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MASTER

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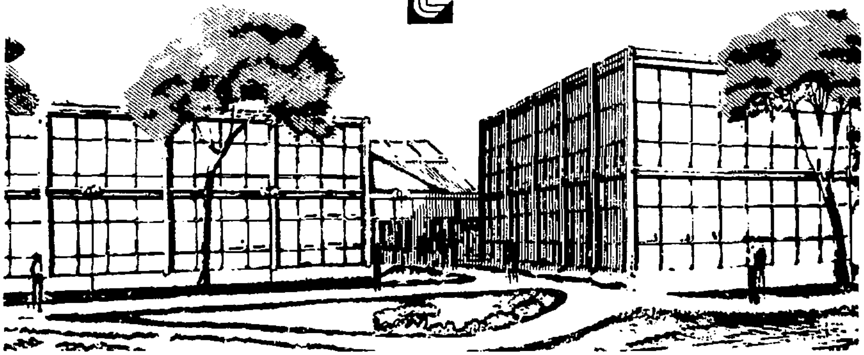

MO200: A MODEL FOR EVALUATING SAFEGUARDS THROUGH MATERIAL ACCOUNTABILITY FOR A 200 TONNE PER YEAR MIXED-OXIDE FUEL-ROD FABRICATION PLANT*

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ABSTRACT

MO200 is a computer simulation model of a proposed 200 tonne+ per year mixed-oxide fuel-rod fabrication plant that has been u ed to investigate the safeguarding of plutonium dioxide through material accountability. The computer program operating the model was constructed so that replicate runs could provide data for statistical analysis of the distributions of the randomized variables. The plant model was divided into material balance areas associated with definable unit processes. Indicators of plant operations studied were modified end-of-shift material balances, end-of-blend errors formed by closing material balances between blends, and cumulative sums of the differences between actual and expected performance.

INTRODUCTION

It is possible that recycled plutonium in the form of plutonium dioxide (PuO_2) derived from the reprocessing of spent fuel from nuclear reactors will be introduced into the nuclear fuel cycle. This has forced a thorough examination of the present methods of safeguarding Strategic Special Nuclear Material (SSNM) by the Nuclear Regulatory Commission (NRC). The GESMO report (1) concludes that all aspects of safeguarding SSNM should be improved, not only because of the threats of theft or diversion, but also because of the substantial health hazard of PuO_2. The goal is to develop methods and statistics good enough to assure adequate safeguards in the processing of SSNM. Physical security of SSNM must be supplemented by inventory and accounting techniques.

Present day material balance accounting for the relatively small quantities of PuO_2 involved in the commercial sector generally has limits of error of the order of 0.5 to 1% of throughput. When extrapolated to the tonnes possible in the future, these errors amount to kilogram quantities of SSNM. Moreover, results are only available at monthly or bimonthly intervals since physical inventories are required. The sensitivity and timeliness of today's method of material control needs to be greatly improved.

Automated accounting systems that log SSNM in and out of material balance areas (MBAs) improve the availability of accurate records, but cannot verify the actual presence of SSNM. Periodic physical inventories are still required to reconcile the book inventory with the actual content of th MBA. Maximum limits on inventories could be set in order to reduce the chance of significant loss. However, if information from the logs were put in a time reference frame and compared to standard behavior it could be used for timely, sensitive loss detection. This means that intimate knowledge of the process must be incorporated into the safeguarding of SSNM.

A plant can be divided into "unit processes" where material changes in form or composition or where by-product is generated. It would be convenient to incorporate the unit processes in MBAs. If the parameters of a unit process are identifiable and the time behavior in either a continuous or discrete sense is thoroughly consistent, then criteria can be developed for detecting unexpected loss mechanisms.

Existing plants where PuO_2 is handled utilize pilot plant production lines that use conventional equipment enclosed in glove boxes. Attempting to instrument such process lines for demonstrating the adequacy of new material control techniques has been suggested but would require great expense and time, disrupt the present use of the process lines, and produce results that might not be applicable to a high-throughput custom-designed operation. Simulation of plants of the future, however, is one way to investigate both the plant operations and the material control instrumentation and to have results available in a reasonable time.

