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OF STATE SYSTEMS OF ACCOUNTING FOR
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SESSION 13: SAFEGUARDING NUCLEAR POWER STATIONS

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I. INTRODUCTION

Most of the world's inventory of plutonium is contained in the spent-fuel assemblies that reside in the spent-fuel ponds of nuclear power stations. Because reprocessing of these spent-fuel assemblies is occurring at a very low rate and because away-from-reactor storage has not yet occurred to any significant extent, the world's inventory of plutonium will by necessity remain at nuclear power stations for many years. Thus, the nuclear power station is of significant nuclear safeguards interest.

The discussion in this paper focuses on the single facility--the nuclear power station with its inventories of fresh fuel, in-core fuel, and spent fuel. The focus is on the off-load refueled, light-water-cooled power reactor (LWR) because they are found in the greatest numbers in the world; however, attention is also given to the on-line refueled, heavy-water-moderated and cooled reactor (HWR).

The nuclear power station has several characteristics, which are unique to safeguards, in the nuclear fuel cycle. The nuclear material is almost always found in discrete, encapsulated units (called fuel assemblies or fuel bundles) and it remains in the same physical form during its entire residence time at the power station. It arrives at the power station in the form of fuel assemblies, it resides in the reactor core as fuel assemblies, and it is stored in the spent-fuel pond as fuel assemblies. The integrity of the assemblies is therefore maintained. Fuel assemblies are rarely disassembled at nuclear power stations; however, this could change in the future and introduce new safeguards problems. At all other facilities in the nuclear fuel cycle--except the away-from-reactor storage pond--the nuclear material can change both physical and chemical form.

The nuclear power station is the only facility in the entire fuel cycle where large quantities of fissile materials [uranium-235 (^{235}U) and plutonium-239 (^{239}Pu) are consumed and produced. Nuclear material is not conserved. The ultimate result of this consumption and production of fissile materials is, of course, the generation of electrical energy.

Because the integrity of the fuel assemblies is maintained and because the nuclear material content of the fuel assemblies is not conserved, safeguarding at nuclear power stations is primarily done by item accountability, containment, and surveillance, which will be addressed later in detail.

II. CHARACTERISTICS OF NUCLEAR POWER STATIONS[1,2]

A nuclear fission power reactor provides an environment in which fission reactions are initiated, sustained, and controlled; and it provides for removal of heat for power production. Shown in Fig. 1 are certain components common to all reactors: the *core*, *coolant*, *control rods*, and *shielding*. Most current power reactors also include a *moderator*. The coolant, either liquid or gas, flows over the fuel rods and removes the fission heat from the fuel. The control rods, usually made of materials that readily absorb neutrons, are positioned inside the fuel assembly (core) to regulate the fission chain reaction. The shielding consists of special materials that surround different portions of the reactor system to prevent harmful radiation from escaping into the local environment.

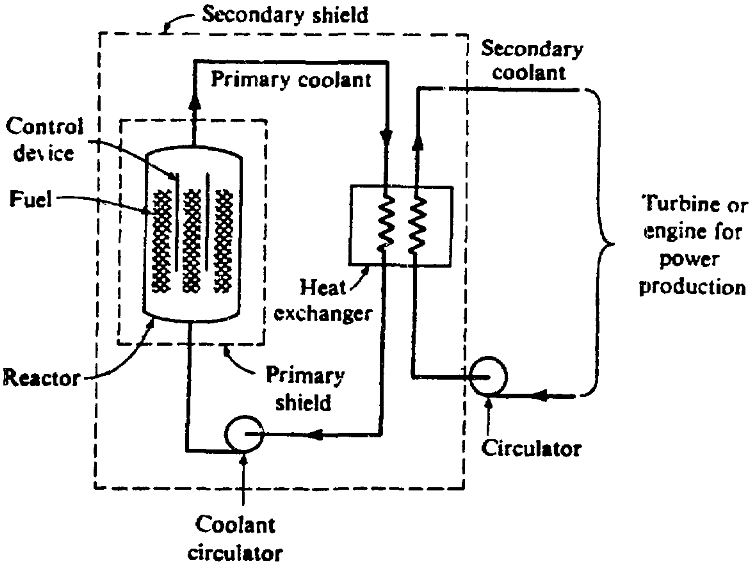

Fig. 1. Schematic of a nuclear power reactor.

The core of the nuclear reactor is that volume that contains the fission fuel. The *fissile* fuels used in nuclear reactors are ^{235}U, uranium-233 (^{233}U), or plutonium-239 (^{239}Pu). Uranium-238 (^{238}U) is not a fissile fuel but it is a *fertile* material that leads to the production of fissile ^{239}Pu. Enrichment of the fuel refers to the amount of fissionable material in the fuel. In the case of uranium it means the isotopic percentage of ^{235}U in the fuel (0.7% is contained in natural uranium). Typical water-cooled power reactors contain 2-4% ^{235}U.

The kinetic energy of the neutrons inducing fission also constitutes an important characteristic of nuclear reactors. Thus, a *thermal* reactor is one in which fission is induced by slow neutrons (neutrons in thermal energy equilibrium with the reactor core material). Most of today's power reactors are indeed thermal. A *moderator* is put into the reactor core to slow the neutrons to thermal energies by scattering collisions. Fast reactors make no attempt to slow the high-energy neutrons produced in the fission chain reaction and thus they contain no moderator. Fast neutron fission favors <u>breeding</u> and opens the possibility of converting vast supplies of ^{238}U and thorium-232 (^{232}Th) to fissile nuclear fuel.

Of the many possible types of nuclear fission power reactors, only two have so far attained worldwide use in electric power systems. These are the light-water-cooled, light-water-moderated reactors developed initially in the United States and the heavy-water-cooled, heavy-water-moderated reactors developed initially in Canada. Gas-cooled, graphite-moderated, thermal reactors, developed initially by Great Britain, have seen only limited application. Although fast breeder reactors hold promise for the future, they are still under development.

As the name implies, LWRs use ordinary water (H_2O, as opposed to heavy water D_2O) as both coolant and moderator. The two common versions of LWR are the boiling-water reactor (BWR) and the pressurized-water reactor (PWR). The major difference between the PWR and the BWR is in the operating pressure. In the PWR, typical operating conditions are 2200 psia (pounds per square inch absolute--compared to 14.7 psia for normal atmospheric pressure) and 330°C, a greatly subcooled condition. At this very high pressure, the water in the reactor cannot boil, even at a 330°C temperature. The high-pressure water removes fission heat from the reactor core and is circulated through a steam generator to produce 290°C, 1000 psia steam. The steam then drives a turbine-generator to produce electrical energy.

