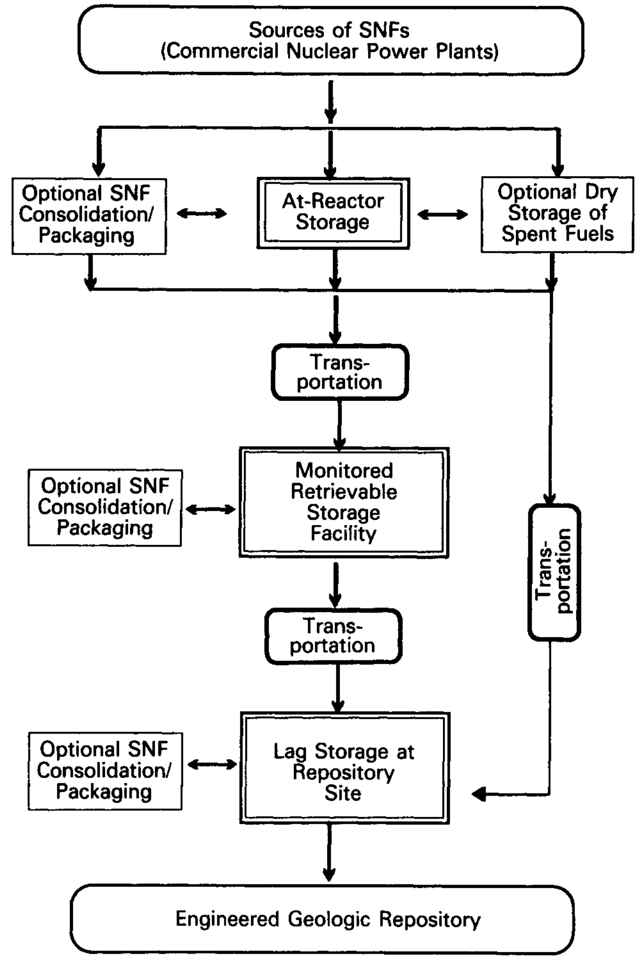

Fig. 1. Major elements of the U.S. program for geologic disposal of spent fuels.

VII. DIVERSION SCENARIOS FOR SPENT NUCLEAR FUELS

In the international safeguards arena, sovereign nations are considered potential diverters of nuclear materials for clandestine use. To design credible safeguards systems to detect and deter such diversions, it is necessary to anticipate possible diversion scenarios and develop scientifically sound approaches to counter them. Although some states may consider diversion scenarios as an affront to their commitments to international safeguards, the relevance of the analysis of potential diversion scenarios to the credibility of international safeguards is important.[18] In domestic and international safeguards, "timely detection" and "deterrence" have become prominent and are even seen by some to be overriding objectives.

To understand possible diversion scenarios of nuclear materials from spent fuels, major features of a fuel rod consolidation facility and operational features of a geologic repository are presented in Figs. 2 and 3, respectively. Because there is

