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Informal Report

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**Preliminary Concepts: Materials Management
in an Internationally Safeguarded
Nuclear-Waste Geologic Repository**

University of California



LOS ALAMOS SCIENTIFIC LABORATORY

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Preliminary Concepts: Materials Management in an Internationally Safeguarded Nuclear-Waste Geologic Repository

C. A. Ostenak
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EXECUTIVE SUMMARY

This preliminary study of materials accountability for a nuclear-waste geologic repository is one of a series of safeguards systems studies of internationally safeguarded nuclear fuel-cycle facilities being undertaken by the Los Alamos Scientific Laboratory (LASL). These studies are intended to define systems concepts, to develop methods for evaluating accountability systems and the data they produce, and to stimulate further development of the facilities, processes, systems, and instrumentation needed to provide more effective safeguards through improved nuclear materials accountability. Containment, surveillance, and physical protection are the subjects of companion studies by the Sandia Laboratories, Albuquerque.

These international safeguards studies are a logical extension of a conceptual-design effort to improve nuclear materials accountability in domestic fuel-cycle facilities. Both the domestic and international safeguards activities are part of an integrated safeguards systems program being implemented by the LASL Safeguards Systems Group (Q-4) at the request of the US Department of Energy's Office of Safeguards and Security (DOE/OSS). Previous domestic and international studies in the safeguards conceptual-design series address the materials management requirements for mixed-oxide fuel refabrication facilities (LA-6536), spent-fuel reprocessing plants (LA-6881 and LA-8042), plutonium-nitrate conversion (LA-7011) and co-conversion facilities (LA-7521 and LA-7746-MS), spent-fuel storage ponds (LA-7730-MS), thorium-uranium fuel-cycle facilities (LA-7372 and LA-7411-MS), and large fast-critical assemblies (LA-7315).

More than 105 nations subscribing to the Non-Proliferation Treaty of 1970 (NPT) have agreed that States' (national or domestic) safeguards systems are the foundation of international safeguards. Safeguards requirements under the NPT are described in the International Atomic Energy Agency (IAEA) document INFCIRC/153, which provides for:

- materials accountability as a safeguards measure of fundamental importance, with containment and surveillance as important complementary measures;
- the incorporation in safeguards agreements of changes resulting from improvements in safeguards technology, operating conditions and experience; and
- making full use of the State's materials accountability system and avoiding unnecessary duplication of this function.

The improved domestic materials accountability systems developed under the LASL-DOE/OSS program therefore form an appropriate base for improved international safeguards in fuel-cycle facilities.

The IAEA's accounting activities depend fundamentally on the State's system of accounting; the materials measurement and accounting system is owned and operated by the State or a licensee of the State. The IAEA is required to verify independently the State's system, and the Agency interacts with the State in a negotiated, well-defined manner. The need for reasonable safeguards goals is highlighted by international requirements for independent verification of the State's materials accountability system. Clearly, the overall effectiveness of the international safeguards system is limited by the operator's materials accountability and control system that provides the basic measurement inputs.

This report describes a reference geologic repository that receives a variety of nuclear wastes subject to both national and international safeguards. Because unnecessary safeguards can be an extravagant waste of resources, this report also addresses the degree of safeguards required and the circumstances under which safeguards might be terminated. The answers to these questions are vitally dependent on national waste-management policy, the types of wastes handled, and their previous treatment and packaging.

In addition to addressing these questions, safeguards strategies are proposed, and the technologies necessary for their implementation are identified. The current status of these technologies and requirements for additional research and development are described. Emphasis is placed on maintaining adequate safeguards for nuclear-waste repositories and in terminating these safeguards whenever possible.

An issue that determines the magnitude of safeguards efforts both nationally and internationally at a geologic repository is the presence or absence of spent fuel. Continuity of knowledge of the spent fuel must be maintained between the spent-fuel shipping point and the repository to detect and deter diversion during transportation. The technology for implementing improved international safeguards for spent fuels is currently under development.

If a waste repository handles only nuclear materials that are known to be "practicably irrecoverable" (INFCIRC/153, para. 11), then only the State's safeguards may be necessary to protect property, to prevent sabotage, and to satisfy other national objectives. The level of protection required is less than that normally afforded nuclear reactors, and, if only treated refractory wastes are involved, these safeguards can be

minimal. Conventional physical protection measures, directed at the sabotage threat, should be adequate. These measures are outside the scope of this report.

Termination of national and international safeguards should, if possible, be carried out as far upstream in the waste cycle as possible. For all secondary wastes, termination of safeguards should be done at the waste source. However, for spent fuels, termination of safeguards at the shipping point is not possible. The necessity for repackaging spent fuel elements prior to emplacement at the repository and the current inability to verify their fissile content will require that international safeguards be maintained for those materials on an item-identification basis, at least throughout the active life of the repository, and, for national safeguards, at least until the fuel canisters are emplaced and the storage area backfilled.

Any backfilled and decommissioned geologic repository, regardless of content, represents improbable national and international safeguards risks that can be addressed adequately with occasional inspections combined with environmental surveillance. Successful covert reopening of a decommissioned repository and exhumation of its contents is not a credible threat because of the magnitude of the excavation effort.

More generally, this report describes three levels of materials accountability applicable to all waste materials and modes of repository operation. In order of increasing effectiveness, they are (1) item identification, (2) item identification with tamper indication, and (3) nondestructive assay. Although the repository can frequently be operated at the lowest level of safeguards, most "waste generators" will require fissile-assay capability for waste verification. In addition, waste-assay capability at the repository may be essential for process control to ensure that health, safety, and criticality criteria are honored. The technologies available to implement these three levels of materials accountability are reviewed, and recommendations are made for additional research and development.

Future studies will address the problem of waste verification at the source, that is, at various types of nuclear production facilities that produce, treat, and package nuclear wastes.

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PRELIMINARY CONCEPTS: MATERIALS MANAGEMENT
IN AN INTERNATIONALLY SAFEGUARDED
NUCLEAR-WASTE GEOLOGIC REPOSITORY

by

C. A. Ostenak, W. J. Whitty, and R. J. Dietz

ABSTRACT

Preliminary concepts of materials accountability are presented for an internationally safeguarded nuclear-waste geologic repository. A hypothetical reference repository that receives nuclear waste for emplacement in a geologic medium serves to illustrate specific safeguards concepts. Nuclear wastes received at the reference repository derive from prior fuel-cycle operations. Alternative safeguards techniques ranging from item accounting to nondestructive assay and waste characteristics that affect the necessary level of safeguards are examined. Downgrading of safeguards prior to shipment to the repository is recommended whenever possible. The point in the waste cycle where international safeguards may be terminated depends on the fissile content, feasibility of separation, and practicable recoverability of the waste; termination may not be possible if spent fuels are declared as waste.

I. INTRODUCTION

A. Scope

The purpose of this preliminary study is to develop materials-accountability concepts to satisfy both national and international safeguards criteria for the geologic isolation of nuclear wastes, defined here as non-recycled materials. Nuclear wastes of primary safeguards concern are those containing ^{233}U , ^{235}U , and plutonium; other transuranic elements could be of future interest. Except for fuel-cycle options that declare spent fuel as waste, all waste streams are so designated because economic recovery of the contained fissile isotopes is limited by current technology.

The main body of this report consists of five major sections. Section I contains background information relating to nuclear waste materials, geologic media, potential threats, and safeguards. To illustrate specific safeguards concepts, a hypothetical reference repository is described in Sec. II. Section III describes the reference repository safeguards system and safeguards options for the materials accepted at the repository. Factors influencing the termination of safeguards are presented in Sec. IV. A summary and our recommendations are presented in the final section.

Two appendixes are included. Appendix A describes the chemical and radiological characteristics of projected waste types, container geometries, and repository receipts, all of which affect both the safeguards requirements and the ability to implement various safeguards techniques. In App. B alternative safeguards techniques ranging from item accounting to nondestructive assay (NDA) methods are described and evaluated for specific waste types.

B. Background

For over thirty years, nuclear wastes have been generated at each operating and decommissioning step of the nuclear fuel cycle.^{1,2} Increasingly large quantities of these nuclear wastes have been stored at a number of surface and shallow-burial sites.² Despite precautions taken to isolate these wastes from the biosphere, surface and near-surface storage may be neither acceptable nor practicable long-term solutions. Of the many options that have been considered for waste isolation, deep underground burial in suitable geologic media is presently the most favored technique.³⁻⁹

The principal requirement for a deep underground geologic repository is that it be operated in strict compliance with procedures and national regulations intended to ensure that the nuclear materials are properly emplaced and that they will remain safely confined for as long as necessary. A functional description of a reference repository serves to illustrate specific safeguards concepts (see Sec. II).

1. Materials Accepted at the Repository. Nuclear process wastes managed at the reference geologic repository arise from fuel-cycle operations as by-product radioactive solids, liquids, and gases having a wide range of physical and chemical properties; these are called "primary" or untreated wastes. No primary wastes will be accepted at the repository except, possibly, spent fuel, which may be accepted for geologic isolation if the fuel cycle is operated without fuel reprocessing. Treatment converts primary nuclear process wastes to more inert "secondary" wastes that are suitable for transportation, handling, and geologic storage or disposal (see App. A).^{4,6,7}

It is assumed for this study that four basic types of secondary wastes will be accepted at the reference geologic repository. The first three types, high-level waste (HLW), cladding waste (CW), and intermediate-level transuranic waste (IL-TRU), are "remote-handled" transuranic (TRU) waste. The fourth type, low-level transuranic waste (LL-TRU), is "contact-handled" TRU waste.

Secondary nuclear wastes from research and development activities could also be isolated deep underground, as could the transuranic-contaminated wastes from the defense programs of a nuclear-weapons State.^{6,8} It is possible that the defense wastes would be stored in a separate geologic repository that would not be subject to international safeguards. (See App. A for more details on waste characteristics and volumes.)

2. Materials Not Accepted at the Repository. For the purposes of this study, nuclear process wastes not accepted for emplacement at the reference geologic repository include those from (1) uranium- and thorium-ore mining, milling, conversion, and enrichment; (2) fresh uranium fuel-element fabrication; and (3) reactor maintenance. Generally, these are low-level wastes* of less concern from the standpoint of safeguards than their plutonium-containing counterparts (LL-TRU), because even those containing fissile or fertile isotopes would require isotopic enrichment, or irradiation plus chemical separation to be useful as weapons materials. Therefore, consignment of these wastes to shallow land burial rather than to deep geologic media is recommended.² Nonetheless, knowledge of the nuclear material contained in these wastes is important, both for completeness of nuclear materials accounting and to ensure that these wastes do not constitute diversion paths for weapons-usable materials that might be sent to shallow land burial. Therefore, they should be measured or identified at the waste source before safeguards are terminated to ensure that they do not contain diverted materials.

C. Geologic Isolation of Nuclear Wastes

The goal of geologic storage or disposal of nuclear wastes in stable geologic media is the isolation of these wastes from the biosphere for as long as necessary.⁶ Geologic disposal refers specifically to initial emplacement that offers little or no opportunity for

*In the US, wastes not suspected to be contaminated with transuranic elements and transuranic wastes at concentrations of less than 10 nCi/g are defined as low-level wastes, and most are consigned to shallow land burial.^{2,3}

subsequent waste retrieval. In contrast, geologic storage uses emplacement techniques intended to permit waste retrieval.^{2,5} Two types of geologic storage are "provisional" storage, which permits retrieval with methods similar to those used for initial emplacement, and "permanent" storage that can only follow "provisional" storage and from which the wastes can be retrieved only by excavation and mining. A geologic repository initially designed and operated for provisional storage can be modified for permanent storage by backfilling and sealing.^{2,7}

A principal requirement of a dry geologic medium for waste isolation is that little or no circulating groundwater be present; thus, mechanisms by which emplaced wastes could reach the biosphere are greatly reduced.^{2,9} Though certain geologic media may meet all the basic criteria for a waste repository, a site chosen within a given geologic formation may still prove unacceptable because of prevailing geologic and/or hydrologic conditions.⁵ Therefore, each potential waste-repository site must be evaluated and selected according to its unique setting.

1. Geologic Media. Suitable geologic media for repository sites can be arranged into three groups:^{5,6,10-13} (1) evaporites, (2) other sedimentary rock deposits, and (3) igneous and metamorphic crystalline rocks. All these geologic media are presently under consideration as hosts for nuclear waste isolation.