This paper describes a simulation model, MO200, that has been used in a ecial Safeguards Stud by the NRC to demonstrate various eguarding techniques that use automated measurements and in mation processing. State-o.-the-art technology was assumed the model in order to assess the present limits of PuO_2 ac untability. The necessary stringent physical security measures were not under consideration for the model. The proposed Westinghouse Recycle Fuels Plant (2) (RFP) for mixed oxide (P /UO_2) fuel rod fabrication at Anderson, S. C., was used as basis of the model in order to test in-line nondestruct assay (NDA) methods in a highly automated plant operatic , and to assess the effects of scale on plutonium accountability. The 200 tonnes of mixed oxide (MO_2) fuel throughput per year will require the processing of about 10 tonnes of PuO_2. The automation envisioned for the RFP plant would not only minimize worker exposure to PuO_2 and provide some physical security, but also would greatly improve the repeatability of opera ns. The repeatability would lead to reliable statistics th would be available for process controls and detection of functions and unexpected losses.

The model was expe d to be versatile so that hypothetical questions could be ned. This required that both parameters and some stru re could be easily modified. The development of a reasona simulation required consideration of the plant as a system. In the process, we obtained insight into the problems of plutonium accountability.

DESCRIPTIVE MODEL

The Westinghouse license application (2) was used in constructing the model. Where necessary information was lacking in the application, nominal values typical of current industry practice were estimated. (3)

Fuel-rod fabrication involves making sintered (ceramic) cylindrical nuclear fuel pellets, stacking them into rods, and eventually assembling the rods into bundles for fueling nuclear reactors. The unit processes for the model were considered as black boxes as far as detailed operation was concerned. They would have characteristic input and output levels, factors for scrap, waste and holdup generation, and a delay from input to output. The holdup is material that accumulates in cracks and crevices and coats the walls of the processing equipment. Flows occur in discrete quantities throughout the plant. The process description that follows is oriented toward PuO_2 since the UO_2 is either natural or depleted in ^{235}U, and not considered SSNM.

Flowchart

The flow chart developed for the model is basically the Westinghouse flowchart with in-line NDA measurements inserted between the unit processes (see Fig. 1). Supporting services that were not really part of the main problem were Analytical Services, Miscellaneous Waste Treatment and Fuel Rod Shipping. Clean Scrap Recovery and Recycle MO_2 Storage were included in the model.

Fuel Rod Fabrication

The MO_2 fuel rod fabrication process for the model was decomposed into the unit processes:

(1) PuO_2 Unloading — PuO_2 receiving and unloading a blend into one of three PuO_2 storage vessels.
(2) Blending — blending of PuO_2, UO_2, and recycle MO_2 to form sub-blends or batches and storage in one of nine MO_2 storage silos.
(3) Pelletizing — pelletizing the blended powder and loading the pellets into sintering boats and storing the boats in green pellet storage.

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+Metric ton.

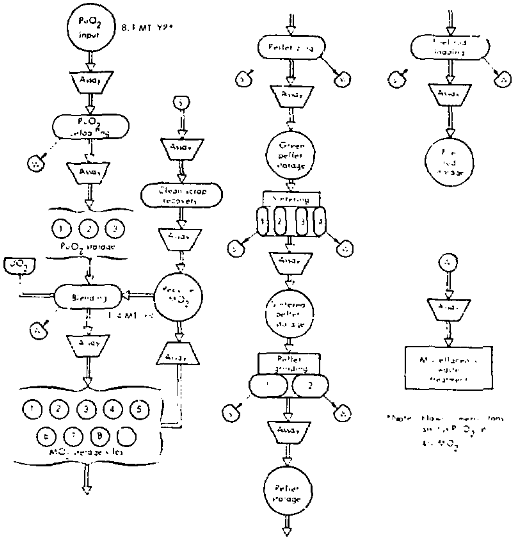

Fig. 1. Flow chart for PuO_2 proposed 200 tonne/year mixed-oxide recycle fuels plant.

(4) Sintering — sintering the pellets of a batch in one of four sintering furnaces and placing the finished boats in storage.
(5) Pellet Grinding — grinding the pellets of a batch in one of two grinders, inspection and loading acceptable pellets onto trays, and storing the trays.
(6) Fuel Rod Loading — loading the pellets into fuel rods, sealing the rods by welding, inspection, gamma scan for uniformity and quantity of PuO_2, and storing the finished fuel rods.
(7) Clean Scrap Recovery — recovering clean scrap produced within the unit processes and adding it to Recycle MO_2 Storage.