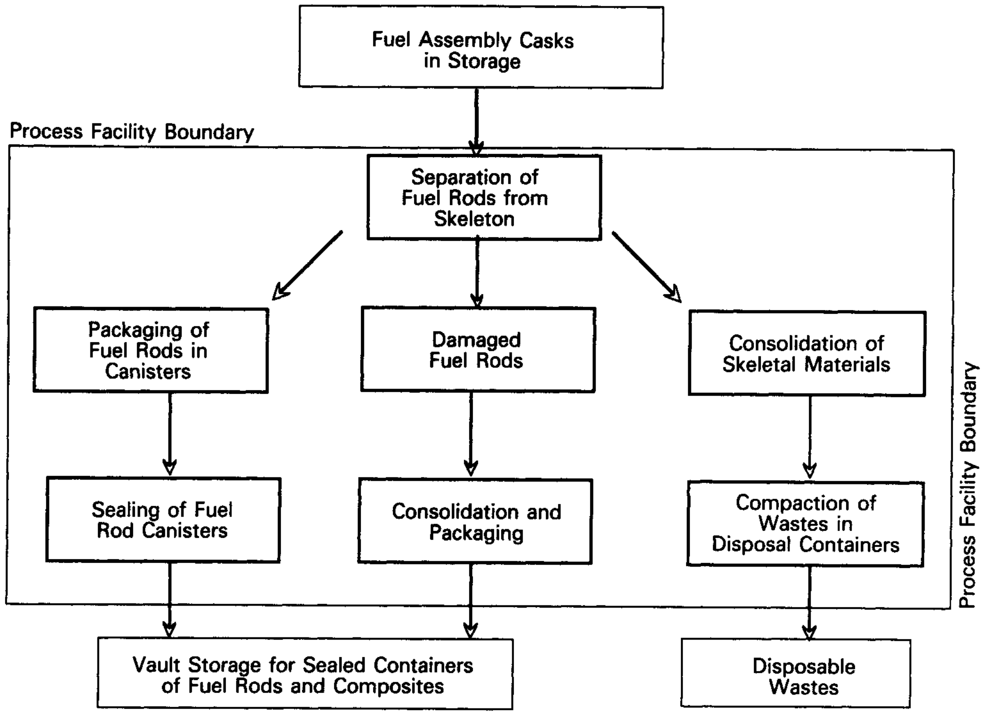

Fig. 2. Major features of a generic fuel rod conditioning facility.

no large-scale consolidation facility or geologic repository in existence at the present time, the features presented in Figs. 2 and 3 are generic to available conceptual designs of geologic facilities.

It is customary to identify relevant diversion scenarios as part of the design of a safeguards system. Each scenario has different risks associated with it, including the risk of detection. In addition, different material types may require different processes to convert the diverted materials into useful (for weapons) nuclear material. In the context of international safeguards for SNFs, possible diversion scenarios involve a variety of locations and include the following, listed in time order as SNF moves from the reactor to the geologic repository:

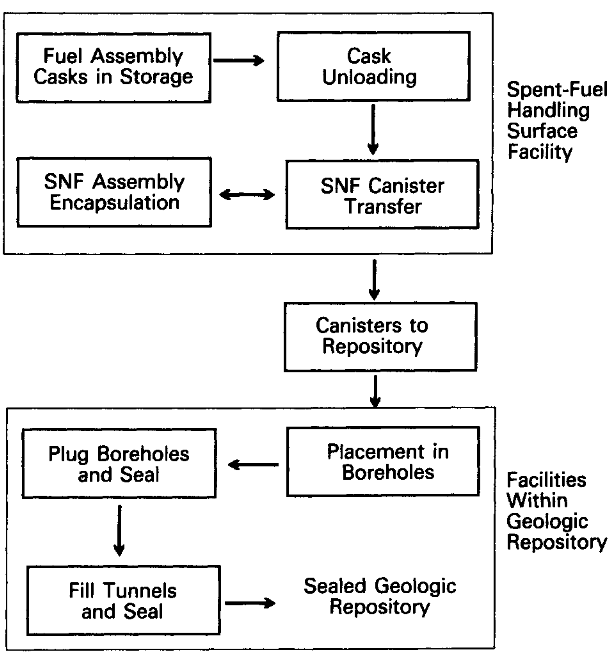

Fig. 3. Operational features of a geologic repository.

1. removal of fuel rods from assemblies at the reactor storage pools
2. removal of fuel rods during in-pool consolidation at reactor sites
3. removal of fuel assemblies from dry storage away from reactor pools
4. removal of fuel rods or assemblies from large interim storage facilities, such as the Monitored Retrievable Storage Facility being planned in the United States
5. removal of fuel rods during consolidation at fuel conditioning facilities
6. removal of fuel assemblies or consolidated fuel rods at the consolidation facility
7. removal of damaged or consolidated fuel rods along with non-fuel-bearing wastes from conditioning facilities
8. removal of canned spent fuel at the repository site
9. removal of spent-fuel containers from boreholes within the repository during the operational or retrievable phase of the geologic repository
10. clandestine removal of the contents of a sealed geologic repository after the repository is closed.