Evaporites are sedimentary rocks⁵ consisting of highly ionic chemical compounds that have accumulated during the evaporation of large bodies of water. Members of the evaporite family include (1) rock salt (bedded or domed), (2) anhydrite, (3) gypsum, and (4) potash.

Sedimentary deposits other than evaporites may also be suitable geologic media for waste repositories. Members of this group include (1) argillaceous formations (clay, claystone, mudstone, siltstone, shale, and slate), (2) calcareous formations (limestone, dolomite, and chalk), and (3) arenaceous sediments (sandstone).

Igneous and metamorphic rocks of interest are crystalline or "hard" rocks that have potential as geologic media for nuclear-waste emplacement. Members of this group include (1) granite, gabbro, basalt, and tuff (igneous rocks) and (2) gneiss and schist (metamorphic rocks).

Extensive data have been generated that support strong arguments in favor of nuclear-waste isolation in several different geologic media. Though geologic predictions are inherently uncertain, it is possible to extrapolate historical geologic events and experiences in an attempt to select acceptable repository sites.^{3,6}

2. National and International Experience. For over 20 years, nuclear-waste research in the US has been directed toward waste emplacement in underground bedded salt.^{3,6,10,14-16} Therefore, the first pilot-scale geologic repository in the US will likely be located in deep bedded salt.³ Among other geologic media being investigated in the US are salt domes, granite, basalt, clay, shale, and tuff. In addition, attempts are being made to develop criteria for repository site selection, suitable environmental standards, and licensing.^{3,6,8,12,13,17}

Internationally, many countries are proceeding with plans and pilot-scale projects for interim underground storage of wastes until acceptable long-term solutions are developed.^{6,11,18-22} Some of these countries and the geologic media that each is studying are (1) the United Kingdom (clay and granite), (2) France (granite and rock salt), (3) Germany (rock salt), (4) Belgium (clay), (5) the Netherlands (rock salt), (6) Italy (clay), (7) Sweden (granite and clay), (8) India (granite, basalt, and non-evaporite sedimentary deposits), (9) Japan (granite, tuffs, and sedimentary deposits), and (10) Canada (granite and rock salt).

Although national programs and projects may differ, waste-management issues are universal to the nuclear community. International cooperation takes place through organizations such as the International Atomic Energy Agency (IAEA), the European Economic Community (EEC), the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD), as well as through bilateral exchanges and agreements.¹¹

D. Safeguards Requirements

1. National Safeguards and the Subnational Threat. The safeguarding of waste at the national level is the responsibility of the State. However, most nuclear wastes sent to a geologic repository will be of no use to a potential subnational divertor except as the basis for national embarrassment or a blackmail threat. Theft, sabotage, or terrorist attacks at the subnational level are addressed by the physical-protection measures provided by the State.^{3,6,12,13,23,24} Moreover, potential subnational acts carried out with the intent of releasing radioactive material from the repository are events with extremely low probability and minimal risks.^{3,6,12,13,23-28} Therefore, the State will be mostly concerned with proper disposal and environmental safety.^{12,23,26} (See App. B.)

2. International Safeguards and the National Threat. Under international safeguards, the responsibility for proper facility operation rests with the State, whose concerns are generally directed to the safety of confinement. However, if spent fuel or other recoverable fissile wastes are consigned to a waste repository, and the possibility of national diversion is of concern, safeguards become the responsibility of an international authority, presently the IAEA, operating under an appropriate agreement with the State. While the State might prefer to restrict its safeguards for spent fuel to increasing the physical protection and surveillance activities at the repository, international safeguards probably would require a materials accountability system that would otherwise not be necessary for less attractive wastes. (See App. B.)

The international safeguards system must be based on the verification of the State's system of accounting and control for nuclear materials.²⁹ Accounting of the spent fuel will be important to the IAEA not only because of diversion risks associated with repository operations, but because accounts of plutonium inventories in spent fuel cannot be closed until the fuel is either reprocessed or, perhaps, committed to isolation.

Diversion of spent fuel from a decommissioned repository by the host State is always a possibility. (See Sec. II.B.) However, for frequent inspections, the probability of detection increases with the time and effort needed for diversion. Therefore, because of the scale of the operations required, it is not credible that a State would attempt covertly to recover and reprocess spent fuel from a decommissioned repository. If the State chose openly to recover spent fuel from a decommissioned repository, international safeguards would be no longer relevant because overt diversion would constitute abrogation of the international agreement.

Another possible national diversion strategy is for the State to declare more waste than is actually generated. An amount of plutonium-bearing material equivalent to the difference between the declared and actual waste could then be diverted to waste operations, followed by plutonium recovery. This diversion would have to occur before the waste is received at the repository. Hence, the strategy of overstating the waste makes it mandatory to verify wastes before they are shipped to the repository. Still another strategy is for the State to divert recoverable nuclear material to a low-level-waste burial ground. From there the nuclear material could be rerouted immediately or retrieved later for weapons production. Again, waste verification at the shipping point by the IAEA would be necessary to detect diversion.

Criteria for terminating safeguards at a geologic repository on the basis of the degree of dilution or extent of irrecoverability of nuclear material in nuclear wastes are

not yet defined by international agreement. However, safeguards for refractory nuclear process wastes should be terminated at the shipper when the contained nuclear material cannot be easily recovered with current technology. In contrast, extraction of nuclear material from spent fuel is well demonstrated by current reprocessing technology, and radioactive decay would eventually make the spent fuel accessible to even less sophisticated processing procedures and equipment. Therefore, physical inaccessibility of the spent fuel in a decommissioned repository may provide the only basis for safeguards termination. (See Sec. IV.)

Given the uncertainty in worldwide energy and defense policies, States may place spent fuel in a retrievable mode that permits accessibility even in a decommissioned repository. Recommendations from waste isolation studies in the US suggest that spent fuel should be retrievable for 20 years.⁸ Because the question of termination of international safeguards based on physical accessibility or inaccessibility has not been resolved, international safeguards for spent fuel might only be downgraded to infrequent casual inspections rather than terminated.

II. CHARACTERISTICS OF A REFERENCE GEOLOGIC REPOSITORY

The primary purpose for emplacing nuclear wastes in stable geologic media is to isolate these wastes from the biosphere for as long as necessary. Geologic isolation is capable of accommodating all nuclear fuel-cycle wastes.² In this section, a reference geologic repository and its three phases of operation (operating, decommissioning, and decommissioned) are described,^{8,12-15,17,30-33} and in Sec. III this repository is used to illustrate specific safeguards concepts.

A. Facility Description

The reference repository¹⁵ consists of several chambers excavated deep within a suitable geologic formation, together with access shafts and various surface structures, including two separate waste-handling and storage facilities: a "contact" facility for LL-TRU wastes in drums and a "remote-handling" facility that requires shielding and hot-cell facilities for wastes in canisters. The hoist house that serves the mine-access shafts is located in a separate structure adjacent to both the contact and remote-handling facilities. Two levels are developed underground. LL-TRU wastes are emplaced at about a 600-m depth and the major heat-producing wastes (HLW, CW, IL-TRU, and, perhaps, spent fuel) are emplaced at about 800 m to permit maximum use of the repository area. A conceptual bi-level repository is illustrated in Fig. 1 (Ref. 15).

B. Facility Operation

1. Operating Phase. Excavation for the reference repository will underlie approximately 2 000 acres. The surface areas above the excavation and outside the perimeter fence could be leased for limited general use. A controlled area of approximately 16 000 acres surrounding the excavated area could be monitored for mining and deep-drilling operations to avoid breaching the repository containment. Surface use within the controlled area would not be restricted.¹⁴

The repository surface facilities cover approximately 200 acres. They are designed to accommodate (1) frequent delivery of waste containers by rail or truck; (2) unloading of waste containers from sealed shipping casks that are in compliance with applicable regulations; (3) transfer of the waste containers to inspection facilities where, if necessary, the containers are decontaminated and/or overpacked; and (4) preparation of the waste containers for descent to the appropriate mine level.³⁰

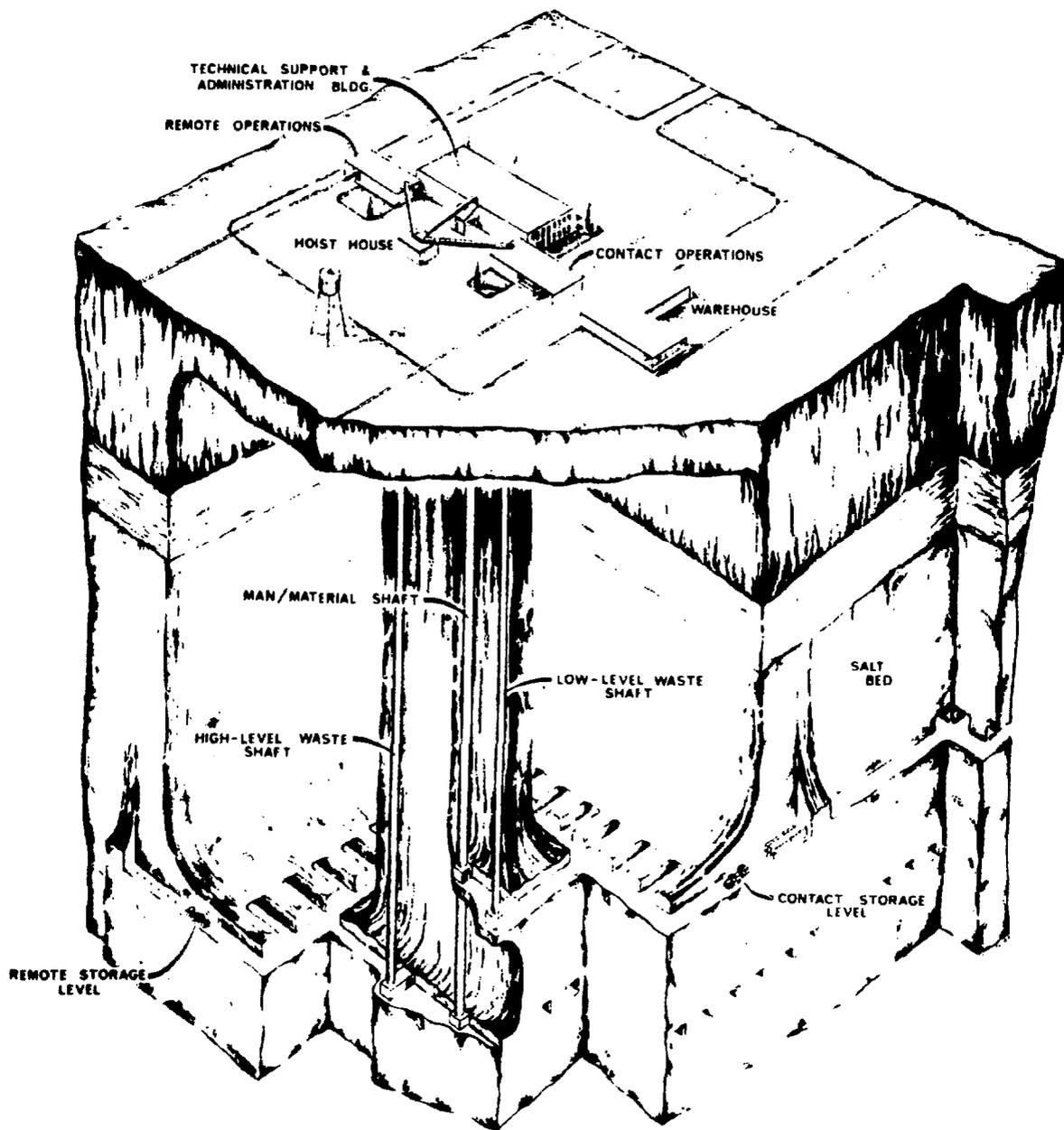


Fig. 1. Conceptual bi-level repository (Ref. 15).

The contact facility, or LL-TRU building, has the capability to receive and handle all LL-TRU shipped to the repository in closed cargo carriers containing drums or pallets. In addition to providing space for the handling and processing of pallets and drums before they are transferred underground, the contact facility accommodates other activities associated with LL-TRU handling. A flow diagram for waste in drums is shown in Fig. 2.

Canister operations within the remote-handling facility are controlled from adjacent operating rooms using manipulators and/or automated systems. Airlocks provide access from the remote-handling areas to the operating galleries and to the cask-unloading areas. Figures 3-5 contain the corresponding flow charts for waste in canisters.