Operation of the Recycle Fuels Plant

It is expected that the Anderson plant will process a blend of mixed oxide powder (about 4% PuO_2) in a week of 21 shifts of 8 h each. The equipment would then be cleaned for two shifts before starting the next blend. The cleanout would progress through the plant, not at the same time for all processes. The unit processes were sized to handle a sub-blend or batch in one shift. The automation includes pneumatic transfer of powder, location of storage vessels on load cells, automated feed hoppers capable of weighing, automated conveyors for pellet boats or pellet trays, walking beams for moving the pellet boats through the temperature profile of the sintering furnaces, and automated pellet testing and inspection.

Process Parameters

The seven unit processes used for the computer model are described in Table 1 by their respective process parameters of average scrap, waste and holdup factors, nominal discrete output quantities of PuO_2, and processing time per unit. Three PuO_2 storage vessels were used so that one would be supplying PuO_2 to the process, one would be waiting for off-line analysis of the PuO_2, and the third would be receiving the next shipment. Off-line analysis of the blended MO_2 powder would require approximately 48 h so the nine MO_2 storage silos provide buffer capacity for input into the pelletizing operation. Off-specification MO_2 would be removed to Recycle MO_2 Storage about once a week. Sintering requires about 20 h so four furnaces would be needed in order to average a batch per shift. Two pellet grinders would even out the supply of pellets to fuel rod loading.

COMPUTER SIMULATION MODEL

Methodology and Programming

Time period modeling was chosen as the simulation method. In this method simulation time is advanced in fixed increments. After each increment the program cycles through the list of possible events, and the time for every event to occur is compared to the simulation time. The progress of each simulation variable during the simulation can be easily displayed. The CSSL3 simulation package, although it uses a continuous system simulation language, was employed in constructing the model. A dummy integration was needed in order to make the translator work properly. The run-time support package of CSSL3 has distinct advantages for run-time modification of parameters, for retaining values of simulation variables at fixed increments in

Table 1. MO200 unit processes.

No.	Unit process	Unit output kg PuO_2	Unit rate h	Scrap factor	Waste factor	Holdup factor
1	PuO_2 Unloading	2.25 (can)	2.222	0.	0.0025	0.3514
2	Blending	9.0 (silo)	7.5	0.	0.0008	0.0019
3	Pelletizing	0.36 (boat)	0.227	0.0044	0.0027	0.0072
4	Sintering	0.36 (boat)	20.	0.0090	0.0009	0.
5	Pellet Grinding	0.36 (tray)	0.354	0.0810	0.0032	0.0070
6	Fuel Rod Loading	0.080(rod)	0.0625	0.0116	0.0007	0.
7	Clean Scrap Recovery	0.934	7.5	0.	0.0043	0.0021

simulation time for subsequent plotting, and for making replicate runs with different randomization. The explicit type of CSSL3 program with INITIAL, DYNAMIC, and TERMINAL sections was written.

The simulated operations of the fabrication plant were carried out in Fortran coded subroutines. The COMMON of the Fortran code created by the CSSL3 translator was extracted from the file containing the code by a short program after successful compilation. It was then inserted into the subroutines where necessary by the MODIFY feature of the CDC SCOPE operating system. This procedure completed the linkage between the CSSL3 generated code and the subroutines and allowed more versatility than using arguments in the subroutine calls. The subroutines were then compiled as the next step in the job sequence. Since a file containing the COMMON was retained during model development the main program had to be translated only when the list of variable or parameter names was changed, or when a change in the sequence of events was desired. Newer versions of subroutines were loaded into the computer by the CDC LINK loader during debugging computer runs.

It was more convenient to treat many of the variables in the subroutines as elements of arrays. This enabled the use of a single subroutine for several or all the unit processes. However, the run-time support system of CSSL3 allows only simple variables to be referenced for input or output since its indexing is by means of a symbol table. It was possible to do both by ordering the first references to the simple variables during initialization in the CSSL3 language program such that the memory locations appeared similar to an array. A DIMENSION statement with a new variable name and an EQUIVALENCE statement in the subroutines was all that was required to properly point to the correct memory location when an index for the array element was used. The collection of declarative statements for the subroutines was in a single record and was inserted into the subroutines during the MODIFY operation.

Design Criteria

The types of computer runs that were expected to be of interest influenced the design of the computer program and model. A partial list of the criteria considered includes:

(1) Test the design and scaling of the plant.
(2) Be able to observe the position identification of SSNM as a function of time.
(3) Evaluate the burden of in-line NDA instrumentation on the throughput of the plant.
(4) Compare different NDA measurement techniques.
(5) Observe the time series behavior of the unit processes and associated MBAs.
(6) Observe the errors in amounts of SSNM to be expected, both "true" errors and relative errors, during shift operations and at the closing of material balances after cleanout between blends.
(7) Evaluate theft detection capability of material accounting for both single and multiple thefts.