In all cases, diversion of material could be accompanied by substitution of dummy items, manipulation of seals, and/or falsification of accounting records, which could help conceal the removal(s) from the IAEA. Note that diversion could, in principle, occur in any number of locations; discovery of missing material at one location need not preclude the possibility that the material was removed elsewhere.

To some, it might seem ideal to have independent IAEA inspectors (or teams) permanently present at each of the facilities. This is impractical and prohibitively expensive. Therefore, the scenarios just listed place a heavy burden on verifiable containment and surveillance. Resource limitations on inspections make immediate detection of diversion less likely. However, periodic inspections offer hope of delayed detection.

VIII. SAFEGUARDS CONCEPTS

Currently, SNFs in the United States are only under domestic safeguards required by the NRC. The large accumulation of SNFs at more than 70 reactor sites in the United States suggests that safeguarding spent fuel would place a heavy burden on resources when the U.S. spent-fuel management regime comes under IAEA safeguards. Although many of the systems and technologies available can be adapted to safeguard spent fuels, other systems are needed.

A number of IAEA member states, including the United States, consider spent fuel as a material form for which safeguards cannot be terminated, even after permanent disposal in a geologic repository.[19] However, there has not yet been a systematic investigation of the consequences of this policy and the practical difficulties of maintaining safeguards for spent fuels under presently accepted regimes.

The long-term safeguards of spent fuels in a geologic repository have no parallels in IAEA's experience. In contrast to bulk-handling facilities, it is not possible to obtain accurate measurements at modest cost. This problem forces increased reliance on physical security measures. Although a number of research efforts are under way to develop better measurements of the fissile contents of spent fuels, none of them are available in the near term.[20,21] The 1991 IAEA consultants' meeting concluded that an unbroken continuity of knowledge of the SNM content of spent fuels should be maintained,[22] but the impracticability of continuous inspector presence makes verification more difficult.

The key elements of a U.S. spent-fuel management system include various surface storage modes, conditioning, containerization, transportation, and geologic emplacement. Although conditioning of SNFs is not a requirement for geologic disposal, currently conceived conditioning and consolidation scenarios for SNFs make measurement and verification of SNM contents even more difficult.[23] Recognition of these realities moves us to discount materials accountancy as the overriding measure for safeguarding spent fuels in the United States. Development of an alternative that is pragmatic and consistent with international safeguards requirements is needed.

Maintenance of safeguards through all stages of SNF storage, transportation, and long-term storage is challenging and resource intensive. In conceptualizing a safeguards system for U.S. spent-fuel management to meet domestic and international safeguards requirements, we recognized the need for resolving several fundamental issues in consultation with the IAEA.

IX. SAFEGUARDS ISSUES

Some of the fundamental issues of safeguards that need examination and near-term resolution may be grouped into three areas:

1. System performance issues

   a. In the international safeguards arena, materials accountancy is considered the primary measure for safeguarding SNM. However, this approach has serious limitations for verifying the fissile contents of spent fuel because of the limitations of available nondestructive assay (NDA) techniques for measuring the fissile contents of spent fuels. In recognition of this limitation, the IAEA currently maintains the integrity of the spent-fuel assemblies discharged from reactors and verifies the item integrity of the assembly.[2] This approach has serious limitations for dealing with storage modes other than spent-fuel pools at reactor sites. Therefore, a serious examination of alternatives, such as containment and surveillance as primary measures to safeguard SNFs in large storage facilities, is necessary for establishing a viable alternative to materials accountancy.