Elevator shafts connect the receiving facilities to the mine and permit delivery of contained wastes to underground vehicles used for transporting the wastes to the proper emplacement area. For the retrievability designs, up to five distinct shafts could be used: a high-level-waste shaft (for HLW, CW, IL-TRU and, possibly, spent fuel), a low-level-waste shaft (for LL-TRU and, possibly, low-level wastes generated on site), a men and materials shaft, a ventilation-intake shaft, and a ventilation-exhaust shaft. The placement of the shafts as well as their basic characteristics, such as size, method of construction, and design, vary according to the purpose of the shafts and their effect on the mine and the shaft-network construction schedule.

Using the low-level-waste shaft, drums of LL-TRU are lowered to the subsurface facility, where forklifts are used to place the drums on flatbed trucks. These trucks are used to transport the drums to the isolation rooms, where the drums are stacked against each wall of the room, leaving a center aisle.

Canister-receiving operations at the subsurface level depend on the waste-material handling and isolation requirements. The method of isolation is a function of the economics and the construction constraints associated with the particular rock type. Subsurface operations begin at a receiving station, where waste-material baskets are unloaded from the waste-handling cage; then the canisters are removed from the basket and placed on a transporter. The transporter proceeds to an isolation room where the vehicle lowers the canisters into vertical holes in the floor, and the holes are plugged for radiation protection. For retrievability, the holes could be lined with steel sleeves, and the transporter equipped to place a concrete plug over the canister after emplacement. For non-retrievable isolation, no sleeve would be used, and the holes would be backfilled with excavated material.

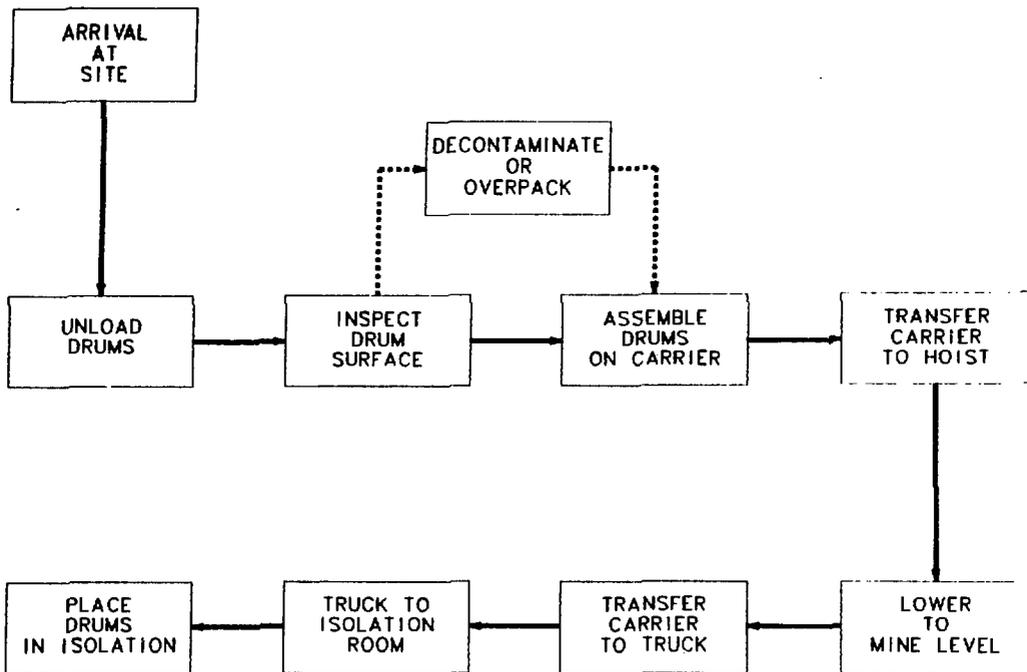


Fig. 2. Nuclear waste in drums: functional flow chart.

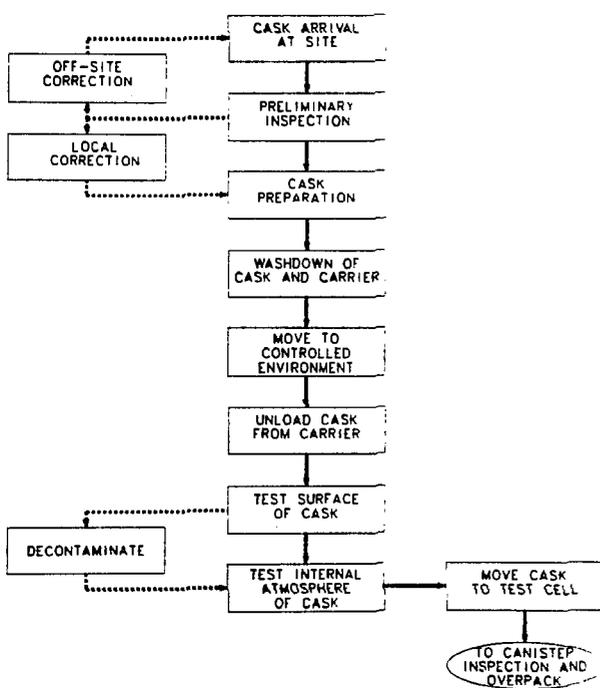


Fig. 3. Nuclear waste in canisters: cask receipt and inspection.

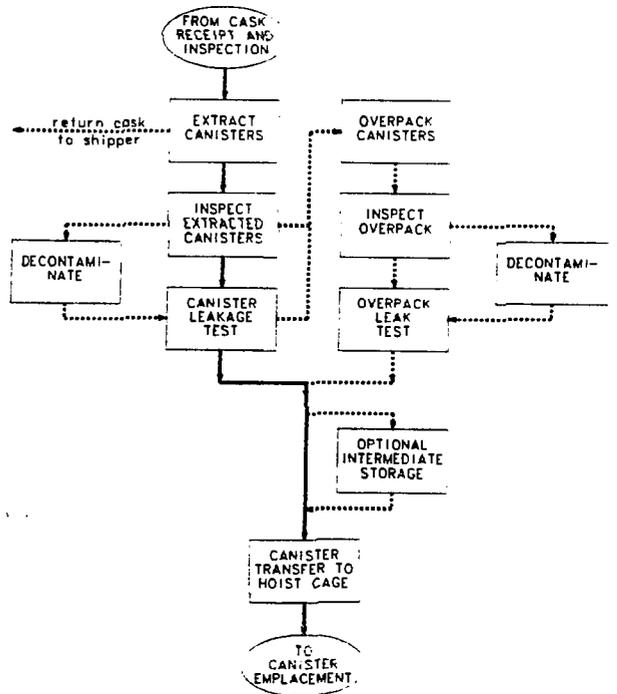


Fig. 4. Nuclear waste in canisters: canister inspection and overpack.

Several repository designs are possible, and many are being studied in an attempt to optimize efficiency and cost. In most of the conceptual repository designs, more than one elevation is used to isolate the wastes. These different elevations facilitate subterranean waste-handling operations around the shaft. The vertical separation between elevations is such that operations on the upper level are not affected by temperature increases from the deeper, heat-generating wastes.

2. Decommissioning Phase. When the repository is filled to capacity or reaches the end of its useful life, it will be retired from active service. The procedure of taking a nuclear facility out of service is termed decommissioning and is a well-documented procedure.^{2,7,13,24,26,30,34,35} Decommissioning a geologic repository involves seal-

ing, with backfill and other appropriate material, all tunnels, shafts, rooms, and holes that provide access from the surface to the chambers below. In addition, dismantling and decontaminating buildings, transporting the waste generated by decommissioning operations (decommissioning waste) to a disposal area (perhaps on site), restoring the site surface, fencing, and posting of warning signs will be required. Decommissioning wastes will consist of contaminated equipment, building materials, decontamination solutions, and, perhaps, decontamination solids resulting from treatment of decontamination solutions.

The actual decontamination and decommissioning operations are of little interest from a safeguards point of view except for the possibility that some waste of safeguards significance could be removed from the facility with the decommissioning wastes or equipment. Protection against possible removal of safeguarded waste could be handled in a

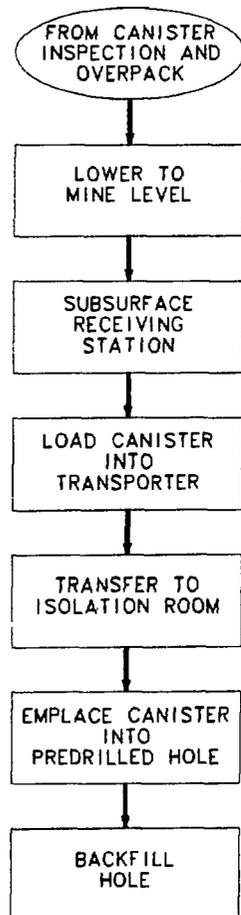


Fig. 5. Nuclear waste in canisters: canister emplacement.

manner similar to that used for the operating phase of the repository. However, the possibility of diverting nuclear material could be greatly reduced if all decommissioning wastes were placed in the repository before final backfilling.

3. Decommissioned Phase. After a facility has been decommissioned, limited site control and access must be continued to detect and prevent any attempts of unauthorized reentry.⁶ The State would probably conduct environmental surveillance at the site, and the technician who takes the environmental samples could double as the State's safeguards inspector. In addition, instrumentation to indicate earth movement could supplement site inspection. If necessary, international safeguards could be accomplished by a visit of an IAEA inspector to the decommissioned site a few times a year. Annual operating costs of national and international safeguards for a decommissioned facility should be minimal.

III. SAFEGUARDS FOR A REFERENCE GEOLOGIC REPOSITORY

A. General Safeguards Considerations

The reference repository has several intrinsically favorable safeguards characteristics: (1) only discrete items are handled; (2) process materials are contained by shielding and by restricted access to underground operations; and (3) outward flows of materials are easily detected and verified. Furthermore, the diversion risks associated with nuclear wastes are greatly reduced as these materials advance through canning, emplacement, and room backfilling to ultimate sealing and decommissioning. Consequently, the safeguards system should be gradually downgraded during this series of operations to provide protection consistent with the inherent risks, attractiveness, and accessibility of each waste type.

The three phases of repository operation, the operating phase, the decommissioning phase, and the decommissioned phase, require different degrees of safeguards. The greatest level of safeguards activity, both at the national and at the international levels, will be required when the repository is receiving nuclear wastes for emplacement. Safeguards concerns during the operational phase are greatest at the transportation link to the repository.^{23,26}

1. National. The safeguarding of nuclear waste at the domestic level is the responsibility of the State in meeting its obligation to protect the public from the potential consequences of subnational threats. During the operational phase of the repository, safeguards could be accomplished by a physical-protection system, required to deter and respond to terrorist attack,^{6,12,13,24} and a system of accounting and control to verify that the material accepted for emplacement is the same material as that shipped from the facility where it was declared waste. (See App. B.)

2. International. If spent fuel is defined to be waste and is emplaced in the repository, the State would be required to have a full-scale materials accounting and control system that could be verified by the IAEA. Both national and international safeguards should, however, be reduced substantially after the facility has been decommissioned. If spent fuel is not consigned to the repository, international safeguards for a decommissioned repository could be terminated after the proper agreements were negotiated between the State and the IAEA. The State would probably

maintain the decommissioned repository as a restricted area and perform some level of environmental surveillance. However, this should not necessarily involve safeguards. (See App. B.)

B. Safeguards Options

Waste materials containing isotopes of uranium or plutonium may be of national and international safeguards significance, depending on the quantity, concentration, and the difficulty of extraction and conversion of these isotopes to weapons-usable materials. However, other than spent fuel, most nuclear wastes accepted at the reference repository will not be of international safeguards concern.

Normal operations at the repository provide for unidirectional flow of nuclear materials in shafts; generally, two-way flow will be unusual. However, when occasional malfunctions or mistakes occur, outward flow is possible and waste may even need to be removed from emplacement. Two such possible malfunctions or mistakes are (1) if the shipper packages and ships to the repository nuclear wastes that are unacceptable; or (2) if a package is damaged in subsurface handling and needs to be returned to the surface for repair. These relatively infrequent occurrences would need to be documented to explain the abnormal two-way flow. (See Figs. 2-5.)

At various points in the reference repository, information for materials accounting and control may be obtained at three levels of increasing sophistication:^{8,12,13,17,36} (1) item control and identification, (2) tamper indication, and (3) nondestructive assay. Each higher level of control presupposes implementation of the lower levels. Item control and identification provide assurance that the proper number of containers are received, and that the waste containers are properly identified for inventory control and records management. Tamper indication provides assurance that the shipping casks have not been opened during transport. NDA and detailed records management verify the declared nuclear materials content of the waste.