Simulation of Measurements

In a real plant, observations (estimations) are made by making measurements that are corrupted by noise. Figure 2 shows a unit process model (4) used for the program and the associated information flow. The amount of material going into storage is measured to an accuracy and precision determined by the systematic and random errors associated with the measurement. The product output of the process is measured before it goes into the next storage area. Scrap and waste output are also measured. The material that accumulates in the form of process holdup can only be known by difference. In order to do material balance accounting, i.e. close the material balance, the residue must be physically measured. This will be considered later.

Simulation of measurement noise and other random processes in the computer model was performed by independent, normal, random number generators for each unit process. Since each computer run uses only one possible sequence of random numbers for each generator, provision was made for making replicate runs with different seeds for each of the generators.

The computer model really contained two parallel models, an independent model of the true values of random variables and a dependent model simulating measured quantities. Each true quantity of PuO₂ had its measured counterpart. Measurements were simulated by multiplying the true contents of a container by the factor (1 + G(SEED,CA,SD)) where the function represents a normally distributed random variable with mean CA, the calibration error, and standard deviation SD, the relative random error. SEED was the seed value for a recursive uniform pseudo-random number generator. The calibration error was picked at each calibration time from a normal distribution with zero mean and standard deviation equal to the relative systematic error of the measurement being simulated. We assumed a 100% NDA assay so there was no sampling error.

Scheduling of Events

In keeping with the automation theme expected for the plant, a subroutine was written for the computer program that would act as a master controller and scheduler. This subroutine could read the status of input storage areas and unit processes and the position of batches throughout the plant for

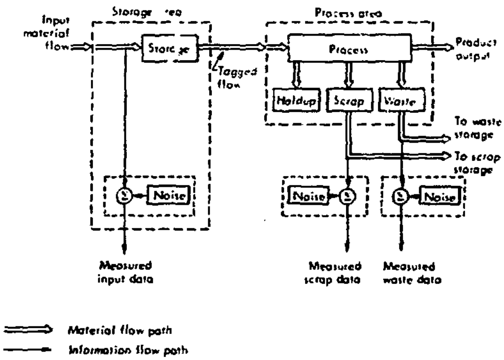

Fig. 2. The structural features of the unit processes for the MOZOO simulation model.

setting startup and cleanout times of the unit processes. Process flags were set greater than zero to indicate that the unit processes were occupied by either processing or cleanout. In some cases the process flag carried the number of containers in the batch. Processing a batch was set to start at the beginning of shifts. Storage flags indicated the number of batches present in the storage areas. A separate variable carried the batch number of each batch in the storage area. Cleanout flags were set to one when the last batch of a blend left the blender and the number of the batch was recorded. Obtaining the proper sequencing of the plant operations required many tests of indicators because of the multiple paths from blending to Fuel Rod Loading and because of the cleanout between blends.

A separate subroutine scheduled measurement times by testing the status of the assay stations and their queues. The measurement time reflected the delay required to perform the measurement.

A dummy diagnostic subroutine that was [illegible] each [illegible] communication interval was included in the model. The dummy could be replaced at load time by debugging diagnostics of unusual events during simulation runs.

Table 2 lists the 24 discrete events of the model. All event times were set initially at 1×10^{3} [illegible]. The schedulers reset the times for the events to occur. When the subroutine that performed the event was called it would reset the event time to 1×10^{10} h. The communication interval was set to [illegible] simulation time, with [illegible] calculation steps per interval. The shortest delay time possible was thus restricted to [illegible].

Table 2. Sequence of the discrete events in [illegible].

Each communication interval [illegible] hours

1. Cleanout [illegible].
2. Calibrate instrument [illegible].
3. Call SCHED (Master Process Scheduler).

Each calculation interval of [illegible] hours

4. Finish calibration of instrument I if $T \geq$ [illegible].

PuO_2 Unloading

5. Receive blend if [illegible] and PuO_2 storage vessel is ready.
6. Measure input can if $T \geq$ [illegible].
7. Unload input can if $T \geq$ [illegible].

Blending

8. Fill blender if $T \geq$ [illegible].
9. Empty blender if $T \geq$ [illegible].

Pelletizing

10. Fill pelletizing input hopper if $T \geq$ [illegible].
11. Load boat with pellets if $T \geq$ TE(3).
12. Measure boat if $T \geq$ TM(3).

