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Advanced Integrated Safeguards Using Front-End-Triggering Devices

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ADVANCED INTEGRATED SAFEGUARDS USING FRONT-END-TRIGGERING DEVICES

by

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ABSTRACT

This report addresses potential uses of front-end-triggering devices for enhanced safeguards. Such systems incorporate video surveillance as well as radiation and other sensors. Also covered in the report are integration issues and analysis techniques

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I. Introduction

Increasing numbers of large nuclear processing facilities, new responsibilities for safeguarding excess weapons materials, and expansion of traditional safeguards to include detection of undeclared activities will stress already limited international inspection resources over the coming years. One response to meeting these increased responsibilities while maintaining the quality of the inspection process is increased reliance on equipment to replace inspectors at facilities. Commonly this is referred to as unattended monitoring, wherein equipment monitors and records aspects of facility operations during the absence of an inspector for later review by an inspector.

This report addresses one element of an unattended monitoring system: a surveillance system that can record operator activities and material movements, assure the continued integrity of stored items, and monitor areas where no activities or movements should occur. Because of the potentially large numbers of surveillance images to be captured, archived, and reviewed when monitoring is frequent or continuous, options for selective collection of data are essential if equipment and personnel resources are to be conserved. The term "front-end triggering" denotes the use of complementary devices such as motion or radiation detectors to enable selective capturing of images while ignoring events that are not of safeguards relevance.

The applicability of this study to the International Atomic Energy Agency's (IAEA's) Programme 93+2 cannot be overlooked. This program for strengthened and more cost-effective safeguards stresses the following cost-saving measures:

- Enhanced technology
- Improved equipment procurement/installation
- Improved use of human resources
- Administration of safeguards

The use of front-end-triggering systems addresses these issues and would provide greater assurances for the accuracy of an inspection and enhance the overall effectiveness of safeguards.

This document is organized in five parts. Section I (this section) provides the background and purpose of the study. Section II covers integration issues. Section III describes some common analysis techniques as well as some new, experimental ones. Section IV describes some types of nuclear-fuel-cycle facilities with suggestions where front-end triggering might be appropriate. Finally, Section V presents conclusions and recommendations.

II. System Integration

An integrated front-end-triggering system is a collection of surveillance and triggering devices that act together to accomplish specific monitoring objectives. The design of such a system must take into account several important factors. We list them here with a brief explanation.

- Monitoring Context - the relevant features of a facility, personnel activities, and material movements at a monitored location
- Monitoring Objective - the objective in terms of the conclusions to be drawn at the monitored location
- Diversion Scenarios - possibilities for diversion in terms of personnel actions, materials, and facility equipment
- Diversion Indicators - the sensible attributes of the diversion scenarios in terms of the types and locations of motion and radiation signatures that distinguish the diversion scenarios from routine facility operations
- Sensor Selection - instruments that can detect these indicators within the background of normal facility operations, based on diversion scenarios
- Sensor Integration - instrument locations, field of view, sensitivity, and system logic (and the hardware/software to implement the system, considering completeness of coverage of all scenarios and defense in depth to avoid vulnerability to a single-point failure)
- Data Fusion - combining data from disparate sources [e.g., nondestructive assay (NDA) and video]
- Data Review - allowing the inspector to apply knowledge and personal judgement, based on visual display of the collected data
- Data Analysis - interpreting the data (does the data represent normal or anomalous facility activity?) and providing a capsule summary of the data (location, duration, and other metrics of "events" that were identified)

Sensors in a typical integrated front-end-triggering system include NDA sensors,[1] environmental monitors, and video together with associated data acquisition computers and networking equipment. While Ethernet is widely used today, commercial vendors offer networking with built-in encryption and time synchronization that have advantages to the safeguards community.[2]

In 1992, the IAEA Integrated Safeguards Instrumentation Programme (IISIP) was established to guide hardware development and selection for unattended monitoring systems for the future. In December 1993, the VXIbus was recommended as a standard. Reasons for this selection were reliability, extensibility, and wide availability of standard modules to run on this robust and open platform. For this standard to be adopted, member states have to support this idea and adopt the use of this standard. Several different hardware designs are in use for unattended monitoring systems, and this proposed standard is still under consideration.[3]

Although data analysis is not traditionally thought of as being a part of an integrated safeguards system, it is anticipated that data complexities, interdependencies, and quantity will necessitate some assistance to the inspector for the understanding required to assure nonproliferation. Two video analysis systems, the MIVS Advanced Review Station (MARS, from Aquila Technologies Group Inc.) and the Multi-System Optical Review Station (MORE)[4] were designed to assist the inspector in reviewing large quantities of video images. We do not expect an analysis program to replace an inspector but rather to enhance the inspector's experience, intuition, and interpretive skills and enhance the overall effectiveness of safeguards evaluations.

For other discussions of integrated safeguards see Refs. 5-9.

III. Analysis Techniques

A. Introduction

As the complexity and throughput of nuclear materials increases at nuclear facilities all over the world, it becomes increasingly important to invest less inspector time per facility without losing safeguards effectiveness. Continuous unattended radiation and surveillance monitoring systems significantly reduce inspector time in facilities. However, these continuous measurement systems produce large safeguards databases and require inspector time for thorough review and analysis.

Advanced analysis techniques can aid the inspector in the review process and have the potential to

- Correlate large quantities of diverse information;
- Relieve the error-prone tedium of personnel reviewing masses of information;
- Efficiently analyze all data, identifying specific trends and flagging unusual

activities;

- Provide inferences and conclusions on normal activity versus anomalous patterns;
- Classify abnormal events, such as diversion of material or faulty data from intermittent sensors; and
- Provide automated verification of facility activity based on video, powerline, and nuclear material signatures.

In the following sections we describe some of these techniques and how they are useful.

B. Anomaly Detection Techniques

With complex and diverse data being collected by nuclear chemical processing plants, nuclear material storage facilities, fuel fabrication facilities, and nuclear reactors, it is time consuming and demanding to effectively examine all the data for consistency and to find subtle anomalies that could be caused by diversion. When one can characterize normal trends and patterns in the data, such anomalies reveal themselves. This radiation signature forms a "fingerprint" that can signal inappropriate activity.

There are several methods for detecting anomalies in large sets of safeguards data. We list them here with brief descriptions and references.

1. Statistical Methods

Multivariate fault detection techniques have been applied to the detection of two diversion scenarios in a chemical processing plant: 1) a steady leak from a tank without replacement and 2) a steady leak for which the lost solution is replaced with water.[10] This involves monitoring the residual differences between process measurements and redundant information obtained from either a model or from other measurement sensors to both detect and characterize faults. The chemical plant model was based on total and individual mass balances for each chemical species in each tank. Simulated measurements and model predictions were obtained from a three-tank system containing nitric acid, plutonium, and uranium.

