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MASTER

Materials Accounting in a Fast Breeder Reactor Fuels Reprocessing Facility: Optimal Allocation of Measurement Uncertainties

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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Edited by Patricia Metropolis

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Materials Accounting in a Fast-Breeder-Reactor Fuels-Reprocessing Facility: Optimal Allocation of Measurement Uncertainties

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EXECUTIVE SUMMARY

This report describes the first in a series of studies in support of the US Department of Energy's (DOE) Consolidated Fuel Reprocessing Program. These studies develop and evaluate designs of advanced materials measurement and accounting systems (MMASs) for various nuclear spent-fuel reprocessing alternatives. This report examines safeguards design concepts for the feed preparation and chemical separations processes of the Hot Experimental Facility (HEF), a conceptual fast breeder reactor spent-fuel reprocessing facility. We propose an MMAS and use optimization techniques to calculate instrument measurement uncertainties that meet four different accounting performance goals while minimizing the total development cost of instrument systems. We identify measurement uncertainty components that dominate the materials balance variance and instruments that require development to meet given performance goals.

Conceptual design efforts for MMASs are a major portion of an integrated safeguards systems study program that is implemented by the Safeguards Systems Group (Q-4) of the Los Alamos National Laboratory, at the direction of the US DOE/Office of Safeguards and Security. These designs invoke technology that has been demonstrated or can be projected within the construction schedules of future nuclear fuel-cycle facilities. The studies define systems concepts, develop methods for evaluating safeguards systems and the data they produce, and should stimulate further development of facilities, processes, systems, and instrumentation needed for improving nuclear materials accounting, thus providing more effective safeguards.

Previous Los Alamos National Laboratory studies in the safeguards conceptual design series address the materials management requirements for mixed-oxide fuel refabrication facilities (LA-6536), domestic and foreign spent-fuel reprocessing plants (LA-6881 and LA-8042), plutonium nitrate conversion (LA-7011) and coconversion facilities (LA-7521 and LA-7746-MS), spent-fuel storage ponds (LA-7730-MS), thorium-uranium fuel-cycle facilities (LA-7372 and LA-7411-MS), large fast-critical reactors (LA-7315), and nuclear waste repositories (LA-8049-MS). In general, these studies calculate the accounting systems performance by proposing a measurement system based on current technology or its reasonable extrapolations. The measurement uncertainties for each proposed instrument are then combined and propagated to obtain an overall materials loss-detection sensitivity. This study reverses the approach. We select specific accounting performance goals for the HEF and use optimization techniques to calculate measurement uncertainties required to meet these goals while minimizing the total development cost of the instrument system.

The design for Oak Ridge National Laboratory's HEF incorporates a modified Purex process that allows coprocessing uranium and plutonium. The flow sheet is based on reprocessing 0.5 tonne/day of breeder reactor fuel having (1) a maximum burnup of 150 000 megawatt-days per tonne, (2) a minimum decay period of 60 days before shipment to the HEF, and (3) a minimum decay period of 90 days before reprocessing. The facility design also provides for nitrate-to-oxide coconversion of mixed uranium-plutonium. In this study we consider only the feed preparation and chemical separations processes. The major process areas include (1) spent-fuel receiving and storage, (2) mechanical processing and feed preparation, (3) codecontamination/partitioning, (4) uranium purification, and (5) uranium-plutonium copurification.

The HEF process has several design features that restrict the application of advanced materials measurement and accounting techniques. The dissolution and feed preparation area, in particular, has some novel features that require additional testing on a laboratory and pilot-plant scale before incorporation into the HEF, such as the voloxidizer, the continuous dissolver, and the constant-volume accountability tank. Other areas of concern include the estimation of in-process inventories in solvent-extraction contactors and other process vessels, coprocessing, recycle streams, and the inaccessibility of nuclear materials for at-line analysis. We recommend revising the HEF design to permit penetration of the cell wall by sampling lines and to allow location of nondestructive analysis instrumentation in a controlled-access instrument gallery. Such a revision would provide more timely information for process control and materials accounting.

The HEF MMAS combines conventional materials accounting and near-real-time accounting (NRTA) and serves several functions including process monitoring, domestic safeguards, and international safeguards. It employs sampling and chemical analysis, weight and volume measurements, and nondestructive assay (NDA) instrumentation, supported by data base management and data analysis techniques. We describe a conventional accounting strategy that divides the facility into five materials balance areas (MBAs) and formulate two NRTA strategies that augment the MBA structure. In strategy 1, the feed preparation processes are treated as one unit process accounting area and the chemical separations processes are treated as another area. In strategy 2, the chemical separations area is further subdivided into codecontamination/partitioning processes and uranium-plutonium copurification processes.

Measurement points for the NRTA strategies are identified, and applicable measurement types and errors representative of current technology are chosen, based on materials and processes descriptions. Reference measurements are used for process control and materials accounting.

We use optimization techniques to calculate measurement uncertainties so that performance goals for detecting materials loss are achieved while the total development cost of the instruments is minimized. The cost of improving each measurement uncertainty component is determined by a hyperbolic cost function. Therefore, where the calculated measurement uncertainty is less than what is currently achievable, a development cost is imposed. Because the cost function is nonlinear, we use a nonlinear optimization technique for calculating measurement uncertainties to minimize instrument development cost.

We calculate measurement uncertainties that meet each of the four accountability performance goals for each unit process accounting area and for several cases of instrument recalibration. For each area, values for the measurement uncertainty components are restricted by specific ranges and by the materials balance standard deviation equations for abrupt (short-term) and protracted (long-term) losses.

We choose performance goals that represent a range of measurement capabilities and domestic and international safeguards goals. The four levels of NRTA performance goals are listed in Table S-I. The first two levels correspond to a likely range of measurement capabilities. The third and fourth levels correspond to desired international and domestic goals. The first performance goal is based on what should be possible using state-of-the-art instrumentation. The second represents reasonable extrapolations of current technology. The third goal is based on International Atomic Energy Agency criteria and the fourth on Nuclear Regulatory Commission goals that are being considered at present.

TABLE S-I

PERFORMANCE GOALS

Goal	Amount @ Detection (kg Pu)	Detection Time	Detection Probability	False-Alarm Probability	Materials Balance Standard Deviation Upper Limit (kg Pu)
1. Current technology					
Abrupt	16	1 day	0.5	0.025	8
Protracted	150	6 months	0.5	0.025	75
2. Improved technology					
Abrupt	8	1 day	0.5	0.025	4
Protracted	40	6 months	0.5	0.025	20
3. IAEA					
Abrupt	8	7-10 days	0.95	0.05	2.4
Protracted	8	1 year	0.95	0.05	2.4
4. NRC					
Abrupt	2	1 day	0.5	0.025	1
Protracted	2	6 months	0.5	0.025	1

Each performance goal includes detection of an abrupt and of a protracted diversion with given detection and false-alarm probabilities. These quantities are used to calculate the maximum value of the materials balance standard deviation that will meet the performance goal.

It should be remembered that plant throughput is ∿111 kg of plutonium per day and that the chemical separation and feed preparation portions of the process can have an inventory of ∿750 kg of plutonium.

Table S-II lists materials balance standard deviations for each unit process accounting area for both one-day and six-month materials balances using current measurement technology. The feed preparation area has larger materials balance standard deviations than other areas because it has more in-process inventory, and the input transfer measurements (spent-fuel NDA) are not well characterized.

Table S-III lists relative costs for developing instrument systems that meet each of the performance goals. One cost unit is the "relative cost" of attaining a measurement uncertainty that is one-half that of current measurement technology. Each halving of measurement uncertainty costs twice what the previous halving did, plus 1. Unit process accounting for the chemical separations processes meets the first goal with weekly recalibration of plutonium concentration measuring instruments for the accountability and product sample tanks. Hence, the total development cost of the system is zero. If periodic recalibration of key transfer measurements is performed, the relative cost of the system can be reduced by 30% or more. The relative cost of achieving goals 3 or 4 is between 20 and 50 times more than the cost of achieving goal 2.

We developed a dynamic computer model of the HEF headend and chemical separations processes. This simulation allows prediction of the dynamic behavior of materials flows, inventories, and measurements over many operating parameters and the rapid accumulation of data that represent relatively long operating periods. Our optimization calculations used nominal values for process variables and did not include waste streams; we therefore applied a dynamic model of the measurement system to the simulated process data, using optimally calculated measurement uncertainties. Materials balance standard deviations obtained from these simulations agreed with optimization results.

TABLE S-II

MATERIALS BALANCE STANDARD DEVIATIONS
WITH CURRENT MEASUREMENT TECHNOLOGY

	1 Day (kg Pu)	6 Months (kg Pu)
UPAA 1 (feed preparation)		
No recalibration	11.6	636
Weekly recalibration	11.6	373
UPAA 2 3 (chemical separations)		
No recalibration	7.6	93
Weekly recalibration	7.6	72
UPAA 2 (codecontamination/partitioning)		
No recalibration	5.9	289
Weekly recalibration	5.9	109
UPAA 3 (copurification)		
No recalibration	5.5	284
Weekly recalibration	5.5	114

TABLE S-III

RELATIVE COST OF ACHIEVING THE PERFORMANCE GOALS

	Goal 1	Goal 2	Goal 3	Goal 4
UPAA 1 (feed preparation)				
No recalibration	20	111	1947	2546
Weekly recalibration	9	64	-	-
Daily recalibration	-	53	942	1350
UPAA 2 3 (chemical separations)				
No recalibration	0.8	32	727	1544
Weekly recalibration	0	22	-	-
Daily recalibration	-	19	495	738
UPAA 2 (codecontamination/partitioning)				
No recalibration	11	74	1404	2023
Weekly recalibration	2	36	-	-
Daily recalibration	-	28	595	853
UPAA 3 (copurification)				
No recalibration	9	65	1263	1666
Weekly recalibration	1.7	29	-	-
Daily recalibration	-	21	518	735

For feed preparation processes, the performance goals cannot be met by current measurement technology. Materials accounting is complicated by in-process inventories and spent-fuel assembly transfers that are difficult to measure. To alleviate these problems, inventories should be reduced wherever possible, spent-fuel NDA techniques should be refined and standards developed, and frequent flushouts of the feed preparation process should be considered.

For the chemical separations area, an abrupt loss-detection sensitivity of 15 kg of plutonium and a protracted loss-detection sensitivity of 150 kg of plutonium are attainable with current measurement technology. These loss-detection sensitivities have 50% detection probability and 2.5% false-alarm probability. If it is desirable to subdivide the chemical separations process and maintain loss-detection sensitivity, then a flow meter with measurement uncertainties comparable to those for the accountability tank must be developed, or buffer accountability tanks must be added at a designated feed tank location.

Achieving second-level performance (8 kg of plutonium abrupt and 40 kg of plutonium protracted) is a reasonable goal for the chemical separations area of the HEF. This requires improving in-process inventory measurement uncertainty to $\sim$1% precision for process tank volume and concentration measurements. It also means improving accountability and plutonium sample tank transfer measurement uncertainties to $\sim$0.04% relative standard deviation (RSD) volume calibration, $\sim$0.04% RSD volume standards, $\sim$0.1% RSD concentration calibration, and $\sim$0.05% RSD concentration standards.

Attaining goals three and four requires inventory measurement or estimate errors <0.2% RSD, transfer random errors <0.03% RSD, and transfer correlated errors <0.002% RSD. For comparison, today's primary standards have errors of about 0.04%. Clearly, the proposed international and domestic safeguards goals cannot be achieved without major breakthroughs in measurement technology and standards preparation.

The optimization method developed for this study can identify measurement uncertainty components that dominate materials balance standard deviations and instruments that require development to meet specific performance goals. Further study is needed to determine the sensitivity of the results to costs and the constraints of measurement uncertainties.

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GLOSSARY

CFRP	Consolidated Fuel Reprocessing Program
CPIT	cleanout physical inventory taking
DOE	Department of Energy
HA	high activity
HAW	high-activity waste
HEF	Hot Experimental Facility
HLW	high-level waste
IAEA	International Atomic Energy Agency
ICA	item accounting area
IMP	inventory measurement point
LMFBR	liquid-metal fast breeder reactor
MBA	materials balance area
MMAS	materials measurement and accounting system
MP	measurement point
NDA	nondestructive assay
NRC	Nuclear Regulatory Commission
NRTA	near-real-time accounting
ORNL	Oak Ridge National Laboratory
PIT	physical inventory taking
S/R	shipper/receiver
SST	solids sample tank
TMP	transfer measurement point
UPAA	unit process accounting area

Purex Process Identifiers

Contactors

- A extraction-scrub for U-Pu or Pu alone
- B U-Pu partition or Pu strip
- C U-Pu strip
- D extraction-scrub for Pu alone
- H preparation columns or streams

Stream

- A aqueous
- F feed
- IS intermediate scrub
- O organic
- P product containing Pu or Pu + U
- R raffinate (no appreciable U or Pu)
- S scrub
- U product containing only U
- W waste (no appreciable U or Pu)
- X extractant

MATERIALS ACCOUNTING IN A FAST BREEDER REACTOR FUELS REPROCESSING FACILITY: OPTIMAL ALLOCATION OF MEASUREMENT UNCERTAINTIES

by

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J. T. Markin, D. P. Martinez, and C. C. Thomas, Jr.

ABSTRACT

This report describes the conceptual design of a materials accounting system for the feed preparation and chemical separations processes of a fast breeder reactor spent-fuel reprocessing facility. For the proposed accounting system, optimization techniques are used to calculate instrument measurement uncertainties that meet four different accounting performance goals while minimizing the total development cost of instrument systems. We identify instruments that require development to meet performance goals and measurement uncertainty components that dominate the materials balance variance. Materials accounting in the feed preparation process is complicated by large in-process inventories and spent-fuel assembly inputs that are difficult to measure. To meet 8 kg of plutonium abrupt and 40 kg of plutonium protracted loss-detection goals, materials accounting in the chemical separations process requires :

- process tank volume and concentration measurements having a precision $\leq 1\%$;
- accountability and plutonium sample tank volume measurements having a precision $\leq 0.3\%$, a short-term correlated error $\leq 0.04\%$, and a long-term correlated error $\leq 0.04\%$; and
- accountability and plutonium sample tank concentration measurements having a precision $\leq 0.4\%$, a short-term correlated error $\leq 0.1\%$, and a long-term correlated error $\leq 0.05\%$.

The effects of process design on materials accounting are identified. Major areas of concern include the voloxidizer, the continuous dissolver, and the accountability tank.

I. INTRODUCTION

The United States Department of Energy (DOE) Consolidated Fuel Reprocessing Program (CFRP), centered at Oak Ridge National Laboratory (ORNL), comprises much of the DOE fuel reprocessing research and development. Its principal objective is the development of technology for reprocessing spent fuel from liquid-metal fast breeder reactors (LMFBRs). Los Alamos National Laboratory is tasked by the DOE/Office of Safeguards and Security to provide technical assistance in materials measurement and accountability technology to the CFRP. This report is the first in a series in support of the CFRP that develops and evaluates conceptual designs of advanced materials measurement and accountability systems for various reprocessing alternatives.

We give the study objectives, materials accounting performance goals, study ground rules, and a brief description of the Hot Experimental Facility (HEF) feed preparation and chemical separations processes in Sec. I. Section II describes materials measurement and accounting strategies. We discuss optimization techniques and their application to the allocation of measurement uncertainties in Sec. III and present results of the optimal allocation calculations in Sec. IV. Section V identifies HEF process design features that affect materials accounting, and Sec. VI gives the summary and conclusions of this study.

A. Objectives

The CFRP completed a conceptual design of the HEF, a pilot-scale plant designed to reprocess LMFBR fuels containing uranium and plutonium. This report describes a materials accounting system for the HEF feed preparation and chemical separations processes. For the proposed system, optimization techniques are used to calculate instrument measurement uncertainties that meet four different accounting performance goals while minimizing the total development cost of instrument systems. We identify measurement uncertainties that dominate the materials balance variance and instruments that require development to meet performance goals.

Previous materials accounting systems studies for various facilities in the nuclear fuel cycle calculated the near-real-time accounting (NRTA) systems performance by proposing a measurement system based on current technology or its reasonable extrapolations.[1-5] The measurement uncertainties for each

proposed instrument were combined and propagated to obtain an overall materials loss-detection sensitivity. This study reverses the approach. We use optimization techniques to calculate measurement uncertainties required to meet selected NRTA performance goals while minimizing the total development cost of the system. In this way we can answer the following questions.

(1) Given limited development resources, what measurement technology improvements provide maximum increase in accounting system performance?

(2) Which measurement uncertainties dominate materials balance variance?

(3) What values of measurement uncertainties are required to meet a given performance goal?

The overall study objective required that we

(1) formulate NRTA performance goals,

(2) define materials accounting strategies,

(3) identify measurement points,

(4) specify a reference materials measurement system that represents current technology,

(5) deduce cost functions for improving each instrument measurement uncertainty, and

(6) construct an optimal measurement allocation technique.

B. NRTA Performance Goals

Table I lists four levels of NRTA performance goals. The first two levels correspond to a likely range of measurement capabilities, the third and fourth levels to desired international and domestic goals. The first performance goal is based on state-of-the-art instrumentation. The second goal represents reasonable extrapolations of current technology. The third goal is based on International Atomic Energy Agency (IAEA) criteria and the fourth on Nuclear Regulatory Commission (NRC) goals that are now being considered.

Each performance goal includes detection of an abrupt (short-term) and a protracted (long-term) diversion with given detection and false-alarm probabilities. These quantities are used to calculate the maximum value of the materials balance standard deviation that will meet the performance goal.

It should be remembered that the plant throughput is $\sim$111 kg of plutonium per day and that the chemical separation and feed preparation portions of the process can have an inventory of $\sim$750 kg of plutonium.

TABLE I

PERFORMANCE GOALS

Goal	Amount @ Detection (kg Pu)	Detection Time	Detection Probability	False-Alarm Probability	Materials Balance Standard Deviation Upper Limit (kg Pu)
1. Current technology					
Abrupt	16	1 day	0.5	0.025	8
Protracted	150	6 months	0.5	0.025	75
2. Improved technology					
Abrupt	8	1 day	0.5	0.025	4
Protracted	40	6 months	0.5	0.025	20
3. IAEA					
Abrupt	8	7-10 days	0.95	0.05	2.4
Protracted	8	1 year	0.95	0.05	2.4
4. NRC					
Abrupt	2	1 day	0.5	0.025	1
Protracted	2	6 months	0.5	0.025	1

C. Study Ground Rules

We used the following ground rules for this study. The sensitivity of the results to the major assumptions will be considered in a subsequent report.

(1) Measurement points are identified and associated measurement uncertainties are calculated to allow us to achieve each performance objective. In most cases, the measurement points coincide with those required for process control.[6]

(2) Materials balances are drawn once a day to coincide with feed and product batches.

(3) Each measurement is independent of all others. This assumption implies that there are no correlations between instruments; for example, each instrument is calibrated independently of any other instrument and with different standards. This, of course, is not the case in actual practice. There are two different assumptions that bracket the range of the materials balance standard deviation. If we assume that input and output instruments are calibrated with similar or identical standards, then the correlations between those instruments reduce the total materials balance standard deviation. Alternatively, if we assume that all input measurements are calibrated using one standard and all output measurements are calibrated using another, then the correlations increase

the materials balance standard deviation. Thus, the assumption of independence results in a materials balance standard deviation that is somewhere in the middle range of practical application.

(4) Each transfer or tank inventory measurement point has two measurement components, for example, volume and concentration. All other measurement points, for example, the inventory in the dissolver and the pulsed columns, have one measurement component.

(5) Each measurement is specified by :

(a) a precision (ε) with variance σ_ε^2,

(b) a short-term correlated error component (η) with variance σ_η^2,

(c) a long-term correlated error component (θ) with variance σ_θ^2,

(d) a calibration frequency.

The short-term correlated error represents those errors that are correlated only over each calibration period. Long-term correlated errors persist over all accounting periods and include errors in the primary and secondary standards and any inherent bias in sampling and measurement methods. All errors are assumed to be normally distributed with mean zero.

(6) A mixed measurement error model is used,

$$m = \mu\ (1 + \varepsilon + \eta) + \theta \quad ,$$

where μ equals the actual value and m equals the measured value.

(7) The "cost" of improving a measurement uncertainty (σ) is described by an equilateral hyperbola,

$$\text{Cost} = A\left[\frac{\sigma_u - \sigma_1}{\sigma - \sigma_1} - 1\right] \quad ,$$

where σ_u is an uncertainty achievable by current technology, σ_l is an uncertainty not achievable at any cost, and A is a relative improvement difficulty index.

(8) The materials balance standard deviation (σ_{MB}) is apportioned among the measurement uncertainties so that

$$\sigma_{MB} = \left[\sum_{i=1}^{N_m} B_{ai} \sigma_i^2 \right]^{1/2} ,$$

where N_m equals the number of measurement uncertainties and $B_{ai}\sigma_i^2$ equals total variance of the ith measurement uncertainty (B_{ai} is a function of the amount of material being measured and the number of measurements), such that the development cost

$$\sum_{i=1}^{N_m} A_i \left[\frac{\sigma_{ui} - \sigma_{li}}{\sigma_i - \sigma_{li}} - 1 \right]$$

is minimized.

D. The Reference Facility

The HEF is a conceptual pilot-scale reprocessing facility that was conceived under the Advanced Fuel Recycle Program at ORNL. Its design, which was initiated in October 1976, was directed toward reprocessing uranium-plutonium fuels from LMFBRs. Consistent with changes since 1976 in US policy regarding fuel reprocessing and breeder reactor technology, the original HEF design has had several revisions, which emphasized proliferation-resistant fuel cycles including thorium-based breeder reactor fuels. Because current emphasis is on the uranium-plutonium fuel cycle, this study addresses only the HEF uranium-plutonium flow sheet.

The current HEF design incorporates a modified Purex process that allows coprocessing uranium and plutonium.[7,8] The flow sheet is based on reprocessing

one-half tonne per day of breeder reactor fuel having (1) a maximum burnup of 150 000 megawatt-days per tonne, (2) a minimum decay period of 60 days before shipment to the HEF, and (3) a minimum decay period of 90 days before reprocessing. The design also provides for nitrate-to-oxide coconversion of mixed uranium-plutonium. In this study we consider only the feed preparation and chemical separations processes. Therefore, the following brief description highlights the major process systems, including (1) spent-fuel receiving and storage, (2) mechanical processing and feed preparation, (3) codecontamination/partitioning, (4) uranium purification, and (5) uranium-plutonium copurification. A more complete description of the process is given in Appendix A.

In the fuel receiving and storage system, spent fuel is received in shipping casks, cleaned, assayed to determine its fissile content, and stored until it is scheduled for reprocessing. Operations include (1) cask unloading, (2) fuel cleaning and waste concentration, (3) fuel storage and water treatment, (4) nondestructive assay (NDA), and (5) sodium handling.

The mechanical processing and feed preparation system prepares a uranium-plutonium dissolved-fuel feed solution for subsequent processing by solvent extraction. Primary feed to this system is cleaned fuel assemblies. Secondary feed streams include fuel assembly fragments, storage-pool filter effluents, metal scrap, and high-activity (HA) centrifuge sludge. Major process steps are (1) mechanical disassembly and shearing, (2) voloxidation, (3) fuel dissolution, and (4) feed clarification.

The codecontamination/partitioning system includes a series of solvent-extraction contactors in which uranium and plutonium are selectively transferred between relatively immiscible, countercurrent aqueous and organic streams. In the first (codecontamination) cycle, fission products are separated from the uranium and plutonium. This cycle provides a fission-product codecontamination factor of $\sim 10^3$. The second cycle produces a partially purified uranium nitrate stream and a partially purified denatured plutonium nitrate stream having a uranium-to-plutonium ratio of 0.13:1.

The uranium purification system includes a solvent-extraction cycle (third cycle) that further purifies the uranium-nitrate product from the partitioning cycle. This purified uranium is concentrated and used to produce UO_3 and to adjust the uranium-plutonium ratio in the copurification system.

The uranium-plutonium copurification system includes two solvent-extraction cycles (fourth and fifth cycles) that further purify the uranium-plutonium nitrate product from the partitioning cycle. The copurification feed is denatured with uranium from the third cycle to increase the uranium-to-plutonium ratio from 0.13:1 to 2:1. Uranium also is added to the plutonium sample tank at the end of the fifth cycle to yield a final uranium-to-plutonium ratio of 3:1.

The liquid product storage system consists of eight plutonium storage tanks that can store up to 30 days of production. The storage tanks provide feed to the mixed-oxide conversion process.

II. MATERIALS MEASUREMENT AND ACCOUNTING SYSTEM

A. Introduction

The primary objective of safeguards is to prevent the deliberate misuse of nuclear materials at both domestic and international levels. At the national level, facility operators' safeguards systems must address currently perceived threats that range from well-armed outsiders attempting forcible theft to well-informed insiders aiming at covert diversion of nuclear materials. These internal threats are addressed by several subsystems, including materials measurement and accounting,[1-5,9,10] physical protection,[11] and process monitoring and control.[12] The goal of international safeguards is to deter diversion of nuclear materials by early detection. The IAEA uses materials accounting and containment/surveillance techniques with appropriate inspections.[13-19] Effective IAEA safeguards depend on the Agency's ability to verify data reported by the facility operator's materials measurement and accounting system (MMAS). The facility operator establishes and maintains MMAS to fulfill both domestic and international requirements.[20,21]

The proposed MMAS combines conventional materials accounting with NRTA. The MMAS employs sampling and chemical analyses, weight and volume measurements, and NDA instrumentation, supported by automated data analysis and data base management technologies. Its three major tasks are

(1) data collection, including materials measurements;

(2) data analysis for assessment ; and

(3) data dissemination, including reporting.

Conventional accounting is based largely on physical inventory taking (PIT) and administrative controls. There are four common PIT methods.

1. Cleanout Physical Inventory Taking (CPIT). This is the best-known and most accurate method of PIT. The process line is drained and flushed into holding tanks for measurement, and residual holdup in the process equipment is measured directly or is estimated based on historical data. The CPIT method requires an extended shutdown period, and therefore it is costly and can be applied only infrequently. However, it provides essential information on the residual plant holdup, which is the zero base for more efficient PIT methods.

2. Draindown Physical Inventory Taking. This method is similar to CPIT, except that there is minimal flushout of the process line after draindown. The draindown PIT method may be an economically attractive alternative to CPIT, if the plant is designed for its effective application.

3. Rapid Physical Inventory Taking. This method provides more efficient materials balances than CPIT by measuring the in-process inventory when the process is operated near steady state. If certain process run conditions are repeated periodically, then in-process inventory is essentially reproducible at those times. By measuring in-process inventory under identical run conditions, biases associated with inventory measurements will tend to cancel from the materials balances, and detection sensitivity will be improved. The process may be divided into accounting units smaller than the materials balance area (MBA), depending on the availability of flow and inventory measurements. Sensitivity is better than might be expected, even though inventory measurement uncertainties are larger than for CPIT, because flow measurements are generally the dominant sources of uncertainty for a reprocessing plant.

4. Running Book Inventory Taking. In this method, not all in-process inventory components are measured. Instead, measurements are made on those process vessels that contain significant fractions of the in-process inventory and that are instrumented for rapid inventory determination. The unmeasured components of the in-process inventory are estimated by difference, and those estimates are compared with independent estimates of normal plant holdup based on historical data. Thus, running book inventory is applied only under normal operating conditions, similar to those required for rapid physical inventory. Also, the process line may be divided into smaller accounting units, and estimates by difference of the in-process output measurements become available. Depending on the variability of unmeasured inventory and the quality of input-output measurements, this method may provide good sensitivity to abrupt diversion.

For conventional materials accounting the facility is divided into MBAs, of which there are two general types.

(1) In an item control area (ICA), materials are maintained as discrete items. Materials accounting is largely vested in item counting and secure storage, with items identified by unique identifiers or seals. The contents of items may be measured if the seal is removed or if a physical inventory is taken.

(2) Process MBAs are commonly areas in which material form and composition are changed. Materials balances are closed following a PIT by adding all receipts to the initial measured inventory and subtracting all shipments and final measured inventory.

In process MBAs, PIT lacks timeliness and sensitivity because (1) PITs are infrequent, so that losses may not be detected for extended periods; (2) MBAs often include the entire plant or a major portion of the process, so that localization of losses is difficult; and (3) the throughput in a facility such as the HEF is large; consequently, the absolute detection sensitivity is large even though relative measurement errors are very small. Materials balances for NRTA are drawn without shutting down the plant: in-process inventories are measured, or otherwise estimated, while the process is operating. A fiducial or reference point for NRTA is established by periodic conventional PITs.

To implement NRTA, a process MBA of the facility may be partitioned into unit process accounting areas (UPAAs), or an MBA may be treated as a single UPAA. The main difference between the MBA of PIT accounting and the UPAA of NRTA is that materials balances are drawn around UPAAs during plant operation. Each UPAA contains one or more chemical or physical processes and is chosen on the basis of process logic and the ability to draw a materials balance, rather than on geography, custodianship, or regulatory requirements. By dividing the facility into UPAAs, quantities of material much smaller than the total, plant inventory can be accounted for on a timely basis, and any discrepancies can be localized to the portion of the process contained in the UPAA.

NRTA requires measurements of materials transfers between UPAAs and measurements or estimates of in-process inventories. Materials transfer measurements made for PITs are used by the NRTA system. Where transfers between UPAAs do not coincide with transfers between MBAs, then a transfer measurement must be added for NRTA. In some cases, process contol

measurements of transfers can be used for NRTA. Measurements of in-process inventories can, in most cases, be based on process control instruments or improvements of those instruments.

The next section gives a brief description of the HEF MBA structure, followed by a description of the UPAA structure. It also discusses transfer and inventory measurement points and measurement methods that represent current technology. These measurements represent a reference case for the optimization calculations.

B. MBA Structure

For this study, the HEF is divided into five MBAs, as shown in Fig. 1. Also shown are PIT accounting measurement points (MPs) for the five areas. MPs are divided into transfer measurement points (TMPs) and inventory measurement points (IMPs). Each TMP can represent several types of measurements of various materials transfers between MBAs. IMPs are designated tanks in which flush

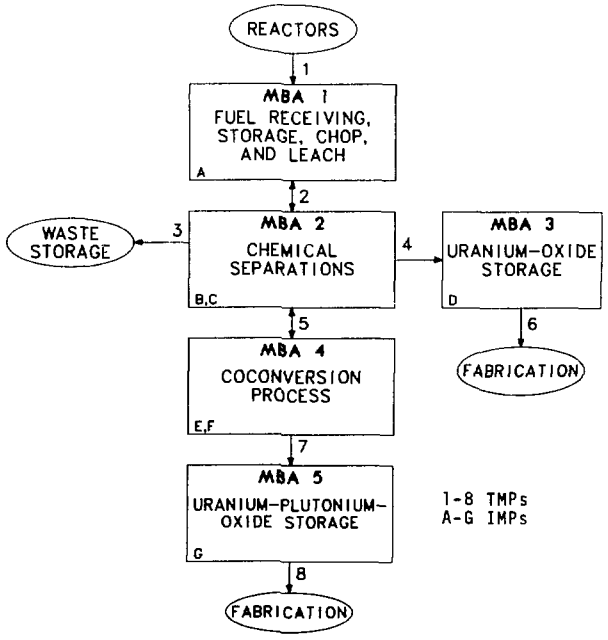

Fig. 1.
MBAs in the HEF.

solutions are collected during a PIT. This MBA structure was chosen so that major materials storage areas are separated from process areas. Other HEF MBA structures were proposed[22] and the final selection will depend on the facility operator's objectives and current regulatory requirements. Each MBA is described briefly below.

1. MBA 1: Fuel Receiving, Storage, Chop, and Leach. MBA 1 includes the spent-fuel receiving and cleaning area, the spent-fuel storage pool, and the disassembly, shearing, voloxidation, and dissolution operations to the accountability tank. MBA 1 comprises both item control areas (the fuel-storage pool and process operations before shearing) and process areas (chop and leach). Shipper/receiver (S/R) differences between the reactor and the HEF must be reconciled in MBA 1. The accountability tank is chosen as the product boundary of MBA 1 because the first accurate measurement can be made there. Accountability tank measurements are used for the receiver's values in settling S/R differences and as input to the chemical separations processes. TMP 1 is for the receipt of irradiated fuel, and TMP 2 is for transfers between MBA 1 and MBA 2. All irradiated fuel received passes through TMP 1. Transfers that pass through TMP 2 include recycle solutions, off gas, leached hulls, fuel assembly scrap, unprocessed high-level waste (HLW), accountability batches, and laboratory samples. We assume that materials sent to waste storage are first processed in MBA 2.

IMP A comprises the spent-fuel storage pool and those process tanks for which reliable volume and concentration measurements can be made--probably digester tanks and the feed solution surge tank. During a PIT spent-fuel assemblies are counted and the process is flushed into designated tanks where the volume is measured and samples are taken for chemical analysis.

A materials balance can be closed about the chop and leach processes after each campaign (approximately every 30-40 days) when major process vessels and associated piping are drained and flushed into the accountability tank. If spent-fuel NDA methods become available, the MBA structure should be modified by making disassembly, shearing, voloxidation, and dissolution processes into a separate process MBA, instead of including those processes with spent-fuel storage. Also, the spent-fuel measurement would be used as the receiver's value to settle S/R differences, which is desirable because losses in the feed

preparation process before the accountability tank would not cloud the S/R differences. Furthermore, the spent-fuel measurement could determine the amount of gadolinium required for criticality safety. NDA methods for verifying declared burnup and cooling time and for assaying fissile content of spent fuel are being developed.[23-27]

2. MBA 2: Chemical Separations. MBA 2 includes solvent-extraction and associated operations from the accountability tank to the uranium-plutonium-nitrate product sample tanks and the uranium-oxide packaging station; acid/water and solvent recovery operations (extraction backcycle system, Nos. 1 and 2 solvent treatment systems, acid/water recycle system, and floor sump/rework operations); waste processing operations up to interim waste storage; and the analytical laboratory. TMP 2 is for transfers between MBA 1 and MBA 2; TMP 3 is for transfers from MBA 2 to waste storage (processed intermediate- and high-level waste); TMP 4 is for transfers from MBA 2 to MBA 3 (uranium oxide canisters); and TMP 5 is for transfers between MBA 2 and MBA 4 (uranium-plutonium nitrate solution and laboratory samples). IMP B consists of those tanks in which solutions are collected when the process is drained and flushed and IMP C is the analytical laboratory.

A PIT in MBA 2 includes a shutdown and flushout of the separations process area, a cleanout of extraneous samples, and a piece-count verification of remaining materials in the laboratory. The process line is drained and flushed into designated tanks (IMP B) (for example, the plutonium catch, plutonium sample, uranium catch, and uranium sample tanks) that have been calibrated so that reliable volume measurements can be made and samples taken for analysis. A materials balance is drawn after each physical inventory by adding all measured receipts (TMPs 2 and 5) to the initial inventory (TMPs B and C, initial) and subtracting all measured removals (TMPs 2, 3, 4, and 5) and the final inventory (TMPs B and C, final).

3. MBA 3: Uranium-Oxide Storage. MBA 3 is the uranium-oxide storage vault and is an ICA. The content of each product canister is obtained from chemical analysis of a sample and weight measurement of the uranium oxide. A physical inventory (IMP D) requires an item count and confirmation that tamper-indicating seals are intact and that prior measurements are still valid.

4. MBA 4: Coconversion Process. MBA 4 includes the eight (seven operating and one spare) parallel 25%-plutonium storage tanks and the entire uranium-plutonium nitrate-to-oxide coconversion process from the mixed-oxide feed tanks to the mixed-oxide packaging. TMP 5 is for transfers between MBA 4 from MBA 2 (uranium-plutonium nitrate solution, recycle solution, and laboratory samples), and TMP 7 is for transfers from MBA 4 to MBA 5 (uranium-plutonium oxide).

During a PIT the uranium-plutonium nitrate storage tanks (IMP E) are isolated, volume measurements are made, and samples are taken for chemical analysis. All process tanks are drained, the precipitators are flushed, and the flush solutions are collected in designated tanks (IMP F). The furnaces and dump-and-assay vessels are swept, and the powder is collected for measurement (IMP F). A materials balance is drawn after each PIT by adding all measured receipts (TMP 5) to the initial inventory (IMPs E and F, initial) and subtracting all measured removals (TMP 7) and the final inventory (IMPs E and F, final).

5. MBA 5: Uranium-Plutonium-Oxide Storage. MBA 5 is the mixed-oxide storage vault and is an ICA. Product canisters are assayed and sealed in MBA 4. A PIT (TMP G) requires item counting and confirmation that tamper-indicating seals are intact and that prior measurements are still valid. Measurements are made by assaying a random sample of the product canisters.

C. UPAA Structure

As noted earlier (Sec. II.A), PIT in process areas lacks timeliness and sensitivity. Clearly, a combination of conventional and NRTA methods is necessary in process areas. NRTA is implemented for timely detection of materials losses between conventional PITs. Under NRTA, a process area may be partitioned into UPAAs, which may include the entire area. Therefore, in many cases UPAA and MBA boundaries are identical. The distinguishing feature of a UPAA is that materials balances are closed frequently by measuring or estimating all significant materials flows and in-process inventories.

The three major process areas in the HEF are chop and leach, chemical separations, and coconversion. NRTA strategies for plutonium in the chop and leach and chemical separations process areas are discussed below. The UPAA structure is shown in Fig. 2. A subsequent report will address NRTA strategies for plutonium in MBA 4.

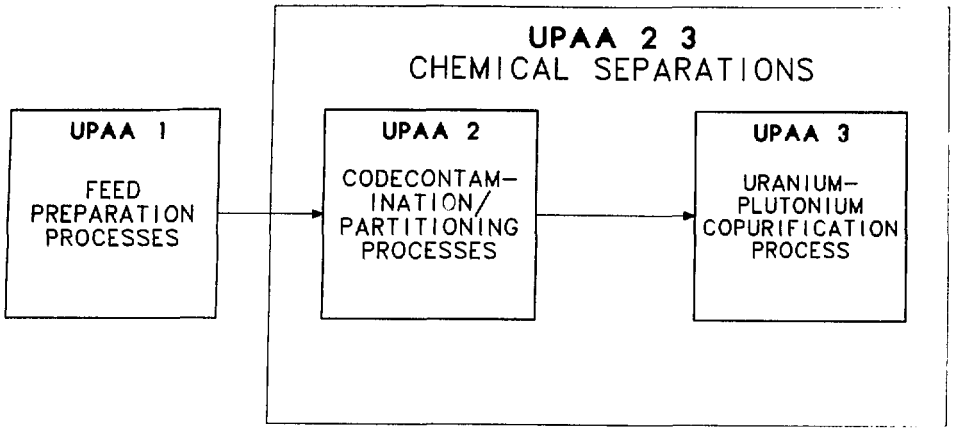

Fig. 2.
UPAAs in the feed preparation and chemical separations process areas.

1. UPAA 1: Feed Preparation Processes. A UPAA can be formed around the feed preparation processes (Fig. A-1) by combining measurements of spent-fuel assembly plutonium content and accountability tank contents with measurements or estimates of the in-process inventory. A near-real-time materials balance can be drawn once every day when an accountability batch is processed. Smaller batches, for example, waste batches sent to MBA 2, are included in materials balances when the measurements become available. Because at present we can only estimate in-process inventory in the shear, voloxidizer, and continuous dissolver, we must draw a materials balance following each flushout between campaigns. Increasing the frequency of flushouts may be desirable from both the materials-accounting and process-control points of view.

2. Chemical Separations Process Area. The chemical separations process area (Fig. 2) can be treated either as a single UPAA (UPAA 2 3) or as two UPAAs: a codecontamination/partitioning process UPAA (UPAA 2) and a uranium-plutonium copurification process UPAA (UPAA 3). A brief discussion of each follows.

a. UPAA 2 3: Chemical Separations Process. The chemical separations process MBA can be treated as a single UPAA if in-process inventory measurements are combined with TMPs 2, 3, 4, and 5 to form a near-real-time

materials balance. Because most material is transferred through the feed and product TMPs, their frequencies govern the frequency of taking materials balances. Under normal operating conditions, one accountability batch and two product batches are processed every day. Therefore, process logic dictates that a materials balance can be taken every day to include an integral number of feed and product batches. Smaller batches, for example, waste batches sent to interim storage, are included in materials balances when the measurements become available.

b. UPAA 2: Codecontamination/Partitioning Processes. A separate UPAA can be formed around the codecontamination/partitioning processes (Fig. A-3) if flow and concentration measurements are added to the 1WB, HAX, HAW, HCW, 1AX, and 1APU streams. The HAX and 1AX stream concentrations are determined at the 1O solvent surge tank in the No. 1 solvent treatment system. A near-real-time materials balance can be taken about UPAA 2 for each feed accountability batch (every 24 h) by combining volume and concentration measurements of the feed batch, flow and concentration measurements of the 1WB, HAX, HAW, HCW, 1AX, and 1APU streams, and the initial and final in-process inventories in the process vessels.

c. UPAA 3: Uranium-Plutonium Copurification Process. Near-real-time materials balances can be taken about the uranium-plutonium copurification process (Fig. A-5) if flow and concentration measurements are added to the aqueous and organic recycle streams (2AX, 2AW, 2BW, 3AX, 3AW, and 3BW). The 2AX makeup and 3AX stream concentrations are determined at the 1O solvent surge tank in the No. 1 solvent treatment system. The balances can be taken about UPAA 3 for each product batch (every 12 h) by combining volume and concentration measurements of the plutonium sample tank, flow and concentration measurements of the 2AX, 2AW, 2BW, 3AX, 3AW, and 3BW streams, and initial and final in-process inventories in the process vessels.

Because UPAA 3 contains material in a relatively attractive form, it may be desirable to close materials balances more frequently. In this case, we can add a flow and concentration measurement at the plutonium concentrator product stream. With these added measurements, we can draw near-real-time materials balances for the copurification process perhaps every 30 min.

D. Measurements for NRTA

In consultation with ORNL, we developed tables of measurement types that can be used for NRTA in the HEF and measurement errors that are representative of current technology.[28-63] Most of these measurements are also used for PITs[22] and for process control.[6] We identified measurement points for NRTA and chose applicable measurement types based on descriptions of materials in the process. This measurement system, which represents current technology, is a reasonable starting point for optimization calculations. Such a reference system provides a perspective on the improvements needed for meeting proposed performance goals and shows which goals can be met today. It includes flow and concentration measurements of the streams between the UPAAs as well as on-line or at-line concentration measurements for determining in-process inventories. Process equipment where in-process inventories cannot be directly measured (such as the solvent-extraction contactors) is based on models using measurements of observable process parameters. (See Appendix B for details on the application of process modeling and simulation.)

Tables II-V show measurement types and errors that represent current technology. The tables list bulk measurements (Table II), NDA measurements of solutions (Table III), NDA measurements of solids (Table IV), and laboratory analysis of solutions (Table V). Volume measurements are listed separately for accountability and product tanks and waste and process tanks, because different accuracies and precisions are required as the optimization results will

TABLE II

BULK MEASUREMENTS

Measurement Category	Range/Limits	Error (%, 1σ) Precision	Short-Term Correlated	Long-Term Correlated
Volume (in-line)	Accountability and product tanks	0.3	0.1	0.1
	Waste and process tanks	3	3	1
Liquid flow	>120 L/h	2.5	1.5	0.5
	<120 L/h	5	3	1

TABLE III

NDA MEASUREMENTS OF SOLUTIONS
(FISSION-PRODUCT CONCENTRATION <10 Ci/L)

Plutonium Concentration	Method	Error (%, 1σ) Precision	Short-Term Correlated	Long-Term Correlated
<1 g/L	Alpha scintillation counter[a]	5	2	2
1-50 g/L	Alpha scintillation counter[b]	5	2	2
	Gamma spectroscopy	1	0.5	0.2
	Absorption-edge densitometry	1	1	1
	X-ray fluorescence	1	1	1
	Spectrophotometry[c]	5	2.5	1.5
>50 g/L	Gamma spectroscopy	1	0.5	0.2
	Absorption-edge densitometry	1	1	1
	X-ray fluorescence	1	1	1
	Passive neutron coincidence[d]	-	-	-

[a]Hanford method.[31] Applicable for concentrations of 10^{-4} to 1 g/L. To avoid excessive background, different scintillation cells should be used for these solutions and >1 g/L solutions.

[b]Hanford method.[31] Applicable for concentrations of 0.1-30 g/L.

[c]Oak Ridge method for uranium only.[32] Concentration range 20-200 g/L.

[d]Passive neutron coincidence counter for solutions under development at Los Alamos.

TABLE IV

NDA MEASUREMENTS OF SOLIDS

Material	Method	Error (%, 1σ) Fission Products <10 Ci/kg: Precision	Short-Term Correlated	Long-Term Correlated	Fission Products >10 Ci/kg: Precision	Short-Term Correlated	Long-Term Correlated
Leached hulls	Gamma spectrometry	-	-	-	10	15	15
	Passive neutron	-	-	-	10	5	5
	Active neutron	-	-	-	20	20	5
Mixed-oxide product cans	Passive neutron	2	1	1	-	-	-
	Active neutron	3	2	1	-	-	-
	Weight and chemistry[a]	0.5	0.5	1	-	-	-
	Calorimetry[b]	0.5	0.5	1	-	-	-
Spent-fuel assemblies	ORNL active neutron	-	-	-	5	5	2
	Gamma spectrometry	-	-	-	5	5	2
	Passive neutron	-	-	-	5	5	2
	Active and passive neutron	-	-	-	4	3	5
Waste containers (packaged waste for burial)	Active neutron	20	5	5	-	-	-
	Segmented gamma scanner	10	5	5	-	-	-
	Passive neutron	5	5	5	-	-	-
Process components[c]							
Sludge from solids sample tank and primary centrifuge[d]							

[a]Plutonium concentration obtained by chemical analysis of samples.

[b]Principal contribution to long-term correlated error is in specific heats of isotopes, because of uncertainty in half-lives.

[c]Plutonium in-process inventory of process components is estimated from modeling.

[d]Sludge may be dried and then analyzed by one of the leached hulls techniques. If the material contains much plutonium, the errors will be lower than stated for leached hulls.

TABLE V

LABORATORY ANALYSIS OF SOLUTIONS

Plutonium Concentration	Method	Error (%, 1σ) Fission Products <10 Ci/L Precision	Short-Term Correlated	Long-Term Correlated	Fission Products >10 Ci/L Precision	Short-Term Correlated	Long-Term Correlated
<1 g/L	Spectrophotometry[a]	1.5	1	1	1.5	1	1
	Extraction and alpha spectrometry or direct alpha spectrometry	5	2	2	7	3	3
	Passive x-ray emission[b]	2	1	1	-	-	-
	Isotope-dilution mass spectrometry	1	0.3	0.5	1	0.5	0.8
1-50 g/L	Spectrophotometry[a]	1.5	1	1	1.5	1	1
	Extraction and alpha spectrometry or direct alpha spectrometry	5	2	2	7	3	3
	X-ray fluorescence	1	1	1	-	-	-
	Isotope-dilution mass spectrometry	1	0.3	0.5	1	0.5	0.8
	Absorption-edge densitometry	1	1	1	-	-	-
	Gamma spectrometry	1	0.5	0.2	-	-	-
	Electrometric titration	0.3	0.2	0.2	0.3	0.2	0.2
>50 g/L	X-ray fluorescence[c]	0.5	0.2	0.2	-	-	-
	Isotope-dilution mass spectrometry	1	0.3	0.3	1	0.3	0.3
	Absorption-edge densitometry[c]	0.5	0.2	0.2	-	-	-
	Gamma spectrometry[c]	1	0.2	0.2	-	-	-
	Electrometric titration	0.3	0.2	0.2	0.3	0.2	0.2

[a]Method applicable if plutonium concentration is >10 mg/L.[34]

[b]Method developed by S-T. Hsue, F. Hsue, and D. Bowersox.[64]

[c]Analysis of product solutions.

demonstrate. Because measurement errors are a function of the materials being measured, ranges are given for flow rates, plutonium concentrations, and fission-product concentrations. Flow rates are listed in two ranges, > 120 L/h and < 120 L/h. Plutonium concentration ranges are < 1 g/L, 1-50 g L, and > 50 g/L. Fission-product concentrations are listed in two ranges, > 10 Ci/L (or > 10 Ci/kg) and < 10 Ci/L (or < 10 Ci/kg).