In the BWR, the operating pressure is reduced to about 1000 psia; the cooling water at this lower pressure boils into 290°C steam directly within the reactor vessel. After passing through moisture separators and steam dryers, the steam then goes directly to the turbine. Thus, the BWR does not require an intermediate heat exchanger (steam generator).

One disadvantage in the use of LWRs for electrical power generation is the relatively low steam temperature (290°C) and resulting low thermal-conversion efficiency. An LWR generates electricity with about 32-33% efficiency as compared with 36-38% net efficiencies achieved with modern fossil-fueled plants.

The use of natural uranium, heavy-water, and on-line refueling are the basic elements in the HWR design philosophy. The most common version of HWR is the CANDU reactor manufactured and marketed worldwide by Atomic Energy of Canada Limited (AECL). CANDU systems employ D_2O as both the moderator and the coolant. The term CANDU is essentially synonymous with CANDU-PHW, the <u>Can</u>adian <u>D</u>eterium <u>U</u>ranium - <u>P</u>ressurized <u>H</u>eavy <u>W</u>ater reactor.

The CANDU-600 reactor, the most common design today, can produce more than 600 MWe with a thermal efficiency in the range of 29-30%. The reactor vessel is a large, horizontally oriented cylindrical tank that contains the low-pressure heavy-water moderator. This tank is penetrated by a number of horizontal fuel channels that contain the natural-uranium fuel and the pressurized, heavy-water coolant. The coolant is pumped through the fuel channels and then through heat exchangers (steam generators) to produce light-water steam at 400 psia and 260°C, which is then fed to the turbine.

III. "TYPICAL" FUEL CHARACTERISTICS AT NUCLEAR POWER STATIONS

The fuel assemblies for the two types of LWRs are very similar. Both use uranium dioxide as the fuel material; the uranium is enriched to 2-4% ^{235}U (Refs. 1,2). The slightly enriched uranium dioxide is fabricated into the form of cylindrical fuel pellets (~8-10 mm diam and ~10 mm long). The pellets are then loaded into long zirconium-alloy cladding tubes to produce fuel pins or fuel rods (~4 m long). A rectangular array of pins forms the final fuel assembly, or fuel bundle. The fuel assemblies are then placed in a steel pressure vessel in a right circular cylinder array. The number of assemblies required depends on the geometrical arrangement, the reactor type, the uranium enrichment, and the operating power level of the reactor.

A shortened cutaway version of a BWR fuel assembly is shown in Fig. 2. The 8 x 8 square pin array typically contains approximately 62 fuel pins per assembly.[1,3] The PWR pin array, 16 x 16 or 17 x 17, is larger than that of the BWR and the fuel assembly shown in Fig. 3 typically contains 236-264 fuel pins.[1,4]

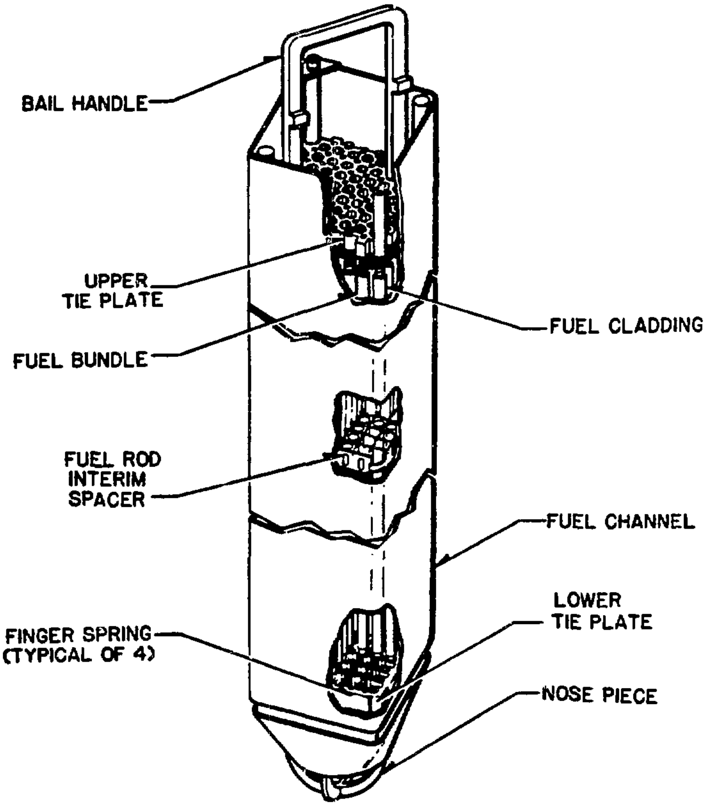

Fig. 2. BWR fuel assembly - shortened cutaway view.[3]

