Paper to be presented at the 36th Annual Meeting of the Institute of Nuclear Materials Management (INMM), Palm Desert, California, July 9-12, 1995.

FUEL CONDITIONING FACILITY MATERIAL ACCOUNTANCY*

by

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*Work supported by the U.S. Department of Energy, Nuclear Energy Programs under Contract W-31-109-ENG-38.

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ABSTRACT

The operation of the Fuel conditioning Facility[1] (FCF) is based on the electrometallurgical processing of spent metallic reactor fuel. It differs significantly, therefore, from traditional PUREX process facilities in both processing technology and safeguards implications. For example, the fissile material is processed in FCF only in batches and is transferred within the facility only as solid, well-characterized items; there are no liquid steams containing fissile material within the facility, nor entering or leaving the facility. The analysis of a single batch lends itself also to an analytical relationship between the safeguards criteria, such as alarm limit, detection probability, and maximum significant amount of fissile material, and the accounting system's performance, as it is reflected in the variance associated with the estimate of the inventory difference. This relation, together with the sensitivity of the inventory difference to the uncertainties in the measurements, allows a thorough evaluation of the power of the accounting system. The system for the accountancy of the fissile material in the FCF has two main components: a system to gather and store information during the operation of the facility, and a system to interpret this information with regard to meeting safeguards criteria. These are described and the precision of the inventory closure over one batch evaluated.

INTRODUCTION

The operation of the Fuel Conditioning Facility (FCF) is based on the electrometallurgical processing of spent metallic reactor fuel. It differs significantly, therefore, from traditional PUREX process facilities in both processing technology and safeguards implications. For example, the fissile material is processed in FCF only in batches and is transferred within the facility only as solid, discrete items; there are no liquid streams containing fissile material within the facility, nor entering or leaving the facility. In addition, it is also a new first-of-a-kind facility, and, as such, amenable to new and innovative design and operating approaches without regard to the limitations posed by retrofitting. For this analysis, we assume that the spent fuel processed in the facility has been discharged from the experimental fast breeder reactor EBR-II, and enters the material balance area (MBA) of the Fuel Cycle Facility as fuel elements. This aspect of the FCF differs greatly from PUREX facilities, where the discharged reactor fuel is first dissolved, and characterized for accountancy by volume determination and sampling the solution, before it enters the MBA of the facility. In the FCF, on the other hand, the mass and composition of the spent fuel, together with the uncertainties, is determined from the fresh fuel specifications, and, with validated computer codes, the calculated change in the as-fabricated composition due to reactor burnup. This approach, although in no way limiting the generalization of the results of this study, is consistent with the startup scenario for the facility, and the future operation of the facility. In this mode of operation the facility will process significant quantities of fissile materials; this requires a tested, evaluated, and qualified system of accountancy.

The system for the accountancy of the fissile material in the FCF has two main components: a system to gather and store information during the operation of the facility, and a system to interpret this information with regard to meeting safeguards criteria. The former aspect is centered about the mass tracking system (MTG).[2] This system tracks the movement of items, particularly those which contain nuclear material, inside the FCF and automatically updates a database with their amount and location. It also assists FCF operations personnel and process control. The mass tracking system generates mass balances of criticality zones within the facility for arbitrary time periods. The mass tracking and data archiving functions reside on engineering workstation computers which use high-level language programs and a commercial database manager. Archival data and the special nuclear material database are stored on hard disks. Tape drives are also provided for permanent archiving of data. The data archival system collects logged data from the file server and archives the data. The subject at hand is the interpretation of the data collected by and stored in the MTG.