The long-term correlated error includes more than the uncertainty in the standard reference material.[33] It also includes errors caused by sample-standard mismatch (how closely the standard approximates the samples to be analyzed), errors caused in the characterization of secondary standards, any bias in the method, and sampling errors for chemical and destructive methods. We have tried to include these factors in our estimates of long-term correlated errors.

The precision and short-term correlated errors also include sampling and weighing or volume measurement errors, if applicable, in addition to analytical errors.[33] Precision is the result of chance alone and indicates the reproducibility of a measurement method. Short-term correlated error is a combination of the errors made in the calibration of an instrument or method. The value of the short-term correlated error changes when a new calibration is performed.

Dissolver solutions and HLW solutions are slated for on-line concentration measurements in the HEF. NDA measurements for these solutions have not been successfully demonstrated. We have assumed that these solutions will be analyzed in the laboratory by isotope-dilution mass spectrometry.

We identified measurement points for NRTA (Sec. II.C) and used the measurements in Tables II-V to develop an NRTA materials measurement system that is representative of current technology. Table VI lists measurement points, measurement types, and measurement errors. This measurement system is the base case in the optimal measurement allocation procedure discussed in the next section. That is, the total system development cost of the base case measurement system is zero, but improvements on this system impose a development cost. The object is to minimize development cost while meeting performance objectives.

E. Peformance Evaluation

This section gives the NRTA systems materials loss-detection levels using the base case measurement system (Table VI). We employ the modeling,

TABLE VI

HEF MEASUREMENT POINTS

Measurement Point	Materials Description[a]	Measurement Type[a]	Relative Difficulty	Current Measurement Errors (%, 1σ) Precision	Short-Term Correlated	Long-Term Correlated
Spent-fuel receiving area	Irradiated fuel assemblies S.S., U, Pu, FP	NDA	1	4	3	2
Disassembly/shear area	Same as above	Est	1	20	-[b]	-
Voloxidizer	Same as above	Est	1	20	-	-
Continuous dissolver	S.S., U, Pu, FP in HNO_3/ solids	Est	1	20	-	-
Leached-hulls NDA unit	S.S., traces of U, Pu, FP	NDA	1	10	5	5
Batch dissolver	S.S., traces of U, Pu, FP in HNO_3/solids	V	1	3	3	1
	Trace of Pu	C	1	1.5	1	1
Batch-dissolver hulls NDA unit	S.S., traces of U, Pu, FP	NDA	1	10	5	5
Batch-dissolver surge tanks (2)	Traces of U, Pu, FP in HNO_3	V	1	3	3	1
	Trace of Pu	C	1	1.5	1	1
Digester surge tanks (2)	U, Pu, FP in HNO_3	V	1	3	3	1
	46 g/L Pu	C	1	1.5	1	1
Primary centrifuge	U, Pu, FP in solids	NDA	1	10	5	5
Secondary dissolver	U, Pu, FP in HF-HNO_3/solids	V	1	3	3	1
	38 g/L Pu	C	1	7	3	3
Solids sample tank	U, Pu, FP in HNO_3/solids ~2g/L Pu (+ Pu solids)	NDA	1	10[b]	5	5
Feed solution surge tank	U, Pu, FP in HNO_3	V	1	3	3	1
	39 g/L Pu	C	1	1.5	1	1
Accountability tank	U, Pu, FP in HNO_3 130 g/L U	V	1	0.3	0.1	0.1
	37 g/L Pu	C	1	1	0.3	0.3
Feed adjustment tank	U, Pu, FP in HNO_3	V	1	3	3	1
	34 g/L Pu	C	1	1.5	1	1
HA feed tank	U, Pu, FP in HNO_3	V	1	3	3	1
	31 g/L Pu	C	1	1.5	1	1
HA centrifuge	U, Pu, FP in HNO_3 31 g/L Pu	Est	1	20	-	-
HA contactor	U, Pu, FP in HNO_3 and organic; Pu inventory	Est	1	20	-	-
HS column	U, Pu, residual FP in HNO_3 and organic; Pu inventory	Est	1	10	-	-

TABLE VI (cont)

Measurement Point	Materials Description[a]	Measurement Type[a]	Relative Difficulty	Current Measurement Errors (%, 1σ) Precision	Short-Term Correlated	Long-Term Correlated
HC column	U, Pu, residual FP in HNO_3 and organic; Pu inventory	Est	1	10	-	-
HCP reduction vessel	U, Pu, residual FP in HNO_3, N_2H_4, and HAN	V	1	3	3	1
	15 g/L Pu	C	1	1	0.5	0.2
1A feed tank	U, Pu, residual FP in HNO_3, N_2H_4, and HAN	V	1	3	3	1
	13 g/L Pu	C	1	1	0.5	0.2
1A column	U, Pu, residual FP in HNO_3 and organic; Pu inventory	Est	1	10	-	-
1APU stream	U, Pu, residual FP in HNO_3, N_2H_4, and HAN					
	422 L/h	F	1	1	0.5	0.2
	11 g/L Pu	C	1	1	0.5	0.2
2A feed tank	U, Pu, residual FP in HNO_3	V	1	3	3	1
	11 g/L Pu	C	1	1	0.5	0.2
2A column	U, Pu, residual FP in HNO_3 and organic; Pu inventory	Est	1	5	-	-
2B column	U, Pu, residual FP in HNO_3 and organic; Pu inventory	Est	1	5	-	-
3A feed tank	U, Pu, residual FP in HNO_3	V	1	3	3	1
	14 g/L Pu	C	1	1	0.5	0.2
3A column	U, Pu, residual FP in HNO_3 and organic; Pu inventory	Est	1	5	-	-
3B column	U, Pu, residual FP in HNO_3 and organic; Pu inventory	Est	1	5	-	-
Pu stripper feed tank	U, Pu, residual FP in HNO_3, N_2H_4	V	1	3	3	1
	17 g/L Pu	C	1	1	0.5	0.2
Pu stripper	U, Pu, residual FP in HNO_3, N_2H_4					
	17-32 g/L Pu	Est	1	10		
Pu concentrator	U, Pu, residual FP in HNO_3	V	1	3	3	1
	32-137 g/L Pu	C	1	1	0.5	0.2
Pu catch tank	U-Pu nitrate solution	V	1	3	3	1
	137 g/L Pu	C	1	1	0.5	0.2
Pu sample tank	U-Pu nitrate solution	V		0.3	0.1	0.1
	95 g/L Pu	C		0.3	0.2	0.2

[a]S.S. = stainless steel, FP = fission products, Est = estimation, V = volume, C = concentration, and F = flow rate.

[b]Correlated errors for inventory measurements and estimates are not listed because these errors tend to cancel when materials balances are drawn.

simulation, and analysis approach that has been used extensively in safeguards systems studies to evaluate the NRTA performance.[1-5]

This approach requires (1) a detailed dynamic model of the process based on actual design data and operator experience, (2) simulation of the model process on a digital computer, (3) a dynamic model of each measurement system based on best estimates of instrument performance and behavior, (4) simulation of accountability measurements applied to nuclear materials flow and in-process inventory data generated by the model process simulation, and (5) evaluation of simulated materials balance data from various materials accounting strategies. Appendix B describes the model process simulation, and Appendix C gives the materials balance and materials balance variance equations.

Table VII presents loss-detection levels for each of the UPAAs. Results are given for 1 day (abrupt) and 6 months (protracted) for two pairs of detection and false-alarm probabilities that coincide with Table I performance goals. Two cases of recalibration frequency are given for each UPAA:

(1) no recalibration within the accounting period and

(2) recalibration of the feed and product concentration measuring instruments once every week.

Goal 1, abrupt and protracted loss-detection goals, can be met in the chemical separations area (UPAA 2 3). The protracted goal can be met only by weekly recalibration of feed and product concentrator measuring instruments. Abrupt loss-detection goals can be met in the codecontamination/partitioning area (UPAA 2) and the copurification area (UPAA 3). The loss-detection sensitivity for UPAA 1 will not meet goal 1 performance. Goals 2, 3, and 4 cannot be met by current measurement technology in any of the UPAAs.

The PIT loss-detection sensitivity is equivalent to that of the 6-months accounting period. Therefore, PIT will satisfy performance goal 1 only in the chemical separations area and only if the feed and product concentration measuring instruments are recalibrated once every week.

TABLE VII

MATERIALS ACCOUNTING LOSS-DETECTION LEVELS
USING CURRENT MEASUREMENT TECHNOLOGY

	DP = 0.5, FAP = 0.025[a]		DP = 0.95, FAP = 0.05	
	1 Day	6 Months	1 Day	6 Months
UPAA 1 - Feed Preparation				
No recalibration	23.2	1272	38.3	2099
Weekly recalibration	23.2	746	38.3	1230
UPAA 2 - Codecontamination/ Partitioning				
No recalibration	11.8	578	19.5	954
Weekly recalibration	11.8	218	19.5	360
UPAA 3 - Copurification				
No recalibration	11.1	568	18.2	937
Weekly recalibration	11.1	228	18.2	376
UPAA 2 3 - Chemical Separations				
No recalibration	15.2	186	25.1	307
Weekly recalibration	15.2	144	25.1	238

[a]DP is detection probability and FAP is false-alarm probability.

III. OPTIMAL ALLOCATION OF MEASUREMENT UNCERTAINTIES

In Sec. II we formulated materials accounting strategies and chose candidate base case instruments representing current technology. We used the base case measurement system to calculate materials loss-detection sensitivities. Current technology cannot meet performance goals 2, 3, and 4, and in some instances performance goal 1. The primary objective of this study is to calculate the measurement uncertainties that meet each of the performance goals while minimizing the overall measurement system cost or development risk.

Optimization techniques can solve many problems, including the best allocation of resources (either maximum or minimum) to achieve a given goal. In this section, we formulate the allocation of measurement uncertainties as an optimization problem, explain the choice of cost functions, and illustrate the optimal measurement allocation with a simple example. Appendix D discusses techniques and describes the computer program chosen for this study.

A. Application of Optimization Techniques

This section discusses a method for calculating measurement uncertanties so that performance goals for detecting materials loss are attained. These performance goals, defined in Sec. I and based in part on IAEA and NRC criteria, are stated as the amount of materials loss to be detected by accounting within a given time and with a specified probability. Performance goals are given for both abrupt and protracted diversions. Measurement system sensitivity to materials loss depends on the size of the materials balance standard deviation; a smaller deviation increases the probability of detecting materials loss. Calculation of uncertainties for each measurement error component requires that the materials balance standard deviation for both diversions be sufficiently small to meet the stated goals.

For this report we calculate measurement uncertainties that meet specified performance goals at minimum instrument development cost. That is, where the calculated uncertainty is below the current attainable value, a development cost is imposed. The optimal set of measurement uncertainties impose minimum measurement system development cost.

The problem of calculating minimum development cost uncertainties to meet a given systems performance goal can be formulated as an optimization problem. To do so, we must write a set of constraint equations for measurement error components (σ_i) and an objective function that relates them to instrument development cost. The materials balance standard deviation (σ_{MB}) must be less than or equal to a specified abrupt systems performance goal (σ_a) and a specified protracted systems performance goal (σ_p).

In addition to the constraints imposed by materials balance uncertainties, upper and lower limits on allowable standard deviation for each measurement error component σ_i are desirable to assure a reasonable uncertainty calculation. Clearly the upper limit (σ_{ui}) should correspond to the current instrument performance, and the lower limit (σ_{li}) should be based on the judgment of instrument designers about reasonably attainable instrument uncertainties. Therefore, the constraints for our problem are given by

$$\left[\sum_{i=1}^{N_m} B_{ai}\sigma_i^2\right]^{1/2} = \sigma_{MB} \leq \sigma_a \quad ,$$

$$\left[\sum_{i=1}^{N_m} B_{pi}\sigma_i^2\right]^{1/2} = \sigma_{MB} \leq \sigma_p \quad , \tag{1}$$

$$\sigma_{li} < \sigma_i \leq \sigma_{ui} \qquad (i = 1, \ldots, N_m) \quad .$$

The coefficients B_{ai} and B_{pi} are calculated from the amount of material being measured and the length of the accounting period (see Appendix C).

B. Cost Functions

To complete formulating uncertainty allocation as an optimization problem, the cost of uncertainty reduction must be incorporated in an objective function. For this study we chose an equilateral hyperbola to represent the relative cost of improving a measurement uncertainty. Any other convex cost function can be

used for each measurement uncertainty component. The relative cost (C_i) of improving the ith measurement error component is given by

$$C_i = A_i \left[\frac{\sigma_{ui} - \sigma_{li}}{\sigma_i - \sigma_{li}} - 1 \right] , \qquad (2)$$

where $A_i \equiv$ relative improvement difficulty factor for σ_i, $\sigma_{ui} \equiv$ upper limit of σ_i (representative of current technology), and $\sigma_{li} \equiv$ lower limit of σ_i (probable limit of development).

Figure 3 shows a family of hyperbolas for σ_{ui} = 0.01 and σ_{li} = 0.001 for several values of A. Each curve gives the relative development cost for achieving a given measurement uncertainty. The hyperbolas cross the cost axis at σ_{ui}; that is, the development cost is zero for an uncertainty achievable by current

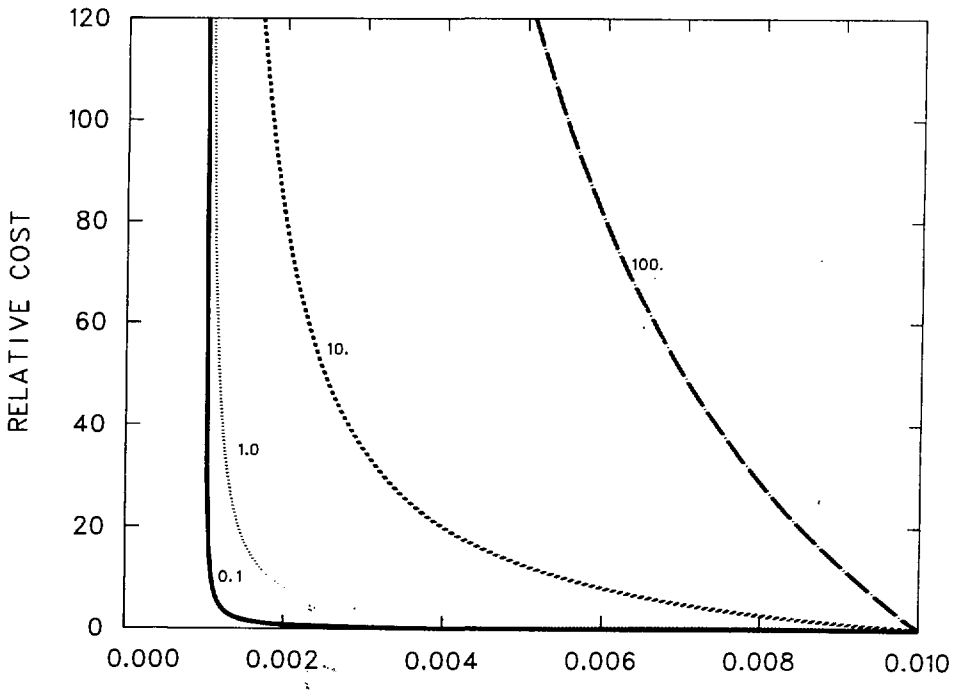

Fig. 3.
Cost function for several values of A.

technology. On the other hand, σ_{li} represents an uncertainty that is not achievable. Hence, the cost is infinite at σ_{li}. The rate of increase in cost as σ decreases within the range $(\sigma_{ui}, \sigma_{li})$ is controlled by the factor A.

The objective function is given by

$$\text{Cost} = \sum_{i}^{N_m} C_i = \sum_{i}^{N_m} A_i \left[\frac{\sigma_{ui} - \sigma_{li}}{\sigma_i - \sigma_{li}} - 1 \right] \quad . \tag{3}$$

Formulation now is complete. Next we must calculate σ_i subject to the constraints in Eq. (1), while minimizing the total development cost, Eq. (3). Because the constraint and objective functions are convex, we are assured that the calculated minimum is a global minimum (see Appendix D).

C. Example

A simple example illustrates the application of optimization techniques in allocating measurement uncertainties to meet given performance goals. Figure 4 represents an ideal process having an in-process inventory of 10 kg and a daily throughput of 2 kg consisting of a single 2-kg feed batch and a single 2-kg product batch. The process is contained in a single UPAA.

Given this process, we must write the materials balance standard deviation σ_{MB} as a function of the measurement error components and specify (1) constraints on the range of each measurement uncertainty and (2) the cost of decreasing those uncertainties within their ranges. Finally, we must allocate the measurement uncertainties so that the total systems development cost is minimized.

For an accounting period of N days, the materials balance (MB_N) is given by

$$MB_N = \Delta I_N + T_N \quad ,$$

where $\Delta I_N = I_0 - I_N$, initial minus final inventory; and $T_N = N(f - p)$, feed minus product for N net transfers. If there were no measurement uncertainties, MB_N would be zero. Of course, that is not the case.

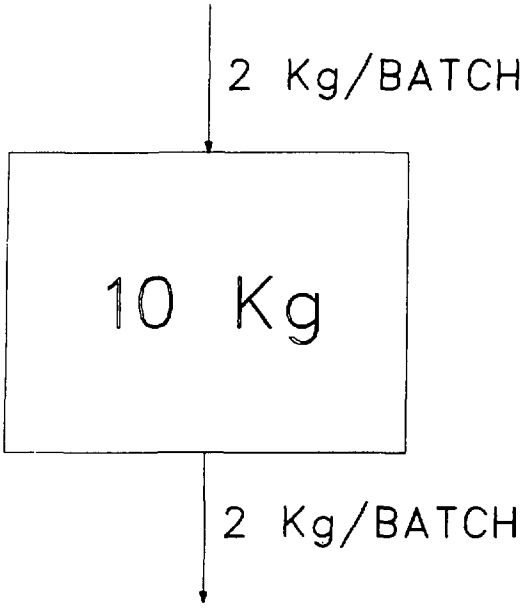

Fig. 4.
Simple process example.

Let each instrument be represented by a multiplicative measurement error model. In this model the measured value M of a true quantity μ is given by

$$M = \mu(1 + \varepsilon + \eta) \quad ,$$

where ε is the uncertainty caused by instrument imprecision and η is the uncertainty caused by correlated effects such as calibration. The variance σ_M^2 of M is given by

$$\sigma_M^2 = \mu^2(\sigma_\varepsilon^2 + \sigma_\eta^2) \quad .$$

Assuming η does not change during a given period, then any two measurements (M_i and M_j) are correlated. The covariance σ_{ij} between M_i and M_j is given by

$$\sigma_{ij} = \mu_i \mu_j \sigma_\eta^2 \quad .$$

These measurement errors produce an uncertainty in the materials balance having a variance σ_{MB}^2 given by

$$\sigma_{MB_N}^2 = \sigma_{\Delta I_N}^2 + \sigma_{T_N}^2 \quad .$$

The variance $\sigma_{\Delta I_N}^2$ of the net change in inventory is given by

$$\sigma_{\Delta I_N}^2 = (I_0^2 + I_N^2)\sigma_{\varepsilon_I}^2 + (I_0 - I_N)^2 \sigma_{\eta_I}^2 \quad .$$

The initial and final inventories are the same; in most processes operating near steady state, $I_0 \sim I_N$. Therefore, the variance of the net change in inventory is given by

$$\sigma_{\Delta I_N}^2 = 2I^2 \sigma_{\varepsilon_I}^2 \quad . \tag{4}$$

The variance $\sigma_{\Delta T_N}^2$ of the net transfer is given by

$$\sigma_{T_N}^2 = N(f^2 \sigma_{\varepsilon_f}^2 + p^2 \sigma_{\varepsilon_p}^2) + N^2 (f^2 \sigma_{\eta_f}^2 + p^2 \sigma_{\eta_p}^2) \quad . \tag{5}$$

If we combine Eqs. (4) and (5) and substitute values for I (10 kg), f (2 kg), and p (2 kg), the materials balance variance is given by

$$\sigma^2_{MB} = 200\sigma^2_{\varepsilon_I} + 4N(\sigma^2_{\varepsilon_f} + \sigma^2_{\varepsilon_p}) + 4N^2(\sigma^2_{\eta_f} + \sigma^2_{\eta_p}) \quad .$$

This equation is the basis for the abrupt and protracted diversion constraints. In this example, let the abrupt constraint be for 1 day (N = 1) and the protracted constraint for 100 days (N = 100).

Each measurement standard deviation is constrained over a range (σ_{ui}, σ_{li}). Table VIII is a list of the assumed relative standard deviations.

As shown in Fig. 5, the cost function for improving each measurement uncertainty is an equilateral hyperbola with σ_{li} vertical asymptote crossing the cost axis at σ_{ui} [see Eq. (2)] where A_i is equal to one.

TABLE VIII

MEASUREMENT RELATIVE STANDARD DEVIATIONS

	σ_{li}	σ_{ui}
σ_{ε_I}	1.E-2	1.E-1
σ_{ε_f}	6.E-3	6.E-2
σ_{η_f}	1.E-3	1.E-2
σ_{ε_p}	5.E-3	5.E-2
σ_{η_p}	8.E-4	8.E-3

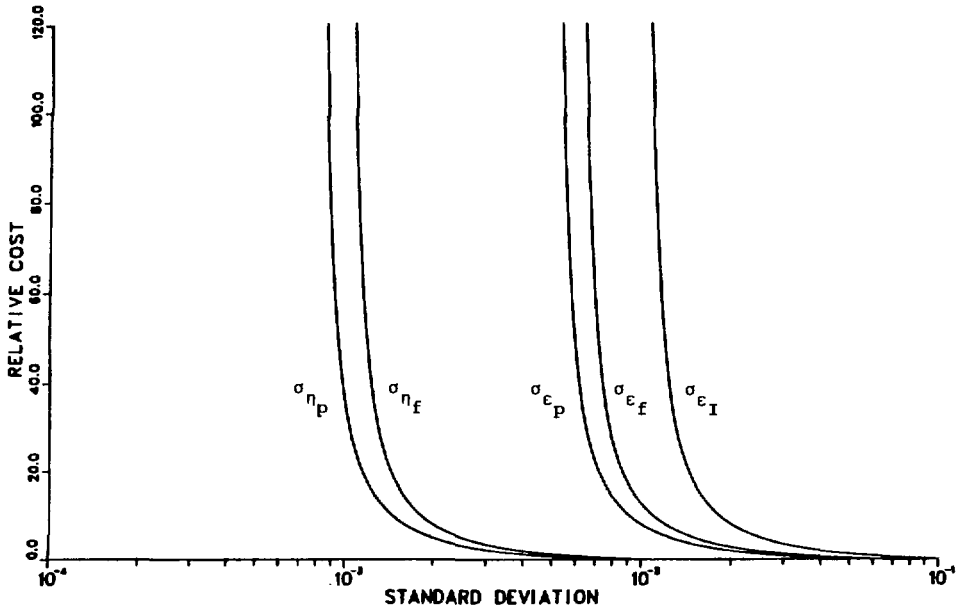

Fig. 5.
Sample process cost functions.

We can now write the optimization problem for the example process.

Constraints :

$$\sigma_A \geq [200\sigma^2_{\varepsilon_I} + 4(\sigma^2_{\varepsilon_f} + \sigma^2_{\eta_f}) + 4(\sigma^2_{\varepsilon_p} + \sigma^2_{\eta_p})]^{1/2}$$

$$\sigma_P \geq [200\sigma_{\varepsilon_I} + 400(\sigma^2_{\varepsilon_f} + \sigma^2_{\varepsilon_p}) + 40\ 000(\sigma^2_{\eta_f} + \sigma^2_{\eta_p})]^{1/2}$$

$$1.E\text{-}2 \leq \sigma_{\varepsilon_I} \leq 1.E\text{-}1$$

$$6.E\text{-}3 \leq \sigma_{\varepsilon_f} \leq 6.E\text{-}2$$

$$1.E\text{-}3 \leq \sigma_{\eta_f} \leq 1.E\text{-}2$$

$$5.E\text{-}3 \leq \sigma_{\varepsilon_p} \leq 5.E\text{-}2$$

$$8.E\text{-}4 \leq \sigma_{\eta_p} \leq 8.E\text{-}3$$

Minimize :

$$\text{Cost} = \left[\frac{9.E-2}{\sigma_{\varepsilon_I} - 1.E-2} - 1\right] + \left[\frac{5.4E-2}{\sigma_{\varepsilon_f} - 6.E-3} - 1\right]$$

$$+ \left[\frac{9.E-3}{\sigma_{\eta_f} - 1.E-3} - 1\right] + \left[\frac{4.5E-2}{\sigma_{\varepsilon_P} - 5.E-3} - 1\right]$$

$$+ \left[\frac{7.2E-3}{\sigma_{\eta_P} - 8.E-4} - 1\right] .$$

Cost minimization results for the σ_A, σ_P constraint pairs are shown in Table IX. Substituting the σ_u shown in Table VIII for each measurement uncertainty into the constraint equations results in $\bar{\sigma}_A$ = 1.42 and $\bar{\sigma}_P$ = 3.32. Therefore, in Case 1, specifying abrupt and protracted constraints $\sigma_A > \bar{\sigma}_A$ and $\sigma_p > \bar{\sigma}_p$ results in measurement uncertainties equal to the σ values and thus zero cost. In Case 2, $\sigma_A < \bar{\sigma}_A$ and $\sigma_P > \bar{\sigma}_P$ are specified. The calculated uncertainties result in much of the cost being assigned to the ε error components, most of which are assigned to the inventory error σ_{ε_I}. This is expected because the abrupt diversion sensitivity is dominated by the precision components, which are dominated by the in-process inventory measurement uncertainty.

TABLE IX

SAMPLE PROCESS MEASUREMENT UNCERTAINTY OPTIMAL ALLOCATION RESULTS

Case No.	Constraints σ_A	Constraints σ_P	Calculated σ_A	Calculated σ_P	Total Cost	σ_{ε_I} Cost$_1$	σ_{ε_f} Cost$_2$	σ_{η_f} Cost$_3$	σ_{ε_P} Cost$_4$	σ_{η_P} Cost$_5$
1	1.5	3.5	1.4	3.3		1.0-1	6.0-2	1.0-2	5.0-2	8.0-3
					0	0	0	0	0	0
2	0.5	3.5	0.50	3.0		3.4-2	6.0-2	9.8-3	4.9-2	7.9-3
					2.9	2.8	5.1-3	2.4-2	3.0-2	8.9-3
3	1.5	0.5	0.23	0.50		1.6-2	9.7-3	1.4-3	8.5-3	1.1-3
					80	14.1	13.4	20.7	12.0	19.9
4	0.15	0.35	0.15	0.35		1.1-2	6.5-3	1.0-3	5.5-3	8.4-4
					771	169	115	216	98.8	172
5	0.5	3.5	0.50	2.6		3.5-2	2.7-2	9.7-3	2.1-2	7.8-3
					6.1	2.6	1.6	3.9-2	1.8	2.6-2

In Case 3, we specify the constraints $\sigma_A > \bar{\sigma}_A$ and $\sigma_P < \bar{\sigma}_P$. We calculate measurement uncertainties where most of the cost results from improving the correlated errors. This again is expected because these errors dominate the protracted diversion sensitivity.

In Case 4, constraints $\sigma_A < \bar{\sigma}_A$ and $\sigma_P < \bar{\sigma}_P$ are specified. The optimization program calculates measurement uncertainties such that both constraints are just satisfied.

In Case 5, we repeat Case 2 but multiply the cost of improving σ_{ε_I} (Cost 1) by 100, for example, $A_1 = 100$. Comparison of Case 2 and Case 5 shows that the total systems cost is greater in Case 5, but the ratio of Cost 1 to Total Cost is less in Case 5. The inventory error was increased while the other precision components decreased.

IV. RESULTS

This section gives measurement uncertainties needed to achieve each of the four MMAS performance goals (Sec. I.B) for each UPAA (described in Sec. II.C). We calculate measurement uncertainties as in the example in Sec. III.C. The materials balance equations, used as constraint equations, are developed in Appendix C. Each measurement uncertainty is constrained in the range $(0, \sigma_{ui})$ where the σ_{ui} represents current technology as shown in Table VI. For this study the lower bound for each measurement uncertainty (σ_{li}) is zero, and the relative improvement difficulty index (A_i) for each measurement uncertainty [see Eq. (2)] is one. In a subsequent study we will examine the effect of these parameters as well as the choice of cost functions on the calculated measurement uncertainties through a sensitivity analysis.

For each UPAA, the constraint equations are

$$\sigma_a \geq \left[\sum_{i=1}^{N_m} B_{ai} \sigma_i^2 \right]^{1/2} ,$$

$$\sigma_p \geq \left[\sum_{i=1}^{N_m} B_{pi} \sigma_i^2 \right]^{1/2} ,$$

$$0 \leq \sigma_i \leq \bar{\sigma}_{ui} \qquad (i = 1, \ldots, N_m) ,$$

and the cost equation is

$$\text{Cost} = \sum_{i=1}^{N_m} \left[\frac{\sigma_{ui}}{\sigma_i} - 1 \right] ,$$

where i is the measurement error component index as given in the results table for each case; N_m is the number of measurement error components for the UPAA; and the coefficients B_{ai} and B_{pi} for the abrupt and protracted goals, respectively, are functions of the nominal measured value, the number of measurements made, and the instrument calibration frequency (see Appendix C).

The calculated optimal measurement uncertainties were applied to the model process (see Appendix B) using the mixed measurement error model discussed in Sec. I.C and Appendix C. Use of this model is necessary because nominal values for transfers and inventories are used in the optimization calculations, whereas the process model allows variation in process parameters. The simulation results show that calculated measurement uncertainties meet the performance goals.

Appendix E gives optimal measurement uncertainties for each UPAA that meet the four performance goals (Table I) while minimizing total systems development cost. Summary tables are given in this section. Tables E-I through E-XXXVI list the measurement error components (ε, η, and θ) for the UPAA and their calculated value, current technology value, uncertainty contribution to the abrupt and protracted goals, and relative cost.

One cost unit is the relative cost of achieving a measurement uncertainty that is one-half of that achievable by current technology ($\sigma_i = 1/2\sigma_{u_i}$). Each halving of σ_i costs twice what the previous halving did, plus 1. For example, the cost of achieving $\sigma_i = 1/4\sigma_{u_i}$ is 3 and of $\sigma_i = 1/8\sigma_{u_i}$ is 7.

In-process inventory uncertainties are entirely a function of precision (ε) (see Sec. III.C and Appendix C). There are two types of inventory determinations: those determined by a single measurement or estimate (such as for the shear) and those calculated from the product of two measured values (such as for the HA feed tank volume and concentration).

Transfer uncertainties are a function of precision and short-term (η) and long-term (θ) correlated instrument errors. There are two types of transfer determinations: those made by a single measurement (such as for the spent fuel) and those calculated from the product of two measurements (such as for the accountability tank volume and concentration).

In the tables, inventory uncertainties are given first, followed by transfer uncertainties. Results are given for cases where instruments are not recalibrated during the accounting period and for periodic recalibration of key transfer measurements (excluding volume measurements). Note that small differences in

measurement uncertainties, and hence relative cost, are not significant, because these differences could result from numerical inaccuracies in the optimization computer program.

We discuss highlights of these results and identify dominant inventory and transfer measurement uncertainties in the following sections. Dominant terms are those measurement uncertainties that contribute most to the materials balance uncertainty and those identified by the optimization calculation as most improving materials balance uncertainty at least relative cost.

A. UPAA 1: Feed Preparation Processes

Materials balances are drawn once each day about the feed preparation processes by combining the following measurements:

(1) feed transfer: spent-fuel assembly plutonium content (7 each day);

(2) product transfer: accountability tank volume and concentration (1 each day);

(3) waste out: hulls plutonium content (48 each day) and centrifuge sludge plutonium content (1 each day);

(4) recycle input: HA centrifuge sludge plutonium content (1 each week); and

(5) inventories: tank volumes and concentrations, and disassembly/shear, voloxidizer, and continuous dissolver estimates (1 each day).

There are 41 measurement uncertainty components for UPAA 1. Tables E-I through E-IX give the measurement uncertainties that satisfy each of the four performance goals for each recalibration case. In the periodic recalibration cases, only the spent-fuel NDA and the accountability tank concentration instruments are recalibrated.

The feed preparation headend processes comprise several process operations for which inventory measurement or estimation is difficult. Each of these process operations contains a large (> 14 kg) plutonium inventory. The dominant inventory uncertainty terms for UPAA 1 result from in-process inventory estimates in the shear, voloxidizer, and continuous dissolver, and volume and concentration measurements in the digesters and the feed solution surge tank.

The dominant transfers are spent-fuel feed and accountability tank product. Of the two, spent-fuel NDA dominates transfer uncertainties and therefore requires greater development.

As shown in Sec. II.E, goal 1 cannot be achieved in UPAA 1 with current measurement technology. With current measurements, σ_{MB} for 1 day is 11.6 kg of plutonium (1σ). For a 6-month balance σ_{MB} is 636 kg of plutonium (1σ) for no recalibration, and for weekly recalibration σ_{MB} is 373 kg of plutonium (1σ).

UPAA 1 optimal measurement uncertainties for dominant inventory and transfer terms that satisfy the four performance goals are summarized in Table X. To achieve goal 1 with weekly recalibration, errors in the estimates of the in-process inventory in the voloxidizer and continuous dissolver must be decreased from 20% each to 13% and 17%, respectively. The spent-fuel NDA η and θ measurement uncertainties must be reduced from 3% and 2% to 1% and 0.3%, respectively, and minor reductions are necessary in a few other measurement uncertainty components.

Goal 2 attainment requires modest improvements in inventory estimate errors and large improvements in transfer measurement errors. Errors in the inventory estimates of the shear, voloxidizer, and continuous dissolver must be reduced from 20% to 13%, 6%, and 7%, respectively. We need spent-fuel transfer measurements having a precision $\leq$1% and correlated errors of $\leq$0.2% short-term and $\leq$0.07% long-term. For the accountability tank, we need volume measurements having a precison $\leq$0.02%, a short-term correlated error $\leq$0.03%, and a long-term correlated error $\leq$0.03%; and we require concentration measurements having a precision $\leq$0.3%, a short-term correlated error $\leq$0.1%, and a long-term correlated error $\leq$0.04%.

To achieve goals 3 or 4 requires measurement improvements of approximately an order of magnitude for the inventories and two to three orders of magnitude for the key transfers. For example, these goals need inventory estimates that are <1% and transfer correlated errors that are <0.002%. Clearly, these goals will not be achieved without major breakthroughs in measurement technology and standards preparation.

B. UPAA 2 3: Chemical Separations Process

Materials balances are drawn once each day about the chemical separations process by combining the following measurements:

(1) feed transfer: accountability tank volume and concentration (one each day);

(2) product transfer: plutonium product sample tank volume and concentration (two each day);

TABLE X

UPAA 1 DOMINANT MEASUREMENT UNCERTAINTIES
(1σ RSD)

Description	Current (1σ)	Goal 1 No Recalibration	Goal 1 Weekly Recalibration	Goal 2 No Recalibration	Goal 2 Weekly Recalibration	Goal 2 Daily Recalibration	Goal 3 No Recalibration	Goal 3 Daily Recalibration	Goal 4 No Recalibration	Goal 4 Daily Recalibration
INVENTORIES										
Shear (ε)	2.0-1	2.0-1	2.0-1	1.3-1	1.3-1	1.3-1	2.3-2	2.3-2	1.0-2	1.2-2
Voloxidizer (ε)	2.0-1	1.4-1	1.3-1	5.7-2	5.8-2	5.5-2	8.1-3	9.9-3	4.4-3	5.2-3
Continous dissolver (ε)	2.0-1	1.7-1	1.7-1	7.2-2	7.1-2	7.3-2	1.1-3	1.2-2	4.6-3	6.2-3
Digesters (2)										
Volume (ε)	3.0-2	3.0-2	3.0-2	2.6-2	2.7-2	2.7-2	4.2-3	5.2-3	1.9-3	2.7-3
Concentration (ε)	1.5-2	1.5-2	1.5-2	1.5-2	1.5-2	1.5-2	3.5-3	4.0-3	2.1-3	2.2-3
Feed solution surge										
Volume (ε)	3.0-2	3.0-2	3.0-2	1.9-2	1.9-2	1.9-2	2.8-3	3.5-3	1.3-3	1.8-3
Concentration (ε)	1.5-2	1.5-2	1.5-2	1.3-2	1.3-2	1.3-2	2.2-3	2.7-3	1.2-3	1.4-3
TRANSFERS										
Spent fuel (ε)	4.0-2	3.3-2	3.7-2	8.8-3	9.8-3	1.0-2	6.1-4	7.8-4	3.9-4	4.9-4
(η)	3.0-2	2.8-3	1.0-2	6.9-4	2.3-3	4.7-3	4.1-5	3.5-4	3.3-5	2.1-4
(θ)	2.0-2	2.5-3	3.1-3	6.0-4	7.1-4	7.6-4	3.6-5	4.6-5	2.8-5	3.4-5
Accountability tank										
Volume (ε)	3.0-3	3.0-3	3.0-3	1.8-3	2.1-3	2.2-3	1.4-4	1.8-4	9.2-5	1.2-4
(η)	1.0-3	9.2-4	9.9-4	2.3-4	2.8-4	2.9-4	1.4-5	1.8-5	1.2-5	1.5-5
(θ)	1.0-3	9.2-4	9.9-4	2.3-4	2.8-4	2.9-4	1.4-5	1.8-5	1.3-5	1.4-5
Concentration (ε)	1.0-2	9.6-3	9.9-3	2.6-3	3.1-3	3.3-3	2.0-4	2.6-4	1.6-4	1.7-4
(η)	3.0-3	1.4-3	3.0-3	3.3-4	1.1-3	2.2-3	2.0-5	1.7-4	1.7-5	1.1-4
(θ)	3.0-3	1.4-3	1.6-3	3.3-4	4.0-4	4.3-4	2.0-5	2.5-5	1.5-5	2.0-5

(3) waste out: HA centrifuge sludge plutonium content (one each week); and

(4) inventories: tank volumes and concentrations and column estimates (one each day).

In the optimization calculations we did not include the aqueous and organic waste streams going from the UPAA to recovery. This reduced the number of variables describing the optimization space. These streams have a very low plutonium concentration and do not contribute significantly to materials balance uncertainty. Flow and concentration measurements are made on waste streams and are included in simulated balance calculations. Without waste streams there are 43 measurement uncertainty components for UPAA 2 3.

Tables E-X through E-XXVII list each measurement component, the measurement uncertainty to achieve each goal, and the relative cost of achieving each measurement uncertainty. For each goal, two cases were simulated:

(1) no recalibration during the accounting period, and

(2) periodic recalibration of the accountability tank and plutonium sample tank concentration measuring instruments, and the NDA instrument measuring the sludge.

We simulated weekly recalibrations for goal 1, both weekly and daily recalibrations for goal 2, and daily recalibrations for goals 3 and 4.

Table XI gives a summary of the dominant inventory and transfer measurements, and Table XII presents the relative cost for improving each measurement. The tables give measurement uncertainties and the relative cost of each for the four performance goals and the recalibration cases.

The dominant inventory uncertainties result from volume and concentration measurements of the HA feed tank and the 2A feed tank contents. For goal 1 with no recalibration, these two inventories have a combined standard deviation of 7.2 kg of plutonium, whereas the 1-day σ_{MB} is 8 kg of plutonium, with volume measurement making the larger contribution of the two components.

The dominant transfers are the accountability and plutonium sample tanks where volume and concentration measurements are made. Of the two measurement types, the concentration measuring instruments require more development.

Goal 1 can be achieved by current measurement technology if the transfer concentration measuring instruments are recalibrated weekly. To achieve goal 2

TABLE XI

UPAA 2 3 DOMINANT MEASUREMENT UNCERTAINTIES
(1σ RSD)

No.	Description	Current (1σ)	Goal 1 No Recalibration	Goal 1 Weekly Recalibration	Goal 2 No Recalibration	Goal 2 Weekly Recalibration	Goal 2 Daily Recalibration	Goal 3 No Recalibration	Goal 3 Daily Recalibration	Goal 4 No Recalibration	Goal 4 Daily Recalibration
	INVENTORIES										
	HA feed tank										
3	Volume (ε)	3.0-2	3.0-2	3.0-2	1.3-2	1.3-2	1.3-2	1.9-3	2.2-3	1.8-3	1.2-3
4	Concentration (ε)	1.5-2	1.5-2	1.5-2	1.1-2	1.1-2	1.0-2	1.8-3	2.1-3	1.5-3	9.3-4
	2A feed tank										
14	Volume (ε)	3.0-2	3.0-2	3.0-2	1.3-2	1.3-2	1.3-2	2.1-3	2.4-3	1.7-3	1.2-3
15	Concentration (ε)	1.0-2	1.0-2	1.0-2	8.8-3	8.3-3	8.8-3	1.4-3	1.7-3	1.1-3	8.1-4
	TRANSFERS										
	Accountability tank										
29	Volume (ε)	3.0-3	3.0-3	3.0-3	2.4-3	2.7-3	2.7-3	1.8-4	2.1-4	1.6-4	1.3-4
30	(η)	1.0-3	9.8-4	1.0-3	3.3-4	3.6-4	3.7-4	1.9-5	2.2-5	1.6-5	1.7-5
31	(θ)	1.0-3	9.8-4	1.0-3	3.3-4	3.6-4	3.8-4	1.9-5	2.2-5	1.3-5	1.7-5
32	Concentration (ε)	1.0-2	9.8-3	1.0-2	3.7-3	4.1-3	4.3-3	2.8-4	3.1-4	1.7-4	1.9-4
33	(η)	3.0-3	2.4-3	3.0-3	4.7-4	1.5-3	2.8-3	2.8-5	2.1-4	9.8-6	1.3-4
34	(θ)	3.0-3	2.3-3	3.0-3	4.7-4	5.2-4	5.4-4	2.7-5	3.1-5	9.7-6	2.4-5
	Pu sample tank										
35	Volume (ε)	3.0-3	3.0-3	3.0-3	2.9-3	2.8-3	3.0-3	2.3-4	2.6-4	1.8-4	1.6-4
36	(η)	1.0-3	9.9-4	1.0-3	3.3-4	3.6-4	3.7-4	1.9-5	2.2-5	1.5-5	1.7-5
37	(θ)	1.0-3	9.8-4	1.0-3	3.3-4	3.6-4	3.8-4	1.9-5	2.2-5	1.0-5	1.7-5
38	Concentration (ε)	3.0-3	3.0-3	3.0-3	2.9-3	2.7-3	3.0-3	2.3-4	2.6-4	6.7-5	1.6-4
39	(η)	2.0-3	1.9-3	2.0-3	4.0-4	1.3-3	2.0-3	2.3-5	1.8-4	9.7-6	1.1-4
40	(θ)	2.0-3	1.8-3	2.0-3	4.1-4	4.6-4	4.7-4	2.5-5	2.7-5	9.7-6	2.1-5

TABLE XII

UPAA 2 3 DOMINANT MEASUREMENT UNCERTAINTIES
RELATIVE COST

		Goal 1		Goal 2			Goal 3		Goal 4	
No.	Description	No Recalibration	Weekly Recalibration	No Recalibration	Weekly Recalibration	Daily Recalibration	No Recalibration	Daily Recalibration	No Recalibration	Daily Recalibration
	INVENTORIES									
	HA feed tank									
3	Volume (ε)	0	0	1.4	1.2	1.3	14	12	16	25
4	Concentration (ε)	0	0	0.4	0.4	0.5	7	6	9	15
	2A feed tank									
14	Volume (ε)	0	0	1.3	1.3	1.3	13	12	17	25
15	Concentration (ε)	0	0	0.1	0.2	0.1	6	5	8	11
	TRANSFERS									
	Accountability tank									
29	Volume (ε)	0.01	0	0.3	0.1	0.1	15	13	17	23
30	(η)	0.02	0	2.1	1.8	1.7	52	45	63	59
31	(θ)	0.02	0	2.1	1.8	1.7	51	45	79	59
32	Concentration (ε)	0.02	0	1.7	1.4	1.3	35	31	63	51
33	(η)	0.2	0	5.4	1.1	0.08	106	13	306	22
34	(θ)	0.3	0	5.4	4.8	4.5	110	96	307	124
	Pu sample tank									
35	Volume (ε)	0	0	0.3	0.08	0	12	10	15	18
36	(η)	0.01	0	2.1	1.8	1.7	51	45	67	59
37	(θ)	0.02	0	2.1	1.8	1.7	51	45	98	59
38	Concentration (ε)	0	0	0.05	0.1	0	12	10	43	18
39	(η)	0.01	0	4.0	0.6	0.01	85	10	205	17
40	(θ)	0.09	0	4.0	3.4	3.3	80	73	206	94
	TOTAL SYSTEM									
	Relative cost	0.8	0	32	22	20	727	495	1544	738

requires that ∿1% RSD volume and concentration measurements be made in process tanks; ∿0.3% RSD precision, ∿0.04% RSD calibration, and ∿0.04% RSD standards for volume measurements be made in primary transfer tanks; and ∿0.3% RSD precision, ∿0.2% RSD calibration, and ∿0.05% RSD standards for concentration measurements be made on samples from primary transfer tanks. To achieve goals 3 and 4 requires that measurement uncertainties be decreased by more than an order of magnitude.

Periodic recalibration of key instruments has a striking effect. For goal 2, as an example, compare the weekly, daily, and no recalibration cases for the η concentration error components of the accountability tank. Compared to the no recalibration case, weekly and daily recalibrations permit increasing η by a factor of ∿3 and ∿6, respectively. Also note that the relative cost of achieving goal 2 is decreased by ∿30% for weekly recalibration.

C. UPAA 2: Codecontamination/Partitioning Processes

The chemical separations UPAA can be divided into two by adding a flow and concentration measurement to the IAPU stream (see Sec. II.C). Materials balances are drawn once each day about the codecontamination/partitioning processes by combining the following measurements :

(1) feed transfer : accountability tank volume and concentration (one each day) ;

(2) product transfer : IAPU stream flow and concentration (every half hour) ;

(3) waste out : HA centrifuge sludge plutonium content (one every week) ; and

(4) inventories : tank volumes and concentrations and column estimates (one each day).

There are 28 measurement uncertainty components for UPAA 2. Measurement uncertainties that meet each of the four performance goals for selected recalibration cases are shown in Tables E-XIX through E-XXVIII. We simulated periodic recalibration only for the accountability tank concentration and the IAPU stream flow and concentration instruments.

The dominant inventory term in UPAA 2 is the HA feed tank. If we compare UPAA 2 3 and UPAA 2 HA feed tank volume and concentration measurement uncertainties that are required to meet a specific goal, we find that

UPAA 2 uncertainties can be larger, hence have a lower development cost. This is because the total inventory in UPAA 2 is less than that in UPAA 2 3. This illustrates control of smaller in-process inventories by UPAA partitioning.

The dominant transfers are the accountability tank and the IAPU stream. Accountability tank measurement requirements for UPAA 2 are tighter than for UPAA 2 3, because the IAPU stream flow and concentration measurements are not as precise or accurate as those for the plutonium sample tank.