Sintering

13. Enter boat into sintering furnace K if $T \geq$ TI(K).
14. Remove boat LJ(K)+1 from furnace K if $T \geq$ TE2(LJ(K)+1, K-3).
15. Measure boat from furnace K if $T \geq$ TM(K).

Pellet Grinding

16. Enter boat into pellet grinding line K if $T \geq$ TI(K).
17. Remove tray from pellet grinding line K if $T \geq$ TE(K).
18. Measure tray from pellet grinding line K if $T \geq$ TM(K).

Fuel Rod Loading

19. Enter tray into Fuel Rod Loading if $T \geq$ TI(10).
20. Remove rod from Fuel Rod Loading if $T \geq$ TE(10).
21. Measure rod from Fuel Rod Loading if $T \geq$ TM(10).

Scrap and Waste Lines

22. Measure clean scrap from process K if BIZ(7).EQ.K and $T \geq$ TMSCP.
23. Measure waste from process K if BIZ(8).EQ.K and $T \geq$ TMWST.
24. Call SMT (Master Measurement Scheduler).

Measurement [illegible]

The measurement [illegible] included [illegible] at [illegible] be [illegible] with plutonium dioxide [illegible] from blend to blend in the amounts of the several [illegible] isotopes present. The [illegible] of a calorimeter, [illegible] is extremely sensitive to the quantity of ^{238}Pu [illegible] can be performed [illegible] relatively high precision [illegible] specific to [illegible]. For all weighings it would [illegible] radiochemical measurement would be [illegible] proper [illegible]. However, [illegible] problems were [illegible] in the model. [illegible] seven MBAs in the [illegible] plant [illegible]. The [illegible] of the design, the measurement [illegible] presented in Table 3 were used in the simulation [illegible] assay of all inputs and outputs. The [illegible] errors for the [illegible] measurement of the [illegible] input [illegible] gives a good measure of the plant input [illegible] of plutonium isotopes [illegible]. Bulk weighing [illegible] for the measurement of small [illegible] instances. [illegible] weighings [illegible] assumed [illegible] done at [illegible] and the fuel [illegible].

Material Balance

The material balance [illegible] period is defined as the beginning inventory [illegible] minus the output. In the model, the [illegible] the combined content of the [illegible] except for fuel rod loading, in which [illegible] was included. [illegible] the next MBA, the physical inventory [illegible] balance was performed between blends [illegible] quantity involved was at a minimum. [illegible] rated as the end of a blend [illegible] cleanout time, material in the storage area [illegible] but was taken as the sum of the [illegible] the quantity measured [illegible] assumed that the storage areas were [illegible] only [illegible] in the [illegible] area was [illegible] tests for the [illegible] ranged from [illegible] PuO_2 unloading. [illegible] material [illegible] remaining residue was subjected to [illegible] a [illegible] relative systematic error and [illegible] relative random error. The rather crude measurement would have [illegible] effect on the end-of-blend [illegible] real improvement [illegible] needed.

Batch Efficiencies

Since the [illegible] plant model was operated in the batch mode, the efficiency of each unit process in the production of batches could be determined. The batch efficiency was defined

Table 3. Measurement parameters for [illegible].

MBA	Measurement	Range kg	Systematic	Random
1	Calorimeter	3	[illegible]	[illegible]
	Weight of PuO_2 Input Cans	3	[illegible]	[illegible]
	Weight of PuO_2 Bulk Storage	1000	[illegible]	[illegible]
2	PuO_2 Weigh Hopper	20	[illegible]	[illegible]
	Recycle MO_2 Weigh Hopper	80	0.00089	[illegible]
	Weight of MO_2 Powder Silo	500	0.00089	0.0032
3	MO_2 Weigh Hopper	50	0.00089	0.0032
	Weight of Green Pellet Boat	20	0.00085	0.0033
4	Weight of Sintered Pellet Boat	20	0.00085	0.0033
5	Weight of Pellet Tray	20	0.00085	0.0033
6	Fuel Rod Scanner	0.5	0.005	0.005
7	Weight of Clean Scrap	30	0.00085	0.0033
	Weight of Recycle MO_2 [illegible] Storage	1000	0.00089	0.0032
	[illegible] of Waste	-	0.05	0.05

as the batch product output divided by the batch input. Both the batch inputs and outputs are distributions of values and care must be taken when the ratio is used. Although they may have normal distributions themselves, the ratio is a Cauchy distribution, which may depart from normality by a large margin. When the ratio is close to 1 and the distributions are well behaved, the ratio may be treated as having normal distributions. The evaluation of batch efficiencies was left to further study.