The accountancy system for the Fuel Conditioning Facility consists of database tables and files, which contain information on the disposition (inventory, additions, or removals) and quantity (measured or modeled) including associated uncertainties of fissile material items. An item is a discrete, unique, and identifiable entity containing fissile material and is a natural unit in the batchwise electrometallurgical process. The measurements are mainly weighings on electronic balances to determine mass (which are made before every transfer of material from a container or zone), chemical and spectrometric analysis of samples to determine elemental and isotopic composition, liquid level measurements for volume determination, and nondestructive assays of waste streams. This information is input to computer codes to establish an inventory difference of the fissile material processed and stored in the facility over some period of time. Since the operation of the facility is characterized by batch mode operation, the time to process a batch lends itself to interpretation as a convenient accounting period, at least during the early stages of operation, when only a single batch is processed at one time in the facility. We focus, therefore, on a single batch in order to study in detail the sensitivity of the effectiveness of the accounting system in the Fuel Conditioning Facility.

The analysis of a single batch lends itself also to an analytical relationship between the safeguards criteria, such as alarm limit, detection probability, and maximum significant quantity of fissile material, and the accounting system's performance, as it is reflected in the variance associated with the estimate of the inventory difference.[3] This relation, together with the sensitivity of the uncertainty in the inventory difference to the uncertainties in the measurements, allows a thorough evaluation of the power of the accounting system, and, if necessary, can point to possible ways for improving the power of the system.

MATERIAL BALANCE AREA

The material balance area (MBA) for the FCF consists of a sequence of unit process areas (UPAs). The MBA, as defined for the initial assessment of the FCF accountability system, is shown schematically in Fig. 1. The material enters the MBA in the form of fuel pins, and as the term A_i^{EC} in Fig. 1, into the first UPA - the element chopper (EC). The fuel then passes sequentially to the electrorefiner (ER), the cathode processor (CP), the casting furnace (CF), and finally to a storage area. We note, that, in this initial evaluation, the final disposition of the nuclear material in this model is the storage area, which is also part of the MBA. Thus, the only routine removal of fissile material from the MBA is in the form of samples R_i^{ECSAM}, $R_i^{SALTSAM}$, and R_i^{PINSAM}. This is consistent with the initial operation of the facility. Eventually the removal of this stored material for final disposition will take place. However, it is not expected that the additional measurements and calculations, to those being exercised in this initial assessment, will significantly affect the results of this assessment. For example, the interrogation of scrap waste containers, although relatively less precise in percent terms than the other measurement systems, will contribute very little to the uncertainty in the inventory difference; by virtue of the fact that experience has shown that the scrap contains very small amounts of heavy metal. A significant diversion would easily be detected by a NDA device.

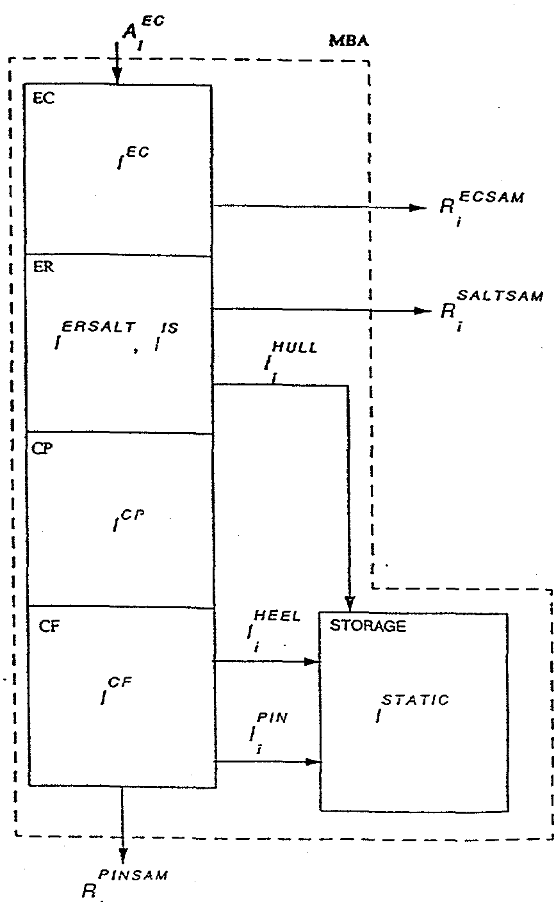

Fig. 1. Materials Balance Area over the FCF

A critical element in the accountancy of nuclear material in any facility is the issue of holdup; material which remains in the MBA from batch to batch and does not take direct part in the process. This material has traditionally contributed to statistically significant inventory differences. We take into account process holdup, which experimental evidence indicates is likely to be significant during full operation of the facility. The major holdup components are associated with holdup in the cathode processor (I^{CP}) and the buildup of insolubles in the electrorefiner (I^{IS}).