   b. Nuclear materials are categorized as "direct-" and "indirect-use" materials based on the ease with which they can be converted into components of nuclear explosives. Spent nuclear fuel comes under the category of indirect-use material. However, 8 kg of plutonium contained in spent fuel is considered a "goal quantity," the loss of which should be detected within a 3-month period. This is an unachievable goal in the context of large distributed inventories of spent fuel within a facility and associated dry and wet storage facilities. Therefore, a serious effort should be directed at developing pragmatic alternatives to current goal quantity and timeliness of detection goals for spent fuels.

   c. Criteria for establishing detection probabilities for diversion or loss for SNFs in storage are extensions of criteria established for bulk nuclear materials. These criteria are important because of their implications in selecting sample sizes for verification, allocating inspection resources, and ensuring nondiversion using available technologies. In light of the enormous quantities of spent fuels that are accumulating at storage facilities, these criteria need reexamination and resolution in favor of a separate set of criteria for spent fuels.

2. Implementation-specific issues

   a. Scenarios for diversion of spent fuels during all phases of storage and placement in geologic repositories (see Sec. IV) should guide the development of specific approaches to implementing safeguards.

   b. Engineered systems for consolidating SNFs should have safeguards features to maintain verifiable continuity of knowledge of SNM during the consolidation process.

   c. Establishment of a separate regime for SNFs based on a properly defined attractiveness level, including burnup and decay time, is necessary. Such a regime must be able to meet the unique challenges involved in maintaining safeguards for spent fuels at a variety of storage locations for extended periods. Such a regime, generally known as "graded safeguards," is also necessary to properly allocate resources in proportion to risks involved.

d. Consequences of consolidation, compaction, and containerization for safeguarding spent fuels for long-term surface storage or geologic disposal or both have not been properly addressed. Similarly, special requirements to maintain safeguards for damaged spent-fuel assemblies and fuel rods during consolidation are necessary.

e. A safeguards regime for international commerce in long-term spent-fuel transfer will require new approaches and innovations.

3. Long-term issues

a. A majority of the member states of the IAEA, including the United States, considers that safeguards on spent fuels cannot be terminated at any storage facility.[19] However, strategies, technologies, and resource requirements for maintaining long-term (perpetual) safeguards for spent fuels placed in long-term surface storage and in geologic repositories have not been addressed. Developing criteria for terminating safeguards for spent fuels in geologic storage may be considered as a possible alternative to perpetual safeguards.

b. New fuel cycle technologies would affect spent-fuel management systems and their safeguards regimes. As such, technology required to maintain a verifiable safeguards regime for spent fuels destined for geologic disposal needs continuous examination.

A safeguards regime for spent fuels that is designed to make verifications less burdensome through containment and surveillance, item accounting, and seal verification seems to be a reasonable approach at this time. Some quantitative measurements are still necessary to meet the safeguards requirements of the IAEA. Therefore, a desirable research goal is the development of an NDA measurement system that can measure fissile contents of spent fuels without reliance on operator-provided data.

X. DESIRABLE FEATURES OF A SAFEGUARDS SYSTEM

The fundamental requirement of international safeguards is the assurance that the continued presence of nuclear materials within designated boundaries can be demonstrated. This requires accounting for and controlling nuclear materials within spent fuels, thereby enabling state and international regulatory agencies to verify the safeguards system. In addition to containment and surveillance, one of the mechanisms IAEA uses to detect diversion of plutonium contained in spent fuels is to verify the plutonium content of fuel assemblies by independent measurements. However, such measurements are time consuming and usually have large uncertainties; both qualities limit their role in verification.

