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**PRELIMINARY CONSIDERATIONS ON
DEVELOPING IAEA TECHNICAL SAFEGUARDS
FOR LMFBR POWER SYSTEMS**

by

P. J. Persiani

MASTER

P 309



ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

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Work performed under the auspices of the
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PREFACE

A prime consideration in the international deployment of the fast breeder power system is safeguards. This preliminary report addresses technical safeguards and assesses the current and developing safeguards techniques and systems consistent with the deployment of fast breeder power systems and reprocessing methods.

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ABSTRACT

Nuclear fuel cycles safeguards should be considered in the dynamic context of a world deployment of various reactor types and varying availability of fuel-cycle services. This is particularly true of the fast breeders, which must be fueled in the transition period with fissile material produced by other types of reactors. There will be a close and controlled interaction between thermal-reactor cycles and the future deployment of breeders that will be critically dependent on the plutonium produced in those cycles. The quantities of plutonium and the reprocessing, conversion, fabrication, and storage methods of the fuel for the fast breeders will have a significant impact on safeguards techniques. The approach to the fast breeder fuel cycle safeguards follows the general safeguards system approach proposed by the IAEA. The objective of IAEA safeguards is the timely detection of diversion of significant quantities of nuclear material and deterrence of such diversion by the risk of early detection. The goal requires the development of highly effective safeguards systems that are both technically and publicly credible. To achieve independent verification of material balance accountancy requires the capability to monitor inventory status and verify material flows and quantities of all nuclear materials subject to safeguards. Containment and surveillance measures are applied to facilitate monitoring at key measurement points, maintain integrity of material balance, and complement material accountancy to effect the timely detection of diversion of significant quantities of nuclear material. The safeguards study attempts to develop a generic reference IAEA Safeguards System and explores various system options using containment/surveillance and material accountancy instrumentation and integrated systems designs.

PRELIMINARY CONSIDERATIONS ON DEVELOPING IAEA TECHNICAL SAFEGUARDS FOR LMFBR POWER SYSTEMS

I. INTRODUCTION

A prime consideration in the international deployment of the fast breeder power system is safeguards. This preliminary report addresses technical safeguards (near real-time material accountability, containment/surveillance measures, and Integrated System concepts) and assesses the current and developing safeguards techniques and systems consistent with the deployment of fast breeder power systems and reprocessing methods.

Nuclear fuel cycles safeguards should be considered in the dynamic context of a world deployment of various reactor types and varying availability of fuel-cycle services. This is particularly true of the fast breeders, which must be fueled in the transition period with fissile material produced by other types of reactors. There will be a close and controlled interaction between thermal-reactor cycles and the future deployment of breeders that will be critically dependent on the plutonium produced in those cycles. The quantities of plutonium and the reprocessing, conversion, fabrication, and storage methods of the fuel for the fast breeders will have a significant impact on safeguards techniques. The plutonium throughput, high fissile content and the use of sodium coolant in the FBR cycle may require additional safeguards techniques development beyond those of the thermal cycle.

The approach to the fast breeder fuel cycle safeguards follows the general safeguards system approach proposed by the IAEA. The objective of IAEA safeguards is the timely detection of diversion of significant quantities of nuclear material (see Table VI) and deterrence of such diversion by the risk of early detection. The goal requires the development of highly effective safeguards systems that are both technically and publicly credible. Ideally, to achieve independent verification of material balance accountancy requires the capability for near real-time monitoring of inventory status and verifying material flows and quantities of all nuclear materials subject to safeguards. In addition, containment and surveillance measures are applied to facilitate monitoring at key measurement points, maintain integrity of material balance, and complement material accountancy to effect the timely detection of diversion of significant quantities of nuclear material (see Table VI).

Technology and subsystem components include measurement methods and instrumentation, process monitoring and control instrumentation, data management and analysis methodology, and containment and surveillance techniques. Nuclear material flow verification objectives can be achieved by developing and applying advanced safeguards systems with emphasis on the independence of measurements by the IAEA. Safeguards techniques that are currently available and are assessed to be directly applicable to the fast breeder cycle, will form the basis of the IAEA FBR safeguards system.

The capability for continuous or near real-time monitoring of nuclear material during all processing and transfer operations is a desirable objective. Advanced automated safeguards systems initially designed into nuclear facilities may facilitate effective international safeguards by providing timely and sensitive information on inventory status.

The IAEA presently implements a safeguards system for periodic material accountancy and a set of containment and surveillance measures. The proposed advanced technical safeguards will allow the current IAEA Safeguards System to incorporate a near real-time level capability for the timeliness criterion. The proposed safeguards techniques include components which are commercially available, or in the laboratory testing phase of development, or in the conceptual stage of development. It is expected that the implementation of these proposed technical safeguards will be initially integrated into the fuel storage phase of the fuel cycle during the transition period from the thermal system to the FBR system.

The safeguards study attempts to develop a generic reference IAEA Safeguards System and explores various system options using containment/surveillance and material accountancy instrumentation and integrated systems designs. This report is structured into the following categories: Section II - Analysis of Safeguards, briefly analyzes the safeguards considerations which are primarily characteristic of the fast breeder fuel cycle system; Section III - IAEA Safeguards, reviews the current IAEA safeguards goals and objectives; Section IV - Methods for Achieving IAEA Safeguards, describes the methods and systems identified for achieving IAEA safeguards objectives; and Section V - Advanced IAEA Safeguards Research and Development, introduces proposed integrated and advanced IAEA safeguards systems and identifies the Research and Development programs necessary for the implementation of these systems.

II. ANALYSIS OF SAFEGUARDS CONSIDERATIONS ASSOCIATED WITH FBR FUEL CYCLE

In the context of assessing the safeguards concerns relating to Fast Breeder Reactors (FBR), the reference system selection was based on the current state of development, design, construction, deployment, operating data and experience which reflects the state of the breeder technology for the first-generation of commercial power systems. The major power breeder programs receiving international-level development support are the liquid-metal cooled reactor systems utilizing the uranium-plutonium mixed-oxide fuel cycle. The commercial-scale systems under construction are: France,¹ Super Phenix Plant; USSR,² BN-350 and -600; and the United Kingdom,³ Commercial Fast Breeder, CFR (in design). The advanced phase of the Super-Phenix reactor design and construction allows specific modeling of the reference system for each major stage of the total operational plant system.

The safeguards concerns are addressed to the major stages of the FBR fuel cycle. The reactor power plant stage includes the annual mass flow in unit fuel and blanket assemblies, storage of fresh and spent fuels, and loading and unloading systems. The transportation stage considers fuel and blanket assemblies, bulk forms of material in canisters and the modes of transport (sea, air, land). The reprocessing-conversion stage involves the processing of LWR spent fuel assemblies during the transition into the deployment of breeder systems and the reprocessing of FBR spent fuel and blanket assemblies. The fabrication stage includes fuel element and fuel assembly manufacturing. The storage stage of the fuel cycle includes the storage of FBR fuel and blanket assemblies during the LWR to FBR transition period, and the LWR spent-fuel storage facilities.

A. FBR Reactor Power Plant System

In the normal operating mode of fast breeder power reactors, the basic unit of one fuel assembly and one blanket assembly is assumed applicable for item accountability. Table I and Fig. 1 include the reference reactor specifications and design characteristics. Typical mass and fuel assembly flows are schematically shown in Fig. 2 and listed in Tables II and III. Table IV and Fig. 3 describes the general design features of the storage facility and the loading and unloading sequence of fresh and spent fuel assemblies.

Fuel assemblies removed from the core are passed from the sodium transfer tank to the rotating storage drum, as shown in Fig. 3. The decay heat of the assemblies is removed by two independent sodium systems connected to sodium-to-air heat exchangers. The assemblies are transferred into the storage drum from the loading ramp by means of a rotating plug and a fuel transfer gripper. Subsequent steps in the fuel handling procedure are: (1) extraction from the storage drum to the conditioning room via a handling cell, (2) preparation for shipment in the conditioning room, transfer to shipping casks, which are filled with sodium and sealed, and (3) transfer of casks to a transport passageway under the cask-loading station.

B. Transportation

To introduce a practical timing perspective to the transport safeguards for the FBR fuel cycle, the near-term French program plan⁴ is used

TABLE I. Core and Fuel Specifications for Typical LMFBR Reactor

Rated Output	Gross Thermal	3000 MW
	Gross Electrical	1260 MW
	Net Electrical	1200 MW
	Station Use	4.8%
Net Efficiency	40%	
Conversion Ratio	1.2	
Core Shape and Size	Hexagonal, 350-cm Equivalent Diameter 100 cm High	
Number of Fuel Channels	358 Fuel Channels in Two Zones	
Core Loading at Rated Power	5900 kg PuO_2 and 30100 kg UO_2	
Average Power Density in Fuel	508 dW/kg PuO_2	
Average Core Power Density	300 kW/liter	
Burnup	Initial 70000 MWd/t	
Fuel Form and Composition	Mixed Oxide ($\text{PuO}_2 - \text{UO}_2$) Annular Pellets, 7.02 mm o.d., in Stainless Steel Tubes 8.65 mm o.d., \times 2700 mm Long PuO_2 Enrichments, Inner Zone 14.6% Outer Zone 18.5%	
Cladding	Type 316 Stainless Steel Tube, 8.65 mm o.d., with Spacer Wire Helically Wound Around Pin	
Fuel Assembly	Hexagonal Assembly, 173 mm Across Flats, Holds Bundle of 271 Fuel Pins Total Length of Assembly is 5400 mm	
Coolant	Sodium	

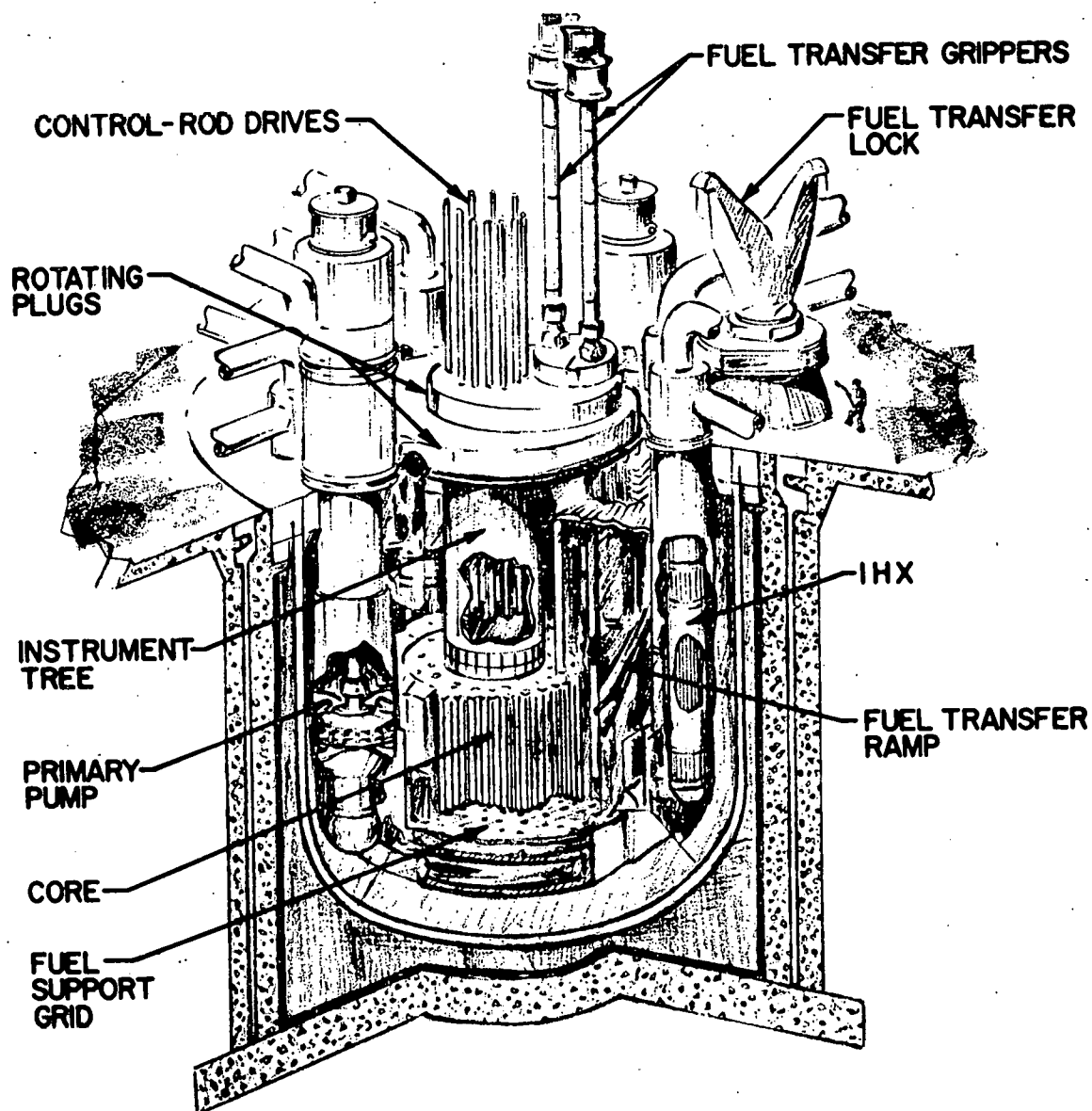


Fig. 1. Sketch of Reference FBR Primary System.

ANNUAL Pu FUEL MASS FLOW DIAGRAMS FOR REFERENCE THE LMFBR

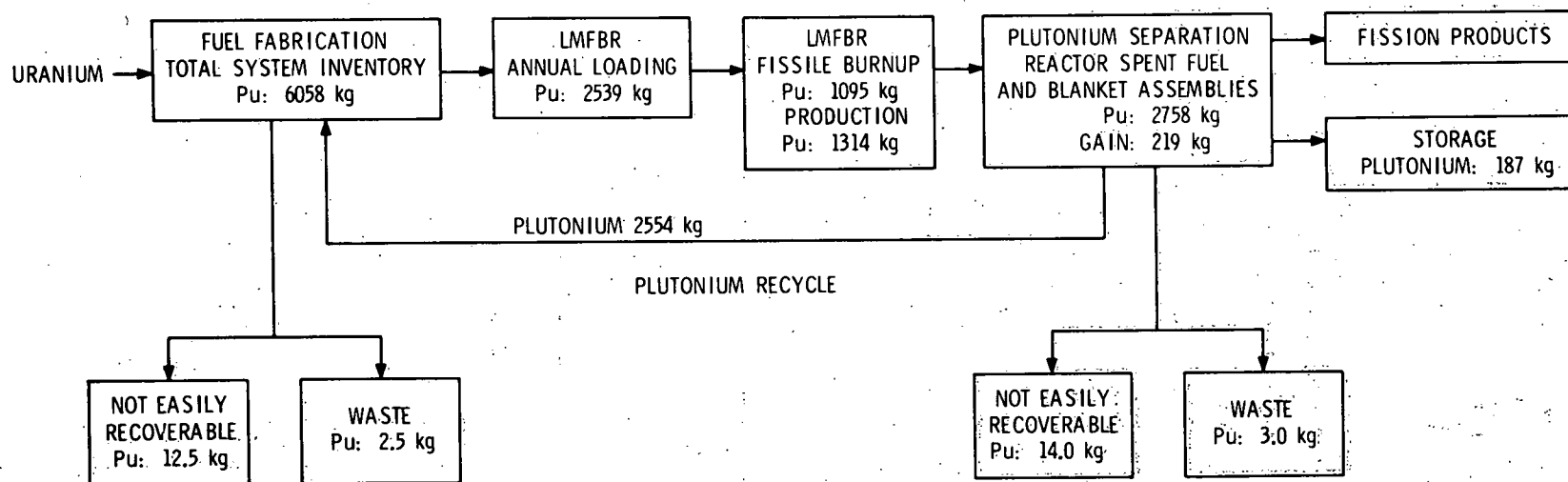


Fig. 2. Diagram of Annual Pu Fuel Mass Flow for the Reference LMFBR.

TABLE II. Annual Fissile Fuel Mass Flow^a
in Typical LMFBR Reactor

Fuel Cycle	Pu/U	
Composition	16.3% Pu/HM 0.2% ²³⁵ U/U	
Total HM (kg)	(Core) 15575	(Blanket) 15100
Charge (kg)		
²³⁵ U	16.1	30.2
Pu	2539	-
Discharge (kg)		
²³⁵ U	16.1	29.3
Pu	2399	359

^a1/2 of core annually
HM; Heavy Metal

TABLE III. Nominal Uranium and Plutonium
Content in Typical LMFBR Fuel Assembly

Fuel Cycle	Pu/U
Composition	16.3% Pu/HM 0.2% $^{235}\text{U}/\text{U}$
Total HM (kg)	87
Charge (kg)	
^{235}U	0.15
Pu	14.2
Discharge (kg)	
^{235}U	0.09
Pu	13.4

TABLE IV. Fuel Handling and Storage for Typical FBR Reactor

Fuel Loading and Unloading	Off-Load Refueling in Argon Atmosphere Two Straight-Pull Grippers with Two Rotating Plugs are Used With a Transfer Machine to Simultaneously Remove a Spent Fuel Assembly and Load a Fresh Fuel Assembly.
Irradiated Fuel Storage	Spent Fuel Assemblies are Temporarily Stored in a Rotating Storage Drum. Subsequently, the Assemblies are Extracted from the Storage Drum to the Conditioning Room Via a Handling Cell, Prepared for Shipment, Transferred to Shipping Casks which are Filled with Sodium and Sealed, and Transferred to Transport Passageway Under the Cask Loading Station.
Refueling Scheme and Schedule	179 Fuel Assemblies are Replaced at Each Annual Refueling. Downtime for Refueling is 2-3 Weeks.

