LA-UR 91-3168

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TITLE SIMULATION OF FACILITY OPERATIONS AND MATERIALS ACCOUNTING FOR A COMBINED REPROCESSING/MOX FUEL FABRICATION FACILITY

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SUBMITTED TO Fourth International Conference on Facility Operations/Safeguards Interface (ANS/INMM)
Albuquerque, New Mexico
September 29--October 4, 1991

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FORM NO. 836 R4
ST. NO. 2629 5/81

Simulation of Facility Operations and Materials Accounting for a Combined Reprocessing/ MOX Fuel Fabrication Facility

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09/28/91

1. Introduction

We are developing a computer model of facility operations and nuclear materials accounting for a facility that reprocesses spent fuel and fabricates mixed oxide (MOX) fuel rods and assemblies from the recovered uranium and plutonium. The model will be used to determine the effectiveness of various materials measurement strategies for the facility and, ultimately, of other facility safeguards functions as well. The design of the reprocessing section of the facility is based on the report *Coordinated Safeguards for Materials Management in a Fuel Reprocessing Plant*, by Hakkila *et al.* (Los Alamos National Laboratory Report No. LA-6881, September 1977). This portion of the facility consists of a spent fuel storage pond, fuel shear, dissolver, clarifier, three solvent-extraction stages with uranium-plutonium separation after the first stage, and product concentrators. The design of the MOX fuel fabrication section of the facility is derived from the report *International Safeguards for an Automated MOX Fuel Fabrication Facility*, by Pillay, Stirpe, and Picard (Los Alamos National Laboratory Report No. LA-11219, May 1988). In this facility area mixed oxide is formed into pellets, the pellets are loaded into fuel rods, and the fuel rods are fabricated into fuel assemblies. These two facility sections are connected by a MOX conversion line in which the uranium and plutonium solutions from reprocessing are converted to mixed oxide. The model of the intermediate MOX conversion line used in the model is based on a design provided by Mike Ehinger of Oak Ridge National Laboratory (private communication).

The facility model uses the simulation program FacSim that has been developed by the Los Alamos Safeguards Systems Group to model nuclear material processing facilities. FacSim is a generic simulation program that provides complete separation of code and data: all facility information is contained in a set of data files, and none in the program itself. As a result, development of a new model only requires that the facility data files be constructed; no programming is necessary. This design greatly simplifies simulation model development. FacSim has previously been used to develop simulation models of several process areas in facilities in the DOE nuclear materials complex.

An initial version of the simulation model has been developed for the entire MOX conversion and fuel fabrication sections of the reprocessing/MOX fuel fabrication facility, and this model has been used to obtain inventory difference variance estimates for those sections of the facility. A significant fraction of the data files for the fuel reprocessing section have been developed, but these data files are not yet complete enough to permit simulation of reprocessing operations in the facility. Accordingly, the discussion in the following sections is restricted to the MOX conversion and fuel fabrication lines.

2. MOX Conversion and Fuel Fabrication

As noted above, the reprocessing section of the model facility produces concentrated uranium and plutonium solutions that serve as the input to the MOX fuel section of the facility. In the MOX fuel section the solutions are mixed and converted to an oxide, the oxide is formed into pellets, the pellets are loaded into fuel rods, and most of the fuel rods are combined into fuel assemblies for use in reactors. The MOX fuel rods and fuel assemblies are the final products generated by the facility.

A more detailed description of the MOX fuel portion of the facility is given in the following sub-sections. The facility has been sized to provide a throughput of 100 metric tons of heavy metal per year, a value that is typical of some existing facilities. However, the design used is generic and does not represent any actual facility.

2.1. MOX Facility Operating Schedule

The MOX conversion and fuel fabrication section of the facility is assumed to operate two eight-hour shifts a day, five days a week. In addition, the operations of filling and sampling the uranium and plutonium accountability tanks are assumed to begin two hours prior to each of these daily shifts; and certain automated processes run into the night after the completion of the second shift.

2.2. MOX Conversion and Fuel Fabrication Processes

The MOX conversion and fuel fabrication section of the facility contains the individual processes shown in Table 1. The processes from the uranium and plutonium accountability tanks through oxide blending convert the uranium and plutonium solutions to a mixed oxide, the processes from jet milling and blending through pellet grinding form the oxide into fuel pellets, and the processes from fuel pin assembly through fuel assembly fabrication incorporate the fuel pellets into fuel rods and fuel assemblies. The remaining processes in the table recover scrap generated at various points in the process operations

Table 1. MOX conversion and fuel fabrication unit processes.