SIMULATION OUTPUT

In general the simulation runs were carried out to 400 h in simulation time, or 100 shifts. A blend consisted of 75 input cans with 2.25 kg of PuO_2 in each. Two blends of PuO_2 were put through the PuO_2 Unloading subroutines for initialization so that material would be ready for blending at time zero. Recycle MO_2 Storage was loaded with 28.8 kg of PuO_2 (115.2 kg of MO_2) before time zero and the weight simulated for a measured value. The rest of the plant was started up clean. The 400 h was sufficient for more than three blends to be completely processed. This was [illegible] slower than the steady-state design [illegible] of [illegible] the simulation included starting [illegible] different [illegible] and measurements were being seen [illegible] the model. [illegible] effort was made to obtain [illegible] the [illegible] was on a [illegible] several [illegible] runs were made in [illegible] to demonstrate the range that values of the random variables [illegible]. [illegible] replicate runs would be needed [illegible] statistics.

The total true error in the plant PuO_2 content was estimated through 20 replicate runs of M0200. The range of [illegible] kg of PuO_2 can be converted into [illegible] of the total equilibrium plant inventory of about 500 kg of PuO_2. This may be viewed as an indication of the quality of the measurement configuration used in the model. The plant output over the course of the simulation was also about [illegible] kg of PuO_2 ([illegible]) fuel rods)

ACCOUNTABILITY AND THEFT DETECTION

The evaluation of PuO_2 accountability and theft detection was the prime interest for the Special Safeguards Study. The NDA assay systems for the model were chosen in conjunction with Science Applications, Inc. (SAI) (3) and were close to state-of-the-art. Practical implementation to the level implied by the errors in Table 3 might prove difficult.

Table 4 gives the range of the end-of-blend (EOB) errors calculated in closing the material balances between blends. These are not the "true" errors, but are the relative errors internal to the measurement model. The results suggest that the model structure for Blending might be defective and that the Clean Scrap Recovery MBA does not have adequate measurements. The model used a survey measurement of the PuO_2 in the Recycle MO_2 Storage vessel and the clean scrap awaiting recovery in order to have a value for closing the material balance. Also included in Table 4 is the end-of-shift (EOS) "true" error in the MBA inventories. The values parallel the EOB errors except for Clean Scrap Recovery. The survey measurement of the Recycle MO_2 Storage vessel was not used for the inventory value.

The PuO_2 Unloading process and MBA were chosen as examples since the PuO_2 was unmixed with UO_2 and thus would be the most attractive for theft purposes. The replicate runs dramatize the fact that the values of variables used in accounting will

Table 4. End-of-Blend (EOB) relative errors and End-of-Shift true errors from replicate runs of M0200.

Material balance area	EOB relative errors kg PuO_2	EOS true errors kg PuO_2
1 PuO_2 Unloading	+1.6 to −2.0	+2.5 to −2.5
2 Blending	+0.37 to −0.25	+0.8 to −0.5
3 Pelletizing	+0.4 to −0.4	+0.55 to −0.42
4 Sintering	+0.18 to −0.18	+0.2 to −0.2
5 Pellet Grinding	+0.19 to −0.21	+0.2 to −0.2
6 Fuel Rod Loading	+0.47 to −0.49	+0.45 to −0.45
7 Clean Scrap Recovery	+8.5 to −8.5	+0.2 to −1.5

be from distributions because of the variability allowed in plant operations and because of measurement errors. Judging whether or not a theft has taken place will depend on whether or not the measured value belongs to the distribution of standard values. Five successive thefts of 0.15 kg of PuO_2 were simulated. Thefts were from single input cans and occurred between weighing of the can and measurement of the contents at the PuO_2 storage vessel. Two cases were considered in order to show that the choice of measuring instrumentation in the plant is important. In Case 1, the weight of the contents of the can at the PuO_2 storage vessel was taken as the difference between the weight of the PuO_2 storage vessel before and after the addition. As the vessel filled the accuracy of the measurement would be degraded because the difference between two large numbers would have to be used. In Case 2 it was assumed that the PuO_2 storage vessel could be provided with an input weigh hopper that would only measure the received contents of one can at a time. This would greatly improve the measurement of each increment into the vessel.

Three different techniques of using measurement data for theft detection in the two cases will be described.