Physical security of nuclear materials through containment and surveillance systems is considered a complementary measure of international safeguards because such systems can sometimes be defeated by state-sponsored insiders. Assuming that the issues identified in Sec. VII will be resolved in favor of operational safety and cost minimization, some of the desirable features of a safeguards system for the long-term storage of U.S. spent fuel may be identified as follows:

1. Facility design and operations

a. building large storage facilities to provide easy access for periodic verification, with minimal radiation hazards

b. maintaining item integrity for spent fuel at reactor storage facilities for several years after the items are discharged from reactors to facilitate access for verification

c. maintaining verifiable records of fuel assemblies that underwent pin exchange or reconstitution and of the subsequent irradiation history of the assembly

d. using item rebatching operations in conditioning and consolidation facilities to ensure that SNM is not lost

e. maintaining a buffer storage and fuel handling facility at the geologic repository for temporary storage of sealed items and, if emergencies arise, for repacking fuels damaged during the transportation and verification of spent-fuel containers

f. using redundant and independent containment and surveillance systems during geologic emplacement and the retrievable phase of repository operations to deter and detect tampering with SNF packages placed in boreholes

g. arranging for IAEA inspectors to witness repository sealing after waste placement and retrievable phase of operation of the repository

h. providing for periodic and challenge inspections by the IAEA.

2. Alternatives to quantitative measurements

a. verifying declared burnup values of spent-fuel assemblies and estimating fissile contents of assemblies

b. using attributes measurements such as weights and characteristic radiation as part of the safeguards system design at all locations of SNF handling, storage, and conditioning; such measurements have the potential to detect a variety of unauthorized activities

c. radiation fingerprinting of packages in boreholes during the retrievable phase of geologic repository operations to detect intrusion into boreholes containing SNF canisters.

3. Use of tamper-indicating seals

a. applying tamper-indicating seals to the fuel assemblies to maintain item integrity for future verification

b. placing tamper-indicating seals on containers of secondary forms of the SNF that have undergone modifications, such as pin exchanges, consolidation, compaction, and containerization

c. designing dry SNF storage locations, such as the Monitored Retrievable Storage Facility, so that SNFs would be in large sealed containers to minimize the number of units for inspection

d. arranging for IAEA inspectors to use tamper-indicating seals to detect intrusions into drift and tunnel closures during waste placement and the retrievable phase of repository operation

e. using tamper-indicating seals during transportation and interim storage to make seal verification a possible safeguards measure.

4. Containment in and surveillance of storage facility

a. establishing item accountancy, item verification, and a site-specific containment and surveillance system as key safeguards measures for spent-fuel management

b. use of well-designed perimeter monitoring systems to monitor the movement of all radioactive materials during the retrievable phase of geologic disposal; a combination of radiation detectors and optical devices with the ability to record events in real time are desirable

c. installing sensing devices at key locations throughout the repository site to detect penetrations to the repository

d. using state-of-the-art sensors at key locations throughout the repository to detect large-scale earth movements in the vicinity

e. remote monitoring of sensors for earth movement and repository penetrations.

To design a pragmatic safeguards system for spent fuels, a variety of cost-benefit trade-offs need intensive study. These efforts are difficult, resource intensive, and have not yet been seriously undertaken. If the safeguards requirements are to be kept constant over time, inspection costs will increase because of increasing inventories and attractiveness of aged fuels.

The newly initiated research and development program by the Office of Arms Control and Nonproliferation of the DOE, the increasing involvement of the NRC, and the continuing efforts of the IAEA can result in the development of necessary systems and equipment to maintain a credible safeguards regime for the U.S. spent-fuel management system.

In addition, it is desirable that the international community recognize that (a) spent fuel is a unique form of nuclear material whose value and desirability for diversion increase with time, (b) the limited resources of the IAEA will require some prioritization of inspections, and (c) spent fuels cannot have a high priority. IAEA fora, such as the Standing Advisory Group on Safeguards Implementation, should discuss these topics objectively to arrive at some pragmatic solutions to address the problems of safeguarding very large inventories of spent fuels accumulating in 30 member states of the IAEA.

To place safeguards issues in a more concrete setting, we examined some spent-fuel discharges from U.S. nuclear power plants. The results of that analysis[3] show that the falsification of several significant quantities of plutonium is unlikely to be detected by materials accountancy alone unless a gross falsification (i.e., a large falsification for an assembly that is inspected) is clearly revealed.