Although safeguards alone may not justify the expense of NDA instrumentation at a nuclear-waste repository, process control, health and safety, and criticality criteria may require implementation of NDA procedures. These procedures would also benefit safeguards by improving materials-accountability at the repository.

The materials accounting and control techniques addressed in this study are listed in Table I. (See App. B for more details on materials accounting and control techniques available to the reference repository.)

TABLE I

LEVELS OF MATERIALS ACCOUNTING AND CONTROL
AVAILABLE TO THE REFERENCE REPOSITORY^a

- LEVEL 1 - ITEM CONTROL AND IDENTIFICATION
- o Alphanumeric identification labels
 - o Magnetic strips
 - o Inscribed identification numbers
 - o Bar-coded identification labels
 - o Notched binary identification numbers
- LEVEL 2 - TAMPER INDICATION
- o Sealing systems
 - o Weight measurements
 - o Radiation scans
 - o Radiation signatures
- LEVEL 3 - NONDESTRUCTIVE ASSAY

^aAdapted from Ref. 42.

1. Nuclear Process Wastes. For nuclear process wastes having residual fissile-material concentrations near the threshold of feasible extraction, the primary concern of the State's waste-control system will be with safe isolation rather than with the diversion of contained nuclear material. In addition, international safeguards at the reference repository may not be necessary for these nuclear process wastes because there would be little or no concern for diversion. If state-of-the-art extraction limits are not achieved, for economic reasons or otherwise, residual nuclear materials might remain attractive for recovery or possible diversion. However, the diversion risks appear to be small because of the greater accessibility and attractiveness of nuclear materials at other fuel-cycle facilities.

A State's accounting and control system would be necessary to maintain records on the physical, chemical, and radiological characteristics of each waste type received at the reference repository and to ensure that all wastes shipped from their point of origin have been received without alteration. Wastes should be assayed for fissile content at the point of origin before being transferred to the reference repository to (1) determine whether safeguards can be terminated; (2) account for the quantities of nuclear materials transferred from the previous safeguarded facility; and (3) ensure that the nuclear-waste containers are not being used to conceal diversion.

Ideally, NDA could account quantitatively for the materials present in each waste container, both prior to shipment and after receipt. This strategy could ensure container integrity and serve to close the materials balances of the waste streams by providing an independent and final determination of the quantity of materials discarded. However, the physical and radiological waste characteristics are not amenable to quantitative measurements of the accuracy required to ensure container integrity. In addition, the operational requirements of NDA instrumentation at the repository could be burdensome. Therefore, implementation of lower levels of materials control may be necessary.³⁶ These are considered below. (Also see App. B.)

High-level-waste characteristics are such that any attempts to divert this material in transit to gain access to its nuclear-material content are nearly inconceivable.³⁶ First, the low concentrations of residual fissile materials contained in the refractory waste matrix would make extraction of these materials impracticable. Moreover, the solid high-level wastes contain almost 100% of the radioactive fission products and their associated lethal radiation levels. Accordingly, we believe that Level 1, item control and identification, should be sufficient for HLW canisters.

Cladding wastes also contain insoluble, residual fissile material and high radiation levels. Therefore, we recommend Level 1, item control and identification, as sufficient to ensure delivery of this material. The integrity of the welded containers in which HLW and CW are delivered should be checked on receipt by remote instrumentation to remove concern over possible loss en route or contamination; implicit tamper-indication control should therefore be practiced. Breach of containment should not cause concern from a safeguards standpoint.³⁶

Intermediate-level transuranic wastes lack the valuable safeguards attribute of lethal radiation levels. In addition, although the average fissile-material density is low, the polymorphic composition makes it possible for a large quantity of fissile materials to be placed in a single container. Therefore, we recommend Level 2 (Level 1 plus explicit tamper indication) as sufficient for materials accounting and control. However, for IL-TRU delivered in sealed, welded containers, remote visual inspection, decontamination, and perhaps leak testing should be sufficient to determine whether the container integrity has been compromised.³⁶

Low-level transuranic wastes present a greater potential safeguards problem than all waste types except spent fuel. LL-TRU originates from a variety of sources, including such personnel-accessible operations as equipment maintenance, waste sorting

and processing, and canister filling and loading. Thus, there is a much greater possibility of including, by mistake or design, large quantities of fissile materials within this waste type. We recommend an increased level of materials control at the shipping point to detect such mistakes or diversions.³⁶

Our recommendation for greater materials control at the LL-TRU point of origin, rather than at the repository, is based on the following considerations.³⁶

- (1) Before encapsulation, the shipper can take more accurate materials measurements, either by sampling or by assay of individual waste constituents.
- (2) Following encapsulation, the shipper will have data on the waste composition of each drum and will be able to construct and maintain calibration standards unique to his wastes, should assay be necessary.
- (3) Unlike the repository, which will receive LL-TRU from a variety of facilities, the shipping facility can employ NDA techniques optimized for its particular waste types.
- (4) Materials control by the shipper can decrease detection times for loss or diversion of fissile material from waste. Measurements could be verified by the State and the IAEA.

In summary, the State's materials accounting and control system for LL-TRU should be subject to international verification at the shipping point and, to a lesser degree, at the repository receiving area. In addition, the State should verify that the repository received the waste shipment without compromise and hence, Level 2 (Level 1 plus explicit tamper indication) should be sufficient.

2. Spent Fuel. LWR spent fuel is usually stored at the reactor (point of origin) in a specially designed water pool. If spent fuel is not reprocessed, it may remain at the reactor or be transferred to an away-from-reactor (AFR) storage facility until a decision is made to reprocess the spent fuel or to isolate it in a waste repository. (See App. B.)

Power-reactor plutonium first appears in LWR spent fuel, and on the basis of plutonium quantity and concentration, spent fuel might be an attractive target for national diversion, even though reprocessing facilities would be required to remove the

fission products and undesirable actinides and to separate the plutonium and uranium. Long-term diversion prospects may be enhanced by radioactive decay of the fission products that provide short-term protection. Therefore, with spent fuel, the primary proliferation threat to be safeguarded against is that a non-weapons State might divert its spent-fuel inventory to the production of nuclear weapons. Theft of spent fuel by subnational groups for the ultimate construction of a nuclear weapon is considered unlikely, and the physical-protection measures of a State should be adequate to prevent such theft.^{12,13}

If spent fuel is consigned to the reference repository, accounting of the fuel will be important to the IAEA because of diversion risks associated with repository operations and because accounts of plutonium inventories in spent fuel are not closed until the fuel is either reprocessed or, perhaps, committed to isolation. Currently, the IAEA has proposed 8 kg of plutonium as a quantity of safeguards significance, with desired detection probability of 95% and detection time of weeks to months for irradiated materials.³⁷ A typical PWR spent fuel assembly contains about 3 or 4 kg of plutonium, and BWR assemblies contain about 1 or 2 kg.³⁸ Therefore, theft of 2 or 3 PWR assemblies or 4 to 8 BWR assemblies generally would provide more than a significant quantity (8 kg) of plutonium.

At present, it is not feasible to make direct, nondestructive measurements of the plutonium content of spent fuel to the accuracy required for safeguards accounting purposes. The best determination that can be made now relies on calculations based on the history of each fuel assembly. Therefore, if it is required to account for the plutonium in spent fuel assemblies at the reference repository, it will be necessary to maintain histories of individual assemblies, including pre-irradiation assay, irradiation history, and subsequent tracking through storage to isolation. Additionally, Level 2 (Level 1 plus explicit tamper indication) should be practiced for materials accounting and control. (See App. B.)

The spent-fuel receiving area is of greatest diversion concern at the reference repository because after spent fuel is moved underground, diversion becomes increasingly difficult. The major safeguards objectives at the receiving area are to ensure that spent fuel entering the facility has been properly identified and to deny the opportunity for replacing canned spent fuel assemblies with canned HLW. At the receiving area, IAEA inspectors may need to be present to remove and inspect shipping-cask seals, observe removal of fuel assemblies from the casks, and record the identity of each fuel

assembly. However, if the deterrent value of occasional inspections is thought capable of providing adequate protection, continuous inspector presence at receiving should not be necessary.

Spent-fuel canning should be performed at the repository rather than off site because after canning, the verification of fuel-assembly presence and identity by direct inspection is not possible, and analytical measurements are more difficult. In addition, if fuel is canned at another site, there could be opportunities and credible incentives for diversion of spent fuel and substitution of canned HLW. Methods for detecting such counterfeits require further development. After canning at the repository, verification by the IAEA on a piece-count sampling basis designed to provide the desired level of assurance should be adequate.

Procedures for monitoring the direction of flow of spent fuel at the repository can be performed remotely, with the information recorded on a tamper-indicating data-collection system. Similar instrumentation also can be employed at other on-site repository locations to detect any flow of spent fuel outside authorized channels or flow in a direction opposite to normal operations. Data from remote instrumentation could be recorded and retrieved whenever an IAEA inspector decided to verify the State's reports and operator's records.

IV. TERMINATION OF SAFEGUARDS AT A REFERENCE GEOLOGIC REPOSITORY

The central and overriding issue affecting the termination of safeguards at a geologic repository in which only verified wastes are received is the presence or absence of spent fuel. This issue drives both national and international safeguards concerns.

A. National

Verified process wastes from recycled-fuel operations, fissile-materials production, and research and development activities present national safeguards concerns more related to health and safety than to the diversion of contained fissile material. However, before shipping, the waste packages should be assayed to ensure that the waste container is not being used to divert nuclear material of strategic interest. If the container assays indicate that only refractory process wastes are present, State safeguards should be terminated or downgraded. If spent fuel is declared to be waste and is placed in a geologic repository, it would require the same level of safeguards as spent fuel handled at other facilities.¹²

After decommissioning a geologic repository, national safeguards, based on site control, will require routine, but infrequent, patrol of the restricted area. Termination of safeguards, if possible, would require an appropriate agreement with the IAEA.

B. International

Provision is made for the termination of international safeguards by the IAEA on the basis that the nuclear material subject to safeguards has been "consumed, or has been diluted in such a way that it is no longer usable for any nuclear activity relevant from the point of view of safeguards, or has become practicably irrecoverable."^{29,39} Hence, the point at which safeguards may be terminated depends on the fissile content, feasibility of separation, and practicable recoverability of the waste.

If state-of-the-art extraction limits are not achieved for plutonium from recycled-fuel waste or if highly enriched uranium is to be disposed of as waste, the IAEA might not permit safeguards termination. In that case, the IAEA and the State will have to arrive at an agreement on the appropriate safeguards measures to be applied.²⁹ For instance, before emplacement, a less intensive safeguards system than that for spent fuel could be applied to waste packages containing residual quantities of plutonium or highly enriched uranium from reprocessing and fabrication operations. After packages are

assayed at the shipping facility, item-accounting and tamper-indicating procedures could be used for both State and international safeguards. International safeguards could verify the State's records on a random-sampling basis and, perhaps, terminate upon backfilling the isolation room, on the basis of irrecoverability.

If spent fuel is placed in a repository, it is unlikely that international safeguards can be terminated, although they should be substantially downgraded after the facility has been decommissioned. After decommissioning, routine visits to the repository site by an IAEA inspector a few times a year should be adequate to verify that exhumation operations are not underway. Additional instrumentation to indicate earth movement, e.g., seismic detectors, could supplement site inspection for both national and international safeguards.⁴⁰

International safeguards probably cannot be terminated at a decommissioned spent-fuel repository because the repository eventually becomes a highly concentrated plutonium ore deposit. If safeguards were terminated, provisions must be made for their reintroduction if and when the State should decide to recover the spent fuel for reprocessing.

V. SUMMARY AND RECOMMENDATIONS

National and international safeguards for a nuclear-waste geologic repository should be much less stringent than for other fuel-cycle facilities. At the national level, there are facilities more attractive than a waste repository for diverting nuclear material, and construction of a nuclear device from material diverted at a waste repository by a subnational group is not a credible event. At the international level, the entire fuel cycle is vulnerable to diversion, especially if the State chooses to operate overtly. However, overt diversion abrogates international agreements and engenders international response. If spent fuel is emplaced in the repository, an increased level of safeguards is required both nationally and internationally.