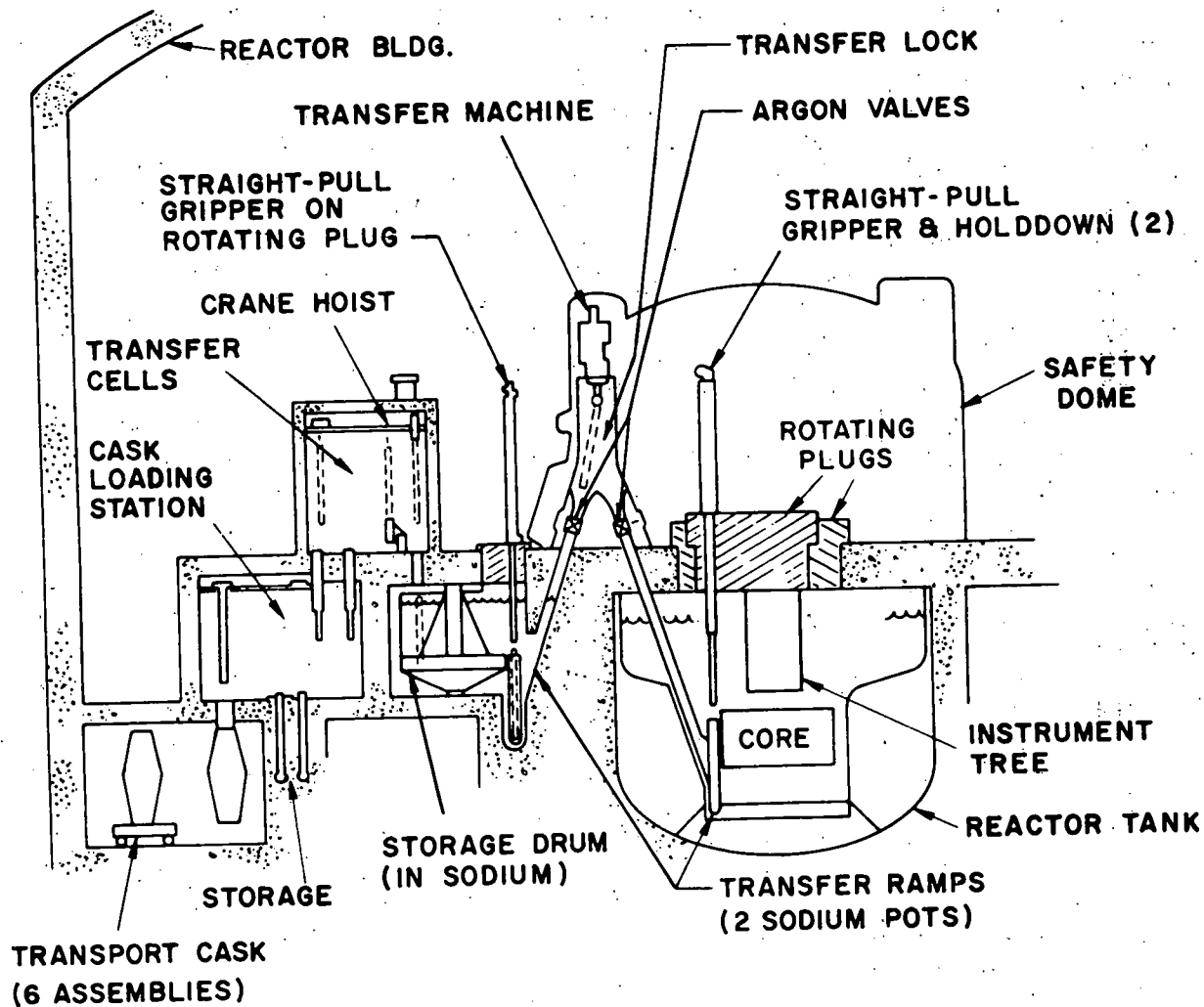


Fig. 3. Reference FBR Fuel Handling Systems.

as a guide. The plan, as outlined in Ref. 4, is to build one to three breeder reactors within the 1980 - 1985 period, and then one 1200-MWe reactor each year from 1986 to 1996. This program implies that safeguards be considered in the near-term disposition with respect to location of reprocessing plants for the LWR spent fuel assemblies and the FBR fuel-fabrication plants. The deployment of FBR's during the transition period from the LWR to the FBR fuel cycle system, would probably not include colocation of power reactors, fabrication plants, and reprocessing plants. Safeguards would have to be given high priority during the transportation of bulk mixed-oxide fuel between the reprocessing plant and the fabrication facility as well as the transportation of fresh and spent fuel assemblies.⁵ In this phase of transportation, item accountability is expected to be the primary technique of safeguards for the shipper-receiver transfers. Non-destructive assay (NDA) and physical signatures would have to be developed for the specific mode in which the bulk container and FBR assemblies are packaged for transport. The NDA techniques that are currently being developed should be assessed for utilization on FBR assemblies which may or may not contain sodium. Containment and surveillance techniques may be utilized to provide a more real time measure of the custody, location and integrity of the nuclear material in transit.

In the bulk mixed-oxide fuel, the NDA and physical signature identification methods may be effectively supplemented by chemical and nuclear analytical assay techniques for fissile accountability.

On the basis that mixed-oxide fuel will be transported off-site on a global scale in bulk form or as fuel assemblies, the three modes of transportation (land, sea, and air) should be factored into the safeguards considerations, which would include:

- a. Land transportation would require development of transport cask units sized for highway load limits, and larger units may be scaled for rail or water transport.
- b. Sea transportation must be considered since reprocessing plants for LWR fuel in various fuel centers would ship fabricated and/or bulk mixed-oxide fuel to deployed power reactors or fabrication facilities in, and would ship fabricated mixed-oxide fuel to other countries.
- c. Protection against national diversion would need to be emphasized. Enroute reporting of seal integrity, identification, and location should be considered for development in long-distance shipments.
- d. Air transport (e.g. through the use of helicopters) would decrease the transport time of nuclear material in fresh assemblies or bulk form.

C. Reprocessing-Conversion

Chemical separations plants^{6,7} are the most complex of the nuclear fuel-cycle facilities requiring safeguards. The fuel-reprocessing or chemical separations plant confronts the safeguards system designer with large quantities of fissile materials in several forms, in various phases of manufacture,

and introduces nuclear material flow verification measurement requirements ranging from highly radioactive and dilute spent-fuel feed material to a high-purity, concentrated fissile product. The facilities present the need for material balance measurement sensitivities to maintain a high level of material accountancy verification. To develop the most effective safeguards system in the chemical separation plant, all available safeguards techniques must be optimized and integrated.

Facilities designed for recovery of enriched uranium residuals, for co-recovery of the uranium and plutonium, for breeder-reactor fuels production, or for separation of the transuranic elements from the spent fuel for storage or future disposition, will all have a common requirement for effective safeguards. Generally the safeguards systems will not differ greatly.

In general, the reprocessing of U-Pu fuel in the Purex system begins with spent fuel receiving, unloading, and intermediate storage in a pool. The headend process consists of mechanical shearing, dissolution of the nuclear fuel in nitric acid, the solvent extractive separation of U-Pu with co-decontamination of fission product, and plutonium and uranium partition followed by further purification of the respective streams. The deployment of FBR would require a more specific reprocessing design to accommodate FBR spent fuel.

The requirement for timely detection of non-verification of material balance involving small quantities of material has led to the development of automated systems for near-real-time measurements and control of fissile materials. Passive and active gamma-ray, x-ray, and neutron interrogation methods for nondestructive assay (NDA) determinations are the primary techniques used in material-control systems. When coupled with the continuously developing chemical and nuclear analytical methods, these measures comprise the safeguards technique of fissile-material balance accountability and control for detecting non-verification of fissile material balance in an acceptable timely mode.

The containment and surveillance systems of safeguards are necessary complementary measures in maintaining integrity of material accountancy measures, in detecting anomalies in nuclear material flows and/or inventories in the fuel cycle facilities. Containment and surveillance adds an overlay of timeliness of detection when coordinated with materials accountancy.

D. Fuel Assembly Fabrication Facility

The fabrication^{8,9} of plutonium fuel involves the weighing and mixing of PuO_2 and UO_2 powder, fabrication into pellets and fuel pin elements, and finally emplacement into fuel assemblies, see Fig. 4. The primary safeguards system throughout this phase of the fuel cycle process would involve item accountability, process monitoring and fissile content measurements by NDA techniques. Physical and nuclear signatures as well as tamper-indicating seals on the finished fuel assembly units would constitute the surveillance and control aspect of safeguarding for the remainder of the fuel cycle flow. These subsequent stages would consist of temporary storage, transport to reactor location (probably in dry transport casks) and assembly preparation for insertion into the sodium environment, and into reactor storage pool for eventual loading into the reactor core. The verification of assembly identity

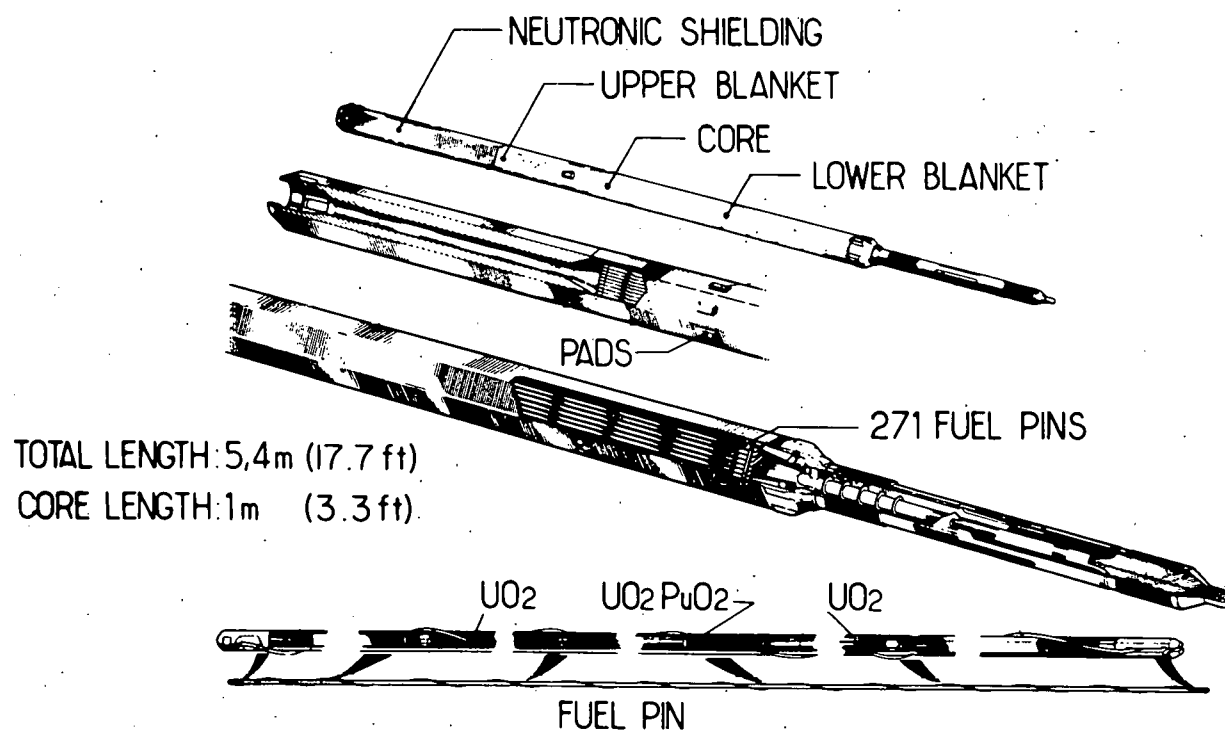


Fig. 4. Reference FBR Fuel Pin and Fuel Assembly.

and storage or core location under sodium can be affected by ultrasonic techniques now in the process of advanced development. Of particular note, the fissile material is in the form most suitable for item accountability for most of its lifetime (years) in the fuel cycle. The period during which it exists in aqueous form, that is in the reprocessing and conversion phase, may be days or weeks compared to years in the item accountably form during the fabrication, storage and in-situ radiation phases of the total power plant cycle. Therefore, to supplement item accountability with nuclear material identification and accountability, the fuel assembly and canister units should include design features which would allow sampling for NDA or chemical assay measurements.

E. Storage of FBR Spent Fuel and Blanket Assemblies

In the LWR to FBR transition phase, the primary fuel feed would be derived from the reprocessing of LWR spent fuel. During this phase the FBR spent fuel and blanket assemblies will be placed in a storage pool. This pool may be colocated with the reactor plant complex but not necessarily within the reactor system, unless FBR systems accommodate spent fuel storage at greater capacities than the normal operational annual reloading schedules. From Table II, the reference FBR spent fuel storage requirements for the initial reactor over 1980 - 1995 would involve approximately 240 tonnes U (36 tonnes of plutonium) from the core assemblies and 240 tonnes U (5 tonnes of plutonium) from the blanket assemblies. Assuming a deployment of about 10 - 15 FBR systems over 1985 - 1995 the total storage requirements would involve about a total of 100 annual reactor loadings or 1600 tonnes U (240 tonnes of plutonium) from the core and 1600 tonnes U (36 tonnes of plutonium) from the blankets.

With the gradual introduction of a breeder technology there will be a significant and accelerating flow of spent LWR and HWR fuel from reactor to storage. From Table V, the spent fuel in storage world-wide¹⁰ contains about 50 tonnes of plutonium and that amount is currently growing at about 18 tonnes per year. As the nuclear economy evolves from only thermal reactors to a mix of thermal and breeder reactors, the fuel for the breeders will initially be manufactured in a process that uses the spent thermal reactor fuel as feedstock for development of a breeder. There will be accumulated tens of years of feedstock for a reprocessing cycle using spent thermal reactor fuel to manufacture fresh breeder reactor fuel. Such a process would require significant modification of facilities to allow the use of spent FBR fuel as feedstock. There may be a transition period of a decade or more during which tens of thousands of tonnes of spent thermal reactor fuel will be recycled to produce fuel for breeder reactors with the breeder fuel placed into interim storage. The fuel for each breeder reactor will require the entire plutonium content from the spent fuel of approximately 14 LWRs.

Planning for the transition from a thermal reactor economy to a breeder economy must therefore include planning for storage of spent breeder reactor fuel. Current design plans for FBR's include only very limited on-site storage and no AFR storage. These plans must reflect the need for a gradual and smooth transition. Although spent breeder reactor fuel has an order of magnitude higher Pu content than spent thermal reactor fuel, the same containment/ surveillance, item accountability, and tamper-indicating methods will be used as safeguards techniques. The safeguards system design

TABLE V. Estimated World Spent Fuel Arisings

Year	Annual (tonnes/yr)		Cumulative (tonnes)	
	Uranium	Plutonium	Uranium	Plutonium
1977	2200	18	6200	50
1985	5900/6500	47/52	37000/38000	296/304
1990	11000/14000	88/112	80000/92000	640/736
1995	18000/26000	144/208	155000/195000	1240/1560
2000	27000/48000	216/384	273000/388000	2184/3104

considerations should anticipate that once reprocessing plants for thermal into breeder fuel are established and operating, there may be economic incentives to operate these facilities near full capacity. Therefore, fresh fabricated breeder reactor fuel assemblies may also need to be stored.

Depending on the growth demand for the deployment of the breeders, the breeder spent fuel may be planned as feed material for the LMFBR system. The breeder net gain, probably in the form of blanket assemblies, would then be stored or become feed for the LWR system for an interim period.

III. IAEA SAFEGUARDS

IAEA safeguards are applied either to all the peaceful nuclear materials in states that are members to the nuclear non-proliferation treaty (NPT), or to the materials and equipment in individual facilities offered to the IAEA by states that are not signatories. In the former case, the IAEA rights and limitations are described in IAEA document, INFCIRC/153:¹¹ in the latter, the responsibilities are described in INFCIRC/66.¹² Although the details of agreements are somewhat different in the two cases, the general objectives and procedures are similar. In the following, the objectives and procedures for the NPT case are discussed.

A. Objectives and Goals

The general form of an agreement between a State and the IAEA, and the general nature of IAEA safeguards, are stated in the following paragraphs of INFCIRC/153:

Objective of Safeguards

- a. The Agreement should provide that the objective of safeguards is the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection.
- b. To this end the Agreement should provide for the use of material accountancy as a safeguards measure of fundamental importance, with containment and surveillance as important complementary measures.
- c. The Agreement should provide that the technical conclusion of the Agency's verification activities shall be a statement, in respect of each material balance area, of the amount of material unaccounted for over a specific period, giving the limits of accuracy of the amounts stated.

National System of Accounting for and Control of Nuclear Material

- a. The Agreement should provide that the Agency, in carrying out its verification activities, shall make full use of the State's system of accounting for and control of all nuclear material subject to safeguards under the Agreement, and shall avoid unnecessary duplication of the States's accounting and control activities.

The IAEA Safeguards Technical Manual¹³, Part A. outlines the objectives, discusses possible diversion paths of nuclear materials, describes the present IAEA safeguards system, and the guidelines for the State's system of material accounting and control (SSAC), in order that the IAEA should be able to achieve its objectives.

Within the IAEA there is general agreement on the meaning of "significant quantities" as related to existing IAEA safeguards practices that involve periodic inventory verification and complementary containment/surveillance of nuclear material. The current IAEA goals^{14,15} for quantities of safeguards significance are contained in Table VI.