INVENTORY DIFFERENCE ESTIMATION

The inventory difference for some specified isotope of nuclear material for the MBA over some specified time period is estimated by the usual relationship:

$$\mathbf{ID}_i = \mathbf{I}_{i-1} + \mathbf{A}_i - \mathbf{R}_i - \mathbf{I}_i ,$$

where $\mathbf{ID}_i$ is the inventory difference for the i-th accounting period, $\mathbf{I}_{i-1}$ the physical inventory at the end of the previous accounting period, $\mathbf{A}_i$ and $\mathbf{R}_i$, the additions and removals during the i-th accounting period, respectively, and $\mathbf{I}_i$ the physical inventory at the end of the i-th accounting period. The estimate, by itself, is insufficient for decisions with regard to material accountancy of special nuclear materials. For this, an estimate of the standard error of the inventory difference estimate is necessary.

For accountancy in FCF the information required for the calculation of the inventory difference and its standard error comes from two basic sources - the mass tracking system (MTG) database, and the measurement error, and methods files. The MTG contains the information with regard to measured or calculated values for all inventory items and for all transfers of material into and out of the MBA. The supplementary information for the standard error calculation is stored in the measurement error and methods files. The MTG is a dynamic database, in that it is updated each time an operation is performed. Such as, for example, when an item is created, destroyed, transferred or measured. The error files, on the other hand, are updated only after the calibration of a measurement instrument. It is only at that time, that the random and systematic variance, which are to be assigned to the values established by the instrument, are estimated through the repeated measurement of standards.

Since no fuel has to date been processed in FCF, nominal values based on data accumulated during the development of the FCF equipment and engineering scale tests are used in the calculation of inventory difference for the MBA in Fig. 1. This is especially true of the holdup estimates; they are mainly theoretical estimates. U-235 is the material of interest in the initial operations. The inventory of U-235 in the FCF consists of two main components - the in-process material in the salt of the electrorefiner (I^{ERSALT}) and the additions in the form of spent fuel elements. The electrorefiner holds about 262 liters of salt at a density of 1.75 gm/cm^3 of which 7% is uranium enriched in U-235 to 63% . This results in an inprocess inventory of U-235 of about 20 kg. An input batch consists of eight baskets of 2.25 kg heavy metal each. The input U-235 of 10.66 kg (A_i^{EC}) is based on an enrichment of 63% and a fissile burnup of 6%.

The inventory (in-process plus additions) and the variance in the estimate of this inventory are shown in Table I. The standard deviation in the estimate of the mass of U-235 in the additions to the MBA is 0.113 kg, and for the in-process material in the electrorefiner 0.374 kg. Safeguards decisions, based on accountancy, however, are not made with regard to inventory, but rather, with regard to inventory difference. To this end, the data are processed with the computer program MAWST[(4)] to give an inventory difference and the associated variance; these are shown in Table II. The estimate of the inventory difference is 0.063 kg with a standard deviation of 0.547 kg. The inventory difference shown in Table II is artificial based on nominal values, since there are no operating data for FCF at this time. The variance estimate of the inventory difference, however, is based on FCF instrument calibrations and, where necessary, on estimates from experience with the operation of engineering scale equipment. The measure of the performance of the accounting system is reflected by the variance in the inventory difference and not the inventory difference itself. It is thus sufficient to focus only on the variance.

