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**QUANTITATIVE EVALUATION OF THE
RETIMAC SYSTEM**

INTERIM REPORT

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1. INTRODUCTION

The Generic Environmental Statement for Mixed Oxide Fuel (GESMO) contains the following statement regarding the Safeguards objective, "It is judged that the objective will not be fully met for plutonium recycle by current Safeguards measures". One of the suggested means of raising the degree of protection afforded strategic special nuclear materials (SSNM) against theft and diversion is the installation of Real Time Material Control (RETIMAC) systems. The basic concepts and objectives of RETIMAC together with a broad outline describing the functions of its components are presented in a Nuclear Regulatory Commission document, "RETIMAC - A Real Time Material Control Concept for Strategic Special Nuclear Material," Working Paper B, Jan. 28, 1975.⁽¹⁾ This document is on file in the NRC Public Document Room.

The basic objectives of RETIMAC as outlined in this paper are given below:

1. To detect any covert attempt to steal special nuclear materials in a time frame that is adequate to contain subcritical quantities of special nuclear material within the boundaries of the material protection system.
2. To maintain current knowledge of the quantity and location of all strategic special nuclear material.
3. To enhance the deterrent to theft that is provided by the combined physical protection and material control and accountability systems.
4. To expedite the transition to automated special nuclear material processing, which offers inherent safeguards advantages.

If these objectives are realized, there is little argument that RETIMAC systems would significantly increase the level of protection presently afforded SSNM. In addition, the growing traffic in SSNM within the maturing nuclear power industry cannot exceed the design capacity of a RETIMAC system. The potential role of RETIMAC has been clearly stated.

The primary purpose of the present study is to test the ability of RETIMAC to attain two of its most important objectives: (1) to detect any covert attempt to steal special nuclear materials in a time frame that is adequate to contain subcritical quantities of special nuclear material within the boundaries of the material protection system; and (2) to maintain current knowledge of the quantity and location of all strategic special nuclear material. The test can be accomplished in a quantitative and unambiguous manner by methodically tracing through the required actions of a diverter (referred to as a diversion path) in a model fuel cycle facility equipped with a RETIMAC system. Specifically, the time intervals between the act of diversion and redundant alarms can be determined and compared with the time required to carry the diverted material outside the material protection system boundaries. This tests the systems ability to satisfy the first objective. Using this same model, one can also calculate the time intervals between material identification points and thus evaluate the ability of the system to meet the second objective.

The model fuel cycle plant chosen for this study is a commercial-scale mixed oxide fuel fabrication plant. Much of the model plant design is based on information contained in the Westinghouse Electric Corp. Recycle Fuels Plant License Application and Environmental Reports,^(2,3) Docket No. 70-1432. These documents are also on file in the NRC Public Document Room.

The Westinghouse plant was selected as a starting point for the model to insure that the model is representative of a commercial, high throughput operation servicing a mature plutonium fuel cycle in the 1980-1990 time frame.

The maximum design capacity of this plant is about 400 MT mixed oxide fuel per year with actual production rates estimated at 200 MT/year--enough fuel to supply 25 reactors. The high throughput expected in this plant magnifies today's task of maintaining adequate control at all times over in-process SSNM; this is exactly the type of problem which RETIMAC is designed to relieve.

For the model plant described in this interim report, two important features of a real plant have been excluded: waste and scrap recycle. Inclusion of waste and scrap recycle streams in a RETIMAC-equipped model plant is planned for the next phase of this study.

Some of the information required for the model MO_2 plant was not present in the license application documents. In this case, informed judgments by SAI participants in the study, as well as those from industrial and government reviewers, were used to fill in any gaps. It must be stated here that this effort represents an exercise to evaluate the hypothetical safeguards improvements which might be realized by incorporating RETIMAC capabilities into a real plant. In no way should the reader gain any impression that the study recommends that Westinghouse so modify their plant, that NRC endorses the specific system selected, or that NRC endorses the general RETIMAC concept.

2. COMMERCIAL PLANT MODEL

A commercial plant model based on the Westinghouse MO_2 fuel plant planned for construction at Anderson, S.C. will be described in this section.

2.1 MATERIAL FLOW RATES AND STORAGE CAPACITIES

The general process model presented earlier has been applied to a specific commercial plant model. Material flow rates for the 16 process steps and material storage capacities for the 7 storage areas are presented in Fig. 2-1. Specific attention is given to the plutonium inventory, expressed in Kg of PuO_2 , at each storage area. Information on the capacities of various containers used during processing is given also.

2.2 PROCESS STEPS

Flow charts and detailed descriptions of the 16 process steps for the commercial MO_2 fuel plant model are presented here.

2.2.1 PuO_2 and UO_2 Receiving (Process Steps 1A and 1B)

The receiving of PuO_2 and UO_2 feed material as shown in the flow chart of Fig. 2-2 is described. From receiving, the PuO_2 is delivered to PuO_2 storage and the UO_2 is delivered to UO_2 storage. The operation is designed to function smoothly and efficiently, consistent with maximum security, safety, minimal contamination, and proper materials accountability. Materials to be received on a yearly basis will be those required to produce approximately 200 MT of mixed uranium-plutonium oxide contained as pellets in fuel rods. Storage areas will be designed for protection of personnel from radiation.

**Fig. 2-1 Material Flow Rates and Storage Capacities
For Commercial Mixed-Oxide Fuel-Rod
Fabrication Plant Model**

Fig. 2-2 Feed Material Receiving And Initial Storage

All incoming shipments must be surveyed to detect the presence of surface contamination on the drums or truck body prior to unloading. In the unlikely event that some surface contamination is detected, necessary cleanup operations will be undertaken before commencing further operations. Containers are then transported on pallets by fork lift trucks or dollies to the respective storage areas.

2.2.2 PuO₂ and UO₂ Powder Storage (Process Steps 2A and 2B)

As indicated in Fig. 2-2, two separate storage areas are provided, one for each of the feed materials utilized in the manufacturing process, PuO₂ and UO₂. The PuO₂ storage can accommodate 88 L-10 containers of PuO₂. The PuO₂ is stored inside the Manufacturing Building, on the second floor level. The PuO₂ storage area is surrounded by a thick shielding wall having a shielded door permitting access for fork trucks conveying PuO₂ shipping containers to or from storage. Each shipping container will be stored within an individual location surrounded on three sides by shielding walls. The first PuO₂ packages to be stored will be placed as far as possible from the access and the first packages taken from storage will be from the location nearest to the access. In this way, radiation exposure to the fork truck operator is limited. Access to the storage area will be administratively controlled to limit radiation exposure to plant personnel and to provide the required physical security.

The L-10 is an AEC and DOT approved shipping container for PuO₂. This shipping container is shown in Fig. 2-3. Dollies fitted with motor driven screw-jacks will be used to transport the L-10 shipping container to the PuO₂ unloading station located on the second floor of the Manufacturing Building. The dollies will be capable of transporting and lifting the containers into a specific matching position within the unloading station. The

Fig. 2-3 L-10 Shipping Container For Plutonium

UO₂ will be received in 55 gallon drums which are approved for shipment of low specific activity materials. Drums of UO₂ will be moved to the UO₂ unloading area by fork truck or dolly. Powder samples for analysis will be taken during the unloading operations.

The UO₂ drum storage area is located on the second floor level in the Feed Material Building. Drums will be stacked two high within the UO₂ powder storage and unloading area. Maximum storage capacity is 150 drums.

2.2.3 PuO₂ Unloading (Process Step 3A)

The unloading of PuO₂ from L-10 containers and the delivery of PuO₂ powder to bulk storage vessels as shown in Fig. 2-4 are described. The PuO₂ unloading station is basically a three compartment shielded glove box enclosure. Each compartmental operation is described below.

1. Compartment 1

The L-10 container is moved into this compartment on a manually propelled dolly fitted with motor-driven screw jacks. The lid assembly is removed and surveyed for any potential contamination. All exposed surfaces of the open L-10 are surveyed. The bagged vermiculite is then removed and a further survey is conducted. The vent valve cover and pressure vessel flange are moved and alpha surveyed. Alpha surveys are conducted routinely on all exposed portions of the L-10 assembly although it is highly unlikely that leaks will occur with the use of inner sealed PuO₂ cans.

The L-10 assembly is then jacked up so that the top of the opened drum mates to a seal around an opening to compartment 2. When the seal is made, as observed by visual inspection, the external container of the L-10 will complete the confinement barrier. The door to compartment 1 is then closed. Compartment 1 is basically a hood assembly and contains a negative pressure with respect to the outside work area.

Fig. 2-4 PuO₂ Unloading From L-10 Containers

2. Compartment 2

A hoist clamp is manually connected to a lifting lug of a large can. This large sealed can contains two sealed cans of PuO_2 . The can assembly is lifted out of the L-10 pressure vessel, the hoist is moved along a monorail and the assembly is lowered through a port into compartment 3. After disconnecting the hoist clamp from the can assembly, the port connecting compartment 2 to compartment 3 is closed. The empty L-10 shipping container in compartment 1 is sealed and returned to storage.

3. Compartment 3

Remote handling is utilized in this compartment and is accomplished by utilization of manipulators. The large outer can will be opened using a can cutter. The two inner cans containing a total of approximately 4.5 Kg PuO_2 are individually weighed. The tops of each can are removed by a mechanical can-opener. A pneumatic transfer tube is inserted into an open can of powder and the contents are transferred to PuO_2 bulk storage vessels. When powder transfer is completed, each empty can, with lid, is reweighed to obtain a tare weight. Reweighing the empty cans allows a comparison to be made against the shipper's weights and also ensures that all the powder has been removed during transfer. Each empty can will then be cleaned to remove any residual powder adhering to the inner walls. The cleaned empty cans are checked by a gamma scanning device and transferred into a drum compacting compartment.

Provision is made in compartment 3 to occasionally sample PuO_2 . This is accomplished by withdrawing a powder sample, transferring the powder to the appropriate vial and pneumatically transferring the vial with powder to the Analytical Services Facility.

Provision is made in compartment 3 for scrap collection and recovery of clean PuO_2 for transfer to the bulk storage vessels.

2.2.4 PuO_2 Powder Storage (Process Step 4A)

The receipt and storage of PuO_2 powder from the PuO_2 unloading station as shown in Fig. 2-4 are described. Three PuO_2 bulk storage vessels

are provided to receive the powder by pneumatic transfer from the unloading station. Each vessel will be designed for a working capacity of 170 Kg of PuO_2 .

One vessel at a time will be receiving PuO_2 powder, another recently filled vessel will be awaiting analysis and the third vessel will be supplying powder in batches as required to the mixed oxide blend station. The three vessels thus provide an uninterrupted supply of PuO_2 to the fabrication operations.

While the material is being pneumatically transferred from the unloading station into these vessels, a pneumatic mixing and aerating operation is activated in the storage vessel. A low pressure dry air supply is used for this operation.

A practicable favorable-geometry vessel configuration is attained by a slab-type design augmented by (a) design limitations on reflection, and (b) incorporation of fixed poisons, as necessary. Reflection is limited by spacing any required shielding materials as far from the vessels as practical, consistent with operability and maintenance requirements. Assuming the need is confirmed by analysis of the detailed design, each vessel is surrounded by a fixed solid poison material, such as cadmium metal sheet protected by stainless steel sheet.

Instrumentation provides the capability for weighing the storage vessels, controlling air flow rates, measuring differential pressure, temperature indication, monitoring gamma radiation and utilization of level indicators and alarms to guard against overfilling a vessel. The exhaust air is taken from the top of the vessel through stainless steel sintered metal filters which retain the PuO_2 within the vessel. A short blow-back pulse of air is employed

periodically to prevent the filters from loading up with powder. A time cycle controller will be utilized to provide the blow-back pulse to all of the several filters, in sequence, in the vessel head. Thus, the normal air flow through the powder bed is not greatly affected.

2.2.5 UO₂ Unloading and Storage (Process Steps 3B and 4B)

UO₂ powder is received in sealed 55-gallon drums. The drums are weighed and placed in UO₂ storage. When production demands require, UO₂ powder is removed from the shipping drums and transferred to the UO₂ transfer hopper via a pneumatic conveyor. The UO₂ transfer hopper serves as storage for UO₂ powder outside the Restricted Access Area. The transfer hopper is equipped with a high powder level alarm to indicate when it is filled and a low level alarm to indicate that more drums of UO₂ should be introduced into the system, and a low-low level alarm that prohibits discharge of UO₂ powder from the transfer hopper. A random selection of empty drums are weighed to establish an average tare weight to confirm the shipper-receiver data.

2.2.6 MO₂ Powder Blending (Process Step 5)

The preparation of mixed oxide powder from UO₂, PuO₂ and recycled MO₂ powders, as indicated in Fig. 2-5, is described.

When a sub-blend of mixed oxide is required for production, the three component (UO₂, PuO₂ and recycled mixed oxide powder) quantities required for the batch are calculated and programmed into the batch control system. The control logic activates the proper equipment to prepare the batch. This is accomplished by first filling the feed hopper, for each component, to its high powder level, then transferring the required weight of each powder component from the respective feed hopper to its respective weigh hopper. Pre-determined quantities from each weigh hopper are transferred into the blender and the operation of the blender is initiated.

Fig. 2-5 MO₂ Powder Blending

1. UO_2 Feed Hopper Charging

UO_2 powder is transferred from the UO_2 transfer hopper to the UO_2 feed hopper, as directed by the batch control system. The following conditions and sequence of events are required for this transfer:

- The UO_2 rate feeder is off
- The high powder level detector in the feed hopper indicates that the high powder level has not been reached
- The manual isolation valve is open
- The double sequencing valve is actuated
- The unit vacuum conveyor is actuated
- The transfer hopper discharge positive shut-off valve is open
- The transfer hopper bin activator and rate feeder are actuated

All devices except the manual isolation valve, which is normally open, are actuated by the batch control system when it receives the command to charge the feeder hoppers. Transfer continues until the feed hopper high powder level detector indicates high powder level at which time the batch control system shuts down the transfer of powder, restoring all intervening automatic devices to their passive mode. The feed hopper is charged to about 120% of the powder required for one batch when the high powder level detector actuates. This powder transfer may be performed with manual controls.

2. PuO_2 Feed Hopper Charging

PuO_2 powder is transferred from one of three preselected PuO_2 storage vessels to the PuO_2 feed hopper as directed by the batch control system concurrent with the charging of UO_2 and recycled mixed oxide powder feed hoppers.

The following conditions and sequence of events are required for this transfer:

- The PuO_2 rate feeder is off.
- The PuO_2 feed hopper high powder level detector, in the feeder hopper, indicates that the high powder level has not been reached.
- The PuO_2 pneumatic conveyor is actuated.
- The isolation valve for the PuO_2 storage vessel selected is energized.
- The feeder for the PuO_2 storage vessel is energized.
- The PuO_2 storage vessel fluidizing system is energized.

Powder transfer continues until the PuO_2 feed hopper high powder level detector senses powder. This indicates that the feed hopper is charged to about 120% of the PuO_2 required for a batch of mixed oxide of maximum enrichment. When the batch control system receives the signal from the feed hopper high powder level detector, it halts the flow of PuO_2 powder from the storage hopper by restoring all devices between PuO_2 storage and the PuO_2 feed hopper to their passive modes. This powder transfer may be performed with manual controls.

3. Recycled Mixed Oxide Feed Hopper Charging

Mixed oxide powder is transferred from one of three preselected storage vessels to the mixed oxide feed hopper, as directed by the batch control system, concurrent with the charging of the UO_2 and PuO_2 feed hoppers.

The following conditions and sequence of events are required for this transfer:

- The mixed oxide rate feeder is off.
- The mixed oxide feed hopper high powder level detector, in the feed hopper, indicates that the high powder level has not been reached.
- The router valve in the discharge line of the mixed oxide storage vessel selected is positioned for flow to the mixed oxide feed hopper.
- The isolation valve of the recycle mixed oxide storage vessel selected is energized.
- The mixed oxide pneumatic conveyor is actuated.
- The feeder for the mixed oxide storage vessel is energized.
- The mixed oxide storage vessel fluidizing system is energized.

Powder transfer continues until the mixed oxide feed hopper high powder level detector senses powder. This indicates that the feed hopper is charged to about 120% of the maximum quantity required for any sub-blend of mixed oxide. When the batch control system receives the signal from the feed hopper high powder level detector, it halts the flow of powder from the storage hopper by restoring all activated devices between the storage and the feed hopper to their passive modes. The router valve remains in its last position until manually changed.

This powder transfer may be performed with manual controls.

4. Charging UO_2 , PuO_2 and MO_2 Weigh Hoppers

After the feed hoppers of all three component (UO_2 , PuO_2 and MO_2) powders are fully charged, the batch control system interlocks will permit the concurrent charging of the UO_2 , PuO_2 and MO_2 weigh hoppers upon initiation signal if the following conditions exist:

- The blender has operated since the last fill-discharge cycle of the weigh hoppers (to prevent double charging of the blender).
- The positive shut-off discharge valve on each weigh hopper is closed
- The moisture detector on each feed hopper indicates less than 1% moisture in powder.
- The weigh hopper load cell calibration cycle has been completed.

When the signal to load the weigh hoppers is received, all rate feeders are started at full speed. As each weigh hopper weighing system indicates that its hopper has received most of its scheduled material, the respective rate feeder switches to low speed and stops when the required amount of material has been received. Hopper vibrators are manually activated when required.

The basis for criticality control in the blender is that all powders contain less than 1% moisture. If the moisture detector on any feed hopper indicates the presence of more than 1% moisture in the powder it contains, the batch control system alarms and the interlocks prevent transfer. Manual clean-out via the clean-out port on the rate feeder of the affected system is required for plutonium bearing components. Rejected PuO_2 is returned to PuO_2 storage for drying. Rejected UO_2 is transported to clean scrap via the blender mill, storage silo discharge route by overriding the UO_2 discharge interlock. Manual mode of operation is required to refill the emptied weigh hopper.

5. Charging and Operating the Blender

After the charging of the weigh hoppers is complete, an operator action is required before the batch control system will permit discharge into the blender. In addition, blender charging can be initiated only if the

three weigh hoppers each possess the desired weight of powder that had originally been programmed into the batch controller.

The blender charging sequence consists of first aligning the blender inlets with and then connecting them to the UO_2 and recycled MO_2 weigh hopper outlets. Interlocking controls prevent discharge of any component if the match points are not aligned.

The contents of the UO_2 and mixed oxide weigh hoppers are discharged by gravity into the blender when the weigh hopper discharge valves and blender inlet valves are opened. Weigh hopper vibrators are manually actuated when required. When all UO_2 and mixed oxide have passed into the blender, the hopper vibrators are deactivated, the hopper discharge and blender inlet valves are closed and the UO_2 and mixed oxide hoppers are disconnected from the blender.

The blender is rotated 180 degrees to align the blender PuO_2 inlet with the PuO_2 weigh hopper outlet, and the blender inlet is connected to the hopper outlet. As previously noted, an operator action is required to initiate discharge, and interlocking controls prevent discharge under conditions of misalignment of match points.

The PuO_2 in the PuO_2 weigh hopper is discharged by gravity into the blender when both the PuO_2 hopper discharge valve and the blender inlet valve are opened. After all the PuO_2 has passed from the weigh hopper into the blender, the hopper agitator is deactivated, the blender inlet valve and the hopper outlet valve are closed, and the hopper is disconnected from the blender. The blender cannot be operated unless the valve position indicators show that the valves are closed. This completes the blender charging operation.

To initiate the blending operation, the blender drive motor and the blender intensifier motor are energized. The blender operates for a predetermined number of revolutions, then shuts down. The blender is then gamma scanned by a fixed probe. Successive readings are taken by revolving the blender a full revolution and re-scanning to verify that the blend is uniform. At the completion of the blending cycle, the blender is aligned with the reduction mill inlet for discharging to one of nine MO_2 storage silos.

2.2.7 MO_2 Powder Storage (Process Step 6)

This system receives, mills, samples, and stores sub-blends of mixed oxide powder released from the blender. Sufficient storage is provided so that powder is available at the rate required by downstream processing.

When a sub-blend of mixed oxide powder is uniformly blended and ready for release from the blender, one of nine mixed oxide silos is selected for storage. The router valves in the pneumatic conveyor which route the powder from the powder reduction mill are positioned for flow to the selected silo. The blender discharge is aligned and coupled with the reduction mill feeder. The blender discharge valve is opened and the reduction mill drive and the mill feeder drive are actuated for a time interval, as required to completely empty the contents of the blender and mill. The discharged milled mixed oxide powder is transferred to the silo via the pneumatic conveyor. The completion of the powder batch transfer is confirmed by the indication of a weigh cell system which is part of the silo. This weigh cell system indicates the tare weight of the silo assembly when empty and the gross weight of the silo and powder when the silo is full.

2.2.8 MO₂ Pelletizing (Process Step 7)

The processes involved in producing pellets of MO₂ from MO₂ powder, as shown in Fig. 2-6, will be described. The operation includes compaction, granulation, size classification, pellet pressing and loading of pellets onto boats. The incoming feed is a 225 Kg sub-blend of MO₂. The products are green pellets for sintering.