The IAEA attempts to identify a timeliness of detection of diversion (to be of the same order of magnitude as conversion time) before the material is processed for component fabrication. This time is a function of the physical and chemical form of the material. The current IAEA proposed guidelines^{14,15} for conversion timeliness are given in Table VII.

B. Basic Assumptions in IAEA Safeguards

The basic function of the IAEA is the independent inventory verification of the flow of nuclear materials. Therefore, a need for high assurance through physical-inventory verification is assumed.

IAEA inspection activities are assumed basic to an international safeguards system. This not only follows directly from the need for independent inventory verification, but also from the number of activities to be performed by an inspector. These may include safeguards equipment maintenance, verification of tamper-indicating features, observation of abnormal operations, nuclear materials shipment and receipt, and monitoring of unusual activities, such as the movement of very large equipment in and out of an area with nuclear materials. Several desirable benefits may also accrue by virtue of on-site inspection activities. These include improved timeliness of detection, assessment of the cause of alarms, surveillance for unauthorized activity, and independent inventory verification by means of analytical chemistry assay.

An acceptable international safeguards system must have the clearly demonstrable capability of satisfying a number of basic functional requirements and conditions. Those assumed to be most important include:

1. High confidence in detecting diversion,
2. Timely detection of diversion,
3. Low false-alarm rate,
4. Minimum interference with facility operations,
5. Acceptable cost, and
6. High reliability and/or maintainability.

C. Current IAEA Safeguards

IAEA safeguards inspections for LWR's now rely on routine reporting by the state and periodic inspection by IAEA personnel.¹⁵ The procedures and the frequency and levels of inspection are negotiated with the state and are documented in accord with the basic documents, 1. INFCIRC/153, and 2. Facility Attachments. Site specific information and agreements are included in the Facility Attachments and the Design Information Questionnaire (DIQ) documents. Generally, the state provides routine monthly reports. Periodic inspection by the IAEA occurs from monthly to annually, depending on the type of facility inspected. The negotiated inspection level and frequency are planned in terms of inspector days per year per facility, with IAEA having

TABLE VI. Quantities of Safeguards Significance

	Material	Quantity of Safeguards Significance (SQ)	SQ applies to:
"Direct-use" Material	Pu	8 kg	Total Element
	^{233}U	8 kg	Total isotope
	U ($^{235}\text{U} > 20\%$)	25 kg	^{235}U
	$\text{Pu} + \text{U}[(^{233}\text{U} + ^{235}\text{U}) > 20\%]$	8 kg	$\text{Pu} + ^{233}\text{U} + \frac{8}{25} ^{235}\text{U}$
"indirect-use" material	U ($^{235}\text{U} < 20\%$) ^a	75 kg	^{235}U
	$\text{Pu} + \text{U}[(^{233}\text{U} + ^{235}\text{U}) < 20\%]$	8 kg	$\text{Pu} + \frac{1}{3} ^{233}\text{U} + \frac{8}{25} ^{235}\text{U}$
	Th	20 t	Total element

^aIncluding natural and depleted uranium.

TABLE VII. Guidelines for Estimated
Material Conversion Times

	Estimated ^b Conversion Time
Pu, HEU, ^a or ²³³ U metal	Order of days (7-10)
PuO ₂ , Pu(NO ₃) ₄ , or other pure compounds. HEU or ²³³ U oxide or other pure compounds	Order of Weeks (1-3)
MOX or other nonirradiated pure mixtures of Pu or U [(²³³ U + ²³⁵ U) > 20%]. Pu, HEU, and/or ²³³ U in scrap or other miscellaneous impure compounds	Order of Weeks (1-3)
Pu, HEU or ²³³ U in irradiated fuels (< 10 ⁵ Ci/kg HEU or ²³³ U or Pu)	Order of months (1-3)
U containing <20% ²³⁵ U and ²³³ U; thorium	Order of one year

^aUranium enriched to 20% or more in the
isotope ²³⁵U.

^bTime to convert to metal form suitable
for fabrication.

some discretion in the allocation of the effort. The continuity of surveillance is partially provided in some stages of the fuel cycle, e.g. fresh and spent fuel storage, by supplementing the procedure with a camera surveillance system.

There are two important facts about current IAEA safeguards. First, the times at which statements are made concerning the status of material inventory (safeguards decision points) occur periodically and often are months apart. Therefore, the timeliness goals stated may be difficult to achieve. Second, the routine report from the state is not of value in the timely detection of an imbalance in the flow of nuclear materials if the state itself is involved.

D. Advanced IAEA Safeguards

The advanced IAEA safeguards system approach which may be used as a basis for the options considered in this study, involve continuous or near-real-time surveillance system. Continuous surveillance systems bridge the time between the safeguards decision points now associated with periodic inspections. This monitoring may be accomplished by inspector surveillance, by instrumentation, by routine inventory, or by a combination of these methods. Unreported actions are sensed by the monitors and cause an alarm to be generated and transmitted to the IAEA. Response to an alarm is a special independent inventory verification procedure which assesses the alarm and includes a sampling of the inventory. This sequence provides the information necessary to reach a safeguards decision. The "timeliness" factor in this approach is the interval from the indication of a possible unauthorized action to the safeguards decision point at the end of the special inventory verification. The times between unauthorized action, alarm, receipt of alarm, and the initiating of the special inventory are system variables that depend upon inspection procedures, communication, and safeguards instrumentation techniques and methods.

The possible total safeguards system approach, since it depends upon inventory procedures that may disrupt normal facility operations, should have a very low frequency of false alarm to be acceptable to the facility operator. Cooperation by the operator in following procedures to minimize false alarms can and should be encouraged by the safeguards system. The approach pursued is to establish agreed upon administrative procedures which are monitored by the safeguards system. A sensor trip and a deliberate facility exit, a procedural violation, or a discrepancy in routine inventory can cause an alarm. If assessed as a valid alarm by the inspector, a special inventory verification is performed and a subsequent statement concerning the situation is made. The level of this inspection effort depends upon the circumstances, e.g., the number of alarms, the type of violations detected, or the amount of elapsed time.

In general, the confidence of verification of nuclear materials flows by means of a special inventory will be a function of the time available for the special inventory and the amount of material imbalance. For a given inspection procedure and time, a continuum of statements can be made concerning confidence of detection and amount of material imbalance. The results of the same inventory verification could be represented as low confidence in detecting the imbalance of small quantities of material or high confidence in detecting

the imbalance of large quantities of material. Therefore, a system that is adequate to detect an abrupt change in inventory of large quantities of material may have limited capability for timely detection during a protracted inventory imbalance of small quantities of nuclear materials.

The introduction of continuous or near-real-time accountability and surveillance techniques (including possibly on-site, full-time IAEA inspectors as an integral part of the total IAEA safeguards systems) would have the equivalent effect of increasing the time available for the special inventory and in effect would give a high confidence of nuclear material flow verification, even for the flow imbalance of small quantities of nuclear materials.

IV. METHODS FOR ACHIEVING IAEA SAFEGUARDS

A. Transition Period

A.1 LWR Spent Fuel in Storage and Reprocessing for FBR Use: The near-term safeguards concerns for phasing the FBR power systems into the existing deployed LWR power fuel cycle systems will be directed primarily to the characteristics of the transition period where the major fuel-cycle facilities such as isotopic enrichment facilities and reprocessing facilities are operating at economies of scale consistent with the LWR power options.

In the early phase of FBR deployment, the FBR's would be started and sustained with plutonium produced by the thermal reactors. The FBR spent fuel would be stored until the excess supplies of thermal-reactor spent fuel had been drawn upon and the breeder reprocessing.

During the interim period, breeder operation would alter the manner in which the total quantities of spent fuel are placed in storage. The quantity of spent fuel at dispersed sites that would need to be safeguarded would be reduced.

In Fig. 5 are typical annual mass flow requirements and spent-fuel output for the reference LWR (U.S.-Indian Point ~900 MWe).¹⁷ Referring to the reference FBR fuel mass flow, Fig. 2, the FBR would absorb the annual spent-fuel production of about 14 LWR's in addition to a two-year backlog. If the LWR spent fuel is stored at the reactor, about 400 tonnes of spent fuel per year is added to the storage at about 14 sites. If the spent fuel is reprocessed to fuel an FBR, the equivalent quantity of contained plutonium is stored in the FBR spent fuel at a single FBR site at a rate of about 31 tonnes per year (core and blanket assemblies containing 2758 kg of plutonium). In addition, about 650 tonnes of spent LWR fuel containing about 6 tonnes of plutonium is committed to the fuel cycle as the FBR core inventory.

The safeguards consideration in this transition period will involve mainly the LWR fuel cycle systems facilities such as isotopic enrichment plants, reprocessing and fabrication facilities, transportation, and storage of spent fuel.

The statistical sampling methods for item (spent core and blanket assemblies) identification and accountability, should form the basis for storage design and management to enhance the effectiveness of surveillance and the containment techniques. The safeguarding of spent fuel is based on item accountability, and the number of fuel elements as well as the dispersed locations add to the demand of safeguards resources. Table VIII shows the number of elements and locations that would be provided by each FBR if fueled with plutonium recovered from LWR or HWR spent fuel.

The introduction of plutonium-containing fuel into the fuel cycle systems introduces a more direct visible profile of the disposition of plutonium. This greater visibility results not only from the application of effective continuous IAEA containment and surveillance methods, but also from the direct applicability of material accountancy by chemical analytical assays (destructive assay) and nondestructive NDA assay.

ANNUAL FUEL MASS FLOW DIAGRAMS FOR REFERENCE PWR REACTOR

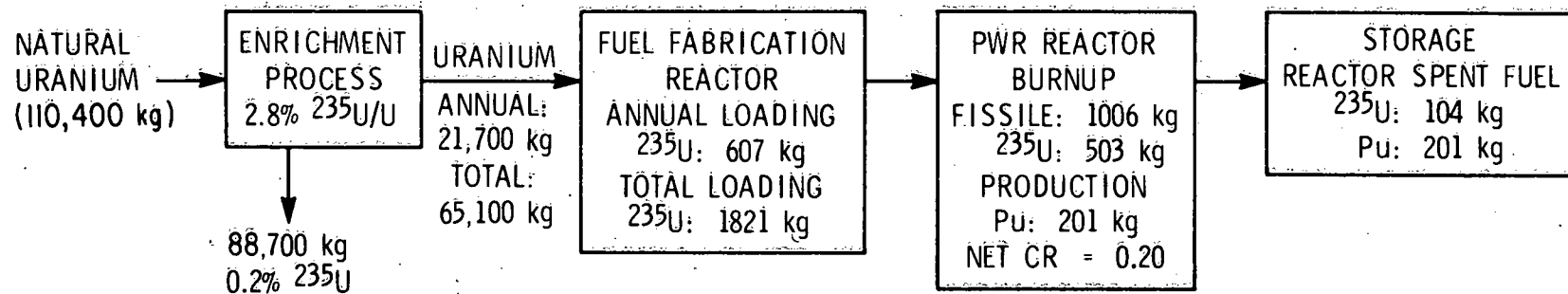


Fig. 5. Diagram of Annual Fuel Mass Flow for the Reference PWR.

TABLE VIII. Relative Magnitudes of
Spent-Fuel Item-Accountability
Tasks for Equivalent Quantities
of Contained Plutonium^a

	Number of Elements Per Year	Number of Sites
LWR	820	14 ^b
HWR	3174	8 ^b
FBR	206	1 ^c

Notes:

^aFBR spent fuel does not appear until about 3-1/2 years after LWR or HWR fuel is removed from item accountability.

^bNominal sites of 1 GWe each.

^cSuper Phenix equivalent (1.2 GWe)

Safeguards at a storage site will use a combination of instrumentation at the site, closed circuit T.V. monitoring, fuel assembly integrity devices, physical inspection by various personnel, and a variety of physical protection mechanisms. Review by inspectors can vary from periodic to residency and can be supplemented by the transmission on a real-time basis of a tamper-indicating communication of data from selected safeguards sensors.

Referring to a possible reference IAEA Safeguards System (Figs. 6 and 7, some sensors (under development at Sandia Laboratories¹⁸) that may be considered for monitoring spent fuel assemblies in storage and handling are radiation monitors, crane monitors, pool acoustic monitors, portal monitors, and fuel assembly identification devices (FAID).

Radiation Monitors: Typical LWR spent fuel assemblies have a radiation source of approximately 10^5 Ci. A shipping cask will not entirely shield this source, resulting in a radiation field of about 5 mR/hr at about 3 meters from a shipping cask. Therefore, a shipping cask containing spent fuel is readily detectable even in comparable background areas. The average radiation level during a time interval is measured and the information is made available to a computer system by tamper-indicating data links.

Crane Monitors: The crane monitor system will provide information concerning crane activity at spent fuel storage facilities. The crane sensor system concept uses strain gauges located in pairs along the crane bridge rails. The pairing establishes the direction of travel as the crane passes the monitor point. The load on the crane can be determined as it passes over the sections of track that have been instrumented with the strain gauges. All components, except the gauges, will be placed in tamper - indicating sensor modules. Voltage and current monitors will indicate tampering with the gauges. The data from the monitor are made available to a data-collection module through tamper-indicating data links.

Pool Acoustic Monitors: The pool acoustic monitor (PAM) will monitor underwater acoustic activity within the storage pool. The primary objective of the PAM will be to provide an intrusion alert output whenever acoustic signals within the pool are characteristic of fuel assembly handling, particularly those activities associated with removal of nuclear fuel from storage locations to either the reprocessing portion of the plant or the cask loading pool.

Portal Monitors: Monitors to control the movement of nuclear materials through access portals, employ radiation detectors to detect the spontaneous emission of gamma-rays or neutrons.

Fuel Assembly Identification Device (FAID): The FAID system provides unique identification and integrity information for independent verification of each fuel assembly in the inventory. The concept being pursued is to place an ultrasonic FAID on each fuel assembly that can be interrogated with an ultrasonic scanner. The data from this sensor will be collected by a data-collection module through tamper-indicating data links.

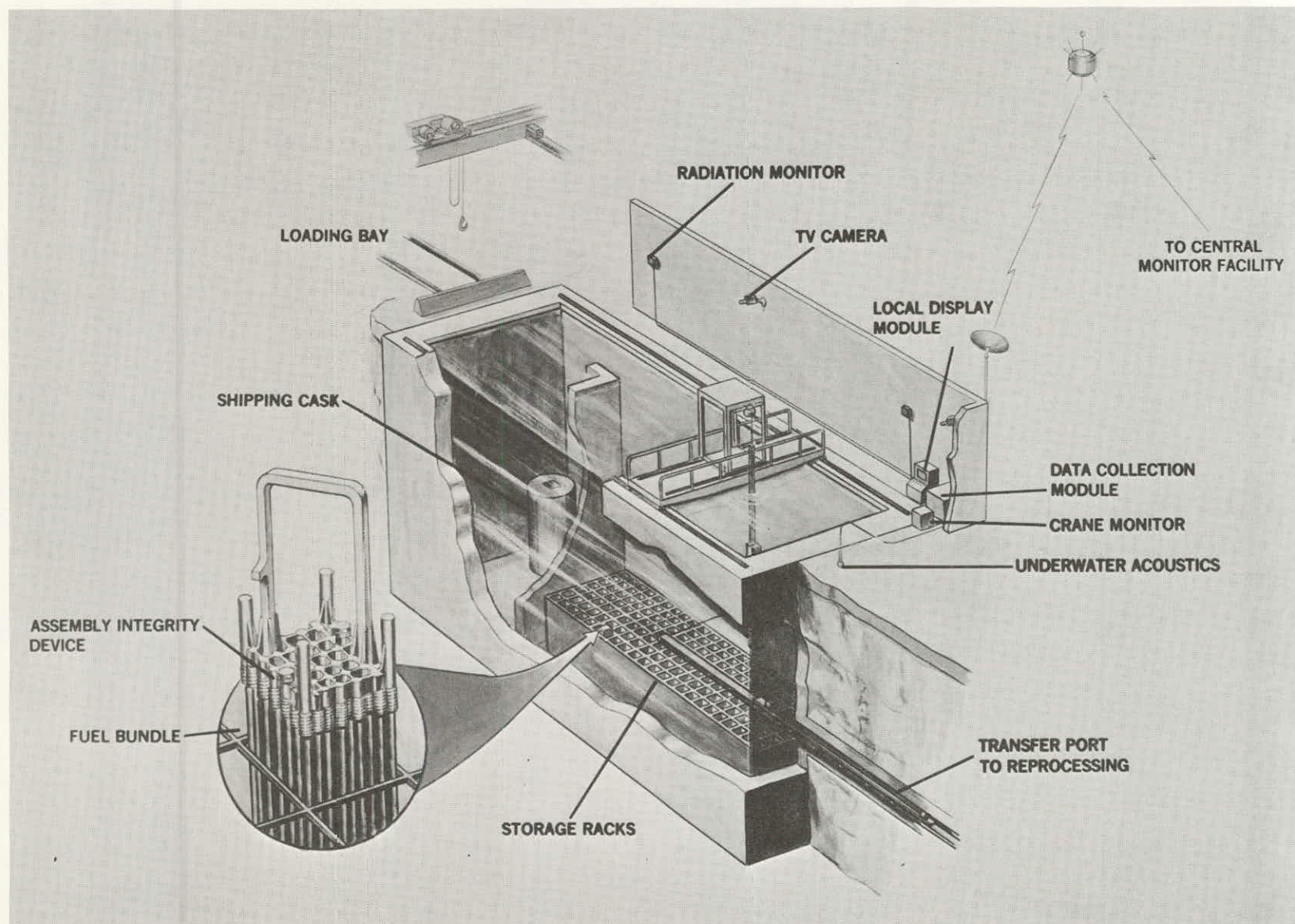


Fig. 6. Unirradiated and Irradiated Fuel Storage Monitoring.
(See ref. 34)