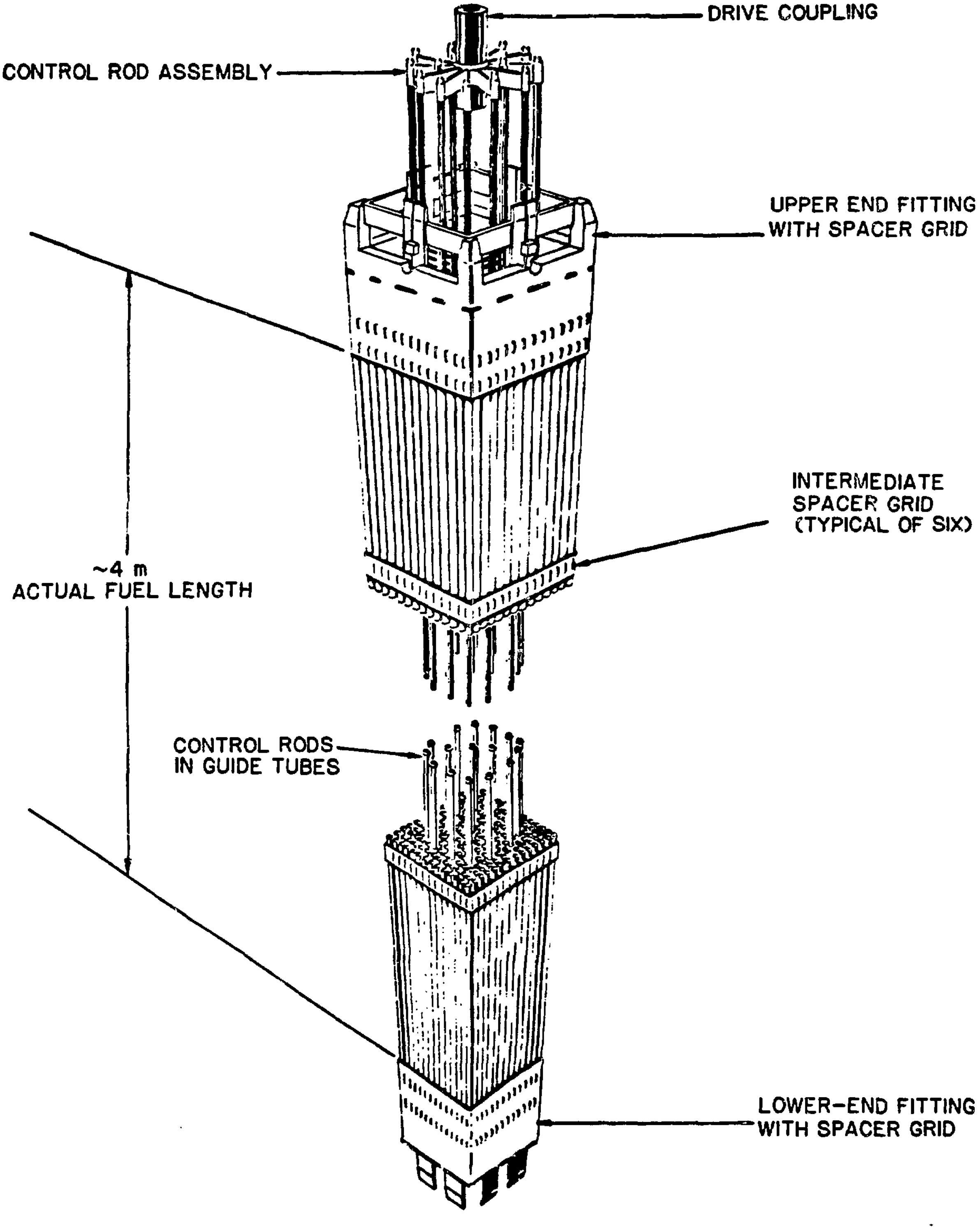

Fig. 3. PWR fuel assembly - cutaway showing partially inserted control rod assembly.[4]

Both the BWR and PWR fuel assemblies have unique serial numbers engraved on the top plate for positive identification.

In the HWR each fuel bundle (about 500 mm long and 100 mm in diameter) is made up of 37 Zircaloy-clad fuel pins containing natural UO_2 pellets (~12 mm diam and ~16 mm long), Fig. 4 (Refs. 1,5). Each fuel bundle contains 20-21 kg of natural uranium dioxide. The heavy-water moderator is contained in a horizontal reactor vessel (calandria), which is about 7.6 m in diameter by 4 m long. The vessel is penetrated by 380 calandria pressure tubes. Twelve fuel bundles are placed end-to-end in each of the pressure tubes such that the heavy-water coolant flows through the tubes and the fuel bundles simultaneously.

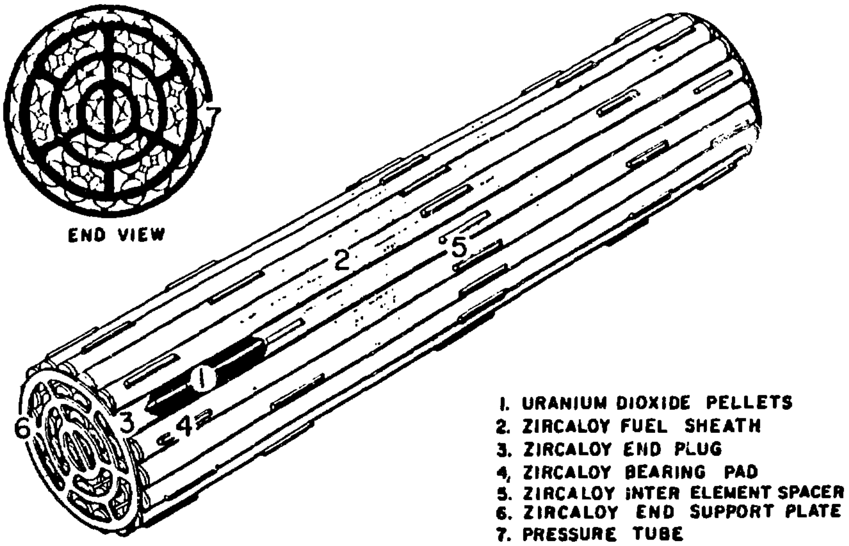

Fig. 4. CANDU fuel bundle.[5]

The characteristics of the PWR fuel listed in Table I correspond to a typical 1000-MWe station that operates on a once-through fuel cycle. The reactor is refueled off-load once a year; that is, the reactor is shut down for refueling. About one-third of the core (approximately 65 fuel assemblies) is replaced during the refueling. The uranium in the fuel is enriched to 2-4%.

The characteristics of the BWR fuel in Table I also correspond to a 1000-MWe plant operating on a once-through fuel cycle. This reactor is refueled off-load once a year during which about one-fourth of the core (or approximately 190 fuel assemblies) is replaced. The uranium in the fuel is enriched to 2-3%.

In both of these LWRs, the fuel in the reactor is inaccessible during periods of operation. The top of the reactor pressure vessel must be removed before the refueling can take place. The fuel assemblies at a LWR are therefore basically stationary during most of the year.

TABLE I

TYPICAL POWER REACTOR FUEL CHARACTERISTICS*

Typical PWR (1000 MWe)

Off-load refueling	1-year interval
Fuel enrichment	2-4%
Core inventory	~200 fuel assemblies 100 000 kg
Reload	~65 fuel assemblies
Spent fuel	~65 fuel assemblies
Pu production	~200 kg/year
Pu content spent fuel	~3 kg/assembly

Typical BWR (1000 MWe)

Off-load refueling	1 year
Fuel enrichment	2-3%
Core inventory	~750 fuel assemblies (150 000 kg)
Reload	~190 fuel assemblies
Spent fuel	~190 fuel assemblies
Pu production	~200 kg/year
Pu content spent fuel	~1 kg/assembly

Typical HWR (600 MWe)

On-line refueling	16 fuel bundles/day
Fuel enrichment	Natural uranium (0.72%)
Core inventory	4600 fuel bundles (380 pressure tubes x 12 fuel bundles per pressure tube) 98 000 kg
Reload	On-line 4500 fuel bundles/year
Pu production	~300 kg/year
Pu content spent fuel	~0.07 kg/bundle

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*Adapted from Refs. 1, 2, 3, 4, 5, and 13.