1. System Control

Once activated, all the pellet fabrication equipment in this system operates continuously with high/low level detectors in the pellet press feed hopper being the principal control activators. Interlocks with the pellet press controls cascade forward to the boat loader and boat handling devices and backward to the classifier and granulator. The granulator supply hopper provides for limited surge accumulation and high/low level detectors contained therein control the on/off cycle of the slug press. The slug press supply hopper contains four level detectors and is fed from two sources; powder from a powder storage silo, and recycle fines from the classifier. When the slug press is running, the recycle fines are returned automatically unless the high-high level detector in the slug press feed hopper is activated. This is an abnormal condition and the signal causes shut down of the pneumatic conveyor from the classifier. The transfer of powder from the storage silo is on demand as controlled by the high/low level detectors. The remaining low-low level detector alerts the operator that more feed is required. The pellet press has a similar low-low level detector with shut-down interlocked controls.

When the slug press requires material, a powder storage silo of released powder is selected. The router valve in the transfer line is positioned to permit transfer from the silo to the slug press feed hopper.

Fig. 2-6 MO₂ Pelletizing

Once the pneumatic transfer system has been activated and powder is being transferred, the slug press can be started, which in turn starts the granulator and classifier. During this time the pellet press would continue to operate until its feed hopper reaches its low level.

2. Compaction

When the slug press operates, it feeds powder into a die and compacts it into short wafers called slugs. The slugs are conveyed to the granulator feed hopper by a mechanical conveyor.

3. Granulating and Classifying

The slug conveyor granulator, and classifier run in response to demand from the pellet press. Slugs, are broken into granules. The resulting granules are passed through the classifier, which screens them into over-size, acceptable sizes, and undersize particles. The over-size granules indicate a broken screen. They are collected as dirty scrap. The acceptable granules are transferred by a pneumatic conveyor to the pellet press feed hopper. The undersize granules are returned to the slug press feed hopper via a pneumatic conveyor.

4. Pressing Granulated Mixed Oxide into Pellets

Granulated powder is fed from the pellet press feed hopper into dies in the pellet press where it is pressed into pellets of a uniform density and size. The pellets are discharged to the boat loader. The level of granules in the feed hopper of the pellet press controls the classifier and granulator stopping them on high level and starting them on low level.

Rejected pellets are collected in a weight monitored scrap container and sent to the clean scrap feed hopper.

5. Pellet Inspection

As pellets are being transferred from the pellet press to the boat loader, samples are extracted from the flow and checked for density. After inspection these sample pellets are put with the pellet press rejects.

6. Boat Loading

Empty boats arrive at the boat loading station from the sintering furnace complex. Pellets from the pellet press are stacked in an empty boat. The control system stops the pellet press if no empty boats are available or in the event the loader fails to discharge a full boat. Loaded boats are conveyed to a green pellet boat transfer station where the boat is picked up and placed in green pellet storage by a boat stacking and retrieving machine.

2.2.9 Green Pellet Storage (Process Step 8)

The green pellet boat storage unit is designed to be serviced by the green pellet stacking and retrieving machine. The storage unit is designed such that boats must be stored only in specific locations which form an array of slabs of favorable geometry. Its maximum normal inventory of MO_2 pellets is less than a critical mass.

The stacking and retrieving machine receives pellet boats from the full boat conveyor and loads them into the storage shelves. It retrieves a boat from storage and places it on a transfer station from which it is removed by a shuttle car. Its operation is automatic with manual override. The maximum hold-up of mixed oxide in this machine is less than a critical mass.

2.2.10 Pellet Sintering (Process Step 9)

The processes involved between the release of green pellets from green pellet storage to the storage of inspected sintered pellets, as shown in Fig. 2-7 are described.

1. Sintering

A boat loaded with green pellets is automatically removed from green pellet boat storage and placed on the shuttle car pickup station. The boat is then picked up by Shuttle Car I and automatically transported to one of five furnaces as furnace space availability and production demands dictate. Each furnace has space for storing 3 boats of green pellets outside the furnace, on the entrance feed conveyor. Upon demand, boats are conveyed individually into the furnace entrance air lock. The furnace operates at approximately 1700°C in a reducing atmosphere of forming gas (about 6% hydrogen and 94% nitrogen) at 2 in. to 4 in. w.g. above ambient pressure.

The air lock is purged with forming gas whenever a boat is inside. The boat remains in the air lock resting on the air lock conveyor until it is required in the furnace. Upon command from the furnace control system, the inner door of the air lock opens and the boat moves from the air lock conveyor on to the Preheat Section conveyor. The inner air lock door is then closed. The boat moves forward on the Preheat Section conveyor until it is engaged by the walking beam conveyor. The walking beam conveyor then advances the boat through the heating section of the furnace in timed incremental steps. At the far end of the furnace the boat leaves the walking beam to be moved by the cooling section conveyor. The cooling section conveyor moves the loaded boat through the cooling section to the exit air lock conveyor in the exit air lock. On command, the inner door of the exit air lock closes, the outer door of the air lock opens and the boat moves out of the air lock onto

Fig. 2-7 MO₂ Pellet Sintering

the exit conveyor. Forming gas is introduced into the exit airlock whenever a boat is inside. When the boats reach the exit conveyor, they are sufficiently cool that no safety problems occur.

The entrance feeders of all furnaces are located within restricted access enclosures having glove ports and view windows for access to equipment and components.

2. Density Inspection

All boats of sintered pellets discharged from any furnace are transported to the sintered pellet density inspection station by Shuttle Car II. The density of selected pellets is measured and the data used to determine the disposition of pellets. Pellet density is determined from the inverse of the volume/weight ratio.

3. Disposition of Inspected Pellets

Boats of under-fired (low density) pellets are transported to the under-fired pellet boat conveyor system via Shuttle Car II to await re-sintering when furnace space is available.

Boat loads of acceptable pellets are transported to the sintered pellet storage to await release to the pellet grinder as production demands require. Shuttle Car II delivers the boat from the inspection station to storage.

Boat loads of over-fired pellets are transported to the rejected pellet boat conveyor system by Shuttle Car II. This system also transports the boats to the reject pellet boat dumper, where the rejected pellets are dumped into a container for transport to clean scrap. The empty boats are collected and placed on the empty boat return conveyor.

2. 2. 11 Sintered Pellet Storage (Process Step 10)

The sintered boat pellet storage is a shielded enclosure having storage racks or compartments with a capacity to store approximately 135 loaded pellet boats.

The stacking and retrieving machine is a device with a capacity of only one pellet boat. It receives pellet boats from Shuttle Car II and loads them into the storage shelves. It retrieves a boat from storage and places it on a sintered pellet boat conveyor for transfer to the boat unloader. Its operation is automatic with manual override. The maximum hold-up of mixed oxide in this machine is less than a critical mass.

2. 2. 12 Pellet Grinding (Process Step 11)

As indicated in Fig. 2-8, the system takes sintered pellets from the sintered pellet storage area, surface grinds them to specified diameter, inspects them and loads them into trays.

1. System Control

Each of the two processing lines is controlled and operates independently. All processing operations from the pellet boat unloading through tray storage operate simultaneously. Control interlocks are provided to prevent pile-up of material between equipment items. Once activated the whole line operates continuously unless interstation capacity becomes completely filled or no empty trays are available at the tray loading station. The primary control source is this tray loading device. Upstream of this unit the pellets travel in single file between the processing stations via separate legs of the conveyor. In this section the control interlocks stop the transfer of pellets, but allow the individual equipment units to operate. Downstream

Fig. 2-8 Pellet Grinding

of the tray loader the equipment is interlocked in such a manner that tray transfers can be made only when space is available.

The stacking and retrieving mechanism is operated via a storage programmer. Programming and data are stored in the control memory. Information on the storage address of each tray together with the pellet tray weight, and powder blend identity are stored in the memory for inventory and retrieval purposes. Individual tray retrieval and transfer to the sampling station is initiated by operator input to the storage programmer.

The grinder coolant supply and sludge recovery system operates continuously whenever the grinder is running. This system is interlocked to stop an individual grinder when lack of coolant flow to that grinder exists.

The operators view the lines by means of a remote controlled TV camera strategically located in the Restricted Access Area and TV monitors located at the consoles. Because of the need to shield, shroud or enclose certain equipment it is not possible to obtain complete viewing, therefore monitoring by electric, pneumatic, photo-optical or mechanical means must be used to indicate conditions in selected areas.

2. Receiving Pellets

Boats loaded with QC released sintered pellets are removed from storage by a stacking and retrieving machine and are conveyed to a router which directs them to either processing line, at the option of the operator. A boat unloading device in each line transfers pellets from the boat, aligns them and directs them to a single-file conveyor which carries pellets to the grinder. Broken pellets and chips are removed from the boats after transfer and collected in scrap cans for transfer to the Clean Scrap Recovery System (CSRS).

3. Grinding Pellets

The conveyor delivers pellets in single file to the grinder. Stopping of the grinder automatically stops the feed of pellets from the boat unloader so that excess pellets cannot flood or jam the system.

The grinders are commercially available units that use water for coolant. The water is pumped from a settling tank to the wheels of both grinders, collected, and pumped back to the settling tank.

The sludge settling tank has sufficient volume to permit sludge to settle out. The tank is mounted over an alarmed, drip pan capable of retaining all the water in the system in case of leakage. The settled sludge, or slurry, is pumped to a continuous dryer where the water is evaporated. The dried grinder sludge is collected in cans, which are tightly covered, and transported mechanically to a pick-up point for transfer to the CSRS.

Make-up water is added upon demand from a level controller that is activated from a level sensor located in the settling tank. Overflow or leakage into the drip pan activates an independent sensor which shuts off the supply and prohibits flooding of the area.

4. Surface Drying of Pellets

Surface water is removed from the pellets by drawing air, at high velocity, over them as they exit the grinder.

5. Dimensional Checking

The dimensional check station checks the diameter of pellets. This station rejects oversized diameter pellets and directs them to a collection container for transfer back to the grinder for regrinding. Undersized, pellets are routed to a clean scrap collection container. Acceptable pellets are conveyed to the chip inspection station. Pellets move from station to

station in single file. Rejected pellets are taken in a container to clean scrap recovery.

6. Nick Inspection Station

Pellets are inspected for nicks, cracks or breakage.

Acceptable pellets are conveyed in single file to the pellet tray loading station. Pellets with defects are rejected and fed to a clean scrap collection can. When full, the container is closed and mechanically transferred to the CSRS.

7. Pellet Tray Weighing

A tare weight is recorded after transferring an empty tray to the tray loader and gross weight is recorded just before transferring from the tray loader. Each tray weight is identified with a specific tray.

8. Tray Loading

Pellets are mechanically conveyed from the nick inspection station and automatically loaded onto storage trays. The pellets are placed in grooves in the trays. One groove is loaded, then the loader indexes the tray to bring the next groove into the loading position. When a tray is fully loaded, it is transferred to the pellet dryer conveyor. Empty trays are mechanically transferred to the Loading Station to permit continuous loading of pellets onto storage trays.

A tray holds approximately 900 pellets. The trays are used to facilitate handling, storage, retrieval and identification of pellet groups in the storage units.

2 2.13 Pellet Inspection and Storage (Process Step 12)

The inspection and storage of the finished pellets, as shown in Fig. 2-9, is described. After the pellets leave the pellet loading and tray weighing stations they are conveyed in a powered roller conveyor into the pellet dryer section of the pellet storage unit.

Interlocks prevent the movement of a tray forward unless the space for it is available.

Conveying terminates at a transfer point outside the drying compartment, but within the storage unit. A stacking and retrieving mechanism then picks up the tray, and places it into a specific storage space in the storage unit.

Tray loads of pellets are placed in one of two storage units where they are held until released for rod loading.

The stacker takes trays of acceptable pellets and places them on a transfer station within the storage unit for transfer to the tube loading station.

After a tray is unloaded, it is returned to this transfer station where it is picked up by the stacker and delivered to the empty tray conveyor within the storage unit.

The storage units have a total capacity for 888 trays of mixed oxide pellets.

The two storage units are connected by a cross conveyor which also services an inspection and sampling station.

Pellets are released for loading into tubes. Pellets with more than the maximum allowable moisture content are returned to the dryer for re-cycle. The rejected pellets are collected in clean scrap containers and returned to the CSRS.

Fig. 2-9 Pellet Inspection And Fuel Rod Loading

2.2.14 Fuel Rod Loading (Process Step 13)

The loading of finished pellets into fuel rods, as shown in Fig. 2-9, is described. The process operations include the receipt of tubes with welded bottom plugs, springs, and top plugs, the receipt of inspected sintered pellets and the delivery of loaded fuel rods to post weld storage prior to fuel rod inspection.

1. Loading Tubes

Batches of empty tubes, with bottom plugs welded in place, are received from storage. These batches are placed in one of the two tube loading enclosures. Tubes are loaded with pellets by positioning the upper end of the tube through a sealed port and locking it in place. A tray of pellets is removed from storage by the stacker and is placed on the tray support adjacent to the loading fixture. A row of pellets on the tray is aligned with the loading fixture and mechanically pushed into the tube. This operation is repeated until the tube has received a specified number of pellets.

2. Decontamination

The tube is removed from the port seal, placed in the decontamination station and the open end of the tube is decontaminated. Following decontamination the rod surface is checked with an alpha monitor to verify the removal of any contamination. If the rod cannot be decontaminated to within specified limits, the end is sealed with a suitable plastic bag which is taped in place, and the rod is sent to rod repair and dismantling station.

3. End Plug Pressing

The decontaminated tube is removed from the decontamination station and placed in the top end plug pressing station, a spring is inserted into the rod and a top end plug is pressed into place.

4. Girth Welding

The assembled rods are removed from the tube loading enclosure and transferred to the rod welding enclosure via a shielded carrier. The rods are placed in the pre-weld storage section of the welding enclosure. One rod at a time is positioned in the girth welding machine. When the girth weld is completed, the weld is visually inspected and if acceptable, the rod is transferred to the pressure welding machine and positioned in the chamber. The machine pressurizes the chamber with helium gas and the rod is seal welded. The weld is visually inspected, and the rod is transferred to the post-weld storage section of the glove box, where the rods are collected on carriers. The carrier is transferred to an air lock. The air lock is located in the wall between the Manufacturing Building and the Rod Inspection Building. The carrier is passed through the air lock into the rod inspection area and stored until ready for testing and inspection.

2.2.15 Fuel Rod Inspection (Process Step 14)

This system, as indicated in Fig. 2-10, receives loaded and sealed rods and inspects them for conformance with production specifications. Acceptable rods are stored and packaged for shipment. Rejected rods are transferred to the Fuel Rod Repair Station for dismantling and recovery of MO_2 pellets.

1. Leak Test

Rods to be tested are removed, from the Air Lock and Pre-inspection Storage, in groups and are placed in one of two vacuum chambers. A vacuum is pulled in the chamber, and the exhausted air is checked with a mass spectrometer to detect the presence of helium. A small leak in a rod is detected by traces of helium in the evacuated air and is cause for rejection of the rod.

Fig. 2-10 Fuel Rod Inspection, Storage and Shipping

2. Gamma Scan

Rods are gamma scanned individually to verify that pellets are of uniform composition, and that no pellets are missing. Rejected rods are collected and sent to the Rod Repair Station for repair or scrapping.

3. X-Ray Examinations

The top plug welds of loaded rods are x-rayed in groups to examine the weld integrity. The bottom plug welds on empty tubes are x-rayed in the same manner.

After being x-rayed, rods and tubes go into hold storage until the radiographs are evaluated. Rejected rods or tubes are sent to their own respective rework areas where they are salvaged or scrapped, depending on the nature of the flaw.

4. Physical Inspection

Rods are given a final inspection manually and visually, for straightness, quality of welds, for dimensional check of diameter and length and are weighed. They are inspected one at a time to minimize operator exposure to radiation. Rejected rods are sent to rod repair for rework or scrapping. Accepted rods go to a hold storage to await shipment.

2.2.16 Fuel Rod Storage (Process Step 15)

After final inspection, the fuel rods are placed in one of four shielded storage compartments. Each pair of compartments is arranged so a stacker operating in a center aisle can store or retrieve channel carriers containing rods on modular racks located on both sides of the aisle. When carriers enter or leave the storage area, a shield door automatically uncovers an

opening at one end of the aisle to allow pass-through. The storage area has shield doors at one end to permit installation and removal. Ventilation air is supplied to the storage area to remove autogeneous heat.

2.2.17 Fuel Rod Shipping (Process Step 16)

Rods to be shipped are removed by shielded carrier from storage and are transferred to shipping boxes. When a shipping box has been filled with approximately 200 rods, it is closed and transported to the loading area. There it is lifted by crane and placed inside the shipping container. A second loaded shipping box is also placed in the shipping container. The container is closed and sealed and then is lifted by crane and placed on to the bed of a truck waiting in the truck well. Health Physics surveys are made prior to shipment.

2.3 PHYSICAL LAYOUT

The overall physical layout of the process area for the commercial MO_2 fuel plant model is shown in Fig. 2-11. The locations of the 16 process steps are shown in this figure. As for the planned Westinghouse MO_2 fuel plant, this model features feed material receiving at the second floor level. Process Steps 1 through 6 are performed on the second floor levels of the feed material building and manufacturing building. More detailed physical layouts of these process steps are shown in the top and side view given in Figs. 2-12 and 2-13. Process Steps 7 through 16 are performed on the first floor levels of the manufacturing building and rod inspection building. Top and side view of the physical layouts for these process steps are given in Figs. 2-14 and 2-15.

Fig. 2-11. Physical Layout of Process Area for Commercial MO₂ Fuel Plant Model

1. RECEIVING DOCK
2. EQUIPMENT AIR LOCK
3. UO_2 STORAGE IN DRUMS
4. UO_2 UNLOADING AREA

Fig. 2-12. Top and Side Views of Feed Material Building for Commercial MO_2 Fuel Plant Model

Fig. 2-13. Top and Side Views of 2nd Floor Manufacturing Building for Commercial MO_2 Fuel Plant Model

Fig. 2-14. Top and Side Views of 1st Floor Manufacturing Building for Commercial MO_2 Fuel Plant

1 FUEL ROD AIR LOCK	10 INSPECTED ROD STORAGE
2 He LEAK TEST VACUUM CHAMBER	11 BOX LOADING TABLE
3 GAMMA SCAN STATION	12 MOTORIZED TRANSFER DOLLY
4 PRE X RAY STORAGE	13 SHIPPING CONTAINER
5 X RAY WELD INSPECTION	14 TRUCK WELL
6 POST X RAY STORAGE	15 TUBE & BOTTOM PLUG RECEIVING
7 WEIGHING & PHYSICAL INSPECTION	16 BOTTOM PLUG WELDING
8 TRACKS	17 PRE X-RAY STORAGE
9 SHIELDED CARRIER	18 X-RAY WELD INSPECTION
	19 POST X RAY STORAGE

Fig. 2-15. Top and Side Views of 1st Floor Fuel Rod Inspection Building for Commercial MO_2 Fuel Plant Model

3. INTEGRATION OF RETIMAC WITH COMMERCIAL MO₂ FUEL PLANT MODEL

3.1 PLANT STRUCTURE FOR RETIMAC

The integration of a RETIMAC system with the model MO₂ fuel plant begins with dividing the plant operation into separate process modules. Each process module contains the following elements:

- Buffer Storage
- Process Stage
- Assay Station

The process modules have been defined according to the specifications laid out in Working Paper B.⁽¹⁾ They are defined in such a manner as to take maximum advantage of material storage locations and groupings of process operations which have been designed on the basis of "good practice for manufacturing and process control." The theoretical plant structure for RETIMAC is illustrated in Fig. 3-1 (taken from Working Paper B). The actual structure for the model plant is given in Table 3-1. The physical layout of the process modules is shown in Fig. 3-2.

The remainder of this section will focus on three principal aspects of a RETIMAC system:

- Material Handling
- Measurements
- Information Processing

Some features of the existing MO₂ fuel plant model that are used directly for generating prompt theft indicators will be described. The most important of these are the access barriers and weight measurements. However, most of

Fig. 3-1 Plant Structure For RETIMAC

TABLE 3-1. RETIMAC PROCESS MODULES

PROCESS MODULE		BUFFER STORAGE	PROCESS STAGE	ASSAY STATION
NUMBER	NAME			
I	PuO ₂ RECEIVING		TRANSPORTATION OF PuO ₂ IN L-10 SHIPPING CONTAINERS TO MO ₂ FUEL PLANT	L-10 CONTAINER WEIGHT (GROSS) PASSIVE n+γ NUCLEAR ASSAY
II	PuO ₂ UNLOADING	PuO ₂ STORAGE IN L-10 SHIPPING CONTAINERS (88) - VAULT STORAGE -	UNLOAD PuO ₂ FROM L-10 SHIPPING CONTAINERS	PASSIVE γ NUCLEAR ASSAY CAN WEIGHT (GROSS AND TARE)
III	MO ₂ POWDER BLENDING	PuO ₂ POWDER STORAGE IN VESSELS (3 X 170 Kg) - VAULT STORAGE -	BLEND PuO ₂ , UO ₂ , AND RECYCLED MO ₂ , MILL BLENDED MIXTURE	PASSIVE n+γ NUCLEAR ASSAY HOPPER WEIGHT (GROSS AND TARE) VESSEL WEIGHT (GROSS AND TARE) FISSILE CONTENT ASSAY (SAMPLE)
IV	MO ₂ PELLETIZING	MO ₂ POWDER STORAGE IN SILOS (9 X 225 Kg)	PRESS SLUGS, GRANULATE, CLASSIFY TO SIZE, PRESS PELLETS, LOAD PELLET BOATS	SILO WEIGHTS (GROSS AND TARE) FISSILE CONTENT ASSAY (SAMPLE) Am γ SCAN OF PELLETS BOAT WEIGHT (GROSS AND TARE)
V	PELLET SINTERING	GREEN PELLET STORAGE IN BOATS (58 WITH 900 PELLETS EACH)	SINTER PELLETS	BOAT WEIGHT (GROSS AND TARE)
VI	PELLET GRINDING	SINTERED PELLET STORAGE IN BOATS (135 WITH 900 PELLETS EACH)	UNLOAD BOATS, GRIND PELLETS, LOAD PELLET TRAYS	BOAT WEIGHT (GROSS AND TARE) Am γ SCAN OF PELLETS TRAY WEIGHT (GROSS AND TARE)

TABLE 3-1. RETIMAC PROCESS MODULES (CONT'D.)