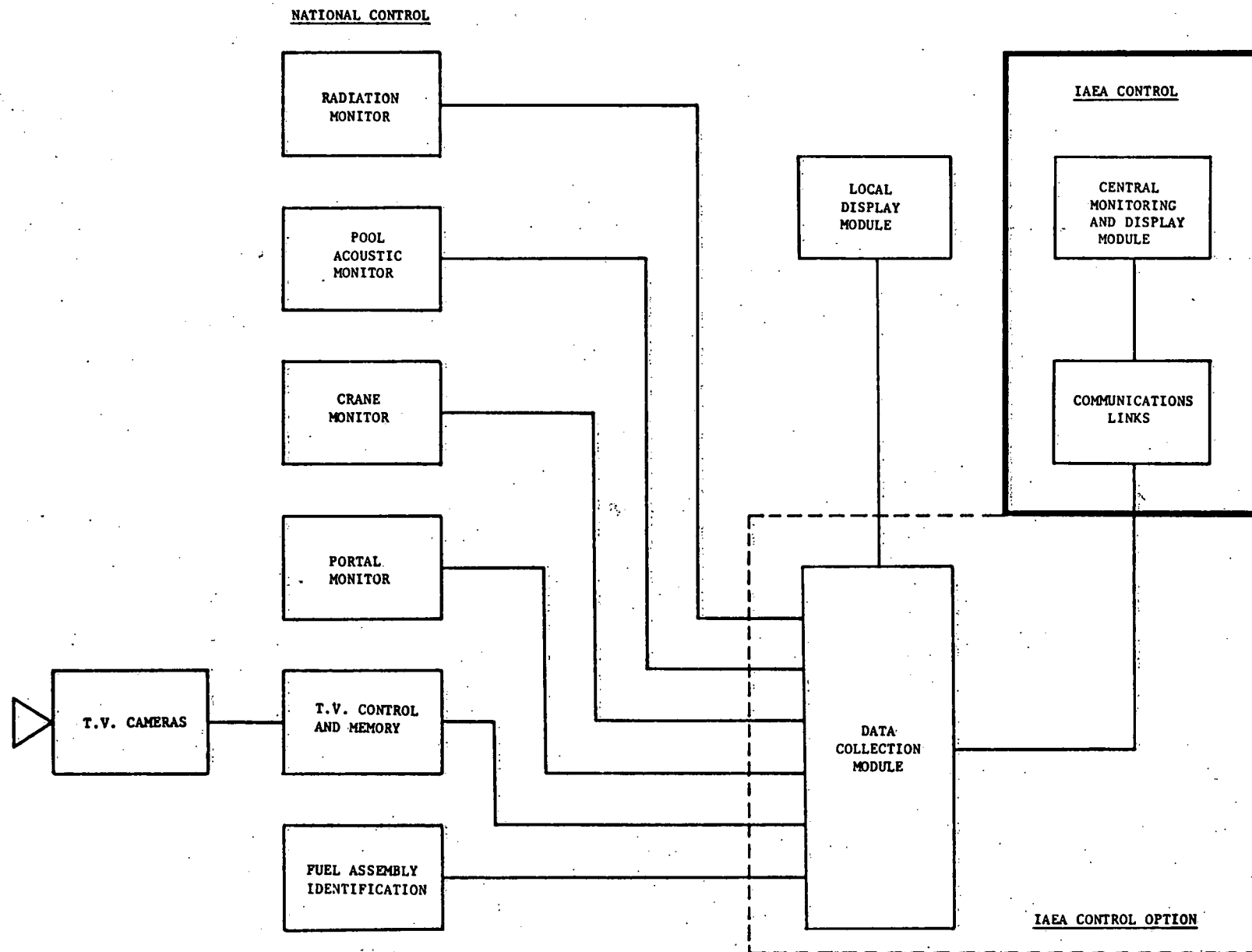


Fig. 7. Facility Data Collection Module Computer System.

Other Systems for Development

1. Underwater Optical Viewing¹⁹,
2. Cerenkov-glow Vision Device²⁰,
3. Spent Fuel Scanning for Neutron and Gamma Emission/Burnup,
4. Spent Fuel Temperature Monitoring, and
5. Active Neutron Interrogation NDA Methods.

A.2 FBR Spent Fuel Reprocessing: The length of the transition period in which only LWR reprocessing operate, will be determined in part by the economics of introducing FBR spent fuel reprocessing systems. In the absence of specific design studies, the economy of scale associated with LWR systems⁶ (1500 tonne/yr), is usually assumed as applicable for FBR systems. Additional factors such as criticality conditions will influence the design features of the FBR reprocessing plants, and the economy of scale for FBR may be in the capacity range of about 200 tonnes/yr. Figures 8 and 9 respectively, show the material flows through an LWR 1500 tonnes/yr reprocessing facility and an FBR 200 tonnes/yr core and blanket reprocessing facility.

The 200 tonnes/yr capacity would service 8-10 FBR's. A comparison of the materials flow in the FBR and LWR at the respective capacities indicates that the total throughput of Pu for the two systems do not differ greatly. The criticality design constraints on fissile-material accumulation and distribution are geometrically safety-related design criteria and as such would be analogous to the LWR reprocessing facility. As a consequence, the major component and techniques of IAEA safeguards systems for the FBR reprocessing are expected to be not too different from those developed for the LWR fuel cycle. In Table IX are listed: Key Measuring Points (KMP), related reprocessing stages, and the amount of material necessary to accumulate the significant quantity of approximately 8 kg of plutonium. The total amount of material for each stage appears to be large enough for detection by NDA techniques of abrupt changes in material inventory. The frequency of inspection and material balance measurements, and containment-surveillance automated control measures would have to be studied for optimizing the detection of protracted material imbalances.

Future studies on the FBR economy of scale for FBR reprocessing systems may result in capacities higher than the 200 tonnes/yr used in the above illustration. In the higher capacity systems, the geometrically related criticality-design constraint may indicate a systems layout where more than one parallel flow streams are utilized with each stream probably having a flow throughput not much higher from that of the 200 tonnes/yr facility. Much of the safeguards systems developed for the closed LWR fuel cycle with some modifications is expected to be applicable to the FBR fuel cycle.

A.3 Direct Fissile Material Accountability in Fresh and Spent Fuel Storage: The IAEA safeguards aspect of long-term interim storage of fresh and spent fuel, the transfer of ownership of the fuel and the resolutions of shipper/receiver balances, may develop the safeguards need for a direct identification of fissile content and a nuclear material balance accountability. The safeguards at AFR storage sites, which will involve a combination of sensors and inspection plans, may have to be supplemented by either Analytical Chemical Assay or by NDA techniques.


```

graph LR
    Input[SPENT FUEL INPUT] -- (A) --> Receive[RECEIVE SPENT FUEL]
    Receive -- "587 kg U  
66 kg Pu  
13 kg F.P." --> Sodium[SODIUM REMOVAL]
    Sodium -- "587 kg U  
66 kg Pu  
13 kg F.P." --> Mech[MECHANICAL PREPARATION]
    Mech -- "587 kg U  
66 kg Pu  
13 kg F.P." --> Chem[CHEMICAL PREPARATION (NITRATES)]
    Chem -- "3200 L/day  
587 kg U  
66 kg Pu  
13 kg F.P." --> Acc1[ACCOUNTABILITY OPERATIONS]
    Mech -.-> Treat[TREAT OFF-GAS]
    Mech -.-> Waste[PROCESS WASTES]
    Chem -.-> Treat
    Chem -.-> Waste
    Acc1 -- (E) --> Solvent[SOLVENT EXTRACTION (NITRATES)]
    Solvent -- "13 kg F.P." --> Waste
    Solvent -- "587 kg U  
66 kg Pu  
153 L/day" --> Acc2[ACCOUNTABILITY OPERATIONS]
    Solvent -- "587 kg U  
66 kg Pu" --> Acc3[ACCOUNTABILITY OPERATIONS]
    Acc2 -- (E) --> ConvertU[CONVERT U PRODUCT (UO2 POWDER)]
    ConvertU -- "587 kg U" --> Acc4[ACCOUNTABILITY OPERATIONS]
    Acc4 -- (F) --> StoreU[STORE AND PACKAGE (UO2 POWDER)]
    Acc3 -- (C) --> ConvertPu[CONVERT Pu PRODUCT (PuO2 POWDER)]
    ConvertPu -- "66 kg Pu" --> Acc5[ACCOUNTABILITY OPERATIONS]
    Acc5 -- (D) --> StorePu[STORE AND PACKAGE (PuO2 POWDER)]
    Waste -- "( <0.2% LOSS HM )  
<182 g Pu" --> End[ ]
  
```

The flowchart illustrates the fuel cycle for a fast reactor. It begins with 'SPENT FUEL INPUT' (A) entering the 'RECEIVE SPENT FUEL' stage. The material then flows through 'SODIUM REMOVAL', 'MECHANICAL PREPARATION', and 'CHEMICAL PREPARATION (NITRATES)', with each stage receiving 587 kg U, 66 kg Pu, and 13 kg F.P. (except for the final stage which also receives 3200 L/day). The 'ACCOUNTABILITY OPERATIONS' stage follows, receiving 587 kg U, 66 kg Pu, and 13 kg F.P. (E). The material then enters 'SOLVENT EXTRACTION (NITRATES)'. From here, 13 kg F.P. (G) is sent to 'PROCESS WASTES', and 587 kg U, 66 kg Pu, and 153 L/day are sent to 'ACCOUNTABILITY OPERATIONS'. The 'SOLVENT EXTRACTION' stage also receives input from 'MECHANICAL PREPARATION' and 'CHEMICAL PREPARATION' via dashed lines. The 'ACCOUNTABILITY OPERATIONS' stage then splits into two paths: one for 'U PRODUCT' (587 kg U, E) and one for 'Pu PRODUCT' (66 kg Pu, C). The 'U PRODUCT' path goes through 'CONVERT U PRODUCT (UO2 POWDER)' and 'ACCOUNTABILITY OPERATIONS' (F) to 'STORE AND PACKAGE (UO2 POWDER)'. The 'Pu PRODUCT' path goes through 'CONVERT Pu PRODUCT (PuO2 POWDER)' and 'ACCOUNTABILITY OPERATIONS' (D) to 'STORE AND PACKAGE (PuO2 POWDER)'. 'PROCESS WASTES' (H) is noted as having a loss of less than 0.2% HM and less than 182 g Pu.

TABLE IX. Key Measurement Points (KMP) Typical Flows and
Diversion Possibilities for 200 tonnes/yr FBR Core and
Blanket Reprocessing Plant

KMP No.	Flow Rates		Concentration		Mass of Materials Required for 8 kg Pu kg
	kg Pu/day	kg U/day	Pu g/L	U g/L	
A (Irradiated Fuel)	66	587	-	-	81
B (U/Pu Nitrate)	66	587	20.6	183	388
C (Pu Nitrate)	66	Neg.	431	Neg.	18.5
D (PuO ₂ Powder)	66	Neg.	-	-	9
E (U Nitrate)	66	587	Neg.	-	-
F (UO ₂ Powder)	Neg.	587	-	-	-
G (High Level Liquid Waste)	<0.13	<1.2	-	-	-

NDA techniques are not currently applicable for direct measurement of fissile content in spent fuel because of the radiation field of fission-product gamma-rays. This leaves the classical analytical chemistry systems to account within acceptable accuracy and reasonable turnaround time, for the disposition of the fissile and fertile materials in storage. However, active neutron interrogation NDA methods for fissile content measurement in fresh and spent fuel may be developed for this purpose.

A.3.1 Isotopic Safeguards Techniques: For this purpose the combination of isotopic correlation safeguards techniques being developed for IAEA Safeguards at Pacific Northwest Laboratories,²¹ Belgium, and Federal Republic of Germany; and the analytical methods of microsample preparation for the simultaneous isotopic analysis of uranium and plutonium may develop into an effective technique.

This safeguards technique is based on the use of fresh and spent fuel data on the plutonium and uranium isotopic content and ratios, and on related changes occurring as a function of the irradiation history in the power reactor. Sampling of fuels from selected representative fuel element rods as processed in a small scale "laboratory facility", coupled with various analytical methods, may be used to measure the uranium and plutonium concentration and isotopic compositions. Relationships existing between the depletion and production of the isotopes have been established and correlated with reactor design codes, and this forms the basis of the data consistency evaluation between analytical measurement (burnup data) and chemical processing and fabrication plant data. The safeguards techniques have been developed to include, a) verification of plutonium content of irradiated fuels measured at input to a chemical reprocessing plant, b) confirmation of available historical information, c) data consistency evaluations, and d) diagnostic evaluation to define burnup characteristics from the measured data.

A.3.2 Microsample Preparation: The method of isotopic analysis of very small samples of plutonium and uranium has been developed in the U.S.²² The method involves the use of anion resins for the separation of both elements and the direct loading of a single resin bead onto a mass spectrometer filament. In the case of irradiated fuels, the direct separation of plutonium and uranium from fission products and from isobaric interferences from americium and curium (these elements do not absorb on the anion resin) has the effect of measuring the isotopic abundance and the total quantity of U and Pu. The microsample (micro-to nano-gram sample sizes) technique possesses many advantages which enhance safeguards assessment: a) more representative sampling, b) reduced radiation hazards from smaller samples, c) less shielding and transport cost for sample handling, d) greatly simplified chemical preparations which eliminate fission products and actinide isobaric interferences, e) direct loading into the mass spectrometer, f) more precisely established minor isotopes, g) reduced time between sampling and measurement analysis.

The preliminary development of this safeguards method indicates that reliable isotopic analysis of plutonium and uranium in fresh and spent FBR reactor fuel can be accomplished with minimal chemistry and sample handling on a very small scale. The international safeguards aspect of this method would introduce the possibility of sampling the unirradiated fuel rods in storage prior to reactor loading and the irradiated fuel rods in storage prior to reprocessing. The analytical chemistry laboratory for attaining and measuring the aliquot solution can be performed at the reprocessing plant site with IAEA control.

B. FBR Fuel Cycle Phase

B.1 FBR Power Plant Safeguards: The significant safeguards concerns of the fast breeder reactor^{23,24,25} is the fuel and blanket assembly surveillance and accountability during the sequential period of: unloading the assemblies from the transport casks (current designs include capacities of 6 to 12 assemblies) into the temporary storage pool, loading the assemblies into the reactor proper, unloading the spent fuel and blanket assemblies from the reactor into the temporary storage pool, and finally the removal of the assemblies from the storage pool and transfer to the shipping cask. The unique feature of this sequence of stages is that the fresh and spent fuel assemblies each containing 12 to 14 kg plutonium are almost continuously submerged in a pool of sodium. This limits direct visual inspection and assembly identification to those times when the assembly is being handled in the transfer tubes of the loading-unloading machine, during the sequence of movement through the transfer (handling) cell to the conditioning cells, and loading into the spent fuel shipping cask. The total time interval from receiving fresh fuel assemblies to shipping of spent fuel and blanket assemblies may be in the order of several years. The usual methods and techniques which the IAEA applies for safeguarding current commercial power reactors would involve excessive agency effort in safeguarding LMFBRs and may not always be adequate.

Diversion analysis considerations for the development of item accountability and containment/surveillance instruments, would have to include two different diversion strategies: (a) The abrupt diversion of at least one assembly (or fuel-dummy substitution) within a short time, and (b) The protracted diversion of a significant quantity of nuclear material by removal of some fuel elements within the assemblies (by pretense of examination for experimental need or by dismantling of failed fuel assemblies) over an extended period of time. The diversion considerations would therefore include nuclear material items which may be diverted within the limits of verification capability and/or exceeding present verification capability.

The diversion analysis approach would involve the selection of MBAs and KMPs to cover: (a) nuclear material flow verification of unirradiated assembly receipts, intact and non-intact irradiated assembly flow disposition, and storage; and (b) physical inventory of unirradiated and irradiated assembly storage areas such as receiving vessels, buffer storage tanks, preparation or conditioning cells, sodium and non-sodium cooling storage vessels. To maintain continuous knowledge of the flow and inventory of assemblies, appropriate and available containment/surveillance measures would necessarily be used to supplement the item accountability measures at KMPs.

B.1.1 Item Accountability: The basic unit of one fuel assembly and one blanket assembly may be assumed applicable for item accountability in the normal operating mode of LMFBRs. However, in the current and near-term development stages of LMFBRs, there may exist experimental assemblies which may be dismantled such as in the U.K. PFR system, there may be a need for dismantling a normal assembly for experimental reasons, or there may be fuel assembly failures which require dismantling, special handling and/or storage. The inventory and flow verification of these assemblies as well as the intact assemblies should be examined with respect to the plant layout design features, operating modes, and handling programs.

Identification marks of the fabricator, and other possible identification signatures with properties of having a unique one-to-one correspondence with the fuel assembly, may be identified and examined for applicability by IAEA to unirradiated and irradiated assemblies in specific reactor plant design and fuel handling systems. Considerations would have to include methods to maintain the integrity of the rod-element configuration within the assembly.

To establish an item accountability system, the design of the loading/ unloading machine, and the transfer-conditioning cells will be examined for design features to allow accommodating direct visual and physical identification techniques for containment/surveillance and accountability purposes. The adaptability of measurement equipment and/or inspection methods may be influenced by the facility constraints. The implementation of the measurement systems available to the Agency and the inspection methods may therefore require some modification for unique applications.