For the first scenario, with a 0.5-L/h leak, volume was detected as a fault, whereas, in the second scenario, density and concentrations of plutonium and uranium in a tank were detected as outliers at the 5% significance level.

A second analysis technique, nonlinear time series analysis, was used to predict loss of material.[11] Time series data is divided into testing and training sets. Then, the training set is used to estimate the conditional mean. The mean squared error of prediction (MSEP) is calculated in the test set for both linear and nonlinear methods. Anomalies are detected by minimizing the standard error of the residuals. The nonlinear methods performed better at predicting nonlinear time series and did as well as the linear methods at predicting the linear values.

2. *Expert Systems*

Expert systems are rule-based. They are useful in detecting anomalies where the process is well characterized and rules of correct operation can be explicitly stated. A good example of the use of an expert system to detect anomalies in a large data set is the system developed at Los Alamos National Laboratory (LANL) to analyze data from the Material Accountancy and Safeguards System (MASS). MASS is an accountability system that tracks and reports the location, use, and status of all the nuclear material items residing at LANL.[12,13] The large amounts of data and the complex and diverse nature of the data make analysis and evaluation extremely difficult. The target of this study was transaction data and locating errors in this database. Because models of transactions exist, expert systems were ideal. Information used in building the rule-base includes the sending and receiving processes, the sending and receiving accounts, the amount of nuclear material involved, the type of measurement technique used to assay or weigh the item, and other key identifiers that describe the nature of the nuclear material.

A total of 757 transactions were evaluated with the expert system. Of those transactions, 153 were judged to be anomalous. Some of the anomalies detected could have been found by manual examination. However, some were of a type not being detected by current methods.

3. *Neural Networks*

A neural network is an iterative numerical technique that facilitates the solution of a number of different types of problems including pattern recognition and categorization of data. They are useful in detecting anomalies where the process is not well characterized, no explicit rules exist, and where sensor interactions are likely to be complex or even nonlinear. A neural network learns to recognize patterns by repeatedly examining examples of those patterns.[14] For example, a network could be trained to recognize radiation signatures and video images. Neural networks are named because they are similar to biological neurons and their connections. They have attracted attention recently, and now that hardware implementations are available, they have greater appeal for data acquisition and control systems. The usefulness of neural network pattern recognition has been demonstrated for a variety of safeguards applications.[15] These include modeling the movement of nuclear material in a bulk processing facility, verifying the shuffling of material in an on-load reactor, and detecting anomalous movements of nuclear material in an item facility.

These applications demonstrate the use of neural network software in processing large quantities of facility data. This software can analyze all data and provide interpretations, predict trends, and identify anomalies. Using these computing and analysis techniques, we can thoroughly analyze large volumes of data to provide inspectors with information that allows them to focus on anomalies and data of interest for effective safeguards, thereby isolating the "needle in the haystack." Systems using these techniques are capable of classifying, clustering, and recognizing features within data; extrapolating features from the data; checking for proper operation of the systems; and detecting anomalies to facilitate understanding.

To have an adaptive system analyze the facility's activities, one must define a set of "normal" or expected activities and provide that data to the adaptive neural network system as a training set. This activity would probably include the removal of nuclear material from storage places and the transport of that material throughout the facility. In addition, there would be a large amount of activity with no direct nuclear overtones. Once the analysis system is "trained" on the benign activity, we would test its capabilities to detect abnormal activities: some legal and some indicative of illegal movement of nuclear materials.

Neural networks provide significant capability to analyze complex data and have the ability to adapt to changing situations. They provide continuity-of-knowledge associated with key facilities as well as the following:

- Pattern recognition,
- Feature extraction,
- Validation of normal operations,
- Anomaly detection in a background of normal activity, and
- Identification of proliferant discriminants.

They form a model based on the input parameters without the use of rules.

C. Integration of Disparate Data

1. Video Time Radiation Analysis Program (VTRAP)

For the past several years, the integration of containment and surveillance (C/S) with NDA sensors for monitoring the movement of nuclear material has focused on the hardware and communications protocols in the transmission network. Until recently, not much progress had been made in using the combined C/S and NDA data for safeguards. One of the fundamental problems in integrating the combined C/S and NDA data is that the two methods operate in different dimensions. The C/S video data is spatial, whereas the NDA sensors provide radiation levels versus time.

A new method has been developed to facilitate this integration of spatial and radiation time information, that is, to transform the video spatial data into the time domain as a function of physical motion in the video data. This is the VTRAP.[17,18] Every 1-2 seconds a video picture of the area of interest is compared with the baseline picture and the quantitative amount of change or movement is converted to a single pixel-difference number. This provides a data compression of ~10^5 to 10^6 and allows a comparison in time with the radiation sensors that are synchronized with the video motion data. More sophisticated versions of the VTRAP concept split the video signal into several regions of interest such as a vault door and vault area and the motion within each region is separately digitized and read out.

The interplay between the multiple regions of interest in the video motion data and the multiple radiation sensors as a function of time can be very complex. Neural networks are used to evaluate the data to distinguish abnormal events from normal activities. The neural network methods can be automated to handle the large quantities of data that are generated with frequent collection periods (1-5 s). The software can easily compress the data in time periods when there are no motion or radiation changes. When there are physical motion or radiation changes, the digital picture can be saved for later review by the inspectors.

The short time intervals (1-5 s) give a continuity of knowledge that is not possible with normal collection of video data. In addition, the essentially continuous data collection avoids the problem of missing a crucial trigger event.

In summary, advantages of the VTRAP method are as follows: each device is self-triggered, so that it gathers data as it sees an event; VTRAP forms a model without rules; video data is greatly compressed; VTRAP allows a data rate that ensures that significant anomalous events are not missed; and VTRAP provides inspectors with a summary of events with an indication of whether it was normal or not.

IV. Survey by Facility Type

The front end of the nuclear power fuel cycle consists of mining uranium-oxide-bearing ore, extracting the uranium oxide from the ore in the milling process, converting the ore concentrate to uranium hexafluoride in the conversion process, increasing the ^{235}U concentration of the uranium in the enrichment process, and finally, converting the enriched uranium hexafluoride to fuel in the fuel-fabrication process.

Back-end operations include spent-fuel reprocessing, converting uranium and nitrate solutions to oxide powders, refluorinating the uranium oxide, and disposing of wastes. When the uranium and plutonium oxides are recycled to a fuel fabrication plant or, the uranium oxide is refluorinated and sent for enrichment, the nuclear fuel cycle is referred to as closed.

When spent fuel is considered to be waste with no economic value, it is sent to a disposal facility and the cycle is called a once-through cycle. It is also possible to reprocess spent fuel without recycling the plutonium and uranium for the production of fuel. In this case the plutonium could be recovered not for the production of fuel but, rather, to reduce long-term storage costs.[19] We do not deal with this option.