End-of-Shift Indicators

Except for the Sintering MBA, there was no PuO_2 in the processing areas at the completion of shifts except for the holdup. A modified material balance calculated at the end of shifts for each MBA would be indicative of the status of the processing area with respect to losses. The End-of-Shift (EOS) Indicator may be defined as:

(Beginning Inventory) + (Flow-in) − (Flow-out) − (PuO_2 in storage area).

The beginning inventory is for the start of a blend and the flows are for the blend period.

Figures 3 and 4 show 20 replicas of the EOS Indicator for PuO_2 Unloading with a theft of 0.75 kg of PuO_2 occurring toward the end of the second blend. The characteristic signature and [illegible] holdup mechanism during each blend is very evident. The general decline in the peak heights was caused by the way the holdup factor was reset between blends. The distribution of values for the shift with the theft overlaps the standard distribution so that the detection probability would be somewhat less than 1.0 if only deviation from the range of permissible values was used for loss detection. If the particular time sequence of values was being followed then it is likely that the 0.75-kg theft would have been detected in both Cases 1 and 2. The theft actually was in five stages, 0.15 kg per stage from successive input cans. The time series for Case 2 were much better behaved than in Case 1 and the detection of just one 0.15 kg theft would appear possible.

End-of-Blend Error

The closing of material balances between blends would produce discrepancies or errors that would lie within certain ranges (see Table 4). Values outside those ranges would point to non-standard behavior. Figures 5 and 6 show the End-of-Blend (EOB) Error for PuO_2 Unloading for Cases 1 and 2, again with the same 0.75 kg theft of PuO_2 from the second blend. The distribution in the EOB Error after the theft overlaps the standard distributions for both of the cases, although less in case 2. The detection probability of the 0.75 kg theft would be substantially less than 1.0 in both cases.

Cumulative Sums

Theft detection would be more sensitive if the standard behavior could be removed from the detection algorithm. The difference between the current value and a nominal value was taken as the basic element of a cumulative sum (Cusum) of the differences. The Cusum should average about zero if all the standard behavior were removed. If standard behavior is not completely removed then the Cusum should be described by a curve with a small slope. This technique amplifies discrepancies. The unit process model was used to provide the standard values. When unit processes are operated in the batch mode, then caution must be used since the first and last values in the sums may depart significantly from the values calculated from using the parameters of the model.

For PuO_2 Unloading in the processing of a blend, the Cusum was defined as:

Cusum = (Increment to PuO_2 storage vessel) − (Measured can content)(1−(holdup factor)−(waste factor)).

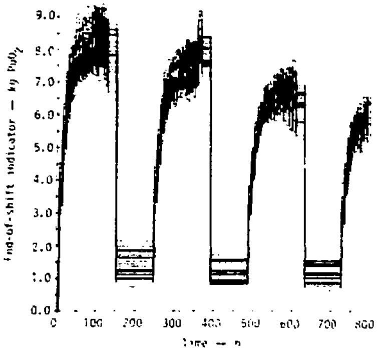

Fig. 3. End-of-shift indicator, PuO_2 Unloading, vs time. Case 1: theft of 0.75 kg of PuO_2 from second blend (20 replicate runs).

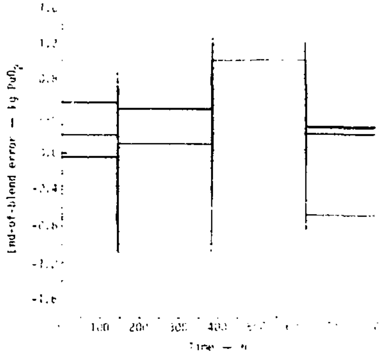

Fig. 5. End-of-blend error, PuO_2 Unloading vs time. Case 1: theft of 0.75 kg of PuO_2 from second blend (20 replicate runs).

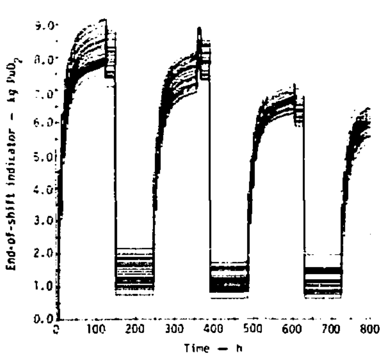

Fig. 4. End-of-shift indicator, PuO_2 Unloading, vs time. Case 2: theft of 0.75 kg of PuO_2 from second blend (20 replicate runs).