For UPAA 2, goal 1 abrupt is achievable by current technology. Achieving goal 1 protracted requires $\sim$30% decrease of the accountability tank θ concentration uncertainty and the η flow rate uncertainty; $\sim$25% decrease of the IAPU θ concentration uncertainty; and $\sim$50% decrease of the IAPU θ flow uncertainty. Goal 2 is achievable by modest improvements in in-process inventory measurements and by about an order of magnitude improvement in transfer correlated errors. Goals 3 and 4 require about an order of magnitude decrease of in-process inventory measurement uncertainties and about two orders of magnitude decrease in transfer correlated uncertainties.

D. UPAA 3: Uranium-Plutonium Copurification Process

Materials balances are drawn once daily about the uranium-plutonium copurification process by combining the following measurements:

(1) feed transfers: IAPU stream flow and concentration (every half hour);

(2) product transfer: plutonium product sample tank volume and concentration (two each day);

(3) inventories: tank volumes and concentrations and column estimates (one each day).

There are 27 measurement uncertainty components in UPAA 3. UPAA 3 optimization results are given in Tables E-XXVIII through E-XXXIV and are similar to those of UPAA 2. For UPAA 3 the dominant inventory uncertainty is the 2A feed tank, and the dominant transfer uncertainties are the IAPU stream and the plutonium sample tank. The relatively poorer quality transfer measurements for the IAPU stream require a greater decrease in plutonium sample tank measurement uncertainties than is required for UPAA 2 3.

V. IMPACT OF THE HEF PROCESS DESIGN ON MATERIALS ACCOUNTING

A. Introduction

Features of process design and operation affect the application to a reprocessing facility of both conventional and NRTA methods.[2,5,20] This section considers the impact of the Oak Ridge HEF process design on safeguards, with special emphasis on the ability to apply advanced materials measurement and accounting techniques. The safeguards system guards against the loss of source and special nuclear material and provides timely indication of possible loss or credible assurance that no loss has occurred. The safeguards systems designer strives to meet required performance goals with minimum process interference. The process designer should consider changes in design and operation that may enhance the effectiveness of materials accounting without sacrificing production capacity or operating convenience. The more frequent the upsets and interruptions, the more vulnerable the process becomes to loss of nuclear materials.

This section describes some requirements for effective materials accounting. We discuss design features of the HEF process that may hinder the application of effective materials accounting techniques and some possible changes that could facilitate their application.

B. Some Requirements for Effective Materials Accounting

Effective near-real-time materials accounting requires accurate and precise measurements of key materials transfers (feed and product) and measurements or estimates of sidestreams and in-process inventories of process vessels. Where there is high plutonium throughput, the relative accuracy between feed and product measurements limits long-term detection sensitivity.[65,66] The process designer should control long-term relative errors between feed and product measurements by careful design of the sampling, measurement, and calibration hardware and procedures.[33,67-69] He should design feed and product accountability vessels for accurate calibration and make possible frequent calibration checks and periodic recalibrations. The best applicable sampling and assay techniques should be used.

In near-real-time materials accounting, precision of in-process inventory measurements and variability of any unmeasured holdup are the limiting uncertainties in short-term detection.[66] Most of the inventory should be in vessels

that are instrumented for on-line measurements. Even if precise measurements are possible, large buffer-storage tanks may introduce large absolute errors that will seriously degrade the short-term detection sensitivity. Relatively minor holdups and sidestreams have little effect on detection sensitivity, and estimates based on historical data will serve until these components are measured, for example, during a physical inventory. The effect of in-process inventory on short-term detection sensitivity is minimized by operating the process near steady state. In case of a severe upset, the ability to drain in-process material into instrumented tanks and then to recover normal operation aids materials accounting and control.

Well-defined input and output batches also facilitate materials accounting. Continuous operation requires continuous measurements of process streams. If there are significant recycle streams, input-output correlations will be of limited value. Semicontinuous operation approximates continuous operation and maintains batch definition by feeding alternately from two or more tanks that are designed for accurate and precise volume and concentration measurements. The decrease in volume of solution in the tanks determines the quantity of material that has entered the process.

C. HEF Process Design Features and Their Effect on Materials Accounting

The HEF process has several design features that restrict application of advanced materials measurement and accounting techniques. The dissolution and feed preparation area, in particular, has some novel features that require additional testing on a laboratory and pilot-plant scale before incorporation into the HEF, such as the voloxidizer, the continuous dissolver, and the constant-volume accountability tank. The effect of elements in other areas of the process also requires assessment. In addition to these specific features, we discuss some general aspects of the HEF process.

1. Voloxidizer. The voloxidizer is designed to remove tritium from the chopped spent fuel before aqueous processing.[70] Voloxidation should remove 90-99% of the tritium and convert it to tritiated water. However, some iodine, krypton, and volatile fission products are volatilized as well, and an additional process is required to separate these gases from each other and also to remove

various aerosols. If only stainless-steel-clad fuel is to be reprocessed, voloxidation may not be necessary, because the tritium should diffuse readily through the stainless-steel cladding while the fuel is in the reactor.

The voloxidizer heats the chopped fuel to the range 450-650°C in an oxidizing atmosphere. The oxidation of UO_2 to U_3O_8 may cause the fuel to crumble to a fine powder, and the accompanying increase in volume is expected to crack the cladding. Although it would be expected that U_3O_8 powder with its larger surface area would dissolve more rapidly, there is evidence that clad UO_2 and powdered U_3O_8 fuel dissolve at about the same rate. Voloxidation almost doubles the amount of insoluble material.[71] The insoluble residue from voloxidized fuel contains more plutonium than does the residue produced without voloxidation.[72] The conditions of fuel pellet fabrication and irradiation histories also influence dissolution characteristics, but subsequent voloxidation always markedly increases the insoluble plutonium.[70-73] This larger quantity complicates subsequent processing and materials accounting.

The voloxidizer is to be operated continuously. A batch of sheared fuel will be transferred to the voloxidizer and a product batch will be discharged every 1.2 min. These operating conditions make measurement or estimation of the in-process inventory complicated if not impossible. Residual holdup (material remaining after runout and cleanout) can only be measured during shutdown at the end of a campaign. The voloxidizer configuration complicates holdup measurement.

2. Continuous Dissolver. The HEF uses a continuous dissolver rather than the submerged-basket type to maintain a continuous off-gas flow and to keep undissolved solids in suspension. The continuous dissolution system consists of a rotating cylindrical dissolver followed by two digester surge tanks. The dissolver is divided into nine compartments: a feed compartment, seven dissolution stages, and a compartment where the hulls are rinsed before discharge from the dissolver. Chopped fuel proceeds though the dissolver in batches, with a residence time of 0.5 h per dissolution stage. There is a continuous counterflow of nitric acid from stage 7 to the feed compartment, and the continuous product stream of dissolved fuel flows from the feed compartment to the digester surge tanks.

The continuous dissolver is an incubus for materials accounting. There is always an in-process inventory of plutonium and uranium, and this inventory is a combination of solution, suspended matter, and undissolved solids. A new batch of fuel enters the feed compartment every 0.5 h and product solution leaves continuously. Under these conditions, estimation of the in-process inventory is extremely complex if not impossible. Backmixing in the rotary dissolver could lead to a buildup in inventory and the possibility of a criticality incident. The configuration of the continuous dissolver makes cleanout and measurement of residual holdup difficult.

3. Primary Centrifuge. Product solution from the continuous dissolver and the digester surge tanks is clarified in the primary centrifuge before transfer to the feed solution surge tank. The undissolved solids contain primarily fission products, cladding fines, and corrosion products, as well as some plutonium. Enough insoluble residue remains, particularly if the spent fuel has undergone voloxidation, to disrupt the first solvent extraction cycle. Separation of these solids is challenging because they consist of 1- to 15-μm particles. There is evidence that centrifugation alone will not clarify the solution, but that a combination of centrifugation and filtration or centrifugation and an organic flocculent may be required.[74-76] The centrifugal contactors used in the first solvent extraction cycle require relatively complete removal of solids.

The treatment given solids separated in the primary centrifuge depends on their nuclear materials content. Centrifuge solids that exceed fissile specification are to be transferred to the secondary dissolution cycle. We need methods for obtaining a representative sample of the solids and analyzing it for nuclear materials content, and for subsequently transferring the solids either to the secondary dissolution cycle or to high-level liquid waste storage.

4. Accountability Tank. The accountability tank is the first point in the HEF process at which we can make accurate and precise measurements of the quantity of nuclear materials and their isotopic composition. Quantity is determined from concentration and volume measurements. Isotope dilution mass spectrometry determines concentration. Volume measurement should equal or closely approach concentration measurement in accuracy and precision.

The accountability tank in the HEF process receives feed from the feed solution surge tank. The volume of solution in the accountability tank is measured by first filling the tank above the overflow line in the necked-down section at its top. The solution is then air-sparged to assure homogeneity. An airlift returns excess solution to the feed solution surge tank by way of the overflow line, which runs uphill.

The above procedure is intended to ensure that the volume of solution in the accountability tank is precisely known and is essentially identical from batch to batch. Additional laboratory and pilot-plant-scale experiments may be required to demonstrate these concepts. We must show that an airlift can precisely and reproducibly adjust the solution level in the neck of the accountability tank. We must also demonstrate that air sparging can homogenize all the solution in the tank, including the portion in its neck above and below the overflow line.

5. In-Process Inventories. Near-real-time materials accounting requires frequent closure of materials balances by measuring or estimating in-process inventories of the principal vessels and columns and all significant materials flows. Because high-quality techniques for direct measurement are not available, we infer in-process inventories of contactors from measurements of flow and concentration on inlet feed, extractant, scrub, outlet product, and waste streams.[77-80] We can obtain many of these measurements from process control instrumentation, but additional on-line instrumentation to nondestructively determine concentrations at important measurement points is desirable. Contactor models use measurement results for estimating in-process inventory.[81,82]

Mathematical models for simulating complex extraction processes are important for safeguards, as well as for process design and control. In reprocessing breeder reactor fuels, the Purex process must be adapted to the uranium-plutonium ratio, radioactivity, and heat generation encountered with these fuels. For example, because of high radioactivity, contact times during extractions are kept short. Whether pulsed columns or centrifugal contactors are more suitable is still undecided.[76] From a safeguards standpoint, centrifugal contactors are preferable, because of their smaller in-process inventories.

The fourth and fifth solvent-extraction cycles are designed for uranium-plutonium copurification. Mathematical models must be developed and validated

for the specific extraction processes of the HEF, which will require quantitative experimental data on mixed systems. On-line instruments for measurement of both plutonium and uranium concentrations will be required at some measurement points.

In-process inventory estimation for some process vessels, such as the plutonium stripper and the plutonium concentrator, would be very difficult by direct measurements. Instead, on-line concentration and flow measurements could be made on the streams that enter the plutonium stripper and leave the plutonium concentrator or on the solution in the plutonium stripper feed tank and the plutonium catch tank.

6. Coprocessing. The HEF process design allows coprocessing of uranium and plutonium from uranium-plutonium oxide fast breeder fuels. Uranium and plutonium in the dissolver solution are codecontaminated and partially separated in the first and second solvent extraction cycles. Uranium is added to the plutonium stream at the beginning of the fourth extraction cycle to increase the uranium-to-plutonium ratio of the feed solution from 0.13:1 to 2:1. Copurification is performed in the fourth and fifth extraction cycles.

Coprocessing has no safeguards advantage over partitioning. On the contrary, greater quantities of material must be handled in a coprocessing facility to achieve a given throughput of fissile material, and this will probably have a deleterious effect on materials accounting. In addition, concentration measurements and in-process inventory estimates of both plutonium and uranium will be required at various points in the fourth and fifth solvent extraction cycles.

7. Recycle Streams. The process design of the HEF incorporates all possible flexibility to allow economical plant operation and the reworking of off-specification materials. As a result, there are numerous recycle loops to facilitate intraplant transfers of material. The recycle routes significantly complicate partitioning the process into UPAAs and establishing correlations based on feed and product measurements. To alleviate these problems, we should make flow and concentration measurements on all recycle streams that cross UPAA boundaries.

8. Inaccessibility. Plant design philosophy is extremely important in a materials accounting system. It affects not only the accessibility of nuclear

materials but also measurement strategy and access to instrumentation for calibration, repair, and replacement. If sample lines are allowed to penetrate the cell wall to transport nuclear materials to an instrument gallery, the choice of analytical instruments and techniques is greatly increased. At the same time, effects of the hostile environment on instrumentation and quality of measurements are decreased and instrument maintenance is simplified. In the case of in-line instrumentation, it is desirable that only the sensor be in the process cell and that other components be in an area shielded from radioactivity and process fumes.

VI. SUMMARY AND CONCLUSIONS

A. Summary

In this study, we calculated materials measurement uncertainties for instruments used by an NRTA system that meet four different performance goals. The first two goals were chosen to represent a range of measurement capabilities, from state-of-the-art measurements to those that may be attainable in the next decade if an aggressive instrument development program is undertaken. The third and fourth goals correspond to desired international and domestic goals. Each performance goal includes an abrupt and a protracted goal for given detection and false-alarm probabilities.

The facility MMAS combines conventional materials accounting and NRTA and serves several functions including process monitoring, domestic safeguards, and international safeguards. It employs sampling and chemical analysis, weight and volume measurements, and NDA instrumentation, supported by data base management and data analysis techniques. We described a conventional accounting strategy that divides the facility into five MBAs and formulated two NRTA accounting strategies that augment the MBA structure. In the first strategy, feed preparation processes were treated as one UPAA (UPAA 1) and chemical separations processes were treated as another (UPAA 2 3). In the second, the chemical separations UPAA was further subdivided into UPAA 2 (codecontamination/partitioning processes) and UPAA 3 (uranium-plutonium copurification processes).

We identified measurement points for NRTA strategies and chose applicable measurement types and errors representative of current technology based on materials and process descriptions. The reference measurements are used for process control and materials accounting.

We used optimization techniques to calculate measurement uncertainties so that performance goals for detecting materials loss are achieved while total development cost of the instruments is minimized. The cost of improving each measurement uncertainty component is determined by a hyperbolic cost function. Therefore, where calculated measurement uncertainty is less than what is currently achievable, a development cost was imposed. Because the cost function is nonlinear, we used a nonlinear optimization technique to calculate measurement uncertainties so that instrument development cost is minimized.

We calculated measurement uncertainties that meet the four accountability performance goals for each UPAA and for several cases of instrument recalibration. For each UPAA, values for the measurement uncertainty components were restricted by specific ranges and by the materials balance standard deviation equations for abrupt and protracted losses.

Table XIII lists materials balance standard deviations for each UPAA for both one-day and six-month materials balances using current measurement technology (Table VI). The feed preparation UPAA (UPAA 1) has larger materials balance standard deviations than the others because it has more in-process inventory, and the input transfer measurements (spent-fuel NDA) are not well characterized. Because the in-process inventory in either UPAA 2 or UPAA 3 is smaller than that of UPAA 2 3 (remember that UPAA 2 3 comprises UPAA 2 and UPAA 3), the one-day materials balance standard deviations are smaller for UPAA 2 and UPAA 3 than for UPAA 2 3. The six-month materials balance standard deviations for UPAA 2 and UPAA 3 are larger than those of UPAA 2 3

TABLE XIII

MATERIALS BALANCE STANDARD DEVIATIONS
WITH CURRENT MEASUREMENT TECHNOLOGY

	1 Day (kg Pu)	6 Months (kg Pu)
UPAA 1		
No recalibration	11.6	636
Weekly recalibration	11.6	373
UPAA 2 3		
No recalibration	7.6	93
Weekly recalibration	7.6	72
UPAA 2		
No recalibration	5.9	289
Weekly recalibration	5.9	109
UPAA 3		
No recalibration	5.5	284
Weekly recalibration	5.5	114

because the intermediate transfer measurement that divides the chemical separations process area into two UPAAs is of lower quality than either the accountability or the plutonium sample tank measurements.

Table XIV lists relative costs for developing the instrument systems that meet each performance goal. One cost unit is the relative cost of attaining a measurement uncertainty that is one-half that of current measurement technology. Each halving of measurement uncertainty costs twice what the previous halving did, plus 1. UPAA 2 3 with weekly recalibration of the plutonium concentration measuring instruments for the accountability and product sample tanks will meet goal 1. Hence, the total development cost of the system is zero. If periodic recalibration of key transfer measurements is performed, the relative cost of the system can be reduced by 30% or more. The relative cost of achieving goals 3 or 4 is between 20 and 50 times more than the cost for achieving goal 2.

We identified dominant inventory and transfer measurement uncertainty terms, which are those absolute measurement uncertainties that contribute most to materials balance uncertainty. Dominant inventory uncertainties result either

TABLE XIV

RELATIVE COST OF ACHIEVING THE PERFORMANCE GOALS

	Goal 1	Goal 2	Goal 3	Goal 4
UPAA 1				
No recalibration	20	111	1947	2546
Weekly recalibration	9	64	-	-
Daily recalibration	-	53	942	1350
UPAA 2 3				
No recalibration	0.8	32	727	1544
Weekly recalibration	0	22	-	-
Daily recalibration	-	19	495	738
UPAA 2				
No recalibration	11	74	1404	2023
Weekly recalibration	2	36	-	-
Daily recalibration	-	28	595	853
UPAA 3				
No recalibration	9	65	1263	1666
Weekly recalibration	1.7	29	-	-
Daily recalibration	-	21	518	735

from large inventories or poor measurements of the inventory. In feed preparation processes, the dominant inventory uncertainties result from in-process inventory estimates in the shear, voloxidizer, and continuous dissolver, and volume and concentration measurements in the digesters and feed solution surge tank. In chemical separations processes, the dominant inventory uncertainties result from volume and concentration measurements of the HA and 2A feed tanks. The dominant transfer terms occur where the bulk of the material is transferred, that is, the input to the shear, the accountability tank, the IAPU stream, and the plutonium product sample tank. Of those transfer points, the NDA instrument for spent fuel and flow and concentration measurements for the IAPU stream require the most development.

We developed a dynamic computer model of the HEF feed preparation and chemical separations processes. Modeling and simulation of these processes allow prediction of the dynamic behavior of materials flows and inventories and materials measurements over any specified range of operating parameters. The model also allows rapid accumulation of data representative of relatively long operating periods. Because our optimization calculations used nominal values for process variables and did not include waste streams, we applied a dynamic model of the measurement system, based on the optimally calculated measurement uncertainties, to the simulated process data. Materials balance standard deviations obtained from these simulations agreed with the optimization results.

We considered the impact of the HEF process design on safeguards, with special emphasis on the ability to apply advanced materials measurement and accounting techniques. Major areas of concern are the voloxidizer, the continuous dissolver, clarification of dissolver solutions, the accountability tank, the estimation of in-process inventories in solvent-extraction contactors and other process vessels, recycle streams, and the analysis of waste solutions.

B. Conclusions

For feed preparation processes, the performance goals cannot be met by current measurement technology. Materials accounting is complicated by in-process inventories and spent-fuel assembly transfers that are difficult to measure. To alleviate these problems, we should reduce inventories wherever possible, refine spent-fuel NDA techniques and develop standards, and consider frequent flushouts of the feed preparation process.

For the chemical separations area (UPAA 2 3), we can attain an abrupt loss-detection sensitivity of 15 kg of plutonium and a protracted loss-detection sensitivity of 150 kg of plutonium with current measurement technology. These loss-detection sensitivities have 50% detection probability and 2.5% false-alarm probability. If it is desirable to subdivide the chemical separations process and maintain loss-detection sensitivity, then we must develop a flow meter with measurement uncertainties comparable to those for the accountability tank or add buffer accountability tanks at the 2A feed tank location.

Achieving performance at the second level (8 kg of plutonium abrupt and 40 kg of plutonium protracted) seems to be a reasonable goal for the chemical separations area of the HEF. This requires improving in-process inventory measurement uncertainty to ∿1% precision for process tank volume and concentration measurements. It also requires improving accountability and plutonium sample tank transfer measurement uncertainties to ∿0.04% RSD volume calibration, ∿0.04% RSD volume standards, ∿0.1% RSD concentration calibration, and ∿0.05% RSD concentration standards.

Goals 3 and 4 require inventory measurement or estimate errors <0.2% RSD, transfer random errors <0.03% RSD, and transfer correlated errors <0.002% RSD. In comparison, today's primary standards have errors of ∿0.04%. Clearly, proposed international and domestic safeguards goals cannot be achieved without major breakthroughs in measurement technology and standards preparation.

The optimization methodology developed for this study can identify measurement uncertainty components that dominate materials balance standard deviations and instruments that require development to meet specific performance goals. Further study is needed to determine the sensitivity of the results to costs and the constraints of measurement uncertainties.

The following will facilitate materials accounting in the HEF.

1. Development and implementation of measurement control programs are vital. Accountability instruments at key materials flow measurement points need frequent recalibration. Otherwise, correlations between flow measurements can degrade detection sensitivities to unacceptably low levels. Computer-controlled dynamic calibration techniques should be investigated for on-line measurements. Measurement control programs should identify error sources.

2. Proper characterization of standards for key transfer measurement points is required. Errors in standards can dominate long-term loss-detection sensitivities.
3. Research and development resources should be concentrated on the development of measurement-control programs, of representative standards, and of volume, flow, and concentration measurements at key transfer measurement points.
4. In-process inventory of individual process vessels should be reduced. Large in-process inventories dominate the short-term detection sensitivity performance.
5. Further subdivision of process areas into unit process accounting areas is not always advantageous. The effectiveness of subdivision depends on the availability of appropriate measurement technology.

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APPENDIX A

HEF PROCESS DESCRIPTION

ORNL is designing the HEF as part of the CFRP. The conceptual design of the HEF, as presented in the Interim Design Report,[7] represents a versatile pilot-scale reprocessing facility that is capable of storing and reprocessing breeder and light-water reactor spent fuels. The process flow sheets are designed to provide for reprocessing three broad classes of fuel:

- thorium-uranium,
- thorium-uranium-plutonium, and
- uranium-plutonium.

The flow sheets were revised in June 1979 and again in April 1980 to emphasize the uranium-plutonium breeder-reactor fuel cycle.[8,83] Hence, this study is concerned only with reprocessing uranium-plutonium fuels.

The basic design philosophy of minimizing personnel radiological exposure by limiting access to materials within the plant has led to a facility designed for remote maintenance. The cell complex is in the form of an H, with two long parallel cells joined in the middle by a third cell. One of the parallel arms houses the high-level-radiation activities, such as fuel shearing, voloxidation, dissolution, feed adjustment, and waste disposal. The other long arm is dedicated to lower-level-radiation activities, such as product purification, mixed-oxide production, product packaging, and analytical chemistry. An extensive network of service corridors, plug galleries, operating galleries, decontamination and maintenance cells, contact maintenance facilities, cask and truck locks, and fuel receiving and storage facilities provides maintenance for the process cells. Remote, overhead cranes and manipulators and floor-mounted manipulators provide maintenance for process cell equipment. A computer-controlled, remote sampling vehicle is available for process sampling.

The HEF uses a modified Purex process flow sheet that incorporates coprocessing of uranium and plutonium instead of the usual plutonium purification process. The flow sheet is based on breeder reactor fuel having (1) a maximum burnup of 150 000 megawatt-days per tonne, (2) a minimum 60-day decay period before shipment to the HEF, and (3) a minimum 90-day decay period before reprocessing. The facility design also provides for the conversion of mixed

uranium-plutonium nitrate to oxide. The design capacity is 0.5 tonne of fuel per day. The process description presented in the following sections is based on information found in Refs. 7 and 83.

I. FUEL RECEIVING AND STORAGE

The fuel receiving and storage system receives spent fuel in rail or truck shipping casks. Next, the fuel assemblies are cleaned of any sodium, assayed to determine their fissile content, and then stored until they enter the mechanical processing and feed preparation steps. Three types of spent-fuel receipts are anticipated: (1) clean fuel assemblies received in helium-pressurized casks, (2) assemblies sealed in sodium-filled canisters within helium-pressurized casks, and (3) assemblies received in sodium-filled casks.

Clean fuel assemblies can be transferred directly to NDA and then to fuel storage, whereas other fuel assemblies must be cleaned to remove sodium contamination before assay and storage. Assembly fragments (scrap) from the cleaning operation are sent to the batch dissolver. Sediments from cleaning that contain nuclear material are recycled through the rework process. Effluents from the fuel-storage and waste-pool filters are transferred to the batch dissolver and to the decontamination waste treatment process, respectively.

II. DISSOLUTION AND FEED PREPARATION

The mechanical processing and feed preparation process, as diagrammed in Fig. A-1, consists of (1) mechanical disassembly and shearing, (2) voloxidation, (3) dissolution, (4) feed clarification, and (5) accountability measurement. Process stream characteristics are given in Table A-I.

Mechanical disassembly and shearing involve removal of the two fuel-assembly end fittings (one by a plasma torch or laser and the other by a roller cutter) removal of the shroud, and shearing of the fuel rods (into short lengths) up to the gas plenum. The end fittings, shroud, and gas plenum are discarded to the metal scrap disposal system on a 3.14-h cycle. Metal fragments (swarf) from the plasma-torch operation are discarded to metal scrap on a 40-day cycle.

TABLE A-I

MECHANICAL PROCESSING AND FEED PREPARATION STREAM CHARACTERISTICS[a]

Stream Ident.	Description	Uranium, kg/h (kg/batch)	Plutonium, kg/h (kg/batch)	Total Mass kg/h (kg/batch)	Cycle Time h	Transfer Time min	Flow Rate L/h	HNO_3 Molarity	Associated Vessel and Maximum Plutonium Inventory
	Disassembly shear input	(50.90)	(14.58)	(210.29)	3.14	-	-	-	Disassembly shear, 15 kg
	Disassembly shear scrap	-	-	(93.86)	3.14	-	-	-	
Swarf	Metal fragments	-	-	(91.72)	960.0	-	-	-	
	Voloxidizer input	(50.90)	(14.58)	(116.13)	3.14	-	-	-	Voloxidizer, 27 kg
	Continuous dissolver feed	16.21	4.64	33.43	-	-	-	-	Continuous dissolver, 19 kg
	Continuous dissolver feed acid	-	-	87.94	-	-	65.53	9.71	
	Continuous dissolver rinse acid	-	-	36.38	-	-	34.32	0.527	
	Hulls to hull drier	(0.01)	(0.005)	(6.90)	0.5	-	-	0.104	
	Off-specification hulls to batch dissolution	(0.96)	(0.48)	(57.64)	48.0	-	-	-	
	Digester feed solution	16.19	4.63	153.36	-	-	106.62	3.66	Digesters 1 & 2, 28 kg each
	Primary centrifuge feed from digesters	(97.14)	(27.77)	(863.85)	6.0	30	-	3.83	Primary centrifuge, 0 kg
	Primary centrifuge feed from batch dissolver surge tanks	-	-	(31.14)	6.0	10	-	12.94	
	Primary centrifuge rinse from batch dissolver surge tanks	-	-	(41.02)	6.0	10	-	0.508	

TABLE A-I (cont)

Stream Ident.	Description	Uranium, kg/h (kg/batch)	Plutonium, kg/h (kg/batch)	Total Mass kg/h (kg/batch)	Cycle Time h	Transfer Time min	Flow Rate L/h	HNO_3 Molarity	Associated Vessel and Maximum Plutonium Inventory
	Secondary dissolver surge tank feed	(2.21)	(1.20)	(43.97)	6.0	10	-	9.62	Secondary dissolver surge tank, 5 kg
	Secondary dissolver feed	(8.84)	(4.78)	(181.15)	24.0	30	-	9.32	Secondary dissolver, 10 kg
	Primary centrifuge centrate	(95.60)	(26.65)	(891.72)	6.0	30	-	3.63	
	Leached solids centrifuge feed	(8.84)	(4.78)	(181.66)	24.0	30		8.50	
	Leached solids centrifuge centrate	(8.84)	(4.78)	(302.35)	24.0	30	-	4.58	
	Solids sample tank feed from leached solids centrifuge	(0.49)	(0.27)	(171.47)	24.0	10	-	0.653	
	Solids sample tank feed from HA centrifuge	-	-	(13.67)	7 days	5	-	12.78	
	Solids sample tank recycle to leached solids centrifuge	(0.49)	(0.27)	(141.89)	24.0	30	-	0.731	
	Solids sample tank to high-level waste	(0.52×10^{-3})	(0.28×10^{-3})	34.71	24.0	10	-	0.289	
	Feed solution surge tank input	(389)	(111)	(3860)	24.0	20	-	3.72	Feed solution surge tank, 111 kg
	Accountability tank feed	(389)	(111)	(3980)	24.0	20	-	3.62	Accountability tank, 111 kg

[a]From drawings 52-B-201, 52-B-203, and 52-B-204 (Ref. 83).

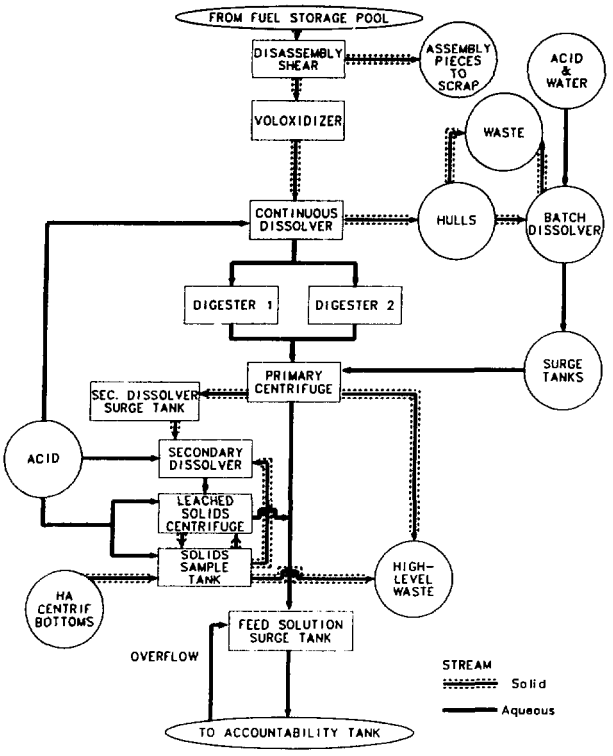

Fig. A-1.
Feed preparation.

The short lengths of fuel rod are fed to the voloxidizer, which is a rotating electric kiln that heats the chopped fuel to between 450-650°C in oxygen or oxygen-augmented air. There, the crystal structure of the fuel is converted from UO_2 to U_3O_8, releasing essentially all of the tritium, which combines with the excess oxygen to form tritiated water. In addition to removing tritium from the fuel before subsequent contact with aqueous processing streams, voloxidation oxidizes residual sodium in the fuel before aqueous contact.[84] The oxidation of UO_2 to U_3O_8 produces a fine powder, and the accompanying increase in volume is expected to crack the cladding. However, despite the concomitant larger surface area of U_3O_8, clad UO_2 and powdered U_3O_8 fuel dissolve at about the same rate. In addition, voloxidation may convert a significant fraction of the total plutonium to forms that are insoluble at the dissolver acid concentration.[71] In the HEF flow sheet, tritium from this step and other off-gas streams is recovered for ultimate disposal as $Mg(OH)_2$.

The continuous dissolution system consists of a steam-heated, rotating cylindrical drum having nine compartments (dissolver), followed by two digester

surge tanks. The voloxidized fuel segments enter the dissolver at one end and are countercurrently contacted with ∿8 M nitric acid. Also entering the dissolver are acid feed (with soluble poison and iodine stripper bottoms), rinse water (with soluble poison), overflow from the hulls handling tank, and purge gas. Exit streams include the continuous dissolved-fuel product stream, the leached hulls batches, and the dissolver off-gas. The dissolved fuel flows alternately to one of two parallel digester surge tanks, after combining with an off-specification stream from the dissolver area catch tank, the rework decanter, and/or the solvent-wash waste decanter. The hulls batches are washed, dried, and monitored for nuclear materials. In-specification hulls are combined with other metal scrap for disposal. Off-specification hulls are releached in a batch dissolver, which also recovers fuel material from the assembly fragments produced in the fuel cleaning operation. The batch dissolver product stream is fed to the primary centrifuge.

The digester surge tanks provide an additional 12-h dissolution time for the undissolved, suspended solids (Fig. A-2). In addition to a 6-h fill time, the 12-h digester cycle includes an evaporation and NO_2 sparge cycle to remove iodine. Product is clarified in the primary centrifuge, which feeds directly to the feed solution surge tank. Undissolved solids remaining in the primary centrifuge are monitored for nuclear material content. Batches meeting specification are sent

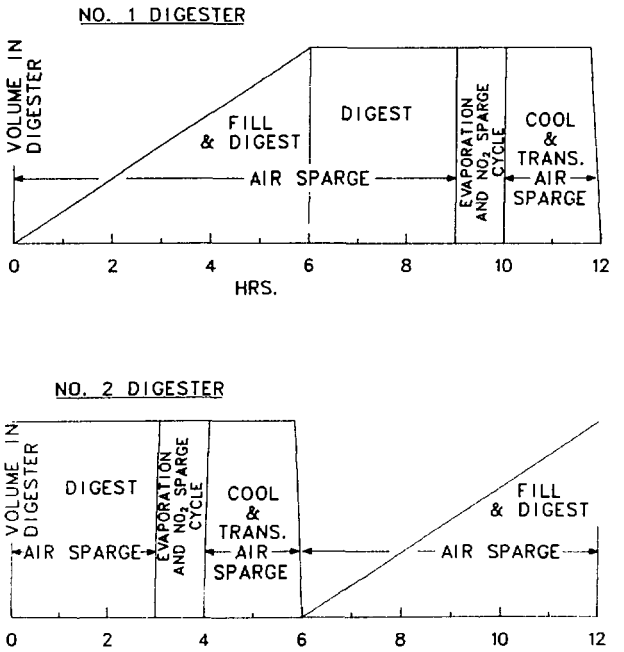

Fig. A-2. Digester surge tank cycle.

to high-level liquid waste. Off-specification batches are sent to a secondary dissolver surge tank where they are accumulated for 24 h. Then, they are transferred to the secondary dissolver and treated with alternative procedures.

Contents of the secondary dissolver are jetted nominally every 24 h to the leached solids centrifuge; its centrate is fed to the feed solution surge tank. After solids in the leached solids centrifuge are rinsed, they are flushed to the solids sample tank for nuclear materials assay. Also, solids from the HA centrifuge are flushed to the solids sample tank every 7 days. When fissile content of the sample tank solids meets specification, the solids are jetted to high-level waste. Otherwise, they are recycled through the leached solids centrifuge and washed with acid until they meet specification. Solids with higher fissile content are jetted to the secondary dissolver.

The feed solution surge tank feeds the accountability tank. A precise volume measurement is made at the accountability tank and a sample (or samples) taken for assay as follows. First, the tank is filled above an overflow line in the necked-down section at its top. Then it is air-sparged to homogenize the feed solution before sampling. Excess solution is returned to the feed solution surge tank through the overflow line; flow in this line occurs only when the airlift is operating because the line runs uphill. These procedures assure that accountability tank volume is precisely known and is essentially identical from batch to batch.

III. URANIUM-PLUTONIUM CODECONTAMINATION AND PARTITIONING

Figure A-3 shows the block diagram for uranium-plutonium codecontamination and partitioning, and Table A-II summarizes the composition of principal streams.

The accountability tank contents are jetted to the feed adjustment tank where the solution acidity and nuclear materials concentrations are adjusted to the HA feed specifications. The adjusted feed is transferred to the HA feed tank. A recycle stream from the extraction backcycle system can be added to the feed. A continuous flow is maintained from the HA feed tank to the HA centrifuge where residual solids are removed. The centrate flows continuously to the HA centrifugal contactor of the first solvent-extraction cycle, and the residual solids are accumulated and then transferred to the solids sample tank every 7 days.

TABLE A-II

URANIUM-PLUTONIUM CODECONTAMINATION AND PARTITIONING STREAM CHARACTERISTICS[a]

Stream Ident.	Description	Uranium, kg/h (kg/batch)	Plutonium, kg/h (kg/batch)	Total Mass kg/h (kg/batch)	Cycle Time h	Transfer Time min	Flow Rate L/h	HNO_3 Molarity	Associated Vessel and Maximum Plutonium Inventory
	Feed adjustment tank input	(389)	(111)	(4100)	24.0	20	-	3.48	Feed adjustment tank, 111 kg
FAP	HA feed tank input No. 1	(388)	(111)	(4430)	24.0	20	-	3.32	HA feed tank, 115 kg
1WB	HA feed tank input No. 2	trace	trace	17.28	-	-	14.07	7.89	
	HA centrifuge feed	16.20	4.64	201.94	-	-	152.01	3.73	
	HA centrifuge solids out	-	-	(13.67)	168.0	5	-	12.78	
HAF	HA contactor feed from HA centrifuge	16.20	4.64	201.94	-	-	152.01	3.73	HA contactor, 0.4 kg
HSR	HA contactor feed (HS column raffinate)	1.27	0.67	55.68	-	-	47.02	3.09	
	Total HA contactor feed	17.47	5.31	257.62	-	-	199.05	3.58	
HAX	HA contactor extractant	-	-	207.50	-	-	257.76	-	
HAW	HA contactor waste	-	-	213.88	-	-	182.22	3.52	
HAP	HS column feed (HA contactor product)	17.46	5.31	251.24	-	-	272.57	0.233	HS column, 3 kg
HSS	HS column scrub	-	-	31.20	-	-	31.34	0.304	

TABLE A-II (cont)

Stream Ident.	Description	Uranium, kg/h (kg/batch)	Plutonium, kg/h (kg/batch)	Total Mass kg/h (kg/batch)	Cycle Time h	Transfer Time min	Flow Rate L/h	HNO_3 Molarity	Associated Vessel and Maximum Plutonium Inventory
HSIS	HS column intermediate scrub	-	-	17.44	-	-	15.18	5.22	
HSP	HC column feed (HS column product)	16.19	4.64	244.20	-	-	268.08	0.026	HC column, 3 kg
HCX	HC column extractant, reductant	-	-	246.52	-	-	236.07	0.011	
HCIX	HC column intermediate extractant	-	-	29.32	-	-	26.87	3.92	
HCW	HC column waste	-	-	207.50	-	-	260.35	6.09×10^{-5}	
HCP	HC product reducer feed	16.19	4.64	312.20	-	-	271.86	0.334	HCP reducer, 15 kg
	HC product reducer reductant feed	-	-	46.65	-	-	44.66	0.018	
1AFR	HC product reducer output	16.19	4.65	358.62	-	-	317.46	0.399	
	1A feed tank acid	-	-	67.13	-	-	49.75	13.07	
1AF	1A feed tank input and 1A column feed	16.20	4.65	425.69	-	-	362.65	2.14	1A feed tank, 11 kg
1AX	1A column extractant	-	-	161.00	-	-	200.00	-	1A column, 3 kg
1BR	1B column raffinate (1A column scrub)	3.97	-	57.27	-	-	47.62	1.87	

TABLE A-II (cont)

Stream Ident.	Description	Uranium, kg/h (kg/batch)	Plutonium, kg/h (kg/batch)	Total Mass kg/h (kg/batch)	Cycle Time h	Transfer Time min	Flow Rate L/h	HNO_3 Molarity	Associated Vessel and Maximum Plutonium Inventory
1AP	1A column aqueous effluent	0.59	4.65	449.99	-	-	401.38	2.10	
1AU	1A column organic effluent (1B feed)	19.58	-	194.97	-	-	208.75	0.119	
1BS	1B column strip	-	-	35.25	-	-	33.36	0.105	
1BIS	1B column intermediate strip	-	-	13.97	-	-	12.20	5.07	
1BP	1B column organic effluent (1C feed)	15.61	-	186.92	-	-	207.45	0.0061	
1CX	1C column extractant	-	-	208.53	-	-	211.78	0.0097	
1CW	1C column waste	-	-	161.00	-	-	200.00	0.0064	
1CU	1C column product	15.61	-	234.45	-	-	204.83	0.016	
1CUC	1C evaporator product	15.61	-	56.20	-	-	35.28	0.090	

[a]From drawings 52-B-204, 53-B-201, and 53-B-202 (Ref. 83).

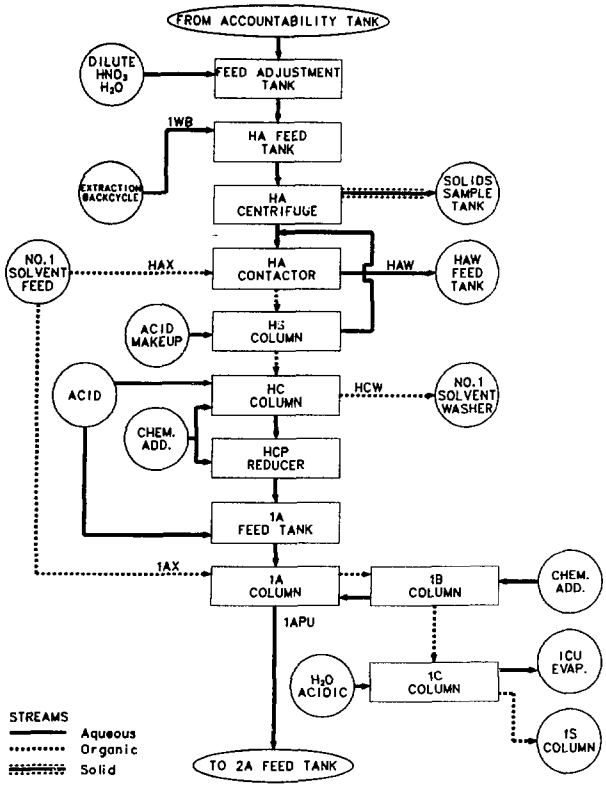

Fig. A-3.
Uranium-plutonium codecontamination and partitioning.

Initial decontamination of nuclear materials occurs in the HA centrifugal contactor, where heavy metals are selectively and quantitatively extracted into the organic stream (decontamination factor of $\sim 10^3$). Most of the fission products remain in the aqueous stream and flow to the high-activity waste (HAW) feed tank. The organic stream flows to the HS column where aqueous stream scrubbing removes ruthenium, zirconium, and niobium. The scrub stream is returned to the HA contactor for nuclear materials recovery. The decontaminated organic stream flows from the HS column to the HC column where the nuclear materials are back extracted (stripped) into the aqueous stream. The product-free organic stream leaving the HC column flows to the No. 1 solvent treatment system. The product-laden aqueous stream (HCP) is sent to the HCP reduction vessel where the plutonium is reduced from Pu(IV) to Pu(III) with a solution of hydroxylamine nitrate and the holding reductant, hydrazine. The aqueous plutonium stream then flows to the 1A column through the 1A feed tank to begin the second solvent-extraction cycle (see Glossary).

In the 1A column, uranium is partitioned from plutonium by extraction into the organic stream. The uranium-to-plutonium ratio in the 1A column aqueous stream is adjusted from ∿0.13:1 to ∿2:1 with ^{238}U as it flows to the 1A decanter. The organic stream from the 1A column is stripped with a dilute nitric-acid stream in the 1B column to remove traces of plutonium. This acid stream then flows to the 1A column for plutonium recovery.

The organic stream from the 1B column is treated with 0.01 M acid in the 1C column to strip the uranium into the aqueous stream. The acid stream used for the stripping is the overhead distillate from the 1C concentrator. The organic stream from the 1C column is routed to the 1S column for recovery of residual nuclear materials, and the aqueous uranium stream flows to the 1CU evaporator and then to the third solvent-extraction cycle, uranium purification.

IV. URANIUM PURIFICATION

Figure A-4 is a diagram of the uranium purification process, and Table A-III lists characteristics of the principal streams. This third solvent-extraction cycle provides uranium nitrate solution for denaturing plutonium and conversion to UO_3.

The aqueous uranium stream from the 1C column is concentrated in the 1CU evaporator. The concentrated product is adjusted in the 2D feed adjustment tank to the required composition for solvent extraction and then is batch-transferred to the 2D feed tank, which continuously feeds the 2D column. Uranium is extracted into the organic stream in the 2D column, scrubbed in the 2S column, and then stripped into the aqueous stream in the 2E column. Column waste streams are recycled internally within the purification cycle or through either the extraction backcycle or the No. 2 solvent treatment systems. The 2E column aqueous uranium stream is concentrated in the 2EU evaporator and routed to the uranium catch tank. From there, the uranium solution is batch-transferred to the uranium sample tank. After sampling and assay, the solution is transferred to either the uranium surge tank or the off-specification uranium tank. Off-specification uranium is recycled to the 2D feed tank for repurification. Uranium product is drawn from the uranium surge tank for denaturing plutonium feed and product in the uranium-plutonium copurification process and for UO_3 production, which includes concentration, denitration, and product packaging.

TABLE A-III

URANIUM PURIFICATION STREAM CHARACTERISTICS[a]

Stream Ident.	Description	Uranium, kg/h (kg/batch)	Plutonium, kg/h (kg/batch)	Total Mass kg/h (kg/batch)	Cycle Time h	Transfer Time min	Flow Rate L/h	HNO_3 Molarity	Associated Vessel and Maximum Plutonium Inventory
1CUC	2D feed adjustment tank feed	15.61	-	56.20	-	-	35.28	0.09	2D feed adjustment tank
2DF	2D feed tank feed	(250.12)	-	(991.79)	16	10	-	1.54	2D feed tank
2DF	2D column feed	15.61	-	61.99	-	-	39.17	1.52	2D column
2DX	2D column extractant	-	-	152.95	-	-	190.00		
2DW	2D column waste	-	-	65.91	-	-	60.29	1.62	
2DU	2D column product (2S column feed)	16.38	-	183.24	-	-	198.60	0.254	2S column
2SS	2S column scrub	-	-	21.06	-	-	21.40	-	
2SIS	2S column intermediate scrub	-	-	8.71	-	-	7.61	5.05	
2SR	2S column raffinate	0.77	-	34.21	-	-	29.06	3.05	
2SU	2S column product	15.61	-	178.80	-	-	196.81	8.06×10^{-4}	
2E Column	(2E column feed)								
2EX	2E column extractant	-	-	164.44	-	-	167.00	9.5×10^{-3}	
2EW	2E column waste	-	-	152.95	-	-	191.91	-	

TABLE A-III (cont)

Stream Ident.	Description	Uranium, kg/h (kg/batch)	Plutonium, kg/h (kg/batch)	Total Mass kg/h (kg/batch)	Cycle Time h	Transfer Time min	Flow Rate L/h	HNO_3 Molarity	Associated Vessel and Maximum Plutonium Inventory
2EU	2E column product (2EU evaporator feed)	15.61	-	190.29	-	-	163.02	0.011	2EU evaporator
UP-1	2EU evaporator product (^{238}U catch tank feed)	15.61	-	54.83	-	-	34.01	0.047	^{238}U catch tank
UP-2	^{238}U sample tank feed	(129.32)	-	(459.4)	8	10	-	0.044	^{238}U sample tank
UP-3	^{238}U surge tank feed	(129.32)	-	(473.2)	8	10	-	0.042	^{238}U surge tank
	Denaturant to Pu sample tank	(55.44)	-	(202.92)	12	10	-	0.044	Pu sample tank
	Denaturant to 1A column product	8.71	-	32.46	-	-	20.54	0.044	1A column
	UNH concentrator feed	2.27	-	8.28	-	-	5.25	0.030	UNH concentrator
UNH	Denitrator feed	2.27	-	4.78	-	-	2.09	-	Denitrator
UO_3	Denitrator product	2.26	-	2.72	-	-	1.36	-	
	Canned UO_3	(151)	-	(181.4)	66.7	-	-	-	

[a]From drawings 53-B-202, 53-B-203, and 54-B-202 (Ref. 83).