PROCESS MODULE		BUFFER STORAGE	PROCESS STAGE	ASSAY STATION
NUMBER	NAME			
VII	FUEL ROD LOADING	FINISHED PELLET STORAGE IN TRAYS (888 WITH 900 PELLETS EACH)	LOAD FUEL RODS, DECON RODS, CLOSE ENDS, PRESSURIZE, WELD	TRAY WEIGHT (GROSS AND TARE) ROD WEIGHT (GROSS) Am GAMMA SCAN TO MEASURE ACTIVE LENGTH OF RODS
VIII	FUEL ROD INSPECTION	PRE-INSPECTION FUEL ROD STORAGE (200 RODS)	LEAK TEST, X-RAY WELD INSPECTION, FISSILE CONTENT, PHYSICAL INSPECTION, LOAD IN/O CHANNELS	PELLET-BY-PELLET FISSILE SCAN TOTAL FISSILE CONTENT OF RODS, ROD WEIGHT (GROSS) CHANNEL WEIGHT (GROSS AND TARE)
IX	FUEL ROD SHIPPING	FINISHED FUEL ROD STORAGE IN CHANNELS (176) -VAULT STORAGE-	CHANNELS LOADED INTO SHIPPING BOX AND CONTAINER, SHIPPING CONTAINERS LOADED ONTO TRUCK	CHANNEL WEIGHT (GROSS)

Fig. 3-2. Physical Layout of Process Area for Commercial MO₂ Fuel Plant Model

this section will deal with changes needed in the existing plant model to implement a RETIMAC system. Special attention is given to the requirements for nuclear assay measurements.

3.2 MATERIAL HANDLING

Implementation of a plutonium containment philosophy for the existing plant model has resulted in the definition of three physical zones within the manufacturing building where all powder and pellet process operations occur. These zones are:

- **Restricted Access** - Houses equipment containing plutonium.
- **Limited Access** - Provides sampling and maintenance access to the restricted access zone.
- **Normal Access** - Contains operational controls and is the normal personnel flow zone.

The access barriers associated with the restricted and limited access zones are a necessary part of a RETIMAC system. Access barriers for these two zones, which are already planned for in the existing plant model as shown in Figs. 3-3 and 3-4, generate important prompt theft indicators.

An operational feature, which is already included in some form for the existing plant model, deals with transmittal of a shipping manifest to the MO_2 fuel plant prior to the arrival of PuO_2 feed material. This shipping manifest, will include data on container identifications, gross container weights, net PuO_2 weights, isotopic compositions and nuclear assay measurements. This manifest should be received and verified by the RETIMAC computer before PuO_2 feed material is unloaded at the receiving dock.

The principal changes needed for material handling may be categorized as follows:

Fig. 3-3. Top and Side Views of 2nd Floor Manufacturing Building for Commercial MO_2 fuel Plant Model

Fig. 3-4. Top and Side Views of 1st Floor Manufacturing Building for Commercial MO_2 Fuel Plant

1. Physical Barriers

A physical barrier is needed in the rod inspection building to keep fuel rods separated from empty tubes.

2. Material Containers

- A. All containers (i.e., shipping containers, boxes, cans and drums, boats, trays, channels and fuel rods) need automatically readable identifications. Real-time container identification by optical devices would supplement other measurements and would improve inventory control.
- B. The channels should be modified to permit them to be used as sealed inner shipping containers. This would permit the fuel rods to be loaded immediately after physical inspection and weighing into a channel which could then be closed, sealed and weighed prior to vault storage. After vault storage, the sealed channel could be loaded into a shipping box with only a gross weight measurement, seal check and alpha survey performed prior to loading.
- C. The L-10 containers may be modified to permit better nuclear assay measurements.

3. Container Seals

The L-10 containers and the modified channels need automatically readable seals.

4. Material Transfer

- A. Secure conveyors are needed at four locations.
 - Receiving dock to storage vault for PuO₂ in L-10 containers.
 - Storage vault for PuO₂ in L-10 containers to PuO₂ unloading station.
 - Tube loading enclosure to rod welding enclosure.
 - Rod welding enclosure to air lock used for pre-inspection storage.

- D. Surveillance of pellet sampling is needed at the inspection stations for green-pellet density, sintered pellet density and finished-pellet moisture content.

5. Material Storage

- A. Position indicators or locators are needed at each storage location for:

- PuO₂ in sealed L-10 containers (88)
- Green-pellet boats (58)
- Sintered-pellet boats (135)
- Finished-pellet trays (888)
- Fuel rods in sealed channels (176)

Real-time monitoring of these locators would provide verification of container positions during storage.

- B. First-In-First-Out (FIFO) material handling is recommended at all storage locations to prevent long storage times for any materials.
- C. The three 170-kg storage vessels for PuO₂ powder should be replaced by fifteen 20-kg storage vessels. This would reduce the total PuO₂ powder inventory at this process step while still maintaining a week's supply. Also, the smaller storage vessels would permit weight measurements to be made with smaller mass uncertainties for any one vessel and hence smaller total mass uncertainties. In addition, this storage area should be equipped with security devices which qualify it as vault storage.

In addition to the above changes, the measurements described in the next section require two new features.

1. An extra compartment and air lock are needed in the PuO_2 unloading station for calorimetry measurements which should be made in a powder-free area.
2. A 3-kg weigh hopper is needed between the PuO_2 unloading station and the PuO_2 powder storage to verify the amount of PuO_2 powder transferred to one of the storage vessels.

Some of the above changes have been incorporated in the physical layout for the MO_2 fuel plant model. These revised layouts are shown in Figs. 3-5 through 3-8.

3.3 MEASUREMENTS

3.3.1 Types of Measurements

The following 8 types of real-time measurements lead to the generation of theft indicators and inventory data for the RETIMAC system used for this study:

- Container Identifications
- Seal Checks and Alpha Surveys
- Weight Measurements
- Nuclear Assay Measurements
- Storage Container Locators
- Residue Monitors
- Process Monitors
- Safety Monitors

Container identifications are read automatically using optical devices at 27 locations throughout the process area. These locations were generally selected because of some other activity occurring simultaneously with the container identification. Examples of these other activities are

1. RECEIVING DOCK
2. EQUIPMENT AIR LOCK
3. UO_2 STORAGE IN DRUMS
4. UO_2 UNLOADING AREA

Fig. 3-5. Top and Side Views of Feed Material Building for Commercial MO_2 Fuel Plant Model

Fig. 3-6. Top and Side Views of 2nd Floor Manufacturing Building for Commercial MO₂ Fuel Plant Model

Fig. 3-7. Top and Side Views of 1st Floor Manufacturing Building for Commercial MO_2 Fuel Plant

Fig. 3-8. Top and Side Views of 1st Floor Fuel Rod Inspection Building for Commercial MO_2 Fuel Plant Model

assay measurements, container loading and unloading, and material sampling from the container for inspection. The 27 container identifications are specified in Table 3-2.

Seal checks and alpha surveys are made for the L-10 containers and modified channels before and after vault storage. These measurements are specified in Table 3-3.

Weight measurements, many of which are part of the existing plant model, are specified at 29 locations throughout the process area. These measurements, along with the appropriate range and accuracy of each, are given in Table 3-4.

Nuclear assay measurements are specified for 10 locations. The type, range and accuracy of each measurement are given in Table 3-5. Because of the high impact of these measurements and the complex technical issues associated with them, they are described in considerable detail in the next section.

Storage container locators are specified for 5 storage areas and a total of 1345 containers. These locators, which are listed in Table 3-6, are monitored to verify that containers arrive, are held and leave the designated storage positions at the appropriate times.

Residue monitors are recommended for 8 locations to verify the absence of significant quantities of plutonium in these areas during certain times. The monitors are specified in Table 3-7. In addition, residue monitors perform their primary function of monitoring material residue in these areas.

TABLE 3-2. CONTAINER IDENTIFICATIONS

Process Step	Measurement Designation	Description
1A	I1	L-10 container at receiving dock
	I2	L-10 container at L-10 container weighing station
	I3	L-10 container at L-10 container assay station
3A	I4	L-10 container at PuO ₂ unloading station
	I5	Outer can at outer-can weighing station
	I6	Inner cans at inner-can weighing station
	I7	Inner cans at inner-can assay station
7	I8	Boat at boat loading station
9	I9	Boat at furnace entrance feed conveyor
	I10	Boat at sintered-pellet density inspection station
11	I11	Boat at boat unloading station
	I12	Tray at tray loading station
12	I13	Tray at moisture inspection station
13	I14	Tray at tray unloading station
	I15	Fuel rod at tube loading station
14	I16	Fuel rod at unwelded-rod weighing station
	I17	Fuel rod at welded-rod weighing station
	I18	Fuel rod at active-length measurement station
	I19	Fuel rod at leak test station
	I20	Fuel rod at x-ray inspection station
	I21	Fuel rod at fissile-content measurement station
	I22	Fuel rod at finished-rod weighing station
	I23	Channel at physical inspection station
	I24	Channel at channel weighing station
	I25	Channel entering storage vault
16	I26	Channel leaving storage vault
	I27	Channel at channel weighing station

TABLE 3-3. SEAL CHECKS AND ALPHA SURVEYS

Process Step	Measurement Designation	Description
1A	S1	L-10 container at receiving dock
3A	S2	L-10 container at PuO ₂ unloading station
14	S3	Channel at channel weighing station
16	S4	Channel at channel weighing station
	S5	Shipping box at loading table
	S6	Shipping container at shipping dock

TABLE 3-4. WEIGHT MEASUREMENTS

Process Step	Measurement Designation	Description	Range (Kg)	Accuracy (g / %)
1A	W1	L-10 container (gross)	150	15/0.01
3A	W2	Outer can (gross)	5	0.5/0.01
	W3	Inner cans (gross and tare)	3	0.3/0.01
4A	W4	PuO ₂ weigh hopper (gross and tare)	4	4/0.1
	W5	PuO ₂ powder storage vessel (gross and tare)	30	150/0.5
5	W6	PuO ₂ weigh hopper (gross and tare)	15	15/0.1
	W7	MO ₂ weigh hopper (gross and tare)	30	30/0.1
	W8	UO ₂ weigh hopper (gross and tare)	300	300/0.1
6	W9	MO ₂ powder storage silo (gross and tare)	300	1500/0.5
7	W10	Under-size granules (gross and tare)	—	—
	W11	Over-size granules (gross and tare)	—	—
	W12	Rejected pellets (gross and tare)	—	—
	W13	Sample pellets (gross and tare)	—	—
	W14	Green—pellet boat (gross and tare) at secure boat—loading station	15	3/0.02
9	W15	Sintered—pellet boat (gross) before and after sample pellets removed for density inspection	15	3/0.02
11	W16	Sintered—pellet boat (gross and tare) at boat unloading station	15	3/0.02
	W17	Broken pellets (gross and tare)	—	—
	W18	Dry grinder sludge (gross and tare)	—	—
	W19	Over-size pellets (gross and tare)	—	—
	W20	Under-size pellets (gross and tare)	—	—
	W21	Broken pellets (gross and tare)	—	—
	W22	Finished—pellet tray (gross and tare) at secure tray—loading station	15	3/0.02
12	W23	Finished—pellet tray (gross) before and after sample pellets removed for moisture inspection	15	3/0.02
13	W24	Finished—pellet tray (gross) before and after 200 pellets removed for fuel rod loading	15	3/0.02
	W25	Unwelded fuel rod (gross)	3	3/0.1
	W26	Welded fuel rod (gross)	3	3/0.1
14	W27	Finished fuel rod (gross)	3	0.3/0.01
	W28	Channel (gross and tare)	150	150/0.1
16	W29	Channel (gross)	150	150/0.1

TABLE 3-5. NUCLEAR ASSAY MEASUREMENTS

PROCESS STEP	MEASUREMENT DESIGNATION	DESCRIPTION	MEASUREMENT TIME	RANGE GRAM PuO ₂	ACCURACY		COMMENTS
					GRAM PuO ₂	%	
1A	N1	SPONTANEOUS-FISSION AND DECAY GAMMA ASSAY FOR PuO ₂ POWDER IN L-10 CONTAINERS	5 MIN	5000	FMD: 150 (γ : 500)	<3 (15)	USING DIRECT OUTPUT USING ISOTOPIC RATIO
3A	N2	DECAY-GAMMA ASSAY FOR PuO ₂ IN INNER CANS	<5 MIN	3000	300	10	
	N3	CALORIMETRIC ASSAY FOR PuO ₂ IN INNER CANS	1 1/2 HR	3000	RELATIVE: 3 ABSOLUTE: <30	0.1 <1	
4A	N4	SPONTANEOUS-FISSION AND DECAY GAMMA ASSAY FOR PuO ₂ POWDER IN FEED PIPE LEADING TO STORAGE VESSELS	5 MIN	3000	FMD: 30 (γ : 150)	1 (5)	EXCLUDING SAMPLING ERRORS
	N5	SMALL-SAMPLE FISSION ASSAY FOR PuO ₂	<5 MIN	1	0.01	1	
6	N6	SMALL-SAMPLE FISSION/FERTILE ASSAY FOR MO ₂	5 MIN	0.05	FISSION 10 ⁻³	<2	
7	N7	GAMMA SCAN AND PELLET COUNTER AT SECURE BOAT-LOADING STATION	0.5 SEC	0.5	0	0	< 1/2 PELLET UNCERTAINTY
11	N8	GAMMA SCAN AND PELLET COUNTER AT SECURE TRAY-LOADING STATION	0.5 SEC	0.5	0	0	
13	N9	GAMMA SCAN FOR ACTIVE LENGTH MEASURE- MENT OF FUEL ROD AFTER WELDING	200 SEC	100	0.25	<0.25	
14	N10	TOTAL AND PELLET-BY-PELLET FISSION CONTENT FUEL-ROD SCANNER	3.75 MIN	100	0.5	0.5	

TABLE 3-6. STORAGE CONTAINER LOCATORS

Process Step	Measurement Designation	Description
2A	L1	88 L-10 containers in PuO_2 powder storage
8	L2	58 boats in green pellet storage
10	L3	135 boats in sintered pellet storage
12	L4	888 trays in finished pellet storage
15	L5	176 channels in finished fuel rod storage

TABLE 3-7. RESIDUE MONITORS

Process Step	Measurement Designation	Description
1A	R1	Gamma level at receiving dock
3A	R2	Gamma level in Compartment 1 of PuO_2 unloading station
	R3	Gamma level in Compartment 3 of PuO_2 unloading station
13	R4	Gamma level in tube loading enclosure
	R5	Gamma level in rod welding enclosure
14	R6	Gamma level at leak test station
	R7	Gamma level at x-ray inspection station
16	R8	Gamma level at shipping dock

Process monitors and safety monitors, both of which are included in the existing plant model, provide additional measurements to supplement the above-mentioned ones. Examples of these monitors are pellet-pressing rates and airborne radioactivity levels.

The general locations of most of the measurements are shown on the physical layouts for the model plant given in Figs. 3-9 through 3-12.

3.3.2 Nuclear Assay Measurements

The assay devices for the RETIMAC system in the model MO_2 fuel plant represents a set of instruments and techniques selected to:

1. Minimize the chances for undetected removal of fissile material from the plant.
2. Shorten the detection time of attempted diversions.
3. Provide RETIMAC with the necessary information for a real-time accountability of the SNM.

The selection brought here represents a practical compromise, in which maximum use is made of regular process measurements and of other simple and reliable non-specific techniques. Weighing, position indicators and optical readers are supplemented by a relatively small number of more sophisticated nuclear non-destructive assay (NDA) techniques for the quantitative measurements of the fissile materials and their flow.

These NDA nuclear techniques are primarily located in areas which are most vulnerable to diversion. In the study model, these areas are the input stage where PuO_2 in L-10 containers are unloaded and the output stage where finished MO_2 fuel rods are stored for shipment. There are additional intermediate stages in the process where relatively long storage times are

1. RECEIVING DOCK
2. EQUIPMENT AIR LOCK
3. UO_2 STORAGE IN DRUMS
4. UO_2 UNLOADING AREA

I = IDENTIFICATION
 R = RESIDUE MONITOR
 S = SEAL CHECK AND ALPHA SURVEY
 W = WEIGHT MEASUREMENT
 N = NUCLEAR ASSAY
 L = LOCATOR

Fig. 3-9. Top and Side Views of Feed Material Building for Commercial MO_2 Fuel Plant Model

Fig. 3-10. Top and Side Views of 2nd Floor Manufacturing Building for Commercial MO_2 Fuel Plant Model

Fig. 3-11. Top and Side Views of 1st Floor Manufacturing Building for Commercial MO_2 Fuel Plant

1 FUEL ROD AIR LOCK	10 INSPECTED ROD STORAGE
2 H_2 LEAK TEST VACUUM CHAMBER	11 BOX LOADING TABLE
3 GAMMA SCAN STATION	12 MOTORIZED TRANSFER DOLLY
4 PRE X-RAY STORAGE	13 SHIPPING CONTAINER
5 X-RAY WELD INSPECTION	14 TRUCK WELL
6 POST X-RAY STORAGE	15 TUBE & BOTTOM PLUG RECEIVING
7 WEIGHING & PHYSICAL INSPECTION	16 BOTTOM PLUG WELDING
8 TRACKS	17 PRE X-RAY STORAGE
9 SHIELDED CARRIER	18 X-RAY WELD INSPECTION
	19 POST X-RAY STORAGE

Fig. 3-12. Top and Side Views of 1st Floor Fuel Rod Inspection Building for Commercial MO_2 Fuel Plant Model

employed and/or manual operation are required, thus increasing the chances for a potential diversion. NDA devices are also proposed for these locations.

Most of the techniques and devices proposed in this study have been already tested or are commercially available. They represent the present state-of-the-art. There is still room for improvements and modifications in the proposed NDA systems, which will further enhance the system performance and the overall RETIMAC system efficiency. Such improvements, however, were not assumed (though they are occasionally mentioned) in the specifications and accuracies used in this work.

3.3.2.1 Nuclear Characteristics of the Material

The material handled in the model MO_2 fuel plant is considered to be well characterized. It is assumed that the plutonium isotopic ratio is well known and represents the material in the plant. This isotopic information is supplied with the PuO_2 feed material. At a later process stage, the analytical laboratory of the MO_2 plant uses accurate mass spectroscopy methods to determine the isotopic composition of representative samples of the PuO_2 (and also after mixing the MO_2). The importance of an accurate knowledge of the isotopic composition stems from the fact that it allows the determination of the fissile content from a measurement of one or several of the isotopes. This can simplify the measuring technique, reduce its cost, and increase its precision.

In addition to the fact that the PuO_2 is well characterized, the nuclear measurement problem is also helped by the well defined geometrical configuration for material encountered throughout most of the plant.

The PuO_2 is contained in a sealed, standardized "beer-can" containing 2.25 kg of PuO_2 --two cans are in each L-10 shipping container. The PuO_2 retains this form through several phases of the process (i.e. through several process-steps) and measuring stations. This fact enhances the potential accuracy one can obtain with NDA techniques. The only parameter which is not controlled under these conditions is the bulk density of the PuO_2 . Movements and handling of the cans can cause some changes in the bulk density of the material, which may affect the various NDA measurements to different degrees. The features of the material and geometry described above enable the employment of several passive NDA techniques through the MO_2 plant. These techniques are inherently simpler and less expensive than active techniques; active techniques are used in a limited number of locations.

Parameters describing the nuclear characteristics of the material in the MO_2 plant are given below. These parameters form the basis upon which the selection of the various NDA techniques were made.

Table 3-8 lists the nuclear constants for the isotopes of plutonium which are relevant primarily for calorimetric measurements. The last column of this table gives the specific power in watts/gram generated by the various isotopes. The importance of the minor isotopes-- ^{238}Pu and ^{241}Am (which results from the β decay of ^{241}Pu)--is obvious.