The variance is divided in Table II into different contributions - the input mass (CALC_FUEL), the electrorefiner insolubles mass (CALC_IS), the cathode processor holdup mass (CALC_CP), the pin casting furnace holdup mass (CALC_CF), the mass of the

Table I. Initial Inventory of U-235 (additions plus in-process)

Inventory, (kg):	31.099350
Standard Deviation, (kg):	0.390986
Measurement Method	**Variance Contribution (kg^2)**
CALC_FUEL	0.012767
CALC_IS	0.036922
CALC_CP	0.00000
CALC_CF	0.00000
CALC_HULL	0.00000
MSPEC	0.020507
VOLUME	0.000681
DENSITY	0.081993
WEIGHT	0.000000
VARIANCE OF ID	0.152870

Table II. Material Balance of U-235 for One Batch

Inventory Difference, (kg):	0.062542
Standard Deviation, (kg):	0.547447
Measurement Method	**Variance Contribution (kg^2)**
CALC_FUEL	0.012767
CALC_IS	0.075064
CALC_CP	0.000514
CALC_CF	0.000040
CALC_HULL	0.002869
MSPEC	0.046238
VOLUME	0.000021
DENSITY	0.162172
WEIGHT	0.000013
VARIANCE OF ID	0.299698

undissolved heavy metal and the mass of salt in the cladding hulls (CALC_HULL), the mass spectrometry measurements (MSPEC), the salt and Cd volume measurements (VOLUME), the salt density (DENSITY), and the mass balance measurements (WEIGHT). The largest contribution, 0.162 kg^2 and one half of the total variance, is that of the estimate of the salt density in the electrorefiner. The next largest, 0.0750 kg^2, is that of the mass of the insolubles holdup in the electrorefiner. Also contributing significantly are the contributions from the mass spectrometry measurements and the estimate of the input mass. The other contributions are at least an order of magnitude smaller.

ANALYSIS

For a single inventory period, such as the processing of a single batch, the system detection probability (1-β), the false alarm rate (α), the material loss, and the inventory difference standard deviation, can be related through an analytic expression. This relationship is shown graphically in Fig. 2 for the estimated FCF inventory difference variance, and false alarm rates of 5% and 10%. The detection probability, the false alarm rate, and the level of acceptable material loss can be considered, to some extent, exogenous to the facility. That is, they are mainly set by regulatory and policy considerations. The designers of the facility control the variance of the inventory difference, through their choice of instruments and the procedures for measurement and sampling.

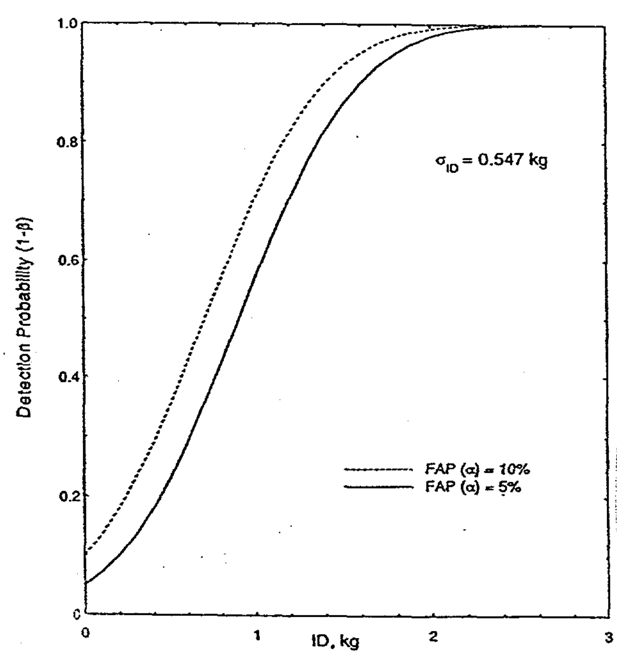

Fig. 2. The Detection Probability as a Function of Inventory Difference

The lack of historical data for the evaluation of the performance of the FCF accountancy system can be overcome, to some extent, through a sensitivity analysis. To this end, the variation in the inventory difference variance has been calculated parametrically with respect to each variance component. The effect of changes in the dominant component of the inventory difference variance, that is the uncertainty in the salt density estimate, is shown in Fig. 3. Thus, for example, halving the uncertainty reduces the standard deviation in the inventory difference by 25%. The consequences of such a reduction in the standard deviation in the inventory difference can be discerned in Fig. 4 for a specified false alarm rate of 5%. For a maximum loss of 1.5 kg (i.e. the value of the alternate hypothesis in a statistical hypothesis test) a 25% reduction in the inventory difference standard deviation from its current value of 0.55 kg would increase the system detection probability from 0.80 to 0.98.