Information for safeguarding nuclear process wastes and spent fuel at a geologic repository may be obtained at three levels of increasing sophistication: (1) item control and identification, (2) tamper indication, and (3) nondestructive assay. For Level 1, each waste container should have a unique identification to help implement item control and record management. A permanent identification (alphanumeric, bar-code, or notched binary) should be inscribed in each container surface before or at the point of shipping to the repository; an optimum identification system for each waste type needs to be determined. In addition, tamper-indicating procedures should be employed along with item control and identification for spent fuel and for IL-TRU and LL-TRU containers. Again, an optimum tamper-indicating system for each container type needs to be identified. These two levels of materials control and accountability should be sufficient to determine whether containers have been breached in shipment. Furthermore, we recommend against the practice of NDA procedures for safeguards at the geologic repository except, perhaps, for spent fuel. (See App. B.)

Generally, nuclear process wastes handled at a geologic repository, including wastes from recycled-fuel operations and research and development activities, have little safeguards significance. Even low-level transuranic-contaminated wastes have large bulk and low average concentrations of nuclear materials, and therefore are relatively unattractive targets for theft or sabotage. However, waste packages should be assayed before shipment to the repository to ensure that the waste containers are not being used to divert more attractive nuclear materials.

For waste packages containing refractory process waste and little or no fissile material, international safeguards will be limited to verifying the container assay records and should terminate at the shipping point on the basis of irrecoverability. (If it were

felt necessary, termination of international safeguards could take place at the repository following verification of the State's records of waste receipt.) Also, State safeguards should be downgraded at the shipping point to reflect concern only for the health and safety aspects of transporting nuclear wastes and emplacing them in the repository. Adequate protection against subnational theft and sabotage can be provided by the State's normal physical-protection measures.

Waste packages containing low residual quantities of plutonium or highly enriched uranium of safeguards concern should be subject to safeguards less stringent than those for spent fuel. These packages can be assayed at the shipping facility and then submitted to item-accounting and tamper-indicating procedures for both national and international safeguards. International safeguards techniques can be used to verify the State's records on a random-sampling basis and should terminate on backfilling the isolation room.

If, despite the limitations described in App. B, assay of nuclear process wastes is required at the reference repository for safeguards or to ensure that the health, safety, and criticality criteria are honored, implementation would affect the repository design. Separate shielded assay rooms, automated waste-container flow systems with container-identification instrumentation, and additional computer data-analysis systems would be required. Each waste type would require different NDA instrumentation and both container and matrix standards because of the differing nuclear-materials contents, package sizes, radiation levels, etc. Even using several flow lines to prevent pile-ups in the surface-storage areas, assay times would probably be long. An increase in both quantity and technical ability of repository personnel would be required to operate and maintain the assay equipment. With all these complications, quantitative assay of nuclear wastes would only be expected to achieve accuracies in the 10 to 30% range; however, this may be sufficient for waste assay.

The relative invulnerability of spent-fuel handling facilities at a geologic repository to subnational theft or terrorism makes safeguarding LWR spent fuel primarily a problem for international safeguards. The international safeguards system would be based on the verification of the State's system of accounting and control and would involve safeguards similar to those for other nuclear fuel-cycle facilities capable of handling spent fuel.

The primary threat to be safeguarded against for spent fuel is that a non-weapons State might divert its spent-fuel inventory to the production of nuclear weapons. Hence, if spent fuel is placed in a geologic repository, it is unlikely that international safeguards can be terminated, although they should be reduced substantially after the facility has

been decommissioned. Moreover, the level of safeguards activity should decrease as the spent fuel progresses through the repository operations of emplacement, backfilling, and, finally, sealing of the chamber, as the diversion risks decrease at each of these operations.

Spent-fuel NDA measurements at the shipping point and, perhaps, at the repository receiving area would have important safeguards benefits. Fissile-assay measurements, made when the spent fuel is received, could be used to draw shipper-receiver balances and to provide a direct verification of the fissile plutonium and uranium contents. However, it is presently infeasible to make direct, NDA measurements of the plutonium content of spent fuel to the accuracy required for safeguards accounting purposes.

After decommissioning, it is not credible that a State would attempt covert spent-fuel recovery from the repository because the scale of the operations would be easily detected. Therefore, safeguards for a decommissioned facility should require only site control by the State and, for international safeguards, routine site visits by an IAEA inspector to verify that exhumation operations are not being conducted.

The following recommendations for safeguarding spent fuel are made on the basis of this preliminary study. (See App. B.)

1. Unique, tamper-indicating identification systems for LWR fuel assemblies should be developed. The effectiveness of proposed systems should be demonstrated, and their potential vulnerabilities should be determined.
2. The development of nondestructive measurement systems for the confirmation of burnup should continue. Portable or transportable passive neutron and gamma-ray systems should be developed for inspector use.
3. The development of fissile assay by active neutron-interrogation of LWR spent fuel should be continued.
4. Safeguards and operational requirements should be analyzed for specific nuclear-waste geologic-repository designs until a decision is made to adopt some form of fuel reprocessing.

Finally, future studies should address the much more detailed problem of waste verification at the various types of nuclear production facilities that produce, treat, and package repository wastes.

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APPENDIX A

MATERIALS ACCEPTED AT THE REFERENCE REPOSITORY

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LASL Safeguards Staff (Q-4)

I. MATERIALS CHARACTERISTICS

Waste properties, including chemical form, nuclear-materials content, radiation levels, thermal power, and container geometries, affect both the safeguards requirements and the ability to implement various measurement techniques. In this report, it is assumed that four basic types of treated primary wastes, or secondary wastes, will be accepted at the reference repository: high-level waste (HLW), cladding waste (CW), intermediate-level transuranic waste (IL-TRU), and low-level transuranic waste (LL-TRU). These waste categories are based on materials content, radioactivity, and heat-generation rate. In addition, LWR spent fuel may be accepted as waste for geologic isolation if the fuel cycle is operated without fuel reprocessing.

The nuclear process wastes and LWR spent fuel accepted at the reference repository are described in Table A-I, and their pertinent physical and chemical characteristics are presented in Table A-II.¹⁻⁵ In addition, Tables A-III and A-IV show some characteristics of boiling-water-reactor (BWR) and pressurized-water-reactor (PWR) spent fuel assemblies at different times following reactor discharge.³ Typical actinide contents of spent fuel and HLW for one metric ton (tonne) of PWR fuel are shown in Table A-V for burnups of 33 000 megawatt-days (thermal) per metric ton of heavy metal (MWd/MTHM).^{2,4} Cladding wastes should have an actinide isotopic mix similar to that of spent fuel.² Actinide isotopics in IL-TRU will vary in concentration between that of spent fuel and HLW.²

Estimates of neutron emission rates from spontaneous fission (S.F.) and (α ,n) reactions in nuclear wastes and spent fuel are given in Table A-VI.²⁻⁴ These emission rates are approximate because waste compositions (especially IL-TRU and LL-TRU) are variable, making the (α ,n) contributions hard to estimate.

The anticipated ranges of densities and container-surface dose rates for nuclear wastes and spent fuel assemblies are illustrated in Fig. A-1.²⁻⁴ For materials other than spent fuel, the characteristics shown in Fig. A-1 are based on spent-fuel reprocessing and plutonium recycle.

TABLE A-1

DESCRIPTIONS OF NUCLEAR WASTES AND LWR SPENT FUEL
ACCEPTED AT THE REFERENCE REPOSITORY^{a,b}

- High-Level Waste (HLW) - Solidified composites of the aqueous waste streams from spent fuels reprocessing. These wastes typically contain more than 99.9% of the nonvolatile fission products, 0.5% of both the uranium and plutonium, and most of the other actinides formed by transmutation of the uranium and plutonium in the reactor. HLW is managed as a refractory matrix surrounded by a container.
- Cladding Waste (CW) - Solid fragments of Zircaloy, stainless steel, and other structural components of spent fuel assemblies that remain after the fuel cores have been dissolved. These fragments are compacted to 70% of theoretical density. In addition to neutron-induced radioactivity, CW contains 0.05% of both the actinides and nonvolatile fission products, and up to 0.1% of the plutonium originally in spent fuel.
- Intermediate-Level Transuranic Waste (IL-TRU) - Solid or solidified materials (other than HLW and CW) that contain long-lived alpha emitters at concentrations greater than 10 nCi/g, and have fission-product gamma-radiation levels that require biological shielding and remote-handling techniques even after packaging. IL-TRU contains about 0.025% of the nonvolatile fission products in spent fuel, and an average of 1 g/m³ of plutonium or uranium before waste compaction.
- Low-Level Transuranic Waste (LL-TRU) - Solid or solidified materials that contain plutonium or other long-lived alpha emitters in known or suspected concentrations greater than 10 nCi/g, but have sufficiently low external radiation levels after packaging that LL-TRU drums can be handled directly. LL-TRU contains about 10 g/m³ of plutonium or uranium before waste compaction.
- Spent Fuel - Unreprocessed, irradiated nuclear fuel containing neutron-activation products, fission products, and actinides, including fissile uranium and plutonium in concentrations that are potentially of both commercial and strategic interest.

^aAdapted from Refs. 1-5.

^bOther classifications for the waste types described above are found in Refs. 6 and 7.

TABLE A-II

CHARACTERISTICS OF NUCLEAR WASTES AND LWR SPENT FUEL ACCEPTED AT THE REFERENCE REPOSITORY^a

Waste Type	Nominal Density (g/cm ³)	Typical Composition	Approximate Actinide Content (kg/m ³)	Approximate Surface Dose Rate ^b (rem/hr)	Approximate Thermal Power Density (kW/m ³)
HLW ^c	3.3	SiO ₂ 25-40 wt% B ₂ O ₃ 10-15 wt% Waste oxides 20-35 wt% ZnO 5-10 wt% Alkali-metal oxides 5-10 wt%	70.0	10 ⁵ -10 ⁶	9
CW ^d	4.5 ^e	Zircaloy 88 wt% Stainless steel 9 wt% Inconel 3 wt%	6.7	10 ³	0.4
IL-TRU ^f	2.0 ^e	Metals, ceramics, ash, fission products, actinides	.01	.01-1	6.7 x 10 ⁻⁴
LL-TRU ^g	2.0 ^e	Metals, ceramics, ash, fission products, actinides	.01-.1	.01	0
Spent Fuel:					
BWR ^h	3.2	Metals, ceramics, fission products, actinides	2.1 x 10 ³	4.1 x 10 ⁴	1.9
PWR ⁱ	3.5	Metals, ceramics, fission products, actinides	2.4 x 10 ³	1.2 x 10 ⁵	2.8

^aAdapted from Refs. 2-5.^bBased on radiation levels at canister surface.^cBased on 10-yr-old HLW.^dBased on 5-yr-old LWR CW; LMFBR CW composition is ~100 wt% stainless steel.^eBased on waste compaction.^fBased on 5-yr-old IL-TRU.^gBased on 5-yr-old LL-TRU.^hBased on 27 500 MWd/MTHM, 10-yr-old spent fuel.ⁱBased on 33 000 MWd/MTHM, 10-yr-old spent fuel.

TABLE A-III

CHARACTERISTICS OF BWR SPENT FUEL ASSEMBLIES^{a,b}

	<u>Time After Discharge from Reactor (years)</u>				
	<u>0</u>	<u>1</u>	<u>2</u>	<u>5</u>	<u>10</u>
Uranium, kg	1.77+2 ^c	1.77+2	1.77+2	1.77+2	1.77+2
Plutonium, kg	1.55+0	1.55+0	1.54+0	1.52+0	1.48+0
Activity, Ci	2.56+7	3.40+5	1.94+5	8.67+4	6.05+4
Thermal, W	2.49+5	1.41+3	7.37+2	2.60+2	1.67+2

^aAdapted from Ref. 3.

^b27 500 Mwd/MTHM.

^cRead "1.77 x 10²."

TABLE A-IV

CHARACTERISTICS OF PWR SPENT FUEL ASSEMBLIES^{a,b}

	<u>Time After Discharge from Reactor (years)</u>				
	<u>0</u>	<u>1</u>	<u>2</u>	<u>5</u>	<u>10</u>
Uranium, kg	4.41+2 ^c	4.41+2	4.41+2	4.41+2	4.41+2
Plutonium, kg	4.19+0	4.21+0	4.18+0	4.11+0	4.02+0
Activity, Ci	9.25+7	1.13+6	6.28+5	2.67+5	1.82+5
Thermal, W	9.08+5	4.81+3	2.49+3	8.49+2	5.25+2

^aAdapted from Ref. 3.

^b33 000 Mwd/MTHM.

^cRead "4.41 x 10²."