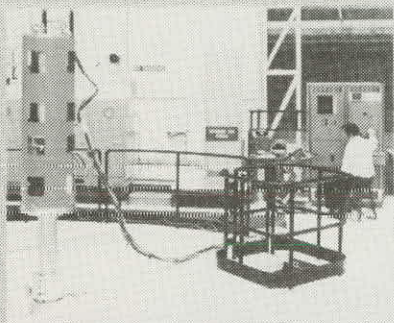
Several assembly-accountability sensor techniques for under-sodium viewing in loading and unloading and storage of fresh and spent fuel are:

B.1.1.1 Ultrasonic: Under Sodium Viewing Systems²⁶: The inspection technique basically uses ultrasonic techniques to provide both imaging and ranging capability. For imaging applications, focused 5-MHz transducers scan the region of the core and blanket with a high degree of resolution (0.150-inch-diameter holes) while operating under 5 meters of liquid sodium. With 2-MHz transducers, ranging scans can accurately measure distances up to 5 meters. The system, although developed for location and positioning of assemblies in the reactor may be used for safeguards purposes to determine the identity of the assemblies, the respective loading positions, and the orientations of the assemblies by forming images of coded notches or indentations. An ultrasonic technique has been developed by Euratom to provide signatures of fuel assemblies using metallic identification. The further development of these techniques with design features emphasizing the safeguards aspect of accountability in the IAEA program of inspection is necessary. The current development status of the under-sodium viewing system is represented in Fig. 10.

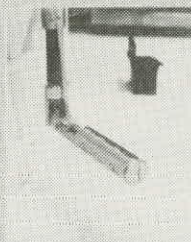
B.1.1.2 Mechanical: Under-Sodium Reader: This concept, while untested and unsophisticated, would consist of a single cylindrical unit similar to a grappling device with a properly designed needle-roller or fine indicating feeler juxtaposed next to sealed contactors. The device would be designed to fit over the top end of a fuel assembly. If the top of the fuel assembly is encoded with a series of raised or indented markings, the spring loaded needle could cause the contactors to open or complete a circuit as the cylindrical unit is rotated about its vertical axis. This technique would require some initial design studies to examine the feasibility of the method. This method would require standardization of the design of fuel assemblies and the adoption of an international code for identification.

B.1.1.3 A Multilayer Fully Encapsulated Self-Powered Direction Gamma Monitor for Use in Spent Fuel Storage Facilities: When a metal-dielectric-metal multilayer structure is placed in a gamma radiation field the electrical response obtained is strongly dependent on the geometry, the applied fields, the external circuitry, and the past history of the geometrical influence on the measured response. A metal-dielectric multilayer

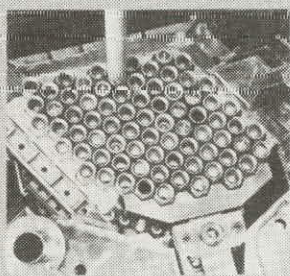
UNDER-SODIUM VIEWING SYSTEM FOR FFTF/LMFBR



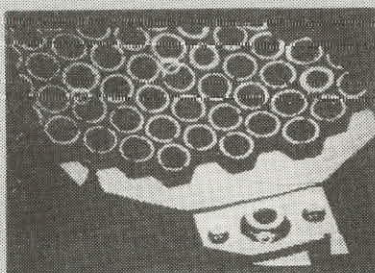
A. USV SYSTEM OPERATING IN CRCTA



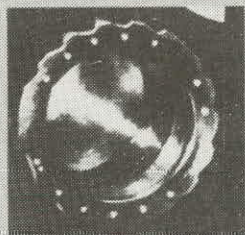
B. SCANNER
CARRIES 34 SPECIAL
ULTRASONIC TRANSDUCERS



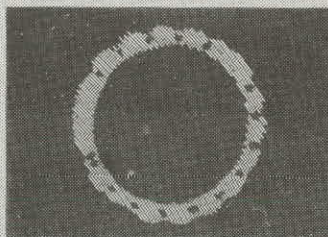
C. CRCTA CORE PRIOR TO FILL WITH
16 FEET OF SODIUM



D. USV IMAGE OF C.



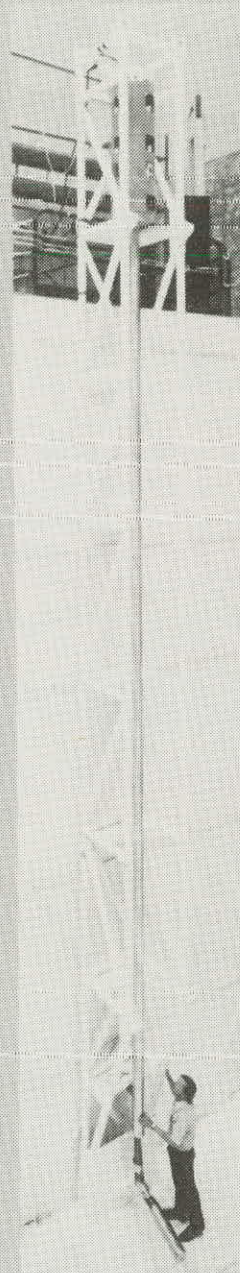
E. TOP OF ONE CORE SUBASSEMBLY



F. IMAGE OF E. WITHOUT
ENHANCEMENT

POTENTIAL APPLICATIONS:

- CORE SUBASSEMBLY LOCATION AND IDENTIFICATION
- PRECISE LOCATION OF IN-VESEL COMPONENTS: (IVHM, CLIRA, INSTRUMENT TREE, LLFM)
- PERIODIC INSPECTION OF CRITICAL COMPONENTS (THERMAL BAFFLES, WELDS)
- SEARCH AND RETRIEVAL GUIDANCE INFORMATION FOR MISPLACED OR FOREIGN OBJECTS



G. FFTF SCANNER

Fig. 10. Under-Sodium Viewing System for FFTF/LMFBR.
(See ref. 26)

arrangement can be found that exhibits directional discrimination. A detector of this type has been constructed and tested in the Argonne Thermal Source Reactor (ATSR).²⁷ The detector has the advantage of requiring minimum maintenance, making it ideal for long-term deployment (e.g., in sealed fuel storage pools). Sensitivity of the detector and its size make it possible to construct an array of these detectors to provide a detailed signature of the fuel in a localized region of the storage pool. The detector array, when operated in a continuous mode, could be used to detect the movement of fuel, particularly the motion along a line in a plane that included the axis of the array of detectors. In the case of irradiated fuel assemblies, a multilayer fully encapsulated monitor of this type will require some testing in an intense gamma/neutron environment to examine the effects of long term irradiation on its response. In addition to radiation damage studies, numerical simulations would be required to establish the optimum thicknesses of the dielectric and proper choice of materials.

B.1.2 Containment/Surveillance: In the reactor power plant phase of the FBR fuel cycle, the item-accountability sensors would be complemented by a combination of instruments at the site such as closed-circuit T.V. monitoring, fuel assembly integrity devices, physical inspections by various personnel, and a variety of physical protection mechanisms. Review by inspectors can vary from periodic to residency and can be further supplemented by the transmission, on a near-real-time basis over tamper-indicating communication of data from selected safeguards instrumentation. The sensors primarily applicable in this phase of the cycle are radiation monitoring devices, crane movement monitors, acoustic detectors for fuel movement under sodium, portal monitors, metal detectors and access control for equipment.

B.1.3 IAEA Inspection: The development of the inspection effort would have to include optimizing surveillance inspection activities, review of data acquisition by sensing instruments, and review of power plant operation records, if available, to independently verify the material inventories. The inspection plan would include considerations such as: equipment maintenance, verification of tamper-indicating features of data acquisition systems, review and evaluation of data relating to reactor power operations, fuel loading schedules, verification of unit assembly flows and storage dispositions, identification of operating anomalies, nuclear materials shipment and receipts, and data relating to movement of operating equipment in the fuel handling system, (including the indexing pattern of the non-concentric rotating plug systems). The inspection activities and frequency of inspection determined for each strategic point would be optimized consistent with the guidelines of INFCIRC/153 and within the limited resources of the Agency.

The fuel and blanket assembly scheduling plans in- and out of- reactor should be reviewed for the plant and maintained as an integral part of IAEA inspection data base. Record keeping systems of reactor operations and fueling schedules, as developed by the State System of Accounting and Control (SSAC) and assumed available to the Agency, are to be studied. This information would be used as a guide in determining inspector access to the systems, frequency of inspection, and the specific type of inspection activity.

To optimize the limited resources of the Agency, the possibility of applying and utilizing tamper-indicating data link and data collection modules, either independently or in a verification mode with the SSAC system, should be an important consideration.

B.1.4 NDA Techniques: The current NDA techniques for item accountability can only distinguish between different classes of assemblies, i.e., fuel, blanket and/or dummy replacement. There is no distinction made between the individual assemblies. It is not apparent how effective NDA techniques may be if this information is not supplemented by subsequent confirmatory information that a replacement has occurred.

The safeguards instrumentation for the identification of unirradiated and irradiated assemblies will probably include the gamma-ray survey instruments: SAM-2 or BSAM, Ge Detector, and G-M counter arrays. The passive and active neutron counters which are currently available are the slab detector (BF_3 counter), and the neutron collar ($^{241}\text{Am-Li}$ neutron source) and would allow a level of identification between classes or types of assemblies i.e. unirradiated or irradiated, fuel or blanket, dummy substitution and/or fuel-blanket interchange. The safeguards effectiveness for some of these instruments is compromised by the self-shielding effect of the heavy-metal and sodium contained in an LMFBR assembly. The effectiveness of the system may therefore have to be evaluated in terms of a combination of sensor measurements performed in a simultaneous mode. The simultaneous reading of the fabricators identification markings, the tamper-indicating signals, and the isotopic-radiation measurements, may prove to be an applicable and an effective measure of introducing assembly flow verification. An added level of consistency in flow verification may be effected if the difference in isotopic-radiation measurements reflect the irradiation history of a specific assembly.

The utilization of overlaying several safeguards techniques for a consistency mode of assembly flow verification within the current resource limitations of the Agency should be considered.

B.2 Reprocessing and Conversion: The safeguards concerns with respect to the reprocessing and conversion phase of the FBR fuel cycle will be based, if applicable, on modifications and adaptations of those safeguards techniques and systems being developed and planned (see Ref. 28 and 29) for use in the LWR spent-fuel reprocessing and conversion facilities and for LWR isotopic enrichment facilities. The design of assay and accountability systems is directed toward providing a system to establish material accountability information on a near-real-time basis. The system is to be designed to determine fissile content of batches of material in process throughout the plant by measuring representative samples coupled with the ability to maintain continuous containment and surveillance of the material flow through the various reprocessing and conversion stages.

The system of material accountancy, containment and surveillance described in the introductory sections is applicable to the reprocessing and conversion phase of the FBR cycle. There are no unique processing requirements for the FBR-related stages including total plutonium throughput. Consequently, the safeguards systems for the LWR plants are directly applicable to the FBR fuel cycle. However, this report will attempt to scope the safeguards options or combination of options that can be designed for the FBR safeguards system using the various sensor systems currently available and/or in the developmental stage.

B.2.1 Material Accountancy: In general, conventional contemporary safeguards systems are based on discrete-item counting and material-balance accounting after periodic shutdown, cleanout, and physical inventory. The typical materials balance generally encompasses the entire facility or a major portion of the process and is formed by adding all measured receipts to the initial measured inventory and subtracting all measured removals from the final measured inventory. During routine production, materials control is primarily vested in administrative and process controls, augmented by secure storage for discrete items, sealed containers, etc.

Although conventional methods of material-balance accounting involving shutdown and inventory are essential for effective control of nuclear materials, there exist inherent limitations in both sensitivity and timeliness. Sensitivity is limited by measurement uncertainties that might obscure the diversion of significant quantities of nuclear materials from a large-throughput plant, timeliness by practical difficulties, economics, and the resulting infrequency of process shutdown, cleanout, and physical inventory.

The development of nondestructive assay (NDA) technology, state-of-the-art conventional measurement methods, and special in-plant sensors, when combined with supportive computer and data-base management technology have provided the technical basis for improved alternative methods for safeguarding nuclear facilities. Greater sensitivity and timeliness in nuclear material control can be achieved by dividing a nuclear facility into discrete accounting sections, material balance areas (MBA), or unit processes, around which individual balances can be drawn, using measurement techniques capable of producing assay results in near-real-time.

A unit process can be one or more chemical or physical processes. It is chosen on the basis of process logic, the residence time of material within the unit process, and the ability to perform rapid quantitative measurements and to draw a near-real-time materials balance. By partitioning a facility into unit processes and measuring all material flows across unit-process boundaries, the location and movement of nuclear material throughout the plant can be localized in both time and space independent of the inventory schedule. Material balances circumscribing such unit processes are called "dynamic" material balances to distinguish them from conventional balances drawn after a shutdown, cleanout, and physical inventory.

B.2.1.1 Nondestructive Assay: The requirement for prompt detection of diversion or losses involving small quantities of material has led to the development and eventual implementation, on commercial-scale facilities, of automated systems for near-real-time measurements and control of fissile materials. The timely, in-line measurements available through nondestructive assay provide the basis for near-real-time materials control. Depending on the types of materials that pass the various measurement points, optimal NDA sensor instrumentation can be adapted from existing designs for in-line operation. The U.S.^{28,29} has been developing a number of NDA systems for use in plutonium facilities. Several NDA methods have been developed for analysis of nuclear materials at various stages in the nuclear fuel cycle. Some of these methods, and their applications in reprocessing, conversion, and fuel fabrication are summarized in Table X.

TABLE X. NDA Methods for Nuclear Material Accountability

	Applicability			
	Enrichment	Reprocessing	Conversion	Fuel Fab.
α Monitor	X	X	X	
Abs. Edge	X	X	X	
γ Ray	X	X	X	X
Neutron		X	X	X
Calorimetry			X	X

a. Alpha Monitors: In-Line alpha monitors were originally designed as a process-control instrument to determine if waste streams from reprocessing, solvent-extraction processes were discharging excessive amounts of plutonium. Some discrimination of beta/gamma radiation from alpha particles is obtained through detector-cell-electronics optimization.

b. Absorption-Edge Densitometry: Both K and L_{III} x-ray absorption-edge densitometry have been proposed for in-line measurements of nuclear material.

The K-edge technique is applicable for concentrations between 20 and 500 g/L. It uses a radioactive source tailored to the element to be determined: ⁷⁵Se-⁵⁷Co for determining plutonium. The L_{III}-edge technique is applicable for concentrations between 1 and 40 g/L. It uses primary radiation from an x-ray tube, secondary radiation from fluorescor designed for the element to be determined, bremsstrahlung sources, or radioisotopes. A crystal spectrometer arrangement can serve as a monochromator or as a coarse energy filter.

c. Gamma-ray Emission: Passive gamma-ray NDA is based on the measurement of the intensity of a gamma ray emitted by the radioisotope of interest in the sample being examined. The central problems in the NDA of samples by this technique are the correction for sample self-attenuation, and the interference of compton scattering in the case of high radiation background.

This technique is used in two operating assay systems, one that assays the plutonium and the other the uranium content in solutions. Both systems use Ge(Li) detectors with standard high-resolution electronics, multichannel analyzers, and minicomputers for data collection and analysis.

The plutonium system is designed primarily to measure ²³⁹Pu over a range of plutonium concentrations from 0.1 g/L to the maximum possible at 500 g/L. Besides a ²³⁹Pu assay, it also provides a useful measure of ²⁴⁰Pu, ²⁴¹Pu, ²⁴¹Am and, to a lesser extent, ²³⁸Pu. Assays are based primarily on the 129.3-keV and 413.7-keV gamma rays of ²³⁹Pu, with the useful gamma rays from the other isotopes falling between these values. A half-hour sample count gives ²³⁹Pu determinations with relative standard deviations (RSDs) of ~1% for solutions with plutonium concentrations of ~0.1 g/L and precisions of about 0.5% for plutonium concentrations of ~5.0 g/L. With material concentrations between 0.5 and 2.0 g/L and one hour counting times, RSDs are reported roughly as follows: ²³⁸Pu-2%, ²³⁹Pu-0.05%, ²⁴⁰Pu-0.4%, and ²⁴¹Pu-0.05%.

The uranium-solution assay system measures the ²³⁵U content in 20-ml samples with uranium concentrations of 1 to 50 g/L by counting the 185.7-keV gamma rays. The obtainable precisions and counting times are comparable to those of the plutonium system.

d. Neutron Methods: Neutron coincidence counting and active neutron-interrogation techniques are being developed as potential sensors in assaying spent-fuel fissile content directly. As these sensors develop and the precision of measurement improve, the data input would be processed as described in the IAEA Reference System.

Some applications of the NDA techniques described in the section for a reprocessing-conversion facility are listed in Table XI.

TABLE XI. Possible NDA Applications for
Reprocessing Plant Solutions

Area	Method
Dissolver	Gamma emission, x-ray fluorescence
1BP tank	X-ray absorption edge densitometry Gamma emission, x-ray fluorescence
U product	X-ray absorption edge densitometry Gamma-ray absorption
Pu product	X-ray absorption edge densitometry
Recycle acid (Pu purification area)	Gamma emission, x-ray fluorescence
Recycle solvent (Pu purification area)	Gamma emission, x-ray fluorescence

An integral part of the system would be a rigorous standards and measurement control program that ensures the credibility of the assay data. The program would provide quantitative limits-of-error information and would ensure that the individual instruments function properly by checking their precision and calibration accuracy. The calibration history of each instrument may be stored as a permanent record for near-real-time comparison of past, present, and future performance. In some cases, diagnostic procedures would be incorporated as an integral part of the instrument independent of the central computer. For example, high-resolution gamma-ray systems commonly would have a built-in gamma source for counting-loss corrections.