CONCLUSIONS

The above analysis has assessed the performance of the FCF accountancy system with regard to the estimated variance of the inventory difference for the electrometallurgical processing of one batch of spent fuel. The simplicity of the process steps and the batch nature of the operation allow reasonable estimation of the system performance with respect to exogenous parameters, such as detection probability, false alarm rate, and significant quantity of special nuclear material. To date FCF has operated with only the pin casting systems. For these operations the accounting system has been tested and shown to be robust.[5] As the additional systems, electrorefiner, cathode processor, etc., become operational, the accumulation of historical data will allow further refinement of the uncertainties that contribute to the variance in the inventory difference. The current analysis, based on upperbound estimates of uncertainties, demonstrates that the FCF accountancy system is expected to meet established safeguards principles.

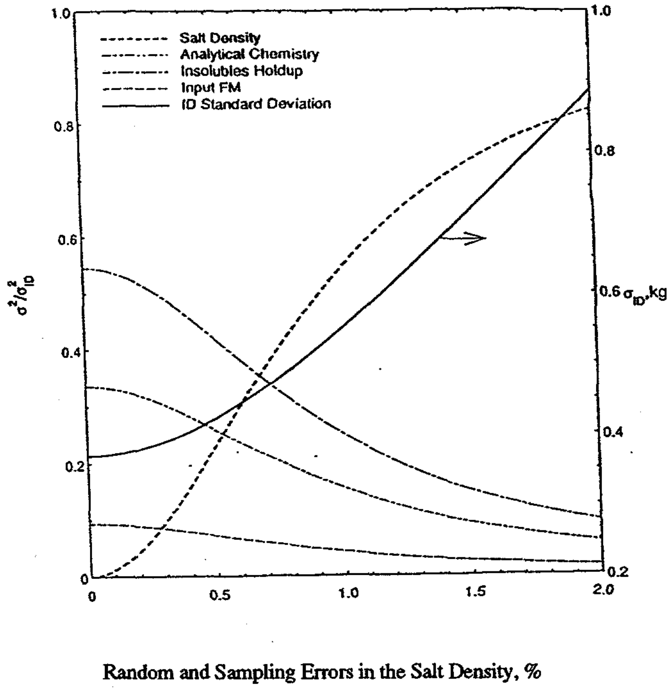

Fig. 3. Sensitivity of the Inventory Difference Variance to Changes in the Errors in the Salt Density Estimate

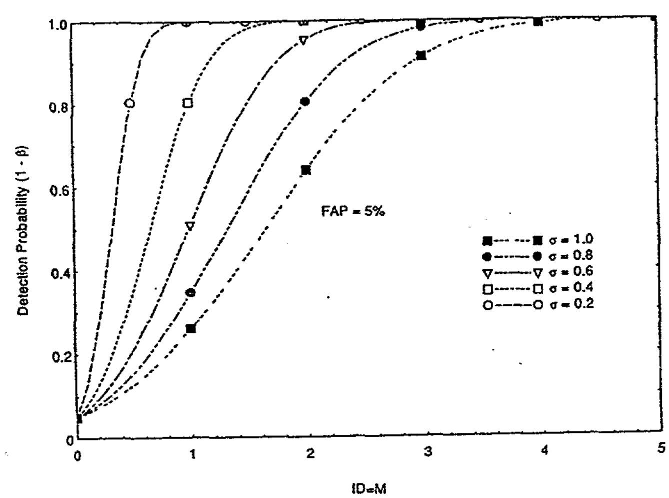

Fig. 4. The Relationship between a Material Loss and its Detection Probability for a given False Alarm Probability (FAP) for Different Inventory Difference Standard Deviations

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