The model agreement for IAEA safeguards under the Non-Proliferation Treaty (NPT) calls for "materials accountancy as a safeguards measure of fundamental importance, with containment and surveillance as important complementary measures."[20] Safeguards agreements for nations not signatory to the NPT are covered under Information Circular 66 which states, "The purpose of safeguards inspections shall be to verify compliance with safeguards agreements and to assist States in complying with such agreements...."[21] NDA instruments provide verification of the operator's data.

A. On-Load Reactors

1. *Facility Description*

Nuclear power stations in the United States contain reactor cores, which can be accessed from only one end, usually the top; fuel can be accessed only when the reactor is shut down. One safeguards advantage to this type of reactor is that it is relatively easy for a nuclear safeguarding agency to monitor the fueling process: an inspector can be sent to the site to oversee the fueling procedure. On-load light-water nuclear reactors (LWRs) differ from those in the United States, in that operators may remotely obtain access to the core from both ends, and the reactors can be continuously fueled without shutting them down. Such an operation offers a fuel management advantage, but a safeguards challenge because it provides a greater opportunity for the diversion of nuclear material.

On-load reactors are well-suited for producing plutonium from their standard fuel bundles. Safeguarding an on-load reactor requires keeping track of fuel as it is pushed through the core. When a fresh-fuel bundle is pushed in one side, a spent-fuel bundle is simultaneously discharged into a collection mechanism on the other side. Using this fueling scheme, a typical on-load reactor will discharge 55 to 65 fuel bundles per week. Figure 1 shows a conceptual diagram of this fueling cycle. Because this is an ongoing process; it is labor intensive for a safeguarding agency to have an inspector on-site to continuously monitor re-fueling.

2. *Current Safeguards Implementation*

The facility accounting and operating records are examined for correctness and internal consistency. These accounting records are compared with inventory change, material balance, and any special reports sent to the IAEA by the State.

The list of inventory items received for the physical inventory verification are compared for consistency with the material balance report and the associated physical inventory listing. Inventory change reports and material balance reports are compared for consistency. There is one physical inventory verification per year.

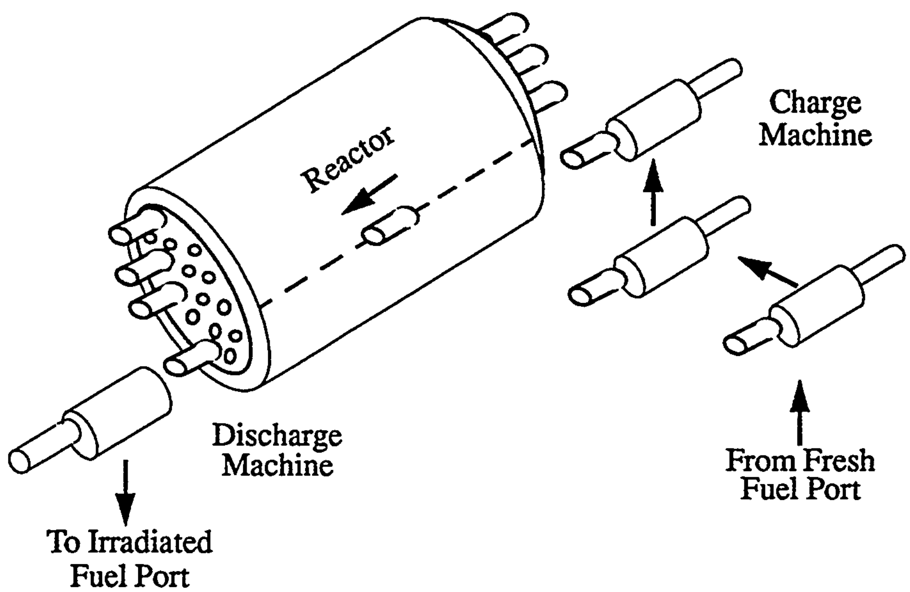

Fig. 1. Sample layout of a typical on-load reactor.

C/S and other verification of fuel discharges, if applicable, ensure that the irradiated fuel bundles discharged from the core since the last physical inventory verification have gone into the spent fuel bay and that no unrecorded removals of spent fuel have taken place. The C/S and other systems are evaluated at interim inspections and at physical inventories.[29]

3. *Proposed Integrated Advanced System*

In this section we describe a proposed front-end triggering system for an on-load reactor. A similar prototype is described in Refs. 22 and 23. A monitoring system collects data continuously and automatically from radiation sensors and cameras that monitor the reactor core and the fueling process of the on-load reactor. Advanced analysis of this collected data can save valuable inspector time by providing a summary of reactor loading activity as an aid to the inspection process

Sensors are gamma-ray and neutron detectors located near the nuclear core: two on each reactor face. The faces of the reactor core in the above diagram are on the east and west sides of the building. Fueling takes place from east to west or west to east and each set of detectors is designated by its location in relationship to the core, either the southeast (SE), northeast (NE), southwest (SW), or northwest (NW) corner as shown in Fig. 2. These sensors and cameras monitor radiation signals from the reactor and take data continuously, showing the discharge of spent fuel from the reactor core.

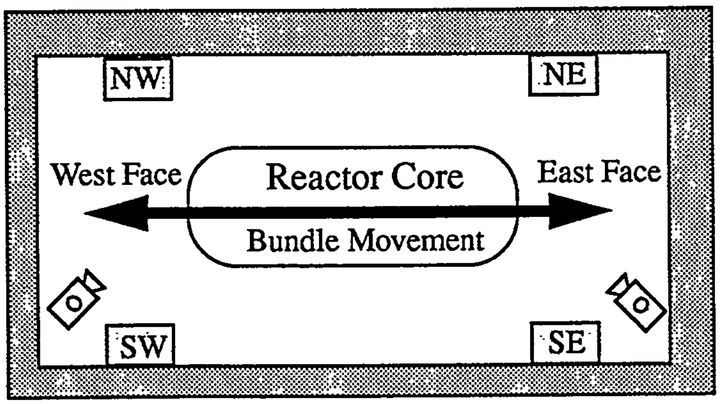

Fig. 2. Conceptual diagram of fueling cycle.

Because this system has the potential to generate massive quantities of data, efficient automatic algorithms are required to help make interpretations. These algorithms must extract information from the data, reduce analysis times, and relieve inspectors from time-consuming manual data reviews. Automated quantitative analysis programs can help safeguarding agencies gain a better perspective on the complete picture of the fueling activity of an on-load nuclear reactor. These programs could provide a cost-effective solution for automated monitoring of on-load reactors, significantly reducing personnel time and effort.

A study[22,23] describing prototype analysis software investigates the feasibility of the following objectives:

- Identifying sections in the data for an inspector to examine in greater detail,
- Locating and counting fuel bundle pushes and determining when they occurred,
- Determining reactor power level as a percentage of full power,
- Correlating events between detector channels to assure the channels are

operating correctly and to check for possible tampering,

- Identifying the fueling channel from which the spent fuel was discharged, and
- Predicting the burnup of discharged spent-fuel bundles.