The characteristics of the HWR fuel listed in Table I correspond to a 600-MWe unit, characterized by the CANDU-600.[5] This reactor is refueled on-line; that is, refueling is done while the reactor is running. The reactor contains approximately 4600 fuel bundles. About 16 fuel bundles are replaced each day while the reactor is operating at full power.

IV. "TYPICAL" FUEL INVENTORIES AT NUCLEAR POWER STATIONS

As illustrated in Fig. 5, the inventories of nuclear material at nuclear power stations can be grouped as:

- Fresh fuel
- In-core fuel
- Spent fuel

The amount of nuclear material in the power station depends on the reactor type, the reactor power level, and the operating history of the station. Estimates of the nuclear material characteristics and flow for "typical" LWRs and HWRs were given in Table I.

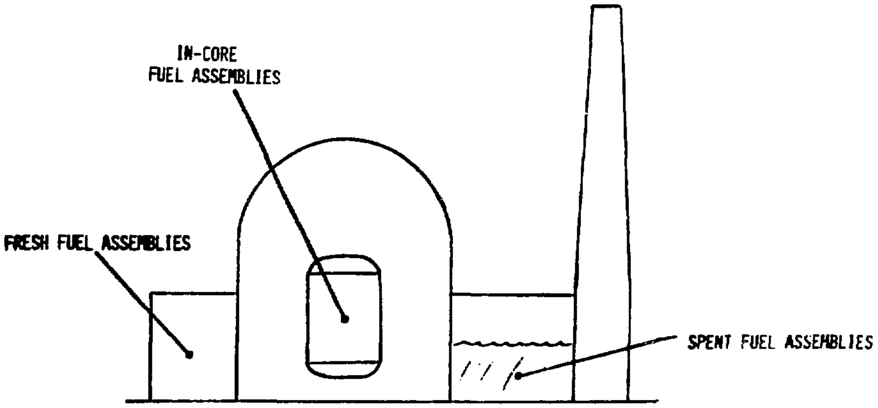

Fig. 5. Inventories of nuclear fuel at a nuclear power station.

Typical fuel assembly inventories for the three types of nuclear power stations are shown in Table II. The PWR has the smallest number of fuel assemblies in the inventory and the HWR has the largest. Spent-fuel ponds are usually designed to hold spent-fuel assemblies from several years of refueling.

Because the "back end" of the fuel cycle is developing slowly, many spent-fuel ponds throughout the world are being reconfigured to hold even more spent-fuel assemblies. Thus, the number of spent-fuel assemblies remaining at the spent-fuel ponds of nuclear power stations is increasing.

The large throughput of fuel bundles in the HWR causes the number of items in the spent-fuel pond to be very large. More

TABLE II

TYPICAL FUEL INVENTORIES AT NUCLEAR POWER STATIONS[13]
(Number of Fuel Assemblies/Bundles)

Reactor Type	Fresh-Fuel Storage	In Core	Spent-Fuel Storage
PWR	75	200	Few hundred
BWR	200	750	Several hundred
HWR	3000	4600	Several thousands

than 20 000 spent-fuel bundles will accumulate at a single 600-MWe power station in 5 years.

V. SAFEGUARDING NUCLEAR POWER REACTORS[7]

Since the fuel in a nuclear power reactor is packaged in large discrete fuel assemblies or bundles, the reactor is classified as an "item facility;" that is, the nuclear fuel is contained in identifiable items, the integrity of which is usually preserved during their presence in the plant. Such items can be followed from the fuel fabrication plant, through the reactor, to reprocessing or long-term storage. Safeguards inspectors can count the fuel bundles, identify them, and verify the fuel composition by nondestructive measurements.

Safeguarding by item accountability requires that the safeguarding authorities, which are both the national authority (including EURATOM) and the international authority (IAEA), be able to verify the identity of the items. This is generally done by item counting and identification of serial numbers. Seals and surveillance cameras (both film and video) are used to complement item accountability to reduce the effort required during physical inventory verification.[6]

A. Safeguards Systems

The main emphasis for safeguarding nuclear reactors is on accounting for each individual fuel assembly, and in this way verifying the quantity of nuclear material present. The quantity of material in these units is not measured by the reactor operator, but instead is based on data supplied by the fuel fabricator and upon theoretical calculations of production and loss resulting from fuel burnup. Physical inventory is established by counting assemblies and identifying serial numbers. Seals and surveillance cameras are used to maintain continuity of safeguards knowledge during time intervals between inspections.[7]

The major components of the safeguards system can be summarized as follows:

- auditing of facility records and comparison with reports submitted to the IAEA,
- periodic closing of the materials balance by the operator (usually annually) by taking a physical inventory,
- independent verification of nuclear material by the IAEA, usually by item counting and serial number identification, and
- application of containment and surveillance measures to maintain knowledge of nuclear material.

B. MBA Structure and Key Measurement Points

Reactor facilities are usually considered as one materials balance area (MBA) subdivided into several key measurement points (KMPs) to determine material flow and inventory. Typical material flow and material inventory KMPs are shown in Table III.

TABLE III

TYPICAL KEY MEASUREMENT POINTS
AT A REACTOR FACILITY

Material Flow KMPs:

KMP1	Receipt of fresh fuel
KMP2	Nuclear loss and production
KMP3	Shipment of irradiation fuel

Material Inventory KMPs:

KMPA	Fresh-fuel storage
KMPB	Fuel in reactor vessel
KMPC	Spent-fuel storage
KMPD	Other locations

Figure 6 schematically illustrates the typical KMP structure at a reactor facility.[8] It depicts the current IAEA policy of having loss and production reported at the time of discharge from the reactor core.

C. Inspection Activities

The IAEA generally performs one physical inventory verification (PIV) per year to verify the entire fuel inventory and three to five additional interim inspections to audit records, review surveillance pictures, check seals, and service cameras. These inspections normally involve a total of 10-15 man-days/year.

The objective of the annual physical inventory verification is to establish that the station's declared inventory is correct. For LWRs, inventory verification generally occurs at the end of

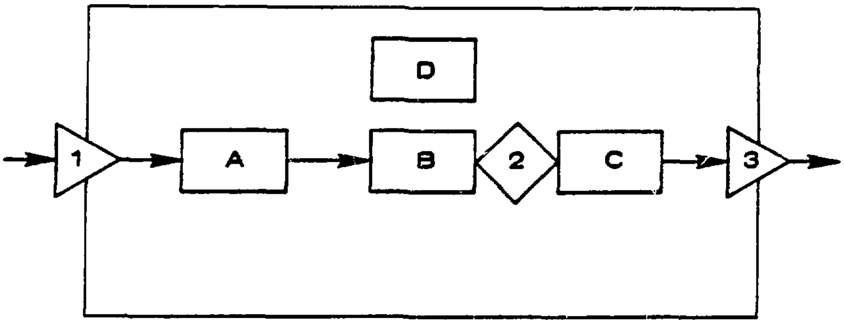

Fig. 6. Typical key measurement points in a power reactor. Inventory key measurement points are: A--fresh fuel, B--in core, C--spent fuel, D--other. Flow key measurement points are: 1--receipt, 2--production, 3--shipment.

the annual refueling, but before the top of the reactor vessel is replaced so that the inventory of items inside the reactor vessel can also be verified. For HWRs, the PIV coincides with the state's annual material balances report and physical inventory list.