An important additional safeguards aspect to utilizing NDA techniques as part of the materials accountancy system, is that in the process it inherently maintains a direct continuous-surveillance on the fissile materials flow.

The above concepts, together with the hardware and software necessary for their implementations are currently being developed by the Los Alamos Scientific Laboratory (LASL)^{28,29} for most facilities in the nuclear fuel cycle. Prototypical near-real-time assay instrumentation and data acquisition systems are being evaluated on industrial-scale unit processes as part of LASL's DYMAC (Dynamic Materials Accounting) program including the DYMAC Demonstration Program.³⁰ Near-real-time materials control and accounting systems and/or experiments are being developed at several foreign facilities, including Chalk River, Canada (INMACS), Tokai-Mura, Japan (PNC), Karlsruhe, Federal Republic of Germany.

B.2.1.2 Analytical Chemistry Assay: Chemical methods for the determination of plutonium and uranium³¹ can be classified as gravimetric, spectrophotometric, electrometric, mass spectrometric, alpha spectrometric, and fluorimetric. These six methods can be used to determine (1) major constituents in the dissolver solutions and product tanks and (2) minor constituents in recycle streams and wastes. The methods will be discussed briefly as they are used in a safeguards system for fuel reprocessing-conversion facilities, isotopic enrichment facilities, and fabrication facilities. Chemical assay procedures for measurements of materials to be safeguarded in various process streams within a fuel cycle and their areas of application are summarized (not exhaustively) in Table XII.

a. **Gravimetric Methods:** Gravimetric methods rely on separating a compound of the element to be determined and igniting it to a constant-weight stoichiometric compound. The method is used for determining the content of uranium in nitrate solutions, oxides, and UF₆. The method is applicable only to relatively pure materials; impurities must be determined using spectrographic or other procedures and corrections applied to the final weight by difference.

b. **Spectrophotometric Methods:** Spectrophotometric methods rely on the principle that a compound in solution will absorb a quantity of light of a specific wavelength proportional to the concentration of the measured species.

TABLE XII. Application of Chemical Assay Procedures

Procedure	Applicability			
	Enrichment	Conversion	Fabrication	Reprocessing
Gravimetry	X	X	X	X
Chemical Redox Titrimetry	X	X	X	X
Electrochemical Titrimetry	X	X	X	X
Spectrophotometry				X
X-ray Fluorescence Spectrometry			X	X
Radiochemical Counting				X
Isotope Dilution				X

The spectrophotometric methods for trace concentrations of uranium are of interest for determining uranium in waste streams and possibly in the final plutonium product. The determination of uranium with PADAP has been modified specifically for determining uranium in reprocessing-plant waste streams and in plutonium nitrate and oxide products.

The differential spectrophotometric method for determining plutonium can be used for plutonium-nitrate product with precision equivalent to that obtainable by the best electrometric methods.

c. Electrometric Methods: Both uranium and plutonium can be determined with high precision and accuracy using titrations involving oxidation-reduction reactions. These methods generally are classified by the method used to detect the titration end point as potentiometric, amperometric, or coulometric.

Controlled-potential and constant-current coulometry are well-established methods for determining uranium and plutonium in solutions. The methods are based on the principle that the weight of a substance oxidized or reduced at an electrode is proportional to the quantity of electricity (coulombs) passed through the electrode.

d. Mass-Spectrometric Methods: In most existing reprocessing plants, thermal ionization mass spectrometry is used to determine the amount of each isotope of uranium and plutonium, and consequently the effective atomic weights for calculating total uranium and plutonium from chemical analyses of samples from the accountability tanks. Isotope-dilution mass spectrometry can also be used to measure the plutonium and uranium concentrations in the tanks.

e. Alpha-Spectrometric Methods: Quantitative alpha-particle spectrometry is based on measuring the intensity of the alpha radiation of the sample. The alpha particles are ejected with discrete energies, and for uranium, neptunium, plutonium, and americium isotopes characteristic of the nuclear fuel cycle, these energies range from 4 to 5.5 MeV. The method has been applied to the determination of plutonium in dissolver solutions following solvent extraction separation of the plutonium.

f. X-ray Fluorimetric Method: The HEDL development of the Fuels Assay X-ray System (FAXS) employs an energy dispersive X-ray fluorescence analyzer to measure U and Pu with better than 0.5% RSD precision in a total analysis time of 2 to 4 minutes. To optimize precision in this short interval a high count rate for excited x-rays must be obtained. In FAXS, this is done using dual detectors and a very "close" geometry between exciting x-ray source, sample, and detectors.

B.2.1.3 Measurement Precision and Accuracy: The precision of measurements is essential to limit the uncertainty in the quantities of materials being measured. The currently applied analytical chemistry methods for nuclear materials accountability have measurement precisions ranging from relative standard deviations (RSD) of typically 0.05% for gravimetric methods, 0.1 - 0.25% RSD for titrimetric methods, and 1 - 10% for spectrophotometry (with further development, may be improved to better than

0.5 RSD). The HEDL development of the fuels assay x-ray system (FAXS) indicates a 0.5% RSD. These precisions in some cases are state-of-the-art methods now used by most laboratories and have resulted from several years of extensive effort to achieve the routine precision indicated. Accuracies of these assay procedures depend on suitable standards and adequate standards which must be maintained for mixed oxide material. Consequently, it is assumed that a total accuracy of measurement is the range of 0.5 - 1%. This accuracy may be adopted for the NDA technique, in estimating error margins in material flow throughout the FBR fuel cycle.

The above measurement techniques (with related precisions) being developed for LWR enrichment, conversion, fabrication and reprocessing facilities are directly applicable to the FBR reference fuel cycle.

B.2.1.4 Conversion Facility: The conversion of plutonium nitrate to commercial plutonium oxide,³² carbide or metal is the final stage of the reprocessing operation. For safeguards concerns the plutonium nitrate-to-oxide conversion facility is an important component of the closed LWR and FBR nuclear fuel cycles. It is the intermediate state between the spent-fuel reprocessing and fuel fabrication facilities and as a consequence processes large quantities of plutonium in both liquid and solid forms. However, safeguards sensor systems designs are not expected to differ between closed LWR and FBR fuel cycle reprocessing-conversion facilities.

The end product of mixed oxide powder would have to be packaged into an item-accountable container designed for safeguards concern in the accountability and control of the fissile material and in the transport of the oxide to the fuel assembly fabrication facility when the fabrication is not colocated with the reprocessing and conversion complex. Accountability, and control techniques involving both NDA and chemical and nuclear methods should probably be applied at both shipping and receiving stages.

B.2.2 Isotope Correlations and Measurement Techniques: Isotope correlations and measurement techniques have the potential as a safeguards accountability measure in the dissolver stage of the nuclear fuel cycle. Throughout the major portion of the fuel cycle, the fissile accountability is basically in the form of item accountability (fuel powder containers, pellets, elements, and assemblies). The measurement of the material balance input and product in the reprocessing phase of the cycle is the primary direct fissile material flow verification. The materials balance accountability gap which exists between the fabrication plant output and the input to the reprocessing plant can be minimized by the utilization of Isotope Correlation Techniques (ICT) at the dissolver stage of the processing plant. The safeguards significance of the ICT is that the input accountability would allow a level of verification of the fabricators' uranium and plutonium isotopic content specification, the irradiation history, and the subsequent spent fuel assembly flow to the reprocessing plant.

B.2.2.1 Isotope Correlations: The isotope correlation functions which are currently being considered as most effective for safeguards purposes, involve combinations of isotopic concentrations that exhibit a reasonably monotonic behavior over a broad range of reactor conditions and burnup. Some of these functions are: Pu/U vs. depletion ^{235}U , Pu/U vs. $(100 - ^{239}\text{Pu})$, Pu/U vs. $^{239}\text{Pu} \times ^{242}\text{Pu}/^{240}\text{Pu}^2$, and ^{236}U vs. ^{235}U . The linear relationships being

independent of reactor operating conditions and burnup, effect a means of verifying the input to a reprocessing plant, and methods for establishing internal consistency of input analytical measurements, and a level of verification on initial isotopic concentrations prior to burnup. Some of the suggested functionals also include fission product isotope correlations in addition to the major and minor isotopes of uranium and plutonium.

B.2.2.2 Measurement Systems: The selection of the more safeguards effective functionals will depend not only on the level of reliability for verification, but also on the capability and difficulty of developing measurement methods. Proposed measurement techniques cover the general areas: (1) simultaneous multicomponent analysis techniques, (2) ion-cyclotron-resonance mass spectrometry, (3) x-ray fluorescence or densitometry with high flux monochromatic x-ray sources and high dispersion spectrometers (4) synchrotron radiation, and (5) active neutron interrogation.

Most of the proposed systems are capable of measuring the elemental ratio, Pu/U. However, only a limited number of systems appear to have the capability of determining the isotopic correlation functions of interest. Assessments of measurement systems should include the capability of isotopic measurements and the potential that a measurement system can be developed for on-line or near-real-time assay of the dissolver solution. The application of the measurement techniques under actual operating conditions would be a primary objective of a development program.

B.2.3 Containment and Surveillance: Containment and surveillance functions applicable to reprocessing and conversion facilities would consist primarily of nuclear materials movement and/or handling integrity. The c/s measures would utilize optimum positioning of closed circuit T.V., radiation monitors, and portal monitors to assure recording of any unplanned changes in the content or location of nuclear materials, maintaining integrity of agency instrumentation and devices, and integrity of samples, packages or seals. The plant design should include features that would enhance specifically the safeguards effectiveness by accommodating the safeguards system.

B.2.4 Impact on Safeguards Techniques from High Burnups, Sodium, and Radiation Spiking: The FBR reprocessing aspects differing from the LWR spent fuels are mainly in the high burnup and the presence of sodium. The high burnup fuels have been reported to result in a higher fraction of plutonium to remain dissolved after leaching in the dissolver tank (about 1.5% in FBR to 0.04% in LWR of total plutonium). Therefore the safeguards techniques on the waste stream should be developed with more stringent identification and accountability balance determination of the fissile material. The presence of sodium does not appear to impact on safeguards concerns, since it would only require a modification to the head-end stage of the reprocessing system for complete removal of the sodium under an inert and controlled environment. The problems with the removal of residual sodium are not expected to effect any significant safeguards difference between the LWR and FBR reprocessing systems.

A measure of effective safeguards is the degree of compromise to the accuracy, precision, or even operational feasibility in fissile materials accountability techniques that results from introducing the "denatured" and/or "radiation spiked" fuels as alternate fuel technologies.

The safeguards concern is that the IAEA safeguards systems of direct fissile identification and accountability via analytical-chemistry assay or nondestructive assay via neutron or gamma-ray sensors would be compromised if not made completely nonfunctional. In the NDA system, the continuous on-line direct identification of the fissile isotopes in the bulk flow, is affected by the measurements of the gamma-ray spectra unique to the fissile isotope. These "radiation signatures" are completely submerged in the radiation-noise background of the gamma-ray fields from the fission products, from added spikants at lethal dose levels, or from the ^{232}U daughter chain in thorium fuel cycles.

B.3 MOX Fabrication and Scrap Recovery: The implementation of IAEA safeguards to MOX fabrication and scrap-recovery facilities have been considered for the LWR plutonium-recycle systems. The base-case MOX fabrication facility usually assumes a nominal production capacity of 200 tonnes/yr, with a plutonium content of about 4%. The reference MOX fabrication facility for the FBR fuel cycle would be a plant process capacity of about 100 tonnes/yr with a plutonium content of about 16%. This is consistent in plutonium flow rate with the reference fuel reprocessing plant capacity of 200 tonnes/yr. The reference manufacturing process requires storage capability for feed powder, process line buffer, finished fuel pins, and completed assemblies. In addition, accumulation points are required for clean (dry) and contaminated (wet) scrap. For normal operation, in-process inventory other than storage may be assumed to be 400 kg/day of fuel (containing 16% Pu), resulting in daily Pu throughput of 64 kg.

The safeguards considerations are therefore not significantly different in total plutonium throughput when compared to the LWR fabrication plant. The higher concentration of plutonium in the FBR MOX pellets, fuel pins and fuel assembly would not affect the selection and performance characteristics of the sensors in an IAEA near-real-time Safeguards System. The containment/surveillance components of the coordinated safeguards system would parallel the design considerations of the safeguards systems planned for the LWR fabrication facility and of the LWR and FBR reprocessing facilities. The design and development of the material-accountancy (NDA and Chemical Analysis) components of the safeguards system would be similar to those used in the reprocessing plant. The higher plutonium concentration in the fuel would enhance the measurement accountancy methods in determining directly the fissile isotope contents.

B.4 Bulk Plutonium Storage and Intraplant Transportation: A safeguards system for bulk plutonium must consider the plutonium packaging area, the vault storage area, and the intraplant transportation of plutonium. An on-line computerized bulk "Plutonium Protection System" (PPS)³⁵ has been developed in the U.S. and is being operationally evaluated at the Hanford Plutonium production and processing facility. All procedures in PPS are monitored by closed-circuit T.V. (CCTV) and by a computer system. In the packaging area, the plutonium cans are further sealed into an overpack container into whose upper half logic circuits and sensors are integrated to provide unit identification, to monitor temperature and can distortions, and to detect tampering. Electronic identification codes are set in each container after registering the weight of the contents. In the vault storage area, containers of plutonium are stored in secure storage modules. Detection and monitoring systems are provided in the

vault area to ensure that activities are proceeding as authorized. Several access control methods such as electronic credential readers, CCTV, electronic scale, metal and nuclear material detectors are implemented. A secure intra-plant transportation truck which contains the necessary physical and electronic design features to maintain physical control and accountability during material movement, is used to move bulk plutonium.

The IAEA Safeguard System for bulk plutonium may include one or any combination of the following three concepts.

- a. Periodic IAEA Inspection: IAEA personnel will periodically inspect the accounting records of the plutonium packaging area and the vault storage area for material accountability, and inspect the sensors and other instruments to establish integrity.
- b. Continuous IAEA Inspection: The IAEA inspector at the facility will be notified of all required plutonium movement operations in the plant. The inspector will also be responsible to see that up-to-date accounting records are maintained in all areas where bulk plutonium is handled.
- c. IAEA Remote Surveillance: IAEA Remote Surveillance Safeguard System (to be described in Section V-D and E) may be interfaced via communication links to the data collection and control centers in PPS using tamper-indicating techniques. This will provide on-line near-real-time monitoring of bulk plutonium in the facility.

B.5 Application of IAEA Safeguards During Transportation: The type of material being transported determines the level of IAEA goals the safeguards system should approach. Presented below are three concepts for safeguarding nuclear material in transit. These concepts do not vary with respect to the distance traveled, but with the time-interval goal for verification and the available safeguards measures.

B.5.1 Periodic Shipping/Receiving Comparison: This concept is based on the comparison and correlation of material transfer records at the origin and destination of shipments, and on the accountancy records maintained at a monitoring agency. The key elements are:

- Notification to the IAEA by the shipper of the transfer and verification by the IAEA of the form and quantity being shipped,
- Use of seals and integrity devices by the IAEA to ensure the integrity of the shipping container or cask and the material contained to provide the IAEA with continuity of knowledge.
- Notification to the IAEA by the receiver of the receipt, and verification by the IAEA of the form and quantity of the nuclear materials received.

The timeliness of detection goal of the IAEA should be no less than the transit time. For nuclear material with short timeliness goals, the above procedures may be inadequate, and additional methods may be needed.

B.5.2 IAEA Escorts: This concept assumes continuous IAEA escort of the transportation vehicle from the point of origin to the destination. The key aspects of this system may include:

- Periodic notification to the IAEA headquarters, by standard telephone or radio, of the position of the transportation vehicle and the integrity of material containment,
- On-site observation of loading, unloading, and IAEA verification of transported nuclear material, and
- Use of seals and integrity devices by the IAEA to ensure the integrity of shipping container or cask and the material contained.

This concept has a capability for rapid detection of anomalies in the shipment during transit.

B.5.3 Remote Surveillance: This concept is based on a monitoring system that verifies, by a remote communication link, the presence and integrity of the material in its container during its transit between the origin of shipment and destination. The information of interest is the location and status of the shipping cask or container. To achieve this requires transport vehicles which are constructed of penetration- and accident-resistant materials and which have onboard the position location modules that can communicate with the IAEA remote-surveillance station by remote communication links. In addition, various sensors, depending upon the material transported, need to be developed to ensure cask or container integrity. Conceptual designs for transport vehicles, containers, and material-accounting sensors have been developed for LWR spent-fuel assembly transport and the bulk plutonium transport. A comparable system would be adopted for fresh and spent FBR assemblies. With this system nearly instantaneous detection of anomalies could be achieved, depending only on the time interval chosen for communication. Since this type of surveillance is in the conceptual stage, feasibility evaluations and demonstration will be required before implementation on an international basis.

V. ADVANCED IAEA SAFEGUARDS RESEARCH AND DEVELOPMENT

OBJECTIVES

IAEA safeguards are the primary measures of reducing the risk of proliferation in the worldwide deployment of nuclear power. Technical and institutional differences in the proliferation risks between the many fuel cycles can be minimized by the introduction of improved safeguards on commercial nuclear activities. It is evident therefore, that effective IAEA safeguards are an essential feature and an important additional dimension to be considered in the development and deployment of nuclear power systems.