TABLE 3-8. NUCLEAR CONSTANTS FOR ISOTOPES
IN PLUTONIUM FUEL ⁽⁴⁾

Isotope	Average Total Disintegration Energy (MeV)	Type Decay	T _{1/2} (yr)	Specific Power (W/g)
²³⁸ Pu	5.592	α	87.78	5.6642 x 10 ⁻¹
²³⁹ Pu	5.243	α	24,140	1.924 x 10 ⁻³
²⁴⁰ Pu	5.255	α	6,538	7.089 x 10 ⁻³
²⁴¹ Pu	0.00721	β	14.39	3.389 x 10 ⁻³
²⁴² Pu	4.98	α	379,000	1.146 x 10 ⁻⁴
²⁴¹ Am	5.635	α	432.7	1.1450 x 10 ⁻¹

Important gamma ray signatures for the two important uranium isotopes and the Pu isotopes are given in Table 3-9 which is based on Ref. 5. A typical spectrum from a plutonium sample measured both with a high resolution Ge(Li) spectrometer and with a low resolution (but high efficiency) NaI(Tl) detector is shown in Fig. 3-13. ⁽⁶⁾

The mass absorption coefficients as a function of the gamma energy for some common elements are shown in Fig. 3-14. Also indicated on this figure are the main gamma lines listed in Table 3-9. The attenuation of the gamma intensity by the various elements, whether they are part of the matrix (Fe, Al, Pb, H₂O) or by the fissile material (UO₂ and PuO₂) itself constitutes the most important limitation on the methods based on detection of low energy gamma rays. The mean-free-path of various gamma energies in common materials encountered in the plant is given in Table 3-10. The equivalent quantities for thermal (between 0.005 eV and 0.14 eV) and fast (between 0.4 MeV and 1.5 MeV) neutrons are also given for comparison.

TABLE 3-9. IMPORTANT GAMMA RAY LINES

Isotope	Energy (keV)	Intensity photons/sec/g isotope
^{235}U	185.72	4.3×10^4
^{238}U	1001.10	1.0×10^2
	766.40	3.9×10^1
^{238}Pu	766.40	1.5×10^5
	152.77	6.5×10^6
^{239}Pu	$\Sigma(320-430)$	1.3×10^5
	413.69	3.4×10^4
	375.02	3.6×10^4
	129.28	1.4×10^5
	51.63	4.7×10^5
^{240}Pu	45.23	3.8×10^6
^{241}Pu	207.98	2.0×10^7
	164.59	1.8×10^6
	148.60	7.5×10^6
^{241}Am	59.54	4.5×10^{10}
^{242}Pu	None

Fig. 3-13. Comparison of Plutonium Gamma-ray Spectra from 30-cm³ Ge(Li) Detector and 7.6- by 7.6-cm NaI Detector. Note the Square Root Scale.

Fig. 3-14. Mass Absorption Coefficients for Gamma Ray Beams for Some Important Elements

TABLE 3-10. MEAN FREE PATH (in cm) FOR
PHOTONS AND NEUTRONS

Material	Density g/cm ²	Gamma			Neutrons	
		400 keV	1 MeV	2 MeV	Thermal	Fast
H ₂ O	1	9.5	14.3	2.0	0.34	2.2
Fe	7.86	1.4	2.9	3.0	0.86	3.6
Pb	11.35	0.4	1.5	2.0	2.7	5.6
UO ₂	10.30	0.4	1.4	3.3	1.3	2.8

The mean free path represents the average path length for the occurrence of any kind of interaction. Thus, Table 3-10 gives an idea of possible interactions between the observable nuclear signature and the matrix or the nuclear material itself. It does not necessarily indicate the magnitude of the correction required.

Many of the plutonium isotopes emit neutrons which can be used as a quantitative signature for plutonium. One important source of neutrons from plutonium compounds such as PuO₂ is the (α , n) reaction. Table 3-11⁽⁶⁾ lists the yields from (α , n) reactions in oxides and fluorides of important uranium and plutonium isotopes.

TABLE 3-11. (α, n) YIELDS FROM OXIDES AND FLUORIDES

Material	Yield neut/sec/gram isotope
$^{234}\text{UO}_2$	~ 14
$^{234}\text{UF}_6$	5.8×10^2
$^{235}\text{UF}_6$	12.2×10^{-2}
$^{238}\text{UF}_6$	12.9×10^{-3}
$^{238}\text{PuO}_2$	1.4×10^4
$^{238}\text{PuF}_4$	5.1×10^6
$^{239}\text{PuO}_2$	45
$^{239}\text{PuF}_4$	4300
$^{240}\text{PuO}_2$	170
$^{240}\text{PuF}_4$	1.6×10^4
$^{241}\text{PuO}_2$	~ 10
$^{241}\text{AmO}_2$	3754
$^{242}\text{PuO}_2$	~ 10

The importance of accurate knowledge of the relative quantity of the minor isotopes ^{238}Pu and ^{241}Am , when such a signature is being used, is again very obvious here as in Table 3-8. This table also illustrates the importance of limiting possible traces of fluorides and beryllium in the PuO_2 to very low levels. The neutron energies from (α, n) reactions are relatively

high in comparison to the fission spectrum (see Fig. 3-15) and are therefore more penetrating.

Another unique feature of some of the Pu isotopes which is very useful as a signature is the phenomenon of spontaneous fission. The half-lives for this mode of decay, the number of neutrons ($\bar{\nu}$) emitted in spontaneous fission, and the number of spontaneous fissions, Sp. F. per second per gram are given in Table 3-12. ⁽⁶⁾

TABLE 3-12. SPONTANEOUS FISSION OF FISSIONABLE ISOTOPES

Isotope	Sp. F. Half-Life (year)	$\bar{\nu}$	Yield Sp. F./sec/g
²³² Th	1.4×10^{18}		4.1×10^{-5}
²³⁴ U	2.0×10^{16}	~2	2.8×10^{-3}
²³⁵ U	1.9×10^{17}	~2	2.96×10^{-4}
²³⁶ U	2×10^{16}	~2	2.8×10^{-3}
²³⁸ U	9.86×10^{15}	1.95	5.64×10^{-3}
²³⁸ Pu	4.9×10^{10}	2.26	1.1×10^3
²³⁹ Pu	5.5×10^{15}	2.2	1.0×10^{-2}
²⁴⁰ Pu	1.17×10^{11}	2.17	4.71×10^2
²⁴¹ Pu	5.0×10^{15}	2.2	1.1×10^{-2}
²⁴² Pu	6.8×10^{10}	2.16	8.0×10^2
²⁴¹ Am	2×10^{14}	2.3	0.27
²⁵² Cf	86	3.8	6.14×10^{11}

The typical energy spectrum of fission neutrons is shown in Fig.

3-15.

Fig. 3-15. Typical Energy Spectrum of Fission Neutrons

The fission process is characterized not only by simultaneous emission of several neutrons (with an average number $\bar{\nu}$ of about 2.2), but also by simultaneous and copious emission of prompt gamma rays. A typical average number ($\bar{\nu}_\gamma$) for these gamma rays is about 7. Table 3-13⁽⁷⁾ gives the number of prompt photons and the energy emitted per fission as a function of the photon energy range for the thermal fission of ^{235}U , ^{239}Pu and the spontaneous fission of ^{252}Cf . It is plausible to assume that the equivalent quantities for ^{238}Pu , ^{240}Pu and ^{242}Pu are bracketed by the given values in the table.

The prompt fission gamma ray spectra for the three isotopes mentioned in Table 3-13 are shown in Fig. 3-16.⁽⁷⁾

**TABLE 3-13 ENERGY EMITTED PER FISSION IN THE FORM OF
PROMPT γ -RAYS AND THE NUMBER OF γ -RAYS PER FISSION
FOR VARIOUS γ -RAY ENERGY INTERVALS**

PHOTON ENERGY RANGE (MeV)	PROTONS/FISSION			MeV/FISSION		
	²³⁵ U	²³⁹ Pu	²⁵² Cf	²³⁵ U	²³⁹ Pu	²⁵² Cf
0.14-0.3	0.833	1.267	1.270	0.181 $\pm$ 0.005	0.275 $\pm$ 0.007	0.282 $\pm$ 0.007
0.3-0.5	1.318	1.473	1.855	0.532 $\pm$ 0.013	0.596 $\pm$ 0.015	0.759 $\pm$ 0.019
0.5-0.7	1.182	1.219	1.613	0.709 $\pm$ 0.028	0.737 $\pm$ 0.019	0.963 $\pm$ 0.024
0.7-1.0	1.191	1.097	1.067	1.021 $\pm$ 0.026	0.939 $\pm$ 0.023	0.908 $\pm$ 0.023
1.0-1.5	1.072	0.998	0.838	1.337 $\pm$ 0.034	1.241 $\pm$ 0.031	1.044 $\pm$ 0.026
1.5-2.0	0.451	0.450	0.442	0.804 $\pm$ 0.020	0.787 $\pm$ 0.020	0.778 $\pm$ 0.020
2.0-2.5	0.258	0.268	0.292	0.582 $\pm$ 0.015	0.606 $\pm$ 0.015	0.660 $\pm$ 0.017
2.5-3.0	0.158	0.175	0.183	0.434 $\pm$ 0.012	0.482 $\pm$ 0.014	0.503 $\pm$ 0.013
3.0-4.0	0.143	0.173	0.160	0.490 $\pm$ 0.015	0.597 $\pm$ 0.017	0.550 $\pm$ 0.014
4.0-5.0	0.060	0.0714	0.068	0.220 $\pm$ 0.015	0.318 $\pm$ 0.019	0.254 $\pm$ 0.010
5.0-6.0	0.021	0.0266	0.019	0.116 $\pm$ 0.011	0.145 $\pm$ 0.018	0.102 $\pm$ 0.009
6.0-7.0	0.0098	0.0104	0.0057	0.064 $\pm$ 0.015	0.067 $\pm$ 0.012	0.038 $\pm$ 0.005
7.0-10.0	0.0027	0.0015	0.0004	0.019 $\pm$ 0.015	0.019 $\pm$ 0.012	0.0019 $\pm$ 0.0014
0.14-10.0	6.70	7.23	7.80	6.51	6.81	6.84

Fig. 3-16. Unfolded Prompt γ -ray Energy Spectra for the Thermal-Neutron Fission of ^{235}U and ^{239}Pu and for the Spontaneous Fission of ^{252}Cf

Spontaneous fission is a process that occurs entirely within one nucleus. The (α, n) reaction, however involves transport of the alpha particles through the material being investigated. Whereas the rate of emission of (α, n) neutrons is highly dependent upon the nature of the matrix containing the fissionable material being assayed, the rate of neutrons and gamma emission from the spontaneous fission process depends only upon the nuclear properties and the quantities of the fissioning isotopes present. Although the number of neutrons and photons detected from a sample will be influenced by absorption and scattering processes within the sample, these effects are in general far less severe than the alpha attenuation effects that influence the yield from (α, n) reactions. Therefore, for accurate assay by passive neutron counting, one usually selects the spontaneous-fission neutrons, discriminating against (α, n) neutrons by requiring that detected neutrons be in coincident

pairs. Similarly, for an accurate assay using passive fission-gamma rays and neutron counting, one can discriminate against the other passive gamma background and (α , n) neutrons by requiring that several particles (gamma and/or neutrons) be detected coincidentally. Obviously, even here, as with most of the other signatures mentioned before, it is necessary to know the isotopic composition to arrive at a measure of the fissile components.

3.3.2.2 Magnitude of Passive Signatures

Heat and Neutron Emission

The passive signatures identified in the previous section are applied in this section to different isotopic compositions of plutonium⁽⁸⁾ which may be used during the life time of the MO₂ plant. Tables 3-14 through 3-16 give the neutron and heat emission rate per gram of plutonium which is aged 1 year after reprocessing. The three tables show the dominance of the minor isotope ²³⁸Pu in heat generation (and in (α , n) neutron production) which is the signature used for calorimetric measurements. Thus the accuracy of the determination of the fissile material content from this technique hinges dramatically upon the accurate knowledge of the isotopic composition, especially the minor isotopes. When spontaneous fission is used as a signature, the dominant isotopes are ²⁴⁰Pu, and to a lesser extent ²⁴²Pu. These are not minor isotopes for high burn-up fuel. It should be noted that the heat signature and the spontaneous fission signature basically represent independent information, since they inherently depend on different Pu isotopes. Hence these signatures complement each other and making the possibility of a sophisticated diversion (e.g., replacing PuO₂ with UO₂ spiked with ²⁴¹AmO₂) readily detectable and therefore less plausible.

**TABLE 3-14 EMISSION RATE FOR 1 GRAM Pu FROM YANKEE FUEL
WITH 35,000 MWD/TU BURN-UP**

Isotope	Weight %	Spontaneous Fission		Spontaneous Fission Prompt Neutron		(α,n) Neutron From PuO ₂		Specific Power (Heat)	
		Sp. F/Sec	%	Neut/Sec	%	Neut/Sec	%	Watts	%
²³⁸ Pu	1.9	20.9	14.8	47.2	15.3	266.0	76.1	0.0108	75.1
²³⁹ Pu	63.0	0	0	0	0	28.4	8.1	0.0012	8.3
²⁴⁰ Pu	19.0	89.5	63.8	194.2	63.2	32.3	9.2	0.0013	9.0
²⁴¹ Pu	12.0	0	0	0	0	1.2	0.3	0.0004	2.8
²⁴² Pu	3.8	30.4	21.6	65.7	21.4	0.4	0.1	0.0	0.0
²⁴¹ Am	0.6	0	0	0	0	21.4	6.1	0.0007	4.9
Total		140.8	100.0	307.1	100.0	349.7	100.0	0.0144	100.0

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**TABLE 3-15 EMISSION RATE FOR 1 GRAM Pu OF AVERAGE
COMPOSITION (INCLUDING RECYCLE IN 1990)**

Isotope	Weight %	Spontaneous Fission		Spontaneous Fission Prompt Neutron		(α,n) Neutron From PuO ₂		Specific Power (Heat)	
		Sp. F/Sec	%	Neut/Sec	%	Neut/Sec	%	Watts	%
²³⁸ Pu	1.2	13.2	7.2	30.0	7.5	168.0	63.6	0.0068	62.4
²³⁹ Pu	53.0	0	0	0	0	23.9	9.0	0.0010	9.2
²⁴⁰ Pu	25.8	121.5	66.5	264.0	66.4	43.9	16.6	0.0018	16.5
²⁴¹ Pu	13.5	0	0	0	0	1.4	0.5	0.0005	4.6
²⁴² Pu	6.0	48.0	26.2	103.7	26.1	0.6	0.2	0.0	0
²⁴¹ Am	0.7	0	0	0	0	26.3	10.0	0.0008	7.3
Total		182.7	100.0	397.7	100.0	264.1	100.0	0.0109	100.0

TABLE 3-16 EMISSION RATE FOR 1 GRAM Pu -
(WITH ISOTOPIC COMPOSITION OF EQUILIBRIUM RECYCLE)

ISOTOPE	WT %	SPONTANEOUS FISS.		SP. F. PROMPT NEUT.		(α,n) NEUT. FROM PuO ₂		SPECIFIC POWER (HEAT)	
		SP. F./SEC	%	NEUT/SEC	%	NEUT/SEC	%	WATTS	%
²³⁸ Pu	3.4	37.4	14.5	84.5	15.0	476.0	83.7	0.0193	82.8
²³⁹ Pu	41.7	0	0	0	0	18.8	3.3	0.0008	3.4
²⁴⁰ Pu	27.1	127.6	49.3	276.9	49.1	46.1	8.1	0.0019	8.2
²⁴¹ Pu	15.4	0	0	0	0	1.5	0.3	0.0005	2.1
²⁴² Pu	11.7	93.6	36.2	202.2	35.9	1.2	0.2	0	0
²⁴¹ Am	0.7	0	0	0	0	25.0	4.4	0.0008	3.4
TOTAL		258.6	100	563.6	100	568.6	100	0.02330	100

Gamma Emission

In the previous section the spontaneous fission, heat and gross neutron generation were discussed as possible signatures. Analysis of these signatures clearly illuminates the fact that none of them are related to the fissile isotopes, ^{239}Pu and ^{241}Pu . The only practical signature of the former is the "400" keV gamma lines (see Table 3-9). This signature can be a quantitative one only for samples of PuO_2 of relatively small size and low density because of the self absorption of the gamma-ray. For small samples with low density, the lower energy line at 208 keV due to ^{241}Pu can also be used. Indeed, specially prepared samples studied with a high resolution gamma spectrometer [Ge(Li)] can yield the isotopic composition, excluding ^{242}Pu , with accuracies of about 1% to 6% for the different isotopes. (4)

The gamma ray emission rates from various samples that may be possibly used in the various assay stations in the MO_2 plant are given in Table 3-17.

TABLE 3-17. APPROXIMATE PASSIVE GAMMA RAY EMISSION RATES FROM PuO_2 AND MO_2 SAMPLES

Sample*	Pu Weight (gram)	320-430 keV (^{239}Pu)	208 keV (^{241}Pu)	59.54 keV (^{241}Am)
PuO_2 loose powder - 1.13 g, $\rho \ll 1$ g/cc	1.0	8×10^4	2×10^6	3×10^8
MO_2 green pellet - 10 g, $\rho \sim 5$ g/cc	0.352	2×10^4	2×10^5	4×10^6
MO_2 sintered pellet - 10 g, $\rho = 10.4$ g/cc	0.352	1×10^4	1×10^5	2×10^6
PuO_2 - beer can - 2.25 Kg $\rho \sim 2.5$ g/cc	1985.0	5×10^7	8×10^8	-

* Isotopic composition of Yankee fuel with 35000 MWDTU burn up, 1 year after reprocessing.

The intensities given in the table clearly indicate that there is ample signal for use as a qualitative signature. The use of these signatures as a quantitative entity depends critically on the amount of self-shielding. The latter quantity can be computed from an external gamma transmission measurement, if the density of the material (e.g., PuO_2) can be assumed to be uniform. This procedure may be applicable to cases where the correction for self shielding does not exceed about 1.5 and reasonably well known standards are available.

3.3.2.3 Active NDA-Nuclear Data

Although maximum use is made of the specific passive radiations emitted by the various Pu isotopes, an accurate measurement of the total fissile content of the end product is required in order to reduce the limit of error and complete the plant fissile content balance.

The proper active interrogation for the MO_2 plant would be fissions induced by neutrons from an external source. If the interrogating neutron spectrum is moderated sufficiently so as not to cause fission in the highly abundant ^{238}U present in the MO_2 (i.e., if most of the neutron energies are less than about 0.6 MeV), then the resulting fissions will occur only in the fissile isotopes of ^{239}Pu , ^{241}Pu and ^{235}U . The fission cross section for these three fissile isotopes and for ^{238}U , weighted with a typical LWR neutron spectrum, is given in Table 3-18⁽⁹⁾ along with the other pertinent parameters such as the number of prompt neutrons per fission, $\bar{\nu}$; the number of delayed neutrons per fission β^* and the number of delayed gamma rays per fission, β_γ^* (see also Table 3-19).

**TABLE 3-18 MICROSCOPIC FISSION CROSS-SECTIONS
(IN BARNS= 10^{-24} cm²) AND OTHER NUCLEAR PARAMETERS
FOR ²³⁵U, ²³⁹Pu, ²⁴¹Pu and ²³⁸U**

GROUP NO.	AVERAGE ENERGY (eV)	²³⁵ U	²³⁹ Pu	²⁴¹ Pu	²³⁸ U
1	8.4×10^6	1.4	2.1	1.8	0.741
2	2.6×10^6	1.5	2.3	2.0	0.607
3	8.4×10^5	1.3	1.9	1.8	0.0301
4	2.1×10^5	1.5	1.6	2.0	0.00007
5	3.4×10^4	2.3	1.8	2.8	0.000005
6	3.6×10^3	5.4	3.4	6.2	0
7	2.5×10^2	23.8	20.5	33.6	0
8	9.0×10^0	37.1	51.2	146.7	0
9	1.7×10^0	17.1	19.2	25.9	0
10	1.0×10^0	59.2	33.1	25.8	0
11	6.4×10^{-1}	62.9	99.2	42.9	0
12	2.8×10^{-1}	142.0	997.9	674.9	0
13	4.1×10^{-2}	375.2	535.6	722.2	0
14	2.5×10^{-3}	1090.0	1297.0	1783.0	0
$\bar{\nu}$		2.42	2.88	2.94	2.70
β^*		0.0158	0.0061	0.0015	0.0412
β^*_γ		3.31	3.26	—	5.50

TABLE 3-19. DELAYED GAMMA SPECTRA INTEGRATED OVER ENERGY AND TIME, FROM 0.20 TO 45.0 SEC, AFTER FISSION⁽¹⁰⁾

Isotope	Photons/fission	MeV/fission	MeV/photon
232-Th	5.07 ± 0.71	5.04 ± 0.71	0.99 ± 0.15
233-U	2.02 ± 0.28	1.97 ± 0.28	0.98 ± 0.15
235-U	3.31 ± 0.46	3.18 ± 0.45	0.96 ± 0.14
238-U	5.50 ± 0.77	5.08 ± 0.71	0.92 ± 0.14
239-Pu	3.26 ± 0.82	2.86 ± 0.71	0.88 ± 0.13

The fact that the delayed gamma rays are much more abundant than the delayed neutrons and the relative ease with which gamma rays may be measured as compared to neutrons suggests the use of the former as a signature of the fissile materials. Indeed most of the experience with high precision-high throughput NDA devices for fissile material has been with this type of fission signature.

Table 3-19 lists time integrated delayed gamma data for various isotopes. Table 3-20 gives the time dependence of the delayed gamma rays. The characteristic spectrum of delayed gamma rays as a function of time measured in a practical configuration (fission induced in BWR-3 wt % ²³⁵U enrichment fuel pellets) is shown in Fig. 3-17.⁽¹¹⁾ Very little spectrum changes in the time domain of interest are observed. Also, the measured spectrum is reasonably hard, with an average energy of about 850 keV, and 45% of all photons with energies above 650 keV. Thus the use of the high energy delayed gamma rays alleviates, to a large extent, possible gamma self shielding in samples such as green and sintered pellets.