XI. INVENTORY VERIFICATION

Considerable data are available on spent fuels generated in the civilian sector in the United States since 1968 (Ref. 11). In principle, the burnup data on spent fuels may be verified using unfalsified irradiation history and available fork detectors.[24] The fork detector system, using a combination of neutron and gamma measurements, is capable of detecting gross defects (of 20% or more) in single fuel assemblies. However, fork measurements are time consuming and resource intensive.

As an illustrative example, consider a not-so-hypothetical storage location in the U.S. system that has ~770 spent-fuel assemblies. This initial inventory increases at the rate of ~77 spent-fuel assemblies per year. Assume quarterly inspections during which it is possible to verify 10 assemblies using a combination of quantitative measurements and that there are resources to verify the seals of 80 additional fuel assemblies. According to current estimates, this limited inspection will cost the IAEA approximately $250 000 annually for a single storage facility. Cost to each facility may be slightly less, not including downtime for the associated reactor(s).

During the initial inspection, a specified assembly has a probability of 760/770 = 98.7% of escaping quantitative measurement and a probability of 680/770 = 88% of escaping inspection. In other words, the probability of a specified assembly in the initial inventory being verified by attributes measurement is ~1%. Similarly, the probability of a specified assembly in the initial inventory being verified by measurement or seal verification is <12%.

By the end of the first 3 months, assuming a steady-state input, 19 new assemblies will have arrived at the storage location. The preceding probabilities for the quarterly inspection are 779/789 (or 98.7%) and 699/789 (or 89%), respectively. Combining these figures with the results of the initial inspection, it can be seen that the probability that a specified assembly present in the initial inventory escapes inspection during both the initial inventory and the first quarter is 78%, equal to the product of the two noninspection probabilities.

Figure 4 shows how the probability of verifying a fuel bundle in the initial inventory increases over 20 yr (or 80 quarters). The dotted line shows the probability of a fuel assembly from the initial inventory being selected for verification through measurement, and the solid line represents the probability of being selected for seal verification or measurement. This figure quantifies one measure of timeliness, namely, the probability that an assembly escapes inspection for a time period. For example, we see that an assembly in initial inventory will, with probability exceeding 60%, be inspected within 2 yr. The same rationale

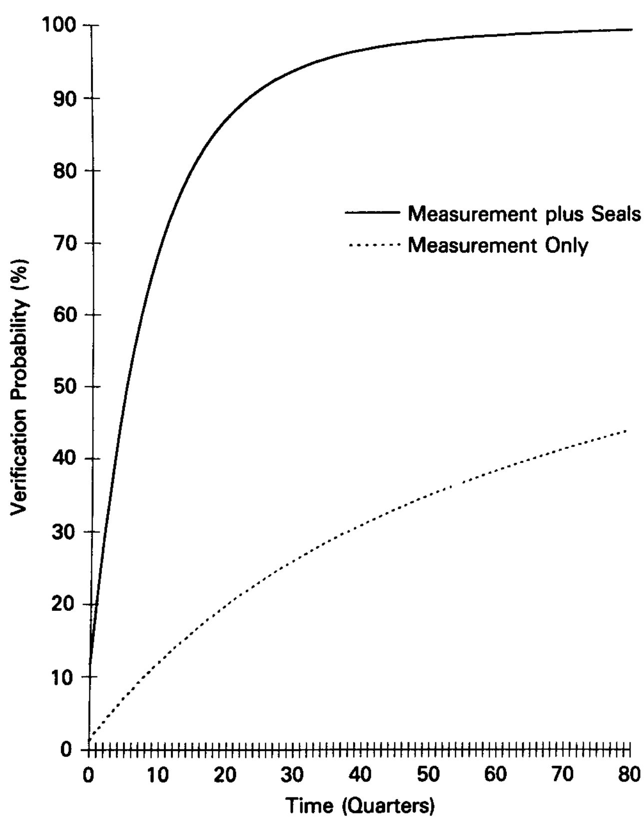

Fig. 4. Probabilities of selection of a spent-fuel assembly in the initial inventory for verification during quarterly inspections for 20 yr.

applies to quantitative measurement, except that the result is ~10%.