Processes in the MOX Conversion/Fuel Fabrication Section of the Facility
Uranium Accountability Tank
Plutonium Accountability Tank
Uranium-Plutonium Blend Tank
Concentrator Feed Tank
Concentrator
Rotary Calciner
Oxide blending
Jet-Milling and Blending
Compaction and Granulation
Pellet Press
Debinding and Sintering
Broken Pellet Grinding
Outgassing
Pellet Grinding
Fuel Pin Assembly
Fissile Assay
Fuel Assembly Fabrication
Condensate Treatment
Scrubber
Off-gas Treatment

The processes are described in more detail below. Unless otherwise stated, there is a single unit of each process, and this unit operates on the day and evening shifts.

2.2.1. Uranium Accountability Tank.

Two hours prior to the beginning of each eight-hour shift, the uranium accountability tank is filled with 950 liters of a nitrate solution containing 200 grams of uranium per liter. For varying applications the uranium in the solution might be depleted, natural, or low-enriched. The solution is mixed, sampled for quality control, and transferred to the uranium-plutonium blend tank by the beginning of the eight-hour shift.

2.2.2. Plutonium Accountability Tanks.

There are two plutonium accountability tanks. Two hours prior to the beginning of each eight-hour shift, each plutonium accountability tank is filled with 25 liters of a nitrate solution containing 200 grams of plutonium per liter. The solution is mixed, sampled, and transferred to the uranium-plutonium blend tank by the beginning of the eight-hour shift.

2.2.3. Uranium-Plutonium Blend Tank.

At the uranium-plutonium blend tank the 950 liters of uranium nitrate solution and the 50 liters of plutonium nitrate solution are each split into ten sub-batches and cross-blended to produce ten 100-liter batches of uranium-plutonium solution containing 5% plutonium. It is assumed that one 100-liter blended batch is produced every 48 minutes and transferred to the concentrator feed tank.

2.2.4. Concentrator Feed Tank.

The concentrator feed tank feeds the blended uranium-plutonium solution continuously to the concentrator at the rate of 125 liters per hour.

2.2.5. Concentrator.

The concentrator receives 200 gram per liter uranium-plutonium solution from the concentrator feed tank at a flow rate of 125 liters per hour and concentrates it to a 600 gram-per-liter solution, which is approximately the saturation limit for a uranium-plutonium nitrate solution. It is assumed that 99.9896% of the plutonium entering the concentrator leaves in the concentrated solution, .01% leaves in condensate, and .0004% is removed in off gas. The condensate and off gas are directed to condensate treatment and off-gas treatment, respectively. The concentrated uranium-plutonium solution flows continuously from the concentrator to the rotary calciner at the rate of 41.67 liters per hour.

2.2.6. Rotary Calciner.

The concentrated uranium-plutonium solution flows continuously into one end of the rotary calciner at 41.67 liters per hour and is converted to an oxide as it moves slowly through the calciner to the other end. Residence time in the calciner is 4 hours. It is assumed that .06% of the plutonium entering the rotary calciner leaves in the off gas, which is directed to the scrubber. The oxide leaving the calciner flows to oxide blending and packaging.

2.2.7. Oxide Blending and Packaging.

Oxide flows from the rotary calciner to oxide blending and packaging at the rate of about 29.6 kilograms per hour. There it is collected into 30 kg MOX batches, blended, canned, and transferred to storage until it is needed by jet milling and blending. Because this is a somewhat dusty operation, .03% of the plutonium entering the oxide blending and pack-

aging process is deposited in filters. When approximately 100 grams of plutonium have accumulated in the filters, the filters are sent to a recovery storage area for eventual recovery of the plutonium.

This is the last process in the MOX conversion line. The mixed oxide generated in this line and placed in the storage area goes next to the MOX pellet fabrication line.

2.2.8. Jet Milling and Blending.

The jet milling and blending process is the first process in the MOX pellet fabrication line, and it operates only on the day shift. It draws mixed oxide from the storage area where it has been placed by the MOX conversion line, and combines it with mixed oxide recycled from the grinding and pellet grinding processes to form batches of 65 to 100 kilograms. Milling and blending this batch is assumed to require 0.75 hours, and then the oxide is repackaged in 30 kilogram cans and placed in storage until needed by the compaction and granulation process. Because of recycle streams of broken pellets and oxide from pellet grinding, the first four processes in the MOX fuel fabrication line (jet milling and blending process, compaction and granulation, the pellet press, and debinding and sintering) must handle about half again as much bulk throughput as is generated by the MOX conversion line.