1. Auditing of Records and Reports. The facility accounting records are examined to ensure that

(a) adequate records are being kept,
(b) they are arithmetically correct and internally consistent, and
(c) they agree with reports submitted to the IAEA from the state safeguards authority.

Based on the records examination, the inspector is able to establish the "book" inventory of nuclear material at the facility, that is, the amount of material to be accounted for. In addition to accounting records, operating records may be examined to confirm that records of core changes and fuel movements are consistent with accounting records.

2. Inspection Reports. Since the reactor is classified as an item facility, quantitative measurements of nuclear materials are generally not performed. Inspectors' reports, therefore, are based on verification of the major components of the safeguards system described on page 10, that is, audit of records, physical inventory, and containment and surveillance (C/S) measures.

VI. SAFEGUARDING LIGHT-WATER REACTORS[13]

A. Fuel Inventory

The items (fuel assemblies) being safeguarded are located at three places in the LWR power station: fresh-fuel storage, reactor vessel, and spent-fuel storage. Upon arrival at the reactor site, fuel assemblies are stored in a fresh-fuel storage area (usually dry, vertical racks) where they are accessible for inspection. The number of fresh-fuel assemblies in storage may range from 5-10 shortly after refueling to approximately 120-200 shortly before a scheduled refueling shutdown. The total annual flow of fresh fuel at a large LWR is ~35 000 kg of low-enriched uranium or 800 kg of ^{235}U (Refs. 1-4).

The reactor core contains 50 000-150 000 kg of uranium, depending upon reactor size. Refueling occurs annually with about one-third (PWR) or one-fourth (BWR) of the spent fuel replaced with fresh fuel. The irradiated elements remaining in the core may be shuffled to new locations to optimize power and fuel utilization. Fuel assemblies inside the core are accessible only during the refueling shutdown.

Irradiated fuel elements removed from the core are stored underwater in a storage pond. Most reactors are designed with a spent-fuel storage capacity of two to four complete cores, but safety procedures require that sufficient capacity always be available to permit a total core unloading in case of an emergency.

From a safeguards viewpoint, the irradiated fuel is strategically important because it contains roughly 1 and 3 kg of plutonium in BWR and PWR assemblies, respectively (see Table I). To ship spent fuel, a massive shielded shipping cask is lowered onto a special pad in the spent-fuel pond and loaded underwater with up to seven irradiated assemblies. Although it was initially envisioned that spent fuel be stored at reactor sites only temporarily (~1 year), the lack of reprocessing has resulted in large accumulations of irradiated fuel in reactor storage ponds.

B. Detection Targets

Based on material type and form, the technical objectives of IAEA safeguards at LWRs should be the detection of diversion of (1) 75 kg of ^{235}U contained in low-enriched fuel within 1 year or (2) 8 kg of plutonium within 1-3 months (see Appendix).[10] At 3% ^{235}U, which is a typical midvalue for LWRs, 75 kg contained ^{235}U is equal to 2500 kg of uranium, which corresponds to ~6 PWR or ~13 BWR assemblies. Similarly, 8 kg plutonium is contained in ~3 PWR and ~8 BWR assemblies.

However, because of the widely accepted safeguards approach at LWRs, namely item accounting for discrete fuel assemblies, the IAEA has adopted the goal of (a) detecting the absence of one or more spent-fuel assemblies within 2-3 months and (b) the absence of one or more fresh-fuel assemblies within 1 year.[11]

C. Diversion Possibilities

Table IV shows individual diversion possibilities, associated concealment methods, and corresponding safeguards measures.[8] The basic diversion threats at power reactors fall into two categories: (1) removal of discrete assemblies (either fresh or irradiated, with or without the substitution of dummies) and (2) irradiation of undeclared fertile material.

TABLE IV

SUMMARY OF DIVERSION POSSIBILITIES FOR LIGHT-WATER REACTORS[8,13]

Diversion Possibilities	Concealment Methods	Safeguards Measures
Removal of fuel elements from the fresh-fuel storage	Substitution with dummies	Item counting and identification Application of seals NDA measurements
Removal of fuel elements from the core	Substitution with dummies	Item counting and identification Seals Optical surveillance
Irradiation of undeclared fuel elements in the core	Undeclared shutdowns	Seals Optical surveillance
Removal of fuel elements from the spent-fuel pond	Substitution with dummies	Item counting and identification Optical surveillance NDA measurements
Removal of fuel elements from consignment when or after they leave the facility	Substitution with dummies or consignment. Understating of number of elements shipped and substitution with dummies in spent-fuel pond	Sealing of shipping container before shipment and verification of content at recipient facility, if possible

D. Inspection Activities

Typical activities that occur during inspections at an LWR are shown in Table V, which is an abbreviated version of a table in Ref. 12.[13]

E. Verification of Nuclear Material[13]

Typical safeguards verification activities that take place at an LWR are shown in Fig. 7. The inventory of fresh-fuel assemblies is verified by identification of the serial numbers that are stamped on the top of the fuel assemblies. The fresh-fuel assemblies are either verified while they are in their storage containers (where they are dry) or in the storage pool just prior to being transferred to the reactor building for insertion into the reactor. Inspection of serial numbers of assemblies in the storage pool where they are located under several meters of water requires the use of an optical magnifier, such as binoculars.

TABLE V

SAFEGUARDING ACTIVITIES AT A LIGHT-WATER REACTORS[13]

Event	Task
After receipt of fresh fuel (one visit)	Removal of seals at assemblies and identification, records audit, check of seal at vessel, routine identification of irradiated assemblies, maintenance of camera.
After shutdown but before refueling	Removal of seal at vessel; identification and counting of fuel at reactor vessel, fresh-fuel storage and spent-fuel storage; records audit; maintenance of camera.
After refueling but before start-up	Identification and counting of fuel vessel and storages, fixing of seal to vessel, and maintenance of camera records audit.
Intermediate inspections (three visits)	Identification and counting of fuel at storages, check of seal at vessel, re-records audit, maintenance of camera.
After completion of shipment of irradiated fuel	Identification and counting of fuel at storages, check of seal at vessel, records audit, isotopic data acquisition; maintenance of camera.