**TABLE 3-20. DELAYED GAMMA SPECTRA INTEGRATED
OVER ENERGY FOR DIFFERENT TIME
INTERVALS AFTER FISSION**

Isotope	Time Interval (sec)	Photons/ fission-sec	MeV/ fission-sec	MeV/ photon
²³⁷ Th	0.2- 0.5	0.966	0.916	0.948
	1.0- 2.0	0.487	0.501	1.029
	4.0- 5.5	0.267	0.246	0.921
	10.0-13.0	0.118	0.112	0.949
	35.0-45.0	0.0343	0.0343	1.000
²³³ U	0.2- 0.5	0.312	0.303	0.971
	1.0- 2.0	0.189	0.177	0.937
	4.0- 5.5	0.0958	0.0885	0.924
	10.0-13.0	0.0490	0.0465	0.949
	35.0-45.0	0.0161	0.0161	1.000
²³⁵ U	0.2- 0.5	0.613	0.564	0.920
	1.0- 2.0	0.324	0.311	0.960
	4.0- 5.5	0.169	0.153	0.905
	10.0-13.0	0.0775	0.0706	0.911
	35.0-45.0	0.0225	0.0221	0.982
²³⁸ U	0.2- 0.5	1.42	1.32	0.930
	1.0- 2.0	0.636	0.618	0.972
	4.0- 5.5	0.289	0.255	0.882
	10.0-13.0	0.110	0.0988	0.898
	34.0-45.0	0.0303	0.0281	0.927
²³⁹ Pu	0.2- 0.5	0.608	0.529	0.870
	1.0- 2.0	0.344	0.296	0.860
	4.0- 5.5	0.166	0.138	0.831
	10.0-13.0	0.0746	0.0624	0.836
	35.0-45.0	0.0209	0.0197	0.943

Fig. 3-17. Pulse Height Distribution of Fission Product Gamma Rays LWR Pellet. (t_i is the irradiation time = the measuring time.)

The time decay following irradiations of different duration (2, 5 and 10 seconds) is shown in Fig. 3-18. ⁽¹¹⁾ The energy bias in these measurements was 150 keV. The decay is relatively slow (i.e., there is a higher proportion of slowly decaying groups than in the delayed neutron case), and is rather independent of energy in the time domain of interest.

3.3.2.4 Assay Measurements

The capabilities, limitations and the general specifications of the NDA techniques selected for implementation in the model MO₂ plant are described in this section.

Assay Measurement N1 - Spontaneous Fission and Decay Gamma Assay for PuO₂ Powder in L-10 Containers

The main purpose of this measurement is to accurately determine the spontaneous fission rate in the PuO₂ powder just received from the shipper. An additional purpose is to make a quick semi-quantitative assessment of the amount of ²³⁹Pu by measuring the emission rate of the 385 keV complex (actually the sum of all lines from about 320 keV to 430 keV--see Table 3-9).

The spontaneous fission rate is dominated (e.g., constituting, typically more than 80%) by ²⁴⁰Pu and ²⁴²Pu. The conversion of this rate into the total fissile content, or into the content of each Pu isotope, requires the knowledge of the isotopic ratio. However, if the same type of measuring device were also located at the shipper site, one could compare the fission rate directly, and establish quickly (independent of an accurate knowledge of the Pu-isotopics) that no tampering with the L-10 container or its contents occurred. The spontaneous fission process and its signature is very complex, hence a sophisticated diversion attempt to produce the same fission rate with less plutonium is implausible.

Fig. 3-18. Decay Curves of Delayed Gamma (Energy Bias = 150 keV)

The technique proposed for the measurement of fission rate is based on the Fission Multiplicity Detector (FMD) concept. ^(12, 13) Physically, it identifies the fission process by its high multiplicity of emitted radiations (about 2.2 neutrons and 7 photons on the average). By observing signals which are strong functions of the multiplicity one can get a set of signatures which cannot be easily imitated.

The high multiplicity and the expected high fission rate (approximately 7×10^5 fissions/sec for a L-10 container) allows one to look for multiplicities of the prompt neutrons alone, ⁽¹⁴⁾ of the high energy prompt gammas alone, or combination of both. ⁽¹³⁾ Also, ratios of some multiplicity signatures have been shown to reduce self-shielding effects. ⁽¹⁵⁾

A generic system for performing the measurements of the above mentioned signatures is shown in Fig. 3-19. The L-10 container rotates at the center of the FMD. The latter is made of long (relative to the length of the PuO_2 powder cans) fast neutron and gamma detectors (e.g., plastic or liquid scintillators). The response of these detectors is very fast (a few nanoseconds) and allow the use of very short coincidence time gates. Consequently, the number of chance coincidences produced primarily by (α, n) neutrons ($\approx 1.5 \times 10^6$ neut/sec for a L-10 container) and those due to intermediate and high energy gamma rays ($\approx 10^7$ from ^{238}Pu - 766 keV line and residual fission products), are small.

The hydrogenous fast scintillator is decoupled from the plutonium bearing container by a layer of B_4C . A lead shield is interposed behind the B_4C in order to harden the detected prompt gamma spectrum.

The electronic circuit consists of a fast discriminator and N-fold majority coincidence unit (N is the number of individual scintillators used) which allows one to record various levels of coincidences M_1 out of N

Fig. 3-19 Fission Multiplicity Detector (FMD) for Detection of Spontaneous Fission Rate - Block Diagram of Electronic Logic

(labeled M_1/N), M_2/N and so on, down to $1/N$. The latter is very closely related to the sum of the single count-rate of the individual scintillators. An electronic processor analyzes the data to yield the measured fission rate and its uncertainty. If the isotopic ratios are supplied to the processor, the amount of each Pu isotope and the total fissile content can also be calculated.

The neutron and the higher energy gamma (e. g., $E_\gamma \geq 1$ MeV) self shielding in the PuO_2 cans should be rather small and can be further reduced by taking proper ratios of multiplicity functions. ^{(15)*} A fundamental limitation on the accuracy of many nuclear techniques is neutron multiplication within the sample. This effect is important only when large amounts of almost pure fissile materials are present. When the isotopic composition, geometry, and material density are known, one can calculate the neutron multiplication (in this case--fast neutron multiplication) and correct for it. The only parameter that may vary in the present case is the bulk density of the PuO_2 within its can. The magnitude of the multiplication and its variation from can to can has to be determined experimentally. It is reasonable to anticipate that with this correction, the accuracy of the spontaneous fission rate determination can be improved.

The presence of a stabilized NaI(Tl) gamma spectrometer with the FMD at both shipper and receiver sites enhances the overall capability of the system in directly measuring the ^{239}Pu signature and possibly also fission product levels. The relatively large gamma self shielding within the PuO_2 cans and the packing (or bulk) density variation significantly limits the accuracy of this ^{239}Pu measurement. However, it is nonetheless very useful information to have.

* This applies only to the prompt gamma rays.

Assay Measurement N2 - Decay Gamma Assay for PuO₂ Powder in Inner Can

The main purpose of this measurement is to ascertain that, within reasonably short time after breaking the seal on the L-10 container and the removal of the two PuO₂ powder cans, a PuO₂ can is being inserted into the calorimeter. Without a quick measurement of the kind proposed, a diversion performed by replacement of the can with a UO₂ can of the same weight will be detected only after the long time required to make the calorimetric measurement. The removal of the PuO₂ can from the calorimeter within the prescribed measuring time (which means unlawful tampering) or at the end of the measurement will be detected almost instantly.

The technique proposed for this measurement is the detection of the "385" keV complex of gamma lines emitted by ²³⁹Pu. The measurement will be performed with a stabilized NaI(Tl) gamma ray spectrometer as shown schematically in Fig. 3-20. The expected count-rate at a distance of about 60 cm from the can center, taking into account the gamma self attenuation, will be about 10⁴ cps.

The main factor that limits the accuracy of this technique is the gamma self attenuation within the PuO₂ can. Only about 30% of the emitted photons leave the can surface. If the powder density is uniform and known, one can accurately calculate the correction factor and obtain an accurate ²³⁹Pu assay. While the density can be measured by a gamma transmission of an external source, one cannot ascertain the uniformity of the density distribution. It is nonetheless proposed to correct the raw data with a calculated self-shielding factor, using the best estimates for the bulk density, and determine the limit of error based on repeated measurements with known standards. It is anticipated that overall accuracies of better than 10%, and probably around 5% will be obtained.

Fig. 3-20 Schematic Diagram of ^{239}Pu Passive Gamma Monitoring Prior to the Calorimetric Measurement of PuO_2 Cans

A more sophisticated and potentially very useful experimental correction method⁽¹⁶⁾ for gamma self attenuation might also be applied in this case, because the PuO_2 material is well characterized. The method is based on the fact that the isotopic ratio and the chemical composition of the material under investigation must be well known. By measuring the ratio of the strong ^{241}Pu line at 208 keV (see Table 3-17) to ^{239}Pu γ lines and using the known ratio of the specific gamma emission rates (and/or using proper standards), one can determine the effective density of the measured powder and use it for correcting the observed emission rate. A Ge(Li) system, with its high resolution, will probably yield more accurate results for this correction.⁽¹⁶⁾ It is anticipated, however, that with good standard PuO_2 powder-cans, a NaI(Tl) system can yield accuracies of better than 5%.

Assay Measurement N3 - Calorimetric Assay for PuO_2 Powder in Inner Cans

The main purpose of this measurement is to obtain a highly accurate determination of the Pu content of the PuO_2 powder can. Calorimetry is a precise nondestructive method for plutonium concentrations such as the PuO_2 powder discussed here. Calorimetry, with proper calibration, is capable of a very high accuracy regardless of the matrix material present. Thus, a representative standard for a calorimetric measurement need only be similar to the unknown in a few characteristics, the most important of which is the relative abundance of each radionuclide.

Calorimetry is the measurement of heat or the rate of heat emission (see Tables 3-8 and 3-14 through 3-16). Calorimetry can therefore be applied as a nondestructive method for determining the quantity of plutonium in material in bulk form by measuring the thermal power generated as a result of radionuclide decay. As a plutonium assay technique, calorimetry

must be accompanied by supplemental measurements to determine the proper algorithms for converting the thermal power to a quantity of plutonium. Although the actual power measurement is accurate for a wide range of materials, it is the ability to accurately determine the conversion relationship that limits the application of calorimetric plutonium assay.

The conversion of a power measurement to a mass of plutonium is sometimes accomplished by considering calorimetry an absolute plutonium assay method, i. e., an assay technique that does not depend on representative calibration standards for accurate assay. Indeed, the technique recommended here is to compare the reading of the calorimeter at the present assay station directly to the reading of an identical calorimeter stationed at the shipper end. The calorimeter reading, as well as the FMD assay results from the shipper, ought to be part of the bill of lading.

Theoretically, a measurement of the thermal power from plutonium can be converted directly to plutonium mass if the relative abundance of each plutonium isotope and americium-241 is known. Practically, this general method for converting calorimetric measurements of power to plutonium mass has two limitations: (1) the nuclear decay constants of the plutonium isotopes used in the conversion are known only to within approximately $\pm 0.5\%$ and (2) the present state-of-the-art in measuring the relative abundance of plutonium isotopes limits the accuracy of this approach. Generally, the precision of the calorimeter measurement is greater than the uncertainty associated with the mass spectrometric determination, which is ⁽⁴⁾ no better than 0.3% for isotopes with concentrations greater than 10%. For isotopes whose concentration lies between 0.1 and 1%, the minimum error is 1%. Concentrations less than 0.1% may have errors from 5% to as much as 100% for concentrations in the range of 0.0010%. Unfortunately, most of the heat

generation in the PuO_2 powder (60% to 80%, see Tables 3-14 through 3-16) is due to the minor isotope ^{238}Pu , which is present with concentrations of 1% to 3%. Therefore, as stated above, it would be advantageous to compare the sample power at any time to the predicted value based on earlier calorimetric determinations. Even with these limitations, the use of calorimetry as an absolute measurement (with an interpretation based on fundamental nuclear constants) is adequate in many situations. ⁽⁷⁾

The presence of a calorimetric assay in sequence with other radio-metric plutonium assay methods of the spontaneous fission rate and quantitative gamma ray spectroscopy (assay N1 and N2) can greatly improve the accuracy of these assay techniques and ease the task of estimating the error in the other NDA methods. Each of the NDA techniques mentioned above is essentially dependent on different isotopes of plutonium. The first two methods, N1 and N2, are susceptible to interferences resulting from variations in the density of the powder being assayed and thus rely on good representative standards for accurate assay. Calorimetry is not susceptible to most of these interferences. Therefore, if the relative abundance of the Pu isotopes is constant for each batch, errors can be detected and calibrations corrected by comparison of assay results for the other NDA methods with calorimetric results.

Components used in a typical calorimeter system are shown in Fig. 3-21. ⁽¹⁸⁾ The length of the calorimeter measurement is dictated by the slow process of achieving thermal equilibrium. Typically 4 to 8 hours are required to come within 0.1% of equilibrium with no servo control of the temperature of the calorimeter chamber and 1-1/2 hours with the servo-control. It is conceivable that 1-1/2 to 1 hour measuring times will be routine for 2 to 3 Kg PuO_2 powder cans. ⁽¹⁸⁾

Fig. 3-21 Components Used in a Typical Isothermal Calorimeter System

The relative accuracy of the calorimetric measurement is 0.1%. The absolute accuracy, which involves an accurate knowledge of the isotopic ratios, is somewhat better than 1%.

Assay Measurement N4 - Spontaneous Fission and Decay Gamma Assay for PuO₂ Powder in Feed Pipe Leading to Storage Vessel

The main purpose of this assay station is to accurately assay the PuO₂ loose powder immediately after transfer from its can and prior to storing it in one of the 15 PuO₂ bulk storage vessels. The fact that the Pu can was manually opened and that its content will be mixed with other cans and stored for several days requires assurance that no tampering with the powder has occurred.

The assay method selected for this station is essentially identical to the assay method selected for N1, a gamma and FMD system. However, in this case, the geometry of the sample container is not predetermined and it is accessible. Conceptually the envisioned geometry is a narrow pipe leading to the storage vessel, with a removable blockage. The pneumatically transferred powder fills the blocked pipe up to a certain height depending on the packing density. The radius of the pipe is chosen so as to reduce the fast neutron multiplication to a level where the density variation effect will contribute less than 1% to the uncertainty of the assay result. The accuracy of the gamma assay for the ²³⁹Pu is also greatly enhanced because of the reduction in the gamma self attenuation.

A description of a conceptual FMD system and NaI(Tl) detector is shown in Fig. 3-22. The conceptual electronic block diagram and its capabilities is identical to that presented in Fig. 3-19 and discussed with assay measurement N1.

Fig. 3-22 Conceptual Schematic Cross Section of the FMD and NaI (Te) System for PuO_2 Powder in the Feed Pipe Leading to Bulk Storage Vessel

Assay Measurement N5 - Small Sample Fissile Assay for PuO₂

The main purpose of this assay station is to continuously assay small samples from the PuO₂ bulk storage vessels to ascertain that no substitution of PuO₂ with other materials (UO₂) is occurring while the material is in storage.

The assay method selected for this station is a passive gamma assay for the 385 keV complex of ²³⁹Pu in thin "absorptionless" samples of PuO₂.

A schematic diagram of the nuclear detection part of the sampling system is similar to the one shown in Fig. 3-23. The main feature of this system is a high efficiency NaI(Tl) well counter. The accurately weighed sample vials are placed into the detector well by an automatic sample changer. The PuO₂ sample weight should be limited to around 1 gram, in order to minimize the self shielding correction. This reduces the uncertainty in this calculated or measured quantity. The estimated accuracy of the measurement is about 1% and the measuring time is less than 5 min.

One or two small sample fissile assay systems in conjunction with a sampling device and a sample changer could continuously provide accurate monitoring of all the PuO₂ bulk storage vessels.

Assay Measurement N6 - Small Sample Fissile/Fertile Assay for MO₂

The purpose of this assay station is to continuously assay small samples from the various MO₂ bulk storage silos to ascertain that no substitution of MO₂ with other material like UO₂ is occurring while the material is in storage.

The assay method selected for this station is identical to assay measurement N5 (see Fig. 3-23)--a passive gamma assay for the 385 keV complex of ²³⁹Pu in small thin samples of MO₂. In addition to the ²³⁹Pu

Fig. 3-23 Schematic Diagram of ^{239}Pu and ^{238}U Passive Small Sample Assay System

(and possibly $^{241}\text{Pu}/^{239}\text{Pu}$ ratio) measurement, the amount of ^{238}U will be measured by the detection of the 766 keV and 1000 keV lines (see e.g. Table 3-9). One gram of MO_2 will typically emit about 3×10^3 γ /sec in the 208 keV line due to ^{241}Pu , and 30 γ /sec in the 766 keV and 80 γ /sec in the 1000 keV lines of ^{238}U (see also Fig. 3-24). Because of the low activity of the ^{238}U , a 5 min. or longer measuring time will be required to get better than 1% counting statistics.

The uncorrected (for possible self-shielding) ratio of the gamma activities of ^{239}Pu and ^{238}U provides a sensitive indication of any serious substitution attempt for each sample measurement. The ratio of the accumulated count of the two isotopes can reveal an attempt for small, but continuous, substitution attempts. Since the required corrections to the data will be small, this assay station could provide the MO_2 plant with very valuable data on the mixing process.

Assay Measurement N7 - Gamma Scan and Pellet Counter at Secure Boat Loading Station

The purpose of this assay station is to count the number of discrete green pellets produced and ascertain that there has been no substitution of pellets with dummy pellets.

The assay technique selected for this station is a passive gamma measurement of the 60 keV (^{241}Am), 208 keV (^{241}Pu) and 385 keV complex (^{239}Pu). This is done with a collimated NaI(Tl) system with three single channel analyzers bracketing the above mentioned lines. The collimation size should be about half the diameter size of the pellet ($\sim 1/2$ cm) since the green pellets come out of the press vertically standing and well separated (about 1.5 in. apart). The integrated count for each pellet would be approximately 5×10^3 , 5×10^4 and 10^6 counts for ^{239}Pu , ^{241}Pu and ^{241}Am ,

respectively. Any major change in these integrated counts when a pellet passes in front of the detector system will indicate a substitution attempt.

Assay Measurement N8 - Gamma Scan and Pellet Counter at Secure Tray Loading Station

The purpose of this assay station is to count the number of sintered pellets produced before they are loaded into the tray and ascertain that no substitution of sintered pellets with dummy pellets has occurred.

The assay technique selected for this station is identical to the one chosen for N7. The only difference is a tighter collimation, since the sintered pellets are transported on a belt, end to end with very small gaps between successive pellets. A collimation of about 0.3 cm and data integration over time equivalent to the passage of a full length pellet, should permit the identification of a dummy pellet.

Assay Measurement N9 - Gamma Scan for Active Length Measurement of Fuel Rod After Welding

The purpose of this assay system is to quickly measure the active length of loaded fuel rod, ascertaining that the exact number (typically 200) of MO_2 pellets have been inserted into the rod.

The assay technique selected for this task measures about 16 rods per hour; it is a collimated (e. g., 0.3 cm collimation) NaI(Tl) system measuring the strong line of ^{241}Am at 60 keV. Using this gamma line, one only scans the surface of pellets. It should also be possible to use the Pu x-ray lines and the ^{241}Pu 208 keV line (see Fig. 3-24) for this relatively high speed (~ 1 pellet/sec) qualitative measurement. The use of 2 to 3 different lines will make a sophisticated substitution (e. g., UO_2 pellet spiked with $^{241}\text{AmO}_2$) virtually impossible.

Fig. 3-24 Typical Pulse Height Distribution From Mixed Oxide (~4% Pu) Fuel Rod

Assay Measurement N10 - Total Pellet-by-Pellet Fissile Content Fuel Rod Scanner

The purpose of this assay station is to accurately measure the total fissile content of the finished mixed oxide fuel rod, and to provide information on the distribution of the pellet-by-pellet fissile content along the rod length. The first requirement of accurate total fissile content is dictated by the RETIMAC system, since this is the last measurement performed (closing the SNM balance) before the rod is shipped. The second requirement of pellet-by-pellet fissile distribution is dictated by the fuel quality assurance (QA) program. Other devices serving QA requirements, such as density and gap measurements, can readily be added to the scanner.

The assay technique proposed for this task is the ^{252}Cf active/passive assay system. A fuel rod scanner based on some features of existing devices^(19,20) is described below.

The ^{252}Cf fuel rod assay system utilizes both active and passive techniques⁽¹⁹⁾ for the measurement of fissile content and pellet-to-pellet uniformity in mixed oxide fuel rods.

For the active portion of the measurement, a 0.5 - 1.5 mg ^{252}Cf neutron source is used to interrogate the fuel rods. The source is positioned at or near the center of the moderator shown in Fig. 3-25 and the fuel rods are moved past the source and into a gamma-ray detector. The total fissile content is then determined by counting the high-energy delayed gamma rays resulting from the induced fission reactions.