A prototype pattern-recognition software tool was developed off-line to test these objectives. A neural network model was used to test the feasibility of predicting fuel burnup and location of fuel discharged from the reactor. For this study, only about 30 days of data were available. Although the total amount of data was sparse, the analysis software still performed well, suggesting this approach could be developed into a useful tool for inspections.

This tool has shown the potential for automated analysis of on-load reactor data to determine refueling activity and to monitor the reactor power level. Neural network implementations for determining the location of fuel discharge and the burnup of fuel bundles appear successful enough to warrant further research. It appears that neural network models could be developed to provide close to 100% accuracy in predicting position and burnup if a complete set of representative data from an operating on-load reactor were available. The data needed to achieve this capability should include fuel pushes from all 460 channels of the reactor face and a complete cycle of fuel through all 13 positions in every channel. Additional sensors to give a better geometric neural network model and a camera at each end could enhance effectiveness.

For front-end triggering in the spent-fuel transfer route of a CANDU reactor see Ref. 24.

B. Spent Fuel Reprocessing Plants

1. Facility Description

Spent fuel is reprocessed to separate plutonium and uranium from one another and the fission products to recover the plutonium and the uranium for the production of new fuel. Although detailed designs vary from plant to plant, the fundamental operations are the same. The most common use for the uranium and plutonium recovered is the production of uranium or mixed-oxide (MOX) fuel. The spent fuel is delivered to the reprocessing plant in shielded casks. At the reprocessing plant the casks are unloaded from the truck or rail transport vehicles. Casks are lowered into a cask unloading pool where the fuel assemblies are either stored in the casks or removed from the casks for storage. The fuel is moved to a fuel-storage pool to await reprocessing. After a time in storage the assemblies are transferred from the storage pool through a channel between the storage pool and the head-end of the process. Here they are fed to a mechanical shearer where they are sheared into 5-8 cm lengths to expose the oxide fuel. The sheared material is dissolved, leaving a nitric acid solution and cladding hulls.

Subsequent steps package the hulls for disposal, separate the uranyl nitrate and the plutonium nitrate, transfer the uranyl nitrate to a conversion facility for production of uranium hexafluoride, convert the plutonium nitrate to plutonium oxide, store the plutonium oxide in shipping canisters, and finally, ship the canisters to the MOX fuel fabrication plant(s).[25-28] [In some plants MOX may be produced for subsequent shipment to a MOX fuel fabrication plant. This situation is shown in Fig. 3.. Purified uranium in the form of uranyl nitrate solution can be shipped to an enrichment (or other) plant that would have the ability to produce UF_6. We do not consider the shipment of nitrate solutions.]

2. *Current Safeguards Implementation*

Reprocessing plants handle large amounts of nuclear material in different physical and chemical forms as well as having several processes and use a wide variety of equipment to handle the material. Declared transfer measurements in and out of the plant and material contained in the plant are independently verified on a monthly basis. Physical inventory taking, which occurs once a year, is also independently verified by the IAEA.[19]

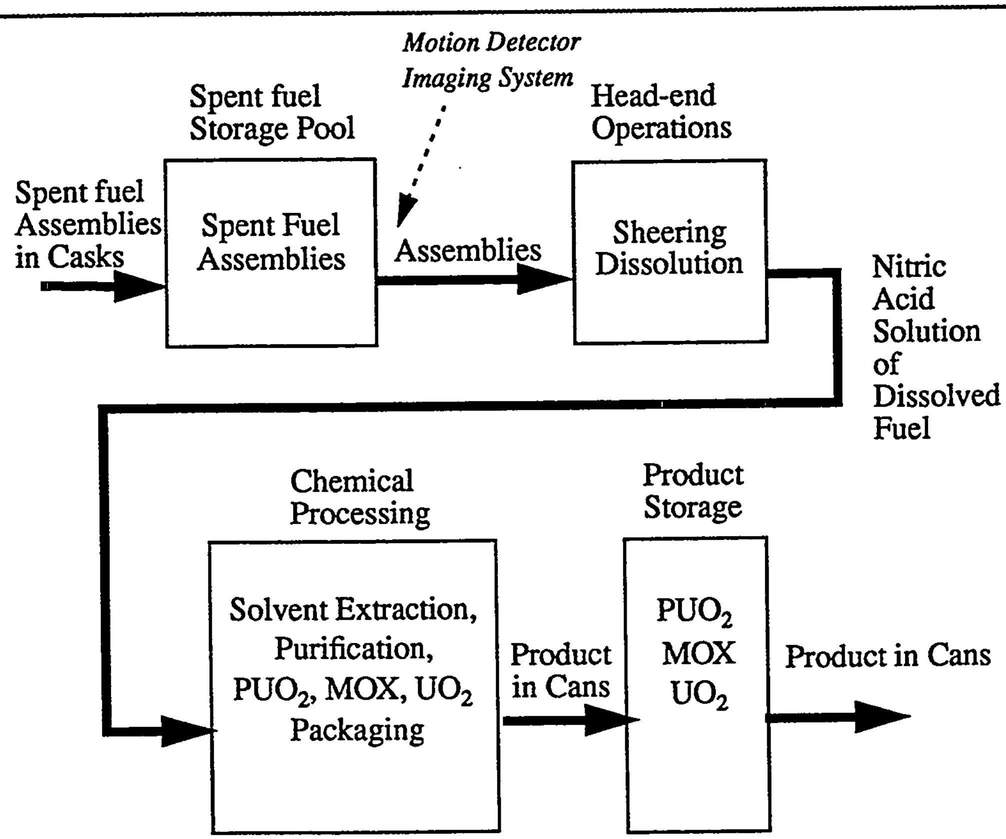

Fig. 3. Flow of Material in a Reprocessing Plant.

Measures are taken to confirm the operator's declaration for containers capable of removing 0.3 significant quantities or more of spent fuel before the containers (including casks) are removed from the storage pond.[29]

3. Proposed Integrated Advanced System

Safeguards measures applied at the spent-fuel storage pond are item accounting and redundant, independent C/S measures. Indicators of movement are the motion of the crane or other lifting device in the spent-fuel storage pond, motion of an object in the channel, and increased radiation in the channel. All transfers of assemblies are computer controlled and remotely operated. Fuel assemblies can be identified by video recording of their serial numbers where the video equipment can be triggered by the movement of the crane moving the assemblies in the channel. This will assure 1) that movements of spent fuel occur only at declared times, 2) that only the items declared are moved, and 3) that the direction of material movement is only from the pond into the head end.