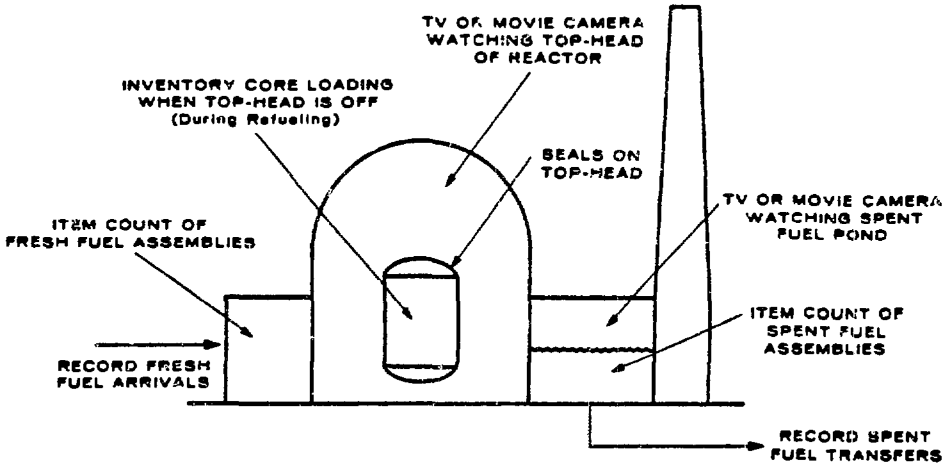

Fig. 7. Safeguards verification activities at an LWR power station.[13]

During refueling when the reactor vessel is open, the in-core inventory is verified by counting and identification of serial numbers. The in-core fuel assemblies are located under about 10 m of water, and binoculars are required for the identification of the serial numbers of these fuel assemblies. After the refueling is complete and the reactor vessel is closed, seals are applied to the shielding blocks above the reactor vessel.[14,15] Since these seals must be broken prior to the removal of the top of the reactor vessel, they provide verification that the in-core inventory was not changed during the absence of the inspector. Also, a surveillance camera is installed inside the reactor vessel as a backup to the seals. Because removal of both the shielding blocks above the reactor vessel and the head of the reactor vessel takes considerable time (days), this surveillance camera needs to take frames only infrequently; as few as 400 frames in a period of 6 months will ensure that an unreported opening of the reactor vessel will be detected.[14]

As spent-fuel assemblies are removed from the reactor vessel and are transferred to the storage pond, a map giving the grid location of each assembly is made. In the storage pond, as in the reactor vessel, the assemblies are located under about 10 m of water. During a physical inventory the inspector verifies with binoculars that the spent-fuel assemblies are in their proper locations. Also, surveillance cameras (film or video) are installed inside the spent-fuel bay to record the movement of the crane, fuel assemblies, spent-fuel cask, and the entrance and exit doors. The surveillance pictures are reviewed by the inspector to verify that the station's record of activities since the past inspections is correct. The surveillance cameras ensure the authenticity of the assemblies in the spent-fuel pond and reduce the effort required to complete the inspection. If the surveillance equipment fails, the integrity of the pond must be re-established by visual verification of all the assemblies.

Inspectors also collect data from the operators of the station that are related to calculated burnup, nuclear consumption and production, which will be useful for safeguards of reprocessing plants.[16]

VII. SAFEGUARDING HEAVY-WATER REACTORS

The CANDU-600 reactor, the most common design today, will serve as the model system in this description. The CANDU-600 falls into that class of nuclear facility characterized by a continual flow of nuclear material. But since the fuel is packaged in discrete fuel bundles, this reactor is still classified as an "item facility."

The CANDU safeguards system also follows the principle of establishing item inventories and flows within the MBA, whereby measurements are made at KMPs for the determination of flow or inventory. These KMPs are the new fuel storage room, the reactor core, and the irradiated-fuel storage areas. Examples of item flows are deliveries of new fuel to the storage room, transfer of new fuel from storage into the reactor core, and discharges of irradiated fuel from the core into the spent-fuel storage bays.

Safeguarding an HWR is characterized by keeping track of a very large number of items that are primarily inaccessible. A PIV of bundles inside the reactor is not possible because the fuel bundles are not visible inside the pressure tubes. Verification of the bundles in the spent-fuel pond is difficult because most of the bundles, stacked vertically on trays, cannot be seen. Only the fresh-fuel bundles are readily accessible.

A. Fuel Inventory

In the CANDU-600 each fuel bundle contains 20-21 kg of natural uranium dioxide, giving a total core loading of roughly 98 000 kg in 4600 fuel bundles or ~700 kg of ^{235}U (Ref. 1). Fresh-fuel assemblies are stored in dry boxes (32 bundles per box) where they can be available for inspection. The number of fresh-fuel bundles in storage may vary from a few hundred to a few thousand, but generally at least a 9-month supply is on hand. Under normal operating conditions, a CANDU-600 reactor charges 16 fresh-fuel bundles and discharges 16 irradiated-fuel bundles each day, which contributes to an annual inventory of 4000-5000 spent-fuel bundles.[5] The basic features of the fuel-handling facilities and sequences are shown in Fig. 8.

Fresh fuel is transferred from its storage area through an equipment lock into the reactor containment building. It is then loaded into the "charge" portion of the fueling machine. The charge-machine and the accept-machine attach to opposite ends of the same pressure tube without disrupting the flow of heavy-water coolant or reactor energy production. As the charge-machine