The neutron moderator should be designed to give a reasonably hard neutron spectrum irradiation (the irradiation channel is lined with Cd) as well as a high fissile to fertile fission ratio ($\sim 1000/1$). These requirements stem from possible neutron self shielding in the fuel rod and the high ratio

Fig. 3-25 Schematic Layout for a Mixed Oxide Rod Scanner

of fertile ($^{238}\text{U} + ^{240}\text{Pu}$) to fissile ($^{239}\text{Pu} + ^{241}\text{Pu} + ^{235}\text{U}$) * material present in the MO_2 fuel rod.

In order to measure the delayed gamma rays from the fuel rod, a 5 in. diam NaI detector with a through-hole for the passage of the fuel rods is positioned near the output side of the ^{252}Cf shield as shown in Fig. 3-25. Only the high-energy delayed gamma rays (> 1000 keV) are normally used for the total fissile measurement because of their higher penetration through the rod and good signal-to-background ratio.

In addition to the total fissile active assay, it is also possible to determine the pellet-to-pellet uniformity by counting the more intense lower-energy passive gamma rays (see Table 3-17) from the fuel using the background NaI detectors (see Fig. 3-25). The background detectors have a thin tungsten sleeve with a collimation slit of ≤ 0.5 cm. This slit is only effective for the ^{241}Am line of 60 keV. The background detector has one energy window centered on the 60 keV line; a second energy window is located above the Pu x-rays and includes the 385 keV complex to measure radiation relating only to Pu. It thus provides a qualitative measure of the fissile plutonium in the rod (see also Fig. 3-24). If a large change in the ^{241}Am count-rate is not associated with similar change in the "Pu" window, it does not necessarily indicate an off-spec pellet, but possibly a pellet from a different batch with a different amount of ^{241}Pu . A third discriminator for $E_\gamma > 1000$ keV in the background detector measures the background radiation to be used with the delayed gamma signal. It is anticipated that with rod scan speed of about 2 cm/sec, which will comply with the expected throughput of the MO_2 plant (16 rods/hr), the total fissile will be measured with accuracy of about 0.5% and the pellet-by-pellet performance will meet the normal quality assurance requirements. An increase in the expected throughput will require a dual channel rod scanner using the same ^{252}Cf source allowing simultaneous scanning of two fuel rods.

* It is assumed that the degree of ^{235}U enrichment (e.g., 0.7% or depleted to 0.4%) is accurately known from the mass spectroscopy analysis.

The accuracy of the total fissile content depends to a large extent on a good calibration; this is provided by measuring accurate standard rods. The preparation of good standard-rods covering range of mixed oxide fuel rods with various enrichments and burn-ups is an important facet of the scanner operation and usefulness.

3.4 INFORMATION PROCESSING

The function of information processing is to acquire measurement data and translate it into theft indicators and material inventories. This section discusses an appropriate organization of equipment and software to provide the required level of nuclear material accountability. The system design at this point is general. Working Paper B provided the conceptual basis for the system specifications.

3.4.1 Design Criteria

The information processing system is required to support three distinct tasks:

- On-line monitoring
- Process model analysis
- Recording and reporting of results

The first task includes collection of measurement data from the 16 process steps, logical tests of that data for consistency and recording of results. The data recorded will be used for real time consistency checks and for long term analysis and historical reporting.

A second line of defense against theft or accidental loss is provided by process modeling. An additional level of testing is obtained by comparing actual against model performance. This activity is carried out in parallel with and independent of the on-line monitoring. Process model predictions are also recorded for long term analyses and historical surveys. Correction of the model will be performed via feedback from empirical results. Feedback loops may be automatic or manual. Manual feedback loops will require appropriate authorization (see Section 3.4.7).

Each of the above testing techniques has time-base attributes. Some measurements will be sensitive to material diversions during the period of the measurement. If the measurement is direct, a location sensor for example, an immediate theft is indicated. If the measurement is indirect, i.e., based on several direct measurements distributed in time, a longer term diversion is indicated.* The period of direct measurements is typically measured in seconds or minutes. The indirect measurement base may be expressed in hours or days.

The results of the monitoring and modeling activity are recorded and displayed. A variety of central and local process displays are maintained. Other indicators such as bells, lights, closure effectors will be accommodated. The equipment and software for this function may be viewed as a subsystem.

The relationship of the three system tasks described above is shown in Fig. 3-26. This discussion has centered on a single process step. The results of multi-process and whole plant activities will also be tested in a manner paralleling that for a single process. To reduce the chance of subversion of the monitoring system and reduce the likelihood of false alarms, the computer system itself must be checked. System integrity will be verified at random intervals (but never longer than a few minutes). Integrity tests will be of two kinds: instrumentation calibration and software security. The measurements subsystem can be calibrated by means of standard samples, redundant sensors or manual adjustments. Calibration here means a procedure that can return a GO-NO GO response about an instrument within tens of milliseconds. The security of computer programs can be tested by performing polynomial sum checks over the instructions and comparing to hard-wired values. Read-only or hardware program security can be tested by

* Recovery techniques will be different for these two threats. In the case of an immediate theft attempt, alarms sound, etc. Other arrangements are required for longer term diversions.

Fig. 3-26. RETIMAC Process Evaluation

appropriate seal checks on these elements. The security of the RETIMAC system is an important key to its success; the security question is one which deserves more detailed thinking and analysis.

The ultimate result of all foregoing computations is real time knowledge of the location and state of all special nuclear material within the plant. Deviations from the normal plant operating condition triggers one of three states of alert. These have been defined in Working Paper B and are shown in Table 3-21.

3.4.2 System Configuration

The RETIMAC computational system is configured to provide for the following requirements:

- Function reliably
- Distribute processing appropriately
- Serve the management and personnel structure

Reliability of a process stream is a function of the number of elements involved and the quality of those elements. Knowledge of mean-time-between-failure (MTBF) and mean-time-to-repair (MTTR) for all elements is required. Any designed level of reliability can then be obtained by providing redundant processing paths. Two or three fold redundancy will prove adequate at most processing nodes. However, degree of replication of elements will vary depending upon MTBF/MTTR and process criticality.

The computational requirements of some measurements is so high as to require computer processing at the measurement site. The data and computational throughput required by RETIMAC argue for processing data in parallel by a number of computers. The viability and modest cost of microprocessors and minicomputers has been demonstrated in many processing environments. As these hardware elements decline in cost, the principal costs will be for instrumentation and personnel.

TABLE 3-21 RETIMAC INDEX

LEVEL	ACTION STATE	CONDITIONS	REQUIRED ACTION
1	EMERGENCY	PROMPT INDICATORS SIGNAL THEFT ATTEMPT	TAKE REQUIRED ACTION TO CONTAIN MATERIAL AND CAPTURE OR NEUTRALIZE ADVERSARIES. QUARANTINE AFFECTED AREAS, IMMEDIATE SURROUNDINGS, AND PERSONNEL UNDER ARMED GUARD. INTENSIFY PERIMETER MONITORING. SEAL PLANT ENTRANCES AND EXITS EXCEPT TO EMERGENCY PERSONNEL. TRANSMIT ALARMS TO NRC, LLEA. CEASE OPERATIONS PENDING NRC REVIEW.
2	CRISIS	DELAYED INDICATORS SIGNAL SYSTEMATIC SMALL QUANTITY THEFTS	CEASE OPERATIONS. INITIATE INVESTIGATION INCLUDING TOTAL RECOVERY INVENTORY, MEASUREMENT SYSTEMS APPRAISAL, SEARCH FACILITY FOR UNAUTHORIZED MATERIAL STORAGE. TRANSMIT ALARM TO NRC. DETAIN PERSONNEL HAVING ACCESS TO PROBLEM AREAS. CEASE OPERATIONS PENDING NRC REVIEW.
3	ALERT	ABNORMAL CONTROL CONDITIONS NOT CONCLUSIVELY INDICATIVE OF ATTEMPTED THEFT	INVESTIGATE CAUSE -- ESCALATE TO LEVEL 1 IF ATTEMPTED THEFT. IF NOT, DETERMINE CAUSE AND REMEDY UNDER CONTINUOUS OBSERVATION BY MATERIAL CONTROL STAFF PERSONNEL. PERFORM NORMALIZATION TESTS TO CLEAR PROBLEM.
4	NORMAL	ALL INDICATORS WITHIN NORMAL CONTROL LIMITS	CYCLE THROUGH TEST SERIES TO CONTINUALLY UPDATE THEFT INDICATORS.

Specification and development of software and ongoing management of the manufacturing process will be facilitated by locating computational facilities on the same basis as the supporting people organization. Thus, the lines of communication can be defined and implemented in a way that supports rather than inhibits cooperation between working groups.

These considerations lead naturally to a distributed system configuration with several hierarchical levels of computers. A general system block diagram is shown in Fig. 3-27. The following notes apply to the figure:

1. Sufficient measurement signal lines go directly to the on-line computer to validate intervening computers.
2. Some measurements justify their own processing element, typically vendor supplied. Only the measurement result is passed to the on-line computer.
3. Some process or processes may require an initial assessment of data and local display. Typically the on-line system developer will provide this element as well.
4. Many measurements will be passed directly to the on-line computer. However, the instrumentation provided for these measurements may include local data display.
5. State-of-the-plant information will be passed to a data management facility organized on a regional or center basis. Both communications with this facility and RETIMAC Central would use a commercially available data transmission scheme (Bi-sync, SDCL, etc.).

Preliminary judgements regarding redundancy requirements are indicated at each level. Plant and instrument specific analysis is required, as noted above, to establish the appropriate location of processors.

The raw data provided by signal lines (1) plus the results of subsequent analysis are recorded on a random access media (disk) by the on-line

Fig. 3-27. Information Processing System Configuration

RETIMAC computer. This control data base is available to the three on-line computers in the plant control center and could be made available as soon as desired to process computers at the next lower level (by automatic or manual means). Thus as further security against system failure, the provision of a centralized data base permits one processor to assume the burden of another.

Preliminary analysis indicates the following organization of these components:

1. Two on-line computers operating redundantly to support accountability testing. Lack of unanimity between the machines alerts operators.
2. Third computer is available for long term diversion analyses, random over-the-shoulder inspection of on-line operation, program development and maintenance.
3. No process level installations.
4. Three measurement level computers to facilitate nuclear assays at three process steps.

Figure 3-28 illustrates the measurement activity at process module II.

Interactive contact with operating personnel will be required, most notably at receiving, fuel rod inspection and fuel rod shipping. Based on process monitoring or operator requests, a dialogue will be established to collect and authenticate alphanumeric data. Results of alpha checks, seal observation and data from shipping manifests are examples of this kind of input. A video display station with keyboard (and light pen) input is the most likely equipment for this purpose.

The on-line computer will derive from measurement and model results information on the inventory and location of nuclear material. This information will be displayed on equipment located in a central RETIMAC control room.

Fig. 3-28. Measurements for Process Module II

This equipment is shown in Fig. 3-29. Functional requirements for each equipment group are summarized below:

Data Acquisition: Analog and digital input modules acquire process data upon program command.

- Digital switch closures as follows:
 - 600 bits - weighing
 - 2000 bits - storage sensing
 - 1400 bits - process sensing
- Eight analog channels, 12 bits, double-ended, should suffice. (Only a single channel has been identified at this time.)
- Some 29 optical scanner channels are identified. They are interfaced as RS-232B serial by bit ASCII character streams. This equipment is fully redundant.

Command Module: Digital switch outputs to drive controls and indicators are provided. Boat release, storage door unlock, etc. are examples.

- 200 bits - central and remote display
- 100 bits - physical security requirements (e.g., gate closures, bells, etc.)
- 100 bits - process commands*

Remote Terminals: Six video terminals are used at operating stations for entering and displaying data. These terminals have standard type-writer keyboards. A minimum display of eight lines of 40 characters is required. Transmission rate minimum of 100 characters/second is proposed. One spare terminal will be available to replace a failed unit.

Central Control: Supervisory personnel at central control access the following equipment:

* Required only if RETIMAC computer assumes process control duties.

Fig. 3-29 RETIMAC Control Room

- Console for status displays.
- Video terminal to command the system, review data, call for reports, etc.
- Logging Printer, a nominal 30 characters/second device for recording system status messages.
- Report printer, a nominal 300 lines/minute impact printer for publishing system cumulative reports.
- Teletype: This device is available for backup of any of the above devices. It also provides a means of input of paper tapes of equipment diagnostics.

Processing: The controlling element of this system is an extended minicomputer having 32,768 words of local memory (or more if required by an operating system). The computer should be well adapted (via input/output flexibility, interrupt handling) to real time functions. Interfaces to peripherals equipment reside in the computer. The associated peripherals are:

- Disk: A top-loading cartridge disk system with storage capacity of 10 million characters is sufficient for accountability and probably would accommodate process control functions. Two media are required, at least one of which is removable.
- Magnetic Tape: The magnetic tape will be used as a means of communication with other systems and as storage of historical data.
- Synchronous Modem: On-line communication with RETIMAC Central will be provided by this device. The line protocol required by the RETIMAC Central computer will be implemented in the minicomputer.

Switch Module: Manual switches operating relays will be provided to shift peripherals from 'on-line' to 'stand-by' processing strings. Switches will exist for each peripheral device, although similar units may be 'ganged' to a single operator console switch, e.g., all remote displays.

All of the central equipment is triply redundant except as follows:

peripherals such as console status displays, magnetic tape and teletype are not critical to system performance. Loss of these units for short periods for maintenance would not effect plant monitoring.

3.4.3 Data Processing Systems Analysis

In the preceding sections, sixteen process steps associated with PuO_2 mixed oxide fuel manufacturing have been discussed. The measurements required for material accountability are based on a detailed analysis of each process control step. The D.P. equipment, operator and equipment I/O, and system process associated with each of these steps is summarized for Steps 1A and 2A. Similar treatment is accorded each process step based on the measurement data available and plant time analysis.

Steps 1A and 2A

Operator Stimuli:

Operator ID, Shipping Manifest data, Alpha Scan and Visual Seal Inspection Pass/No Pass.

Process Stimuli:

- I1 L-10 container optical label read; at dock
- I2 L-10 optical label read; at weighing station
- I3 L-10 optical label read; at assay station
- W1 L-10 gross weight
- N1 Nuclear assay of L-10 for PuO_2
- S1 Optical scan of seal
- L1 L-10 container present at storage location
- R1 Gamma level at receiving dock

Information Processing:

1. Operator ID check
2. Shipping Manifest check (is shipment expected?)

3. Display instructions to operator, request acknowledge each manual process step.
4. Verify I1, I2 and I3 against shipping manifest.
5. Verify W1, N1, S1 against shipping manifest. Log W1 and N1.
6. Check elapsed time between stations I1, I2 and I3.
7. Check residual gamma level R1 during unloading.
8. Request operator assigned storage location. Record assignment verify container reaches position L1.
9. Periodically scan L1 for container present.

Equipment at site:

Video operator station
Scale interface
Optical scanners (3)
Storage presence detectors (89)

3.4.4 Equipment

The processing requirement is consistent with minicomputer processors. The inherent flexibility in configuration of these devices also supports their use in this system.

All equipment indicated by initial processing estimates falls within the realm of present commercial standards. Subsequent evolution of the technology provides a conservative cushion for these estimates.

The rough processor specification would include the following features:

- Priority interrupt structure.
- Sub-microsecond cycle time.
- Hardwired floating point arithmetic.
- Instruction set suited to both arithmetic and operations file management.
- Input/Output structure to readily accept many and varied devices.

- Memory protect feature.
- Asynchronous memory.

Desirable characteristics of the processor would be multiport memory access and inter-computer communication path. These features would facilitate the network structure of machines. It would simplify the software required to implement, for example triply redundant, simultaneously acting processors using a majority voting decision principle.

It is desirable that all computing elements in the RETIMAC system be supplied by a single vendor and integrated by the system contractor. This will represent the best use of resources during development and downstream maintenance. It is recognized that microprocessors and minicomputers that are integral to instrumentation packages would not be subject to this consideration.

The following complement of processors is foreseen:

- a. RETIMAC Control Room - 3 Processors
- b. Process Computers - No present need
- c. Measurement Computers - 6 (2 each,
Process Steps 1A, 5 & 14)
- d. Region or Center Processors - 2 Processors*

Representative equipment vendors capable of supplying processors, peripherals and operating system software suitable for this system are the following:

<u>Vendor</u>	<u>Model</u>	<u>Operating System</u>
Varian Associates	V73	VORTEX
Digital Equipment Corp.	PDP11-45	RTSX-110
Hewlett-Packard	2100MX	RTE III
Data General	Eclipse C300	RDOS/INFOS
Modular Computer Systems	Modcomp IV	BOSS
Interdata	8/32	OS32/MT

* This optional level may be outside the scope of a plant RETIMAC development.

3.4.5 Software

The performance attributes of this system are determined by its software. The salient points of concern in the RETIMAC system are as follows:

- Large number of user stations.
- Combination of arithmetic and data management tasks.
- Signal sources equally divided between synchronous (input scheduled by computer) and asynchronous (input cannot be anticipated).
- External events will have different priorities.
- Variety and number of input signals.
- Maintainability.

Table 3-22 notes a suitable organization of major programming segments. This breakdown facilitates management of development, documentation and maintenance. The suggested structure is that of a number of co-routines utilizing variable time slices to support each user. Each program (except the Executive) is re-entrant so that it can be used concurrently by several stations. This organization is due to RAND and supports multi-user situations effectively (Ref. 22). Alternatively, a vendor supplied disk-based operating system could be employed. Several credible efforts are presently in the marketplace (Ref. 22).

The Executive module provides those machine dependent routines used for input/output, interrupt processing, and memory allocation. The Transient program is executed only upon recognition of a "wake-up" call. Posting of time displays is a simple example. The Supervisor program exercises a general overview of system performance. The Supervisor is normally tied to a video terminal in the RETIMAC control room. A variety

TABLE 3-22 MAJOR SOFTWARE MODULES

- **EXECUTIVE**
 - ▲ **RESOURCE ALLOCATION**
 - ▲ **USER BLOCK MULTIPLEXING**
- **TRANSIENT**
 - ▲ **PERIODIC WAKE-UP**
 - ▲ **SCANS STORAGE FACILITIES**
 - ▲ **UPDATES STATUS HISTORY TO DISK**
 - ▲ **MAKES TIME BASED DISPLAYS**
- **SUPERVISOR**
 - ▲ **OPERATOR COMMAND FUNCTIONS**
 - ▲ **MAINTENANCE OF FILES**
 - ▲ **AUTHENTICATES USER TRANSACTIONS**
- **ALARMIST**
 - ▲ **OBSERVES ALARM FILE**
 - ▲ **DISPLAYS ALARMS TO PROCESS AND SECURITY OPERATORS**
 - ▲ **EFFECTS REQUIRED CLOSURES**
- **PROCESS k (1 BLOCK EACH OF 21 PROCESSES)**
 - ▲ **MONITORS PROCESS**
 - ▲ **PERFORMS FILE UPDATES**
- **MODEL k (1 BLOCK EACH OF 21 PROCESSES)**
 - ▲ **GENERATE PREDICTED PROCESS STATE**
 - ▲ **RECORD PREDICTIONS TO DISK**
- **SPOOLER**
 - ▲ **DUMPS REPORT TEXT TO PRINTER WHEN AVAILABLE**
 - ▲ **INITIATES LOGGING MESSAGES**

of system command functions can be executed by this program including on-line maintenance of files. An important activity of this program is checking the authority of any user input (including the Supervisor himself). Special program to effect displays are characterized by the program Alarmist. High priority indications of alarms are handled by this program. An in-core matrix of alarm conditions is set by Process programs and reviewed by Alarmist. The Process programs use measurement data, as noted in Section 3.4.3, to provide theft indicators. State data is recorded to disk for long term small scale diversion analysis and delayed theft indicators. A process block of code exists for each process. A final process block provides consistency checks for inter-process and whole plant activity. An example of combination of measurements to provide theft indicators is shown in 3.4.3 in the form of boolean equations and algorithms. Each process block also includes an estimator section that compares actual to model generated data. Parallel to each Process block is a Model block. Running separately but synchronized by time and status, these blocks provide predictions of material and vessel states for comparison to actual process operation. Model parameters are derived from theoretic and empiric results. Should resources permit, an automatic feedback mechanism could be coded as a part of the process model to use run data on the disk (from an extended period) for updating model parameters. The Spooler program handles reports requiring extensive data collection and printing. This low priority code buffers text on the disk till time and equipment are available for printing.

Software specification will proceed from finer detailing of the accountability process. Development must be in a higher level language for ease of documentation and maintenance. It is expected that in a highly interactive system that the installation/final debugging process will require intensive effort. Language and operating systems that enhance diagnosis and correction

of software troubles are key to a successful effort. Therefore, a structured language in a real time disk based operating system would be most desirable.

Because of the variety and extent of data input, some Input/Output driver software will be implemented in assembly language.

3.4.6 Database

The system database will be established in a number of files. These files are defined on the disk storage unit but may be core or disk resident when in operation, i.e., frequency of use may cause particular file data to be retained indefinitely in local memory.

About two million characters of storage are required for the RETIMAC system. Average access time to any data item may range up to 100 milliseconds without impact upon system performance. This is within the bounds of present commercial equipment.

Files will be locked and made inaccessible to unauthorized operators by using a variety of software and hardware techniques, e.g., operator passwords, read-only hardware, etc.