Sensors such as motion detectors, video devices, radiation monitors, and other NDA devices would allow unattended verification of inventory and transfers maintaining the continuity of knowledge of items in storage and would permit reliable item identification, thus reducing inventory verification. Rapid identification of transfers before and at physical inventories would be possible. For example, an unattended system for monitoring the movement containers of spent fuel has been installed in the transfer channel between the cask unloading pool and the main storage pool at the THORPE reprocessing plant. A Gamma Ray and Neutron Detector (GRAND) system detects movement in any direction and triggers a video system for recording the movement.[30] Figure 3 shows a motion-detector video system from the spent-fuel storage pool that could be crane activated or activated by another motion detector.

C. Uranium Enrichment

Enriched uranium is classified as either low-enriched uranium (LEU), which is defined as uranium enriched to less than 20% ^{235}U, or high-enriched uranium (HEU), which is defined as uranium enriched to 20% ^{235}U or more. Most large enrichment plants produce LEU for power reactors. LEU can be diverted to reactors for the production of weapons-grade plutonium. Enrichment plants declared for the production of LEU for peaceful purposes also can produce HEU clandestinely for nuclear explosives. The production of HEU from declared plants using low-enrichment centrifuges is a major IAEA concern. International safeguards for these plants are intended to detect diversion of LEU that could be used as feed for undeclared plants or the unauthorized production of HEU. Any gas-centrifuge plant of reasonable size can be reconfigured to produce HEU. Gaseous-diffusion plants are less attractive than gas-centrifuge plants for the production of HEU. Gaseous-diffusion plants are usually one-cascade plants, thus requiring the entire plant to be misused for HEU production. The production of excess LEU is possible and difficult to detect.[19]

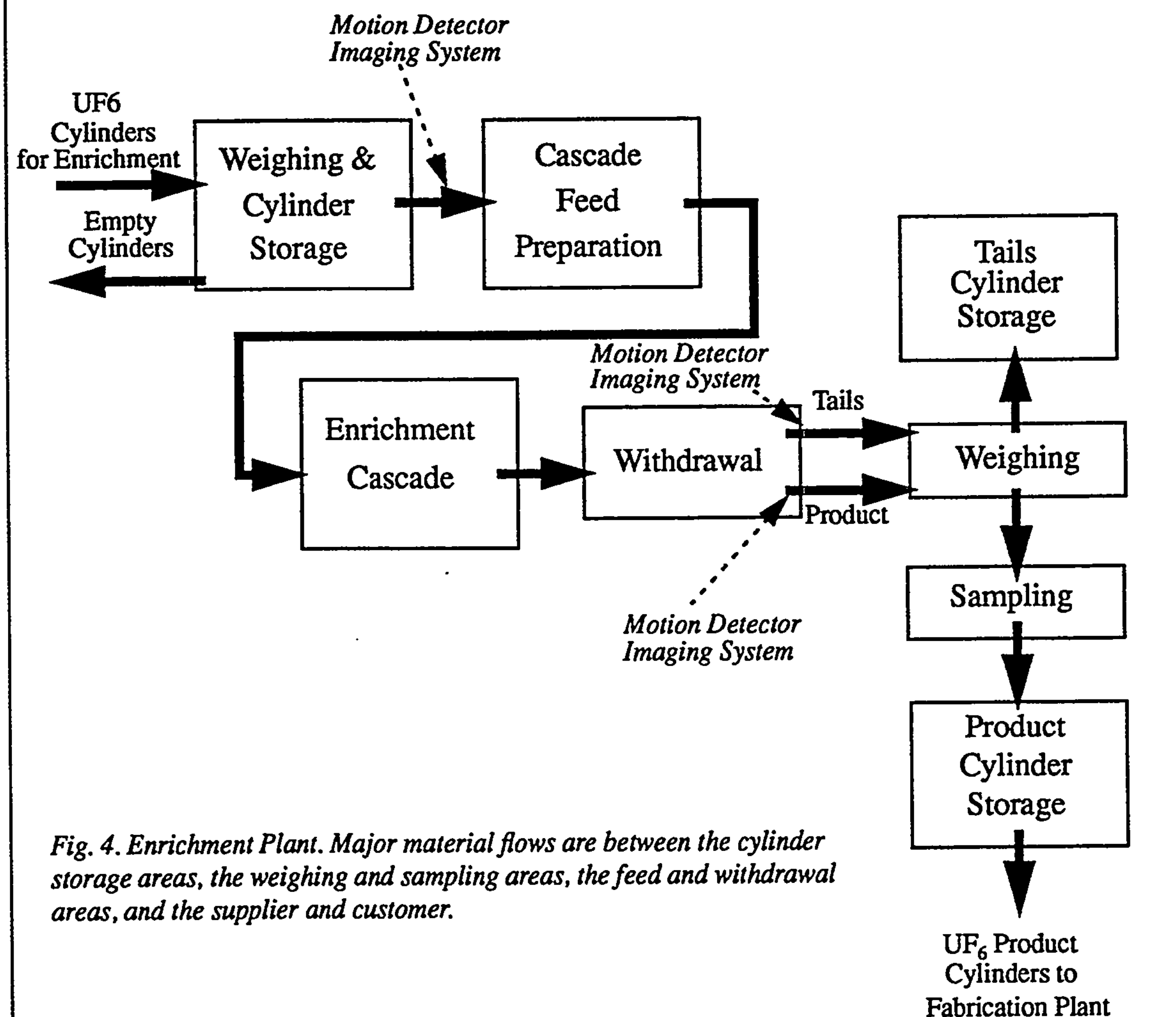

Fig. 4. Enrichment Plant. Major material flows are between the cylinder storage areas, the weighing and sampling areas, the feed and withdrawal areas, and the supplier and customer.

All the large-scale LEU enrichment plants are either based on the gas-centrifuge process or on the gaseous-diffusion process. Both processes use uranium hexafluoride. The IAEA safeguards objectives at enrichment plants are to detect diversion of significant quantities of declared materials, the production and diversion of significant quantities of undeclared enriched uranium at declared enrichments, and the production and diversion of significant quantities of enriched uranium at greater than declared enrichments.[31,32] The major flows of uranium hexafluoride entering and leaving a plant are the feed, product, and tails all in cylinders of 10 tons or more. Gaseous diffusion plants were, until recently, mostly operated by weapons states. Currently, the U. S. is the only weapons state operating a diffusion plant. One small-scale diffusion plant is operated by Argentina, which is now under IAEA safeguards.

1. Gaseous-Centrifuge Plants

a) Facility Description

The gas-centrifuge enrichment process is employed in almost one-third of the world's enrichment plants.[33] The process is based on the different centrifugal forces on molecules of different masses in a rotating cylinder. More of the heavier molecules of $^{238}UF_6$ move closer to the outside of the cylinder than the lighter $^{235}UF_6$ molecules.[34] The centrifuge is a fairly simple device, but the output of a single centrifuge is low and the gain in concentration is low also.[35] To compensate for these limitations a large number of centrifuges are arranged in cascade. Cascades employ varying numbers of centrifuges operating in parallel for a given operating range as a stage. The stages are connected in series with other stages to achieve the desired enrichment. Uranium hexafluoride is received in cylinders from conversion plants. The uranium hexafluoride is vaporized and fed into the cascade. Waste uranium hexafluoride depleted in ^{235}U is moved to the bottom of the cascade by condensing the gas into cylinders for storage. The product is removed from the top of the cascade and placed into steel cylinders for weighing, sampling, and storage before shipment to fabrication plants.

b) Current Safeguards Implementation

Centrifuge plants consist of possibly different combinations of cascades, enriching stages, and equipment that do not have a significant effect on the implementation of safeguards.