TABLE A-V

GRAMS OF ACTINIDES IN SPENT FUEL AND
HLW FOR ONE TONNE OF PWR FUEL^{a, b}

Nuclide	Spent Fuel		HLW	
	Initial	10-yr Decay	Initial	10-yr Decay
Th-228	1.82-6 ^c	1.94-5	2.76-6	1.72-7
Th-230	9.13-4	4.44-3	1.06-3	1.08-3
Th-232	2.34-4	1.53-3	2.90-4	2.97-4
Th-234	1.36-5	1.36-5	1.36-5	6.79-8
Pa-231	5.13-4	5.91-4	5.17-4	5.17-4
Pa-233	1.58-5	1.17-5	1.66-5	1.67-5
U-232	2.83-4	8.13-4	1.74-6	4.08-6
U-233	4.80-3	6.34-3	2.45-5	1.73-3
U-234	1.21+2	1.34+2	6.10-1	1.02+0
U-235	7.98+3	7.98+3	3.99+1	3.99+1
U-236	4.55+3	4.55+3	2.27+1	2.27+1
U-237	1.06+1	1.92-5	1.55-7	9.41-8
U-238	9.43+5	9.43+5	4.71+3	4.71+3
Np-237	4.72+2	4.86+2	4.82+2	4.83+2
Np-239	7.97+1	7.81-5	7.82-5	7.82-5
Pu-236	6.57-4	5.81-5	2.97-6	2.60-7
Pu-238	1.61+2	1.60+2	8.36-1	5.50+0
Pu-239	5.19+3	5.27+3	2.63+1	2.64+1
Pu-240	2.17+3	2.17+3	1.08+1	2.01+1
Pu-241	1.03+3	6.43+2	5.06+0	3.15+0
Pu-242	3.54+2	3.54+2	1.77+0	1.78+0
Am-241	2.51+1	4.12+2	4.63+1	4.75+1
Am-242m	9.42-1	9.00-1	9.40-1	8.99-1
Am-242	7.83-2	1.08-5		
Am-243	9.43+1	9.44+1	9.44+1	9.44+1
Cm-242	1.01+1	2.17-3	5.14+0	2.17-3
Cm-243	8.07-2	6.50-2	7.99-2	6.43-2
Cm-244	3.02+1	2.06+1	2.97+1	2.02+1
Cm-245	1.93+0	1.93+0	1.93+0	1.93+0
Cm-246	2.22-1	2.21-1	2.22-1	2.21-1
Cm-247	2.86-3	2.86-3	2.86-3	2.86-3
Cm-248	1.93-4	1.93-4	1.93-4	1.93-4

^aAdapted from Refs. 2 and 4.^b33 000 MWd/MTHM.^cRead "1.82 x 10⁻⁶."

TABLE A-VI

ESTIMATED NEUTRON EMISSION RATES FROM SPONTANEOUS FISSION
AND (α, n) REACTIONS IN NUCLEAR WASTES AND SPENT FUEL^a

<u>Waste Type</u>	<u>Neutron Source</u>	<u>Initial (n/s·m³)</u>	<u>1-yr (n/s·m³)</u>	<u>10-yr (n/s·m³)</u>
HLW	S.F.	5.65+9 ^b	4.46+9	2.98+9
	(α, n)	7.13+8	2.12+8	5.82+7
	Total	6.36+9	4.67+9	3.04+9
CWC ^c	S.F.	2.96+6	2.52+6	1.60+6
	(α, n)	4.16+5	2.25+5	9.04+4
	Total	3.38+6	2.75+6	1.69+6
IL-TRUC ^c	S.F.	4.99+5	4.25+5	2.70+5
	(α, n)	7.02+4	3.81+4	1.52+4
	Total	5.69+5	4.63+5	2.85+5
LL-TRUC ^c	S.F.	2.9+4	2.9+4	2.9+4
	(α, n)	6.4+4	6.7+4	8.5+4
	Total	9.3+4	9.6+4	1.1+5
Spent Fuel:				
BWR ^d	S.F.	7.31+8	3.86+8	2.11+8
	(α, n)	4.53+8	1.13+8	2.19+7
	Total	1.18+9	4.99+8	2.33+8
PWR ^e	S.F.	1.09+9	6.30+8	3.65+8
	(α, n)	5.97+8	1.53+8	3.31+7
	Total	1.69+9	7.83+8	3.98+8

^aAdapted from Refs. 2-4.^bRead "5.65 x 10⁹."^cBased on compacted waste.^dBased on 27 500 Mwd/MTHM.^eBased on 33 000 Mwd/MTHM.

Each waste type will be placed in standard containers suitable for geologic isolation. Because HLW, CW, and most IL-TRU require external shielding, canisters for these waste types will be similar in design. For example, a proposed US HLW canister having an approximate waste volume of 0.18 m³ (Refs. 2 and 4) is shown in Fig. A-2.^{2,4} Spent fuel also will require external shielding; however, the container design has not been specified. In addition, it is assumed that spent fuel, unlike the other waste types, will be canned at the repository site. This is discussed further in Sec. III of the main text. LL-TRU does not require external shielding and will probably be delivered in 210-L (55-gal) drums, or in large plywood or metal boxes that may be more efficient for storage.^{2,7}

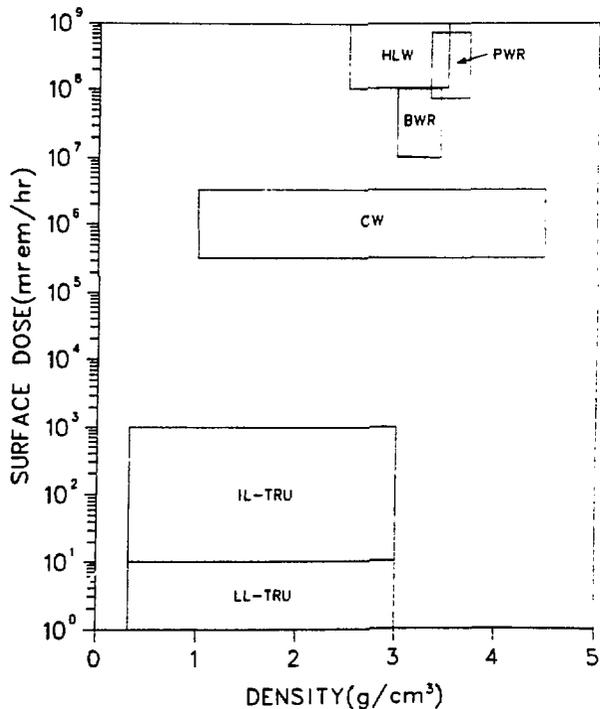


Fig. A-1. Estimated ranges of densities and container-surface dose rates for nuclear wastes and spent fuel. (Adapted from Refs. 2-4.)

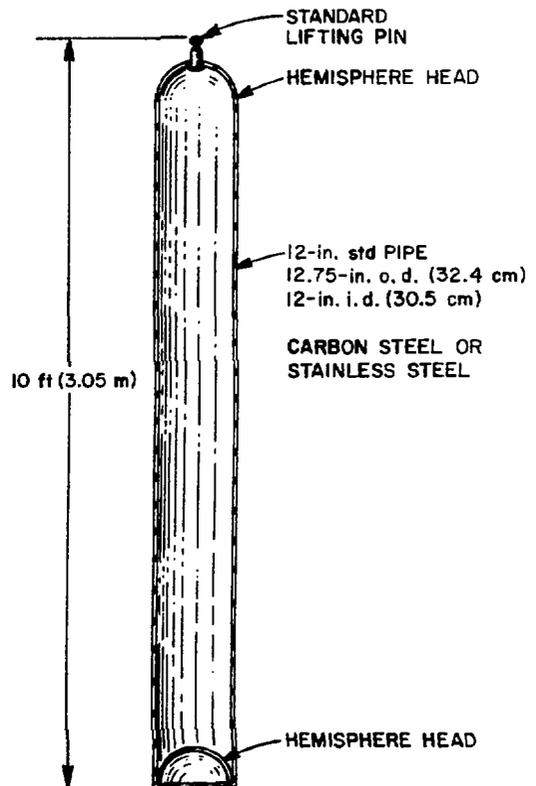


Fig. A-2. Proposed US HLW canister. (Adapted from Refs. 2 and 4.)

II. PROJECTED MATERIALS FLOWS

Table A-VII was derived from a late 1976 projection of the volume of waste units generated annually in the US that will be available for isolation at the reference repository from 1986 to 2000.⁵ In the year 2000, the estimated annual number of HLW, CW, and IL-TRU canisters is 12 990, and the number of LL-TRU drums is 34 580. This converts to an average of about 250 canisters and 665 drums per week, or about 35 canisters and 95 drums per day. Although the waste-unit volumes derived here are based on a 1976 projection of nuclear-power growth in the US (468 GW-electric by the year 2000)⁵ that is higher than current projections (a maximum of 400 GW-electric by the year 2000),⁸ the waste-unit numbers should not be greatly affected because of the current backlog of spent fuel and waste. In addition, because fuel-cycle wastes are proportional to the total energy generated, wastes resulting from a lower installed nuclear generating capacity may be estimated by multiplying the waste quantities shown in Table A-VII by the ratio of the low-growth to high-growth energy projections.⁸ Clearly, any safeguards system implemented at the reference repository must be designed for high-volume operations.

Table A-VIII shows a projection of the number of waste units that will be accumulated in the US through the year 2000.⁵ The total quantity of plutonium contained in these waste units by the beginning of the 21st century was derived from Ref. 5 and is estimated at 1.5 tonnes, assuming about 0.9% of the heavy metal in spent fuel is plutonium.

At present, spent fuel discharged from US power reactors is stored in on-site cooling ponds.⁹ Limitations of on-site storage capacity and delays in the startup of fuel reprocessing will mandate an outlet for spent fuel within a few years, or utilities will have to reduce their nuclear-power generation. Recently, it has been proposed that spent fuel be consigned to geologic isolation until questions concerning the safeguardability of fuel-reprocessing plants are resolved.

Table A-IX was derived from a 1977 projection³ of the number of BWR and PWR spent fuel assemblies that will be accumulated in the US through the year 2000 if there is no fuel reprocessing. The total quantity of plutonium contained in these spent-fuel assemblies by the year 2000 is projected at 740 tonnes. A comparable amount of plutonium is estimated to exist in foreign spent fuel.⁹ The quantity of residual ²³⁵U in LWR spent fuel is 0.8 to 1.0% of the total uranium and is about equal to the quantity of plutonium in LWR spent fuel.

TABLE A-VII
 PROJECTED ANNUAL NUMBER OF NUCLEAR WASTE PACKAGES
 ACCEPTED AT A US REFERENCE REPOSITORY^{a, b}

Year	HLW ^c	CW ^d	IL-TRU ^e	LL-TRU ^f
1986		400	420	480
1987		1 100	990	4 800
1988		1 100	1 130	9 610
1989		1 100	990	16 330
1990		1 400	1 410	17 770
1991	240	2 200	1 410	12 490
1992	720	2 200	1 550	15 370
1993	720	2 500	1 410	10 090
1994	720	3 200	1 840	13 930
1995	960	3 600	1 980	21 610
1996	1 430	4 300	2 400	28 340
1997	1 430	4 700	2 540	31 700
1998	1 670	5 400	2 970	32 180
1999	2 150	5 800	3 390	29 300
2000	2 390	6 500	4 100	34 580

^aAdapted from Ref. 5.

^bAssuming US fuel reprocessing begins in 1981 and that by the year 2000 the installed nuclear generating capacity will be 468 GW-electric.

^cBased on 10-yr-old HLW.

^dBased on 5-yr-old CW.

^eBased on 5-yr-old IL-TRU.

^fBased on 5-yr-old LL-TRU.