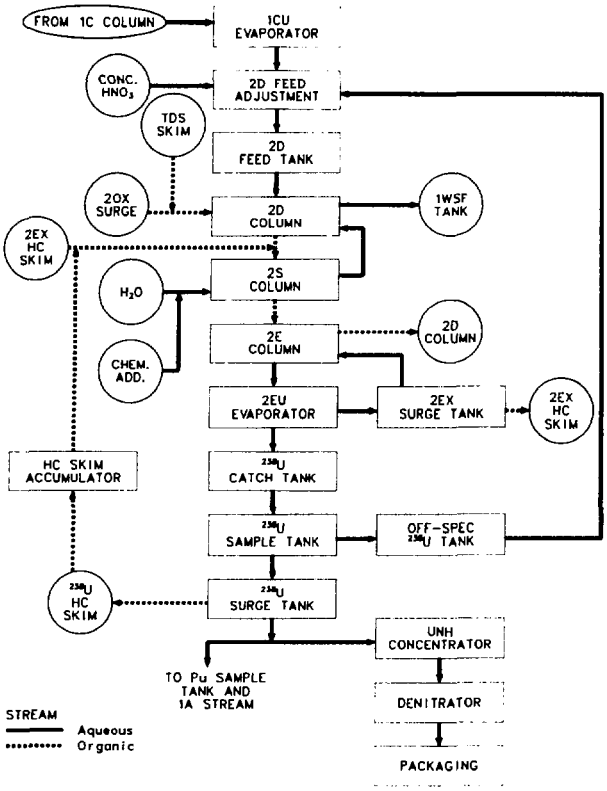

Fig. A-4.
Uranium purification.

V. URANIUM-PLUTONIUM COPURIFICATION

Figure A-5 is a block diagram for the fourth and fifth solvent-extraction cycles, and Table IV gives the compositions of principal streams. The aqueous plutonium stream from the 1A column is denatured with ^{238}U at the 1A decanter to provide a uranium-to-plutonium ratio of ∿2:1 in the 2A feed tank. The acid concentration in the 2A feed tank is adjusted to oxidize the plutonium from Pu(III) to Pu(IV) for solvent extraction.

The 2A feed tank continuously feeds the 2A extraction-scrub pulsed column where nuclear materials are extracted into the organic stream. The 2A organic stream flows to the 2B column where the nuclear materials are stripped into the aqueous stream. The aqueous stream then flows to the 3A feed tank where its acidity is adjusted before the next extraction-scrub and stripping sequence in the 3A and 3B columns.

TABLE A-IV

URANIUM-PLUTONIUM COPURIFICATION STREAM CHARACTERISTICS[a]

Stream Ident.	Description	Uranium, kg/h (kg/batch)	Plutonium, kg/h (kg/batch)	Total Mass kg/h (kg/batch)	Cycle Time h	Transfer Time min	Flow Rate L/h	HNO_3 Molarity	Associated Vessel and Maximum Plutonium Inventory
1AP	1A column product	0.59	4.65	449.99	-	-	401.38	2.10	
UNF	^{238}U denaturing feed	8.71	-	32.46	-	-	20.54	0.425	
1APu	2A feed tank feed	9.30	4.65	482.45	-	-	421.95	2.01	2A feed tank, 111 kg
	2A feed tank acid feed	-	-	11.20	-	-	8.33	12.84	
	Off-spec Pu to 2A feed tank	(111.56)	(55.68)	(650.88)	As Required		-	2.93	
2AF	2A column feed	9.30	4.64	491.10	-	-	428.82	2.14	2A column, 3 kg
2AS	2A column scrub	-	-	41.60	-	-	38.99	2.26	
2AX	2A column extractant (3BW)	-	-	161.00	-	-	200.00	-	
2AX	2AX makeup	-	-	36.23	-	-	45.01	-	
2AP	2B column feed (2A column product)	9.30	4.64	226.25	-	-	254.00	0.261	2B column, 3 kg
2AW	2A column waste	trace	0.002	503.68	-	-	455.13	2.06	
2BX	2B column extractant	-	-	269.18	-	-	255.37	0.022	
2BIX	2B column intermediate extractant	-	-	29.11	-	-	25.18	5.47	

TABLE A-IV (cont)

Stream Ident.	Description	Uranium, kg/h (kg/batch)	Plutonium, kg/h (kg/batch)	Total Mass kg/h (kg/batch)	Cycle Time h	Transfer Time min	Flow Rate L/h	HNO_3 Molarity	Associated Vessel and Maximum Plutonium Inventory
2BW	2B column waste to 1S column	trace	trace	197.23	-	-	247.47	1.82×10^{-4}	
2BP	3A feed tank feed (2B column product)	9.30	4.64	327.26	-	-	290.81	0.739	3A feed tank, 13 kg
3AFA	3A feed tank acid feed	-	-	48.35	-	-	35.85	13.03	
3AF	3A column feed	9.30	4.64	375.15	-	-	324.90	2.07	3A column, 3 kg
3AX	3A column extractant	-	-	161.00	-	-	200.00	-	
3AS	3A column scrub	-	-	27.85	-	-	26.75	1.49	
3AW	3A column waste	-	0.002	376.39	-	-	340.64	2.0	
	2AW plus 3AW to 1 WSF tank	trace	0.005	880.07	-	-	795.77	2.0	
3AP	3B column feed (3A column product)	9.30	4.64	187.62	-	-	207.36	0.136	3B column, 3 kg
3BX	3B column extractant	-	-	252.58	-	-	239.62	0.021	
3BIX	3B column intermediate extractant	-	-	27.64	-	-	23.58	5.47	
3BW	3B column waste	-	-	161.00	-	-	200.00	-	
3BP-PFF	3B column product-Pu stripper feed tank feed	9.30	4.64	306.43	-	-	273.89	0.611	Pu stripper feed tank, 2 kg

TABLE A-IV (cont)

Stream Ident.	Description	Uranium, kg/h (kg/batch)	Plutonium, kg/h (kg/batch)	Total Mass kg/h (kg/batch)	Cycle Time h	Transfer Time min	Flow Rate L/h	HNO_3 Molarity	Associated Vessel and Maximum Plutonium Inventory
PSF	Pu stripper feed	9.30	4.64	306.43	-	-	268.41	0.624	Pu stripper, 4 kg
PSC	Pu concentrator feed (stripper product)	9.30	4.64	171.60	-	-	144.95	1.08	Pu concentrator, 19 kg
PCP	Pu catch tank feed (concentrator product)	9.30	4.64	54.24	-	-	33.96	2.93	Pu catch tank, 56 kg
	Pu sample tank input (catch tank out)	(111.56)	(55.68)	(650.88)	12.0	30.0	-	2.93	Pu sample tank, 56 kg
HNO_3	Pu sample tank acid feed	-	-	(54.00)	12.0	10.0	-	0.317	Off-spec Pu tank, 56 kg
UN	^{238}U denaturing feed	(55.60)	-	(203.16)	12.0	10.0	-	0.044	
PUP	Pu sample tank product	(167.16)	(55.68)	(908.04)	12.0	30.0	-	2.07	

[a]From drawings 53-B-202, 53-B-204, and 53-B-205 (Ref. 83).

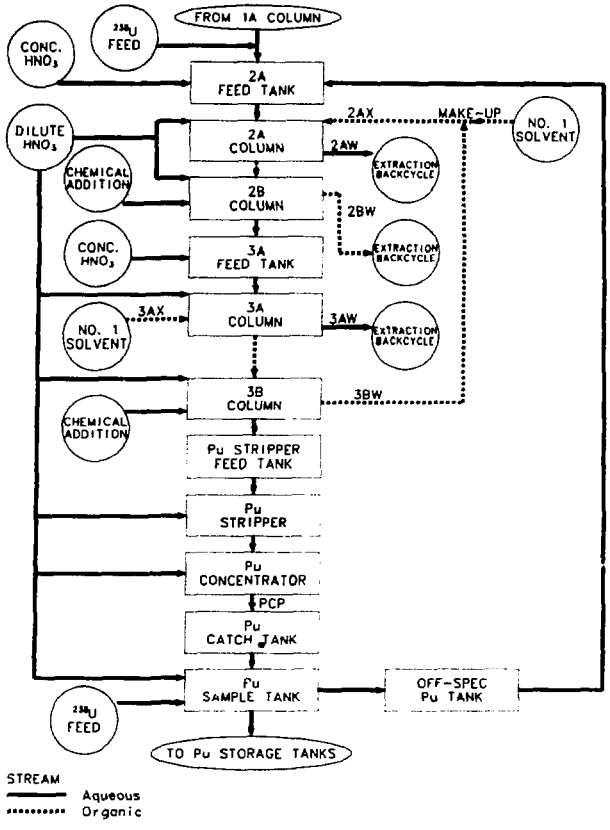

Fig. A-5. Uranium-plutonium copurification.

The aqueous product stream from the 3B column flows to the plutonium stripper feed tank where the solution is steam stripped to remove organics. The stripper product stream then is concentrated in the plutonium concentrator, routed continuously to the plutonium catch tank, and transferred on a batch basis to the plutonium sample tank. The contents of the plutonium sample tank are sampled and assayed, and off-specification batches are transferred to the off-specification plutonium tank and then recycled to the 2A feed tank as required. For batches meeting specifications, ^{238}U is added to bring the uranium-plutonium ratio to 3:1 and batch acidity is adjusted. The product is then transferred to the uranium-plutonium nitrate storage tanks.

VI. NITRATE-TO-OXIDE COCONVERSION

The uranium-plutonium nitrate solution is stored in seven parallel liquid product storage tanks. An eighth tank is used as a spare and for sump collection. These tanks have a 30-day production capacity but nominally will contain a maximum of 10 days of production. For coconversion, the nuclear materials solution is diluted, valence adjusted, precipitated, centrifuged, dried, calcined, blended, sampled, and packaged. A subsequent report will address these processes.

VII. EXTRACTION BACKCYCLE

Organic and aqueous waste streams are processed in the extraction backcycle to recover residual nuclear materials before subsequent waste processing. The system includes an extraction column for processing organic streams, a stripping column, and an evaporator for processing aqueous stream.

VIII. SOLVENT TREATMENT

Radioactive impurities and solvent degradation products are removed from the organic solvent streams in two independent but identical systems. The No. 1 solvent treatment system processes solvent from the codecontamination/partitioning cycles (HCW), floor sumps, and rework system. The No. 2 system only treats solvent from the uranium purification cycle (2EW) to minimize plutonium contamination of the uranium product.

IX. LIQUID WASTES

The aqueous waste processing and recovery systems reduce waste streams by concentration. All aqueous streams are recovered and fractionated to yield a strong acid solution and water. Excess nitric acid is removed by the NO_x catalytic destruction system. Water from the fractionator overhead is either

recycled to cold chemical make-up or discharged through the stack to maintain the plant water balance; tritiated water is concentrated and converted to $Mg(OH)_2$ for final disposal.

X. OFF-GAS TREATMENT

The off-gas treatment system removes radioactive contaminants from the dissolver off-gas and the vessel off-gas systems to control plant emissions. It also reduces the level of other contaminants (such as NO_x and R-12 refrigerant) in the effluent air from the plant.

APPENDIX B

DYNAMIC MODEL OF THE HEF CHEMICAL SEPARATIONS PROCESS

I. INTRODUCTION

Computer modeling and simulation aided the design and evaluation of the NRTA system for the conceptual HEF chemical separations process. Modeling and simulation techniques allow prediction of the dynamic behavior of materials flows and measurements over any specified range of operating parameters and also rapid accumulation of data that represent relatively long operating periods. Alternative operating, measurement, and accounting strategies can be readily compared. In contrast, even if the HEF existed and had an NRTA system, its use in the design and evaluation of such strategies probably would be time-consuming and expensive.

The modeling and simulation approach has been used extensively in studies by the Los Alamos Safeguards Systems Group.[1-5,9,10] This approach has included (1) a detailed dynamic model of the process based on actual design data and operator experience; (2) simulation of the process model on a digital computer; (3) a dynamic model of each measurement system based on best estimates of instrument performance and behavior; (4) simulation of accountability measurements applied to nuclear materials flow and in-process inventory data generated by the process model simulation; and (5) evaluation of simulated materials balance data from various materials accounting strategies.

This appendix describes briefly (1) the HEF feed preparation and chemical separations processes model and (2) the MODEL and HEF model (HEFMOD) computer programs, which together simulate operation of the HEF model. Sample process simulation results also are presented.

II. DYNAMIC MODEL

A. Introduction

The detailed HEF model was developed to estimate quantitatively the NRTA system sensitivity for the HEF feed preparation and chemical separations

processes because process uncertainty (for example, undefined materials side-streams and in-process inventories) can significantly affect materials control and accountability. Standard Monte Carlo techniques developed for dynamic systems are used to simulate operation of the HEF model.[85,86] The dynamics of each process step is described by the continuity equations for flows of bulk material and nuclear material:

$$\frac{dI_{BLK}(t)}{dt} = \sum_i F_i(t)$$

and

$$\frac{dI_{NM}(t)}{dt} = \sum_i C_i(t)F_i(t) \quad ,$$

where $I_{BLK}(t)$ is bulk material in process at time t, $I_{NM}(t)$ is nuclear material in process at time t, $F_i(t)$ is bulk volumetric or mass flow rate at time t in stream i (inputs positive, outputs negative), and $C_i(t)$ is nuclear material concentration at time t in stream i.

Dynamics for the entire HEF model is described by the solution of the complete set of coupled differential equations for all process operations, subject to initial conditions and subsidiary constraints. Random variation in the HEF model is determined by the statistics selected for independent random variables, which execute a random walk in time. These variables and their statistics were defined after a detailed examination of the conceptual process and operating procedures.

B. HEF Model

1. Introduction. The HEF model is based on ORNL's modified Purex process flow sheet for the conceptual HEF (see Appendix A). This flow sheet allows coprocessing uranium and plutonium instead of the usual plutonium purification process. Development of the HEF model required a detailed review and analysis of several reports (Refs. 71, 72, 84, 87-105) and of the HEF process

information that ORNL transmitted directly to Los Alamos.[7,8,83] Process data and descriptions were clarified, supplemented, and updated in discussions with ORNL personnel.

The HEF model has three modules: feed preparation, codecontamination/partitioning, and copurification. Brief descriptions follow of a few major process steps and modeling assumptions for each module. (See Appendix A for details.)

2. Brief Description. Figure A-1 is a diagram of the feed preparation processes of the HEF model. Major process steps include (1) mechanical disassembly and shearing, (2) voloxidation, (3) fuel dissolution, and (4) feed clarification. A uranium-plutonium dissolved-fuel feed solution is prepared from spent-fuel assemblies for subsequent codecontamination, partitioning, and copurification by solvent extraction.

A spent-fuel assembly is received and disassembled every 3.14 h and then sheared into 157 batches [~1.3 cm (0.5-in.) fuel segments, or hulls], each of which is produced and transferred to the voloxidizer every 0.02 h (1.2 min). For each voloxidizer feed batch received, a product batch is discharged, and these batches are accumulated for 0.5 h in the feed compartment of the seven-stage continuous dissolver. Every 0.5 h the feed compartment contents (hulls) are transferred into stage one of the continuous dissolver, and a batch of leached hulls is discharged from stage seven.

Hulls proceed in batches through the continuous dissolver with a 0.5-h/stage residence time, while contacting a continuous countercurrent flow of nitric acid. Estimating in-process plutonium inventory in the continuous dissolver is complex.[106] In the HEF model, 90% of the plutonium in each batch of hulls dissolves in stage one, and 5% dissolves in stage two. After 0.5-h hulls residence in stage two, the MODEL code generates a deviate representing the fraction of total undissolved plutonium in stage two that will ultimately be discharged from stage seven in the leached hulls (see Table B-I). The value of this deviate, which is sampled from a lognormal distribution,[107] is subtracted from the total undissolved plutonium in stage two, and the difference yields the quantity of undissolved plutonium in stage two that will dissolve in stages three through seven. This quantity is modeled to dissolve 40% in stage three, 30% in stage four, 15% in stage five, 10% in stage six, and the remaining 5% in stage seven. The continuous dissolved-fuel product stream flows from the feed end of the continuous dissolver to the digester surge tanks, then to the primary centrifuge.

TABLE B-I

HEFMOD INDEPENDENT PROCESS VARIABLES[a]
(FEED PREPARATION, CODECONTAMINATION AND PARTITIONING, AND COPURIFICATION)

MBA	Stream Identification	Batch Size	Distribution[b]	Flow Rate	Distribution[b]	Pu Concentration	Distribution[b]	Cycle Time (h)
1	Disassembly:							
	Feed (fuel assembly)	210.29 kg	--	--	--	0.0693 kg/kg	T, ±2%	3.14
	Scrap (incl. swarf)	94.16 kg	T, ±2%	--	--	0 kg/kg	--	3.14
	Shear:							
	Plutonium output	--	--	4.643312 kg/h	UC, ±10%, ±20%	--	--	--
	Voloxidizer:							
	Plutonium output	--	--	4.643312 kg/h	UC, ±10%, ±20%	--	--	--
	Continuous dissolver:							
	Acid	--	--	98.898 L/h	UC, ±1%, ±10%	0 kg/L	--	--
	Plutonium input	--	--	--	--	--	--	0.5
	Hulls plutonium output	5 g	LN, 1.4908 g -2.3026 g, 2.9957 g, 0.4870 g	--	--	--	--	0.5
	Product solution	--	--	99.1315 L/h	UC, ±1%, ±10%	--	--	--
	Digesters (2):							
	Evaporation (each)	34.84 L	T, ±2%	--	--	0 kg/L	--	12
	Batch dissolver:							
	Acid	172.72 L	T, ±2%	--	--	0 kg/L	--	48
	Rinse	312.96 L	T, ±2%	--	--	0 kg/L	--	48
	Batch dissolver surge tanks:							
	Product solution	60.71 L	T, ±2%	--	--	--	--	6
	Primary centrifuge:							
	Solids plutonium output	1.20 kg	U, ±100%	--	--	--	--	6
	Flush to SDST[c]	30.37 L	T, ±10%	--	--	--	--	6
	Secondary dissolver:							
	Acid	3.88 L	T, ±2%	--	--	0 kg/L	--	24
	Leached-solids centrifuge:							
	Solid plutonium output to SST:[d,e]							
	No recycle (P = 0.5)	0.012 kg	U, ±100%	--	--	--	--	24
	1 recycle (P = 0.35)	0.297 kg	U, ±91.919%	--	--	--	--	24
	2 recycles (P = 0.1)	0.870 kg	U, ±34.48%	--	--	--	--	24
	3 recycles (P = 0.04)	1.450 kg	U, ±19.31%	--	--	--	--	24
	4 recycles (P = 0.01)	2.100 kg	U, ±17.61%	--	--	--	--	--
	Acid flush (each)[f]	80.85 L	T, ±10%	--	--	0 kg/L	--	--

TABLE B-I (cont)

MBA	Stream Identification	Batch Size	Distribution[b]	Flow Rate	Distribution[b]	Pu Concentration	Distribution[b]	Cycle Time (h)
	Solids sample tank:							
	Solid plutonium output to HLW[g]	0.012 kg	U, ±100%	--	--	--	--	24
2	Accountability tank:							
	Overflow solution	25 L	T, ±20%	--	--	--	--	24
	Feed adjustment tank							
	Acid + water	1119.343 L	T, ±2%	--	--	0 kg/L	--	24
	HA feed tank:							
	Product solution	--	--	152.01 L/h	UC, ±1%, ±10%	--	--	--
	HA centrifuge:							
	Solids plutonium output	0.0075 kg	U, ±33.333%	--	--	--	--	168
	HA contractor:							
	Extractant	--	--	270.107 L/h	UC, ±1%, ±10%	0 kg/L	--	--
	Waste	--	--	196.08 L/h	UC, ±1%, ±10%	--	--	--
	Product	--	--	272.57 L/h	UC, ±1%, ±10%	--	--	--
	HS column:							
	Scrub	--	--	46.52 L/h	UC, ±2%, ±20%	0 kg/L	--	--
	Recycle	--	--	--	--	0.01430 kg/L	UC, ±2%, ±20%	--
	Top disengagement[h]	14.268 L	UC, ±2%, ±20%	--	--	--	--	--
	Bottom disengagement[h]	27.95 L	UC, ±2%, ±20%	--	--	--	--	--
	HC column:							
	Extractant	--	--	271.86 L/h	UC, ±1%, ±10%	0 kg/L	--	--
	Waste	--	--	--	--	0 kg/L	--	--
	Top disengagement	69.15 L	UC, ±2%, ±20%	--	--	--	--	--
	Bottom disengagement	42.37 L	UC, ±2%, ±20%	--	--	--	--	--
	HCP reducer:							
	Reductant	--	--	44.66 L/h	UC, ±1%, ±10%	0 kg/L	--	--
	Product solution	--	--	316.52 L/h	UC, ±1%, ±10%	--	--	--
	1A feed tank:							
	Acid	--	--	49.75 L/h	UC, ±1%, ±10%	0 kg/L	--	--
	Product solution	--	--	366.27 L/h	UC, ±1%, ±10%	--	--	--
	1A column:							
	Extractant	--	--	200.00 L/h	UC, ±2%, ±20%	0 kg/L	--	--
	Scrub	--	--	33.68 L/h	UC, ±2%, ±20%	0 kg/L	--	--
	Waste	--	--	--	--	0 kg/L	--	--
	Top disengagement	73.55 L	UC, ±2%, ±20%	--	--	--	--	--
	Bottom disengagement	5.5975 L	UC, ±2%, ±20%	--	--	--	--	--

TABLE B-I (cont.)

MBA	Stream Identification	Batch Size	Distribution[b]	Flow Rate	Distribution[b]	Pu Concentration	Distribution[b]	Cycle Time (h)
	2A feed tank:							
	Acid	--	--	8.33 L/h	UC, ±1%, ±10%	0 kg/L	--	--
	^{238}U solution	--	--	20.54 L/h	UC, ±1%, ±10%	0 kg/L	--	--
	Product solution	--	--	428.82 L/h	UC, ±1%, ±10%	--	--	--
	2A column:							
	Extractant	--	--	245.00 L/h	UC, ±2%, ±10%	0 kg/L	--	--
	Scrub	--	--	38.99 L/h	UC, ±2%, ±10%	0 kg/L	--	--
	Waste	--	--	--	--	4.32 E-06 kg/L	UC, ±2%, ±10%	--
	Top disengagement	14.268 L	UC, ±2%, ±10%	--	--	--	--	--
	Bottom disengagement	27.95 L	UC, ±2%, ±10%	--	--	--	--	--
	2B column:							
	Extractant	--	--	280.55 L/h	UC, ±2%, ±10%	0 kg/L	--	--
	Waste	--	--	--	--	0 kg/L	--	--
	Top disengagement	69.15 L	UC, ±2%, ±10%	--	--	--	--	--
	Bottom disengagement	42.374 L	UC, ±2%, ±10%	--	--	--	--	--
	3A feed tank:							
	Acid	--	--	35.85 L/h	UC, ±2%, ±10%	0 kg/L	--	--
	Product solution	--	--	316.40 L/h	UC, ±2%, ±10%	--	--	--
	3A column:							
	Extractant	--	--	200.00 L/h	UC, ±2%, ±10%	0 kg/L	--	--
	Scrub	--	--	26.75 L/h	UC, ±2%, ±10%	0 kg/L	--	--
	Waste	--	--	--	--	7.21 E-06 kg/L	UC, ±2%, ±10%	--
	Top disengagement	14.268 L	UC, ±2%, ±10%	--	--	--	--	--
	Bottom disengagement	27.95 L	UC, ±2%, ±10%	--	--	--	--	--
	3B column:							
	Extractant	--	--	263.20 L/h	UC, ±1%, ±10%	0 kg/L	--	--
	Waste	--	--	--	--	0 kg/L	--	--
	Top disengagement	69.15 L	UC, ±2%, ±10%	--	--	--	--	--
	Bottom disengagement	42.374 L	UC, ±2%, ±10%	--	--	--	--	--
	Pu-stripper feed tank:							
	Product solution	--	--	263.20 L/h	UC, ±1%, ±10%	--	--	--
	Pu stripper:							
	Solvent (for 1A column)	--	--	118.25 L/h	UC, ±1%, ±10%	0 kg/L	--	--
	Product solution	--	--	144.95 L/h	UC, ±1%, ±10%	--	--	--
	Pu concentrator:							
	Evaporation	--	--	110.99 L/h	UC, ±1%, ±10%	0 kg/L	--	--
	Product solution	--	--	33.96 L/h	UC, ±1%, ±10%	--	--	--

TABLE B-I (cont)

MBA	Stream Identification	Batch Size	Distribution[b]	Flow Rate	Distribution[b]	Pu Concentration	Distribution[b]	Cycle Time (h)
	Pu sample tank:							
	Acid	54.01 L	T, ±2%	--	--	0 kg/L	--	12
	^{238}U solution	128.72 L	T, ±2%	--	--	0 kg/L	--	12

[a]These quantities are independent, stochastic variables in the computer simulation.

[b]T denotes a triangular distribution, and the second term is the range.
U denotes a uniform distribution, and the second term is the range.
UC denotes a constrained uniform distribution, the second term is the range, and the third term is the maximum change within the range for each time step.
LN denotes a four-parameter lognormal distribution, the second term is the normal mean, the third and fourth terms are the normal minimum and maximum values, respectively, and the fifth term is the normal standard deviation.

[c]SDST denotes secondary dissolver surge tank.

[d]SST denotes solids sample tank.

[e]Values represent the initial (pre-recycle) quantities of solid plutonium output to the SST and the probabilities (for 6 d/wk without the addition of HA centrifuge solids) corresponding to each recycle case. These probabilities are lowered slightly 1 d/wk when HA centrifuge solids are added to the SST.

[f]The number of acid flushes equals the number of recycles plus one, except for the 4-recycle case for which solids are transferred to the secondary dissolver after the fourth flush.

[g]HLW denotes high-level waste.

[h]Top disengagement volumes are organic, and bottom disengagement volumes are aqueous.

The leached hulls discharged from the continuous dissolver are transferred to metal scrap disposal, where individual batches are segregated on the basis of plutonium content. Ninety percent of the batches are modeled to meet specification (<8.3 g of plutonium/batch) and are transferred to waste as they are segregated. The off-specification batches are accumulated for 48 h and then transferred to the batch dissolver, where they are releached. Ninety-nine percent of the plutonium fed to the batch dissolver is recovered and transferred to the batch-dissolver surge tanks, and the releached hulls, containing the remainder of the plutonium, are transferred to waste. The product solution received in the batch-dissolver surge tanks is transferred to the primary centrifuge as eight separate batches, with one batch transfer made every 6 h.

In the primary centrifuge, batches from the batch-dissolver surge tanks and alternately from one of the two digesters are combined and clarified every 6 h. Solids collected in the centrifuge are segregated on the basis of their plutonium content. Only ∿1% of the solids batches meet specification (<24 g of plutonium/batch) and these are transferred to HLW. The remaining off-specification batches are transferred to the secondary-dissolver surge tank and then to the secondary dissolver for additional dissolution treatment.

The secondary dissolver contents are transferred every 24 h to the leached-solids centrifuge, where the secondary dissolvent is clarified. Each batch of collected solids is washed with acid and then transferred to the solids sample tank. Solids from the HA centrifuge are transferred once every 7 d to the solids sample tank and combined with the solids transferred that day from the leached-solids centrifuge. Subsequent treatment of each batch depends on plutonium content. Off-specification batches (>24 g of plutonium/batch) are recycled to the leached-solids centrifuge up to three times and then, if the solids are still above specification, they are recycled to the secondary dissolver and combined with its contents for more intensive dissolution treatment. Batches meeting specification are transferred to HLW. Without the addition of HA centrifuge solids, ∿50% of the batches transferred to the solids sample tank require recycle. With the addition of HA centrifuge solids, once every 7 days ∿60% of the batches require recycle. Table B-I gives the quantity of plutonium (five possible ranges) that a batch can contain when it is transferred from the leached-solids centrifuge to the solids sample tank for the first time. The probabilities associated with these ranges govern the likelihood that a batch will

contain a certain amount of plutonium. When a batch requires ≤ 3 recycles, each recycle reduces the quantity of undissolved plutonium to the next smaller range of plutonium values until the smallest range (no recycle) is reached. Then the batch is transferred to HLW. All recycling of batches requiring ≤ 3 recycles is completed within 24 h. When a batch requires four recycles, the first three recycles reduce the quantity of undissolved plutonium to a value within the one-recycle range, and then the batch is transferred from the solids sample tank to the secondary dissolver. Recycling time for batches requiring four recycles is ≥ 48 h and depends upon the subsequent recycle requirements of the secondary dissolver solids to which these batches are added.

Figures A-3 and A-5 represent the codecontamination/partitioning and copurification processes, respectively, of the HEF model. Together, these processes separate the fission products from the uranium and plutonium and produce (1) a purified, denatured uranium stream and (2) a purified, denatured plutonium stream having a uranium-to-plutonium ratio of 3:1.

The process equipment for codecontamination/partitioning and copurification includes a centrifuge, various process tanks, and a series of solvent-extraction contactors (one centrifugal contactor and the rest pulsed columns). In the contactors, uranium and plutonium are selectively transferred between relatively immiscible, countercurrent, aqueous and organic streams. Estimation of in-process plutonium inventory in the solvent-extraction contactors is complex (Refs. 81, 82, 108-126). Modern systems identification and state estimation techniques potentially can provide the best possible estimates of contactor inventory.[124-126]

The full development of dynamic state estimation techniques for contactor inventory is a future goal for near-real-time materials accounting. A more restricted approach is used to estimate the contactor in-process inventories in the HEF model. We refer to this restricted state estimation scheme as "reduced-order" dynamic state estimation because, although the same three elements (models, measurements, and statistics) are required for its implementation, the scope of the required input information is restricted to a currently practicable level. The penalty is that the estimation model only applies over a limited range of near-steady-state run conditions.

Figures B-1 and B-2 give the basic equations for the restricted estimation model for the A-type (extraction/scrub) pulsed column of Fig. B-3. Figure B-1 lists the assumptions and the basic linear state and measurement equations. The

Assumptions

1. The column is operating near a steady-state operating point.
2. The column inventory near the operating point is linear in the concentrations.
3. Concentration measurements are available in near-real time.
4. The column inventory at the nominal operating point has been previously determined from chemical model calculations and calibration experiments.

State Equations

Mass Balance:

$$H(k+1)=H(k) + (C_f F - C_p P - C_w W)\, t(k,k+1) - M(k,k+1)$$

Loss: $M(k+1) = \; : \; (k+1/k)\; M(k)$

Measurement Equations

Total Inventory: $h(k) = h^o(k) + h^a(k)$

Organic Phase:

$$h^o(k) = h^o_t(k) + h^o_b(k) + h^o_s(k) + h^o_e(k)$$

Aqueous Phase:

$$h^a(k) = h^a_t(k) + h^a_b(k) + h^a_s(k) + h^a_e(k)$$

Fig. B-1.
Pulsed-column inventory linear estimator.

Top Section

$$h^o_t(k) = h^o_{t0} \left| \frac{C_p(k)}{C_{p0}} \cdot \frac{V_t(k)}{V_{t0}} \quad 1 \right|$$

$$h^a_t(k) = h^a_{t0}$$

Bottom Section

$$h^o_b(k) = h^o_{b0}$$

$$h^a_b(k) = h^a_{b0} \left| \frac{C_w(k)}{C_{w0}} \cdot \frac{V_b(k)}{V_{b0}} \quad 1 \right|$$

Scrub Section

$$h^o_s(k) = h^o_{s0} \left| \frac{C_p(k)}{C_{p0}} \right|$$

$$h^a_s(k) = h^a_{s0} \left| \frac{C_f(k)}{C_{f0}} \right|$$

Extraction Section

$$h^o_e(k) = h^o_{e0} \left| \frac{C_p(k)}{C_{p0}} \right|$$

$$h^a_e(k) = h^a_{e0} \left| \frac{C_f(k)}{C_{f0}} \right|$$

Fig. B-2.
"A" column measurement equations.

*The subscript 0 denotes nominal values at the operating point; V_t and V_b denote phase disengagement volumes at the top and bottom ends of the column, respectively.

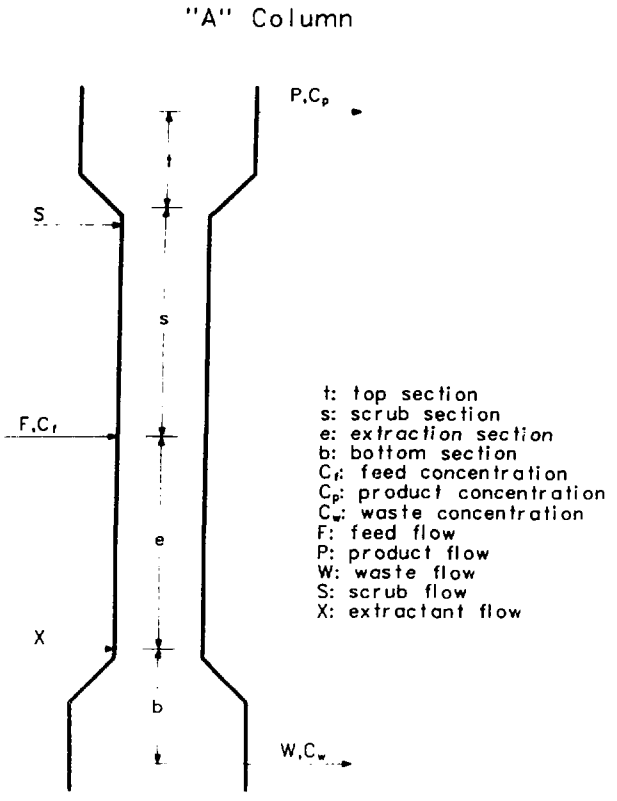

Fig. B-3.
Extraction/scrub pulsed column.

first state equation is the materials balance relating the column inventory (H) at time k + 1 to the inventory at time k. The remaining terms in the materials balance equation are the measured transfers of material across the column in the feed, product, and waste streams and any unmeasured losses (M). The second state equation describes any postulated loss mechanism by choosing the specific form of the function ϕ.

The inventory measurement equations in Figs. B-1 and B-2 are linear equations for the inventories in the organic (superscript o) and the aqueous (superscript a) phases of the four sections of the column: top, bottom, scrub, and extraction. The inventory in each section is given by a first-order Taylor series expansion about the steady-state inventory. The first-order terms depend on ratios of the measured concentrations and volumes.

Steady-state column inventory values can be calculated for the expected run conditions using a detailed chemical model that has been validated experimentally for the particular contactor system. Alternatively, experiments

can be performed to determine the expected inventories directly by bringing the columns to steady state and then draining their contents into holding tanks for measurement. For the HEF model, we used ORNL's steady-state inventory estimate of 3 kg of plutonium for each pulsed column because design and operating information necessary for calculating steady-state inventory estimates was not available.

C. MODEL Computer Code

1. Introduction. The MODEL code[127] was developed by the Los Alamos Safeguards Systems Group to model and simulate operation of nuclear materials processing facilities. Capability to address a variety of facility operations and ease of application were major considerations in the development of the code. MODEL is written in FORTRAN IV and employs the GASP IV simulation language[128] for event scheduling and overall integration of the process dynamics. The MODEL code, in conjunction with the GASP IV simulation language, can model any processing facility where process behavior can be described by algebraic and differential equations. The primary outputs from the code are the important variables describing the process.

The MODEL code has been under development for about four years. A user's manual was published recently.[128] Although developed on a PRIME 750 computer, the code is easily adapted to other machines. Recently it was implemented at the EURATOM Research Laboratories in Ispra, Italy, and Karlsruhe, Federal Republic of Germany.

2. Basic Structure. MODEL is divided into three parts for user convenience (Fig. B-4). Part I (MODFIX) is process independent and contains the main driver, input/output routines, and subroutines for modeling commonly occurring unit processes such as tanks and pulsed columns. Part II (GASP IV) is the GASP IV simulation package, which provides event scheduling, integration of differential equations, and other dynamic aspects of the modeling. Part III (MODVAR) is the user-supplied portion of the code and consists of process-dependent subroutines.

3. GASP IV Simulation Language. The MODEL code uses GASP IV simulation language primarily for integrating differential equations, scheduling events, and computing statistics for a given process. Process variables can be

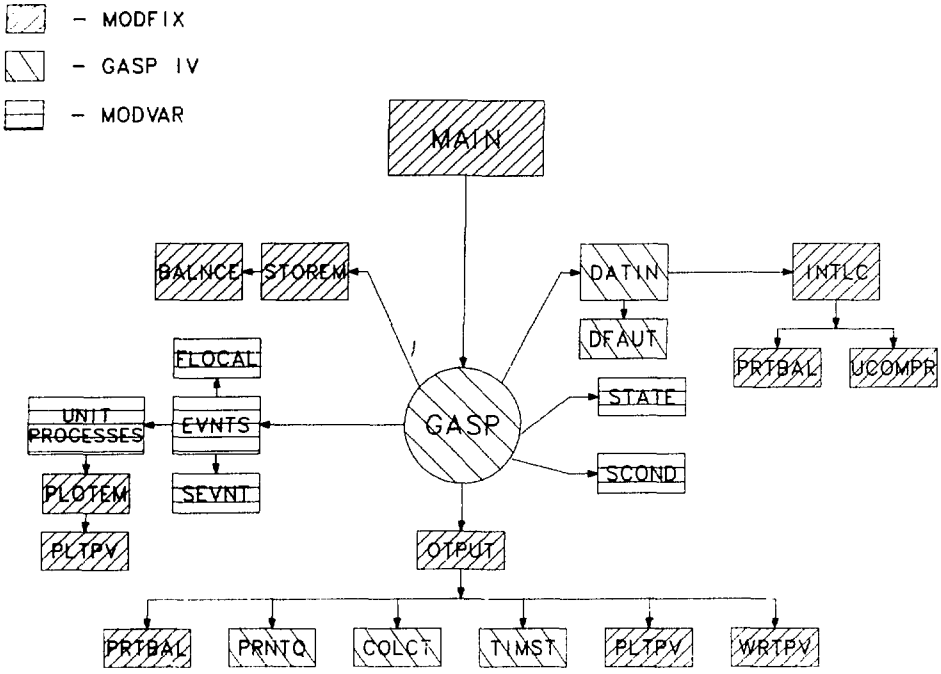

Fig. B-4.
MODEL code structure.

either discrete or continuous. GASP IV employs a fourth-order Runge Kutta algorithm for numerical integration of continuous process variables. GASP IV also can schedule both discrete and state events. Discrete events are scheduled to take place at a prescribed time and state events occur when a continuous variable crosses a prescribed boundary.

Any process variable can be modeled as a random variable by using the random-deviate generators within GASP IV. The five random-deviate generators that are currently available as function subroutines in the GASP IV portion of the MODEL code are the following.

UNFRM generates a deviate from a uniform distribution over some specified interval.

UNFRC is the same as UNFRM except that the change in the random variable on a given call to function UNFRC is limited to a specified subset of the uniform distribution interval.

RNORM generates a deviate from a normal distribution.

TRIAG generates a deviate from a triangular distribution.

RLOG generates a deviate from a lognormal distribution.

D. HEFMOD Computer Code

1. Introduction. The HEFMOD computer code was developed by the Los Alamos Safeguards Systems Group to simulate operation of the HEF model. HEFMOD is written in FORTRAN IV and comprises the unit-process subroutines in parts I and III of the MODEL code. As part of the MODEL code, HEFMOD employs GASP IV simulation language to schedule both discrete and state events and to provide other process dynamics. HEFMOD was developed and tested using a PRIME 750 computer and consists of ∿4000 FORTRAN statements. Process simulations require ∿55 000 16-bit words of storage, and additional storage is needed for graphics. A simulation of 1 yr (8760 h) of process operation requires ∿0.56 h of computer time.

2. Basic Structure. Subroutines in parts I and III of the MODEL code constitute HEFMOD and are used to model and simulate individual unit processes. Subroutines for the more common unit processes, such as the feed tanks, sample tanks, and solvent-extraction contactors, are available to the user in part 1 of the MODEL code. Part III of the MODEL code has subroutines for the more specialized unit processes, such as the continuous dissolver and solids sample tank. In many cases, a single subroutine models several unit processes of the same type to minimize programming efforts.

When an event (for example, a mass transfer or an in-process inventory operation) occurs for a particular unit process, (1) a value for each independent random variable is sampled from the associated probability distributions, (2) the dependent process variables are calculated using mass conservation equations, and (3) all process variables are stored in the appropriate data array. The data arrays for all unit processes are stored sequentially in a data file. These data are available for further processing and as input to computer codes that simulate accountability measurements and materials balances.

To minimize FORTRAN coding changes required for evaluating alternative process operations, the input data contain much process-specific information. Input data include initial values for all process variables and values of the statistical parameters that describe each independent, stochastic variable. Nominal values and probability distributions for the independent random variables of the HEF model are given in Table B-I.

III. SAMPLE SIMULATION RESULTS

Figures B-5 through B-20 are examples of nuclear material transfers and in-process inventories from a 1-wk period of simulated steady-state process operation (24 h/day, 7 days/wk production). In each graph, the process variables plotted are either discrete (defined at prescribed times) or continuous. Except as noted in the text, the process variables are single-valued functions.

Collectively, Figs. B-5 through B-8 show plutonium content of the mass transfers and in-process inventory of the continuous dissolver. Figure B-5 shows the plutonium content (nominally ∿2.32 kg of plutonium) of the hulls accumulated every 0.5 h in the feed compartment of the continuous dissolver; the hulls are subsequently transferred into the first dissolver stage. Figure B-6 shows the plutonium mass flow rate (nominally ∿4.64 kg/h of plutonium) in the continuous product stream of the dissolution process. Figure B-7 shows the plutonium in-process inventory (nominally ∿19 kg of plutonium) of the continuous dissolver. The inventory variation results from the 0.5-h dissolution cycle comprising hulls feed followed by hulls dissolution. Figure B-8 shows the lognormally distributed plutonium content (nominally ∿5 g of plutonium) of leached hulls discharged from stage seven of the continuous dissolver.

Figures B-9 and B-10 show the plutonium inventory of the in-specification and off-specification hulls, respectively. Figure B-9 shows the batch transfers of in-specification hulls to waste (<∿8 g of plutonium/batch) and their subsequent accumulation over 24 h. If each batch of leached hulls discharged from the continuous dissolver had met specification, transfers to waste would have occurred every 0.5 h. However, ∿10% of the hulls batches are off specification and are accumulated for the batch dissolver rather than transferred to waste. Therefore, Fig. B-9 shows a few constant inventory periods of >0.5 h. Figure B-10 shows three complete 48-h cycles during which off-specification batches are accumulated for 48 h and then transferred to the batch dissolver. Six batches are accumulated in the first cycle, nine in the second, and eight in the third.

Figure B-11 shows the plutonium content of the solids batches transferred from the leached-solids centrifuge to the solids sample tank. Solids meeting specification (<24 g of plutonium/batch) and thus requiring no additional recycle are received at ∿0 h, ∿72 h, ∿96 h, and ∿120 h, and subsequently transferred to HLW. Off-specification batches are received at ∿24 h, ∿48 h, and ∿144 h, and

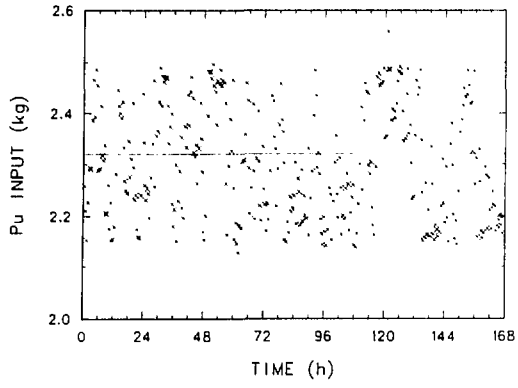

Fig. B-5.
Plutonium batch feed to the continuous dissolver.

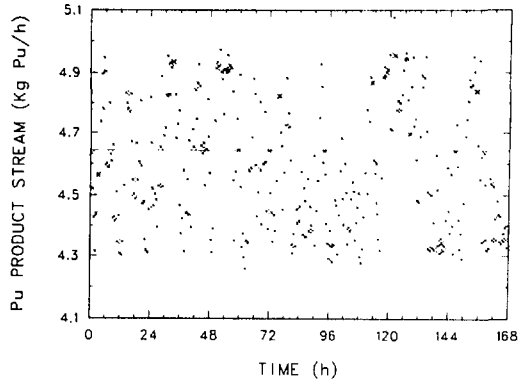

Fig. B-6.
Plutonium mass flow rate from the continuous dissolver.

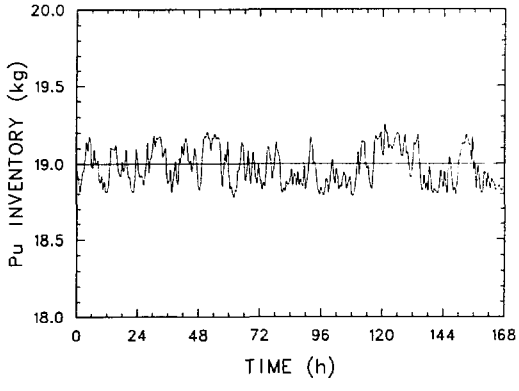

Fig. B-7.
Plutonium in-process inventory of the continuous dissolver.

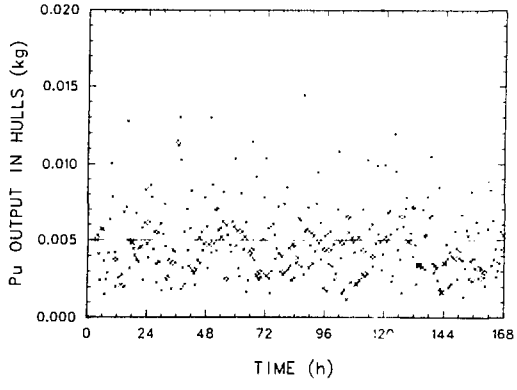

Fig. B-8.
Plutonium content of leached hulls discharged from the continuous dissolver.

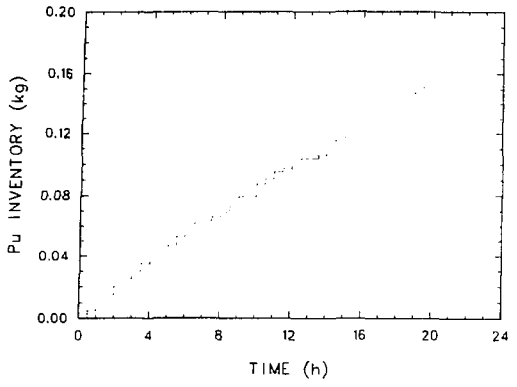

Fig. B-9.
Plutonium inventory of the in-specification leached hulls.

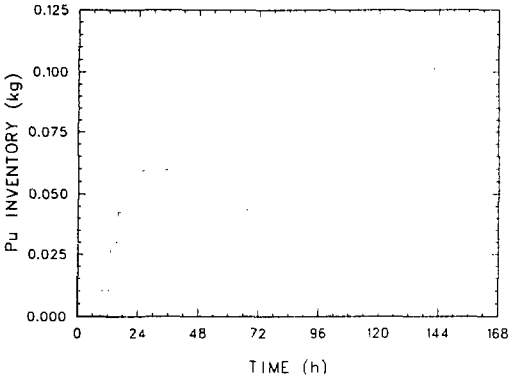

Fig. B-10.
Plutonium inventory of the off-specification leached hulls.

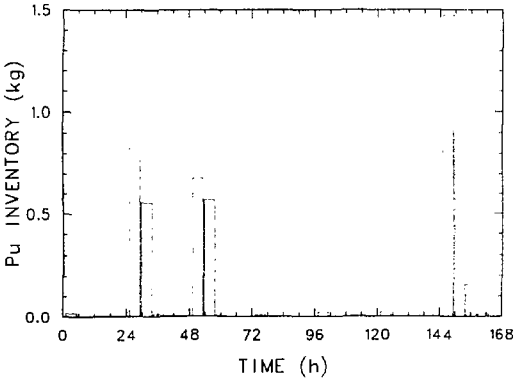

Fig. B-11.
Plutonium inventory of the solids sample tank.