The initial estimate of file requirements is noted in the following table:

<u>Receiving File:</u>	1 Record for each can 2 cans per L-10 container One year's history maintained Bill of lading information noting accounting data, weight, container, numbers, etc. Approximately 5400 records, 60 characters/ record Total 324,000 characters
<u>Material File:</u>	500 characters for each process and model 50 processes Current material weight maintained for ready inventory of material Total 50,000 characters

Shipping File: 1 Record each shipment
 100 shipments/year
 One year's history maintained
 Approximately 100 records, 80 characters/record
 Total 8,000 characters

Fuel Rod File: 1 Record per rod
 400 rods/day
 Maintain 2 month history
 Approximately 20,000 records, 40 characters/
 record
 Total 800,000 characters

Storage Files: 1 Record per slab
 500 slabs/storage
 4 storages
 Container ID, weight, Occupancy
 Switch
 2000 records, 10 characters/record
 Total 20,000 characters

Container Files: 1 Record/Container
 Boats, Trays
 Container ID, Weight, Status/Time pairs
 1000 records, 20 characters/record
 Total 20,000 characters

Alarm File: One record file of all alarm conditions. Although
 defined as a file for convenience, it is typically
 core-resident. An alarm may be off (=0) or on
 (=time alarm set)
 Total Negligible

Program Files 500,000 characters
 Spool File 100,000 characters
Miscellaneous Database 50,000 characters
 Accountability Database 1,872,000 characters

3.4.7 Operating Procedures

Operating procedures will be defined to support and enhance automated techniques. Additional physical security arrangements will be made to satisfy the implicit timing of theft indicators.

A primary requirement of all interactions between personnel and the RETIMAC system is that the transactions be authorized. Two primary techniques are suggested.

- a. Access restrictions both, physical and programmed, will preclude use of most system options from most user stations. For example, switching of equipment and data media will be available only from full-function video terminals within the Control Room; input of container identification at the receiving dock is programmatically restricted to the assigned terminal at the receiving dock;
- b. Passwording: A personal password will be used by each system operator. No function may be performed unless an authorized operator has logged in with an appropriate personal password. When a new operator is assigned, he is introduced to the system by his supervisor. The supervisor establishes work shift and authorized work stations; the operator selects and defines to the system his personal password (a combination of not less than two digits and two letters).

4. DETERMINATION OF REPRESENTATIVE TIME INTERVAL (τ) TO CARRY DIVERTED SNM OUTSIDE THE MATERIAL PROTECTION SYSTEM BOUNDARIES

The physical plant layout for the Westinghouse MO_2 fuel plant was used to map out potential diversion paths. The following characteristics have been assumed to describe the diversion and subsequent transport of SNM outside the plant boundary.

diverter walking speed - 3 mph
diverter-vehicle driving speed - 15 mph (within inner perimeter)
health physics/air lock delay time - 3 min.
clothing change time - 5 min.
gate delay time (personnel) - 1 min.
gate delay time (vehicle) - 5 min.
penetration time of restricted access area - 1 min.
penetration time of limited access area - 1 min.

The values for τ shown below represent diversion paths for which the diverter violates no plant safety or procedural rules. The diverter personally transports the SNM through the plant gate at the inner security perimeter. Paths considered include those which require that the diverter be carried in a vehicle from the truck loading dock to the plant gate at the inner security perimeter.

<u>Diversion Point</u>	<u>τ (min.)</u>
Manufacturing Building	14 ± 1
Rod Inspection Building	5 ± 1
Receiving Dock	8 ± 1

If procedural and safety rules are violated (e. g. emergency exits are used, material is thrown over the inner perimeter fence to be picked up later, unauthorized pathways through the shipping area are used to exit the rod inspection area), the material alone or the material plus diverter could be outside the inner security perimeter in about 3 minutes.

Additional procedures can be instituted to cause an increase in τ . Several examples of the impact on τ of more restrictive security measures are given below:

Example 1

Access to the rod inspection building and to the loading dock is limited to a single path through a health physics/security inspection area (similar to the air lock access to the manufacturing building). Delay time in the inspection area is 3 minutes. All plant personnel are required to wear work uniforms; they are required to shower, change clothes, and check out of the locker room before leaving the facility (delay time = 5 min.).

<u>Diversion Point</u>	<u>τ (min.)</u>
Manufacturing Building	14 + 1
Rod Inspection Building	13 + 1
Receiving Dock	Same as rod inspection building

Example 2

Private autos are parked outside a gate at the outer plant perimeter (0.6 miles from the inner plant perimeter entrance). Personnel are transported by bus to the plant perimeter where they pass through a

second guard station (personnel ID check only) to the parking lot.

Delay during bus transport = 8 min.

$$\tau = 20 \text{ min.}$$

The same effect produced in Example 2 could be achieved by requiring an 8 minute delay at the outer perimeter guard station for all personnel leaving the plant.

The present study does not directly address the relationship of RETIMAC with the physical security system. However, one immediately observes the strong interaction between physical security measures and RETIMAC requirements when considering changes in τ . Results from this section are summarized in Table 4.1.

**TABLE 4-1 DETERMINATIONS OF τ FOR WESTINGHOUSE MO₂
FUELS PLANT, ANDERSON, S. C.**

SECURITY LEVEL	DIVERSION POINT	DIVERSION PATH	τ (MINUTES)
NORMAL	MANUFACTURING BLDG	AUTHORIZED	14 ± 1
NORMAL	ROD INSPECTION BLDG	AUTHORIZED	5 ± 1
NORMAL	RECEIVING DOCK	AUTHORIZED	8 ± 1
NORMAL	ALL BLDGS	UNAUTHORIZED	~ 3
MODERATE INCREASE	ALL BLDGS	AUTHORIZED	13 ± 1
SIGNIFICANT INCREASE	ALL BLDGS	AUTHORIZED	~ 20

5. ANALYSIS OF RETIMAC RESPONSE TO MATERIAL DIVERSION

The plant RETIMAC system responds to a diversion of material from the production line by generating material theft indicators. A RETIMAC system designed along the conceptual guidelines presented in Ref. will typically generate redundant theft indicators for any specific material diversion. The total number of theft indicators per diversion and the times during the diversion at which these indicators appear comprise the essential data for an evaluation of the anti-theft effectiveness of RETIMAC. The descriptions of the techniques used to obtain this data for the model MO₂ plant (Section 2) and presentations of the results are contained in this section.

5.1 TECHNIQUE DESCRIPTION

A representative sample of possible diversion points was selected for the plant model described previously. Diversion points were selected in all areas of the plant. Multiple diversion points were selected at every process stage where plant personnel have direct contact with the material or where the material is contained in forms, concentrations, and packages most attractive for diversion. Fewer diversion points were selected in process stages where the material is awkward or difficult to divert. The positions of diversion points included in the sample are shown in Fig. 5-1 through Fig. 5-3. The diversion points are labeled D1 - D25.

An event tree, describing the RETIMAC response to a diversion, was constructed for each diversion point in the sample. Each event tree starts with the act of penetrating a limited or restricted access enclosure or the material containment vessel. Continued development of the event

Fig. 5-1. Top and Side Views of 2nd Floor Manufacturing Building for Commercial MO_2 Fuel Plant Model 1

Fig. 5-2. Top and Side Views of 1st Floor Manufacturing Building for Commercial MO_2 Fuel Plant

- 1 FUEL ROD AIR LOCK
- 2 He LEAK TEST VACUUM CHAMBER
- 3 GAMMA SCAN STATION
- 4 PRE X-RAY STORAGE
- 5 X-RAY WELD INSPECTION
- 6 POST X-RAY STORAGE
- 7 WEIGHING & PHYSICAL INSPECTION
- 8 TRACKS
- 9 SHIELDED CARRIER

- 10 INSPECTED ROD STORAGE
- 11 BOX LOADING TABLE
- 12 MOTORIZED TRANSFER DOLLY
- 13 SHIPPING CONTAINER
- 14 TRUCK WELL
- 15 TUBE & BOTTOM PLUG RECEIVING
- 16 BOTTOM PLUG WELDING
- 17 PRE X-RAY STORAGE
- 18 X-RAY WELD INSPECTION
- 19 POST X-RAY STORAGE

Fig. 5-3. Top and Side Views of 1st Floor Fuel Rod Inspection Building for Commercial MO_2 Fuel Plant Model

tree traces the behavior of RETIMAC system in time as RETIMAC checks for unauthorized actions, records material measurements, and monitors the location of material within the system. Two examples of event trees for the MO_2 plant model are shown in Figs. 5-4 and 5-5. These correspond to diversion points D4 and D10 in Fig. 5-1.

The first example (D4) describes a diversion of PuO_2 in the PuO_2 unloading area (process Step 3A). The diversion scenario follows: using manipulators, the diverter removes an inner can from the calorimeter and cuts off the top with a mechanical can opener (a normal operation). The diverter then transfers only a fraction of the PuO_2 to the bulk storage weight hopper and attempts to divert the remainder. The series of events which follow this action are shown to the right of the event tree. Those events which initiate RETIMAC diversion indicators are shown with vertical legs extending to the bottom of the diagram. The indicators appear unless the monitor, locator, measurement device, and related data processing units fail to operate or are somehow circumvented by the diverter. Some indicators have a lower limit of sensitivity or cannot detect a substitution of similar material (such as uranium oxide). The sensitivity limits are noted in parentheses (); inability of the device or monitor to detect material substitution is denoted by the term "no sub" within the parentheses.

The elapsed time from the beginning of the diversion attempt, to each event which can initiate a diversion indicator, is given in the lower portion of the figure. The time (zero) at which material is diverted from the line is denoted with the symbol "D". Time intervals before "D" are preceeded by a negative sign; time intervals after "D" are positive. The time sequence for the appearance of indicators at each diversion point is referred to as a "time line."

Fig. 5-4 Event Tree For Diversion Point 4

Fig. 5-5 Event Tree For Diversion Point 10

A total of 25 diversion points were chosen in the sample under study. Three different quantities of diverted material were considered at each point. The definitions of these quantities change slightly at different points in the process, but they correspond roughly to: (A) 1 to several Kg PuO_2 , (B) 100 to several hundred grams PuO_2 , and (C) approximately 10 g PuO_2 . Table 5-1 gives specific definitions for the quantities of material considered.

Table 5-1. Quantities of Diverted Material Considered

Area	A	B	C
PuO_2 (process steps 1A - 5)	Inner can of PuO_2 powder (2, 25 Kg) 1 Kg PuO_2 powder	100 g PuO_2 powder	10 g PuO_2 powder
MO_2 (process steps 6-12)	10 Kg MO_2 1 pellet boat (4.5 Kg MO_2) 1 pellet tray (9 Kg MO_2)	1 Kg MO_2 or 100 pellets	100 g MO_2 or 10 pellets
Rod Loading (process Step 13)	1 complete rod (2 Kg MO_2)	1 Kg MO_2 or 100 pel- lets	100 g MO_2 or 10 pellets
Rod Inspection (process Steps 14-15)	1 complete rod (2 Kg MO_2)	1 broken rod ($\leq$ 2 Kg MO_2)	-
Rod Snipping (process Step 16)	$\leq$ 1 channel (1-50 rods; 2-100 Kg MO_2)	-	-

At each diversion point, and for each quantity of material considered, the cases of (a) material substitution (UO_2 substituted for PuO_2) or (b) no material substitution were both considered. The total number of individual diversions (and associated time-lines) considered in this study was 129.

5.2 SUMMARY OF RESULTS

The results from analysis of the time lines are displayed in Figs. 5-6 through 5-10. Figures 5-6 through 5-9 show the cumulative number of RETIMAC

PuO₂ AREAS

Fig. 5-6 Average Cumulative Number of RETIMAC Diversion Indicators As a Function of Time for PuO₂ Areas (6 Diversion Points)

Fig. 5-7 Average Cumulative Number of RETIMAC Diversion Indicators As a Function of Time for MO₂ Areas (11 Diversion Points)

Fig. 5-8 Average Cumulative Number of RETIMAC Diversion Indicators As a Function of Time For Rod Loading Area (2 Diversion Points)

Fig. 5-9 Average Cumulative Number of RETIMAC Diversion Indicators for Area Handling Completed (Welded and Sealed) Rods

ROD INSPECTION AREAS

Fig. 5-10. Average Cumulative Number of RETIMAC Diversion Indicators for Individual Areas. Data Includes both Substitution and No-Substitution Diversions and All Three Weight Categories

theft indicators which are initiated as a function of time during the diversion for the plant areas indicated. The data is presented separately for diversion of different quantities of material and for the material substitution and no-substitution cases. Figure 5-10 shows the combined results for individual plant areas which include all three weight categories of material and both substitution and no-substitution cases. The relative dependence of the RETIMAC system on access indicators in each plant area is shown in this figure.

6. RETIMAC EVALUATIONS

The RETIMAC system response data given in the previous section for the MO_2 plant model and other model parameters are examined from several different aspects in order to evaluate the effectiveness of RETIMAC in meeting stated design goals and objectives.

6.1 EVALUATION OF RETIMAC OBJECTIVE 1

A stated objective (hereafter referred to as Objective One) of the RETIMAC concept is "to detect any covert attempt to steal special nuclear materials in a time frame that is adequate to contain subcritical quantities of special nuclear material within the boundaries of the material protection system." This section compares RETIMAC performance in the model MO_2 plant with Objective One.

The RETIMAC response data (in terms of the average number of cumulative alarms which are initiated as a function of time during a diversion) for the entire plant have been broken down into plant areas (Figs. 5-6 through 5-10). The data are displayed in this manner instead of combining the results for the entire plant because comparisons of the RETIMAC response characteristics for individual plant areas show important differences; this point is illustrated by comparing the shapes of the histograms shown in Fig. 5-10.

Underlying explanations for some of the important differences in response between areas are:

- Unauthorized access indicators are typically set off shortly before or at the time the material is physically removed from the

process line; they provide early indication of a diversion. Unauthorized access indicators are found in areas where there is no requirement for personnel to come in direct contact with the material (e.g., the MO_2 area and to a lesser extent the PuO_2 and shipping areas). Redundant access indicators are relatively easy to design into the system in these areas.

- Measurement or material loss indicators are set off after material is physically removed from the process line. They can be used anywhere in the plant. In areas where plant personnel normally come in direct contact with the material, they are the only available diversion indicators (e.g., the rod loading area). In these areas, redundancy in theft indicators can be achieved by spacing measurements close enough together so that a loss in the normal process flow rate will trigger a given number of indicators in a specified time frame.
- Locators in the buffer and vault storage areas can provide theft indicators at the time material is diverted from the process. They are most useful in areas where material flows into and out of the storage area via programmed conveyors (e.g., L-10 containers, green pellet boat, sintered pellet boat, and finished pellet tray storages). Constant weight monitors of bulk storage vessels also serve as effective locators with programmed pneumatic transfer of material into and out of storage (e.g., PuO_2 and MO_2 bulk storage). Locators are of marginal usefulness in storage locations where plant personnel manually load and unload the storage and where the storage has a large throughput of material (e.g., fuel rod inspection area).

In view of the differences observed in RETIMAC response between different plant areas, the ability of the RETIMAC system to achieve Objective 1 will be considered as a function of individual plant areas versus the entire plant as a single entity.

Tables 6-1 and 6-2 compare the RETIMAC response data with results from Section 4 on τ (τ is the representative time interval required to carry diverted SNM outside the material protection boundaries).

Table 6-1. CUMULATIVE RETIMAC DIVERSION INDICATORS OCCURRING WITHIN τ FOR NORMAL PLANT SECURITY CONDITIONS

Area	Approximate τ (min)	Average Cumulative Number of RETIMAC Diversion Indicators Occurring Before τ for Specified Classes of Diversion							
		A*		B		C		All	
		No-Sub	Sub	No-Sub	Sub	No-Sub	Sub	Access	Total
P _u O ₂	15	3.6	2.9	3.2	2.9	3.2	2.7	1.6	3.1
MO ₂	15	3.6	2.9	3.5	2.8	3.1	2.8	2.2	3.1
Rod Loading	5	0	0	0	0	0	0	0	0
Rod Insp.	5	0	0	0	0	0	0	0	0
Shipping	5	1.3	1.0	- Not Applicable -				1.0	1.3

*A,B,C refer to amounts of material diverted (approximately equivalent to 1 Kg, 100 g, 10 g, and P_uO₂ respectively. (See Table 5-1).

Table 6-2. CUMULATIVE NUMBER OF RETIMAC DIVERSION INDICATORS OCCURRING WITHIN τ FOR A MODERATE INCREASE IN PLANT SECURITY*

Area	Approximate τ (min)	Average Number of RETIMAC Diversion Indicators Occurring For Specified Diversion Classes							
		A		B		C		All	
		No-Sub	Sub	No-Sub	Sub	No-Sub	Sub	Access	Total
P _u O ₂	15	3.6	2.9	3.2	2.9	3.2	2.7	1.6	3.1
MO ₂	15	3.6	2.9	3.5	2.8	3.1	2.8	2.2	3.1
Rod Loading	15	1.0	1.0	2.0	1.0	2.0	1.0	0	1.3
Rod Insp.	15	0	0	0	0	0	0	0	0
Shipping	15	2.0	1.7	- Not Applicable -				1.0	1.8

*The increase essentially requires similar health physics and safety measures to be applied to the rod inspection building and dock areas as are normally applied to the manufacturing building. See Section 4, Example 1.

Table 6-1 results can be summarized for all cases considered as follows: the PuO_2 and MO_2 areas are well protected by RETIMAC (in terms of theft indicator redundancy). Some protection is afforded the shipping area. The fuel rod loading and fuel rod inspection areas are not protected.

Table 6-2 results, corresponding to a moderate increase in security, * can be summarized as follows: the PuO_2 and MO_2 areas are well protected by RETIMAC. Less, but adequate protection is afforded the fuel rod loading and shipping areas. The fuel rod inspection area is not protected by RETIMAC.

The same analysis, assuming a τ of 20 minutes for the entire plant (see Section 4, example 2), gives results which are very similar to those shown in Table 6-2.

With a minor increase in plant security procedures, * the RETIMAC system, as designed for the model MO_2 plant, can produce redundant theft indicators within the time period τ for covert diversions of material from the main process stream in all plant areas except the fuel rod inspection area. The redundancy in theft indicators is higher for the areas handling material in forms most attractive for diversion (PuO_2 areas). This level of protection was achieved by making only minor changes in material handling systems which are being specified for commercial MO_2 plants now on the drawing boards. With the exception of the fuel rod inspection area, the specified RETIMAC system does detect covert diversions of material in a time frame adequate to contain subcritical quantities of material within the plant boundary. At this stage of the study, subcritical refers to quantities of material

* The increase essentially requires that similar health physics and safety measures be applied to the rod inspection building and dock areas as are normally applied to the manufacturing building. See Section 4, example 1.

greater than 10 g PuO_2 or 100 g MO_2 . The present study therefore demonstrates that a RETIMAC system which makes maximum use of existing commercial design features can satisfy Objective 1 for all areas of a commercial MO_2 plant with the exception of the fuel rod inspection area.

Analysis of the data available also shows that the portion of the RETIMAC system in the fuel rod inspection area could be designed to produce redundant alarms within a time τ of 15 minutes. The following steps would be required:

- Automate the fuel rod inspection process from pre-inspection storage to the final visual inspection. This would include the leak test, x-ray, and pellet-by-pellet assay inspection stations and all transport between stations.
- Install buffer storages with automated rod placement and retrieval. Place locators at every present rod storage location (~ 1000) in the inspection area.

This automation would constitute a major revision to present planned commercial plant designs. An alternative route for providing protection would be to rely on physical security in the fuel rod inspection area. Although outside the scope of this study, the following simple but important points should be mentioned concerning this alternative approach:

- The material is contained in sealed rods with individual identification markings. An entire rod or rods must be diverted or a rod must be broken into and a portion of the material diverted.
- Simple physical access measures (e.g., revolving doors) can prevent the 12-foot length rods from being removed from the inspection area except in sealed channels through a single authorized access port.
- Every broken rod with pellets missing and every total or partial rod substitution will be detected within 24 hours and the plant would know with certainty that a diversion had taken place. Multiple diversions of small amounts of material are therefore not feasible in this area.

- The diverter would have to remove 125 Kg of material (about 60 rods $\approx 1/2$ of an 8-hour shift production) in order to obtain 5 Kg of PuO_2 in a single diversion. A scenario in which this can reasonably take place is difficult to envision.

Although a thorough cost analysis has not been performed, the considerations above lead one to believe that specifying physical protection measures may be a more effective and less costly way to produce a level of diversion protection in the fuel rod inspection area which is comparable to that provided by RETIMAC in other areas of the plant.

6.2 ACTIONS REQUIRED TO PERFORM A SUCCESSFUL COVERT DIVERSION

This section lists the minimal actions required by the diverter(s) to fool or circumvent the RETIMAC system for a period of 15 minutes following the removal of more than the equivalent of 10 g PuO_2 or 100 g MO_2 from the main process line at representative points throughout the plant.

Area	Actions Required
PuO_2 unloading dock	By-pass the automatic seal check. Unloader fails to report defect on visual seal check. Remove the material without contaminating the L-10 container. Remove less than 100 g PuO_2 and substitute an equivalent amount of UO_2 within about 10 g or remove less than 10 g PuO_2 . Perform these operations in about 6-8 minutes without being observed.
L-10 storage vault	Subvert vault access alarms. Remove material without disturbing locator. Avoid TV surveillance within the vault.
L-10 opening compartment	Subvert a glove box penetration alarm. Remove less than 200 g PuO_2 at the L-10 container opening station and substitute an equal amount of UO_2 with a weight difference of less than 0.1 g.