TABLE A-VIII

PROJECTED ACCUMULATED NUMBER OF NUCLEAR WASTE PACKAGES ACCEPTED AT A US REFERENCE REPOSITORY^{a,b}

End of Year	HLW ^c		CW ^d		IL-TRU ^e		LL-TRU ^f	
	Total Number	Total Pu Content (kg)	Total Number	Total Pu Content (kg)	Total Number	Total Pu Content (g)	Total Number	Total Pu Content (g)
1986			400	3	420	1	480	3
1987			1 500	15	1 410	3	5 280	40
1988			2 600	25	2 540	6	14 890	110
1989			3 700	35	3 530	9	31 220	260
1990			5 100	50	4 940	15	48 990	420
1991	240	15	7 300	75	6 350	20	61 480	595
1992	960	65	9 500	100	7 900	30	76 850	805
1993	1 680	115	12 000	130	9 310	35	86 940	990
1994	2 400	175	15 200	165	11 150	50	100 870	1245
1995	3 360	260	18 800	205	13 130	60	122 480	1645
1996	4 790	380	23 100	250	15 530	75	150 820	2165
1997	6 220	500	27 800	305	18 070	90	182 520	2750
1998	7 890	640	33 200	365	21 040	110	214 700	3340
1999	10 040	820	39 000	430	24 430	130	244 000	3880
2000	12 430	1015	45 500	510	28 530	155	278 580	4515

^aDerived from Ref. 5.^bAssuming US fuel reprocessing begins in 1981 and that by the year 2000 the installed nuclear generating capacity will be 468 GW-electric.^cBased on 10-yr-old HLW.^dBased on 5-yr-old CW.^eBased on 5-yr-old IL-TRU.^fBased on 5-yr-old LL-TRU.

TABLE A-IX
PROJECTED ACCUMULATION OF SPENT FUEL ASSEMBLIES IN THE US^a

Year	BWR Assemblies ^b		PWR Assemblies ^c		Accumulated Pu Content (tonnes)
	Annual Addition	Accumulation (End of Year)	Annual Addition	Accumulation (End of Year)	
1980	2 830	15 980	1 860	8 910	47
1985	4 400	34 200	3 390	21 960	120
1990	7 550	65 910	5 720	46 330	250
1995	11 080	113 940	8 140	81 960	460
2000	15 300	182 020	10 980	131 250	740

^aDerived from Ref. 3.

^bBased on 27 500 MWD/MTHM.

^cBased on 33 000 MWD/MTHM.

Waste quantities generated within the repository will be small if not negligible. This waste will be treated on site to reduce its volume and make it acceptable for disposal at the repository.^{10,11}

Although the annual volumes of transuranic-contaminated nuclear wastes generated by the defense and research programs of a State may be small compared to the waste volumes from commercial power production, accumulation of these non-commercial wastes at national sites may be significant.⁷ Retrieving, processing, and packaging of these wastes would be necessary before their consignment, if deemed desirable, in a geologic repository. The effect on repository operations of accepting these transuranic-contaminated wastes should be minimal if these wastes are taken into consideration at the repository design phase.

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APPENDIX B

MATERIALS ACCOUNTING AND CONTROL TECHNIQUES FOR THE REFERENCE REPOSITORY*

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I. ITEM-CONTROL AND IDENTIFICATION TECHNIQUES

For Level 1 of materials management, item control and identification, the basic unit is the waste package and, perhaps, the canned spent fuel assembly. This level of management should be the minimum applied to all waste types, with each package having a unique identification.¹ Simple piece-counting of containers may be adequate after the materials progress through the surface operations to emplacement underground.

Identifications for containers shipped to the repository should have certain characteristics. They should be difficult to alter or duplicate and should not be susceptible to damage. Furthermore, identifications should be designed for automatic reading. The large number of waste packages that must be processed and the radiation levels associated with certain packages proscribe manual reading.

Several different procedures can be used to identify waste packages received at the repository. Five common types are considered here:¹ (1) alphanumeric identification labels; (2) magnetic strips; (3) inscribed identification numbers; (4) bar-coded identification labels; and (5) notched binary identification numbers.

Alphanumeric labels, perhaps the simplest type of identification, and magnetic strips containing identification information that can be read automatically have many disadvantages. Both alphanumeric labels and magnetic strips are sensitive to damage, with labels being particularly susceptible to alteration or duplication. In addition, the information contained in labels and magnetic strips might tend to decompose or become obscured by the high temperatures associated with some waste types.¹

Inscribing identification numbers on metal containers has the following advantages: (1) the numbers are difficult to alter; and (2) they are relatively invulnerable to damage from heat or abrasion. In addition, imprinting numbers at several locations on the container surface could further reduce the risk of losing identification through accidental obliteration. However, inscribed identification numbers cannot be easily adapted for automatic reading.¹

*Some of App. B is adapted from Refs. 1, 6, and 7.

Bar-coded identification labels have several advantages: (1) bar-coded information can be painted or inscribed directly on the container or on labels fixed to the container; (2) information can be read rapidly and automatically; (3) unique coding systems can make alteration or duplication difficult; and (4) each bar-coded label can contain much information.¹ This information could include container identification number, shipper identification number, fissile content, total weight, surface-radiation level, etc. Also, a coded verification number could be included to determine whether information has been accurately read or has been altered. However, bar-coded labels may be damaged during shipment; damage potential can be reduced by inscribing the code into the container surface at several locations.

Notched binary identification numbers represent a different coding technique whereby notches can be inscribed along the container circumference at a specific axial location.¹ If, for example, there are 20 radial notches, over one million unique identification numbers are possible.

Both the bar-coded identification labels and the notched binary identification numbers are relatively insensitive to damage, alteration, or duplication, and they are adaptable to automatic reading. However, these techniques require the shippers to have either premarked containers or the capability for inscribing identifications. In addition, shippers and repository operators would need equipment for reading the identifications.

Advantages and disadvantages of the five identification systems considered here are shown in Table B-I.¹

II. TAMPER-INDICATION TECHNIQUES

Level 2 of materials management, tamper indication, has been recommended for LL-TRU and IL-TRU containers and for any spent-fuel casks received at the reference repository.¹ Application to LL-TRU and IL-TRU containers is recommended because these containers lack the valuable safeguards attribute of high radiation levels and because they may contain large quantities of fissile materials. In addition, if spent fuel is received at the repository, spent-fuel casks should be inspected at the point of origin by IAEA inspectors, and tamper indication as a minimum safeguards system should be implemented to ensure that the shipping casks have not been compromised in transport.

It is desirable that any method proposed for upgrading LL-TRU, IL-TRU, and spent-fuel safeguards does not result in a significant increase in inspection manpower

TABLE B-I
 ADVANTAGES AND DISADVANTAGES OF TYPICAL
 ITEM-CONTROL AND IDENTIFICATION TECHNIQUES^a

<u>Identification Techniques</u>	<u>Advantages</u>	<u>Disadvantages</u>
Alphanumeric labels	Simple implementation	Susceptible to alteration, duplication, accidental damage; automatic reading difficult
Magnetic strips	Difficult to alter or duplicate, adaptable to automatic reading	Susceptible to accidental damage
Inscribed identification numbers	Simple implementation; resistant to accidental damage	Automatic reading difficult; most applicable to LL-TRU drums
Bar-coded identification labels	Difficult to alter or duplicate; adaptable to automatic reading	Susceptible to accidental damage unless inscribed
Notched binary identification numbers	Difficult to alter or duplicate; adaptable to automatic reading; resistant to accidental damage	Development work required (mechanical readers and notch-cutting machines)

^aAdapted from Ref. 1.

requirements or operator requirements. For example, the containment and surveillance (C-S) concept for spent-fuel storage proposed by Sandia Laboratories, Albuquerque,² is based on infrequent inspections and unattended surveillance instrumentation having local and remote read-out capabilities. Implementation of this concept could provide timely detection without increasing on-site inspection requirements.

A key element of the C-S tamper-indication concept is the development of a shipping-cask seal that offers long-term resistance to tampering and radiation damage.

Sealing systems have been used successfully by the transportation industry for many years to indicate entry or tampering during shipment. A disadvantage of sealing systems is that seals may be damaged accidentally, requiring additional tamper-indicating procedures. There are several ways that back-up tamper indication can be accomplished, including inspector presence, camera recording, or use of coded, tamper-indicating, remotely readable seals.

Ultrasonic identification and integrity devices ("seals") have been under development at the Ispra Laboratories since 1970.³⁻⁵ An item is identified by non-destructive ultrasonic signals reflected from random or systematically dispersed inclusions or defects such as welds. The use of the Ispra or a similar seal in conjunction with a secure tamper-indicating data-gathering system would be perhaps the most effective tamper-indicating method not requiring continual operator presence. The efficacy of the ultrasonic seal developed at Ispra Laboratories (Euratom) is currently being evaluated.

Several types of ultrasonic seals have been developed for different applications. Integrity is maintained by rendering the seal unusable when it is removed from the item to which it is attached; inclusions can still be read to identify the seal after removal. The seal-identity pattern should include at least eight amplitude peaks; thus, at least one million seals with random inclusions can have unique signatures.⁵ A long-term objective is to develop a tamper-indicating fuel-assembly identification system for the lifetime of LWR fuel assemblies.⁶ The continuous integrity of any such system during reactor irradiation remains to be demonstrated. In practice, two types of seals may be necessary: one for fresh fuel from fabrication to reactor charge and the other for spent fuel from reactor discharge to final disposition.

In addition to seals, a C-S system could use a combination of radiation, crane, acoustic, portal, electric power, and closed-circuit television monitors to detect the movement of fuel assemblies and specific waste containers. The pertinent hardware and development activities include tamper-indicating devices.

Using relatively simple instrumentation for radiation scanning, gross gamma-and/or neutron-radiation measurements could be made at known distances from the container for comparison with shipper values. Also, unfolding techniques could be used to estimate the strength, position, and direction of travel of the nuclear material.

Radiation-signature methods could also be used for tamper indication. Radiation signatures representing specific gamma-ray energies, gamma-ray energy spectra, and/or neutron energy spectra could be taken before shipment and at repository receipt;

tampering would be assumed if a signature mismatch occurred. However, the disadvantages of this procedure include: (1) the requirement for elaborate instrumentation; (2) the necessity for identical instrumentation at the point of shipment and at the repository for signature comparison; (3) the necessity for custom instrumentation for waste types emitting different radiations; (4) the requirement for sophisticated computer data-analysis systems; and (5) the requirement for additional personnel to operate and maintain radiation-signature instrumentation at the repository.¹

Crane monitors could be used to indicate the position, load, direction of travel, and physical activity of waste containers and spent fuel assemblies. The sensors for these four functions are strain gauges. For example, with weight-measurement procedures at the repository, the weight of waste containers could be accurately measured and compared with shipper values.

Acoustic monitors could provide an intrusion alert whenever acoustic signals within an area are consistent with unauthorized container movements. Methods are being developed to distinguish between expected background signals and unauthorized signals.

Portal monitors could indicate door openings and electric-power monitors could indicate the use of any electric motors.

A closed-circuit television system could record a TV picture upon command of the inspector or when an anomalous condition is detected by sensors.

Finally, a computer for data collection and analysis could receive sensor-transmitted data through a tamper-indicating system. The computer could provide on-site analysis and transmittal of data on command to a remote monitoring station.

Advantages and disadvantages of four tamper-indicating procedures are listed in Table B-II.¹

III. NONDESTRUCTIVE ASSAY TECHNIQUES

A preliminary evaluation of nondestructive assay (NDA) techniques for the third level of materials control is presented for the reference repository.

A. Nuclear Process Wastes

The following conclusions are the result of an analysis of various NDA techniques and their applicability to several types of nuclear process wastes.^{1,7,8}

Calorimetric techniques, by which radioactive-decay heat can be measured very accurately, are not applicable to the waste and container types expected at the

TABLE B-II
 ADVANTAGES AND DISADVANTAGES OF TYPICAL
 TAMPER-INDICATING TECHNIQUES^a

<u>Tamper-Indicating Techniques</u>	<u>Advantages</u>	<u>Disadvantages</u>
Sealing systems	Well developed; commonly used in transportation industry	Susceptible to accidental damage; require back-up procedures
Weight measure- ments	Simple implementation	Not a positive tamper indicator
Radiation scans	Simple implementation; difficult to duplicate	Not a positive tamper indicator
Radiation signa- tures	Nearly positive tamper indicator	Identical instrumen- tation required by all shippers and the repository; compli- cates repository design and operation

^aAdapted from Ref. 1.

reference repository. The major factors that limit the application of this method to wastes are (1) the lack of knowledge of relative isotopic abundances, (2) long assay times, and (3) the dilution of plutonium with inert materials.

Assay of HLW and CW canisters to determine accurately their residual fissile-material content requires extensive development of NDA techniques. High radiation levels and low concentrations of nuclear material preclude application of either passive or active methods at the reference repository.^{1,7}

Assay of IL-TRU canisters using passive gamma-ray or neutron techniques to determine fissile content also requires further development because of the high fission-product gamma-ray activity and transuranic neutron activity. In addition, large container volumes and heterogeneous mixtures seriously degrade the measurement accuracy of NDA methods.