The current safeguards related efforts have been aimed at the implementation of safeguards systems to the five basic phases of the fuel cycle; uranium enrichment, thermal and fast power reactors and fuel handling systems, commercial-scale reprocessing of spent fuel, mixed oxide fuel fabrication, and interim storage of irradiated uranium and/or separated plutonium. The objectives of these safeguards measures are to provide a timely detection of the diversion of significant quantities of nuclear materials from peaceful nuclear activities and consequently affect a measure of deterrence of such diversion by the risk of early detection

The safeguards systems currently employed have been based on material accountancy supplemented by containment and surveillance measures. Although the experience with these methods has indicated a general capability of providing effective international safeguards, these procedures appear to be inadequate to meet the significant quantity and timeliness goals and guidelines of detection which are advocated by some member states of the IAEA for the anticipated deployment of large scale nuclear facilities.

Potential improvements in the accuracy of measurements by analytical chemistry assay and/or nondestructive assay (NDA) techniques are essential to meeting the materials accountancy goals and guidelines but would not impact on the timeliness goals.

A necessary, but not sufficient, condition to satisfy the timeliness goals is the research and development of advanced nondestructive assay methods which essentially applies nuclear physics, nuclear chemistry, and instrumentation to the measurement of nuclear material in a more near-real-time mode. The sufficiency condition will be satisfied by the research and development of advanced containment/surveillance methods to complement materials accountancy. The objective of timely detection will necessitate materials inventory verification and accountancy integrity by the implementation of containment/surveillance measures at strategic points between key measurement positions.

The implementation of the proposed advanced components of safeguards into an operable on-line near-real-time IAEA Safeguards system will depend on continuing and expanding the safeguards research and development program. The general technology program includes a broad range of developments designed to provide the IAEA with advanced measurement and accountancy technology, data analysis, and containment/surveillance capabilities. Although the partial listing of some R&D requirements refers mostly to advanced

sensor instrumentation, a major area of effort would have to be directed toward determining the optimum integration of sensor components coupled into a safeguards system design and applied to operating facilities in order to establish the operability under plant conditions.

A. Materials Control and Accountancy

The effort in developing and evaluating analytical techniques for measuring plutonium and uranium have been based mainly on commercial process-control considerations. The R&D programs in chemical assay and NDA techniques are now emphasizing the advanced safeguards requirements and, where possible, developing methods to satisfy both process control and safeguards. The precision and accuracy of the measurement methods are in some cases directly dependent on the accuracies of physical and chemical constants such as the half-life of the fissile isotopes. The R&D program should therefore include improving the accuracies of these and other necessary critical basic constants. The advanced sensor techniques and technology developments include:

A.1 Analytical Chemistry Assay

- a. Fuels Assay X-Ray System (FAXS): The operational use of the x-ray fluorescent technique introduces a rapid-turnaround time in the chemical technique for uranium and plutonium in breeder fuels.
- b. Amperometric and Coulometric Methods: Accuracies of these assay procedures depend upon suitable standards. Adequate standards for mixed oxide materials (PuO_2 and UO_2) are a continuing developmental program.
- c. Resin-Bead Techniques: Demonstration of the resin-bead collection technique for using microgram quantities for independent off-site chemical analysis or onsite at reprocessing-conversion plants, fabrication facilities, or unirradiated and irradiated fuel storage facilities.
- d. Isotopics: Isotope correlation techniques for dissolver solution, unirradiated and irradiated fuel storage sampling assay.

A.2 Advanced NDA Techniques for Safeguards Systems

- a. Gamma-ray assay of plutonium content in wet (on-line) and dry waste streams.
- b. X-ray fluorescence in radioactive dissolver solution.
- c. High-resolution gamma-ray spectrometry for isotopic analysis of plutonium in solution.
- d. Gamma-ray absorption to determine plutonium concentration in the presence of uranium.
- e. Nondestructive-analysis techniques for use in waste solidification technology should be adopted.

- f. Active and passive neutron interrogation technique developments should be advanced toward implementation as potential sensors in assaying fissile content directly and independent of form i.e. bulk (powder or metallic), unirradiated and irradiated fuel assemblies, mixed-oxide pellets, and/or reprocessing solutions.
- g. Development of measurement techniques for on-line near-real-time assay should include: simultaneous multicomponent isotopic analysis techniques, x-ray fluorescence or densitometry with high energy or wavelength dispersion spectrometers, and active neutron interrogation.

B. Containment/Surveillance

Some of the C/S sensor development and evaluation programs should include:

B.1 Crane Monitor System:

- a) The ability to determine optimum techniques for monitoring crane loads. b) The utility of crane load, direction of travel position, and activity information in assessing fuel handling operations. c) The automation and reliability of the above parameters over long periods of time.

B.2 Storage Acoustic Monitor:

- a) Determination of the unique acoustic signals of fuel handling in storage pools. b) Development of hardware and software to identify fuel handling acoustic signals with acceptable possibilities of detection and false alarms. c) Development of criteria to correlate detection of fuel handling with possible fuel diversion.

B.3 Fuel Assembly Identification Devices (FAID):

- a) FAIDs having unique ultrasonic signatures that (1) will be altered if the FAID is removed from the fuel assembly, (2) will prevent disassembly while in place, (3) can be interrogated in place, and (4) is compatible with all fuel assembly environment conditions. b) FAID readers that can be positioned over the FAID while it is attached to the fuel assemblies, either as fresh fuel or as irradiated fuel submerged in the pool. c) The establishment of criteria and development of a system for automating the FAID identification process.

B.4 Under-Sodium Viewing (USV) System

- a) Expanding the demonstration program of the ultrasonic imaging (USV) system for use in storage facilities of fresh and spent fuel assemblies on-site or away from reactor sites. b) Demonstrating the applicability of this viewing system in a Water-Pool Storage System.

B.5 Other Systems for further Development Include:

1. Underwater Optical Viewing System,
2. Cerenkov-Glow Vision Device,
3. Spent Fuel Scanning for Neutron and Gamma Emission/Burnup, and
4. Spent Fuel Temperature Monitoring.

Interfacility Transportation:

- a) Evaluating commercially available transportation components that could be used in the system. b) Designing and building system elements using the most suitable components. c) Performance-testing the elements under simulated and actual fuel transportation operations.

C. Input Measurements

Development of systems for on-line measurements of volume, densities, and temperatures of process solutions.

D. On-Line, Near-Real-Time IAEA Advanced Safeguards System

To optimize the limited resources of the Agency, the possibility of applying and utilizing tamper-indicating data link and data collection modules, either independently or in a verification mode with the SSAC system, will be an important consideration in determining the need and feasibility of the near-term application of automated data acquisition systems.

Advanced concepts being developed in the U.S., 28,29,34,35 parts of which can be modified, expanded, and used for IAEA safeguards, includes advanced instrumentation of (1) sensors, (2) data collection modules, (3) communication links, and (4) monitoring and display units. Each of these components may supplement and eventually be phased into the current methods of IAEA site inspections for safeguards related surveillance and verification of materials accountancy. The system would allow the application of on-line near-real-time computer systems. One such possible system is schematically presented in Fig. 11 where certain combinations of the components of containment/surveillance, and material accountancy systems may be placed under national and/or IAEA control. Other options may include the Data Collection Module under IAEA control, or the total system may be an independently controlled component of the IAEA.

The advanced IAEA system concept is in principle a generic system and is applicable to all elements of the LWR and FBR fuel cycle; spent-fuel and fresh-fuel storage, plutonium storage, transportation, isotopic enrichment, reprocessing, fabrication, and the transportation of mix-oxide fuels, provided that appropriate sensors be applied or developed based on the characteristic properties of the fuel cycle element to be safeguarded.

The original conceptual design is a system for the containment and surveillance of spent fuel storage, handling and transportation operations on the national level of safeguards concern. In this section the concept is generalized to include all elements of the LWR and FBR fuel cycle. This

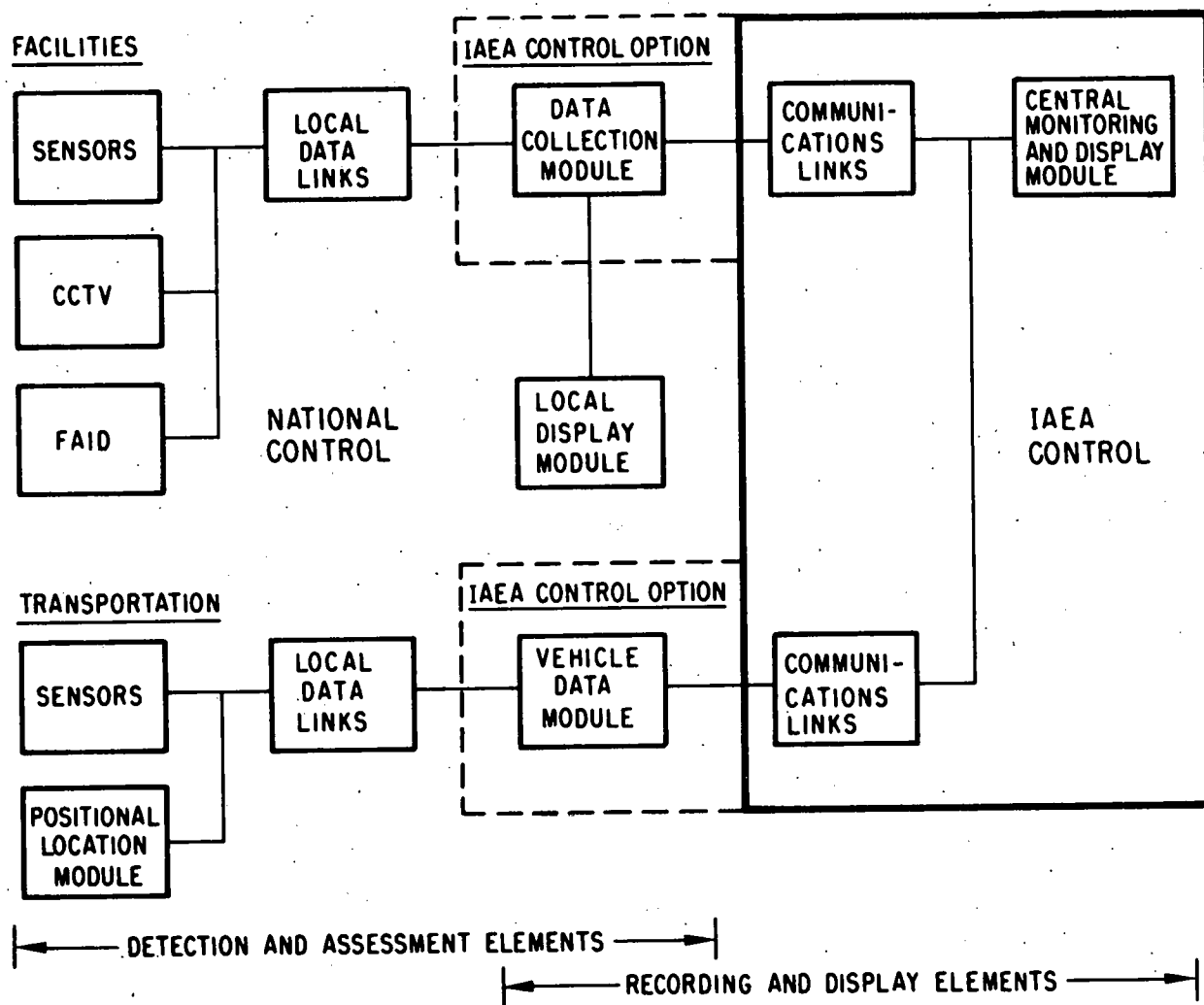


Fig. 11. Conceptual Overview Containment and Surveillance System.

generalization extends the role of the IAEA Safeguards Systems from the traditional concepts of periodic inspection of the facilities by IAEA inspectors to the concept of continuous or almost continuous inspection. The reference system emphasizes an overall structure in which other computer based on-line systems, such as the near-real-time material control and accountancy, can be included as one subsystem in this generalized approach.

Factors governing the choice of containment and surveillance (C/S) instruments are (1) the availability of off-the-shelf hardware for each monitor and (2) guidelines developed from facility constraints and performance requirements. The capabilities of the C/S system include the following:

1. Detect both reported and unreported movements
2. Provide assessment information for both reported and unreported movements.
3. Provide inventory verification data
4. Operate with a high degree of reliability
5. Allow timely reporting of data
6. Provide tamper-indicating capability throughout the system
7. Operate as simply and cost-effectively as possible within preceding constraints.
8. Minimize the impact on facility and transportation operations
9. Minimize the required number of inspectors and inspections.

E. Description of Reference Advanced Safeguards System:

The reference safeguards system includes advanced instrumentation: (1) sensors, (2) data links, (3) data-collection modules, (4) communication links, (5) monitoring and display units, (6) closed-circuit T.V., (7) the image processor, (8) tamper-indicating techniques, and finally, (9) a computer system. Main emphasis is on the on-line near-real-time capability for early detection of diversion and the timely reporting of such diversion.

One characteristic of this approach as shown schematically in Fig. 11, is the separation of safeguards aspects into two categories with some units under national control while others are under IAEA control. The central monitoring units may be thought of as being located at either IAEA headquarters or at some IAEA regional station if this option is considered feasible. The data links, communication links, and equipment under national control are protected by tamper-indicating techniques. Figures 12 and 13 are schematic sketches of such techniques. Closed-circuit T.V., coupled with the digital image processor, provides an added dimension to the tamper-indicating methods in addition to

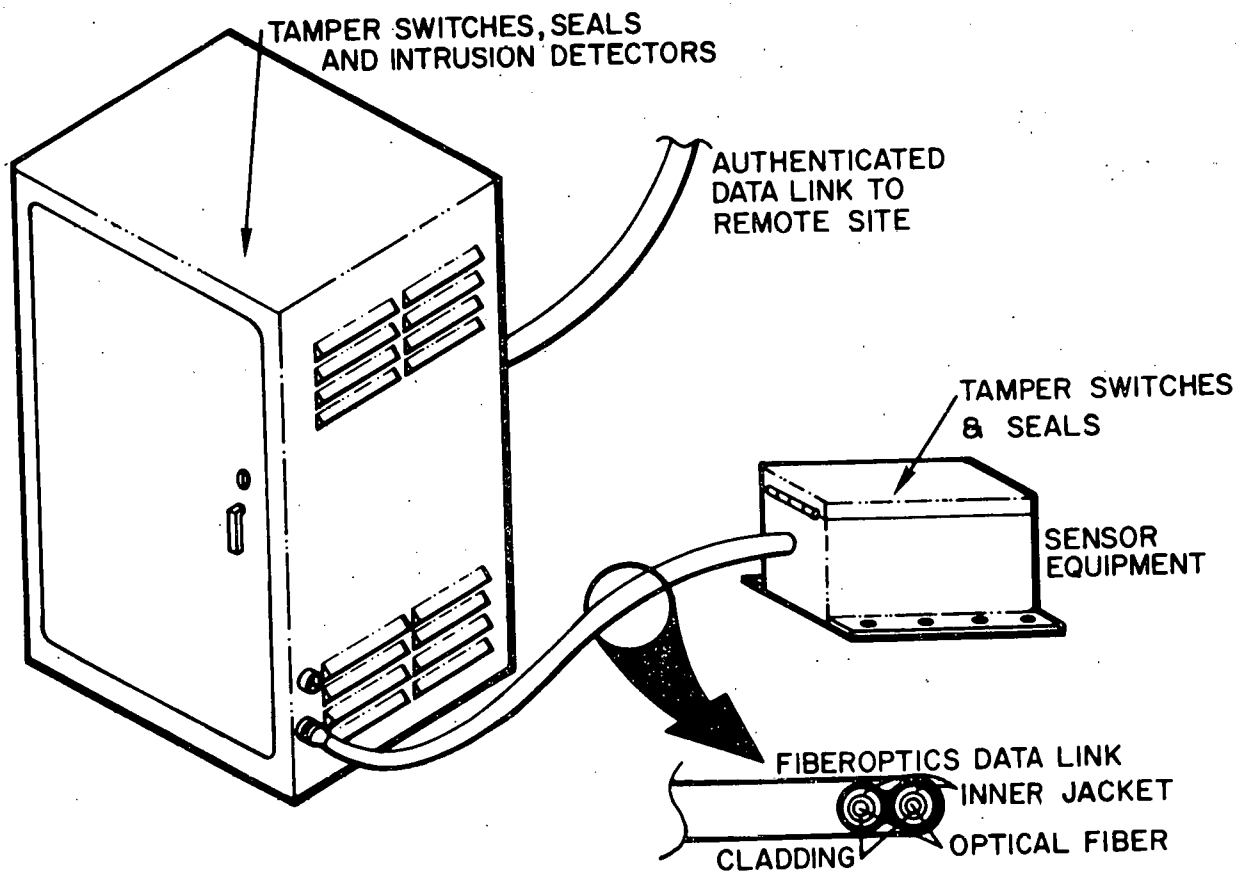


Fig. 12. Tamper-Indicating Techniques.
(See ref. 34)