Area	Actions Required
L-10 opening compartment (cont.)	Reseal the outer and inner cans before transferring them to the next compartment.
PuO_2 bulk storage	Subvert restricted area and vault access alarms. Remove less than 100 g PuO_2 . Remove material without triggering α -monitors. Remove material without disturbing weight monitor. Avoid TV surveillance within the area.
Blender	Subvert restricted area access alarm. Remove less than 200 g PuO_2 . Avoid TV surveillance within the area.
MO_2 storage	Subvert restricted area access alarm. Remove less than 200 g MO_2 . Remove material without disturbing weight monitor. Avoid TV surveillance within the area.
Pelletizing	Subvert restricted area access alarm. Subvert glove box penetration alarm. Remove less than 10 Kg of MO_2 . Avoid TV surveillance within the area.
Green pellet storage	Subvert restricted area access alarm. Substitute an equal amount of UO_2 material for MO_2 or remove less than 100 g MO_2 . Remove material without disturbing locator. Avoid TV surveillance within the area.
Sintering	Subvert restricted area access alarm. Subvert secure conveyor penetration alarm. Substitute an equal amount of UO_2 material for MO_2 . Avoid TV surveillance within the area.
Sintered pellet storage	Same as green pellet storage (above).

Area	Actions Required
Pellet grinding	Subvert restricted area access alarm. Subvert glove box penetration alarm. Avoid TV surveillance within a restricted area. (Weight loss indicator appears within 20 minutes unless equal amount of UO_2 material substituted for MO_2).
Finished pellet storage	Same as green pellet storage (above).
Tube loading	Remove material through empty rod insertion port or subvert glove box penetration alarm. Subvert glove box residue monitor after removal of material. Substitute an equal number of UO_2 pellets for MO_2 pellets. (Active length scan indicator appears within 22 minutes for all diversion scenarios).
Tube welding	Remove material through finished rod storage access or subvert glove box penetration alarm. Subvert glove box residue monitor after removal of material. Substitute an equal number of UO_2 pellets for the MO_2 pellets. Subvert active length measurement.
Channel storage	Subvert vault access alarm. Substitute UO_2 material for MO_2 . Remove MO_2 without disturbing locator. Avoid TV surveillance within the area.
Channel loading	Subvert automatic seal check. Substitute an equal amount of UO_2 material for the rods which are taken. Perform the operation in less than 5 minutes.

If the steps listed above are undertaken by the diverter, it only assures that he will not be detected within 15 minutes after removing the material; the sequence of steps do not imply that the diversion will not be

detected at later times. The preceding is a list of the fewest number of direct steps that a diverter can take to accomplish his goal. There are many more sophisticated and complicated routes to diversion which can be postulated. Diversion schemes which include tampering with the RETIMAC software are a very important subset of these more complex routes; they are mentioned here for completeness, but are not considered in the present study.

To summarize briefly, in all cases considered, at least three independent steps must be taken to avoid detection of the diversion within 15 minutes; the average number of steps is about four. Every successful diversion considered requires that only a relatively small amount of material be removed (<0.2 Kg) or that UO_2 material be carefully substituted for the MO_2 that is removed. In most cases, except where a very small amount (<10 g PuO_2 and <100 g MO_2) of material is taken, the diversion will be identified at a later time.

6.3 RETIMAC COMPARED TO A CONVENTIONAL ACCOUNTABILITY SYSTEM

This section discusses the relative effectiveness of a conventional accountability system (limited NDT, no computer, chemical sampling) with the RETIMAC system. The model MO_2 plant, with and without a RETIMAC system, forms the basis for the discussion. As in previous sections, the approach chosen was to consider individual plant areas versus the entire plant as a whole.

PuO_2 Areas – The most substantial reduction in the plant's vulnerability to diversion due to the introduction of RETIMAC takes place with the specification of secure conveyors for L-10 container transport within the plant and with the designation of the L-10 container storage as a RETIMAC vault

storage area (no personnel access during normal operation). This enhances the effectiveness of access indicators and TV surveillance, measures employed under both conventional accountability (CA) and RETIMAC systems. In addition, even assuming the CA and RETIMAC systems both have the same access indicators, the CA would have none of the four RETIMAC on-line nuclear assay measurements and only 4 of the 6 RETIMAC weight measurement stations. These devices account for more than half of the redundant diversion indicators in the plant areas which contain material in the most attractive form for diversion. The CA system would rely almost completely on access diversion indicators in PuO_2 areas; this is not adequate because there are several points in the process where personnel are normally in direct or remote contact with the material. In summary, CA provides some protection against diversion in the PuO_2 areas; RETIMAC enhances that protection substantially.

MO₂ Areas - Both the CA and RETIMAC systems rely heavily on access control in the MO₂ areas. Since a completely automated material handling system was specified for the CA system, RETIMAC offers only limited additional protection. One of the areas where increased protection was achieved with the RETIMAC system is in buffer storages where locators are specified. In summary, RETIMAC provided some additional protection against a successful diversion compared to CA, but only a moderate amount.

Rod Loading Area - The RETIMAC system specifies individual rod identification symbols, limited storage capacities between process steps, active length measurements, residue monitors and secure conveyors for transport between steps. These requirements provide all the diversion indicators shown in Fig. 5-10. The CA system would have to rely completely on physical security at this stage in the production process. RETIMAC provides adequate protection against diversion through timely detection in

the rod loading area; CA provides little or none.

Rod Inspection Area — Problems with RETIMAC design in this area are discussed in Section 6.1. The RETIMAC design described in Section 3 provides very good item control information, but does not offer any significant advantage in preventing a diversion through timely detection.

Shipping Area — RETIMAC and CA systems are almost identical at this process stage. The CA system already calls for a vault type shortage with an automated loading/unloading capability. RETIMAC requires sealed channels and locators in the shipping area storage. These give some additional protection compared to the CA system. Both systems rely on limited accessibility for protection. An estimate of the reduction in the vulnerability of this process stage produced by the introduction of RETIMAC falls somewhere between that described for the PuO_2 area (substantial reduction) and MO_2 area (moderate reduction).

6.4 EVALUATION OF RETIMAC INVENTORY CONTROL

A second stated objective of the RETIMAC concept is "to maintain current knowledge of the quantity and location of all strategic special nuclear material". To evaluate this objective, the average storage and processing times for plutonium in each of the 16 process steps has been analyzed. The results of this analysis are shown in Table 6-3. The average time for plutonium to move from PuO_2 Receiving to Fuel Rod Shipping is 37.1 days. This total time is divided into vault storage (67.4%), buffer storage (27.7%), discrete processing (2.5%) and continuous processing (2.4%).

Because the quantity and location of fuel material that is in storage is known by the RETIMAC system, material inventory is immediately available

TABLE 6-3. AVERAGE STORAGE AND PROCESSING TIMES FOR PuO_2 AND MO_2

PROCESS STEP	AVERAGE STORAGE TIME (DAYS)		AVERAGE PROCESSING TIME (HOURS)		UNIT	QUANTITY OF PuO ₂ (Kg)		
	VAULT	BUFFER	DISCRETE	CONTINUOUS				
1A	6.4 d	0.2 d ⁽¹⁾	0.5 h		2 L—10 CONTAINERS OF PuO ₂	9		
2A					2 L—10 CONTAINERS OF PuO ₂	9		
3A			2.5 h		4 INNER CANS OF PuO ₂	9		
4A			7.2 d		1 PuO ₂ POWDER VESSEL STORAGE	20		
5		2.0 d	4.0 h	7.0 h	1 BATCH (225 Kg MO ₂)	9		
6					1 BATCH (225 Kg MO ₂)	9		
7					1 BATCH (225 Kg MO ₂)	9		
8					25 BOATS (900 PELLETS EACH)	9		
9		1.0 d ⁽²⁾		7.0 h	25 BOATS (900 PELLETS EACH)	9		
10		0.8 d		7.0 h	25 BOATS (900 PELLETS EACH)	9		
11		5.2 d			25 BOATS (900 PELLETS EACH)	9		
12					25 TRAYS (900 PELLETS EACH)	9		
13	11.4 d	0.8 d ⁽³⁾	6.2 h		100 RODS (200 PELLETS EACH)	8		
14			6.2 h		2 CHANNELS (50 RODS EACH)	8		
15			4.0 h		2 CHANNELS (50 RODS EACH)	8		
16					1 SHIPPING CONTAINER (8 CH. EACH)	24		
Total	25.0 d	10.3 d	22.5 h ⁽⁴⁾	21.0 h	—	—		
Per Cent	67.4	27.7	2.5	2.4	—	—		

¹ TIME IN CALORIMETER (1)² TIME IN FURNACES (4, 1 SPARE)³ TIME IN PRE-INSPECTION, PRE-X-RAY AND POST-X-RAY STORAGES, AND FEED TRAY FOR NUCLEAR ASSAY MEASUREMENT⁴ NORMALIZED TO 9 Kg QUANTITY OF PuO_2

for, on the average, 95% of the plutonium in the plant. The remaining 5% is in process. The average process time is less than a shift for 1 batch (225 Kg) of MO_2 or 9 Kg of PuO_2 . Hence, real-time inventory with delays of less than one shift would be practical for the RETIMAC system described here.

7. COMPATIBILITY OF THE RETIMAC SYSTEM WITH FACILITY OPERATIONS

The commercial MO_2 fuel plant model, as described in Sections 2 and 3 is evaluated in this section for compatibility of the RETIMAC System with other facility operational programs. The 16 process steps are investigated individually. RETIMAC requirements which conflict, supplement or duplicate other plant program requirements such as quality assurance, security, industrial safety, maintenance and operational process parameter control will be discussed.

PuO_2 and UO_2 Receiving (Process Steps 1A and 1B)

The RETIMAC material movement steps and time intervals are consistent with normal inventory control measures required for receipt of direct production materials. Piece count and unique identification of each shipping container for Bill of Lading acceptance, material control, and production planning and scheduling would be required if there were no RETIMAC requirements. The availability of a computerized listing of the individual shipping containers will enable the receipt inspection and shipping document acceptance operation to be performed more reliably and efficiently. Additional security personnel or TV scanning would probably be required to monitor the unloading of the nuclear material containers under normal plant operating procedures. These will further improve upon the level of protection already provided by RETIMAC.

PuO₂ and UO₂ Powder Storage (Process Steps 2A and 2B)

The RETIMAC time intervals and sequence of material process movements would not conflict with the normal process requirements for receipt and storage of nuclear materials. The PuO₂ containers for material accepted as one blend from the vendor should be removed from storage on a blend to blend basis rather than removing material from the location nearest to the fork truck access. The RETIMAC system does not presently provide for oxide sampling and analyses for acceptance of chemical impurity levels and physical properties on a lot or blend basis prior to transfer and mixing of blends in bulk storage vessels. This sampling, analysis and contractual acceptance of each blend would normally be accomplished during the initial extended storage period. Contractual rejection could still be accomplished at the bulk storage vessels under step 4A provided oxide blends had not been mixed. This may be impractical in large volume process storage vessels. Sampling and analysis is required not only for contractual acceptance of each oxide blend, but also for quality assurance release of direct materials to the process.

PuO₂ and UO₂ Powder Unloading and Storage (Process Steps 3A, 3B and 4A, 4B)

The sequence and timing of operations described under Steps 3A and 3B appear to be reasonable based upon the assumption that all transfer equipment has a high on-line availability factor. The question of reliability and maintainability of the automated equipment is one that must be addressed before the RETIMAC concept moves much further along. The transfer methods and systems suggested are definitely more desirable from a dusting (safety) standpoint and more efficient and sophisticated than the systems presently in operation in the commercial low enriched UO₂ powder transfer operations.

MO₂ Powder Blending (Process Step 5)

The principal risk of injury to health in a MO₂ facility is the inhalation or ingestion of Pu or the inadvertent release of radioactivity in the event of an accident. The containment and semi-remote operations of this facility present no basis for additional industrial safety measures as a result of imposing the RETIMAC requirements. In fact, RETIMAC emphasis on remote handling and automated process equipment complements the health and safety requirements for MO₂ plant operation.

The allocated milling time may not be sufficient unless the PuO₂ and UO₂ powders are procured to the desired particle size of approximately 0.3 to 0.5 microns. UO₂ powder, unmilled, normally runs from 0.7 microns to 1.2 microns. Both UO₂ and PuO₂, should be approximately the same particle size during blending in order to assure homogeneity, uniformity and sinterability of the MO₂ pellets. If the milling operation is only intended to break up agglomerates, then the allocated time sequence for this step is sufficient.

MO₂ Powder Storage (Process Step 6)

The residence time for storage of blended MO₂ powder in the silos cannot be lowered until pilot pellet performance tests are no longer required of each batch. These tests are almost universally run by all of the low enriched UO₂ fuel producers including the Westinghouse Plant in Columbia, S.C. The data obtained from a pilot pellet test of approximately 20-60 pellets per powder blend is utilized to establish the unique processing parameters for that blend of material. These parameters include slug density, press pressure and dwell time during pressing of green pellet, green pellet density, sintering furnace tray push rate, and sintering furnace temperature profile. These parameters can possibly be estimated, reducing the frequency and

need for pilot performance tests, as data is compiled. The fact that pellet performance tests are continuing on each blend of low enriched UO_2 fuel produced commercially today, indicates lack of uniformity from blend to blend in the UO_2 powder.

Pilot test pellets representing a range of recycled MO_2 percentages, green densities and pressing pressures are normally run with the preceding batch of pellets and require a minimum of 30 hours to process and accumulate the data.

The RETIMAC accountability measurements for MO_2 weight and fissile content of the material would also be required by quality control at this point prior to further processing to provide assurance that the proper composition of total plutonium and uranium weight ratios are present and each fissile content is correct. These compositions cannot easily be adjusted after the material is compacted.

MO_2 Pelletizing, Green Pellet Storage and Pellet Sintering (Process Steps 7, 8 and 9)

The system requirements outlined under the RETIMAC program are reasonable and represent no additional major efforts. A green pellet density check would be required for quality control purposes, however counting of green pellets is an additional requirement unique to the RETIMAC program.

The system design basis should either allow for pellet press shut-down or sufficient green and sintered pellet storage capacity to accommodate resintering of low density pellets and storage of acceptable pellets. A sintered density check of pellets is a requirement imposed by QC.

In addition to process recycle storage capability, equipment breakdown and maintenance requirements will require surge storage capacity.

The most common equipment failure is the sintering furnace. Because of the failure of heating elements and collapse or deterioration of furnace muffle materials at the operating temperature of about 1700°C , entrance of maintenance personnel to the restricted furnacing area will be required. Prior to performing the above type furnace repairs, the furnace has to be emptied of pellets and cooled to ambient temperature. These pre-maintenance preparatory steps will require approximately 2 to 4 days. Maintenance and health-physics monitoring personnel will require security surveillance during these and similar maintenance repair operations. RETIMAC must be designed to operate portions of the plant independently and possibly portions of individual process steps.

Sintering cycle times will vary from 4 to 8 hours in the maximum heat zone due to the variation in MO_2 powder blend characteristics affecting sintering. This time range for pellets in the maximum temperature zone yields a total furnace cycle time range of 12 to 24 hours. The RETIMAC system will have to be flexible enough to allow for different process rates.

Sintered Pellet Storage (Process Step 10)

The RETIMAC system requirements under this step may require expansion of sintered pellet storage capability in order to accommodate the periodic maximum surge storage requirements resulting from process and equipment changes and repairs.

Pellet Grinding (Process Step 11)

The RETIMAC system sequence and allocated time for grinding is compatible with normal fuel pellet grinding operation requirements. The Westinghouse MO_2 facility planned for construction at Anderson, S. C. and

the RETIMAC MO_2 process model indicate a wet grinding operation. There are dry grinders presently in commercial operation at low enriched UO_2 fuel fabrication facilities. The resultant ground powder can be blown down into a receiving hopper and monitored on a weight gain basis. This eliminates the need for filtering and drying the grinder sludge and performing a chemical analysis on the scrap sludge material.

EXXON Nuclear Company proposed a similar dry pellet grinding operation in the final Environmental Statement for a Mixed Oxide Fabrication Plant, June 1974; Docket No. 70-1257. The addition of a dry grinding process would be a design choice in step with the RETIMAC goals concerning material handling.

Pellet Inspection and Storage (Process Step 12)

Release for pellet moisture content is one of the more critical inspection releases performed at this step. Analysis and release for total plutonium and uranium contents and content of Pu and U isotopes will also be required. The chemical purity level and the physical properties, such as internal microstructure characteristics and homogeneity of the plutonium in the binary mixture, will require release by QC prior to loading pellets into rods. Pellet samples for QC release of these attributes can be forwarded to Analytical Services after pellet sintering which allows sufficient time for analysis and QC release at time of rod loading. These QC data, although not very timely, will supplement on-line data already in the RETIMAC system. Conversely, RETIMAC on-line measurements are not accurate enough to satisfy QC requirements.

Fuel Rod Loading (Process Step 13)

It is present commercial practice in the major fuel fabrication facilities for lower quality enriched UO_2 fuel pellets to be loaded in specified maximum length and sections at each end of a fuel rod. These Grade B type pellets can normally be outside the higher quality Grade A type pellets for the following specification characteristics: smaller diameter up to 1 mil, lower density by approximately 1% of theoretical density and greater surface defects in accordance with approved visual standards. This reduces the clean scrap recycle quantity to be processed and improves the economics of the fuel fabrication facility.

It is common practice to fabricate sufficient quantities of varying length pellets, referred to as half-length pellets, that are utilized at the rod loading station to adjust the pellet stack length in each rod to be within the specified pellet stack length tolerances. If these practices are to be included in the MO_2 facility, provision for rod loading of the three types of pellets; Grade A, Grade B and half-length would have to be considered in designing the RETIMAC system.

There have been instances in the past of pellets becoming cocked or bound at a small angle during rod loading creating gaps between the pellets.

Fuel Rod Inspection (Process Step 14)

The process steps and inspections are in accordance with the normal commercial low enriched UO_2 fuel fabrication processes. The time assigned for each sequence appears reasonable.

The active gamma scanner (^{252}Cf) is presently being utilized for fissile content scanning by the major light water UO_2 fuel fabricators with varying degrees of success. The scanner has the capability of detecting missing pellets or pellet gaps of 0.050in. or greater. It will detect pellet to cladding gaps in excess of the 3 to 5 mil range. It will also detect low density pellets which have been inadvertently loaded.

Fuel Rod Storage and Shipping (Process Steps 15 and 16)

The exterior surface of the final inspected fuel rods will require cleaning by wiping with an acetone saturated cloth and a smear test taken for compliance with surface radioactivity limits. It would be desirable, in order to minimize production activities, to accomplish the above just prior to placing the rods in the channel carriers. This assumes that the packing arrangement and the design of the channel carrier will allow that it be sealed during storage. The loaded channel carrier would be loaded directly into the shipping container. These steps would be very helpful in product control, however the assumption should be checked for practicality.

8. SUMMARY OF INTERIM RESULTS

- A commercial mixed-oxide fuel-rod fabrication plant model was constructed based on the Westinghouse plant planned for construction near Anderson, S. C. This model includes flow charts and physical layouts for 16 process steps. Average material flow rates and storage capacities are specified throughout the plant model based on an output of 200 MT MO_2 /year with 4% PuO_2 content. A RETIMAC system, which includes material handling, measurements and information processing features, was designed and integrated with the plant model.
- The representative time interval (τ) required to carry diverted material outside the material protection system boundary was found to vary from about 5 to 14 minutes for different diversion paths under normal security conditions. A moderate increase in security conditions (achieved through minor procedural changes) produced a (τ) of about 13 minutes for all plant areas; a more significant increase in security raised (τ) to about 20 minutes for all plant areas.
- A RETIMAC design was developed for monitoring material flow in the main process stream. It produced redundant diversion indicators for covert attempts to steal SNM within 15 minutes of the actual material diversion in all plant areas except the rod inspection area. The minimum amount of diverted material which was protected by RETIMAC indicators was about 10 g PuO_2 or 100 g MO_2 . It can therefore be stated that this RETIMAC design achieved the first general RETIMAC objective for all plant areas except the rod inspection area. The RETIMAC system could be redesigned to achieve the first objective in the rod inspection area as well, however, alternative schemes for achieving the same level of protection in this area should be considered.
- A minimum of three to four independent steps are required by the diverter to evade detection by RETIMAC within 15 minutes of the actual diversion of SNM. The successful diversions considered required that less than 200 g of material be taken or that UO_2 material

be carefully substituted for the diverted material. Except in cases where a very small amount of material is taken, most diversions considered will be detected at a later time.

- The real-time inventory control provided by the RETIMAC system was evaluated by examining the average storage and processing times for each of the 16 process steps. It was found that, on the average, 95% of the plutonium is in storage where its quantity and location are known by the RETIMAC system. The remaining 5% is in process where data on its quantity and location can be determined with delays of less than one shift.
- The relative effectiveness of RETIMAC in preventing a diversion through timely detection as compared to a conventional accountability system that uses chemical sampling, limited NDT, and no computer depended on the plant area under consideration. Results are given below:

<u>Plant Area</u>	<u>Change in Material Protection through RETIMAC</u>
PuO ₂	Substantial increase
MO ₂	Moderate increase
Rod Loading	Very substantial increase
Rod Inspection	No change
Shipping	Moderate to substantial increase

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