Assay of LL-TRU drums by passive gamma-ray methods is complicated by the high density and heterogeneity of the waste matrix. In addition, independent NDA analysis at the reference repository requires that the chemical composition of the waste and the isotopic composition of the nuclear material be known so that measurements can be compared with standards. Therefore, passive gamma-ray techniques can be applied to well-characterized LL-TRU; however, unknown matrixes and heterogeneities can limit measurement accuracy. Assay of LL-TRU drums by passive neutron methods also is possible, but (α ,n) neutrons and undefined plutonium isotopic mixtures severely limit these methods.^{1,7}

Promising NDA techniques for determining the fissile content of IL-TRU and LL-TRU containers include active interrogation methods using either gamma rays or neutrons. For LL-TRU in drums, accuracies of 5-20% may be obtained using a particle accelerator to generate interrogating radiation. However, this method is expensive and difficult to operate and maintain. Isotopic ^{252}Cf or (γ ,n) sources also can be used, but long assay times are required to achieve accuracies of 10-30%.

Radiation-signature, attribute, and go-no-go measurements are relatively simple to make and are well developed. However, equipment would need to be designed for specific applications. Passive techniques or a combination of active and passive techniques using isotopic sources could be used to make measurements.^{1,7}

Although a variety of NDA techniques and instruments is available for assaying the fissile nuclide contents of a wide range of materials and container sizes, we do not recommend an important safeguards role for process-waste NDA techniques at the reference repository. However, waste measurement capability at the repository may be essential for process control to ensure that health, safety, and criticality criteria are honored. The major responsibility for closing the materials balances for nuclear process wastes should rest with the shipper, for whom the materials are more accessible, better characterized, and more amenable to sampling. Furthermore, appropriate controls and procedures should be instituted at the shipping point to ensure compliance with the repository criteria for materials form and content, and to terminate safeguards as soon as possible.

B. Spent Fuel

NDA techniques are being developed to confirm the burnup and to verify directly the fissile content of irradiated nuclear fuels.^{6,9} Most of these techniques rely on measurements of characteristic gamma-ray or neutron signatures. Other proposed

techniques use Cerenkov radiation, reactivity, or calorimetric measurements. All of these techniques require further development, and suitable field instrumentation currently is not available for any of them.

1. Gamma-Ray Techniques. Gamma-ray measurement techniques can be divided into two categories, gamma-ray spectroscopy and gross gamma-ray measurements. Such measurements potentially can be related to both cooling time and burnup after a cooling time of several months.

The gamma-ray spectroscopy methods that have been investigated are absolute gamma-activity measurements and gamma activity-ratio measurements. Both methods measure the gamma activity of selected fission products. Fuel burnup and cooling time may be inferred from these measurements.

The selection of the fission products to be measured is vital. They should have nearly equal fission yields for the major fissioning nuclides in the fuel, a low neutron-capture cross section, a relatively long half life, a low migration in the fuel, and easily resolvable spectra having relatively high-energy gamma rays. The fission products that satisfy most of these criteria are ^{95}Zr , ^{106}Ru , ^{106}Rh , ^{134}Cs , ^{137}Cs , ^{144}Ce , ^{144}Pr , and ^{154}Eu .

Gamma-ray spectroscopy measurements generally use intrinsic germanium detectors that view a portion of the spent fuel assembly through a collimator. To obtain accurate measurements of burnup and cooling time by high-resolution gamma-ray spectroscopy, an axial scan of the assembly or a standard gamma-ray profile are required.

For the absolute gamma-ray activity method, the detection efficiency must be known and the measurement geometry must be carefully controlled. For the gamma-ray activity-ratio method, only a relative detection efficiency is required, and the ratio method is less sensitive to variations in measurement geometry. These are important advantages for the activity-ratio method; however, the effective fission yields of some of the isotopes used in the activity-ratio method are not known.

Gamma-ray spectrometric techniques require relatively long counting times for good statistics. A recent work¹⁰ demonstrates the use of gas chambers to provide a simple, accurate, and rapid method for measuring the axial gross gamma-ray profiles of spent fuel assemblies.

The gross gamma-ray method may have an accuracy approaching 10% for confirmation of burnup, if the cooling time is known independently. When used in conjunction with high-resolution gamma-ray spectroscopy, the accuracy is improved.

If calibrations of the gas-chamber response versus burnup for various cooling times could be determined empirically, then the gas chamber could provide a relatively simple tool for independently confirming the burnup.

2. Neutron Techniques. Neutron measurement techniques can be divided into two categories, active and passive. Active techniques involve sample irradiation with neutrons to produce fissions. The resulting neutron "signals" are interpreted to determine quantitatively the amount of fissile material present. Passive techniques measure the naturally occurring radiation from the sample.

Neutron techniques potentially have some advantages over gamma-ray techniques. Neutron measurements probably could be made immediately after discharge from the reactor; gamma-ray measurements require a cooling period. Attenuation is not nearly so much of a problem for neutron techniques because neutrons have a very high penetrability in nuclear materials relative to gamma rays. In other words, neutron measurements "see" the interior rods of the fuel assembly; gamma-ray measurements do not.

Active neutron techniques might make it possible to determine directly the total fissile content and perhaps the ^{235}U and fissile-plutonium contents separately as well; one may only infer the burnup and, hence, estimate the fissile content from passive gamma-ray or neutron techniques. Moreover, active neutron measurements probably would not require an accurate measurement of cooling time; passive gamma-ray and neutron measurements would.

On the other hand, neutron techniques have some disadvantages. The presence of moderators or neutron poisons may introduce errors. Self-shielding corrections that are required for thermal-neutron interrogation may not be easily determined, and active neutron-interrogation systems tend to be large and non-transportable.

Passive neutron techniques measure neutrons that arise from either spontaneous fission or (α, n) reactions in the spent fuel assemblies. The even isotopes of plutonium and curium have greater rates of spontaneous fission than their odd isotopes. The (α, n) neutrons result from reactions of alpha particles (from the radioactive decay of plutonium, americium, and curium) with light elements (mostly oxygen) in the spent fuel matrix. The neutron yield is a function of alpha-particle energy, the (α, n) cross sections of the matrix elements, and the matrix configuration. In a spent fuel assembly, the neutron-emission rate depends strongly on the quantity of curium present (Fig. B-1).⁹ The quantity of ^{242}Cm (162.8-day half life) is particularly important for cooling times less than five years.

Recent investigations^{9,11,12} indicate that the total neutron emission rate is proportional to burnup at constant cooling time. Passive neutron measurements using a fission chamber are described in Ref. 10. The neutron emission rate varied approximately as the 3.4 power of the burnup for both PWR and BWR fuels (Fig. B-2).⁹ Comparison of an axial scan using the fission chamber with an axial gamma-ray scan using an intrinsic germanium detector showed good correlation between the passive gamma-ray and neutron profiles.

Passive neutron measurements appear promising because a simple room-temperature detector is used, electronics are simple, and measurement and data-processing techniques are straightforward. However, the effect of cooling time on neutron signals over a wider range of burnups and the use of detectors other than fission chambers must be investigated.

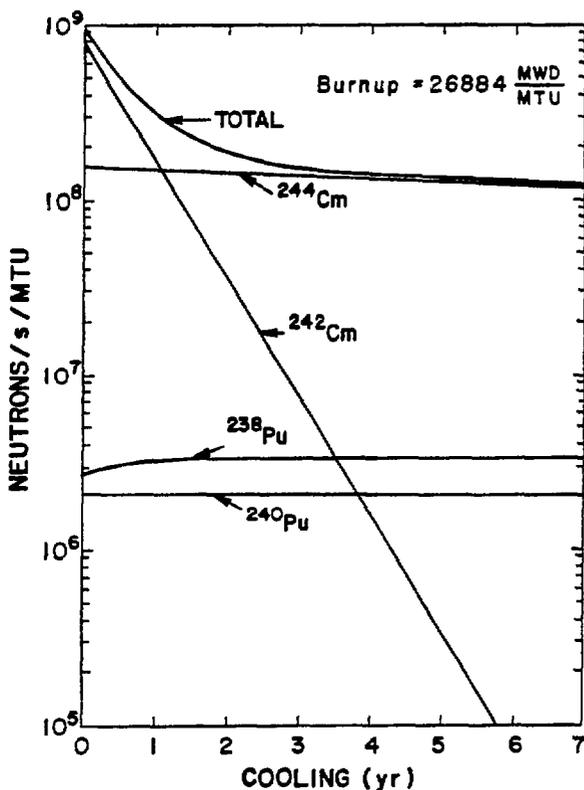


Fig. B-1. Neutrons per second from ^{238}Pu , ^{240}Pu , ^{242}Cm , and ^{244}Cm isotopes at a burnup of 26 884 MWD/MTU. (Taken from Ref. 9.)

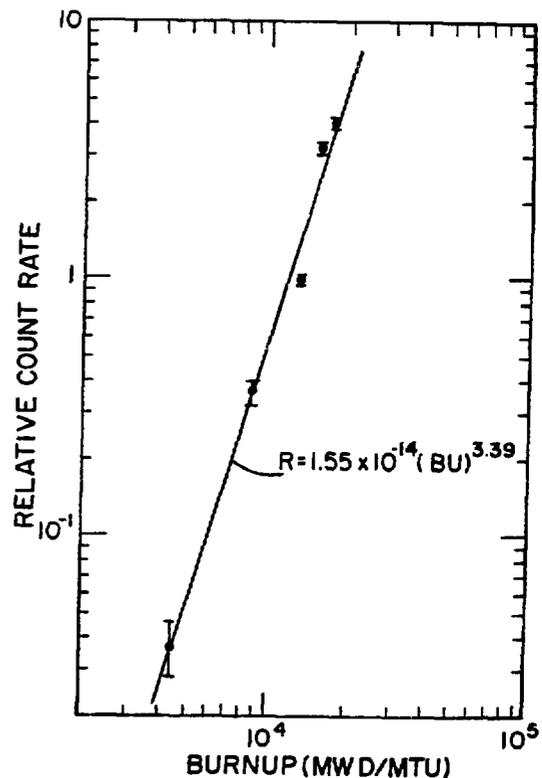


Fig. B-2. Relative fission-chamber response versus burnup for five BWR spent fuel assemblies. (Taken from Ref. 9.)

Active neutron-interrogation techniques use neutrons from a radioactive source (^{252}Cf or a gamma-induced photoneutron source such as $^{125}\text{Sb-Be}$) to induce fissions in the sample. The resulting fission neutrons, both prompt and delayed, are counted to determine the total fissile content and to identify the fissile elements. Active neutron systems for LWR spent fuel have been proposed,⁹ and such systems appear to be feasible. Potentially, active neutron systems could provide a direct assay of the fissile-plutonium and uranium contents.

Most active neutron techniques measure the total number of neutrons emitted from the sample. Two alternative techniques are the slowing-down spectrometer (SDS) and neutron resonance absorption.

Using a SDS, the ^{235}U and ^{239}Pu contents could be distinguished by the differences in their cross sections at certain neutron energies. However, accuracy is lost because the 1-eV resonance of the unknown amount of ^{240}Pu may overlap the 0.3-eV ^{239}Pu resonance. Also, it is not known if the SDS can be used to measure an entire assembly because the response across the assembly is not uniform, and consequently energy resolution is lost.

Neutron resonance-absorption techniques potentially can determine the uranium and plutonium fissile contents using a fast chopper and a time-of-flight spectrometer. An intense epithermal neutron source, probably from a reactor, is required. However, this method may not be applicable to spent fuel assemblies because, in addition to the complicated equipment, interpretation of the signals can be difficult if the sample is not in a slab geometry.

3. Other Measurement Techniques. The measurement of Cerenkov radiation to deduce the burnup and cooling time of irradiated nuclear fuel has been proposed,¹³ and a preliminary feasibility study has been completed.

Cerenkov radiation is produced by the passage of high-energy charged particles through a transparent medium at a particle velocity greater than the local velocity of light in the medium. In spent-fuel pools, Cerenkov radiation is produced by Compton electrons resulting from fission-product gamma rays; hence, the Cerenkov radiation is related to the total gamma-ray activity. Research is continuing to examine possible correlations between Cerenkov radiation and burnup.¹⁴

Reactivity techniques basically measure the total "worth" of an assembly. Differentiation between uranium and plutonium could be obtained by tailoring the neutron or "adjoint" flux. Estimates indicate that such systems would be relatively accurate, but expensive.

Calorimetric techniques measure the heat output generated predominantly by the fission products within a spent fuel assembly. Calorimetric measurements require detailed irradiation and cooling histories that may or may not be available.

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