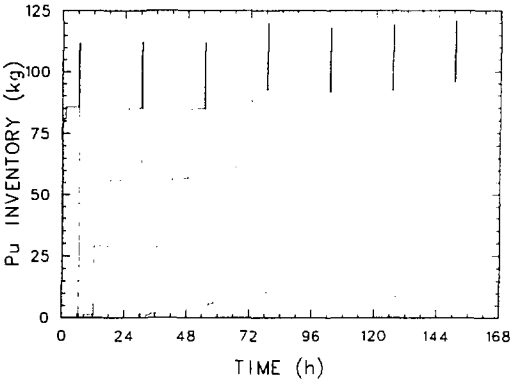

Fig. B-12.
Plutonium inventory of the feed solution surge tank.

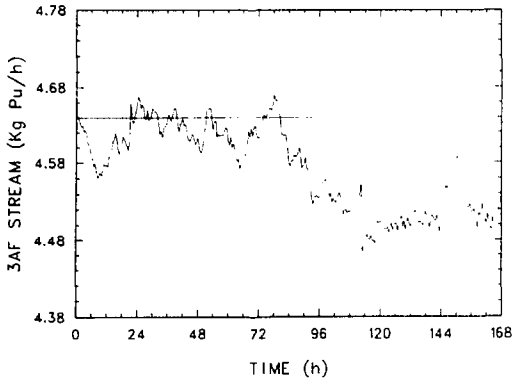

Fig. B-13.
Plutonium inventory of the accountability tank.

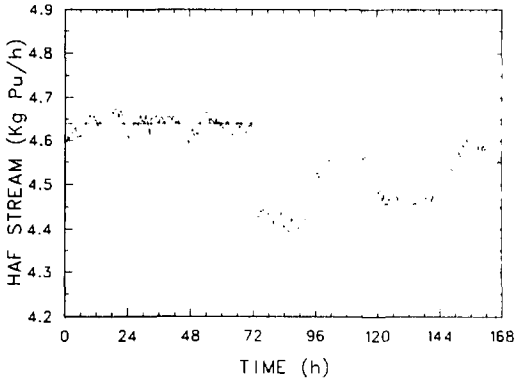

Fig. B-14.
Plutonium mass flow rate into the HA centrifugal contactor.

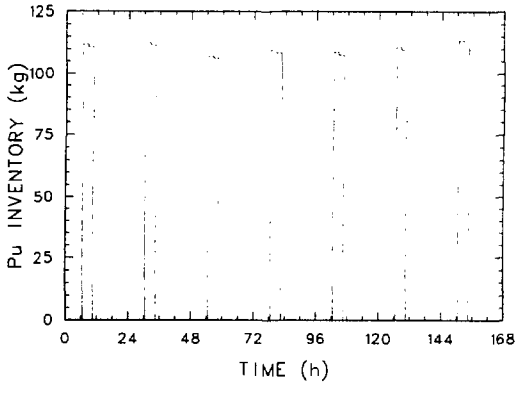

Fig. B-15.
Plutonium mass flow rate into the 3A pulsed column.

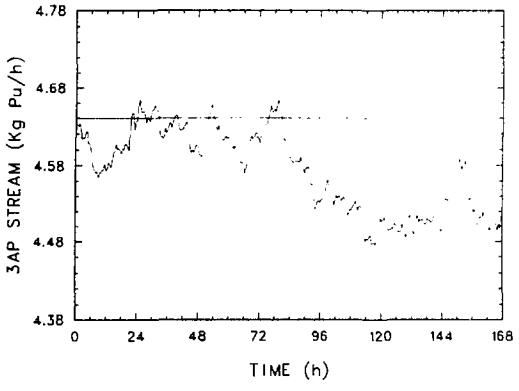

Fig. B-16.
Plutonium mass flow rate of the 3A pulsed-column product stream.

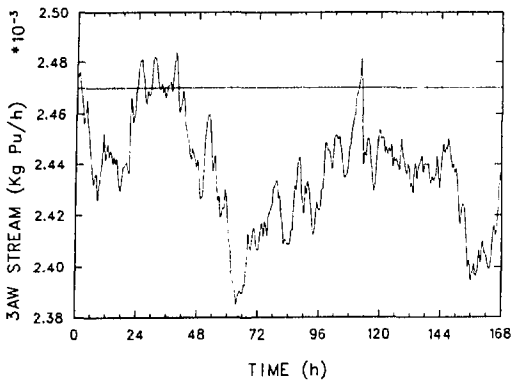

Fig. B-17.
Plutonium mass flow rate of the 3A pulsed-column waste stream.

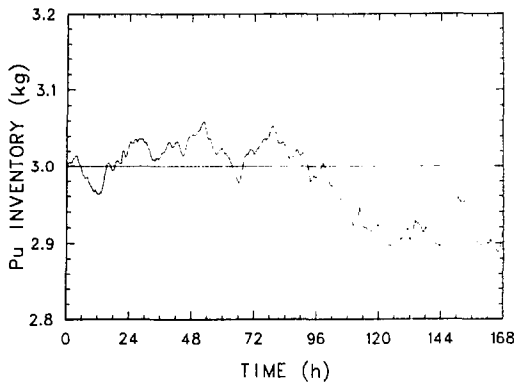

Fig. B-18.
Plutonium in-process inventory of the 3A pulsed column.

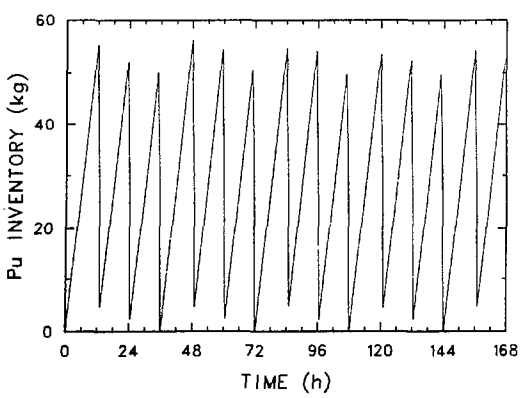

Fig. B-19.
Plutonium inventory of the plutonium catch tank.

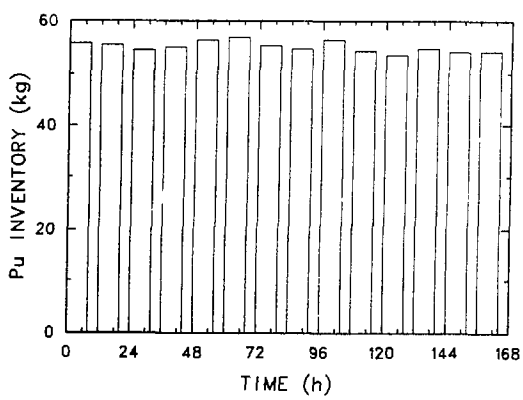

Fig. B-20.
Plutonium inventory of the plutonium sample tank.

these are recycled two, two, and three times, respectively, to meet specification. Each recycle reduces the quantity of undissolved plutonium to the next smaller range (Table B-I) until the smallest range (no recycle) is reached. Then the batch is transferred to HLW. All recycling of each batch requiring ≤ 3 recycles is completed within 24 h.

Figure B-12 shows the plutonium inventory of the feed solution surge tank. Six complete 24-h cycles of plutonium accumulation and discharge are shown, each comprising four batch receipts from the primary centrifuge, batch receipts from the leached-solids centrifuge and the accountability tank, and a single batch transfer to the accountability tank. For example, the third cycle begins at ∿54 h with a small inventory (heel) in the feed solution surge tank. Several batches are added to this heel, including those from : (1) the accountability tank (overflow) at ∿57 h (Fig. B-13); (2) the leached-solids centrifuge at ∿58 h and ∿73 h (Fig. B-14); and (3) the primary centrifuge at ∿60 h, ∿66 h, ∿72 h, and ∿78 h. The third cycle finishes at ∿78 h, 24 h after it began, with a batch transfer to the accountability tank.

Figure B-13 shows the plutonium inventory of the accountability tank, which receives a batch from the feed solution surge tank every 24 h. Two hours after a batch is received, the accountability tank volume is adjusted and the overflow (excess volume) is transferred back to the feed solution surge tank. Two hours later, the entire contents (nominally ∿112 kg of plutonium) of the accountability tank are transferred to the feed adjustment tank.

Figure B-14 shows the plutonium mass flow rate (nominally ∿4.63 kg/h of plutonium) in the continuous feed stream of the HA centrifugal contactor. The smaller mass flow rates between ∿72 and ∿96 h and again between ∿120 and ∿144 h coincide with the smaller plutonium inventory transferred from the accountability tank at ∿58 h and ∿106 h, respectively (see Fig. B-13).

Together, Figs. B-15 through B-18 show plutonium content of the mass transfers and in-process inventory of the 3A extraction-scrub pulsed column. Figure B-15 shows plutonium mass flow rate (nominally ∿4.63 kg/h of plutonium) in the continuous aqueous feed stream. Figure B-16 shows plutonium mass flow rate (nominally ∿4.63 kg/h of plutonium) in the continuous organic product stream. Figure B-17 shows plutonium mass flow rate (nominally <2.5 g/h of plutonium) in the continuous aqueous waste stream. Figure B-18 shows total plutonium in-process inventory of the 3A pulsed column. The in-process

inventory was calculated using a reduced-order dynamic state estimation technique (see Appendix B, Sec. II.B.2) based on first-order perturbations about the expected steady-state column inventory. ORNL's steady-state inventory estimate of 3 kg of plutonium was used for each conceptual pulsed column in the HEF model because design and operating information necessary for calculating steady-state inventory estimates was not available.

Figure B-19 shows plutonium inventory of the plutonium catch tank, which is fed continuously by the plutonium concentrator. The contents (nominally ∿56 kg of plutonium) of the plutonium catch tank are transferred every 12 h to the plutonium sample tank.

Figure B-20 shows the plutonium inventory of the plutonium sample tank. Eight hours after batch receipt from the plutonium catch tank, the contents (nominally ∿56 kg of plutonium) of the plutonium sample tank are transferred to either the off-specification plutonium tank (for off-specification batches) or the plutonium storage tanks (for in-specification batches). Batch transfer from the plutonium sample tank occurs every 12 h.

APPENDIX C

MATERIALS ACCOUNTING EQUATIONS

I. INTRODUCTION

Materials balance equations and their associated variance equations are derived in this appendix. The materials balance variance equations are used as constraints in the optimization calculations in Sec. IV. As indicated in Sec. I of the main text, materials accounting performance goals are based on the standard deviations of the short-term and long-term materials balances.

In the optimization calculations, materials inventories and transfers are assumed to be constants. This assumption simplifies the constraint variance equations, and its effects are negligible, as demonstrated by the modeling and simulation results.

II. MEASUREMENT MODELS

Because the materials balances are computed using measured values of process variables, they contain measurement errors. Statistical properties for the errors can be determined from individual measurement error statistics.

In this study the measurements are modeled with the following equation:

$$m = \mu(1 + \varepsilon + \eta) + \theta \quad , \qquad \text{(C-1)}$$

where μ is the actual value of a process variable, m is the measured value of μ, ε is the precision measurement error, η is the short-term correlated measurement error, and θ is the long-term correlated measurement error.

The above equation represents a mixed-mode measurement error model in that precision and short-term correlated errors are multiplicative and long-term correlated error is additive. The short-term correlated error (η) changes when the measuring instrument is recalibrated, whereas the long-term correlated error

(θ) remains constant. A major assumption in this study is that all measurement errors are mean-zero random variables.

III. MATERIALS BALANCE

In the general case, consider a UPAA where there are L inventories and K transfer locations. Then the conservation of mass, or materials balance (MB) equation over a time interval $t_o - t_f$ is

$$MB = \sum_{k=1}^{L} [I_k(o) - I_k(f)] + \sum_{j=1}^{K} \sum_{i=1}^{N_j} T_{ij} \quad , \qquad \text{(C-2)}$$

where $I_k(o)$ is the kth initial inventory, $I_k(f)$ is the kth final inventory, T_{ij} is the ith transfer at location j, and N_j is the number of transfers at location j over the interval $t_o - t_f$.

The transfers, T_{ij}, are positive for inputs and negative for outputs. If the change in inventory, ΔI_k, is defined by

$$\Delta I_k = I_k(o) - I_k(f) \quad , \qquad \text{(C-3)}$$

then the materials balance becomes

$$MB = \sum_{k=1}^{L} \Delta I_k + \sum_{j=1}^{K} \sum_{i=1}^{Nj} T_{ij} \quad . \qquad \text{(C-4)}$$

This equation is valid for both the short-term and long-term materials balances. N_j is larger for long-term materials balances because of the longer time intervals.

IV. MATERIALS BALANCE VARIANCE

We now develop a general expression for the materials balance standard deviation. Random variable theory[129] defines the mean value of a random variable η as

$$\mu = E\{\eta\} \quad , \tag{C-5}$$

where μ is the mean value of η and $E\{\eta\}$ is the expected value operator. The variance σ_η^2 of the random variable η is defined as

$$\sigma_\eta^2 = E\{(\eta - \mu)^2\} \quad . \tag{C-6}$$

Two mean-zero random variables η and ε are uncorrelated if

$$E\{\eta\varepsilon\} = E\{\eta\}E\{\varepsilon\} \quad . \tag{C-7}$$

The variance of the sum of uncorrelated random variables is equal to the sum of the individual variances; that is, if ε_i, ε_j, η_k, ... are uncorrelated random variables, then

$$\sigma^2_{(\varepsilon_i+\varepsilon_j+\eta_k+\ldots)} = \sigma^2_{\varepsilon_i} + \sigma^2_{\varepsilon_j} + \sigma^2_{\eta_k} + \ldots \quad . \tag{C-8}$$

If two random variables η_1 and η_2 are uncorrelated and C_1 and C_2 are constants, then $C_1\eta_1$ and $C_2\eta_2$ are also uncorrelated.

For the product of the constant C and the random variable η,

$$\sigma^2_{C\eta} = C^2\sigma^2_\eta \quad . \tag{C-9}$$

The variance of constant C is zero, that is,

$$\sigma_C^2 = 0 \quad . \tag{C-10}$$

The above fundamentals from random variable theory are used below to develop an equation for the materials balance variance. The random variables in the materials balance equation [Eq. (C-4)] are the measurement errors in Eq. (C-1) for the general measurement model. A major simplifying assumption in this development is that the measurement error types, that is, ε, η, and θ in Eq. (C-1), are not correlated with each other. This leads to the conclusion that inventory changes $\Delta I_k (k = 1, 2, ..., L)$ are not correlated with transfer sums $\Sigma\ T_{ij}\ (j = 1, 2, ..., K)$. It follows from Eqs. (C-4) and (C-8) that

$$\sigma_{MB}^2 = \sum_{k=1}^{L} \sigma_{\Delta I_k}^2 + \sum_{j=1}^{K} \sigma_{\sum T}^2 \quad , \tag{C-11}$$

where

$$\sum T = \sum_{i=1}^{N_j} T_{ij} \quad .$$

Eq. (C-11) forms the basis for the materials balance variance calculations.

V. INDIVIDUAL INVENTORY VARIANCES

In the preceding section the general expression for the materials balance variance was developed as in Eq. (C-11). In this section, individual inventory variances $\sigma_{\Delta I_k}^2$ are derived for each inventory type encountered in the HEF

process. There are two types of inventory determinations: (1) Type 1 is determined by a single measurement (for example, NDA) or estimate, and (2) Type 2 is determined by a product of two measurements (for example, volume and concentration).

A. Inventory as One Measured Value (Type 1)

The measured inventories at times t_o and t_f are, respectively,

$$I_m(o) = I_a(o)(1 + \varepsilon_I^o + \eta_I^o) + \theta_I \qquad \text{(C-12)}$$

and

$$I_m(f) = I_a(f)(1 + \varepsilon_I^f + \eta_I^f) + \theta_I \quad , \qquad \text{(C-13)}$$

where $I_m(o)$ is measured inventory at t_o, $I_m(f)$ is measured inventory at t_f, $I_a(o)$ is actual inventory at t_o, and $I_a(f)$ is actual inventory at t_f. Because by definition

$$\Delta I = I_m(o) - I_m(f) \quad ,$$

it follows from Eqs. (C-12) and (C-13) that

$$\Delta I = I_m(o)(1 + \varepsilon_I^o + \eta_I^o) - I_m(f)(1 + \varepsilon_I^f + \eta_I^f) \quad . \qquad \text{(C-14)}$$

From Eqs. (C-8) and (C-9) it follows that the variance of the inventory change is

$$\sigma^2_{\Delta I} = [I_a(o)^2 + I_a(f)^2]\sigma^2_{\varepsilon_I} + [I_a(o) - I_a(f)]^2\sigma^2_{\eta_I} \quad , (C\text{-}15)$$

where $\sigma^2_{\varepsilon_I}$ is the variance associated with precision inventory error and $\sigma^2_{\eta_I}$ is the variance associated with short-term correlated inventory error.

The actual value of the inventory is not known. Therefore, we estimate the variance by substituting the measured value for the actual value and will, henceforth, denote this estimate by an unsubscripted variable. We assume that the process is at steady state, that is, that it is in equilibrium about a constant mean. Thus, inventory in a given process vessel will not change significantly, that is, $I(o) \approx I(f)$. This condition implies that dependence of $\sigma^2_{\Delta I}$ on $\sigma^2_{\eta_I}$ is weak [Eq. (C-15)]; hence, a well-known value of $\sigma^2_{\eta_I}$ is not required and the variance associated with change in inventory is

$$\sigma^2_{\Delta I} = 2I^2\sigma^2_{\varepsilon_I} \quad . \qquad (C\text{-}16)$$

B. Inventory as the Product of Two Measured Values (Type 2)

In this case, the measured inventory at any time is

$$I_m(t) = I_{1m}(t)I_{2m}(t) \quad , \qquad (C\text{-}17)$$

where $I_{1m}(t)$ and $I_{2m}(t)$ are the two measured values (for example, volume and concentration) whose product yields the measured inventory (I_m).

Using the same procedure as in the previous section, the variance of the inventory change is

$$\sigma^2_{\Delta I} = 2(I_1I_2)^2(\sigma^2_{\varepsilon I1} + \sigma^2_{\varepsilon I2}) \quad . \qquad (C\text{-}18)$$

VI. INDIVIDUAL TRANSFER VARIANCES

Contributions of transfers to the materials balance variances are considered in this section. From Eq. (C-11), this contribution is

$$\sum_{j=1}^{K} \sigma^2_{\sum T} \quad ,$$

where

$$\sum T = \sum_{i=1}^{N_j} T_{ij} \quad . \tag{C-19}$$

In this expression, K represents the number of different locations in the accounting area where transfers occur and N_j equals the number of transfers at a specific location over the materials balance interval. Transfers are positive for inputs and negative for outputs.

In considering the contribution of transfers to the overall materials balance variance, we cannot assume that correlated errors are zero. In most cases, these correlated errors are major contributors to the materials balance variance. Both short-term correlated errors (η) and long-term correlated errors (θ) must be considered.

In deriving transfer variances, it is assumed that each short-term correlated error is recalibrated at regular intervals so that the number of transfers taking place between recalibrations is constant. Recalibration frequency, however, can be different for each short-term correlated error.

As with inventory variance calculations, we assume that transfers at a given process location are equal. This steady-state assumption simplifies the resulting transfer variance equations.

In the following two subsections, transfer variances are derived for the two cases occurring in the HEF process, (1) where the transfer equals a measured

value and (2) where it equals the product of two measured values. The objective is to obtain the variance of transfer sums at a single location

$$\sum T = \sum_{i=1}^{N} T_i \quad , \tag{C-20}$$

where N represents the number of transfers taking place over the materials balance interval.

A. Transfer as One Measured Value (Type 1)

The ith transfer having one measured value is

$$T_{im} = T_i(1 + \epsilon_T^i + \eta_T^i) + \theta_T \quad , \tag{C-21}$$

where T_{im} is the measured value of the ith transfer at some location in the process, T_i is the actual process value of the transfer, ϵ_T^i is the precision for i^{th} transfer, η_T^i is the short-term correlated transfer error for i^{th} transfer, and θ_T is the long-term correlated transfer error.

In general, the precision ϵ_T^i is different for each transfer, the short-term correlated error η_T^i changes only when the measuring instrument is recalibrated, and the long-term correlated error θ_T is constant over the entire materials balance interval. For the short-term correlated errors we assume M intervals separated by recalibrations, with n transfers taking place in each interval. Thus, the total number of transfers N is

$$N = Mn \quad , \tag{C-22}$$

where N is the total number of transfers over the materials balance interval, M is the number of intervals separated by recalibrations, and n is the number of transfers in each recalibration interval. For the case of no recalibrations, M = 1 and n = N.

With M and n defined in the above manner, and letting

$$\sum T = \sum_{i=1}^{N} T_{im} \quad , \tag{C-23}$$

it follows from Eq. (C-21) that

$$\sum T = NT + T \sum_{i=1}^{N} \varepsilon_T^i + nT \sum_{j=1}^{M} \eta_T^j + N\theta_T \quad . \tag{C-24}$$

In the above equation all error terms are uncorrelated. Hence, the variance of $\sum T$ can be found by adding the variances of each individual term. Because NT is a constant, it has a zero variance (Eq. C-10), and it follows that for a transfer consisting of one measured value

$$\sigma^2_{\sum T} = NT^2\sigma^2_{\varepsilon_T} + M(Tn)^2\sigma^2_{\eta_T} + N^2\sigma^2_{\theta_T} \quad . \tag{C-25}$$

B. Transfer as the Product of Two Measured Values (Type 2)

The ith transfer having two measured values is

$$T_{im} = [T_1(1 + \varepsilon^i_{T1} + \eta^i_{T1}) + \theta_{T1}]$$

$$\cdot\ [T_2(1 + \varepsilon^i_{T2} + \eta^i_{T2}) + \theta_{T2}] \quad , \tag{C-26}$$

where T_1 and T_2 are the actual process values whose product yields the transfer, and ε^i_{Tk}, η^i_{Tk}, and θ_{Tk} $(k = 1, 2)$ are the associated measurement errors.

For $k = 1$ or 2, let N equal the total number of transfers over the materials balance interval, M_k equal the number of intervals separated by recalibrations for η_{Tk}, and n_k equal the number of measurements in the recalibration interval for η_{Tk}. It follows that $N = M_k n_k$ $(k = 1, 2)$. With no recalibrations, $M_k = 1$ and $n_k = N$.

If we perform the indicated multiplications in Eq. (C-26) and neglect second-order error terms, we obtain

$$T_{im} = T_1 T_2 (1 + \varepsilon^i_{T1} + \varepsilon^i_{T2} + \eta^i_{T1} + \eta^i_{T2}) + T_1 \theta_{T2} + T_2 \theta_{T1} \quad . \tag{C-27}$$

Using the definition of $\sum T$ from Eq. (C-23) and N, M_k, and n_k $(k = 1, 2)$ as defined above, it follows that

$$\sum T = N T_1 T_2 + T_1 T_2 \sum_{i=1}^{N} (\varepsilon^i_{T1} + \varepsilon^i_{T2}) + n_1 T_1 T_2 \sum_{j=1}^{M_1} \eta^j_{T1} + n_2 T_1 T_2 \sum_{j=1}^{M_2} \eta^j_{T2} + N T_2 \theta_{T1} + N T_1 \theta_{T2} \quad . \tag{C-28}$$

Again, because all error terms are uncorrelated, the variance of the sum equals the sum of the individual variances associated with each error. Applying Eqs. (C-9) and (C-10) gives

$$\sigma^2_{\sum T} = N (T_1 T_2)^2 (\sigma^2_{\varepsilon T1} + \sigma^2_{\varepsilon T2}) + (n_1 T_1 T_2)^2 M_1 \sigma^2_{\eta T1} + (n_2 T_1 T_2)^2 M_2 \sigma^2_{\eta T2} + (N T_2)^2 \sigma^2_{\theta T1} + (N T_1)^2 \sigma^2_{\theta T2} \tag{C-29}$$

as the variance equation for type 2 transfers.

VII. MATERIALS BALANCE VARIANCES FOR HEF UPAA

As indicated previously, this appendix derives materials balance variances associated with HEF UPAAs being considered in this study. Assuming uncorrelated measurement errors, we simplified materials balance variances to terms associated with individual inventory and transfer errors.

Section V of this appendix developed the inventory variance terms for the two types of inventories appearing in the HEF processes. In type 1, the inventory equals a single measured value or an estimate, whereas type 2 is computed from the product of two measured values. Examples of type 1 are the voloxidizer and the pulsed columns, where the plutonium inventories are estimated. An example of type 2 is the HA feed tank, where the inventory is the product of volume and concentration measurements.

The materials balance variances associated with the two types of transfers in the HEF accounting areas were derived in Sec. VI of this appendix. Type 1 is computed from a single measured value, whereas type 2 equals the product of two measured values. As an example, input to the disassembly is modeled as a type 1 transfer because plutonium content of the input fuel assembly is measured directly by NDA. Output from the accountability tank to the feed adjustment tank is an example of a type 2 transfer, where the transfer is the product of volume and concentration measurements. Because we assume constant process variables, we can consider the output of the 1A column as a type 2 transfer. The two measurements in this case are flow rate and concentration. The transfer is the product of flow rate, concentration, and the interval (ΔT) between the measurements, which is assumed to remain constant. By including the constant ΔT with flow rate and considering the first measurement to be the product of flow rate and ΔT, we can consider this transfer as type 2.

The materials balance variance for a given accounting area can be computed by summing its appropriate inventory and transfer variances. Equation (C-18) provides the variances for type 1 and type 2 inventories, respectively, and Eqs. (C-25) and (C-29) represent the corresponding variances for type 1 and type 2 transfers. Inspection of these equations reveals that they all have a similar structure, namely, a sum of terms where each term is the product of a constant and the variance of a measurement error. Hence, the total materials balance

variance for a given accounting area can be written as the sum of terms consisting of the individual measurement variances multiplied by suitable constants; that is,

$$\sigma^2_{MB} = \sum_{i=1}^{N_m} B_i \sigma_i^2 \quad , \qquad \text{(C-30)}$$

where N_m is the number of measurement errors contributing to the materials balance variance, B_i is the constant associated with the ith measurement errors, and σ_i^2 is the variance of the ith measurement error.

The constants B_i in Eq. (C-30) can be obtained from Eq. (C-18) for type 1 and type 2 inventories and from Eqs. (C-25) and (C-29), respectively, for type 1 and type 2 transfers. Because the amount of material processed is a function of time, a different constant is required for the abrupt (B_{α_i}) and protracted (B_{p_i}) constraints.

Table C-I contains the information necessary to compute the materials balance variances for each accounting area considered. Measurement errors in the table contribute a term in the sum for the materials balance variance σ^2_{MB}. The first column of the table gives the measurement location. Column 2 gives the particular measurement type. For these measurements

T = plutonium transfer,

I = plutonium inventory,

V = volume,

C = concentration,

F = flow rate, and

ΔT = interval between flow rate measurements.

The nominal values for these measured values are given in column 3 of the table. Transfers and inventories are in kilograms, volumes in liters, concentrations in kilograms per liter, flow rates in liters per hour, and time in hours. Measurement error types are given in the fourth column, where ε is the precision error, η is the short-term correlated error, and θ is the long-term correlated error. The corresponding measurement error relative standard deviations (1σ) are given in

TABLE C-I

CONSTANTS FOR THE MATERIALS BALANCE VARIANCE EQUATION

$$\sigma^2_{MB} = \sum_{i=1}^{N_m} B_i \sigma_i^2$$

	Process	Measurement	Nominal Value	Error	σ_i	Type	B_i	Short Term (Goal 1) N	Short Term (Goal 1) M	Short Term (Goal 1) n	Long Term (Goal 1 Recalibration) N	Long Term (Goal 1 Recalibration) M	Long Term (Goal 1 Recalibration) n
1	Disassembly input	T	14.58	ϵ	0.04	T1	NT^2	8	1	8	1200	21	56
2	Disassembly input	T	14.58	η	0.03	T1	$M(nT)^2$	8	1	8	1200	21	56
3	Disassembly input	T	14.58	θ	0.29	T1	N^2	8	1	8	1200	21	56
4	Disassembly	I	14.58	ϵ	0.2	I1	$2I^2$	-	-	-	-	-	-
5	Shear	I	7.29	ϵ	0.2	I1	$2I^2$	-	-	-	-	-	-
6	Voloxidizer	I	26.24	ϵ	0.2	I1	$2I^2$	-	-	-	-	-	-
7	Continous dissolver	I	19.0	ϵ	0.2	I1	$2I^2$	-	-	-	-	-	-
8	Digester (2)	V	594.79	ϵ	0.3	I2	$2(VC)^2$	-	-	-	-	-	-
9	Digester (2)	C	0.0468	ϵ	0.015	I2	$2(VC)^2$	-	-	-	-	-	-
10	Hulls	I	0.24	ϵ	0.1	I1	$2I^2$	-	-	-	-	-	-
11	Hulls to hulls waste	T	0.005	ϵ	0.1	T1	NT^2	8	1	8	1200	21	56
12	Hulls to hulls waste	T	0.005	η	0.05	T1	$M(nT)^2$	8	1	8	1200	21	56
13	Hulls to hulls waste	T	0.005	θ	0.00025	T1	N^2	8	1	8	1200	21	56
14	Batch dissolver	V	314.3	ϵ	0.03	I2	$2(VC)^2$	-	-	-	-	-	-
15	Batch dissolver	C	0.00137	ϵ	0.015	I2	$2(VC)^2$	-	-	-	-	-	-
16	Acid surge tank	V	273.22	ϵ	0.03	I2	$2(VC)^2$	-	-	-	-	-	-
17	Acid surge tank	C	0.0009	ϵ	0.015	I2	$2(VC)^2$	-	-	-	-	-	-

TABLE C-I (cont)

	Process	Measurement	Nominal Value	Error	σ_i	Type	B_i	Short Term (Goal 1) N	Short Term (Goal 1) M	Short Term (Goal 1) n	Long Term (Goal 2 Recalibration) N	Long Term (Goal 2 Recalibration) M	Long Term (Goal 2 Recalibration) n
18	Primary centrifuge to HLW	T	0.024	ε	0.1	T1	NT^2	0	0	0	6	1	6
19	Primary centrifuge to HLW	T	0.024	η	0.05	T1	$M(nT)^2$	0	0	0	6	1	6
20	Primary centrifuge to HLW	T	0.024	θ	0.0012	T1	N^2	0	0	0	6	1	6
21	Secondary dissolver surge tank	I	2.4	ε	0.1	I1	$2I^2$	-	-	-	-	-	-
22	Secondary dissolver	V	125.36	ε	0.03	I2	$2(VC)^2$	-	-	-	-	-	-
23	Secondary dissolver	C	0.03829	ε	0.07	I2	$2(VC)^2$	-	-	-	-	-	-
24	SST to HLW	T	0.012	ε	0.1	T1	NT^2	1	1	1	150	21	7
25	SST to HLW	T	0.012	η	0.05	T1	$M(nT)^2$	1	1	1	150	21	7
26	SST to HLW	T	0.012	θ	0.0006	T1	N^2	1	1	1	150	21	7
27	HA centrifuge to SST	T	0.0076	ε	0.1	T1	NT^2	0	0	0	22	1	22
28	HA centrifuge to SST	T	0.0076	η	0.05	T1	$M(nT)^2$	0	0	0	22	1	22
29	HA centrifuge to SST	T	0.0076	θ	0.00038	T1	N^2	0	0	0	22	1	22
30	Feed solution surge tank	V	1220.7	ε	0.03	I2	$2(VC)^2$	-	-	-	-	-	-
31	Feed solution surge tank	C	0.044	ε	0.015	I2	$2(VC)^2$	-	-	-	-	-	-
32	Accountability tank output	V	2528.9	ε	0.003	T2	$N(VC)^2$	1	1	1	150	1	150
33	Accountability tank output	V	2528.9	η	0.001	T2	$M(nVC)^2$	1	1	1	150	1	150
34	Accountability tank output	V	2528.9	θ	2.529	T2	$(NC)^2$	1	1	1	150	1	150
35*	Accountability tank output	C	0.044	ε	0.01	T2	$N(VC)^2$	1	1	1	150	21	7
36	Accountability tank output	C	0.044	η	0.003	T2	$M(nVC)^2$	1	1	1	150	21	7
37	Accountability tank output	C	0.044	θ	0.000132	T2	$(NV)^2$	1	1	1	150	21	7

TABLE C-I (cont)

	Process	Measurement	Nominal Value	Error	σ_i	Type	B_i	Short Term (Goal 1) N	Short Term (Goal 1) M	Short Term (Goal 1) n	Long Term (Goal 2 Recalibration) N	Long Term (Goal 2 Recalibration) M	Long Term (Goal 2 Recalibration) n
38	HA feed tank	V	3648.24	ε	0.03	I2	$2(VC)^2$	-	-	-	-	-	-
39	HA feed tank	C	0.0305	ε	0.015	I2	$2(VC)^2$	-	-	-	-	-	-
40	HA centrifuge	I	0.00374	ε	0.2	I1	$2I^2$	-	-	-	-	-	-
41	HA contactor	I	0.4	ε	0.2	I1	$2I^2$	-	-	-	-	-	-
42	HS column	I	3.0	ε	0.1	I1	$2I^2$	-	-	-	-	-	-
43	HC column	I	3.0	ε	0.1	I1	$2I^2$	-	-	-	-	-	-
44	HCP reducer	V	1024.59	ε	0.03	I2	$2(VC)^2$	-	-	-	-	-	-
45	HCP reducer	C	0.01468	ε	0.01	I2	$2(VC)^2$	-	-	-	-	-	-
46	1A feed tank	V	869.565	ε	0.03	I2	$2(VC)^2$	-	-	-	-	-	-
47	1A feed tank	C	0.01268	ε	0.01	I2	$2(VC)^2$	-	-	-	-	-	-
48	1A column	I	3.0	ε	0.01	I1	$2I^2$	-	-	-	-	-	-
49	1A column output	$F\Delta T$	199.975	ε	0.025	T2	$N(F\Delta TC)^2$	48	1	48	7200	21	336
50	1A column output	$F\Delta T$	199.975	η	0.015	T2	$M(nF\Delta TC)^2$	48	1	48	7200	21	336
51	1A column output	$F\Delta T$	199.975	θ	2.00	T2	$(NC\Delta T)^2$	48	1	48	7200	21	336
52	1A column output	C	0.0116	ε	0.01	T2	$N(F\Delta TC)^2$	48	1	48	7200	21	336
53	1A column output	C	0.0116	η	0.005	T2	$M(nF\Delta TC)^2$	48	1	48	7200	21	336
54	1A column output	C	0.0116	θ	0.000023	T2	$(NF\Delta T)^2$	48	1	48	7200	21	336
55	2A feed tank	V	10268.27	ε	0.03	I2	$2(VC)^2$	-	-	-	-	-	-
56	2A feed tank	C	0.010817	ε	0.01	I2	$2(VC)^2$	-	-	-	-	-	-
57	2A column	I	3.0	ε	0.05	I1	$2I^2$	-	-	-	-	-	-

TABLE C-I (cont)

	Process	Measurement	Nominal Value	Error	σ_i	Type	B_i	Short Term (Goal 1) N	Short Term (Goal 1) M	Short Term (Goal 1) n	Long Term (Goal 2 Recalibration) N	Long Term (Goal 2 Recalibration) M	Long Term (Goal 2 Recalibration) n
58	2B column	I	3.0	ε	0.05	I1	$2I^2$	-	-	-	-	-	-
59	3A feed tank	V	885.702	ε	0.03	I2	$2I^2$	-	-	-	-	-	-
60	3A feed tank	C	0.0147	ε	0.01	I2	$2I^2$	-	-	-	-	-	-
61	3A column	I	3.0	ε	0.05	I1	$2I^2$	-	-	-	-	-	-
62	3B column	I	3.0	ε	0.05	I1	$2I^2$	-	-	-	-	-	-
63	Pu stripper feed tank	V	113.4	ε	0.03	I2	$2(VC)^2$	-	-	-	-	-	-
64	Pu stripper feed tank	C	0.0176	ε	0.01	I2	$2(VC)^2$	-	-	-	-	-	-
65	Pu stripper	I	4.0	ε	0.10	I1	$2I^2$	-	-	-	-	-	-
66	Pu concentrator	V	139.23	ε	0.03	I2	$2(VC)^2$	-	-	-	-	-	-
67	Pu concentrator	C	0.1366	ε	0.01	I2	$2(VC)^2$	-	-	-	-	-	-
68	Pu sample tank output	V	590.249	ε	0.003	T2	$N(VC)^2$	2	1	2	300	1	300
69	Pu sample tank output	V	590.249	η	0.001	T2	$M(nVC)^2$	2	1	2	300	1	300
70	Pu sample tank output	V	590.249	θ	0.59	T2	$(NC)^2$	2	1	2	300	1	300
71	Pu sample tank output	C	0.0942	ε	0.003	T2	$N(VC)^2$	2	1	2	300	21	14
72	Pu sample tank output	C	0.0942	η	0.002	T2	$M(nVC)^2$	2	1	2	300	21	14
73	Pu sample tank output	C	0.0942	θ	0.00018	T2	$(NV)^2$	2	1	2	300	21	14

column 5. These standard deviations are generally thought to be achievable with current technology (see Sec. II.D of the main text). The sixth column with the heading "Type" indicates the type of transfer or inventory associated with the measurements; that is, T1 is a type 1 transfer or a transfer as one measured value, T2 is a type 2 transfer or a transfer as the product of two measured values, I1 is a type 1 inventory or an inventory as one measured value, and I2 is a type 2 inventory or an inventory as the product of two measured values.

In the "B_i" or seventh column are the actual coefficients associated with individual measurement error variances in the materials balance variance equation. The N, M, and n integer values appearing in the coefficients relating to transfers represent the following:

N is the total number of measurements in the overall simulation,

M is the total number of intervals separated by recalibrations, and

n is the total number of measurements per recalibration interval (n = N and M = 1 for no recalibration).

The particular values of N, M, and n used in the HEF simulations for goal 1 are presented in the last six columns of the table. The short-term materials balance case applies to a 1-day interval, whereas the long-term materials balance is computed on the basis of a 150-day interval. Selected instruments are recalibrated at 7-day intervals. In a type 2 transfer consisting of a volume and a concentration, the volume measuring instrument is not recalibrated. Also, because of their infrequency, the transfers from HLW to the primary centrifuge and from the HA centrifuge to the solids sample tank (SST) are not recalibrated. The N, M, and n integer values for long-term materials balances correspond to the case with recalibration. For long-term materials balances with no recalibration, N remains the same, M equals 1, and n equals N.

Inventories for digester 1, the primary centrifuge, the leached solids centrifuge, the SST, the feed adjustment tank, and the plutonium catch tank do not appear in the table because these units are empty when measurements are made. In addition, the accountability tank and the plutonium sample tank inventories are not included because these inventories are considered as output transfers in the materials accounting equations.

The materials balance variance for a given UPAA can be computed from the table by summing the products of B_i and σ_i^2 for each measurement error

associated with that UPAA. UPAA 1 includes all the unit processes from the disassembly through the feed adjustment tank. Hence, the materials balance variance σ^2_{MB1} for UPAA 1 is

$$\sigma^2_{MB1} = \sum_{i=1}^{37} B_i \sigma_i^2 \quad . \tag{C-31}$$

UPAA 2 includes the feed adjustment tank through the 1A column. It follows that

$$\sigma^2_{MB2} = \sum_{i=27}^{29} B_i \sigma_i^2 + \sum_{i=32}^{54} B_i \sigma_i^2 \quad . \tag{C-32}$$

The first three terms (i = 27, 28, and 29) in the above equation represent the transfer from the HA centrifuge to the SST. UPAA 3 includes the 2A feed tank through the plutonium sample tank. Hence,

$$\sigma^2_{MB3} = \sum_{i=49}^{73} B_i \sigma_i^2 \quad . \tag{C-33}$$

Finally, for UPAA 2 3, the accounting area for combined UPAA 2 and UPAA 3,

$$\sigma^2_{MB23} = \sum_{i=27}^{29} B_i \sigma_i^2 + \sum_{i=32}^{48} B_i \sigma_i^2 + \sum_{i=55}^{73} B_i \sigma_i^2 \quad . \tag{C-34}$$

APPENDIX D

OPTIMIZATION TECHNIQUES

I. INTRODUCTION

An optimization problem can be characterized as maximizing or minimizing a numerical function of one or more variables, which can be independent or related through constraints. Often such problems arise in allocating scarce product resources so that the products meet certain specifications. The general optimization problem can be formulated as follows.[130-132] Determine the values for n variables $x_1, \ldots, x_n$ that satisfy the m inequalities or equations

$$g_i(x_1, x_2, \ldots, x_n) \begin{matrix} \leq \\ = \\ \geq \end{matrix} b_i \qquad (i = 1, 2, \ldots, m) \qquad \text{(D-1)}$$

and in addition maximize or minimize the scalar, real-valued function

$$z = f(x_1, x_2, \ldots, x_n) \quad . \qquad \text{(D-2)}$$

The restrictions in Eq. (D-1) are called the constraints, and Eq. (D-2) is the objective function. The values of m and n need not be related; that is, $m < n$, $m = n$, or $m > n$ are allowed. A solution to the problem in Eqs. (D-1) and (D-2) is any set of numerical values for $x_1, x_2, \ldots, x_n$ that minimizes (maximizes) Eq. (D-2) while satisfying the constraints in Eq. (D-1).

II. LINEAR OPTIMIZATION

Linear problems are a special class of optimization problems for which effective solution methods have been developed.[133] For this class both the

constraint equations and the objective function are linear in the unknowns x_1, x_2, ..., x_n. The general linear problem has the constraints

$$g_i(x_1, x_2, \ldots, x_n) = \sum_{j=1}^{n} a_{ij}x_j \begin{matrix} \leq \\ = \\ \geq \end{matrix} b_i \qquad \text{(D-3)}$$

$$(i = 1, 2, \ldots, m) \quad ,$$

where a_{ij} and b_i are known constants, and the objective function

$$f(x_1, x_2, \ldots, x_n) = \sum_{j=1}^{n} c_j x_j \quad , \qquad \text{(D-4)}$$

where c_j are known constants. Frequently for such problems, the additional constraint that each $x_j \geq 0$ is imposed as a convenience in making numerical calculations. This is not a real restriction because any problem in which the unknowns are unrestricted in sign can be transformed to one with all variables nonnegative.

Figure D-1 gives an example of a linear optimization problem. The constraints are

$$x_1 + x_2 \leq 3 \quad , \quad x_1 \geq 1 \quad , \quad \text{and} \quad x_2 \geq 0 \quad , \qquad \text{(D-5)}$$

and the objective function is

$$\max Z = x_1 + 2x_2 \quad . \qquad \text{(D-6)}$$

The maximum is attained at the point (1, 2).

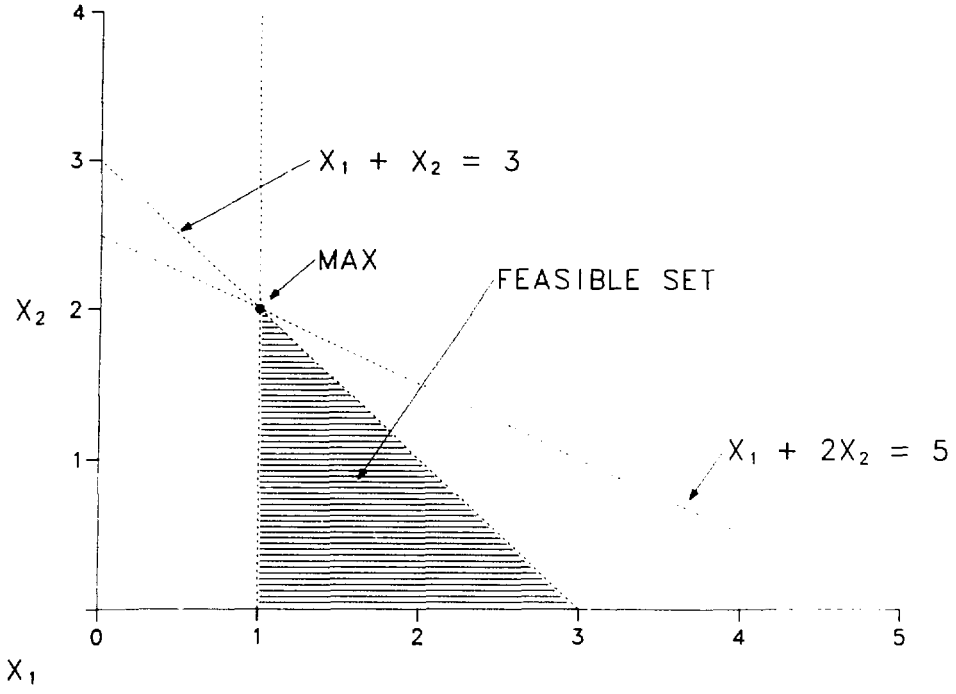

Fig. D-1.
Linear optimization example.

This problem illustrates some general characteristics of a linear optimization problem.

(1) The set of all feasible points, that is, those points that satisfy all constraints, is a convex set and has a finite number of corners.

(2) A local maximum (minimum) of the objective function is always a global maximum (minimum).

(3) If the optimal value of the objective function is finite, then at least one of the corner points is an optimal solution.

These characteristics are exploited by the simplex method for solving such problems, which is an iterative procedure that yields an optimum solution in a finite number of steps. The solution procedure consists of an efficient method for evaluating the objective function at corner points until an optimum point is found.

III. NONLINEAR OPTIMIZATION

In a nonlinear optimization problem, either the constraints and/or the objective function may be nonlinear.[131] There are several differences between linear and nonlinear optimization problems that make solution of the nonlinear problem more difficult. Unlike local minimums of objective functions in linear problems, those in nonlinear problems may not be global. Thus, without additional restrictions on the objective function and the constraint equations, there is no general method comparable to the simplex method that guarantees a global minimum. Further, because the minimum need not occur at some finite set of predetermined points as in the linear problem, there is no method that finds a solution in a finite number of iterations as the simplex method does.

If the objective function f is convex,

$$\{[f(\alpha x + \beta y) \leq \alpha f(x) + \beta f(y),\ 0 \leq \alpha,\ \beta \leq 1,\ \alpha + \beta = 1\} \quad ,$$

and the set of feasible points is also convex, then a local minimum will also be a global minimum. The set of points where the global minimum is attained reduces to a single point if f is strictly convex $f(\alpha x + \beta y) < \alpha f(x) + \beta f(y)$.

An example of a nonlinear optimization problem in which the constraints and the objective function are convex is shown in Fig. D-2. The constraints are

$$x^2 + y^2 \leq 2 \quad , \quad x \geq 0 \quad , \quad \text{and} \quad y \geq 0 \quad , \tag{D-7}$$

and the objective function is

$$\max Z = xy \quad . \tag{D-8}$$

The objective function assumes its maximum at the point (1,1), which is the unique maximizing solution to this problem because of the strict convexity of f. Note that in general the objective function may assume its optimum value either on the boundary or in the interior of the constraint set.