The facility accounting and operating records are examined for correctness and internal consistency. The accounting records are compared with inventory change, material balance, and any special reports sent to the IAEA by the State. The list of inventory items received for the physical inventory verification is compared for consistency with the material balance report and the associated physical inventory listing. Inventory change reports and material balance reports are compared for consistency.[29]

There is one physical inventory verification per year. The process is not shut down, so cylinders are connected to the process equipment. Both cylinders and the process equipment contain UF_6. The IAEA uses the operator's measurement system for the UF_6 in the process and on its own measurements for the UF_6 in the cylinders.[29,36] Transfers are verified at the physical inventory verification, at interim inspections approximately monthly, or as required by notification. Verification is performed before cylinders are connected to the process for receipts and before leaving the plant for shipments. At interim inspections transfers to and from the process are verified and then compared to verifications for receipts and for shipments.

c) Proposed Integrated Advanced System

Cylinders have unique identifying numbers either on a plate on the cylinder or etched on the cylinder itself. This number and a sequential serial number placed on a tag or label on the cylinder uniquely identifies each batch of material. Each cylinder forms a batch except when several cylinders are received from one shipper and identified by the shipper as one batch.

Gas centrifuges can be operated in different configurations and by procedures leading to the production of HEU or the production of more LEU than declared with the attendant diversion of the excess LEU as feed to undeclared facilities. The HEU production and the excess LEU might be detected by the use of motion detectors and imaging systems. Here the equipment would be placed where the cylinders are connected to the plant for feed, product, and tails. Comparison with the operator's records would verify what came into and left the plant.

2. *Gaseous-Diffusion Plants*

a) Facility Description

The gaseous-diffusion process is based on the principle that, on the average, lighter gas molecules travel faster than heavier gas molecules because in a gas with different types of molecules, each type of molecule has the same average kinetic energy. The lighter molecules tend to collide more often with a porous barrier than the heavier molecules. Because of the difference in the number of collisions and the many holes (pores) in the barrier, the lighter molecules will enter the holes more often than the heavier molecules. This produces a gas on the other side of the barrier that is enriched in the lighter molecules. Uranium hexafluoride gas is primarily made up of $^{235}UF_6$ and $^{238}UF_6$. The $^{235}UF_6$ molecules, on the average, are slightly faster resulting in an enrichment of $^{235}UF_6$. The amount of separation of a single stage is small so many stages are necessary to produce LEU fuel. About 4000 stages are necessary for

HEU, and the equilibrium time is 1 year.[19,25,37,38]

Gaseous-diffusion plants have a much greater in-process inventory in the cascade than in the gas-centrifuge plants of the same capacity. This in-process inventory is a major component of the overall nuclear material inventory for the plant. From experimental work at gaseous-diffusion plants,[39] we determine that a measurement of the 185.7-keV gamma ray is the best method for determining the ^{235}U in a diffuser, whereas the best method for thick-walled items is neutron techniques.

b) Current Safeguards Implementation

The gaseous diffusion plant operated by Argentina is currently shut down. Initial inventory verification activities for the Cascade Material Balance Area have been proposed. Verification experiments with NDA instruments for the process inventory in this facility have been undertaken jointly by Argentina and the United States. The IAEA has extensive experience inspecting gas centrifuge enrichment plants, but the Argentina plant is the first gaseous diffusion plant subject to international safeguards.[39] We assume the facility accounting and operating records will be examined for correctness and internal consistency similar to the examination for centrifuge plants. Likewise, we assume the list of inventory items received for the physical inventory verification will be compared for consistency with the material balance report and the associated physical inventory listing. The inventory change reports and material balance reports will also be compared for consistency.

c) Proposed Integrated Advanced System

Front end triggering for gaseous diffusion plants would be the same as for gas centrifuge enrichment plants discussed above. IAEA safeguards are applied at gas-centrifuge uranium enrichment plants for the production of LEU.

D. Spent Fuel Storage - Reactor Pond

1. Facility Description

In a typical LWR, spent fuel that is removed from the reactor must be stored underwater, usually in "baskets" for positioning and spacing. The spent fuel is stored in on-site water-cooled ponds to dissipate the heat generated by the decay of the short-half-life fission products. It is stored from 90 days to years due to lack of reprocessing capabilities (in the United States where there is no reprocessing). Spent fuel awaiting reprocessing outside the United States from LWRs and other reactors, such as fast breeder reactors (FBRs) and advanced thermal reactors (ATRs), is stored similarly but the time period is from six months to several years before being shipped to a reprocessing plant. (We do not consider the option of geologic disposal for spent fuel used in the once-through fuel cycle because no country has a licensed site. However, interim storage is needed until disposal options for spent fuel from the once-through fuel and excess spent fuel from the closed cycle are available.[40] Interim storage, either at the reactor site or away from the reactor site, has many of the same characteristics of storage in reactor ponds.) Another newer option is dry storage where the spent fuel is stored in a shielded, gas-cooled canister. The canisters can be stored at the reactor site or away from reactor.[41] (See discussion below.)

Assemblies to be removed from a storage pond are packaged in shielded containers. They are placed in these containers under water and then removed from water for decontamination and transport. During either of these transfers, either to or from the storage pond, diversion is possible. It is here, along the transport line, that the front-end triggering systems can be used beneficially.