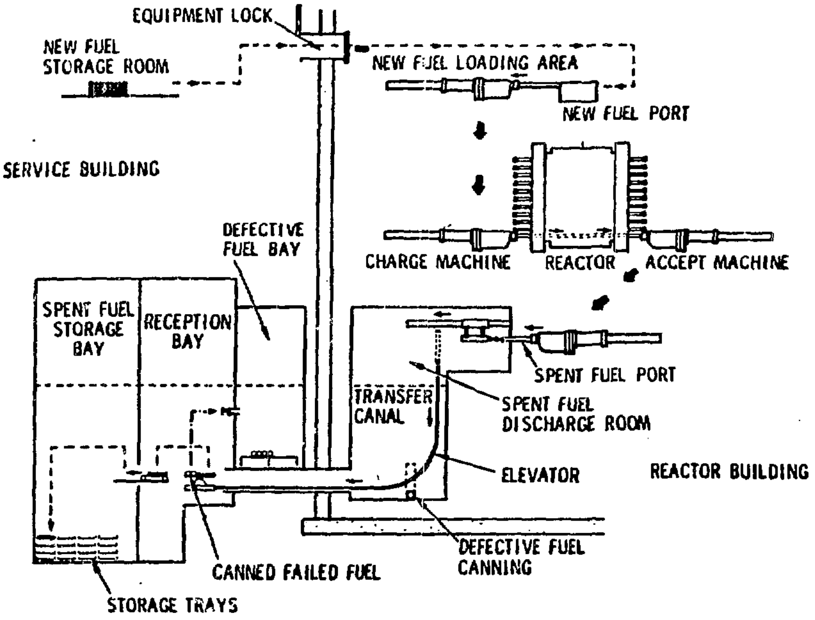

Fig. 8. CANDU fuel-handling sequence.[1,5]

inserts a fresh-fuel bundle into the channel, a spent bundle is pushed through to the accept-machine. The accept-machine then moves to the spent-fuel discharge ports and the bundles are pushed through the containment onto the ladles of the discharge elevators, where the spent fuel travels underwater through the transfer canal to the storage pond. There the irradiated bundles are loaded onto trays, each holding 24 or more bundles, which are then stacked in modular assemblies consisting of two stacks 18-20 trays high piled on a common base.[17] After 10 years of operation the spent-fuel storage pond may contain 40 000-50 000 bundles, with a total inventory of 3000-4000 kg of plutonium.

B. Detection Targets

The HWR safeguards system is designed to detect unreported removal of (1) fresh fuel from the facility, (2) irradiated fuel from the core, and (3) spent fuel from the irradiated-fuel storage bays. IAEA report STR-90 gives the following estimates of minimum removal times for one significant quantity of nuclear material from a CANDU reactor:[17]

Fresh fuel	1/2 day
Reactor vessel	2-30 days
Spent-fuel storage	<1 day

The design of a CANDU safeguards system is therefore based on the following detection considerations:

1. The natural-uranium fuel bundles receive minor safeguards emphasis before they are loaded into the reactor. Natural uranium has a high significant quantity (10.5 tonnes), long conversion time (10-18 months), and is considered "indirect-use" nuclear material. Indirect-use material is defined as nuclear material that must undergo enrichment or transmutation in a nuclear reactor prior to its use in a nuclear explosive device.[9]

2. A direct inventory verification of the core is avoided.[18] Due to the inaccessibility of the reactor core and the on-line refueling, direct verification would be difficult and highly intrusive to the operator of the facility. Emphasis is therefore placed on safeguarding irradiated fuel.

3. Irradiated bundles are discharged at burnups in the range of 165-250 MWh/kg uranium, with an average of 196 MWh/kg uranium (~8000 MWd/tonne uranium). Since the conversion ratio of HWRs is ~0.8, somewhat higher than that of LWRs, the bundles contain typically 40-90 g of plutonium with an average of ~70 g/bundle.[17,19] Thus, approximately 115 spent-fuel bundles contain a significant quantity of plutonium.

4. Although the absence of one or more spent-fuel bundles throws a cloud of uncertainty over the entire accounting

and inventory procedures, only the absence of a relatively large number of bundles (perhaps 10-20) within 2 or 3 months would have safeguards significance.

An instrumented CANDU detection system typically consists of the following items:[18]

1. Core input monitors--to count the number of unirradiated fuel bundles loaded into the core.
2. Closed-circuit television or film cameras--in areas where the unirradiated or irradiated fuel moves or is stored, to record anomalies that might indicate diversion.
3. Irradiated-fuel bundle counters--to count the number of irradiated-fuel bundles discarded from the reactor and to verify that the objects counted are highly radioactive.
4. Yes/no monitors--to indicate when irradiated fuel has been abnormally moved through penetrations or routes that do not have KMPs.
5. Irradiated fuel verifiers--to verify authenticity of irradiated fuel in the storage bay.
6. Tamper-indicating containers and seals--to hold irradiated fuel in large batches. A check of the integrity of the seal and container shows that no fuel has been removed.

C. Diversion Possibilities

Considering that the fresh-fuel bundles are indirect-use nuclear material and that the core is never really "open" to diversion, the undeclared removal of irradiated fuel from the spent-fuel storage bay is considered to be the most attractive diversion possibility for HWRs. Casks and transfer equipment are readily available. Furthermore, since the fuel in the bay has decayed significantly, it would be feasible to remove one significant quantity in one or two operations. The diversion possibilities are summarized in Table VI.

D. Inspection Activities

As with LWRs, two types of inspections are required each year: three to five routine (interim) inspections and an annual (PIV) inspection. During routine (interim) inspections, newly transferred fuel bundles must be sealed and safeguards/equipment must be serviced. The minimum activities that need to be performed at the facility are the following:

(1) Audit operating records and reports.

(2) Service each film camera system and complete appropriate forms. Films will be developed and reviewed off-site.

TABLE VI

SUMMARY OF DIVERSION POSSIBILITIES FOR HEAVY-WATER REACTORS

Diversion Possibilities	Concealment Methods	Safeguards Measures
Removal of fuel bundles from fresh-fuel storage	Substitution with dummies	Item counting and identification Container (box) counting NDA techniques (box verifier)
Removal of fuel bundles from the core	Substitution with dummies	Core input counters Irradiated-fuel bundle counters Closed-circuit TV or film cameras Yes/no monitors
Irradiation of undeclared fuel bundles in the core	Substitution with dummies	Core input counters Irradiated-fuel bundle counters Closed-circuit TV or film cameras Yes/no monitors
Removal of fuel bundles from spent-fuel pond	Substitution with dummies	Closed-circuit TV or film counters Yes/no monitors Irradiated-fuel verifiers Containers and seals
Removal of fuel elements from consignment when or after they leave the facility	Substitution with dummies or consignment. Understating of number of bundles shipped and substitution with dummies in spent-fuel pond	Sealing of shipping container before shipment and verification of content at recipient facility, if possible

(3) Service all fuel bundle counters and fuel bundle counters/attribute verifiers.

(4) Examine all yes/no monitors and convenience seals.

(5) Verify that spent-fuel stacking frames to be sealed are full and verify the sealing of such stacking frames.

(6) Verify fresh-fuel boxes received (box serial numbers) if possible.

(7) Proceed with follow-up activities when required.

Review of appropriate film and bundle counter printouts for agreement with the operator's records is usually performed off-site. Verification of off-site shipments, which requires advance notification, would be in addition to the above activities. To perform these activities the inspector requires (inter alia) access to the spent-fuel bays and fresh-fuel storage and loading rooms.