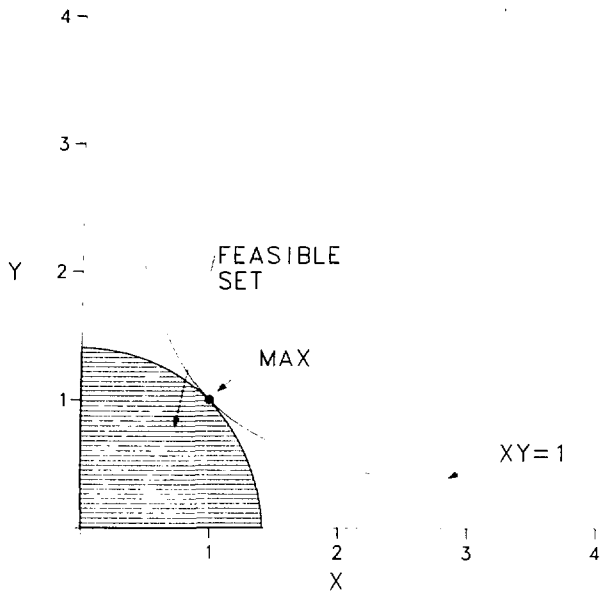

Fig. D-2.
Nonlinear optimization example.

There are numerous methods for solving the nonlinear optimization problem.[130,131,133] Many of these methods, however, are an inefficient use of computation time when the number of variables is large. When such is the case, the gradient and direct-search methods appear to be most efficient. Gradient methods tend to search along a path of steepest descent on the objective function hypersurface. However, they usually require first and sometimes second derivatives of the objective and constraint functions with respect to each of the variables. Direct-search techniques, on the other hand, do not require derivative functions. Hence, they are more useful from the standpoint of possible convergence with a variety of problems and they also make problem preparation easier. A particularly efficient direct-search method (PCON) was used to calculate minimum cost measurement uncertainties to HEF instrumentation.

IV. PCON COMPUTER PROGRAM

Calculating measurement uncertainties for the HEF requires a computerized solution method because of the large number of variables. PCON (Powell CONstrained) is an efficient, direct-search method for finding the constrained minimum of a general, nonlinear, multivariable function.[134] The minimization

algorithm employed in PCON combines Powell's direct-search conjugate-direction method[135] with the technique of Fiacco and McCormick for handling the constraints.[136] Analytic derivatives are not required for the Powell method, which makes the program easy to use and applicable to a large range of problems.

Powell's method was originally developed for unconstrained minimization problems. It employs one-dimensional searches in a direction that reduces the objective function. When no further reductions are possible, a new direction of search is chosen that is conjugate or orthogonal to the previous direction. Sequentially, applied conjugate directions ensure convergence to a minimum of a quadratic function of n variables in n searches, one in each of n conjugate directions. The algorithm of Fiacco and McCormick converts the constrained minimization problem to an artificial unconstrained problem that can be solved with Powell's conjugate-search method. With this algorithm, the constraints are included in the objective function by means of a penalty function approach. The modified objective function is

$$U = f - r \sum_i \frac{1}{g_i} \quad , \tag{D-9}$$

where U is the modified objective function, f is the unconstrained function to be minimized, r is a constant, and g_i is an inequality constraint with $g_i < 0$. As the minimum of U is approached, the constant r is decreased, thus allowing the modified objective function U to approach the unconstrained function f. PCON extends the Fiacco and McCormick method by introducing automatic scaling of the constraints as compared both to other constraints and to the objective function.

The Powell conjugate-search method makes it possible for PCON to minimize complex objective functions with only modest computer time requirements. Minimization of an objective function with 5 variables and 12 inequality constraints requires 3-4 s on a PRIME 750 minicomputer. Objective functions with $\sim$40 variables coupled with $\sim$80 inequality constraints require $\sim$150 s.

The PCON code was designed to minimize functions having a maximum of 30 variables. For the HEF problem, the PCON code was modified to handle a maximum of 50 variables. In addition, the direct-search step sizes were individually scaled to provide faster and more dependable convergence.

Computer central memory requirements are relatively modest. The complete PCON code, along with the necessary arrays for minimizing objective functions with up to 50 variables and 100 inequality constraints, requires $\sim$ 17 000 16-bit words of computer central memory. All floating point arithmetic is in double precision to minimize convergence difficulties caused by computer roundoff and truncation errors.

APPENDIX E

OPTIMAL MEASUREMENT UNCERTAINTIES

Tables E-I through E-XXXVI list measurement uncertainties for each UPAA that will meet the performance goals specified in Sec. I of the main text. These uncertainties are a result of optimization calculations. They yield materials loss-detection sensitivities that meet a given performance objective while minimizing total instrument systems development cost. These results are discussed in Sec. IV of the main text.

TABLE E-I

MEASUREMENT UNCERTAINTIES: UPAA 1, GOAL 1, NO RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε INVENTORY - DISASSEMBLY	3.96-2	4.00-2	8.17-1	8.17-1	9.02-3
2	ε INVENTORY - SHEAR	1.99-1	2.00-1	2.05	2.05	7.06-3
3	ε INVENTORY - VOLOXIDIZER	1.40-1	2.00-1	5.19	5.19	4.31-1
4	ε INVENTORY - CONTINUOUS DISSOLVER	1.67-1	2.00-1	4.49	4.49	1.96-1
5	ε VOLUME - DIGESTER	2.98-2	3.00-2	1.17	1.17	6.49-3
6	ε CONCENTRATION - DIGESTER	1.49-2	1.50-2	5.88-1	5.88-1	4.95-3
7	ε INVENTORY - HULLS	1.00-1	1.00-1	3.39-2	3.39-2	7.95-5
8	ε VOLUME - BATCH DISSOLVER	3.00-2	3.00-2	1.83-2	1.83-2	2.85-4
9	ε CONCENTRATION - BATCH DISSOLVER	1.50-2	1.50-2	9.13-3	9.13-3	7.43-4
10	ε VOLUME - ACID SURGE TANK	3.00-2	3.00-2	1.04-2	1.04-2	2.85-4
11	ε CONCENTRATION - ACID SURGE TANK	1.50-2	1.50-2	5.21-3	5.21-3	2.87-4
12	ε INVENTORY - SECONDARY DISSOLVER SURGE TANK	9.98-2	1.00-1	3.39-1	3.39-1	2.27-3
13	ε VOLUME - SECONDARY DISSOLVER	3.00-2	3.00-2	2.04-1	2.04-1	1.70-4
14	ε CONCENTRATION - SECONDARY DISSOLVER	6.95-2	7.00-2	4.72-1	4.72-1	6.51-3
15	ε VOLUME - SST	3.00-2	3.00-2	0.00	0.00	2.85-4
16	ε CONCENTRATION - SST	7.00-2	7.00-2	0.00	0.00	2.84-4
17	ε VOLUME - FEED SOLUTION SURGE TANK	2.97-2	3.00-2	2.26	2.26	9.34-3
18	ε CONCENTRATION - FEED SOLUTION SURGE TANK	1.49-2	1.50-2	1.13	1.13	6.96-3
19	ε VOLUME - ACCOUNTABILITY TANK	3.00-3	3.00-3	0.00	0.00	3.35-4
20	ε CONCENTRATION - ACCOUNTABILITY TANK	1.00-2	1.00-2	0.00	0.00	1.42-4
21	ε TRANSFER - INPUT TO DISASSEMBLY	3.29-2	4.00-2	1.36	1.66+1	2.16-1
22	η TRANSFER - INPUT TO DISASSEMBLY	2.84-3	3.00-2	3.31-1	4.96+1	9.57
23	θ TRANSFER - INPUT TO DISASSEMBLY	2.48-3	2.00-2	2.90-1	4.35+1	7.05
24	ε TRANSFER - HULLS TO HULLS WASTE	1.00-1	1.00-1	1.41-3	1.73-2	2.30-5
25	η TRANSFER - HULLS TO HULLS WASTE	5.00-2	5.00-2	2.00-3	3.00-1	3.30-4
26	θ TRANSFER - HULLS TO HULLS WASTE	4.99-2	5.00-2	2.00-3	2.99-1	1.72-3
27	ε TRANSFER - PRIMARY CENTRIFUGE TO HLW	1.00-1	1.00-1	0.00	5.88-3	2.29-5
28	η TRANSFER - PRIMARY CENTRIFUGE TO HLW	5.00-2	5.00-2	0.00	7.20-3	1.13-4
29	θ TRANSFER - PRIMARY CENTRIFUGE TO HLW	5.00-2	5.00-2	0.00	7.20-3	1.13-4
30	ε TRANSFER - SST TO HLW	1.00-1	1.00-1	1.20-3	1.47-2	2.29-5
31	η TRANSFER - SST TO HLW	4.98-2	5.00-2	5.97-4	8.96-2	4.72-3
32	θ TRANSFER - SST TO HLW	5.00-2	5.00-2	6.00-4	9.00-2	4.97-4
33	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	0.00	3.56-3	2.29-5
34	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	1.13-4
35	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	1.13-4
36	ε VOLUME - ACCOUNTABILITY TANK OUTPUT	2.98-3	3.00-3	3.31-1	4.06	7.24-3
37	η VOLUME - ACCOUNTABILITY TANK OUTPUT	9.21-4	1.00-3	1.03-1	1.54+1	8.53-2
38	θ VOLUME - ACCOUNTABILITY TANK OUTPUT	9.23-4	1.00-3	1.03-1	1.54+1	8.37-2
39	ε CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	9.58-3	1.00-2	1.07	1.31+1	4.39-2
40	η CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	1.37-3	3.00-3	1.52-1	2.28+1	1.19
41	θ CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	1.38-3	3.00-3	1.53-1	2.30+1	1.18

TABLE E-II

MEASUREMENT UNCERTAINTIES: UPAA 1, GOAL 1, WEEKLY RECALIBRATION

NO.		DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε	INVENTORY - DISASSEMBLY	4.00-2	4.00-2	8.24-1	8.24-1	6.38-4
2	ε	INVENTORY - SHEAR	2.00-1	2.00-1	2.06	2.06	2.47-3
3	ε	INVENTORY - VOLOXIDIZER	1.33-1	2.00-1	4.93	4.93	5.04-1
4	ε	INVENTORY - CONTINUOUS DISSOLVER	1.70-1	2.00-1	4.56	4.56	1.78-1
5	ε	VOLUME - DIGESTER	3.00-2	3.00-2	1.18	1.18	1.04-3
6	ε	CONCENTRATION - DIGESTER	1.50-2	1.50-2	5.90-1	5.90-1	7.53-4
7	ε	INVENTORY - HULLS	9.99-2	1.00-1	3.39-2	3.39-2	5.91-4
8	ε	VOLUME - BATCH DISSOLVER	3.00-2	3.00-2	1.83-2	1.83-2	5.77-4
9	ε	CONCENTRATION - BATCH DISSOLVER	1.50-2	1.50-2	9.13-3	9.13-3	5.78-4
10	ε	VOLUME - ACID SURGE TANK	3.00-2	3.00-2	1.04-2	1.04-2	5.78-4
11	ε	CONCENTRATION - ACID SURGE TANK	1.50-2	1.50-2	5.21-3	5.21-3	5.78-4
12	ε	INVENTORY - SECONDARY DISSOLVER SURGE TANK	9.99-2	1.00-1	3.39-1	3.39-1	6.44-4
13	ε	VOLUME - SECONDARY DISSOLVER	3.00-2	3.00-2	2.04-1	2.04-1	5.72-4
14	ε	CONCENTRATION - SECONDARY DISSOLVER	7.00-2	7.00-2	4.75-1	4.75-1	4.34-4
15	ε	VOLUME - SST	3.00-2	3.00-2	0.00	0.00	5.78-4
16	ε	CONCENTRATION - SST	7.00-2	7.00-2	0.00	0.00	5.78-4
17	ε	VOLUME - FEED SOLUTION SURGE TANK	2.99-2	3.00-2	2.27	2.27	2.72-3
18	ε	CONCENTRATION - FEED SOLUTION SURGE TANK	1.50-2	1.50-2	1.14	1.14	4.28-4
19	ε	VOLUME - ACCOUNTABILITY TANK	3.00-3	3.00-3	0.00	0.00	5.78-4
20	ε	CONCENTRATION - ACCOUNTABILITY TANK	9.99-3	1.00-2	0.00	0.00	5.75-4
21	ε	TRANSFER - INPUT TO DISASSEMBLY	3.70-2	4.00-2	1.53	1.87+1	8.01-2
22	η	TRANSFER - INPUT TO DISASSEMBLY	1.01-2	3.00-2	1.18	3.77+1	1.97
23	θ	TRANSFER - INPUT TO DISASSEMBLY	3.12-3	2.00-2	3.64-1	5.46+1	5.41
24	ε	TRANSFER - HULLS TO HULLS WASTE	9.99-2	1.00-1	1.41-3	1.73-2	5.78-4
25	η	TRANSFER - HULLS TO HULLS WASTE	5.00-2	5.00-2	2.00-3	6.41-2	5.77-4
26	θ	TRANSFER - HULLS TO HULLS WASTE	5.00-2	5.00-2	2.00-3	3.00-1	4.93-4
27	ε	TRANSFER - PRIMARY CENTRIFUGE TO HLW	9.99-2	1.00-1	0.00	5.88-3	5.78-4
28	η	TRANSFER - PRIMARY CENTRIFUGE TO HLW	5.00-2	5.00-2	0.00	7.20-3	5.78-4
29	θ	TRANSFER - PRIMARY CENTRIFUGE TO HLW	5.00-2	5.00-2	0.00	7.20-3	5.78-4
30	ε	TRANSFER - SST TO HLW	9.99-2	1.00-1	1.20-3	1.47-2	5.78-4
31	η	TRANSFER - SST TO HLW	5.00-2	5.00-2	6.00-4	1.92-2	5.78-4
32	θ	TRANSFER - SST TO HLW	5.00-2	5.00-2	6.00-4	8.99-2	5.77-4
33	ε	TRANSFER - HA CENTRIFUGE TO SST	9.99-2	1.00-1	0.00	3.56-3	5.78-4
34	η	TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	5.85-4
35	θ	TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	5.78-4
36	ε	VOLUME - ACCOUNTABILITY TANK OUTPUT	2.99-3	3.00-3	3.33-1	4.08	2.86-3
37	η	VOLUME - ACCOUNTABILITY TANK OUTPUT	9.94-4	1.00-3	1.11-1	1.66+1	6.00-3
38	θ	VOLUME - ACCOUNTABILITY TANK OUTPUT	9.94-4	1.00-3	1.11-1	1.66+1	6.39-3
39	ε	CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	9.93-3	1.00-2	1.10	1.35+1	7.46-3
40	η	CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	2.99-3	3.00-3	3.33-1	1.07+1	3.49-3
41	θ	CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	1.61-3	3.00-3	1.79-1	2.68+1	8.68-1

TABLE E-III

MEASUREMENT UNCERTAINTIES: UPAA 1, GOAL 2, NO RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε INVENTORY - DISASSEMBLY	3.61-2	4.00-2	7.45-1	7.45-1	1.07-1
2	ε INVENTORY - SHEAR	1.35-1	2.00-1	1.39	1.39	4.79-1
3	ε INVENTORY - VOLOXIDIZER	5.70-2	2.00-1	2.11	2.11	2.51
4	ε INVENTORY - CONTINUOUS DISSOLVER	7.18-2	2.00-1	1.93	1.93	1.79
5	ε VOLUME - DIGESTER	2.62-2	3.00-2	1.03	1.03	1.43-1
6	ε CONCENTRATION - DIGESTER	1.46-2	1.50-2	5.74-1	5.74-1	2.83-2
7	ε INVENTORY - HULLS	1.00-1	1.00-1	3.39-2	3.39-2	4.26-5
8	ε VOLUME - BATCH DISSOLVER	3.00-2	3.00-2	1.83-2	1.83-2	4.96-5
9	ε CONCENTRATION - BATCH DISSOLVER	1.50-2	1.50-2	9.13-3	9.13-3	3.65-6
10	ε VOLUME - ACID SURGE TANK	3.00-2	3.00-2	1.04-2	1.04-2	8.14-6
11	ε CONCENTRATION - ACID SURGE TANK	1.50-2	1.50-2	5.22-3	5.22-3	1.14-5
12	ε INVENTORY - SECONDARY DISSOLVER SURGE TANK	1.00-1	1.00-1	3.39-1	3.39-1	4.58-4
13	ε VOLUME - SECONDARY DISSOLVER	3.00-2	3.00-2	2.03-1	2.03-1	7.47-4
14	ε CONCENTRATION - SECONDARY DISSOLVER	6.69-2	7.00-2	4.54-1	4.54-1	4.66-2
15	ε VOLUME - SST	3.00-2	3.00-2	0.00	0.00	4.00-5
16	ε CONCENTRATION - SST	7.00-2	7.00-2	0.00	0.00	2.29-5
17	ε VOLUME - FEED SOLUTION SURGE TANK	1.85-2	3.00-2	1.41	1.41	6.18-1
18	ε CONCENTRATION - FEED SOLUTION SURGE TANK	1.30-2	1.50-2	9.91-1	9.91-1	1.50-1
19	ε VOLUME - ACCOUNTABILITY TANK	3.00-3	3.00-3	0.00	0.00	3.47-5
20	ε CONCENTRATION - ACCOUNTABILITY TANK	1.00-2	1.00-2	0.00	0.00	3.97-5
21	ε TRANSFER - INPUT TO DISASSEMBLY	8.82-3	4.00-2	3.64-1	4.46	3.53
22	η TRANSFER - INPUT TO DISASSEMBLY	6.87-4	3.00-2	8.01-2	1.20+1	4.27+1
23	θ TRANSFER - INPUT TO DISASSEMBLY	6.01-4	2.00-2	7.01-2	1.05+1	3.23+1
24	ε TRANSFER - HULLS TO HULLS WASTE	1.00-1	1.00-1	1.41-3	1.73-2	3.71-7
25	η TRANSFER - HULLS TO HULLS WASTE	4.98-2	5.00-2	1.99-3	2.99-1	3.66-3
26	θ TRANSFER - HULLS TO HULLS WASTE	4.99-2	5.00-2	1.99-3	2.99-1	2.96-3
27	ε TRANSFER - PRIMARY CENTRIFUGE TO HLW	1.00-1	1.00-1	0.00	5.88-3	1.59-5
28	η TRANSFER - PRIMARY CENTRIFUGE TO HLW	5.00-2	5.00-2	0.00	7.20-3	1.94-5
29	θ TRANSFER - PRIMARY CENTRIFUGE TO HLW	5.00-2	5.00-2	0.00	7.20-3	1.87-5
30	ε TRANSFER - SST TO HLW	1.00-1	1.00-1	1.20-3	1.47-2	5.81-5
31	η TRANSFER - SST TO HLW	5.00-2	5.00-2	6.00-4	9.00-2	3.97-4
32	θ TRANSFER - SST TO HLW	5.00-2	5.00-2	6.00-4	9.00-2	1.25-4
33	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	0.00	3.56-3	8.06-6
34	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	2.50-5
35	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	4.32-6
36	ε VOLUME - ACCOUNTABILITY TANK OUTPUT	1.81-3	3.00-3	2.02-1	2.47	6.53-1
37	η VOLUME - ACCOUNTABILITY TANK OUTPUT	2.31-4	1.00-3	2.57-2	3.85	3.33
38	θ VOLUME - ACCOUNTABILITY TANK OUTPUT	2.31-4	1.00-3	2.57-2	3.86	3.32
39	ε CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	2.63-3	1.00-2	2.92-1	3.58	2.81
40	η CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	3.31-4	3.00-3	3.68-2	5.52	8.07
41	θ CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	3.31-4	3.00-3	3.68-2	5.52	8.07

TABLE E-IV

MEASUREMENT UNCERTAINTIES: UPAA 1, GOAL 2, WEEKLY RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε INVENTORY - DISASSEMBLY	3.79-2	4.00-2	7.81-1	7.81-1	5.62-2
2	ε INVENTORY - SHEAR	1.33-1	2.00-1	1.37	1.37	5.03-1
3	ε INVENTORY - VOLOXIDIZER	5.76-2	2.00-1	2.14	2.14	2.47
4	ε INVENTORY - CONTINUOUS DISSOLVER	7.14-2	2.00-1	1.92	1.92	1.80
5	ε VOLUME - DIGESTER	2.68-2	3.00-2	1.06	1.06	1.19-1
6	ε CONCENTRATION - DIGESTER	1.50-2	1.50-2	5.90-1	5.90-1	1.24-3
7	ε INVENTORY - HULLS	1.00-1	1.00-1	3.39-2	3.39-2	5.30-6
8	ε VOLUME - BATCH DISSOLVER	3.00-2	3.00-2	1.83-2	1.83-2	1.57-5
9	ε CONCENTRATION - BATCH DISSOLVER	1.50-2	1.50-2	9.13-3	9.13-3	4.27-5
10	ε VOLUME - ACID SURGE TANK	3.00-2	3.00-2	1.04-2	1.04-2	4.79-5
11	ε CONCENTRATION - ACID SURGE TANK	1.50-2	1.50-2	5.22-3	5.22-3	3.23-5
12	ε INVENTORY - SECONDARY DISSOLVER SURGE TANK	1.00-1	1.00-1	3.39-1	3.39-1	2.78-4
13	ε VOLUME - SECONDARY DISSOLVER	3.00-2	3.00-2	2.04-1	2.04-1	6.60-5
14	ε CONCENTRATION - SECONDARY DISSOLVER	6.99-2	7.00-2	4.75-1	4.75-1	1.20-3
15	ε VOLUME - SST	3.00-2	3.00-2	0.00	0.00	3.34-5
16	ε CONCENTRATION - SST	7.00-2	7.00-2	0.00	0.00	3.34-5
17	ε VOLUME - FEED SOLUTION SURGE TANK	1.85-2	3.00-2	1.40	1.40	6.24-1
18	ε CONCENTRATION - FEED SOLUTION SURGE TANK	1.32-2	1.50-2	1.01	1.01	1.33-1
19	ε VOLUME - ACCOUNTABILITY TANK	3.00-3	3.00-3	0.00	0.00	1.52-5
20	ε CONCENTRATION - ACCOUNTABILITY TANK	1.00-2	1.00-2	0.00	0.00	3.27-5
21	ε TRANSFER - INPUT TO DISASSEMBLY	9.84-3	4.00-2	4.06-1	4.97	3.07
22	η TRANSFER - INPUT TO DISASSEMBLY	2.34-3	3.00-2	2.73-1	8.74	1.18+1
23	θ TRANSFER - INPUT TO DISASSEMBLY	7.09-4	2.00-2	8.27-2	1.24+1	2.72+1
24	ε TRANSFER - HULLS TO HULLS WASTE	1.00-1	1.00-1	1.41-3	1.73-2	3.39-5
25	η TRANSFER - HULLS TO HULLS WASTE	5.00-2	5.00-2	2.00-3	6.42-2	4.93-5
26	θ TRANSFER - HULLS TO HULLS WASTE	5.00-2	5.00-2	2.00-3	3.00-1	4.51-4
27	ε TRANSFER - PRIMARY CENTRIFUGE TO HLW	1.00-1	1.00-1	0.00	5.88-3	3.36-5
28	η TRANSFER - PRIMARY CENTRIFUGE TO HLW	5.00-2	5.00-2	0.00	7.20-3	3.36-5
29	θ TRANSFER - PRIMARY CENTRIFUGE TO HLW	5.00-2	5.00-2	0.00	7.20-3	3.36-5
30	ε TRANSFER - SST TO HLW	1.00-1	1.00-1	1.20-3	1.47-2	3.38-5
31	η TRANSFER - SST TO HLW	5.00-2	5.00-2	6.00-4	1.92-2	2.93-5
32	θ TRANSFER - SST TO HLW	5.00-2	5.00-2	6.00-4	9.00-2	2.96-5
33	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	0.00	3.56-3	3.35-5
34	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	3.37-5
35	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	3.36-5
36	ε VOLUME - ACCOUNTABILITY TANK OUTPUT	2.09-3	3.00-3	2.32-1	2.84	4.39-1
37	η VOLUME - ACCOUNTABILITY TANK OUTPUT	2.79-4	1.00-3	3.10-2	4.66	2.58
38	θ VOLUME - ACCOUNTABILITY TANK OUTPUT	2.76-4	1.00-3	3.07-2	4.60	2.63
39	ε CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	3.12-3	1.00-2	3.47-1	4.26	2.20
40	η CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	1.11-3	3.00-3	1.24-1	3.98	1.69
41	θ CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	3.99-4	3.00-3	4.44-2	6.65	6.53

TABLE E-V

MEASUREMENT UNCERTAINTIES: UPAA 1, GOAL 2, DAILY RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε INVENTORY - DISASSEMBLY	3.86-2	4.00-2	7.95-1	7.95-1	3.71-2
2	ε INVENTORY - SHEAR	1.31-1	2.00-1	1.35	1.35	5.23-1
3	ε INVENTORY - VOLOXIDIZER	5.45-2	2.00-1	2.02	2.02	2.67
4	ε INVENTORY - CONTINUOUS DISSOLVER	7.27-2	2.00-1	1.95	1.95	1.75
5	ε VOLUME - DIGESTER	2.65-2	3.00-2	1.04	1.04	1.33-1
6	ε CONCENTRATION - DIGESTER	1.50-2	1.50-2	5.90-1	5.90-1	1.10-3
7	ε INVENTORY - HULLS	1.00-1	1.00-1	3.39-2	3.39-2	6.71-5
8	ε VOLUME - BATCH DISSOLVER	3.00-2	3.00-2	1.83-2	1.83-2	6.87-5
9	ε CONCENTRATION - BATCH DISSOLVER	1.50-2	1.50-2	9.13-3	9.13-3	6.50-5
10	ε VOLUME - ACID SURGE TANK	3.00-2	3.00-2	1.04-2	1.04-2	6.51-5
11	ε CONCENTRATION - ACID SURGE TANK	1.50-2	1.50-2	5.22-3	5.22-3	6.34-5
12	ε INVENTORY - SECONDARY DISSOLVER SURGE TANK	1.00-1	1.00-1	3.39-1	3.39-1	3.26-5
13	ε VOLUME - SECONDARY DISSOLVER	3.00-2	3.00-2	2.04-1	2.04-1	7.23-5
14	ε CONCENTRATION - SECONDARY DISSOLVER	7.00-2	7.00-2	4.75-1	4.75-1	2.00-4
15	ε VOLUME - SST	3.00-2	3.00-2	0.00	0.00	6.35-5
16	ε CONCENTRATION - SST	7.00-2	7.00-2	0.00	0.00	6.30-5
17	ε VOLUME - FEED SOLUTION SURGE TANK	1.88-2	3.00-2	1.43	1.43	5.97-1
18	ε CONCENTRATION - FEED SOLUTION SURGE TANK	1.34-2	1.50-2	1.02	1.02	1.21-1
19	ε VOLUME - ACCOUNTABILITY TANK	3.00-3	3.00-3	0.00	0.00	4.99-5
20	ε CONCENTRATION - ACCOUNTABILITY TANK	1.00-2	1.00-2	0.00	0.00	6.30-5
21	ε TRANSFER - INPUT TO DISASSEMBLY	1.03-2	4.00-2	4.23-1	5.10	2.90
22	η TRANSFER - INPUT TO DISASSEMBLY	4.70-3	3.00-2	5.48-1	6.71	5.38
23	θ TRANSFER - INPUT TO DISASSEMBLY	7.60-4	2.00-2	8.86-2	1.33+1	2.53+1
24	ε TRANSFER - HULLS TO HULLS WASTE	1.00-1	1.00-1	1.41-3	1.73-2	6.52-5
25	η TRANSFER - HULLS TO HULLS WASTE	5.00-2	5.00-2	2.00-3	2.45-2	6.47-5
26	θ TRANSFER - HULLS TO HULLS WASTE	5.00-2	5.00-2	2.00-3	3.00-1	2.51-5
27	ε TRANSFER - PRIMARY CENTRIFUGE TO HLW	1.00-1	1.00-1	0.00	5.88-3	6.38-5
28	η TRANSFER - PRIMARY CENTRIFUGE TO HLW	5.00-2	5.00-2	0.00	7.20-3	6.40-5
29	θ TRANSFER - PRIMARY CENTRIFUGE TO HLW	5.00-2	5.00-2	0.00	7.20-3	6.41-5
30	ε TRANSFER - SST TO HLW	1.00-1	1.00-1	1.20-3	1.47-2	6.42-5
31	η TRANSFER - SST TO HLW	5.00-2	5.00-2	6.00-4	7.35-3	6.38-5
32	θ TRANSFER - SST TO HLW	5.00-2	5.00-2	6.00-4	9.00-2	4.00-5
33	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	0.00	3.56-3	6.34-5
34	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	6.46-5
35	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	6.44-5
36	ε VOLUME - ACCOUNTABILITY TANK OUTPUT	2.16-3	3.00-3	2.40-1	2.94	3.91-1
37	η VOLUME - ACCOUNTABILITY TANK OUTPUT	2.88-4	1.00-3	3.20-2	4.81	2.47
38	θ VOLUME - ACCOUNTABILITY TANK OUTPUT	2.93-4	1.00-3	3.26-2	4.90	2.41
39	ε CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	3.30-3	1.00-2	3.68-1	4.50	2.03
40	η CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	2.22-3	3.00-3	2.47-1	3.02	3.53-1
41	θ CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	4.27-4	3.00-3	4.75-2	7.13	6.02

TABLE E-VI

MEASUREMENT UNCERTAINTIES: UPAA 1, GOAL 3, NO RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε INVENTORY - DISASSEMBLY	8.43-3	4.00-2	1.74-1	1.74-1	3.74
2	ε INVENTORY - SHEAR	2.33-2	2.00-1	2.40-1	2.40-1	7.60
3	ε INVENTORY - VOLOXIDIZER	8.08-3	2.00-1	3.00-1	3.00-1	2.38+1
4	ε INVENTORY - CONTINUOUS DISSOLVER	1.06-2	2.00-1	2.86-1	2.86-1	1.78+1
5	ε VOLUME - DIGESTER	4.23-3	3.00-2	1.67-1	1.67-1	6.09
6	ε CONCENTRATION - DIGESTER	3.45-3	1.50-2	1.36-1	1.36-1	3.34
7	ε INVENTORY - HULLS	1.00-1	1.00-1	3.39-2	3.39-2	3.79-5
8	ε VOLUME - BATCH DISSOLVER	3.00-2	3.00-2	1.83-2	1.83-2	2.39-5
9	ε CONCENTRATION - BATCH DISSOLVER	1.50-2	1.50-2	9.13-3	9.13-3	1.41-5
10	ε VOLUME - ACID SURGE TANK	3.00-2	3.00-2	1.04-2	1.04-2	4.35-5
11	ε CONCENTRATION - ACID SURGE TANK	1.50-2	1.50-2	5.22-3	5.22-3	7.55-6
12	ε INVENTORY - SECONDARY DISSOLVER SURGE TANK	3.49-2	1.00-1	1.18-1	1.18-1	1.87
13	ε VOLUME - SECONDARY DISSOLVER	1.46-2	3.00-2	9.91-2	9.91-2	1.06
14	ε CONCENTRATION - SECONDARY DISSOLVER	1.96-2	7.00-2	1.33-1	1.33-1	2.57
15	ε VOLUME - SST	3.00-2	3.00-2	0.00	0.00	2.76-5
16	ε CONCENTRATION - SST	7.00-2	7.00-2	0.00	0.00	2.76-5
17	ε VOLUME - FEED SOLUTION SURGE TANK	2.75-3	3.00-2	2.09-1	2.09-1	9.91
18	ε CONCENTRATION - FEED SOLUTION SURGE TANK	2.19-3	1.50-2	1.66-1	1.66-1	5.84
19	ε VOLUME - ACCOUNTABILITY TANK	3.00-3	3.00-3	0.00	0.00	1.80-5
20	ε CONCENTRATION - ACCOUNTABILITY TANK	1.00-2	1.00-2	0.00	0.00	1.75-5
21	ε TRANSFER - INPUT TO DISASSEMBLY	6.14-4	4.00-2	6.70-2	4.39-1	6.41+1
22	η TRANSFER - INPUT TO DISASSEMBLY	4.13-5	3.00-2	3.37-2	1.44	7.26+2
23	θ TRANSFER - INPUT TO DISASSEMBLY	3.61-5	2.00-2	2.95-2	1.26	5.53+2
24	ε TRANSFER - HULLS TO HULLS WASTE	1.00-1	1.00-1	3.74-3	2.45-2	8.32-7
25	η TRANSFER - HULLS TO HULLS WASTE	1.13-2	5.00-2	3.17-3	1.36-1	3.42
26	θ TRANSFER - HULLS TO HULLS WASTE	1.15-2	5.00-2	3.22-3	1.38-1	3.35
27	ε TRANSFER - PRIMARY CENTRIFUGE TO HLW	1.00-1	1.00-1	2.40-3	8.31-3	4.71-5
28	η TRANSFER - PRIMARY CENTRIFUGE TO HLW	5.00-2	5.00-2	1.20-3	1.44-2	1.27-6
29	θ TRANSFER - PRIMARY CENTRIFUGE TO HLW	5.00-2	5.00-2	1.20-3	1.44-2	3.33-5
30	ε TRANSFER - SST TO HLW	1.00-1	1.00-1	3.17-3	2.08-2	2.04-5
31	η TRANSFER - SST TO HLW	2.71-2	5.00-2	2.28-3	9.75-2	8.45-1
32	θ TRANSFER - SST TO HLW	2.56-2	5.00-2	2.15-3	9.21-2	9.54-1
33	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	7.60-4	5.04-3	3.81-5
34	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	3.80-4	1.67-2	2.73-5
35	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	3.80-4	1.67-2	3.58-5
36	ε VOLUME - ACCOUNTABILITY TANK OUTPUT	1.37-4	3.00-3	4.03-2	2.64-1	2.09+1
37	η VOLUME - ACCOUNTABILITY TANK OUTPUT	1.38-5	1.00-3	1.08-2	4.62-1	7.12+1
38	θ VOLUME - ACCOUNTABILITY TANK OUTPUT	1.38-5	1.00-3	1.08-2	4.62-1	7.13+1
39	ε CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	2.00-4	1.00-2	5.90-2	3.86-1	4.89+1
40	η CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	1.99-5	3.00-3	1.55-2	6.63-1	1.50+2
41	θ CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	1.99-5	3.00-3	1.55-2	6.63-1	1.50+2

TABLE E-VII

MEASUREMENT UNCERTAINTIES: UPAA 1, GOAL 3, DAILY RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε INVENTORY - DISASSEMBLY	8.67-3	4.00-2	1.79-1	1.79-1	3.61
2	ε INVENTORY - SHEAR	2.34-2	2.00-1	2.41-1	2.41-1	7.57
3	ε INVENTORY - VOLOXIDIZER	9.86-3	2.00-1	3.66-1	3.66-1	1.93+1
4	ε INVENTORY - CONTINUOUS DISSOLVER	1.20-2	2.00-1	3.22-1	3.22-1	1.57+1
5	ε VOLUME - DIGESTER	5.20-3	3.00-2	2.05-1	2.05-1	4.77
6	ε CONCENTRATION - DIGESTER	4.01-3	1.50-2	1.58-1	1.58-1	2.74
7	ε INVENTORY - HULLS	9.99-2	1.00-1	3.39-2	3.39-2	5.62-4
8	ε VOLUME - BATCH DISSOLVER	3.00-2	3.00-2	1.82-2	1.82-2	1.41-3
9	ε CONCENTRATION - BATCH DISSOLVER	1.50-2	1.50-2	9.12-3	9.12-3	1.46-3
10	ε VOLUME - ACID SURGE TANK	2.99-2	3.00-2	1.04-2	1.04-2	2.52-3
11	ε CONCENTRATION - ACID SURGE TANK	1.50-2	1.50-2	5.21-3	5.21-3	1.69-3
12	ε INVENTORY - SECONDARY DISSOLVER SURGE TANK	3.86-2	1.00-1	1.31-1	1.31-1	1.59
13	ε VOLUME - SECONDARY DISSOLVER	1.58-2	3.00-2	1.07-1	1.07-1	8.98-1
14	ε CONCENTRATION - SECONDARY DISSOLVER	2.14-2	7.00-2	1.45-1	1.45-1	2.28
15	ε VOLUME - SST	3.00-2	3.00-2	0.00	0.00	4.86-4
16	ε CONCENTRATION - SST	7.00-2	7.00-2	0.00	0.00	4.86-4
17	ε VOLUME - FEED SOLUTION SURGE TANK	3.45-3	3.00-2	2.62-1	2.62-1	7.69
18	ε CONCENTRATION - FEED SOLUTION SURGE TANK	2.65-3	1.50-2	2.02-1	2.02-1	4.65
19	ε VOLUME - ACCOUNTABILITY TANK	3.00-3	3.00-3	0.00	0.00	5.14-4
20	ε CONCENTRATION - ACCOUNTABILITY TANK	1.00-2	1.00-2	0.00	0.00	4.86-4
21	ε TRANSFER - INPUT TO DISASSEMBLY	7.79-4	4.00-2	8.50-2	5.56-1	5.03+1
22	η TRANSFER - INPUT TO DISASSEMBLY	3.54-4	3.00-2	1.09-1	7.15-1	8.37+1
23	θ TRANSFER - INPUT TO DISASSEMBLY	4.60-5	2.00-2	3.75-2	1.61	4.34+2
24	ε TRANSFER - HULLS TO HULLS WASTE	9.99-2	1.00-1	3.74-3	2.45-2	1.16-3
25	η TRANSFER - HULLS TO HULLS WASTE	4.66-2	5.00-2	4.93-3	3.23-2	7.24-2
26	θ TRANSFER - HULLS TO HULLS WASTE	1.35-2	5.00-2	3.77-3	1.62-1	2.71
27	ε TRANSFER - PRIMARY CENTRIFUGE TO HLW	9.95-2	1.00-1	2.39-3	8.27-3	4.97-3
28	η TRANSFER - PRIMARY CENTRIFUGE TO HLW	4.98-2	5.00-2	1.19-3	1.43-2	4.87-3
29	θ TRANSFER - PRIMARY CENTRIFUGE TO HLW	4.97-2	5.00-2	1.19-3	1.43-2	6.14-3
30	ε TRANSFER - SST TO HLW	9.43-2	1.00-1	3.00-3	1.96-2	6.00-2
31	η TRANSFER - SST TO HLW	4.98-2	5.00-2	1.58-3	1.03-2	4.18-3
32	θ TRANSFER - SST TO HLW	2.91-2	5.00-2	2.45-3	1.05-1	7.16-1
33	ε TRANSFER - HA CENTRIFUGE TO SST	9.96-2	1.00-1	7.57-4	5.02-3	4.23-3
34	η TRANSFER - HA CENTRIFUGE TO SST	4.87-2	5.00-2	3.70-4	1.63-2	2.68-2
35	θ TRANSFER - HA CENTRIFUGE TO SST	4.91-2	5.00-2	3.73-4	1.64-2	1.80-2
36	ε VOLUME - ACCOUNTABILITY TANK OUTPUT	1.76-4	3.00-3	5.17-2	3.39-1	1.61+1
37	η VOLUME - ACCOUNTABILITY TANK OUTPUT	1.77-5	1.00-3	1.38-2	5.90-1	5.56+1
38	θ VOLUME - ACCOUNTABILITY TANK OUTPUT	1.76-5	1.00-3	1.37-2	5.87-1	5.59+1
39	ε CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	2.55-4	1.00-2	7.52-2	4.92-1	3.81+1
40	η CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	1.71-4	3.00-3	5.02-2	3.29-1	1.66+1
41	θ CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	2.52-5	3.00-3	1.97-2	8.43-1	1.18+2

TABLE E-VIII

MEASUREMENT UNCERTAINTIES: UPAA 1, GOAL 4, NO RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε INVENTORY - DISASSEMBLY	3.30-3	4.00-2	6.80-2	6.80-2	1.11+1
2	ε INVENTORY - SHEAR	1.01-2	2.00-1	1.04-1	1.04-1	1.88+1
3	ε INVENTORY - VOLOXIDIZER	4.38-3	2.00-1	1.63-1	1.63-1	4.47+1
4	ε INVENTORY - CONTINUOUS DISSOLVER	4.58-3	2.00-1	1.23-1	1.23-1	4.27+1
5	ε VOLUME - DIGESTER	1.94-3	3.00-2	7.62-2	7.62-2	1.45+1
6	ε CONCENTRATION - DIGESTER	2.12-3	1.50-2	8.33-2	8.33-2	6.09
7	ε INVENTORY - HULLS	8.70-2	1.00-1	2.95-2	2.95-2	1.49-1
8	ε VOLUME - BATCH DISSOLVER	2.71-2	3.00-2	1.65-2	1.65-2	1.07-1
9	ε CONCENTRATION - BATCH DISSOLVER	1.46-2	1.50-2	8.87-3	8.87-3	2.94-2
10	ε VOLUME - ACID SURGE TANK	2.80-2	3.00-2	9.75-3	9.75-3	7.00-2
11	ε CONCENTRATION - ACID SURGE TANK	1.49-2	1.50-2	5.17-3	5.17-3	9.14-3
12	ε INVENTORY - SECONDARY DISSOLVER SURGE TANK	1.75-2	1.00-1	5.94-2	5.94-2	4.71
13	ε VOLUME - SECONDARY DISSOLVER	6.93-3	3.00-2	4.70-2	4.70-2	3.33
14	ε CONCENTRATION - SECONDARY DISSOLVER	9.59-3	7.00-2	6.51-2	6.51-2	6.30
15	ε VOLUME - SST	3.00-2	3.00-2	0.00	0.00	1.64-3
16	ε CONCENTRATION - SST	6.99-2	7.00-2	0.00	0.00	1.58-3
17	ε VOLUME - FEED SOLUTION SURGE TANK	1.31-3	3.00-2	9.94-2	9.94-2	2.19+1
18	ε CONCENTRATION - FEED SOLUTION SURGE TANK	1.15-3	1.50-2	8.74-2	8.74-2	1.20+1
19	ε VOLUME - ACCOUNTABILITY TANK	2.99-3	3.00-3	0.00	0.00	1.87-3
20	ε CONCENTRATION - ACCOUNTABILITY TANK	9.98-3	1.00-2	0.00	0.00	1.84-3
21	ε TRANSFER - INPUT TO DISASSEMBLY	3.94-4	4.00-2	1.62-2	1.99-1	1.01+2
22	η TRANSFER - INPUT TO DISASSEMBLY	3.31-5	3.00-2	3.86-3	5.79-1	9.05+2
23	θ TRANSFER - INPUT TO DISASSEMBLY	2.76-5	2.00-2	3.22-3	4.83-1	7.24+2
24	ε TRANSFER - HULLS TO HULLS WASTE	9.14-2	1.00-1	1.29-3	1.58-2	9.44-2
25	η TRANSFER - HULLS TO HULLS WASTE	9.73-3	5.00-2	3.89-4	5.84-2	4.14
26	θ TRANSFER - HULLS TO HULLS WASTE	8.23-3	5.00-2	3.29-4	4.94-2	5.08
27	ε TRANSFER - PRIMARY CENTRIFUGE TO HLW	1.00-1	1.00-1	0.00	5.88-3	9.07-5
28	η TRANSFER - PRIMARY CENTRIFUGE TO HLW	4.71-2	5.00-2	0.00	6.78-3	6.13-2
29	θ TRANSFER - PRIMARY CENTRIFUGE TO HLW	4.63-2	5.00-2	0.00	6.67-3	7.92-2
30	ε TRANSFER - SST TO HLW	9.08-2	1.00-1	1.09-3	1.33-2	1.02-1
31	η TRANSFER - SST TO HLW	2.19-2	5.00-2	2.62-4	3.94-2	1.29
32	θ TRANSFER - SST TO HLW	1.94-2	5.00-2	2.32-4	3.49-2	1.58
33	ε TRANSFER - HA CENTRIFUGE TO SST	9.84-2	1.00-1	0.00	3.51-3	1.67-2
34	η TRANSFER - HA CENTRIFUGE TO SST	4.75-2	5.00-2	0.00	7.94-3	5.35-2
35	θ TRANSFER - HA CENTRIFUGE TO SST	4.66-2	5.00-2	0.00	7.79-3	7.27-2
36	ε VOLUME - ACCOUNTABILITY TANK OUTPUT	9.17-5	3.00-3	1.02-2	1.25-1	3.17+1
37	η VOLUME - ACCOUNTABILITY TANK OUTPUT	1.20-5	1.00-3	1.34-3	2.01-1	8.20+1
38	θ VOLUME - ACCOUNTABILITY TANK OUTPUT	1.27-5	1.00-3	1.41-3	2.11-1	7.80+1
39	ε CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	1.56-4	1.00-2	1.74-2	2.13-1	6.29+1
40	η CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	1.65-5	3.00-3	1.83-3	2.75-1	1.81+2
41	θ CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	1.50-5	3.00-3	1.67-3	2.50-1	1.99+2

TABLE E-IX

MEASUREMENT UNCERTAINTIES: UPAA 1, GOAL 4, DAILY RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε INVENTORY - DISASSEMBLY	4.56-3	4.00-2	9.40-2	9.40-2	7.78
2	ε INVENTORY - SHEAR	1.20-2	2.00-1	1.23-1	1.23-1	1.57+1
3	ε INVENTORY - VOLOXIDIZER	5.18-3	2.00-1	1.92-1	1.92-1	3.76+1
4	ε INVENTORY - CONTINUOUS DISSOLVER	6.18-3	2.00-1	1.66-1	1.66-1	3.14+1
5	ε VOLUME - DIGESTER	2.65-3	3.00-2	1.04-1	1.04-1	1.03+1
6	ε CONCENTRATION - DIGESTER	2.20-3	1.50-2	8.66-2	8.66-2	5.82
7	ε INVENTORY - HULLS	9.37-2	1.00-1	3.18-2	3.18-2	6.68-2
8	ε VOLUME - BATCH DISSOLVER	3.00-2	3.00-2	1.83-2	1.83-2	4.51-4
9	ε CONCENTRATION - BATCH DISSOLVER	1.50-2	1.50-2	9.13-3	9.13-3	3.84-6
10	ε VOLUME - ACID SURGE TANK	3.00-2	3.00-2	1.04-2	1.04-2	9.95-14
11	ε CONCENTRATION - ACID SURGE TANK	1.50-2	1.50-2	5.21-3	5.21-3	4.90-4
12	ε INVENTORY - SECONDARY DISSOLVER SURGE TANK	2.02-2	1.00-1	6.85-2	6.85-2	3.96
13	ε VOLUME - SECONDARY DISSOLVER	9.80-3	3.00-2	6.65-2	6.65-2	2.06
14	ε CONCENTRATION - SECONDARY DISSOLVER	1.13-2	7.00-2	7.70-2	7.70-2	5.17
15	ε VOLUME - SST	3.00-2	3.00-2	0.00	0.00	4.73-4
16	ε CONCENTRATION - SST	7.00-2	7.00-2	0.00	0.00	4.98-4
17	ε VOLUME - FEED SOLUTION SURGE TANK	1.78-3	3.00-2	1.35-1	1.35-1	1.59+1
18	ε CONCENTRATION - FEED SOLUTION SURGE TANK	1.40-3	1.50-2	1.06-1	1.06-1	9.73
19	ε VOLUME - ACCOUNTABILITY TANK	3.00-3	3.00-3	0.00	0.00	4.87-4
20	ε CONCENTRATION - ACCOUNTABILITY TANK	1.00-2	1.00-2	0.00	0.00	4.99-4
21	ε TRANSFER - INPUT TO DISASSEMBLY	4.94-4	4.00-2	2.04-2	2.49-1	8.00+1
22	η TRANSFER - INPUT TO DISASSEMBLY	2.11-4	3.00-2	2.46-2	3.02-1	1.41+2
23	θ TRANSFER - INPUT TO DISASSEMBLY	3.41-5	2.00-2	3.98-3	5.97-1	5.86+2
24	ε TRANSFER - HULLS TO HULLS WASTE	1.00-1	1.00-1	1.41-3	1.73-2	6.38-5
25	η TRANSFER - HULLS TO HULLS WASTE	4.86-2	5.00-2	1.94-3	2.38-2	2.93-2
26	θ TRANSFER - HULLS TO HULLS WASTE	1.23-2	5.00-2	4.91-4	7.36-2	3.08
27	ε TRANSFER - PRIMARY CENTRIFUGE TO HLW	1.00-1	1.00-1	0.00	5.88-3	2.48-6
28	η TRANSFER - PRIMARY CENTRIFUGE TO HLW	5.06-2	5.00-2	0.00	7.28-3	1.16-2
29	θ TRANSFER - PRIMARY CENTRIFUGE TO HLW	5.12-2	5.00-2	0.00	7.37-3	2.29-2
30	ε TRANSFER - SST TO HLW	1.03-1	1.00-1	1.23-3	1.51-2	2.65-2
31	η TRANSFER - SST TO HLW	5.00-2	5.00-2	6.00-4	7.35-3	5.07-4
32	θ TRANSFER - SST TO HLW	2.15-2	5.00-2	2.58-4	3.87-2	1.33
33	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	0.00	3.56-3	8.95-6
34	η TRANSFER - HA CENTRIFUGE TO SST	5.02-2	5.00-2	0.00	8.39-3	3.08-3
35	θ TRANSFER - HA CENTRIFUGE TO SST	5.12-2	5.00-2	0.00	8.56-3	2.39-2
36	ε VOLUME - ACCOUNTABILITY TANK OUTPUT	1.20-4	3.00-3	1.33-2	1.63-1	2.40+1
37	η VOLUME - ACCOUNTABILITY TANK OUTPUT	1.45-5	1.00-3	1.61-3	2.42-1	6.80+1
38	θ VOLUME - ACCOUNTABILITY TANK OUTPUT	1.42-5	1.00-3	1.58-3	2.37-1	6.94+1
39	ε CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	1.66-4	1.00-2	1.85-2	2.26-1	5.93+1
40	η CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	1.14-4	3.00-3	1.27-2	1.56-1	2.52+1
41	θ CONCENTRATION - ACCOUNTABILITY TANK OUTPUT	2.01-5	3.00-3	2.24-3	3.36-1	1.48+2