2.2.9. Compaction and Granulation.

The two compaction and granulation units draw cans of jet-milled mixed oxide from the storage area where it has been placed by the jet milling and blending process. Each combines the oxide with a binder and then compacts and granulates it in a continuous-flow process with a maximum flow rate of 24 kilograms per hour. The compacted and granulated oxide is then fed directly to the pellet press.

2.2.10. Pellet Press.

In the pellet press the oxide prepared by compaction and granulation is pressed into pellets in a continuous-flow process that is capable of up to 120 kilograms per hour throughput; its actual throughput is limited by feed availability. The pellets are collected on trays containing 1200 grams each and fed directly to the debinding and sintering furnace.

2.2.11. Debinding and Sintering.

Trays of pellets from the pellet press move through the debinding and sintering furnace, where the binder added in the compaction and granulation process is burned away and the pellets are sintered to retain their shape. The trays of pellets move continuously through the debinding and sintering furnace at a maximum rate of 30 kilograms per hour and with a residence time of 14 hours. On exit from the furnace it is assumed that 25% of the pellets are broken or do not meet size and shape specifications, and these pellets are sent to the broken-pellet grinding process in 5000-gram batches for recycling. The remaining pellets are assumed to be packaged in 1500-gram batches and placed in pellet storage until needed by the fuel pin fabrication line.

2.2.12. Broken-Pellet Grinding.

Broken and substandard pellets transferred to the broken-pellet grinding process are ground to a powder and then repackaged in 5000-gram batches and sent to the jet milling and blending process for recycle. It is assumed that a 5000-gram batch of pellets can be processed to powder in 0.4 hour.

The debinding and sintering furnace and the grinding process form the ends of the pellet fabrication line for standard and substandard pellets, respectively. From the pellet storage area the standard pellets move to the fuel pin/fuel assembly fabrication line.

2.2.13. Outgassing.

Sintered pellets are removed from pellet storage and placed in an outgassing furnace that removes trapped gases from the pellets; the outgassing furnace is assumed to have a throughput capacity of 30 kg per hour. The pellets move directly from the outgassing furnace to pellet grinding.

2.2.14. Pellet Grinding.

The pellet press produces pellets that are intentionally slightly oversized, and the pellet grinding process reduces the pellets to the desired final diameter. It is assumed that there are two pellet grinding units, each with a throughput capacity of 15000 grams per hour. It is also assumed that 10% of the mass of the incoming pellets is converted to a powder that is collected into 5000 gram batches and sent to jet milling and blending for recycle. The remaining 90% of the mass, in the form of correctly-sized pellets, is fed directly to fuel pin assembly.

2.2.15. Fuel Pin Assembly.

In fuel pin assembly the mixed-oxide pellets are loaded into fuel pins each of which holds 1200 grams of pellets. It is assumed that preparing each fuel pellet column, placing it in the pin, and purging the pin of gas and welding it shut requires 10 minutes; so that 5 fuel pin assembly stations are required to provide the necessary facility throughput. The completed fuel pins move directly to fissile assay.

2.2.16. Fissile Assay.

The fissile assay station measures the fissile characteristics of the pins at the rate of one pin every 2 minutes. It is assumed that 10% of the pins are then reserved for use as replacement pins, *etc.*, and are transferred directly to the vault. The other 90% of the pins are fed directly to fuel assembly fabrication.

2.2.17. Fuel Assembly Fabrication.

In the fuel assembly fabrication process bundles of 271 fuel pins are constructed in a process that is assumed to require 4 hours, so that a single fuel assembly fabrication unit provides significant overcapacity. The fuel assemblies are then transferred to the vault for storage until they are shipped.

The fuel assembly fabrication process is the last process in the fuel pin/fuel assembly fabrication line.

2.2.18. Condensate Treatment.

The condensate treatment unit concentrates the concentrator condensate it receives, packages the condensate in containers holding 20 to 25 liters of material, and sends the containers to storage for eventual recovery. The concentration step is assumed to require 0.5

hour. The recovery process for the stored condensate is not currently described in the FacSim data files.

2.2.19. Scrubber.

The scrubber receives off gas from the rotary calciner and scrubs the plutonium it contains into a solution that is packaged in containers holding 20 to 25 liters of material. The containers are sent to storage for eventual recovery of the plutonium by processes that are not described in the current FacSim data files. The concentration of the scrubber solution is assumed to be 4 grams per liter. It is assumed that 0.1% of the plutonium in the off gas is not captured in the scrubber solution and continues in the off gas to the off-gas treatment process.