Similarly, the probabilities of any fuel bundle in the inventory being selected for verification during a single quarterly verification are shown in Fig. 5. The probability of inspecting a particular assembly during a single inspection drops from ~12% during the initial inventory (as noted earlier) to 3.8% for the inventory following 20 yr of operation.

Because inspection resources are assumed constant and the inventory increases over time, detection sensitivity (Fig. 5) decreases with time. Nevertheless, an assembly in the initial inventory has an ~40% chance of a semiquantitative verification at some point during a 20-yr period. The limited resources allow modest detection sensitivity at a modest level of timeliness as reflected in Figs. 4 and 5. Thus, the deterrence value of inspections greatly exceeds that for approaches relying on seals alone.

XII. SUMMARY

The U.S. spent-fuel management system must develop pragmatic approaches to domestic and international safeguards. The approach conceptualized here helps to design a viable, cost-effective safeguards system. The need for very large resource requirements to establish initial inventories and carry out periodic verifications is evident.

The inspection scenario discussed in this Letter to the Editor illustrates the difficulty associated with bringing a very large spent-fuel management system into an international safeguards regime. Inspection scenarios less comprehensive than that described here could be considered if desired. For example, if it proved impractical to inspect 74 locations every 3 months, timeliness of detection might suffer. Calculations similar to those shown earlier could be carried out for such cases. Also, by equating significant quantity to a specified number of assemblies, the probability of detecting such an anomaly could be determined.

Because the anticipated time interval between reactor discharge and geologic disposal may be 25 to 100 yr, maintenance of safeguards during surface storage itself can be enormously expensive. Therefore, a systematic effort is necessary to optimize the use of technologies and resources to meet long-term safeguards requirements. Spent-fuel management in perpetuity is very different from all other nuclear materials management, and consideration should be given to establishing IAEA requirements to meet the unique needs of long-term SNF management.

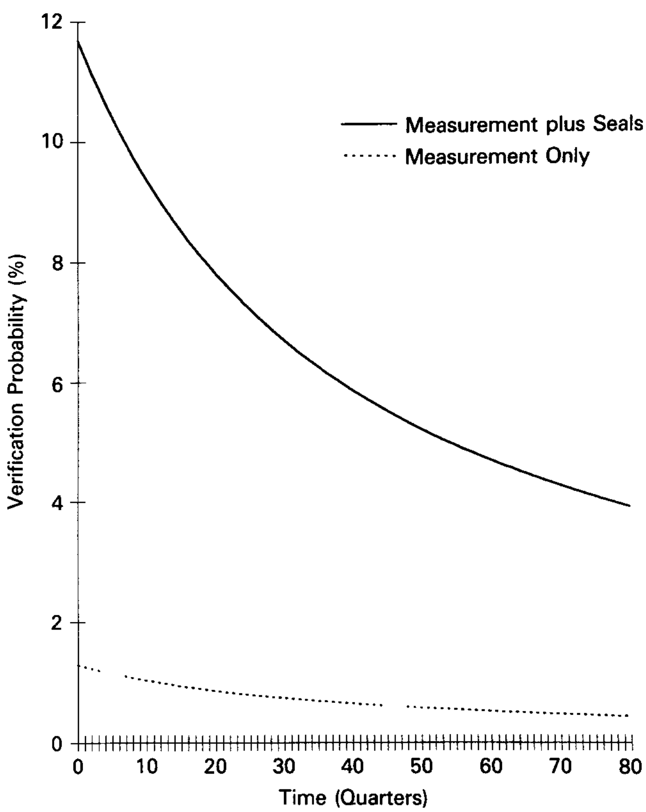

Fig. 5. Probabilities of selection of any spent-fuel assembly in the inventory for verification during quarterly inspections for 20 yr.