TABLE E-X

MEASUREMENT UNCERTAINTIES: UPAA 2 3, GOAL 1, NO RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - FEED ADJUSTMENT TANK	3.00-2	3.00-2	0.00	0.00	2.99-5
2	ε CONCENTRATION - FEED ADJUSTMENT TANK	1.50-2	1.50-2	0.00	0.00	3.03-5
3	ε VOLUME - HA FEED TANK	2.99-2	3.00-2	4.71	4.71	2.74-3
4	ε CONCENTRATION - HA FEED TANK	1.50-2	1.50-2	2.36	2.36	4.47-6
5	ε Pu SOLIDS - HA CENTRIFUGE	2.00-1	2.00-1	1.06-3	1.06-3	4.60-5
6	ε INVENTORY - HA CONTACTOR	2.00-1	2.00-1	1.13-1	1.13-1	4.87-5
7	ε INVENTORY - HS COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	2.70-5
8	ε INVENTORY - HC COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	2.70-5
9	ε VOLUME - HCP REDUCER	3.00-2	3.00-2	6.38-1	6.38-1	2.56-5
10	ε CONCENTRATION - HCP REDUCER	1.00-2	1.00-2	2.13-1	2.13-1	2.32-5
11	ε VOLUME - 1A FEED TANK	3.00-2	3.00-2	4.68-1	4.68-1	2.55-5
12	ε CONCENTRATION - 1A FEED TANK	1.00-2	1.00-2	1.56-1	1.56-1	2.77-5
13	ε INVENTORY - 1A COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	2.77-5
14	ε VOLUME - 2A FEED TANK	2.99-2	3.00-2	4.70	4.70	2.23-3
15	ε CONCENTRATION - 2A FEED TANK	1.00-2	1.00-2	1.57	1.57	4.90-5
16	ε INVENTORY - 2A COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	2.32-5
17	ε INVENTORY - 2B COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	2.32-5
18	ε VOLUME - 3A FEED TANK	3.00-2	3.00-2	5.52-1	5.52-1	2.00-5
19	ε CONCENTRATION - 3A FEED TANK	1.00-2	1.00-2	1.84-1	1.84-1	2.51-5
20	ε INVENTORY - 3A COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	2.32-5
21	ε INVENTORY - 3B COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	2.32-5
22	ε VOLUME - Pu STRIPPER FEED	3.00-2	3.00-2	8.47-2	8.47-2	2.93-5
23	ε CONCENTRATION - Pu STRIPPER FEED	1.00-2	1.00-2	2.82-2	2.82-2	2.87-5
24	ε INVENTORY - Pu STRIPPER	1.00-1	1.00-1	5.66-1	5.66-1	8.17-5
25	ε VOLUME - Pu CONCENTRATOR	3.00-2	3.00-2	8.07-1	8.07-1	5.34-5
26	ε CONCENTRATION - Pu CONCENTRATOR	1.00-2	1.00-2	2.69-1	2.69-1	2.41-5
27	ε VOLUME - Pu CATCH TANK	3.00-2	3.00-2	0.00	0.00	2.94-5
28	ε CONCENTRATION - Pu CATCH TANK	1.00-2	1.00-2	0.00	0.00	2.99-5
29	ε VOLUME - FEED ADJUSTMENT TANK INPUT	2.98-3	3.00-3	3.31-1	4.06	7.82-3
30	η VOLUME - FEED ADJUSTMENT TANK INPUT	9.82-4	1.00-3	1.09-1	1.64+1	1.84-2
31	θ VOLUME - FEED ADJUSTMENT TANK INPUT	9.76-4	1.00-3	1.09-1	1.63+1	2.44-2
32	ε CONCENTRATION - FEED ADJUSTMENT TANK INPUT	9.80-3	1.00-2	1.09	1.34+1	2.00-2
33	η CONCENTRATION - FEED ADJUSTMENT TANK INPUT	2.42-3	3.00-3	2.69-1	4.04+1	2.40-1
34	θ CONCENTRATION - FEED ADJUSTMENT TANK INPUT	2.34-3	3.00-3	2.61-1	3.91+1	2.79-1
35	ε VOLUME - Pu SAMPLE TANK OUTPUT	3.00-3	3.00-3	2.36-1	2.89	2.98-4
36	η VOLUME - Pu SAMPLE TANK OUTPUT	9.87-4	1.00-3	1.10-1	1.65+1	1.33-2
37	θ VOLUME - Pu SAMPLE TANK OUTPUT	9.84-4	1.00-3	1.09-1	1.64+1	1.64-2
38	ε CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.99-3	3.00-3	2.35-1	2.88	2.15-3
39	η CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.85-3	2.00-3	2.06-1	3.09+1	7.86-2
40	θ CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.84-3	2.00-3	2.04-1	3.07+1	8.77-2
41	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	0.00	3.56-3	2.95-5
42	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	4.60-5
43	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	2.91-5

TABLE E-XI

MEASUREMENT UNCERTAINTIES: UPAA 2 3, GOAL 1, WEEKLY RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - FEED ADJUSTMENT TANK	3.00-2	3.00-2	0.00	0.00	0.00
2	ε CONCENTRATION - FEED ADJUSTMENT TANK	1.50-2	1.50-2	0.00	0.00	0.00
3	ε VOLUME - HA FEED TANK	3.00-2	3.00-2	4.72	4.72	0.00
4	ε CONCENTRATION - HA FEED TANK	1.50-2	1.50-2	2.36	2.36	0.00
5	ε Pu SOLIDS - HA CENTRIFUGE	2.00-1	2.00-1	1.06-3	1.06-3	0.00
6	ε INVENTORY - HA CONTACTOR	2.00-1	2.00-1	1.13-1	1.13-1	0.00
7	ε INVENTORY - HS COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	0.00
8	ε INVENTORY - HC COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	0.00
9	ε VOLUME - HCP REDUCER	3.00-2	3.00-2	6.38-1	6.38-1	0.00
10	ε CONCENTRATION - HCP REDUCER	1.00-2	1.00-2	2.13-1	2.13-1	0.00
11	ε VOLUME - 1A FEED TANK	3.00-2	3.00-2	4.68-1	4.68-1	0.00
12	ε CONCENTRATION - 1A FEED TANK	1.00-2	1.00-2	1.56-1	1.56-1	0.00
13	ε INVENTORY - 1A COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	0.00
14	ε VOLUME - 2A FEED TANK	3.00-2	3.00-2	4.71	4.71	0.00
15	ε CONCENTRATION - 2A FEED TANK	1.00-2	1.00-2	1.57	1.57	0.00
16	ε INVENTORY - 2A COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	0.00
17	ε INVENTORY - 2B COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	0.00
18	ε VOLUME - 3A FEED TANK	3.00-2	3.00-2	5.52-1	5.52-1	0.00
19	ε CONCENTRATION - 3A FEED TANK	1.00-2	1.00-2	1.84-1	1.84-1	0.00
20	ε INVENTORY - 3A COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	0.00
21	ε INVENTORY - 3B COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	0.00
22	ε VOLUME - Pu STRIPPER FEED	3.00-2	3.00-2	8.47-2	8.47-2	0.00
23	ε CONCENTRATION - Pu STRIPPER FEED	1.00-2	1.00-2	2.82-2	2.82-2	0.00
24	ε INVENTORY - Pu STRIPPER	1.00-1	1.00-1	5.66-1	5.66-1	0.00
25	ε VOLUME - Pu CONCENTRATOR	3.00-2	3.00-2	8.07-1	8.07-1	0.00
26	ε CONCENTRATION - Pu CONCENTRATOR	1.00-2	1.00-2	2.69-1	2.69-1	0.00
27	ε VOLUME - Pu CATCH TANK	3.00-2	3.00-2	0.00	0.00	0.00
28	ε CONCENTRATION - Pu CATCH TANK	1.00-2	1.00-2	0.00	0.00	0.00
29	ε VOLUME - FEED ADJUSTMENT TANK INPUT	3.00-3	3.00-3	3.34-1	4.09	0.00
30	η VOLUME - FEED ADJUSTMENT TANK INPUT	1.00-3	1.00-3	1.11-1	1.67+1	0.00
31	θ VOLUME - FEED ADJUSTMENT TANK INPUT	1.00-3	1.00-3	1.11-1	1.67+1	0.00
32	ε CONCENTRATION - FEED ADJUSTMENT TANK INPUT	1.00-2	1.00-2	1.11	1.36+1	0.00
33	η CONCENTRATION - FEED ADJUSTMENT TANK INPUT	3.00-3	3.00-3	3.34-1	1.07+1	0.00
34	θ CONCENTRATION - FEED ADJUSTMENT TANK INPUT	3.00-3	3.00-3	3.34-1	5.01+1	0.00
35	ε VOLUME - Pu SAMPLE TANK OUTPUT	3.00-3	3.00-3	2.36-1	2.89	0.00
36	η VOLUME - Pu SAMPLE TANK OUTPUT	1.00-3	1.00-3	1.11-1	1.67+1	0.00
37	θ VOLUME - Pu SAMPLE TANK OUTPUT	1.00-3	1.00-3	1.11-1	1.67+1	0.00
38	ε CONCENTRATION - Pu SAMPLE TANK OUTPUT	3.00-3	3.00-3	2.36-1	2.89	0.00
39	η CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.00-3	2.00-3	2.22-1	7.13	0.00
40	θ CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.00-3	2.00-3	2.22-1	3.34+1	0.00
41	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	0.00	3.56-3	0.00
42	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	0.00
43	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	0.00

TABLE E-XII

MEASUREMENT UNCERTAINTIES: UPAA 2 3, GOAL 2, NO RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - FEED ADJUSTMENT TANK	3.00-2	3.00-2	0.00	0.00	1.31-5
2	ε CONCENTRATION - FEED ADJUSTMENT TANK	1.50-2	1.50-2	0.00	0.00	1.31-5
3	ε VOLUME - HA FEED TANK	1.27-2	3.00-2	2.00	2.00	1.37
4	ε CONCENTRATION - HA FEED TANK	1.08-2	1.50-2	1.70	1.70	3.85-1
5	ε Pu SOLIDS - HA CENTRIFUGE	2.00-1	2.00-1	1.06-3	1.06-3	1.31-5
6	ε INVENTORY - HA CONTACTOR	2.00-1	2.00-1	1.13-1	1.13-1	1.70-5
7	ε INVENTORY - HS COLUMN	9.96-2	1.00-1	4.23-1	4.23-1	3.98-3
8	ε INVENTORY - HC COLUMN	9.96-2	1.00-1	4.23-1	4.23-1	3.64-3
9	ε VOLUME - HCP REDUCER	2.93-2	3.00-2	6.24-1	6.24-1	2.31-2
10	ε CONCENTRATION - HCP REDUCER	1.00-2	1.00-2	2.13-1	2.13-1	1.06-4
11	ε VOLUME - 1A FEED TANK	2.99-2	3.00-2	4.66-1	4.66-1	3.99-3
12	ε CONCENTRATION - 1A FEED TANK	1.00-2	1.00-2	1.56-1	1.56-1	4.98-5
13	ε INVENTORY - 1A COLUMN	9.81-2	1.00-1	4.16-1	4.16-1	1.93-2
14	ε VOLUME - 2A FEED TANK	1.29-2	3.00-2	2.03	2.03	1.32
15	ε CONCENTRATION - 2A FEED TANK	8.81-3	1.00-2	1.38	1.38	1.35-1
16	ε INVENTORY - 2A COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	2.56-5
17	ε INVENTORY - 2B COLUMN	4.99-2	5.00-2	2.12-1	2.12-1	2.67-3
18	ε VOLUME - 3A FEED TANK	2.95-2	3.00-2	5.44-1	5.44-1	1.53-2
19	ε CONCENTRATION - 3A FEED TANK	1.00-2	1.00-2	1.84-1	1.84-1	3.75-4
20	ε INVENTORY - 3A COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	2.33-4
21	ε INVENTORY - 3B COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	2.22-4
22	ε VOLUME - Pu STRIPPER FEED	3.00-2	3.00-2	8.47-2	8.47-2	4.99-5
23	ε CONCENTRATION - Pu STRIPPER FEED	1.00-2	1.00-2	2.82-2	2.82-2	1.52-5
24	ε INVENTORY - Pu STRIPPER	9.76-2	1.00-1	5.52-1	5.52-1	2.43-2
25	ε VOLUME - Pu CONCENTRATOR	2.91-2	3.00-2	7.83-1	7.83-1	3.03-2
26	ε CONCENTRATION - Pu CONCENTRATOR	9.98-3	1.00-2	2.69-1	2.69-1	1.60-3
27	ε VOLUME - Pu CATCH TANK	3.00-2	3.00-2	0.00	0.00	1.31-5
28	ε CONCENTRATION - Pu CATCH TANK	1.00-2	1.00-2	0.00	0.00	1.31-5
29	ε VOLUME - FEED ADJUSTMENT TANK INPUT	2.44-3	3.00-3	2.71-1	3.32	2.32-1
30	η VOLUME - FEED ADJUSTMENT TANK INPUT	3.27-4	1.00-3	3.64-2	5.46	2.06
31	θ VOLUME - FEED ADJUSTMENT TANK INPUT	3.27-4	1.00-3	3.64-2	5.46	2.06
32	ε CONCENTRATION - FEED ADJUSTMENT TANK INPUT	3.70-3	1.00-2	4.12-1	5.05	1.70
33	η CONCENTRATION - FEED ADJUSTMENT TANK INPUT	4.73-4	3.00-3	5.26-2	7.89	5.35
34	θ CONCENTRATION - FEED ADJUSTMENT TANK INPUT	4.68-4	3.00-3	5.20-2	7.81	5.42
35	ε VOLUME - Pu SAMPLE TANK OUTPUT	2.92-3	3.00-3	2.30-1	2.81	2.66-2
36	η VOLUME - Pu SAMPLE TANK OUTPUT	3.25-4	1.00-3	3.61-2	5.42	2.08
37	θ VOLUME - Pu SAMPLE TANK OUTPUT	3.27-4	1.00-3	3.64-2	5.46	2.06
38	ε CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.85-3	3.00-3	2.24-1	2.74	5.30-2
39	η CONCENTRATION - Pu SAMPLE TANK OUTPUT	4.00-4	2.00-3	4.45-2	6.67	4.00
40	θ CONCENTRATION - Pu SAMPLE TANK OUTPUT	4.07-4	2.00-3	4.52-2	6.78	3.92
41	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	0.00	3.56-3	1.31-5
42	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	1.31-5
43	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	1.31-5

TABLE E-XIII

MEASUREMENT UNCERTAINTIES: UPAA 2 3, GOAL 2, WEEKLY RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - FEED ADJUSTMENT TANK	3.00-2	3.00-2	0.00	0.00	2.73-5
2	ε CONCENTRATION - FEED ADJUSTMENT TANK	1.50-2	1.50-2	0.00	0.00	2.73-5
3	ε VOLUME - HA FEED TANK	1.34-2	3.00-2	2.10	2.10	1.24
4	ε CONCENTRATION - HA FEED TANK	1.06-2	1.50-2	1.67	1.67	4.18-1
5	ε Pu SOLIDS - HA CENTRIFUGE	2.00-1	2.00-1	1.06-3	1.06-3	2.74-5
6	ε INVENTORY - HA CONTACTOR	2.00-1	2.00-1	1.13-1	1.13-1	1.41-5
7	ε INVENTORY - HS COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	1.66-4
8	ε INVENTORY - HC COLUMN	9.99-2	1.00-1	4.24-1	4.24-1	5.71-4
9	ε VOLUME - HCP REDUCER	2.92-2	3.00-2	6.20-1	6.20-1	2.87-2
10	ε CONCENTRATION - HCP REDUCER	1.00-2	1.00-2	2.13-1	2.13-1	3.30-4
11	ε VOLUME - 1A FEED TANK	2.96-2	3.00-2	4.61-1	4.61-1	1.40-2
12	ε CONCENTRATION - 1A FEED TANK	1.00-2	1.00-2	1.56-1	1.56-1	1.07-4
13	ε INVENTORY - 1A COLUMN	9.76-2	1.00-1	4.14-1	4.14-1	2.43-2
14	ε VOLUME - 2A FEED TANK	1.28-2	3.00-2	2.01	2.01	1.34
15	ε CONCENTRATION - 2A FEED TANK	8.31-3	1.00-2	1.30	1.30	2.03-1
16	ε INVENTORY - 2A COLUMN	4.96-2	5.00-2	2.10-1	2.10-1	8.68-3
17	ε INVENTORY - 2B COLUMN	4.91-2	5.00-2	2.08-1	2.08-1	1.91-2
18	ε VOLUME - 3A FEED TANK	2.95-2	3.00-2	5.43-1	5.43-1	1.82-2
19	ε CONCENTRATION - 3A FEED TANK	9.89-3	1.00-2	1.82-1	1.82-1	1.08-2
20	ε INVENTORY - 3A COLUMN	4.89-2	5.00-2	2.07-1	2.07-1	2.30-2
21	ε INVENTORY - 3B COLUMN	4.90-2	5.00-2	2.08-1	2.08-1	2.13-2
22	ε VOLUME - Pu STRIPPER FEED	3.00-2	3.00-2	8.46-2	8.46-2	1.01-3
23	ε CONCENTRATION - Pu STRIPPER FEED	1.00-2	1.00-2	2.82-2	2.82-2	2.75-5
24	ε INVENTORY - Pu STRIPPER	9.76-2	1.00-1	5.52-1	5.52-1	2.43-2
25	ε VOLUME - Pu CONCENTRATOR	2.66-2	3.00-2	7.15-1	7.15-1	1.28-1
26	ε CONCENTRATION - Pu CONCENTRATOR	9.82-3	1.00-2	2.64-1	2.64-1	1.88-2
27	ε VOLUME - Pu CATCH TANK	3.00-2	3.00-2	0.00	0.00	2.73-5
28	ε CONCENTRATION - Pu CATCH TANK	1.00-2	1.00-2	0.00	0.00	2.73-5
29	ε VOLUME - FEED ADJUSTMENT TANK INPUT	2.66-3	3.00-3	2.96-1	3.62	1.29-1
30	η VOLUME - FEED ADJUSTMENT TANK INPUT	3.61-4	1.00-3	4.02-2	6.03	1.77
31	θ VOLUME - FEED ADJUSTMENT TANK INPUT	3.61-4	1.00-3	4.02-2	6.03	1.77
32	ε CONCENTRATION - FEED ADJUSTMENT TANK INPUT	4.13-3	1.00-2	4.59-1	5.63	1.42
33	η CONCENTRATION - FEED ADJUSTMENT TANK INPUT	1.45-3	3.00-3	1.62-1	5.18	1.07
34	θ CONCENTRATION - FEED ADJUSTMENT TANK INPUT	5.19-4	3.00-3	5.77-2	8.66	4.79
35	ε VOLUME - Pu SAMPLE TANK OUTPUT	2.77-3	3.00-3	2.18-1	2.67	8.15-2
36	η VOLUME - Pu SAMPLE TANK OUTPUT	3.61-4	1.00-3	4.01-2	6.02	1.77
37	θ VOLUME - Pu SAMPLE TANK OUTPUT	3.64-4	1.00-3	4.04-2	6.07	1.75
38	ε CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.72-3	3.00-3	2.14-1	2.62	1.02-1
39	η CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.28-3	2.00-3	1.42-1	4.55	5.68-1
40	θ CONCENTRATION - Pu SAMPLE TANK OUTPUT	4.55-4	2.00-3	5.06-2	7.58	3.40
41	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	0.00	3.56-3	2.73-5
42	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	2.73-5
43	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	2.73-5

TABLE E-XIV

MEASUREMENT UNCERTAINTIES: UPAA 2 3, GOAL 2, DAILY RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - FEED ADJUSTMENT TANK	3.00-2	3.00-2	0.00	0.00	1.38-5
2	ε CONCENTRATION - FEED ADJUSTMENT TANK	1.50-2	1.50-2	0.00	0.00	1.38-5
3	ε VOLUME - HA FEED TANK	1.28-2	3.00-2	2.01	2.01	1.34
4	ε CONCENTRATION - HA FEED TANK	1.02-2	1.50-2	1.60	1.60	4.78-1
5	ε Pu SOLIDS - HA CENTRIFUGE	2.00-1	2.00-1	1.06-3	1.06-3	1.38-5
6	ε INVENTORY - HA CONTACTOR	2.00-1	2.00-1	1.13-1	1.13-1	9.95-6
7	ε INVENTORY - HS COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	1.04-4
8	ε INVENTORY - HC COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	2.60-4
9	ε VOLUME - HCP REDUCER	2.98-2	3.00-2	6.34-1	6.34-1	5.99-3
10	ε CONCENTRATION - HCP REDUCER	1.00-2	1.00-2	2.13-1	2.13-1	3.55-4
11	ε VOLUME - 1A FEED TANK	2.99-2	3.00-2	4.66-1	4.66-1	3.07-3
12	ε CONCENTRATION - 1A FEED TANK	1.00-2	1.00-2	1.56-1	1.56-1	4.72-4
13	ε INVENTORY - 1A COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	3.67-4
14	ε VOLUME - 2A FEED TANK	1.29-2	3.00-2	2.03	2.03	1.32
15	ε CONCENTRATION - 2A FEED TANK	8.84-3	1.00-2	1.39	1.39	1.31-1
16	ε INVENTORY - 2A COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	4.41-4
17	ε INVENTORY - 2B COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	4.78-4
18	ε VOLUME - 3A FEED TANK	2.99-2	3.00-2	5.51-1	5.51-1	2.03-3
19	ε CONCENTRATION - 3A FEED TANK	1.00-2	1.00-2	1.84-1	1.84-1	3.25-4
20	ε INVENTORY - 3A COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	3.63-4
21	ε INVENTORY - 3B COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	2.54-4
22	ε VOLUME - Pu STRIPPER FEED	3.00-2	3.00-2	8.47-2	8.47-2	2.75-5
23	ε CONCENTRATION - Pu STRIPPER FEED	1.00-2	1.00-2	2.82-2	2.82-2	1.64-5
24	ε INVENTORY - Pu STRIPPER	9.97-2	1.00-1	5.64-1	5.64-1	3.21-3
25	ε VOLUME - Pu CONCENTRATOR	2.91-2	3.00-2	7.84-1	7.84-1	2.94-2
26	ε CONCENTRATION - Pu CONCENTRATOR	9.99-3	1.00-2	2.69-1	2.69-1	7.51-4
27	ε VOLUME - Pu CATCH TANK	3.00-2	3.00-2	0.00	0.00	1.38-5
28	ε CONCENTRATION - Pu CATCH TANK	1.00-2	1.00-2	0.00	0.00	1.38-5
29	ε VOLUME - FEED ADJUSTMENT TANK INPUT	2.72-3	3.00-3	3.02-1	3.70	1.04-1
30	η VOLUME - FEED ADJUSTMENT TANK INPUT	3.72-4	1.00-3	4.14-2	6.20	1.69
31	θ VOLUME - FEED ADJUSTMENT TANK INPUT	3.78-4	1.00-3	4.21-2	6.31	1.65
32	ε CONCENTRATION - FEED ADJUSTMENT TANK INPUT	4.30-3	1.00-2	4.78-1	5.85	1.33
33	η CONCENTRATION - FEED ADJUSTMENT TANK INPUT	2.77-3	3.00-3	3.09-1	3.78	8.18-2
34	θ CONCENTRATION - FEED ADJUSTMENT TANK INPUT	5.43-4	3.00-3	6.04-2	9.06	4.53
35	ε VOLUME - Pu SAMPLE TANK OUTPUT	2.99-3	3.00-3	2.35-1	2.88	4.38-3
36	η VOLUME - Pu SAMPLE TANK OUTPUT	3.71-4	1.00-3	4.12-2	6.18	1.70
37	θ VOLUME - Pu SAMPLE TANK OUTPUT	3.77-4	1.00-3	4.19-2	6.28	1.66
38	ε CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.98-3	3.00-3	2.35-1	2.87	5.06-3
39	η CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.98-3	2.00-3	2.20-1	2.69	1.22-2
40	θ CONCENTRATION - Pu SAMPLE TANK OUTPUT	4.66-4	2.00-3	5.18-2	7.77	3.29
41	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	0.00	3.56-3	1.38-5
42	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	1.38-5
43	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	1.38-5

TABLE E-XV

MEASUREMENT UNCERTAINTIES: UPAA 2 3, GOAL 3, NO RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - FEED ADJUSTMENT TANK	3.00-2	3.00-2	0.00	0.00	6.01-5
2	ε CONCENTRATION - FEED ADJUSTMENT TANK	1.50-2	1.50-2	0.00	0.00	3.19-5
3	ε VOLUME - HA FEED TANK	1.94-3	3.00-2	3.05-1	3.05-1	1.45+1
4	ε CONCENTRATION - HA FEED TANK	1.84-3	1.50-2	2.89-1	2.89-1	7.17
5	ε Pu SOLIDS - HA CENTRIFUGE	2.00-1	2.00-1	1.06-3	1.06-3	3.66-5
6	ε INVENTORY - HA CONTACTOR	1.89-1	2.00-1	1.07-1	1.07-1	5.99-2
7	ε INVENTORY - HS COLUMN	3.66-2	1.00-1	1.55-1	1.55-1	1.73
8	ε INVENTORY - HC COLUMN	3.56-2	1.00-1	1.51-1	1.51-1	1.81
9	ε VOLUME - HCP REDUCER	8.14-3	3.00-2	1.73-1	1.73-1	2.68
10	ε CONCENTRATION - HCP REDUCER	5.65-3	1.00-2	1.20-1	1.20-1	7.70-1
11	ε VOLUME - 1A FEED TANK	1.01-2	3.00-2	1.58-1	1.58-1	1.96
12	ε CONCENTRATION - 1A FEED TANK	6.68-3	1.00-2	1.04-1	1.04-1	4.96-1
13	ε INVENTORY - 1A COLUMN	3.49-2	1.00-1	1.48-1	1.48-1	1.86
14	ε VOLUME - 2A FEED TANK	2.10-3	3.00-2	3.29-1	3.29-1	1.33+1
15	ε CONCENTRATION - 2A FEED TANK	1.43-3	1.00-2	2.25-1	2.25-1	5.97
16	ε INVENTORY - 2A COLUMN	2.81-2	5.00-2	1.19-1	1.19-1	7.78-1
17	ε INVENTORY - 2B COLUMN	2.76-2	5.00-2	1.17-1	1.17-1	8.14-1
18	ε VOLUME - 3A FEED TANK	8.88-3	3.00-2	1.64-1	1.64-1	2.38
19	ε CONCENTRATION - 3A FEED TANK	6.07-3	1.00-2	1.12-1	1.12-1	6.47-1
20	ε INVENTORY - 3A COLUMN	2.74-2	5.00-2	1.16-1	1.16-1	8.24-1
21	ε INVENTORY - 3B COLUMN	2.82-2	5.00-2	1.20-1	1.20-1	7.73-1
22	ε VOLUME - Pu STRIPPER FEED	2.63-2	3.00-2	7.42-2	7.42-2	1.41-1
23	ε CONCENTRATION - Pu STRIPPER FEED	1.00-2	1.00-2	2.82-2	2.82-2	3.37-5
24	ε INVENTORY - Pu STRIPPER	2.91-2	1.00-1	1.65-1	1.65-1	2.43
25	ε VOLUME - Pu CONCENTRATOR	6.94-3	3.00-2	1.87-1	1.87-1	3.32
26	ε CONCENTRATION - Pu CONCENTRATOR	4.88-3	1.00-2	1.31-1	1.31-1	1.05
27	ε VOLUME - Pu CATCH TANK	3.00-2	3.00-2	0.00	0.00	3.52-5
28	ε CONCENTRATION - Pu CATCH TANK	1.00-2	1.00-2	0.00	0.00	2.90-5
29	ε VOLUME - FEED ADJUSTMENT TANK INPUT	1.84-4	3.00-3	5.40-2	3.54-1	1.53+1
30	η VOLUME - FEED ADJUSTMENT TANK INPUT	1.87-5	1.00-3	1.46-2	6.24-1	5.25+1
31	θ VOLUME - FEED ADJUSTMENT TANK INPUT	1.92-5	1.00-3	1.49-2	6.41-1	5.11+1
32	ε CONCENTRATION - FEED ADJUSTMENT TANK INPUT	2.75-4	1.00-2	8.11-2	5.31-1	3.53+1
33	η CONCENTRATION - FEED ADJUSTMENT TANK INPUT	2.80-5	3.00-3	2.18-2	9.33-1	1.06+2
34	θ CONCENTRATION - FEED ADJUSTMENT TANK INPUT	2.71-5	3.00-3	2.11-2	9.04-1	1.10+2
35	ε VOLUME - Pu SAMPLE TANK OUTPUT	2.32-4	3.00-3	4.82-2	3.16-1	1.19+1
36	η VOLUME - Pu SAMPLE TANK OUTPUT	1.94-5	1.00-3	1.51-2	6.47-1	5.06+1
37	θ VOLUME - Pu SAMPLE TANK OUTPUT	1.91-5	1.00-3	1.49-2	6.37-1	5.14+1
38	ε CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.29-4	3.00-3	4.77-2	3.12-1	1.21+1
39	η CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.32-5	2.00-3	1.81-2	7.75-1	8.51+1
40	θ CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.48-5	2.00-3	1.93-2	8.26-1	7.98+1
41	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	7.60-4	5.04-3	3.70-5
42	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	3.80-4	1.67-2	5.04-5
43	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	3.80-4	1.67-2	4.00-5

TABLE E-XVI

MEASUREMENT UNCERTAINTIES: UPAA 2 3, GOAL 3, DAILY RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - FEED ADJUSTMENT TANK	3.00-2	3.00-2	0.00	0.00	9.90-5
2	ε CONCENTRATION - FEED ADJUSTMENT TANK	1.50-2	1.50-2	0.00	0.00	3.68-5
3	ε VOLUME - HA FEED TANK	2.24-3	3.00-2	3.53-1	3.53-1	1.24+1
4	ε CONCENTRATION - HA FEED TANK	2.07-3	1.50-2	3.25-1	3.25-1	6.26
5	ε Pu SOLIDS - HA CENTRIFUGE	2.00-1	2.00-1	1.06-3	1.06-3	3.69-5
6	ε INVENTORY - HA CONTACTOR	1.97-1	2.00-1	1.12-1	1.12-1	1.42-2
7	ε INVENTORY - HS COLUMN	4.17-2	1.00-1	1.77-1	1.77-1	1.40
8	ε INVENTORY - HC COLUMN	3.98-2	1.00-1	1.69-1	1.69-1	1.52
9	ε VOLUME - HCP REDUCER	9.06-3	3.00-2	1.93-1	1.93-1	2.31
10	ε CONCENTRATION - HCP REDUCER	6.21-3	1.00-2	1.32-1	1.32-1	6.11-1
11	ε VOLUME - 1A FEED TANK	1.12-2	3.00-2	1.75-1	1.75-1	1.67
12	ε CONCENTRATION - 1A FEED TANK	7.71-3	1.00-2	1.20-1	1.20-1	2.96-1
13	ε INVENTORY - 1A COLUMN	4.01-2	1.00-1	1.70-1	1.70-1	1.50
14	ε VOLUME - 2A FEED TANK	2.36-3	3.00-2	3.70-1	3.70-1	1.17+1
15	ε CONCENTRATION - 2A FEED TANK	1.66-3	1.00-2	2.60-1	2.60-1	5.04
16	ε INVENTORY - 2A COLUMN	3.15-2	5.00-2	1.34-1	1.34-1	5.86-1
17	ε INVENTORY - 2B COLUMN	3.17-2	5.00-2	1.35-1	1.35-1	5.76-1
18	ε VOLUME - 3A FEED TANK	9.89-3	3.00-2	1.82-1	1.82-1	2.03
19	ε CONCENTRATION - 3A FEED TANK	6.93-3	1.00-2	1.28-1	1.28-1	4.43-1
20	ε INVENTORY - 3A COLUMN	3.14-2	5.00-2	1.33-1	1.33-1	5.95-1
21	ε INVENTORY - 3B COLUMN	3.14-2	5.00-2	1.33-1	1.33-1	5.91-1
22	ε VOLUME - Pu STRIPPER FEED	2.71-2	3.00-2	7.64-2	7.64-2	1.09-1
23	ε CONCENTRATION - Pu STRIPPER FEED	1.00-2	1.00-2	2.82-2	2.82-2	5.07-5
24	ε INVENTORY - Pu STRIPPER	3.27-2	1.00-1	1.85-1	1.85-1	2.05
25	ε VOLUME - Pu CONCENTRATOR	7.75-3	3.00-2	2.08-1	2.08-1	2.87
26	ε CONCENTRATION - Pu CONCENTRATOR	5.41-3	1.00-2	1.45-1	1.45-1	8.50-1
27	ε VOLUME - Pu CATCH TANK	3.00-2	3.00-2	0.00	0.00	4.92-5
28	ε CONCENTRATION - Pu CATCH TANK	1.00-2	1.00-2	0.00	0.00	3.68-5
29	ε VOLUME - FEED ADJUSTMENT TANK INPUT	2.11-4	3.00-3	6.21-2	4.07-1	1.32+1
30	η VOLUME - FEED ADJUSTMENT TANK INPUT	2.16-5	1.00-3	1.69-2	7.22-1	4.52+1
31	θ VOLUME - FEED ADJUSTMENT TANK INPUT	2.16-5	1.00-3	1.68-2	7.20-1	4.53+1
32	ε CONCENTRATION - FEED ADJUSTMENT TANK INPUT	3.12-4	1.00-2	9.18-2	6.01-1	3.11+1
33	η CONCENTRATION - FEED ADJUSTMENT TANK INPUT	2.09-4	3.00-3	6.16-2	4.04-1	1.33+1
34	θ CONCENTRATION - FEED ADJUSTMENT TANK INPUT	3.08-5	3.00-3	2.40-2	1.03	9.63+1
35	ε VOLUME - Pu SAMPLE TANK OUTPUT	2.63-4	3.00-3	5.46-2	3.58-1	1.04+1
36	η VOLUME - Pu SAMPLE TANK OUTPUT	2.16-5	1.00-3	1.68-2	7.19-1	4.54+1
37	θ VOLUME - Pu SAMPLE TANK OUTPUT	2.15-5	1.00-3	1.68-2	7.19-1	4.54+1
38	ε CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.63-4	3.00-3	5.47-2	3.58-1	1.04+1
39	η CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.83-4	2.00-3	5.38-2	3.52-1	9.93
40	θ CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.70-5	2.00-3	2.10-2	9.01-1	7.31+1
41	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	7.60-4	5.04-3	3.64-5
42	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	3.80-4	1.67-2	4.75-5
43	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	3.80-4	1.67-2	3.94-5

TABLE E-XVII

MEASUREMENT UNCERTAINTIES: UPAA 2 3, GOAL 4, NO RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - FEED ADJUSTMENT TANK	3.00-2	3.00-2	0.00	0.00	5.97-4
2	ε CONCENTRATION - FEED ADJUSTMENT TANK	1.50-2	1.50-2	0.00	0.00	4.58-4
3	ε VOLUME - HA FEED TANK	1.79-3	3.00-2	2.81-1	2.81-1	1.58+1
4	ε CONCENTRATION - HA FEED TANK	1.46-3	1.50-2	2.30-1	2.30-1	9.27
5	ε Pu SOLIDS - HA CENTRIFUGE	2.00-1	2.00-1	1.06-3	1.06-3	4.67-4
6	ε INVENTORY - HA CONTACTOR	1.46-1	2.00-1	8.29-2	8.29-2	3.65-1
7	ε INVENTORY - HS COLUMN	3.30-2	1.00-1	1.40-1	1.40-1	2.03
8	ε INVENTORY - HC COLUMN	4.02-2	1.00-1	1.71-1	1.71-1	1.49
9	ε VOLUME - HCP REDUCER	7.79-3	3.00-2	1.66-1	1.66-1	2.85
10	ε CONCENTRATION - HCP REDUCER	4.34-3	1.00-2	9.22-2	9.22-2	1.31
11	ε VOLUME - 1A FEED TANK	9.93-3	3.00-2	1.55-1	1.55-1	2.02
12	ε CONCENTRATION - 1A FEED TANK	8.22-3	1.00-2	1.28-1	1.28-1	2.16-1
13	ε INVENTORY - 1A COLUMN	3.55-2	1.00-1	1.51-1	1.51-1	1.82
14	ε VOLUME - 2A FEED TANK	1.67-3	3.00-2	2.61-1	2.61-1	1.70+1
15	ε CONCENTRATION - 2A FEED TANK	1.06-3	1.00-2	1.67-1	1.67-1	8.42
16	ε INVENTORY - 2A COLUMN	2.96-2	5.00-2	1.25-1	1.25-1	6.92-1
17	ε INVENTORY - 2B COLUMN	2.89-2	5.00-2	1.23-1	1.23-1	7.29-1
18	ε VOLUME - 3A FEED TANK	7.71-3	3.00-2	1.42-1	1.42-1	2.89
19	ε CONCENTRATION - 3A FEED TANK	6.67-3	1.00-2	1.23-1	1.23-1	4.99-1
20	ε INVENTORY - 3A COLUMN	2.84-2	5.00-2	1.20-1	1.20-1	7.61-1
21	ε INVENTORY - 3B COLUMN	2.79-2	5.00-2	1.19-1	1.19-1	7.90-1
22	ε VOLUME - Pu STRIPPER FEED	2.98-2	3.00-2	8.41-2	8.41-2	6.95-3
23	ε CONCENTRATION - Pu STRIPPER FEED	1.00-2	1.00-2	2.82-2	2.82-2	3.14-4
24	ε INVENTORY - Pu STRIPPER	2.83-2	1.00-1	1.60-1	1.60-1	2.53
25	ε VOLUME - Pu CONCENTRATOR	6.41-3	3.00-2	1.73-1	1.73-1	3.68
26	ε CONCENTRATION - Pu CONCENTRATOR	5.50-3	1.00-2	1.48-1	1.48-1	8.19-1
27	ε VOLUME - Pu CATCH TANK	3.00-2	3.00-2	0.00	0.00	4.58-4
28	ε CONCENTRATION - Pu CATCH TANK	1.00-2	1.00-2	0.00	0.00	4.58-4
29	ε VOLUME - FEED ADJUSTMENT TANK INPUT	1.64-4	3.00-3	1.83-2	2.24-1	1.73+1
30	η VOLUME - FEED ADJUSTMENT TANK INPUT	1.57-5	1.00-3	1.74-3	2.61-1	6.29+1
31	θ VOLUME - FEED ADJUSTMENT TANK INPUT	1.25-5	1.00-3	1.39-3	2.09-1	7.90+1
32	ε CONCENTRATION - FEED ADJUSTMENT TANK INPUT	1.56-4	1.00-2	1.74-2	2.13-1	6.29+1
33	η CONCENTRATION - FEED ADJUSTMENT TANK INPUT	9.77-6	3.00-3	1.09-3	1.63-1	3.06+2
34	θ CONCENTRATION - FEED ADJUSTMENT TANK INPUT	9.73-6	3.00-3	1.08-3	1.62-1	3.07+2
35	ε VOLUME - Pu SAMPLE TANK OUTPUT	1.83-4	3.00-3	1.44-2	1.77-1	1.53+1
36	η VOLUME - Pu SAMPLE TANK OUTPUT	1.47-5	1.00-3	1.64-3	2.46-1	6.69+1
37	θ VOLUME - Pu SAMPLE TANK OUTPUT	1.01-5	1.00-3	1.13-3	1.69-1	9.76+1
38	ε CONCENTRATION - Pu SAMPLE TANK OUTPUT	6.89-5	3.00-3	5.42-3	6.64-2	4.25+1
39	η CONCENTRATION - Pu SAMPLE TANK OUTPUT	9.73-6	2.00-3	1.08-3	1.62-1	2.05+2
40	θ CONCENTRATION - Pu SAMPLE TANK OUTPUT	9.67-6	2.00-3	1.08-3	1.61-1	2.06+2
41	ε TRANSFER - HA CENTRIFUGE TO SST	9.99-2	1.00-1	0.00	3.56-3	6.73-4
42	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	5.89-4
43	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.35-3	6.12-4

TABLE E-XVIII

MEASUREMENT UNCERTAINTIES: UPAA 2 3, GOAL 4, DAILY RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - FEED ADJUSTMENT TANK	3.00-2	3.00-2	0.00	0.00	1.35-5
2	ε CONCENTRATION - FEED ADJUSTMENT TANK	1.50-2	1.50-2	0.00	0.00	1.45-5
3	ε VOLUME - HA FEED TANK	1.17-3	3.00-2	1.83-1	1.83-1	2.47+1
4	ε CONCENTRATION - HA FEED TANK	9.26-4	1.50-2	1.46-1	1.46-1	1.52+1
5	ε Pu SOLIDS - HA CENTRIFUGE	2.00-1	2.00-1	1.06-3	1.06-3	1.27-5
6	ε INVENTORY - HA CONTACTOR	9.52-2	2.00-1	5.39-2	5.39-2	1.10
7	ε INVENTORY - HS COLUMN	1.94-2	1.00-1	8.23-2	8.23-2	4.16
8	ε INVENTORY - HC COLUMN	1.94-2	1.00-1	8.24-2	8.24-2	4.15
9	ε VOLUME - HCP REDUCER	4.41-3	3.00-2	9.38-2	9.38-2	5.81
10	ε CONCENTRATION - HCP REDUCER	3.06-3	1.00-2	6.52-2	6.52-2	2.26
11	ε VOLUME - 1A FEED TANK	5.44-3	3.00-2	8.48-2	8.48-2	4.51
12	ε CONCENTRATION - 1A FEED TANK	3.77-3	1.00-2	5.88-2	5.88-2	1.65
13	ε INVENTORY - 1A COLUMN	1.93-2	1.00-1	8.19-2	8.19-2	4.18
14	ε VOLUME - 2A FEED TANK	1.16-3	3.00-2	1.83-1	1.83-1	2.48+1
15	ε CONCENTRATION - 2A FEED TANK	8.07-4	1.00-2	1.27-1	1.27-1	1.14+1
16	ε INVENTORY - 2A COLUMN	1.53-2	5.00-2	6.51-2	6.51-2	2.26
17	ε INVENTORY - 2B COLUMN	1.53-2	5.00-2	6.50-2	6.50-2	2.26
18	ε VOLUME - 3A FEED TANK	4.86-3	3.00-2	8.94-2	8.94-2	5.18
19	ε CONCENTRATION - 3A FEED TANK	3.37-3	1.00-2	6.20-2	6.20-2	1.97
20	ε INVENTORY - 3A COLUMN	1.53-2	5.00-2	6.49-2	6.49-2	2.27
21	ε INVENTORY - 3B COLUMN	1.53-2	5.00-2	6.48-2	6.48-2	2.27
22	ε VOLUME - Pu STRIPPER FEED	1.69-2	3.00-2	4.77-2	4.77-2	7.75-1
23	ε CONCENTRATION - Pu STRIPPER FEED	9.99-3	1.00-2	2.82-2	2.82-2	9.83-4
24	ε INVENTORY - Pu STRIPPER	1.58-2	1.00-1	8.97-2	8.97-2	5.31
25	ε VOLUME - Pu CONCENTRATOR	3.77-3	3.00-2	1.01-1	1.01-1	6.97
26	ε CONCENTRATION - Pu CONCENTRATOR	2.62-3	1.00-2	7.04-2	7.04-2	2.82
27	ε VOLUME - Pu CATCH TANK	3.00-2	3.00-2	0.00	0.00	1.10-5
28	ε CONCENTRATION - Pu CATCH TANK	1.00-2	1.00-2	0.00	0.00	1.46-5
29	ε VOLUME - FEED ADJUSTMENT TANK INPUT	1.28-4	3.00-3	1.42-2	1.74-1	2.25+1
30	η VOLUME - FEED ADJUSTMENT TANK INPUT	1.67-5	1.00-3	1.86-3	2.79-1	5.89+1
31	θ VOLUME - FEED ADJUSTMENT TANK INPUT	1.67-5	1.00-3	1.85-3	2.78-1	5.90+1
32	ε CONCENTRATION - FEED ADJUSTMENT TANK INPUT	1.91-4	1.00-2	2.13-2	2.60-1	5.14+1
33	η CONCENTRATION - FEED ADJUSTMENT TANK INPUT	1.28-4	3.00-3	1.42-2	1.74-1	2.25+1
34	θ CONCENTRATION - FEED ADJUSTMENT TANK INPUT	2.41-5	3.00-3	2.68-3	4.02-1	1.24+2
35	ε VOLUME - Pu SAMPLE TANK OUTPUT	1.61-4	3.00-3	1.27-2	1.55-1	1.76+1
36	η VOLUME - Pu SAMPLE TANK OUTPUT	1.67-5	1.00-3	1.86-3	2.78-1	5.89+1
37	θ VOLUME - Pu SAMPLE TANK OUTPUT	1.67-5	1.00-3	1.86-3	2.78-1	5.89+1
38	ε CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.61-4	3.00-3	1.27-2	1.55-1	1.76+1
39	η CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.12-4	2.00-3	1.24-2	1.52-1	1.69+1
40	θ CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.10-5	2.00-3	2.34-3	3.50-1	9.42+1
41	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	0.00	3.56-3	1.33-5
42	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	1.74-5
43	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	1.89-5