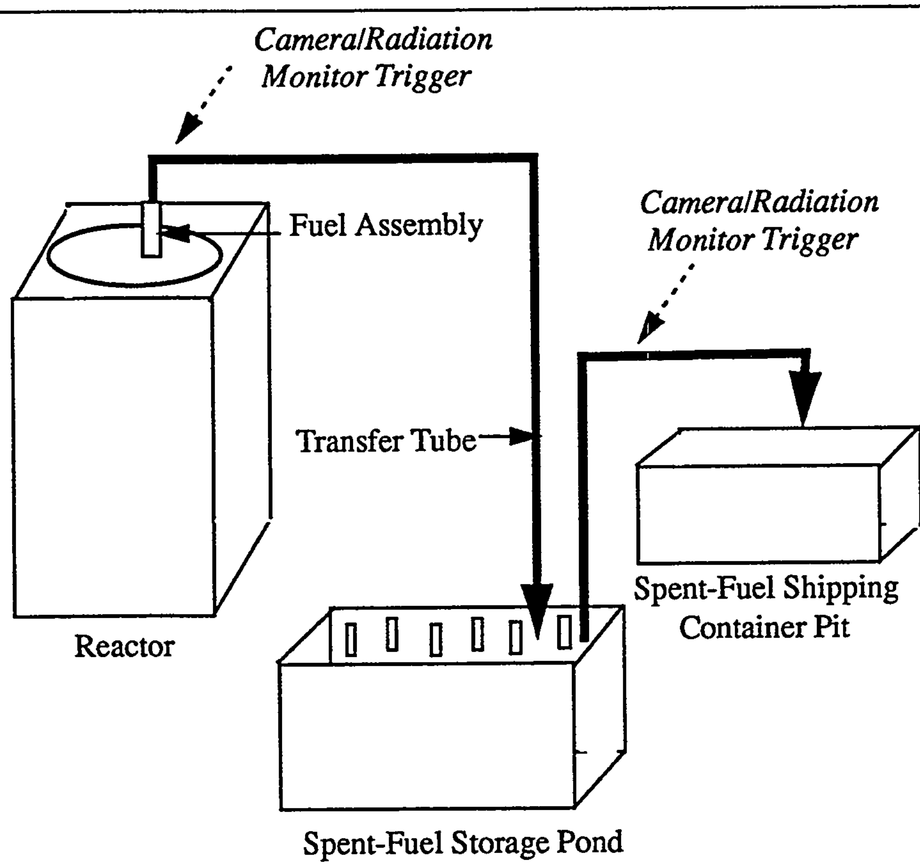

Fig. 5. Spent fuel storage pond and material transfer paths.

A sketch of a spent-fuel storage pond with the material transfer paths is shown in Fig. 5.

2. *Current Safeguards Implementation*

The IAEA uses item accountability for fuel assemblies with on-site inspections and a physical inventory verification of the operator's physical inventory once a year.

Current safeguards involves examining the following information:

- Records and reports at the facility for correctness and internal consistency. This includes accounting records (inventory changes, information related to nuclear loss and production, measurement results for physical inventory), operating records (for example, date and duration of shut-downs, date and description of dismantling operations, accident information, and actions related to physical inventories), and special reports (special circumstances such as loss of one or more fuel pins or assemblies, broken fuel assemblies, or any interference with safeguards devices)
- Physical inventory
- Flow verification
- Containment and surveillance (including the use of seals and video tape).

Further efforts involve verifying the Cerenkov glow, examining the integrity of the spent-fuel area, and reviewing optical surveillance. Records, reports of assemblies shipped, optical records, and random NDA measurements are compared.

3. *Proposed Integrated Advanced System*

Sensors such as cameras, radiation monitors, and other NDA devices placed along the transport line to and from the storage pond would allow unattended verification of inventory and transfers, thereby maintaining the continuity of knowledge of items in storage and permitting reliable item identification, thus reducing the need for inventory verification. Transfers before and during physical inventory could rapidly be identified. The inspector's presence could be reduced to random authentication activities.

The triggering could be by a radiation detector, or by the camera itself, saving images only when movement is detected or saving a pixel difference such as that described in the VTRAP technique above.

E. Research Reactor Water Channel

1. Facility Description

Research reactors, which are more numerous than power reactors, are usually situated at universities and research institutions. Fuel for these reactors differs widely because of the nature of the reactors; different procedures exist for handling the spent fuel at the various reactors. Some spent fuel is placed in interim storage and other fuel is reprocessed. Storage can be dry or in water-filled ponds. A large number of reactors are moderated and cooled by water and use a cooling pond connected to the reactor by a water channel much like power reactors. Other options include storing the spent fuel in a portion of the reactor pool dedicated to initial cooling with later transfer in shielded casks to a long-term storage pool. In some cases the spent fuel is held until the reactor is shut down and decommissioned. In many cases spent fuel was intended to be returned to the country of origin but since 1988 this has not always been possible. Thus, much spent-fuel, including HEU, is being stored in facilities not originally designed for long-term storage of spent fuel.[42]

2. Current Safeguards Implementation

Facility accounting and operating records and supporting documents are examined for correctness and internal consistency. The accounting records are compared with inventory change reports, material balance reports, and any special reports sent to the IAEA. The operator's physical inventory is verified once each year. Spent fuel under C/S is examined to verify seals. The items of spent fuel not under C/S are counted. Transfers recorded by the operator are compared to corresponding records by shippers and receivers.[29]

3. Proposed Integrated Advanced System

Systems designed for front-end triggering for spent fuel from research reactors will vary with the type of reactor. Where a channel is used for transfer to or from a reactor pond, a movement detector with an imaging system could verify declared movement or provide assurance that fuel was not moved. Where fuel is stored at the storage end of the reactor pool, a movement detector and imaging system would focus on the stored spent-fuel elements.

F. Fuel Fabrication Plants

1. Facility Description

Fuel for LWR is fabricated from natural uranium and LEU. Enriched uranium hexafluoride received from the enrichment plant is converted to uranium oxide, which is blended, milled, granulated, pressed, and sintered into ceramic uranium oxide pellets. The pellets are loaded into cladding tubes that are fitted with end plugs and sealed. The cladding tubes or fuel pins are later grouped together as fuel assemblies. The uranium oxide can also come from fuel reprocessing plants or natural uranium conversion plants. Bulk-handling plants that store large amounts of plutonium and those that produce fuel from MOX are some of the most sensitive plants from a safeguards perspective.[43]

Fuel for LWRs also can be fabricated from oxides of plutonium and uranium, which are called mixed oxides or MOX. The PuO_2 and UO_2 are blended with some recycled MOX from the process stream. MOX fuel fabrication is similar to enriched-uranium fuel fabrication. After the MOX powder is blended, it is pressed into pellets, which are processed to obtain the proper physical characteristics. The finished pellets are loaded into the fuel pins. The fuel pins are fabricated into fuel assemblies.[25,44] FBRs also use MOX fuel. We concentrate on MOX fuel fabrication plants because they are slightly more complex because of the plutonium handling.

The major material handling areas are MOX feed storage, the fuel fabrication process (pellet fabrication, pin fabrication, and assembly), and fuel assembly storage. The IAEA treats the entire plant as a single Materials Balance Area (MBA). However, each of the handling areas mentioned above can be an MBA. NDA systems were developed at Los Alamos for use in an automated MOX fabrication plant in Japan.[45,46]

2. *Current Safeguards Implementation*

The frequency of safeguards inspections varies with the type of facility. The operator's physical inventory is verified once a year for MOX, HEU, and LEU fabrication plants. MOX fuel fabrication plants have on-site interim inspections on a monthly basis and a short-notice random inspection. (LEU plants also have the short-notice random inspections.) The plant accounting and operating records and supporting documents are examined for correctness and consistency.