The prime purpose of the <u>annual inspection</u> is to verify the ending physical inventory entries provided in the state's annual Material Balance Report and Physical Inventory List. Verification of physical inventory may be accomplished by direct measurement (bundle count and random attribute test), or by accepted substitute techniques such as checking sealing systems. In addition, newly transferred fuel bundles are required to be sealed and all safeguards equipment is required to be serviced. The minimum activities that need to be performed during the annual inspection are as follows:

(1), (2), (3), (4), and (5) Same as for routine (interim) inspections.

(6) Inspect the seals and covers of randomly selected sealed stacks in all spent-fuel bays.

(7) Perform the fresh-fuel inventory verification activities.

(8) Perform off-site (at IAEA Headquarters or a Field Office) inspection activities as follows:

(a) Review the appropriate film and compare with operations records including crane operations list and large object removal list.

(b) Check for discrepancies among the approximate bundle counter printouts and for discrepancies in the operator's records.

(c) List the verified physical inventories for all categories of nuclear material or verified book inventory.

(d) Compare the state's accounting report (ICR, MBR, PIL) to the facility records to ascertain that the state's report is consistent, accurate, and complete.

(e) Calculate material unaccounted for (MUF) based on difference between ending book inventory and ending physical inventory.

(f) Proceed with follow-up activities when required.

(g) Update IAEA records and prepare inspection report on the basis of the inspection activities.

E. Verification of Nuclear Material

Typical safeguards verification activities that take place at a HWR are shown in Fig. 9. Fresh-fuel inventory verification consists of a count of containers (boxes) plus a count of loose (unpackaged) bundles in combination with a random check of containers to assure that these contain the stated number of natural-uranium fuel bundles. Such testing is accomplished by NDA techniques (box verifier), which do not require opening of boxes.

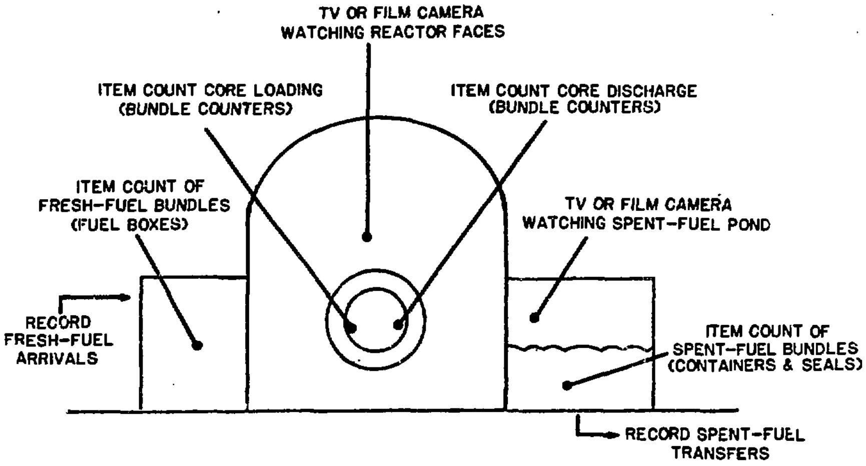

Fig. 9. Safeguards verification activities at a HWR power station.

The inspector can verify the inaccessible inventory in the core and fueling machines by the use of flow difference and C/S techniques. Flows can be independently measured by using core input counters and core discharge counters. The structural containment of the reactor building and additional C/S devices such as surveillance cameras, yes/no monitors, and seals provide a containment boundary and assure that undeclared removal of irradiated fuel by the more credible diversion routes will not occur without triggering anomalies.

Verification of the inventory in the spent-fuel bay makes use of the simplications afforded by sealing the irradiated fuel and also uses flow difference and C/S techniques. Bundles discharged into the spent-fuel bay are counted by the core discharge counters. These counters also incorporate an attribute test (fuel verifier) to provide assurance that all bundles counted were irradiated bundles. Any bundles shipped off-site (out of the bay) can be verified by an inspector being present. The structural containment of the walls of the storage bay and the use of C/S devices such as surveillance cameras, sealing system for spent fuel, as well as the discharge counters' reverse flow counting capability, are used to provide the containment boundary needed for the flow difference technique to be a valid means of verifying inventory. These C/S devices provide assurance that transfers other than through-flow KMPs did not occur. At each inspection the inspector would verify that stacks of irradiated fuel to be sealed are full, assuming the bundle counter and surveillance have indicated no anomalies. Verification of sealed fuel in future inspections will then consist of verifying the integrity of the sealing system.

APPENDIX[9]

SIGNIFICANT QUANTITIES

	Material	Significant Quantity	Safeguards Apply To
Direct-use nuclear material	Pu*	8 kg	Total element
	U-233	8 kg	Total isotope
	U(U-235 $\geq$ 20%)	25 kg	U-235 contained
	- Plus rules for mixtures where appropriate -		
Indirect-use nuclear material	U(U-235 < 20%)**	75 kg	U-235 contained
	Th	20 t	Total element
	- Plus rules for mixtures where appropriate -		

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*For Pu containing less than 80% Pu-238.
**Including natural and depleted uranium.

ESTIMATED MATERIAL CONVERSION TO FINISHED Pu AND U METAL COMPONENTS

Beginning Material Form	Conversion time
Pu, HEU or U-233 metal	Order of days (7-10)
PuO_2, $Pu(NO_3)_4$, or other pure Pu compounds; HEU or U-233 oxide or other pure compounds; MOX or other non-irradiated pure mixtures containing Pu, U[(U-233 + U-235) $\geq$ 20%]; Pu, HEU and/or U-233 in scrap or other miscellaneous impure compounds	Order of weeks (1-3)*
Pu, HEU or U-233 in irradiated fuel**	Order of months (1-3)
U containing <20% U-235 and U-233; Th	Order of one year

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*This range is not determined by any single factor, but the pure Pu and U compounds will tend to be at the lower end of the range and the mixtures and scrap at the higher end.
**Criteria for establishing the irradiation to which this classification refers are under review.

POWER REACTOR FUEL DETECTION TARGETS

SIGNIFICANT QUANTITIES & TIMES

Material	Mass	Time	No. PWR Assemblies	No. PWR Assemblies	No. HWR Bundles
U-235 in LEU	75 kg	1 Year	~6	~13	>500
Pu	8 kg	1-3 Months	~3	~8	>100

INSPECTION TARGETS

			1	1	~10-20**

** Note the discussion of this number in the text, item B-4, page 13-17.

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