2.2.20. Off Gas Treatment.

The off gas entering the off-gas treatment process passes through high-efficiency particulate air filters that trap 99.9% of the plutonium contained in the off gas. The remaining plutonium, which amounts to less than 1 gram per two-month accounting period, escapes into the environment with the off gas. When the filters have accumulated 100 to 150 grams of plutonium they are replaced, and the used filters are sent to storage for recovery by processes that are not currently described in the FacSim data files.

2.3. Measuring Instruments

A variety of measurements are performed on materials as they move through the process steps, both for accounting and for quality control purposes. The measuring instruments and their assumed accuracies are described below.

2.3.1. Chemical Analysis.

Chemical analysis is used to measure the plutonium concentrations of uranium and uranium-plutonium solutions and of mixed oxide. The uncertainties associated with these concentration measurements by chemical analysis are assumed to be the following.

1. Uranium and plutonium solution concentration measurement:
   random error: normal distribution with 1.02% relative standard deviation;
   correlated error: normal distribution with 0.2% relative standard deviation.

2. Mixed oxide plutonium concentration measurement:
   random error: normal distribution with 0.44% relative standard deviation;
   correlated error: normal distribution with 0.05% relative standard deviation.

The larger error for solutions arises from the inclusion of sampling error, which can be significant in the large tanks from which these samples are drawn.

2.3.2. Solution Assay.

Solution assay is used to measure the plutonium concentrations of scrap solutions such as condensate and scrubber solutions. The uncertainties associated with these solution assay concentration measurements are assumed to be the following.

Scrap solution plutonium concentration measurement:
random error: normal distribution with 2.0% relative standard deviation;
correlated error: normal distribution with 1.5% relative standard deviation.

2.3.3. Gamma Counter.

A gamma counter is used to measure the plutonium content of the filters that are used to collect plutonium-containing dust. The uncertainties associated with these plutonium content measurements are assumed to be the following.

Filter plutonium content measurement:
random error: normal distribution with 1.0% relative standard deviation;
correlated error: normal distribution with 0.75% relative standard deviation.

2.3.4. Accountability Tank Volumes.

The volumes of the uranium and plutonium accountability tanks must be measured with considerable accuracy in order to obtain good input values for the material processed by the MOX fuel fabrication portion of the facility. The uncertainties associated with these accountability tank volume measurements are assumed to be the following.

Plutonium accountability tank volume measurement:
random error: normal distribution with additive standard deviation 0.25 liter;
correlated error: normal distribution with additive standard deviation 0.125 liter.

Uranium accountability tank volume measurement:
random error: normal distribution with additive standard deviation 5 liters;
correlated error: normal distribution with additive standard deviation 2.5 liters.

2.3.5. Scrap solution volumes.

The volumes of scrap solutions may be measured with less relative accuracy than is required for the accountability tank volumes, and the volumes measured are also much smaller. The uncertainties associated with these scrap solution volume measurements are assumed to be the following.

Scrap solution volume measurement
random error: normal distribution with additive standard deviation 0.1 liter;
correlated error: normal distribution with additive standard deviation 0.05 liter.

2.3.6. Balances/Scales.

Balances and scales are used to measure the masses of various containers with additive uncertainties that depend on the maximum mass that the instrument is designed to measure. Because these uncertainties are typically of the order of grams or less, and contribute negligibly to the measurement variances of interest, we shall not list them individually here.

2.4. Measurements

The accounting and quality-control measurements that are performed with the instruments described in Section 2.3 are the following.

2.4.1. Plutonium Accountability Tank Measurements.

Each time the plutonium accountability tank is filled, the tank volume is measured and a sample of the solution is taken for chemical analysis.

2.4.2. Uranium Accountability Tank Measurements.

Each time the uranium accountability tank is filled, the tank volume is measured.

2.4.3. Concentrator Feed Tank Measurements.

Each time the concentrator feed tank is filled, the tank volume is measured and a sample of the solution is taken for chemical analysis.

2.4.4. Oxide Blending Measurements.

Each can of mixed oxide packaged in the oxide blending process is weighed and a sample is taken for chemical analysis. When the glove box filter is replaced, the old filter is weighed and its plutonium content is measured with a gamma counter.

2.4.5. Jet Milling and Blending Measurements.

The jet-milled and blended oxide is weighed after repackaging.

2.4.6. Pellet Grinding Measurements.

In the pellet grinding process both the pellets and the oxide powder are weighed and samples are taken for chemical analysis.

2.4.7. Fuel Assembly Fabrication Measurements.

The fuel assemblies produced in the fuel assembly fabrication process are weighed.

2.4.8. Condensate Treatment Measurements.

The volume of the condensate produced in condensate treatment is measured and the plutonium concentration of the condensate is measured by solution assay.