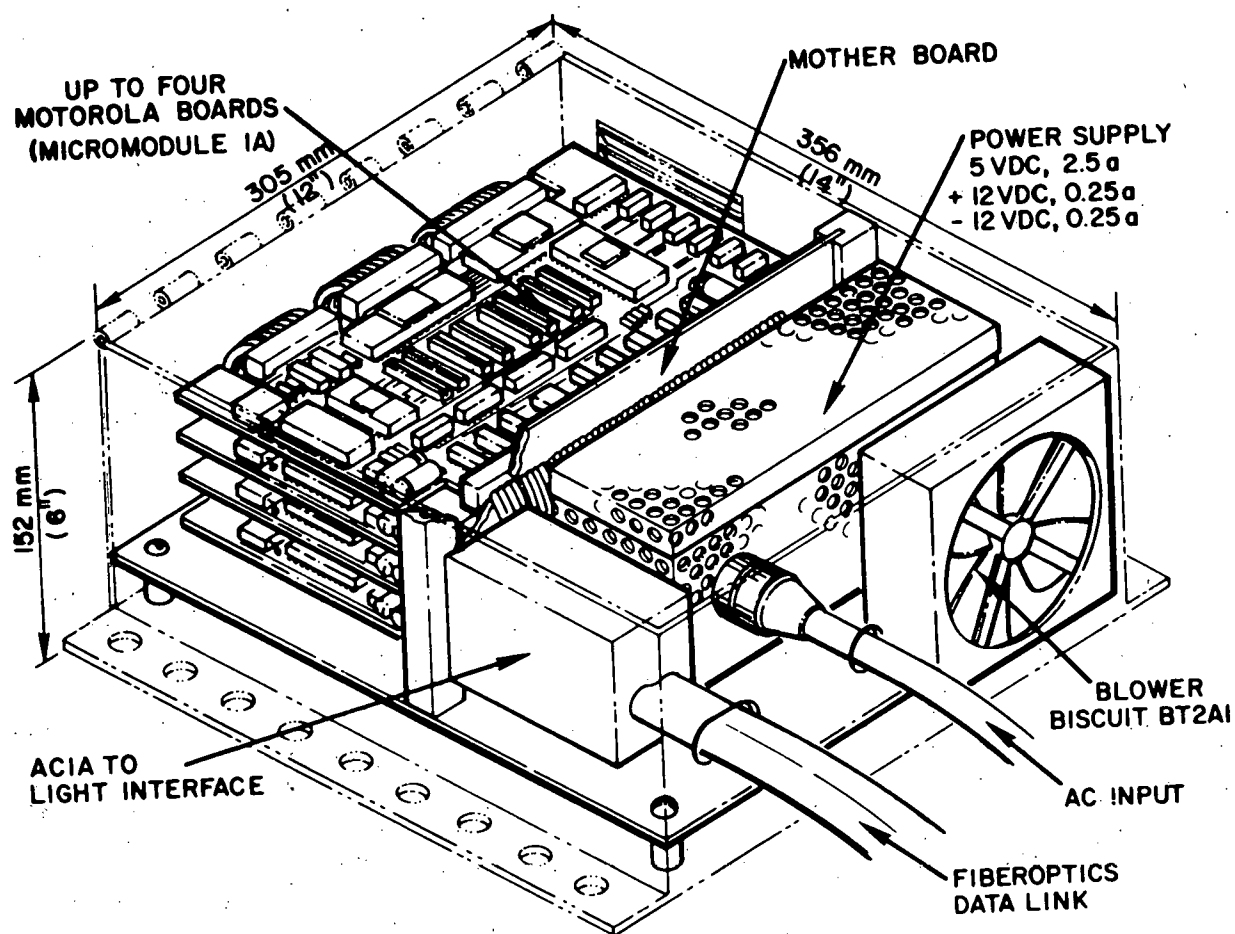


Fig. 13. Tamper-Indicating Sensor Module.
(See ref. 34)

being useful in the physical protection phase of the systems being safeguarded. Fig. 14 is a schematic sketch of a closed circuit T.V. system. The data-collection module shown in Fig. 11 has two independent functions: The local display is for the national operation systems, and the other is for the communication of the data to an IAEA central monitoring station. The data-collection module would be designed such that its software could not be altered by the local personnel.

Some of the components to be developed for the system are briefly described below:

a. **Sensors:** These would be the instruments designed for the specific characteristics of a phase of the fuel cycle. In the fresh or spent-fuel assembly storage systems, the sensor may be a passive radiation monitor or an active neutron interrogation monitor, the unique characteristic of the fuel cycle element being the emission of radiation. These monitors may be applicable when the assembly is passed through an access port in entering the storage pool. Other sensors operating on different principles for the same fuel cycle phase would provide an improved safeguard system: for example, acoustic monitors, under sodium viewing, or underwater optical viewing monitors for sensing fuel assembly movements within the storage pools, or direct viewing, and devices for scanning signatures of assemblies.

b. **Data-Collection Links:** The local data links transmit data from the sensors to the data collection module. These components would be protected by tamper-indicating techniques and tamper-indicating sensor modules, schematically presented in Figs, 13 and 14.

c. **Data-Collection Module (DCM):** The DCM collects, correlates and stores data from the instruments in the facilities and communicates the information to both the local display module and the IAEA central monitoring and display module (CMDM). This unit is protected so that its software may not be altered by the local personnel. Figure 15 is a schematic of the data flow at the DCM.

d. **Local Display Module:** This provides local personnel and the IAEA inspector with a means of obtaining on-site data for assessment.

e. **Communication Links:** These transmit information from the DCM to IAEA CMDM either by telephone lines or by satellite lines. An image processor capable of transmitting video data from closed circuit T.V. system is also included. The data from the communication links is authenticated by using tamper-indicating techniques.

f. **Closed Circuit T.V. (CCTV):** This provides T.V. pictures for storage (a) when the DCM identifies anomalies in the sensor data, (b) upon command by the central monitoring and display module at the IAEA remote station.

g. **Digital Image Processor:** It allows T.V. data to be stored in a random access memory at video rates. The stored data can then be selectively transferred to the computer and used to drive a communications mode at data rates comparable with phone lines and narrow-bandwidth radio-frequency links.

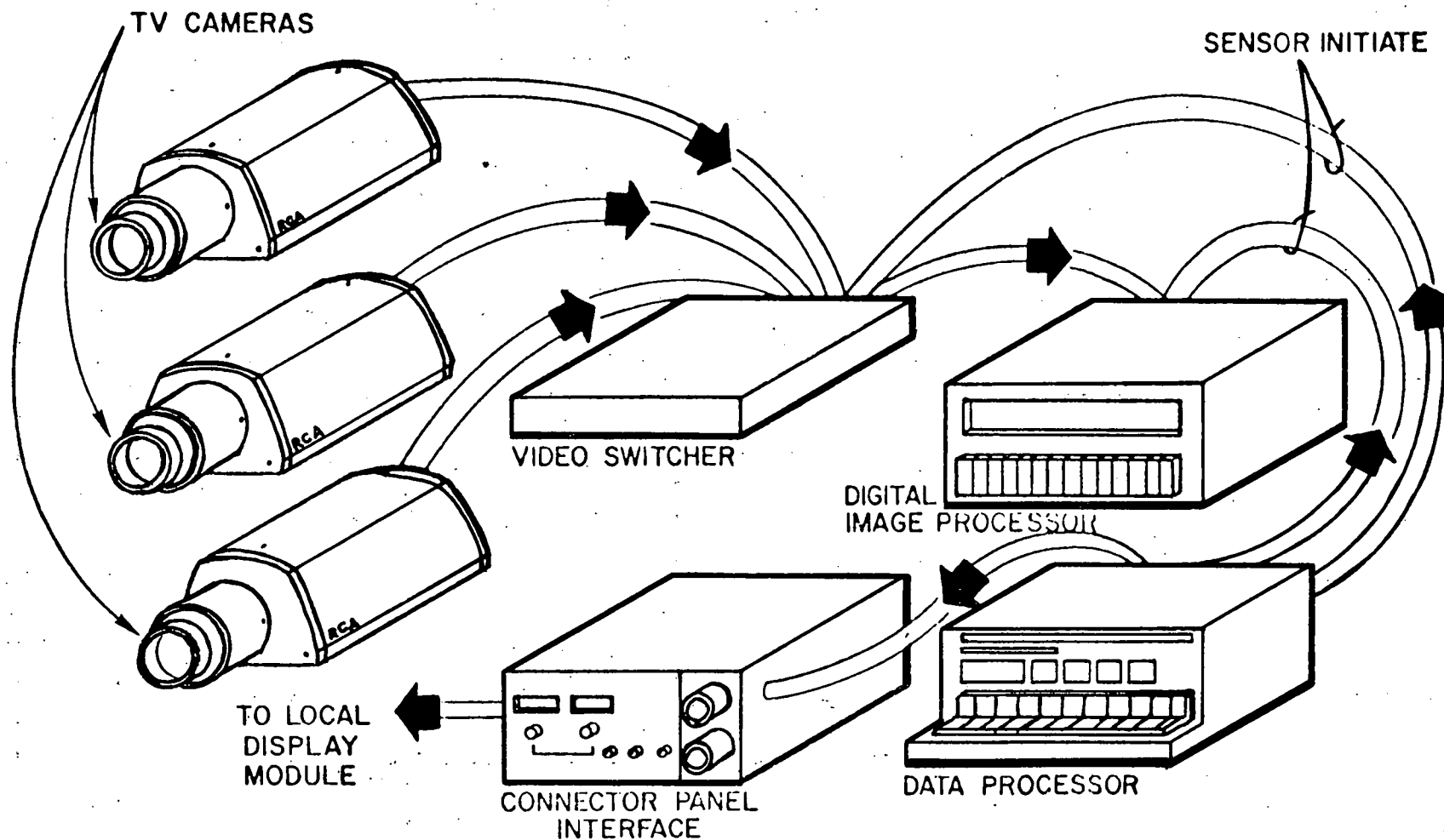


Fig. 14. Closed Circuit T.V.
(See ref. 34)

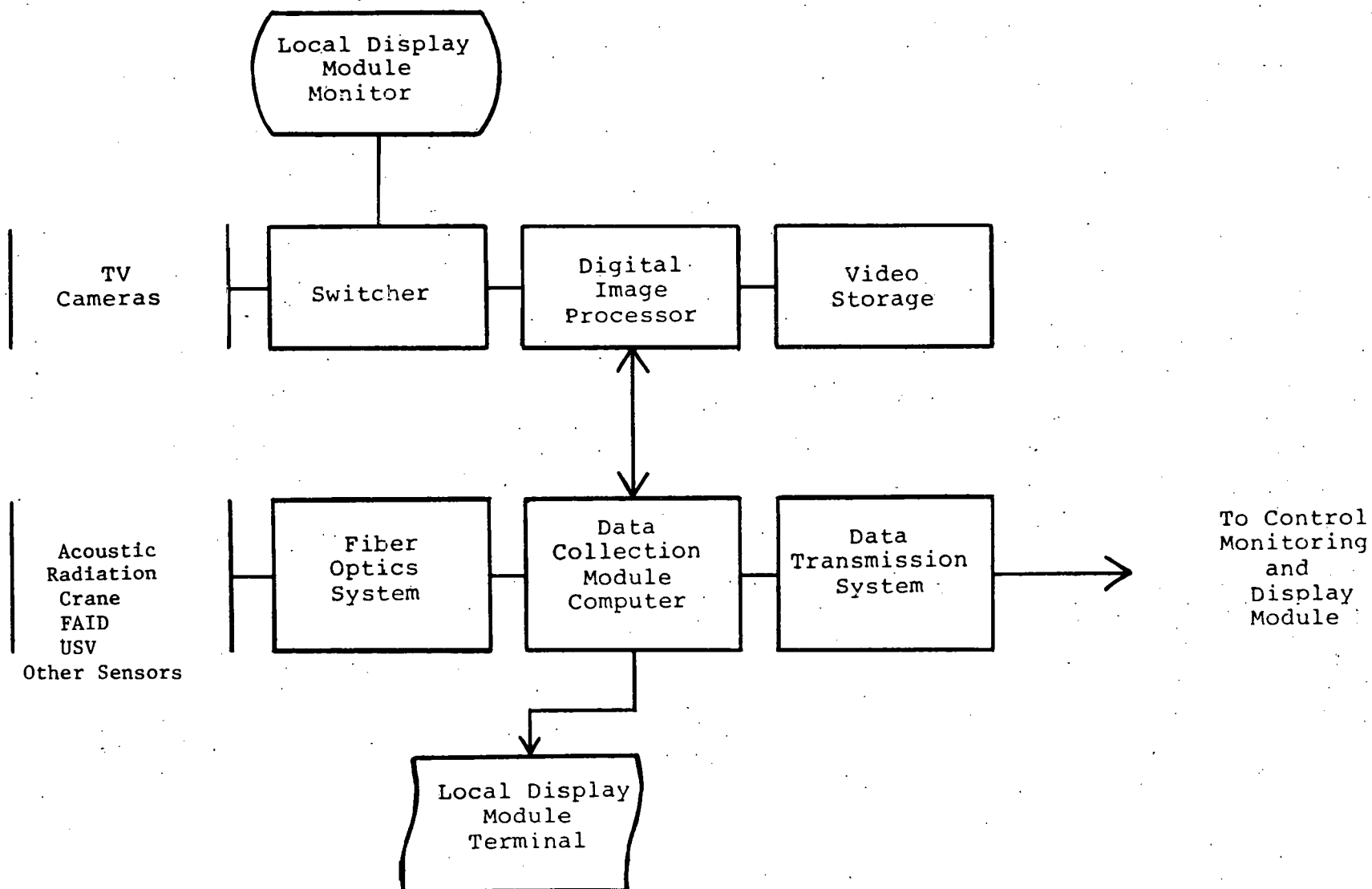


Fig. 15. Data Collection Module Data Flow.
(See ref. 34)

h. Central Monitoring and Display Module: This module receives, interprets, stores, and displays data gathered from different DCM's corresponding to different fuel-cycle elements or phases. Some examples are fuel assembly DCM and transportation DCM. Figure 16 is a schematic of the arrangement and data flow.

F. Implementation of the Safeguards System: The reference advanced IAEA Safeguards System would include inspections in any one or combination of the following modes:

1. Periodic inspection of the fuel-cycle facility by IAEA inspectors to review data acquired by the instruments and verify the material inventories
2. IAEA resident inspector at the facility to review the data and operations and to verify the material inventories
3. Collection of the data by remote techniques as described in this section coupled with periodic on-site inspection of the facility.

The safeguards system for a specific fuel-cycle facility depends upon trade-offs between several factors, two of which are IAEA resources and timeliness of detection.

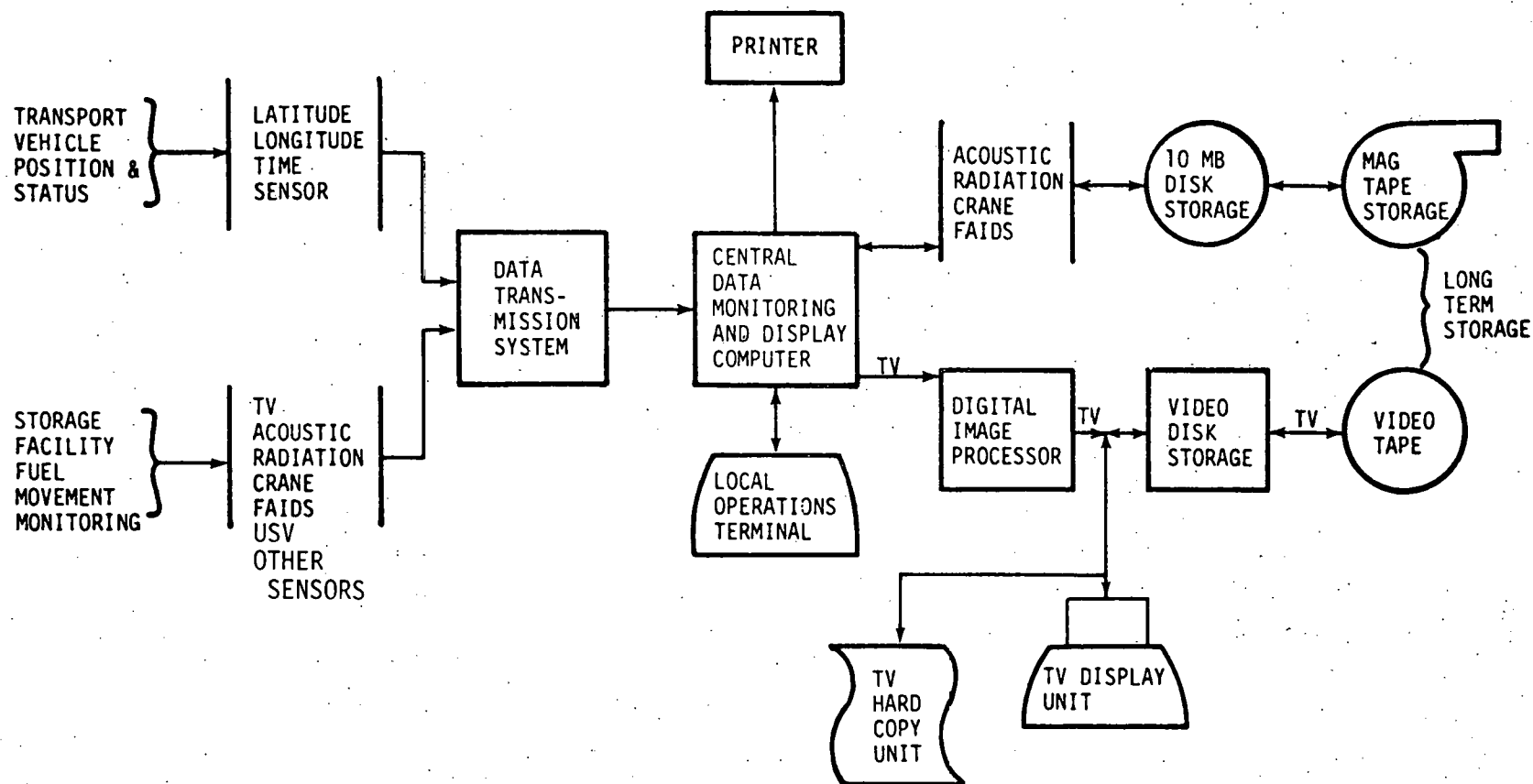


Fig. 16. Central Monitoring and Display Module Data Flow.
(See ref. 34)

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