K. K. S. Pillay
R. R. Picard
J. F. Hafer

Los Alamos National Laboratory
Safeguards Systems Group
Los Alamos, New Mexico 87545

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Comment on "Analysis of Cluster Geometries Using the DP1 Approximation of the $J_{\pm}$ Technique"

This letter is in response to statements made in Sec. I of Ref. 1. Specifically, I wish to point out that the following statement is totally incorrect: "Most calculations performed to date using the $J_{\pm}$ method for two-dimensional geometries made use of the DP_0 approximation, where only isotropic angular fluxes at each interface are considered.[6–8]"

First, Marleau and Hébert's[1] reference to the work of Cheng, McDaniel, and Leonard[2] (listed as Ref. 6 in Ref. 1) and that of Anderson and Honeck[3] (listed as Ref. 7 in Ref. 1) as having applied only the DP_0 approximation in two-dimensions is wrong. Second, Marleau and Hébert appear to be unaware of or to ignore a number of publications from 1975 to 1987 on the use of the interface current ($J_{\pm}$) technique with higher angular current approximations (DP_1 and DP_2). These include some publications on the use of the $J_{\pm}$ technique with higher angular current approximations in combination with the first-flight collision probability technique in exactly the type of fuel cluster geometry as in Ref. 1.

It is well known[4] that in one- or two-dimensional geometry, the DP_0 approximation corresponds to only a one-term half-space angular current expansion (cosine current). The DP_1 approximation results in a two-term expansion[5] in slab geometry and a three-term expansion[3] in two-dimensional geometry. The work of Cheng, McDonald, and Leonard[2] was the first attempt to improve the $J_{\pm}$ technique in two dimensions by considering a two-term expansion better than DP_0. The full DP_1 expansion was used in two dimensions for the first time by Anderson and Honeck[3] and Anderson.[6] Subsequently, Häggblom and Ahlin,[7] Mesina and Emendorfer,[8] Maedar,[9] Sanchez,[10] Wasastjerna,[11] Saji et al.,[12] and Stepanek[13] used the DP_1 approximation to represent angular currents at region interfaces. In most cases, general formulations with the DP_N approximation were given. But, the results were restricted to DP_0 and DP_1 in all the foregoing cases. Since the expansion coefficients are different on the four sides of a rectangle, Maedar called it quadruple P_1 expansion. Wasastjerna termed it sextapole P_1 expansion as applied to hexagons. Out of these, Mesina and Emendorfer,[8] Sanchez,[10] and Saji et al.[12] considered heterogeneous fuel assembly (fuel rods in a square assembly) problems. Also, Sanchez[10] used the $J_{\pm}$ technique to couple cell regions inside which only the collision probability technique was used. I[14] used the DP_2 approximation (six-term expansion) for two-dimensional problems to improve the predictions of the $J_{\pm}$ technique, especially in problems with controlled fuel assemblies. A four-term expansion, which is nearly equivalent to the full DP_2 expansion, was also identified.[14]

In the meantime, Krishnani and Srinivasan[15] had applied the $J_{\pm}$ technique with the DP_0 approximation to couple rod cluster rings, within which the collision probability technique was used, of pressurized heavy water reactor (PHWR) fuel clusters. Later, Krishnani[16] used DP_1 and DP_2 approximations of angular currents in the above method to get more accurate results for PHWR fuel clusters. He applied[17] this method to light water reactor assemblies also.

In view of all the aforementioned developments, the first-mentioned statement of Marleau and Hébert shows that either they are working in isolation or they do not give adequate credit to previous work in the same field.

P. Mohanakrishnan

Reactor Physics Division
Indira Gandhi Centre for Atomic Research
Kalpakkam, Tamil Nadu, 603 102
India

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