3. *Proposed Integrated Advanced System*

Figure 6 shows a MOX fuel fabrication plant using a Fuel Pin Assay System to monitor fuel pins moving to a storage area. For unattended operation, the counter could trigger a camera for fuel-pin tray identification.[47]

The highly automated modern Japanese plants also could be monitored at the entrance to the feed storage area and at the assembly storage output. Feed storage canisters arrive in transportation casks and are transported to the storage area by means of an automatic crane. Fuel assemblies are placed in storage capsules and transported to the assembly storage area by a remotely operated crane. The motion of the cranes could trigger imaging systems for counting and identifying items.

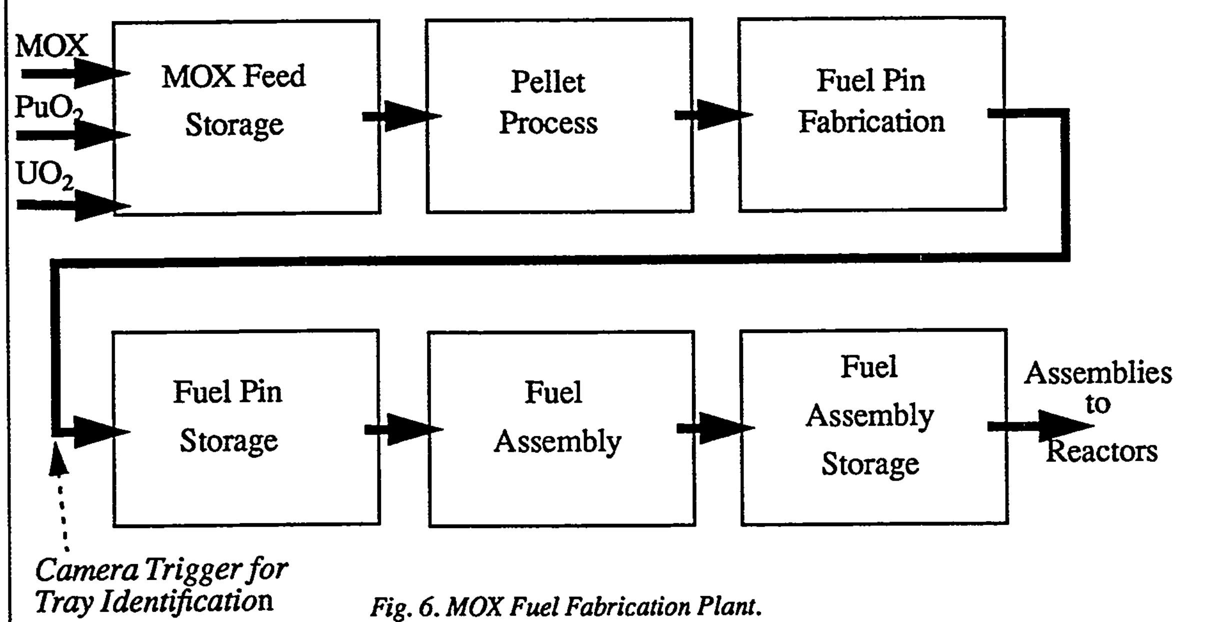

Fig. 6. MOX Fuel Fabrication Plant.

G. Dry Storage

1. Facility Description

Spent fuel has been stored dry for many years in Canada, Europe, and the United States. It is a simple method for temporary storage on-site at a reactor facility. Without dry storage, spent fuel ponds would quickly reach capacity. Dry storage is generally planned as a temporary means until the spent fuel is disposed of in some other manner or reprocessed.

There are three general categories of concepts for dry storage: steel or concrete casks, concrete vaults, and dry wells. A typical cask is shown in Fig 7. It is made of rugged steel and reinforced concrete to shield and protect the spent fuel. Casks may then be stored in an open/protected area

Vaults may consist of surface storage or underground storage, possibly including racks. Spent fuel is kept in tubes made of carbon steel that are vertically stored in a concrete vault. Each tube contains a single assembly. Once the assembly is inserted into a tube, a plug is placed on the top of the tube. We focus on the use of vaults in this discussion, with the goal of reducing inventory frequency.

2. *Current Safeguards Implementation*

The IAEA must be permitted to maintain C/S to assure that no spent fuel has been removed. For dry cask storage, the IAEA provides surveillance of the storage areas and verifies seals.

3. *Proposed Integrated Advanced System*

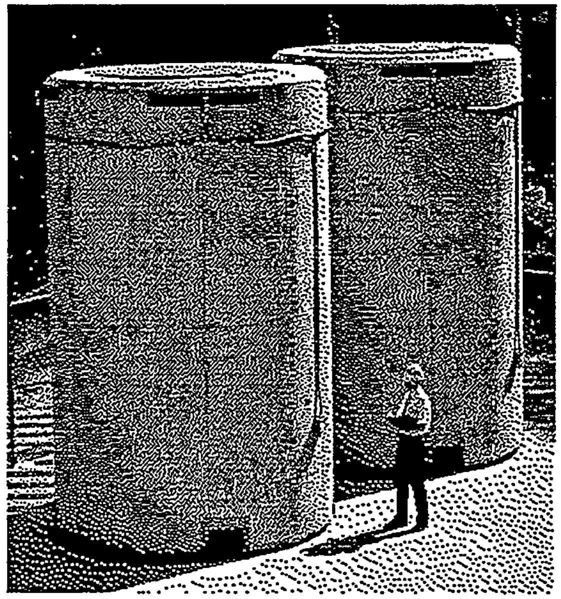

Fig. 7. Dry storage containers.

A proposed method of monitoring dry storage vaults is to place a camera, motion sensors, and radiation sensors at strategic locations in the vault. The camera would trigger on either motion or radiation, so that unexpected movements would be recorded. This would be particularly useful in those areas where movement should not be taking place at all, or very infrequently, and could also apply to geologic storage. The sensor/camera record could provide assurance that no movement has taken place and reduce the necessity for inspector visits to the area.

V. Conclusions and Recommendations

In this report we have addressed those issues surrounding front-end triggering that could provide more cost-effective safeguards and provide greater assurance of the accuracy and completeness of an inspection. We covered integration issues, analysis techniques that could be effectively applied to the data gathered by an unattended front-end triggering system, and some facility types where these measures are appropriate.

The reliability of electronic devices has increased dramatically in the last decade. This increased reliability coupled with a similar decrease in size makes front-end triggering a realistic alternative to increased inspector time for inspecting facilities. Also, the increased reliability of machine-analyzed and summarized data over the manual inspection of sensor information is not to be overlooked. Finally, the capability to compress or selectively store camera records or both augments the human reviewer's ability to correlate data from sensors with the visual record of what has occurred in a facility.

We recommend continuing this investigation of front-end triggering to include devices/systems that can be employed immediately or in the near future. Future research should also investigate the internal processes of highly automated facilities. In addition, a thorough analysis of integration methods should be conducted for unattended systems. Finally, a preliminary investigation should be undertaken for unattended monitoring for geologic disposal.

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