2.4.9. Scrubber Measurements.

The volume of the scrubber solution packaged for recovery is measured and its plutonium concentration is determined by solution assay.

2.4.10. Off-Gas Treatment Measurements.

The used filters from the off-gas treatment process are weighed and their plutonium content determined by a gamma counter. The plutonium content of the escaping off gas is also measured with a gamma counter.

2.5. Material Balance Areas

The MOX fuel fabrication section is assumed to be divided into two process material balance areas (MBAs) and five vault/storage MBAs. Inventory difference values are calculated for each of these MBAs during simulations, and the simulated inventory differences are used to estimate inventory difference variances for the MBAs. The vault areas and processes contained in the various MBAs are described below.

2.5.1. Solutions Storage MBA.

In order to cleanly separate measurement uncertainties in the MOX fuel fabrication section of the facility from those in the reprocessing section of the facility, the uranium and plutonium solutions that enter the MOX conversion line are assumed to be drawn from a separate solutions storage MBA.

2.5.2. MOX Conversion MBA.

The MOX conversion line processes, comprising the uranium and plutonium accountability tanks, the uranium-plutonium blend tank, the concentrator feed tank, the concentrator, the rotary calciner, and oxide blending, are grouped together into the MOX conversion MBA.

2.5.3. Oxide Product MBA.

The storage area in which the oxide product of the MOX conversion line is kept prior to entering the fuel fabrication line constitutes an MBA.

2.5.4. Fuel Fabrication MBA.

The processes that constitute the fuel fabrication line are grouped together into the fuel fabrication MBA. These processes are jet milling and blending, compaction and granulation, the pellet press, debinding and sintering, broken-pellet grinding, pellet grinding, fuel pin assembly, fissile assay, and fuel assembly fabrication.

2.5.5. MOX Fuel Product MBA.

The vault area in which completed fuel pins and fuel assemblies are stored while awaiting shipment constitutes an MBA.

2.5.6. Recovery Storage MBA.

The storage area in which scrap materials are kept pending recovery of the plutonium they contain constitutes an MBA.

2.5.7. Waste Storage MBA.

The storage area in which waste materials are stored pending disposal constitutes an MBA.

In the current model materials are never remeasured between the time they enter a vault area and the time they leave it; so only the two process MBAs (MOX Conversion MBA and Fuel Fabrication MBA) generate nonzero inventory difference values.

3. Inventory Difference Variance Estimates

It was assumed that material balance closures for the facility are made at bimonthly intervals. Only the plutonium is accounted for in these inventories, because the uranium is at most low-enriched (and possibly natural or depleted). The analytical laboratory measurements and radiation instruments are assumed to be recalibrated at bimonthly intervals, but the scales/balances and tank volume measurements are not recalibrated. The inventories are conducted during normal process operations, with in-process materials accounted for at book value. However, the inventory differences are throughput dominated, so results for shutdown inventories would be similar to those given here.

Simulation runs were made for operating periods of two years, three years, and five years. In each case the simulation start date was selected so that the facility operated for a few weeks to establish a "steady-state" before the first balance closure occurred. The individual inventory differences that were obtained for the MOX conversion and MOX fuel fabrication MBAs during the five year run are given in Tables 2 and 3, along with the inventory difference variance estimates that were inferred from them. The results from the two-year and three-year simulation runs agree with the variance estimates given here to within a few percent. The variances correspond to a standard deviation for each of the MBAs of about 2 to 2.1 kg of plutonium -- about 0.22% of throughput for the balance period. However, it can be seen that the individual inventory balances vary widely, with one difference outside the two standard-deviation range for each of the MBAs during the five-year period -- about what one would expect for distributions that should be approximately normal in form.

Table 2. Simulated inventory differences for the MOX conversion MBA.

MOX Conversion MBA Inventory Differences (grams), 5 Year Simulation		
1153	1294	-1582
2883	-1189	968
3888	-430	1221
1691	2320	-3403
1111	-2465	-750
-1901	2736	-832
-1091	1882	-392
1875	-11	1623
-1328	-1277	2567
-447	-138	-5103
Sample variance: 4100000 kg^2		
Standard deviation: 2.0 kg		

Table 3. Simulated inventory differences for the MOX fuel fabrication MBA.

MOX Fuel Fabrication MBA Inventory Differences (grams), 5 Year Simulation		
-1968	-1372	1064
-2537	712	-2111
-4608	703	-1554
-1683	-2117	3900
-700	2627	1467
2166	-1844	441
1289	-2600	458
-2342	-135	-862
1124	912	-2599
-115	553	4696
Sample variance: 4.4 kg^2		
Standard deviation: 2.1 kg		

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