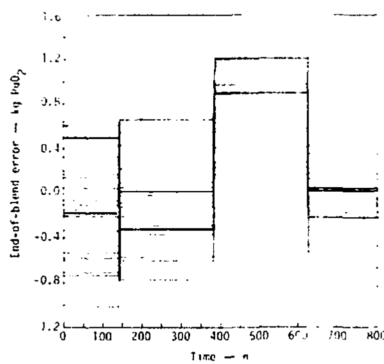

Fig. 6. End-of-blend error, PuO_2 Unloading, vs time. Case 2: theft of 0.75 kg of PuO_2 from second blend (20 replicate runs).

The can content was the value obtained by calorimetry. The holdup and waste factors were those used in the model of the unit process. Figures 7 and 8 show the Cusums for Cases 1 and 2 with the 0.75 kg theft of PuO_2 during the processing of blend two. In Fig. 7 the Cusum for each blend grew in uncertainty as the PuO_2 storage vessel became full. The theft is evident, but not too much different from normal. The improved precision of the measurement of increments to the PuO_2 storage vessel in Case 2 is clearly seen in Fig. 8 in the reduced width of the Cusums of the blends and the definite occurrence of theft during the second blend.

DETECTION PROBABILITY

Distributions can be represented by their means and standard deviations. Statistical tables of the cumulative normal distribution can be used to relate the detection probability of significant deviations from the normal distribution to the standard deviation. (5) Figure 9 presents a family of design curves for the detection probability versus theft levels normalized by the standard deviation. Each member of the family has a threshold normalized by the standard deviation. The intercept for no theft is the false alarm probability. With zero threshold, 50% of the values where no theft has occurred would lie below the mean and result in false alarms. False alarms imply plant disruptions so that alarm thresholds of 3 or 4 standard deviations would be reasonable. The false alarm probabilities would be 0.00135 and 0.000032, respectively. A false alarm probability of 0.00135 means that there is 1 chance in 741 that a result would cause a false alarm. M0200 was used in the Special Safeguards Study to evaluate the standard deviations to be expected for the RFP plant as modelled.

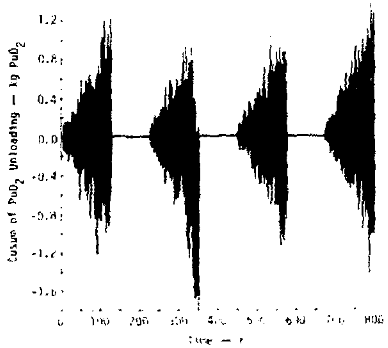

Fig. 7. Cusum of PuO_2 Unloading vs time. Case 1: theft of 0.75 kg of PuO_2 from the second blend (20 replicate runs).

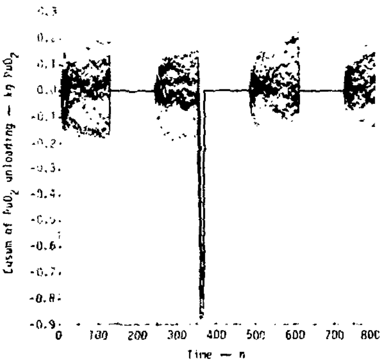

Fig. 8. Cusum of PuO_2 Unloading vs time. Case 2: theft of 0.75 kg of PuO_2 from second blend (20 replicate runs).

SUMMARY

Simulation has been shown to be a useful tool in the study of material accountability in the processing of plutonium dioxide. Improvements in the plant operations and PuO_2 accountability could be made in the proposed Westinghouse RFP plant in Anderson, S.C. Concrete theft detection levels were not stated since the model was of a proposed plant, some important factors were neglected, and the actual instrumentation that would be utilized might be quite different from that assumed in the model. Expected distributions in the plant and accountability variables were important results of the simulation runs. Theft detection capability is directly related to the quality of the distributions. It does appear that the material accounting of large quantities of PuO_2 can be used in a timely manner to reduce the risk of illicit diversion or unexpected losses, especially in conjunction with stringent physical security measures.

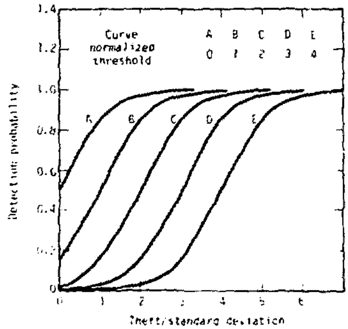

Fig. 9. Design curves for detection probability vs theft levels.

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