TABLE E-XIX

MEASUREMENT UNCERTAINTIES: UPAA 2, GOAL 1, NO RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - FEED ADJUSTMENT TANK	3.00-2	3.00-2	0.00	0.00	1.26-5
2	ε CONCENTRATION - FEED ADJUSTMENT TANK	1.50-2	1.50-2	0.00	0.00	4.88-5
3	ε VOLUME - HA FEED TANK	3.00-2	3.00-2	4.72	4.72	1.29-5
4	ε CONCENTRATION - HA FEED TANK	1.50-2	1.50-2	2.36	2.36	4.67-5
5	ε Pu SOLIDS - HA CENTRIFUGE	2.00-1	2.00-1	1.06-3	1.06-3	4.88-5
6	ε INVENTORY - HA CONTACTOR	2.00-1	2.00-1	1.13-1	1.13-1	5.10-5
7	ε INVENTORY - HS COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	5.29-5
8	ε INVENTORY - HC COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	5.25-5
9	ε VOLUME - HCP REDUCER	3.00-2	3.00-2	6.38-1	6.38-1	5.64-5
10	ε CONCENTRATION - HCP REDUCER	1.00-2	1.00-2	2.13-1	2.13-1	7.55-6
11	ε VOLUME - 1A FEED TANK	3.00-2	3.00-2	4.68-1	4.68-1	5.40-5
12	ε CONCENTRATION - 1A FEED TANK	1.00-2	1.00-2	1.56-1	1.56-1	3.58-5
13	ε INVENTORY - 1A COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	5.36-5
14	ε VOLUME - FEED ADJUSTMENT TANK INPUT	3.00-3	3.00-3	3.34-1	4.09	1.34-5
15	η VOLUME - FEED ADJUSTMENT TANK INPUT	9.19-4	1.00-3	1.02-1	1.53+1	8.84-2
16	θ VOLUME - FEED ADJUSTMENT TANK INPUT	9.56-4	1.00-3	1.06-1	1.60+1	4.61-2
17	ε CONCENTRATION - FEED ADJUSTMENT TANK INPUT	9.58-3	1.00-2	1.07	1.31+1	4.34-2
18	η CONCENTRATION - FEED ADJUSTMENT TANK INPUT	1.50-3	3.00-3	1.67-1	2.51+1	9.98-1
19	θ CONCENTRATION - FEED ADJUSTMENT TANK INPUT	1.57-3	3.00-3	1.75-1	2.63+1	9.05-1
20	ε FLOW RATE - 1A COLUMN OUTPUT	2.50-2	2.50-2	4.02-1	4.92	6.14-5
21	η FLOW RATE - 1A COLUMN OUTPUT	2.65-3	1.50-2	2.96-1	4.43+1	4.65
22	θ FLOW RATE - 1A COLUMN OUTPUT	1.83-3	5.00-3	2.04-1	3.06+1	1.73
23	ε CONCENTRATION - 1A COLUMN OUTPUT	1.00-2	1.00-2	1.61-1	1.97	3.19-5
24	η CONCENTRATION - 1A COLUMN OUTPUT	1.84-3	5.00-3	2.05-1	3.08+1	1.71
25	θ CONCENTRATION - 1A COLUMN OUTPUT	1.33-3	2.00-3	1.48-1	2.22+1	5.05-1
26	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	0.00	3.56-3	4.88-5
27	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	4.88-5
28	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	4.88-5

TABLE E-XX

MEASUREMENT UNCERTAINTIES: UPAA 2, GOAL 1, WEEKLY RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - FEED ADJUSTMENT TANK	3.00-2	3.00-2	0.00	0.00	8.10-7
2	ε CONCENTRATION - FEED ADJUSTMENT TANK	1.50-2	1.50-2	0.00	0.00	4.99-5
3	ε VOLUME - HA FEED TANK	2.99-2	3.00-2	4.70	4.70	3.52-3
4	ε CONCENTRATION - HA FEED TANK	1.50-2	1.50-2	2.36	2.36	4.04-5
5	ε Pu SOLIDS - HA CENTRIFUGE	2.00-1	2.00-1	1.06-3	1.06-3	4.97-5
6	ε INVENTORY - HA CONTACTOR	2.00-1	2.00-1	1.13-1	1.13-1	4.98-5
7	ε INVENTORY - HS COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	4.98-5
8	ε INVENTORY - HC COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	4.98-5
9	ε VOLUME - HCP REDUCER	3.00-2	3.00-2	6.38-1	6.38-1	4.99-5
10	ε CONCENTRATION - HCP REDUCER	1.00-2	1.00-2	2.13-1	2.13-1	4.98-5
11	ε VOLUME - 1A FEED TANK	3.00-2	3.00-2	4.68-1	4.68-1	5.75-5
12	ε CONCENTRATION - 1A FEED TANK	1.00-2	1.00-2	1.56-1	1.56-1	4.98-5
13	ε INVENTORY - 1A COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	4.98-5
14	ε VOLUME - FEED ADJUSTMENT TANK INPUT	3.00-3	3.00-3	3.34-1	4.09	1.21-5
15	η VOLUME - FEED ADJUSTMENT TANK INPUT	9.58-4	1.00-3	1.07-1	1.60+1	4.38-2
16	θ VOLUME - FEED ADJUSTMENT TANK INPUT	9.82-4	1.00-3	1.09-1	1.64+1	1.81-2
17	ε CONCENTRATION - FEED ADJUSTMENT TANK INPUT	9.96-3	1.00-2	1.11	1.36+1	3.77-3
18	η CONCENTRATION - FEED ADJUSTMENT TANK INPUT	2.99-3	3.00-3	3.33-1	1.07+1	3.53-3
19	θ CONCENTRATION - FEED ADJUSTMENT TANK INPUT	2.11-3	3.00-3	2.34-1	3.51+1	4.25-1
20	ε FLOW RATE - 1A COLUMN OUTPUT	2.49-2	2.50-2	4.01-1	4.91	2.09-3
21	η FLOW RATE - 1A COLUMN OUTPUT	1.00-2	1.50-2	1.12	3.58+1	4.96-1
22	θ FLOW RATE - 1A COLUMN OUTPUT	2.63-3	5.00-3	2.93-1	4.40+1	8.98-1
23	ε CONCENTRATION - 1A COLUMN OUTPUT	1.00-2	1 00-2	1.61-1	1.97	2.39-5
24	η CONCENTRATION - 1A COLUMN OUTPUT	4.99-3	5.00-3	5.55-1	1.78+1	2.83-3
25	θ CONCENTRATION - 1A COLUMN OUTPUT	1.62-3	2.00-3	1.81-1	2.71+1	2.33-1
26	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	0.00	3.56-3	4.97-5
27	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	4.98-5
28	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	4.98-5

TABLE E-XXI

MEASUREMENT UNCERTAINTIES: UPAA 2, GOAL 2, NO RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - FEED ADJUSTMENT TANK	3.00-2	3.00-2	0.00	0.00	4.66-5
2	ε CONCENTRATION - FEED ADJUSTMENT TANK	1.50-2	1.50-2	0.00	0.00	4.67-5
3	ε VOLUME - HA FEED TANK	1.75-2	3.00-2	2.75	2.75	7.18-1
4	ε CONCENTRATION - HA FEED TANK	1.39-2	1.50-2	2.19	2.19	7.60-2
5	ε Pu SOLIDS - HA CENTRIFUGE	2.00-1	2.00-1	1.06-3	1.06-3	4.69-5
6	ε INVENTORY - HA CONTACTOR	2.00-1	2.00-1	1.13-1	1.13-1	4.52-5
7	ε INVENTORY - HS COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	1.22-5
8	ε INVENTORY - HC COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	1.11-4
9	ε VOLUME - HCP REDUCER	3.00-2	3.00-2	6.38-1	6.38-1	1.56-5
10	ε CONCENTRATION - HCP REDUCER	1.00-2	1.00-2	2.13-1	2.13-1	4.86-5
11	ε VOLUME - 1A FEED TANK	2.99-2	3.00-2	4.67-1	4.67-1	1.91-3
12	ε CONCENTRATION - 1A FEED TANK	1.00-2	1.00-2	1.56-1	1.56-1	4.07-5
13	ε INVENTORY - 1A COLUMN	9.98-2	1.00-1	4.24-1	4.24-1	1.69-3
14	ε VOLUME - FEED ADJUSTMENT TANK INPUT	1.91-3	3.00-3	2.13-1	2.60	5.71-1
15	η VOLUME - FEED ADJUSTMENT TANK INPUT	2.54-4	1.00-3	2.83-2	4.24	2.94
16	θ VOLUME - FEED ADJUSTMENT TANK INPUT	2.54-4	1.00-3	2.83-2	4.24	2.94
17	ε CONCENTRATION - FEED ADJUSTMENT TANK INPUT	2.92-3	1.00-2	3.25-1	3.98	2.42
18	η CONCENTRATION - FEED ADJUSTMENT TANK INPUT	3.66-4	3.00-3	4.07-2	6.11	7.19
19	θ CONCENTRATION - FEED ADJUSTMENT TANK INPUT	3.66-4	3.00-3	4.07-2	6.11	7.19
20	ε FLOW RATE - 1A COLUMN OUTPUT	1.42-2	2.50-2	2.28-1	2.80	7.59-1
21	η FLOW RATE - 1A COLUMN OUTPUT	6.28-4	1.50-2	6.99-2	1.05+1	2.29+1
22	θ FLOW RATE - 1A COLUMN OUTPUT	4.33-4	5.00-3	4.82-2	7.23	1.06+1
23	ε CONCENTRATION - 1A COLUMN OUTPUT	8.69-3	1.00-2	1.40-1	1.71	1.51-1
24	η CONCENTRATION - 1A COLUMN OUTPUT	4.32-4	5.00-3	4.81-2	7.22	1.06+1
25	θ CONCENTRATION - 1A COLUMN OUTPUT	3.17-4	2.00-3	3.53-2	5.30	5.31
26	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	0.00	3.56-3	4.68-5
27	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	4.32-5
28	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	4.33-5

TABLE E-XXII

MEASUREMENT UNCERTAINTIES: UPAA 2, GOAL 2, WEEKLY RECALIBRATION

NO.		DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε	VOLUME - FEED ADJUSTMENT TANK	3.00-2	3.00-2	0.00	0.00	4.94-5
2	ε	CONCENTRATION - FEED ADJUSTMENT TANK	1.50-2	1.50-2	0.00	0.00	4.94-5
3	ε	VOLUME - HA FEED TANK	2.01-2	3.00-2	3.16	3.16	4.96-1
4	ε	CONCENTRATION - HA FEED TANK	1.26-2	1.50-2	1.98	1.98	1.90-1
5	ε	Pu SOLIDS - HA CENTRIFUGE	2.00-1	2.00-1	1.06-3	1.06-3	4.94-5
6	ε	INVENTORY - HA CONTACTOR	2.00-1	2.00-1	1.13-1	1.13-1	4.98-5
7	ε	INVENTORY - HS COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	6.70-5
8	ε	INVENTORY - HC COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	7.76-5
9	ε	VOLUME - HCP REDUCER	3.00-2	3.00-2	6.38-1	6.38-1	4.70-5
10	ε	CONCENTRATION - HCP REDUCER	1.00-2	1.00-2	2.13-1	2.13-1	5.48-5
11	ε	VOLUME - 1A FEED TANK	3.00-2	3.00-2	4.68-1	4.68-1	4.96-5
12	ε	CONCENTRATION - 1A FEED TANK	1.00-2	1.00-2	1.56-1	1.56-1	7.37-5
13	ε	INVENTORY - 1A COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	5.97-5
14	ε	VOLUME - FEED ADJUSTMENT TANK INPUT	2.29-3	3.00-3	2.55-1	3.13	3.08-1
15	η	VOLUME - FEED ADJUSTMENT TANK INPUT	3.16-4	1.00-3	3.52-2	5.28	2.16
16	θ	VOLUME - FEED ADJUSTMENT TANK INPUT	3.14-4	1.00-3	3.50-2	5.25	2.18
17	ε	CONCENTRATION - FEED ADJUSTMENT TANK INPUT	3.68-3	1.00-2	4.10-1	5.02	1.72
18	η	CONCENTRATION - FEED ADJUSTMENT TANK INPUT	1.26-3	3.00-3	1.40-1	4.50	1.38
19	θ	CONCENTRATION - FEED ADJUSTMENT TANK INPUT	4.48-4	3.00-3	4.98-2	7.47	5.70
20	ε	FLOW RATE - 1A COLUMN OUTPUT	1.68-2	2.50-2	2.70-1	3.30	4.90-1
21	η	FLOW RATE - 1A COLUMN OUTPUT	2.15-3	1.50-2	2.39-1	7.67	5.99
22	θ	FLOW RATE - 1A COLUMN OUTPUT	5.26-4	5.00-3	5.86-2	8.78	8.51
23	ε	CONCENTRATION - 1A COLUMN OUTPUT	8.23-3	1.00-2	1.32-1	1.62	2.15-1
24	η	CONCENTRATION - 1A COLUMN OUTPUT	1.47-3	5.00-3	1.64-1	5.26	2.39
25	θ	CONCENTRATION - 1A COLUMN OUTPUT	3.85-4	2.00-3	4.29-2	6.43	4.20
26	ε	TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	0.00	3.56-3	4.94-5
27	η	TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	4.89-5
28	θ	TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	4.59-5

TABLE E-XXIII

MEASUREMENT UNCERTAINTIES: UPAA 2, GOAL 2, DAILY RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - FEED ADJUSTMENT TANK	3.00-2	3.00-2	0.00	0.00	1.95-5
2	ε CONCENTRATION - FEED ADJUSTMENT TANK	1.50-2	1.50-2	0.00	0.00	1.49-6
3	ε VOLUME - HA FEED TANK	1.59-2	3.00-2	2.51	2.51	8.84-1
4	ε CONCENTRATION - HA FEED TANK	1.38-2	1.50-2	2.18	2.18	8.37-2
5	ε Pu SOLIDS - HA CENTRIFUGE	2.00-1	2.00-1	1.06-3	1.06-3	1.97-5
6	ε INVENTORY - HA CONTACTOR	2.00-1	2.00-1	1.13-1	1.13-1	3.12-5
7	ε INVENTORY - HS COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	4.34-5
8	ε INVENTORY - HC COLUMN	1.00-1	1.00-1	4.24-1	4.24-1	1.75-4
9	ε VOLUME - HCP REDUCER	3.00-2	3.00-2	6.38-1	6.38-1	1.18-4
10	ε CONCENTRATION - HCP REDUCER	1.00-2	1.00-2	2.13-1	2.13-1	2.94-6
11	ε VOLUME - 1A FEED TANK	3.00-2	3.00-2	4.68-1	4.68-1	4.28-5
12	ε CONCENTRATION - 1A FEED TANK	1.00-2	1.00-2	1.56-1	1.56-1	3.38-5
13	ε INVENTORY - 1A COLUMN	9.85-2	1.00-1	4.18-1	4.18-1	1.51-2
14	ε VOLUME - FEED ADJUSTMENT TANK INPUT	2.05-3	3.00-3	2.28-1	2.79	4.65-1
15	η VOLUME - FEED ADJUSTMENT TANK INPUT	3.21-4	1.00-3	3.57-2	5.36	2.11
16	θ VOLUME - FEED ADJUSTMENT TANK INPUT	3.17-4	1.00-3	3.53-2	5.29	2.16
17	ε CONCENTRATION - FEED ADJUSTMENT TANK INPUT	3.47-3	1.00-2	3.87-1	4.73	1.88
18	η CONCENTRATION - FEED ADJUSTMENT TANK INPUT	1.94-3	3.00-3	2.16-1	2.65	5.44-1
19	θ CONCENTRATION - FEED ADJUSTMENT TANK INPUT	4.91-4	3.00-3	5.47-2	8.20	5.11
20	ε FLOW RATE - 1A COLUMN OUTPUT	1.42-2	2.50-2	2.28-1	2.79	7.65-1
21	η FLOW RATE - 1A COLUMN OUTPUT	4.04-3	1.50-2	4.50-1	5.52	2.71
22	θ FLOW RATE - 1A COLUMN OUTPUT	6.71-4	5.00-3	7.47-2	1.12+1	6.45
23	ε CONCENTRATION - 1A COLUMN OUTPUT	8.12-3	1.00-2	1.31-1	1.60	2.31-1
24	η CONCENTRATION - 1A COLUMN OUTPUT	2.41-3	5.00-3	2.69-1	3.29	1.07
25	θ CONCENTRATION - 1A COLUMN OUTPUT	4.21-4	2.00-3	4.69-2	7.03	3.75
26	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	0.00	3.56-3	3.16-5
27	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	4.58-5
28	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	5.71-6

TABLE E-XXIV

MEASUREMENT UNCERTAINTIES: UPAA 2, GOAL 3, NO RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - FEED ADJUSTMENT TANK	3.00-2	3.00-2	0.0%	0.00	1.03-5
2	ε CONCENTRATION - FEED ADJUSTMENT TANK	1.50-2	1.50-2	0.00	0.00	4.26-5
3	ε VOLUME - HA FEED TANK	1.72-3	3.00-2	2.71-1	2.71-1	1.64+1
4	ε CONCENTRATION - HA FEED TANK	1.37-3	1.50-2	2.16-1	2.16-1	9.93
5	ε Pu SOLIDS - HA CENTRIFUGE	2.00-1	2.00-1	1.06-3	1.06-3	9.76-6
6	ε INVENTORY - HA CONTACTOR	1.44-1	2.00-1	8.14-2	8.14-2	3.90-1
7	ε INVENTORY - HS COLUMN	2.93-2	1.00-1	1.25-1	1.25-1	2.41
8	ε INVENTORY - HC COLUMN	2.90-2	1.00-1	1.23-1	1.23-1	2.45
9	ε VOLUME - HCP REDUCER	6.65-3	3.00-2	1.42-1	1.42-1	3.51
10	ε CONCENTRATION - HCP REDUCER	4.62-3	1.00-2	9.83-2	9.83-2	1.16
11	ε VOLUME - 1A FEED TANK	8.24-3	3.00-2	1.28-1	1.28-1	2.64
12	ε CONCENTRATION - 1A FEED TANK	5.75-3	1.00-2	8.97-2	8.97-2	7.39-1
13	ε INVENTORY - 1A COLUMN	2.89-2	1.00-1	1.22-1	1.22-1	2.47
14	ε VOLUME - FEED ADJUSTMENT TANK INPUT	1.54-4	3.00-3	4.52-2	2.96-1	1.85+1
15	η VOLUME - FEED ADJUSTMENT TANK INPUT	1.57-5	1.00-3	1.22-2	5.23-1	6.28+1
16	θ VOLUME - FEED ADJUSTMENT TANK INPUT	1.55-5	1.00-3	1.21-2	5.18-1	6.34+1
17	ε CONCENTRATION - FEED ADJUSTMENT TANK INPUT	2.24-4	1.00-2	6.60-2	4.32-1	4.36+1
18	η CONCENTRATION - FEED ADJUSTMENT TANK INPUT	2.22-5	3.00-3	1.73-2	7.43-1	1.34+2
19	θ CONCENTRATION - FEED ADJUSTMENT TANK INPUT	2.23-5	3.00-3	1.74-2	7.44-1	1.34+2
20	ε FLOW RATE - 1A COLUMN OUTPUT	1.10-3	2.50-2	4.67-2	3.06-1	2.18+1
21	η FLOW RATE - 1A COLUMN OUTPUT	3.79-5	1.50-2	2.96-2	1.27	3.94+2
22	θ FLOW RATE - 1A COLUMN OUTPUT	2.63-5	5.00-3	2.05-2	8.80-1	1.89+2
23	ε CONCENTRATION - 1A COLUMN OUTPUT	8.22-4	1.00-2	3.50-2	2.29-1	1.12+1
24	η CONCENTRATION - 1A COLUMN OUTPUT	2.64-5	5.00-3	2.06-2	8.81-1	1.89+2
25	θ CONCENTRATION - 1A COLUMN OUTPUT	1.95-5	2.00-3	1.52-2	6.51-1	1.02+2
26	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	7.60-4	5.04-3	1.73-5
27	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	3.80-4	1.67-2	2.99-5
28	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	3.80-4	1.67-2	2.54-5

TABLE E-XXV

MEASUREMENT UNCERTAINTIES: UPAA 2, GOAL 3, DAILY RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - FEED ADJUSTMENT TANK	3.00-2	3.00-2	0.00	0.00	4.61-5
2	ε CONCENTRATION - FEED ADJUSTMENT TANK	1.50-2	1.50-2	0.00	0.00	4.70-5
3	ε VOLUME - HA FEED TANK	2.26-3	3.00-2	3.56-1	3.56-1	1.23+1
4	ε CONCENTRATION - HA FEED TANK	1.80-3	1.50-2	2.83-1	2.83-1	7.35
5	ε Pu SOLIDS - HA CENTRIFUGE	2.00-1	2.00-1	1.06-3	1.06-3	9.25-5
6	ε INVENTORY - HA CONTACTOR	1.83-1	2.00-1	1.03-1	1.03-1	9.54-2
7	ε INVENTORY - HS COLUMN	3.86-2	1.00-1	1.64-1	1.64-1	1.59
8	ε INVENTORY - HC COLUMN	3.77-2	1.00-1	1.60-1	1.60-1	1.65
9	ε VOLUME - HCP REDUCER	8.68-3	3.00-2	1.85-1	1.85-1	2.46
10	ε CONCENTRATION - HCP REDUCER	6.04-3	1.00-2	1.29-1	1.29-1	6.54-1
11	ε VOLUME - 1A FEED TANK	1.06-2	3.00-2	1.66-1	1.66-1	1.82
12	ε CONCENTRATION - 1A FEED TANK	7.42-3	1.00-2	1.16-1	1.16-1	3.48-1
13	ε INVENTORY - 1A COLUMN	3.84-2	1.00-1	1.63-1	1.63-1	1.61
14	ε VOLUME - FEED ADJUSTMENT TANK INPUT	1.98-4	3.00-3	5.83-2	3.82-1	1.41+1
15	η VOLUME - FEED ADJUSTMENT TANK INPUT	2.05-5	1.00-3	1.60-2	6.86-1	4.77+1
16	θ VOLUME - FEED ADJUSTMENT TANK INPUT	2.03-5	1.00-3	1.58-2	6.79-1	4.82+1
17	ε CONCENTRATION - FEED ADJUSTMENT TANK INPUT	2.96-4	1.00-2	8.70-2	5.70-1	3.28+1
18	η CONCENTRATION - FEED ADJUSTMENT TANK INPUT	1.98-4	3.00-3	5.81-2	3.81-1	1.42+1
19	θ CONCENTRATION - FEED ADJUSTMENT TANK INPUT	2.95-5	3.00-3	2.30-2	9.85-1	1.01+2
20	ε FLOW RATE - 1A COLUMN OUTPUT	1.46-3	2.50-2	6.21-2	4.06-1	1.61+1
21	η FLOW RATE - 1A COLUMN OUTPUT	3.38-4	1.50-2	9.96-2	6.52-1	4.34+1
22	θ FLOW RATE - 1A COLUMN OUTPUT	3.48-5	5.00-3	2.71-2	1.16	1.43+2
23	ε CONCENTRATION - 1A COLUMN OUTPUT	1.08-3	1.00-2	4.57-2	2.99-1	8.30
24	η CONCENTRATION - 1A COLUMN OUTPUT	2.34-4	5.00-3	6.88-2	4.51-1	2.04+1
25	θ CONCENTRATION - 1A COLUMN OUTPUT	2.57-5	2.00-3	2.01-2	8.59-1	7.67+1
26	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	7.60-4	5.04-3	4.97-5
27	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	3.80-4	1.67-2	2.07-5
28	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	3.80-4	1.67-2	5.18-5

TABLE E-XXVI

MEASUREMENT UNCERTAINTIES: UPAA 2, GOAL 4, NO RECALIBRATION

NO.		DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε	VOLUME - FEED ADJUSTMENT TANK	3.00-2	3.00-2	0.00	0.00	4.93-6
2	ε	CONCENTRATION - FEED ADJUSTMENT TANK	1.50-2	1.50-2	0.00	0.00	9.03-6
3	ε	VOLUME - HA FEED TANK	7.29-4	3.00-2	1.15-1	1.15-1	4.02+1
4	ε	CONCENTRATION - HA FEED TANK	7.59-4	1.50-2	1.19-1	1.19-1	1.88+1
5	ε	Pu SOLIDS - HA CENTRIFUGE	2.00-1	2.00-1	1.06-3	1.06-3	8.46-6
6	ε	INVENTORY - HA CONTACTOR	1.55-1	2.00-1	8.78-2	8.78-2	2.89-1
7	ε	INVENTORY - HS COLUMN	1.38-2	1.00-1	5.86-2	5.86-2	6.24
8	ε	INVENTORY - HC COLUMN	1.45-2	1.00-1	6.13-2	6.13-2	5.92
9	ε	VOLUME - HCP REDUCER	3.14-3	3.00-2	6.68-2	6.68-2	8.55
10	ε	CONCENTRATION - HCP REDUCER	2.71-3	1.00-2	5.77-2	5.77-2	2.69
11	ε	VOLUME - 1A FEED TANK	4.07-3	3.00-2	6.34-2	6.34-2	6.37
12	ε	CONCENTRATION - 1A FEED TANK	3.16-3	1.00-2	4.92-2	4.92-2	2.17
13	ε	INVENTORY - 1A COLUMN	1.90-2	1.00-1	8.05-2	8.05-2	4.27
14	ε	VOLUME - FEED ADJUSTMENT TANK INPUT	1.07-4	3.00-3	1.19-2	1.46-1	2.70+1
15	η	VOLUME - FEED ADJUSTMENT TANK INPUT	1.33-5	1.00-3	1.48-3	2.22-1	7.43+1
16	θ	VOLUME - FEED ADJUSTMENT TANK INPUT	1.20-5	1.00-3	1.33-3	2.00-1	8.26+1
17	ε	CONCENTRATION - FEED ADJUSTMENT TANK INPUT	1.57-4	1.00-2	1.74-2	2.14-1	6.28+1
18	η	CONCENTRATION - FEED ADJUSTMENT TANK INPUT	2.39-5	3.00-3	2.66-3	3.99-1	1.24+2
19	θ	CONCENTRATION - FEED ADJUSTMENT TANK INPUT	8.98-6	3.00-3	9.99-4	1.50-1	3.33+2
20	ε	FLOW RATE - 1A COLUMN OUTPUT	9.67-4	2.50-2	1.55-2	1.90-1	2.48+1
21	η	FLOW RATE - 1A COLUMN OUTPUT	3.20-5	1.50-2	3.56-3	5.35-1	4.68+2
22	θ	FLOW RATE - 1A COLUMN OUTPUT	1.35-5	5.00-3	1.50-3	2.25-1	3.69+2
23	ε	CONCENTRATION - 1A COLUMN OUTPUT	6.01-4	1.00-2	9.66-3	1.18-1	1.56+1
24	η	CONCENTRATION - 1A COLUMN OUTPUT	2.23-5	5.00-3	2.48-3	3.73-1	2.23+2
25	θ	CONCENTRATION - 1A COLUMN OUTPUT	1.62-5	2.00-3	1.81-3	2.71-1	1.22+2
26	ε	TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	0.00	3.56-3	4.53-5
27	η	TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	3.46-5
28	θ	TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	4.44-5

TABLE E-XXVII

MEASUREMENT UNCERTAINTIES: UPAA 2, GOAL 4, DAILY RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - FEED ADJUSTMENT TANK	3.00-2	3.00-2	0.00	0.00	6.22-5
2	ε CONCENTRATION - FEED ADJUSTMENT TANK	1.50-2	1.50-2	0.00	0.00	6.22-5
3	ε VOLUME - HA FEED TANK	1.29-3	3.00-2	2.03-1	2.03-1	2.23+1
4	ε CONCENTRATION - HA FEED TANK	9.86-4	1.50-2	1.55-1	1.55-1	1.42+1
5	ε Pu SOLIDS - HA CENTRIFUGE	2.00-1	2.00-1	1.06-3	1.06-3	2.05-5
6	ε INVENTORY - HA CONTACTOR	1.05-1	2.00-1	5.93-2	5.93-2	9.08-1
7	ε INVENTORY - HS COLUMN	2.08-2	1.00-1	8.81-2	8.81-2	3.81
8	ε INVENTORY - HC COLUMN	2.04-2	1.00-1	8.67-2	8.67-2	3.89
9	ε VOLUME - HCP REDUCER	4.76-3	3.00-2	1.01-1	1.01-1	5.30
10	ε CONCENTRATION - HCP REDUCER	3.28-3	1.00-2	6.98-2	6.98-2	2.05
11	ε VOLUME - 1A FEED TANK	5.70-3	3.00-2	8.89-2	8.89-2	4.26
12	ε CONCENTRATION - 1A FEED TANK	3.99-3	1.00-2	6.22-2	6.22-2	1.51
13	ε INVENTORY - 1A COLUMN	2.09-2	1.00-1	8.85-2	8.85-2	3.79
14	ε VOLUME - FEED ADJUSTMENT TANK INPUT	1.27-4	3.00-3	1.41-2	1.73-1	2.27+1
15	η VOLUME - FEED ADJUSTMENT TANK INPUT	1.63-5	1.00-3	1.81-3	2.71-1	6.05+1
16	θ VOLUME - FEED ADJUSTMENT TANK INPUT	1.70-5	1.00-3	1.89-3	2.83-1	5.80+1
17	ε CONCENTRATION - FEED ADJUSTMENT TANK INPUT	1.62-4	1.00-2	1.80-2	2.20-1	6.08+1
18	η CONCENTRATION - FEED ADJUSTMENT TANK INPUT	1.25-4	3.00-3	1.39-2	1.70-1	2.30+1
19	θ CONCENTRATION - FEED ADJUSTMENT TANK INPUT	2.46-5	3.00-3	2.74-3	4.11-1	1.21+2
20	ε FLOW RATE - 1A COLUMN OUTPUT	9.12-4	2.50-2	1.47-2	1.80-1	2.64+1
21	η FLOW RATE - 1A COLUMN OUTPUT	2.05-4	1.50-2	2.28-2	2.80-1	7.21+1
22	θ FLOW RATE - 1A COLUMN OUTPUT	2.62-5	5.00-3	2.91-3	4.37-1	1.90+2
23	ε CONCENTRATION - 1A COLUMN OUTPUT	6.58-4	1.00-2	1.06-2	1.30-1	1.42+1
24	η CONCENTRATION - 1A COLUMN OUTPUT	1.47-4	5.00-3	1.63-2	2.00-1	3.31+1
25	θ CONCENTRATION - 1A COLUMN OUTPUT	1.82-5	2.00-3	2.03-3	3.04-1	1.09+2
26	ε TRANSFER - HA CENTRIFUGE TO SST	1.00-1	1.00-1	0.00	3.56-3	7.57-5
27	η TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	5.55-5
28	θ TRANSFER - HA CENTRIFUGE TO SST	5.00-2	5.00-2	0.00	8.36-3	7.23-5

TABLE E-XXVIII

MEASUREMENT UNCERTAINTIES: UPAA 3, GOAL 1, NO RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - 2A FEED TANK	3.00-2	3.00-2	4.71	4.71	4.95-5
2	ε CONCENTRATION - 2A FEED TANK	1.00-2	1.00-2	1.57	1.57	4.95-5
3	ε INVENTORY - 2A COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	5.17-5
4	ε INVENTORY - 2B COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	5.17-5
5	ε VOLUME - 3A FEED TANK	3.00-2	3.00-2	5.52-1	5.52-1	3.98-5
6	ε CONCENTRATION - 3A FEED TANK	1.00-2	1.00-2	1.84-1	1.84-1	5.23-5
7	ε INVENTORY - 3A COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	5.17-5
8	ε INVENTORY - 3B COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	5.17-5
9	ε VOLUME - Pu STRIPPER FEED	3.00-2	3.00-2	8.47-2	8.47-2	4.97-5
10	ε CONCENTRATION - Pu STRIPPER FEED	1.00-2	1.00-2	2.82-2	2.82-2	4.12-5
11	ε INVENTORY - Pu STRIPPER	1.00-1	1.00-1	5.66-1	5.66-1	3.96-5
12	ε VOLUME - Pu CONCENTRATOR	3.00-2	3.00-2	8.07-1	8.07-1	4.10-5
13	ε CONCENTRATION - Pu CONCENTRATOR	1.00-2	1.00-2	2.69-1	2.69-1	4.95-5
14	ε VOLUME - Pu CATCH TANK	3.00-2	3.00-2	0.00	0.00	4.12-5
15	ε CONCENTRATION - Pu CATCH TANK	1.00-2	1.00-2	0.00	0.00	4.12-5
16	ε FLOW RATE - 2A FEED TANK INPUT	2.50-2	2.50-2	4.02-1	4.92	3.05-5
17	η FLOW RATE - 2A FEED TANK INPUT	2.75-3	1.50-2	3.07-1	4.60+1	4.45
18	θ FLOW RATE - 2A FEED TANK INPUT	1.90-3	5.00-3	2.11-1	3.17+1	1.63
19	ε CONCENTRATION - 2A FEED TANK INPUT	1.00-2	1.00-2	1.61-1	1.97	6.70-5
20	η CONCENTRATION - 2A FEED TANK INPUT	1.92-3	5.00-3	2.14-1	3.20+1	1.61
21	θ CONCENTRATION - 2A FEED TANK INPUT	1.44-3	2.00-3	1.60-1	2.41+1	3.88-1
22	ε VOLUME - Pu SAMPLE TANK OUTPUT	3.00-3	3.00-3	2.36-1	2.89	4.95-5
23	η VOLUME - Pu SAMPLE TANK OUTPUT	9.88-4	1.00-3	1.10-1	1.65+1	1.19-2
24	θ VOLUME - Pu SAMPLE TANK OUTPUT	9.87-4	1.00-3	1.10-1	1.65+1	1.33-2
25	ε CONCENTRATION - Pu SAMPLE TANK OUTPUT	3.00-3	3.00-3	2.36-1	2.89	4.87-5
26	η CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.37-3	2.00-3	1.52-1	2.28+1	4.64-1
27	θ CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.39-3	2.00-3	1.55-1	2.33+1	4.34-1

TABLE E-XXIX

MEASUREMENT UNCERTAINTIES: UPAA 3, GOAL 1, WEEKLY RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - 2A FEED TANK	2.88-2	3.00-2	4.53	4.53	3.99-2
2	ε CONCENTRATION - 2A FEED TANK	1.00-2	1.00-2	1.57	1.57	2.12-5
3	ε INVENTORY - 2A COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	1.87-5
4	ε INVENTORY - 2B COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	1.40-5
5	ε VOLUME - 3A FEED TANK	3.00-2	3.00-2	5.52-1	5.52-1	3.99-5
6	ε CONCENTRATION - 3A FEED TANK	1.00-2	1.00-2	1.84-1	1.84-1	2.00-5
7	ε INVENTORY - 3A COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	4.78-5
8	ε INVENTORY - 3B COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	3.04-5
9	ε VOLUME - Pu STRIPPER FEED	3.00-2	3.00-2	8.47-2	8.47-2	3.20-5
10	ε CONCENTRATION - Pu STRIPPER FEED	1.00-2	1.00-2	2.82-2	2.82-2	4.05-5
11	ε INVENTORY - Pu STRIPPER	1.00-1	1.00-1	5.66-1	5.66-1	4.44-5
12	ε VOLUME - Pu CONCENTRATOR	3.00-2	3.00-2	8.07-1	8.07-1	4.25-5
13	ε CONCENTRATION - Pu CONCENTRATOR	1.00-2	1.00-2	2.69-1	2.69-1	3.32-5
14	ε VOLUME - Pu CATCH TANK	3.00-2	3.00-2	0.00	0.00	3.14-5
15	ε CONCENTRATION - Pu CATCH TANK	1.00-2	1.00-2	0.00	0.00	3.67-5
16	ε FLOW RATE - 2A FEED TANK INPUT	2.43-2	2.50-2	3.90-1	4.77	3.08-2
17	η FLOW RATE - 2A FEED TANK INPUT	1.10-2	1.50-2	1.23	3.93+1	3.62-1
18	θ FLOW RATE - 2A FEED TANK INPUT	2.92-3	5.00-3	3.25-1	4.87+1	7.14-1
19	ε CONCENTRATION - 2A FEED TANK INPUT	1.00-2	1.00-2	1.61-1	1.97	1.24-5
20	η CONCENTRATION - 2A FEED TANK INPUT	4.81-3	5.00-3	5.35-1	1.72+1	4.05-2
21	θ CONCENTRATION - 2A FEED TANK INPUT	1.73-3	2.00-3	1.92-1	2.89+1	1.58-1
22	ε VOLUME - Pu SAMPLE TANK OUTPUT	2.94-3	3.00-3	2.31-1	2.83	2.09-2
23	η VOLUME - Pu SAMPLE TANK OUTPUT	9.62-4	1.00-3	1.07-1	1.60+1	3.99-2
24	θ VOLUME - Pu SAMPLE TANK OUTPUT	9.49-4	1.00-3	1.06-1	1.58+1	5.39-2
25	ε CONCENTRATION - Pu SAMPLE TANK OUTPUT	3.00-3	3.00-3	2.36-1	2.89	1.68-5
26	η CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.94-3	2.00-3	2.16-1	6.93	3.02-2
27	θ CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.62-3	2.00-3	1.80-1	2.70+1	2.36-1

TABLE E-XXX

MEASUREMENT UNCERTAINTIES: UPAA 3, GOAL 2, NO RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - 2A FEED TANK	1.89-2	3.00-2	2.96	2.96	5.89-1
2	ε CONCENTRATION - 2A FEED TANK	9.38-3	1.00-2	1.47	1.47	6.65-2
3	ε INVENTORY - 2A COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	3.77-5
4	ε INVENTORY - 2B COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	2.59-4
5	ε VOLUME - 3A FEED TANK	2.93-2	3.00-2	5.40-1	5.40-1	2.25-2
6	ε CONCENTRATION - 3A FEED TANK	9.99-3	1.00-2	1.84-1	1.84-1	6.05-4
7	ε INVENTORY - 3A COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	4.16-5
8	ε INVENTORY - 3B COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	1.87-4
9	ε VOLUME - Pu STRIPPER FEED	3.00-2	3.00-2	8.47-2	8.47-2	4.45-5
10	ε CONCENTRATION - Pu STRIPPER FEED	1.00-2	1.00-2	2.82-2	2.82-2	4.81-5
11	ε INVENTORY - Pu STRIPPER	9.75-2	1.00-1	5.51-1	5.51-1	2.61-2
12	ε VOLUME - Pu CONCENTRATOR	2.84-2	3.00-2	7.65-1	7.65-1	5.47-2
13	ε CONCENTRATION - Pu CONCENTRATOR	1.00-2	1.00-2	2.69-1	2.69-1	4.94-5
14	ε VOLUME - Pu CATCH TANK	3.00-2	3.00-2	0.00	0.00	2.26-5
15	ε CONCENTRATION - Pu CATCH TANK	1.00-2	1.00-2	0.00	0.00	3.88-5
16	ε FLOW RATE - 2A FEED TANK INPUT	1.53-2	2.50-2	2.46-1	3.01	6.32-1
17	η FLOW RATE - 2A FEED TANK INPUT	6.41-4	1.50-2	7.13-2	1.07+1	2.24+1
18	θ FLOW RATE - 2A FEED TANK INPUT	4.58-4	5.00-3	5.10-2	7.65	9.92
19	ε CONCENTRATION - 2A FEED TANK INPUT	8.72-3	1.00-2	1.40-1	1.72	1.46-1
20	η CONCENTRATION - 2A FEED TANK INPUT	4.54-4	5.00-3	5.06-2	7.59	1.00+1
21	θ CONCENTRATION - 2A FEED TANK INPUT	3.37-4	2.00-3	3.75-2	5.63	4.94
22	ε VOLUME - Pu SAMPLE TANK OUTPUT	2.29-3	3.00-3	1.80-1	2.20	3.12-1
23	η VOLUME - Pu SAMPLE TANK OUTPUT	2.74-4	1.00-3	3.05-2	4.57	2.65
24	θ VOLUME - Pu SAMPLE TANK OUTPUT	2.68-4	1.00-3	2.98-2	4.47	2.73
25	ε CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.23-3	3.00-3	1.75-1	2.15	3.45-1
26	η CONCENTRATION - Pu SAMPLE TANK OUTPUT	3.35-4	2.00-3	3.73-2	5.59	4.97
27	θ CONCENTRATION - Pu SAMPLE TANK OUTPUT	3.37-4	2.00-3	3.75-2	5.62	4.93

TABLE E-XXXI

MEASUREMENT UNCERTAINTIES: UPAA 3, GOAL 2, WEEKLY RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - 2A FEED TANK	2.12-2	3.00-2	3.33	3.33	4.15-1
2	ε CONCENTRATION - 2A FEED TANK	1.00-2	1.00-2	1.57	1.57	3.30-5
3	ε INVENTORY - 2A COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	2.70-5
4	ε INVENTORY - 2B COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	2.70-5
5	ε VOLUME - 3A FEED TANK	3.00-2	3.00-2	5.52-1	5.52-1	4.86-5
6	ε CONCENTRATION - 3A FEED TANK	1.00-2	1.00-2	1.84-1	1.84-1	1.98-5
7	ε INVENTORY - 3A COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	2.70-5
8	ε INVENTORY - 3B COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	2.70-5
9	ε VOLUME - Pu STRIPPER FEED	3.00-2	3.00-2	8.47-2	8.47-2	4.86-5
10	ε CONCENTRATION - Pu STRIPPER FEED	1.00-2	1.00-2	2.82-2	2.82-2	2.39-6
11	ε INVENTORY - Pu STRIPPER	1.00-1	1.00-1	5.66-1	5.66-1	4.86-5
12	ε VOLUME - Pu CONCENTRATOR	3.00-2	3.00-2	8.07-1	8.07-1	5.30-5
13	ε CONCENTRATION - Pu CONCENTRATOR	1.00-2	1.00-2	2.69-1	2.69-1	2.79-5
14	ε VOLUME - Pu CATCH TANK	3.00-2	3.00-2	0.00	0.00	5.81-6
15	ε CONCENTRATION - Pu CATCH TANK	1.00-2	1.00-2	0.00	0.00	2.44-5
16	ε FLOW RATE - 2A FEED TANK INPUT	1.82-2	2.50-2	2.93-1	3.59	3.72-1
17	η FLOW RATE - 2A FEED TANK INPUT	2.25-3	1.50-2	2.51-1	8.04	5.67
18	θ FLOW RATE - 2A FEED TANK INPUT	5.60-4	5.00-3	6.24-2	9.35	7.93
19	ε CONCENTRATION - 2A FEED TANK INPUT	9.99-3	1.00-2	1.60-1	1.97	1.49-3
20	η CONCENTRATION - 2A FEED TANK INPUT	1.55-3	5.00-3	1.73-1	5.55	2.22
21	θ CONCENTRATION - 2A FEED TANK INPUT	4.17-4	2.00-3	4.64-2	6.96	3.80
22	ε VOLUME - Pu SAMPLE TANK OUTPUT	2.89-3	3.00-3	2.27-1	2.78	3.94-2
23	η VOLUME - Pu SAMPLE TANK OUTPUT	3.24-4	1.00-3	3.61-2	5.41	2.08
24	θ VOLUME - Pu SAMPLE TANK OUTPUT	3.27-4	1.00-3	3.63-2	5.45	2.06
25	ε CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.79-3	3.00-3	2.19-1	2.68	7.61-2
26	η CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.15-3	2.00-3	1.27-1	4.09	7.46-1
27	θ CONCENTRATION - Pu SAMPLE TANK OUTPUT	4.08-4	2.00-3	4.53-2	6.80	3.91

TABLE E-XXXII

MEASUREMENT UNCERTAINTIES: UPAA 3, GOAL 2, DAILY RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - 2A FEED TANK	2.08-2	3.00-2	3.26	3.26	4.45-1
2	ε CONCENTRATION - 2A FEED TANK	1.00-2	1.00-2	1.57	1.57	6.33-5
3	ε INVENTORY - 2A COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	4.28-5
4	ε INVENTORY - 2B COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	3.16-5
5	ε VOLUME - 3A FEED TANK	3.00-2	3.00-2	5.52-1	5.52-1	2.49-5
6	ε CONCENTRATION - 3A FEED TANK	1.00-2	1.00-2	1.84-1	1.84-1	1.81-6
7	ε INVENTORY - 3A COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	3.62-5
8	ε INVENTORY - 3B COLUMN	5.00-2	5.00-2	2.12-1	2.12-1	2.29-5
9	ε VOLUME - Pu STRIPPER FEED	3.00-2	3.00-2	8.47-2	8.47-2	2.69-5
10	ε CONCENTRATION - Pu STRIPPER FEED	1.00-2	1.00-2	2.82-2	2.82-2	1.53-5
11	ε INVENTORY - Pu STRIPPER	1.00-1	1.00-1	5.66-1	5.66-1	3.67-5
12	ε VOLUME - Pu CONCENTRATOR	3.00-2	3.00-2	8.07-1	8.07-1	9.42-5
13	ε CONCENTRATION - Pu CONCENTRATOR	1.00-2	1.00-2	2.69-1	2.69-1	2.42-5
14	ε VOLUME - Pu CATCH TANK	3.00-2	3.00-2	0.00	0.00	2.20-5
15	ε CONCENTRATION - Pu CATCH TANK	1.00-2	1.00-2	0.00	0.00	2.41-5
16	ε FLOW RATE - 2A FEED TANK INPUT	1.96-2	2.50-2	3.15-1	3.85	2.77-1
17	η FLOW RATE - 2A FEED TANK INPUT	4.72-3	1.50-2	5.25-1	6.43	2.18
18	θ FLOW RATE - 2A FEED TANK INPUT	6.09-4	5.00-3	6.78-2	1.02+1	7.21
19	ε CONCENTRATION - 2A FEED TANK INPUT	1.00-2	1.00-2	1.61-1	1.97	4.15-7
20	η CONCENTRATION - 2A FEED TANK INPUT	3.22-3	5.00-3	3.58-1	4.39	5.55-1
21	θ CONCENTRATION - 2A FEED TANK INPUT	4.51-4	2.00-3	5.02-2	7.53	3.43
22	ε VOLUME - Pu SAMPLE TANK OUTPUT	2.84-3	3.00-3	2.23-1	2.73	5.73-2
23	η VOLUME - Pu SAMPLE TANK OUTPUT	3.53-4	1.00-3	3.92-2	5.88	1.84
24	θ VOLUME - Pu SAMPLE TANK OUTPUT	3.54-4	1.00-3	3.94-2	5.91	1.82
25	ε CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.87-3	3.00-3	2.25-1	2.76	4.70-2
26	η CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.88-3	2.00-3	2.09-1	2.56	6.47-2
27	θ CONCENTRATION - Pu SAMPLE TANK OUTPUT	4.43-4	2.00-3	4.92-2	7.38	3.52

TABLE E-XXXIII

MEASUREMENT UNCERTAINTIES: UPAA 3, GOAL 3, NO RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - 2A FEED TANK	1.87-3	3.00-2	2.93-1	2.93-1	1.51+1
2	ε CONCENTRATION - 2A FEED TANK	1.48-3	1.00-2	2.32-1	2.32-1	5.77
3	ε INVENTORY - 2A COLUMN	2.82-2	5.00-2	1.20-1	1.20-1	7.74-1
4	ε INVENTORY - 2B COLUMN	2.64-2	5.00-2	1.12-1	1.12-1	8.93-1
5	ε VOLUME - 3A FEED TANK	7.72-3	3.00-2	1.42-1	1.42-1	2.88
6	ε CONCENTRATION - 3A FEED TANK	5.58-3	1.00-2	1.03-1	1.03-1	7.91-1
7	ε INVENTORY - 3A COLUMN	2.47-2	5.00-2	1.05-1	1.05-1	1.02
8	ε INVENTORY - 3B COLUMN	2.48-2	5.00-2	1.05-1	1.05-1	1.01
9	ε VOLUME - Pu STRIPPER FEED	2.33-2	3.00-2	6.57-2	6.57-2	2.89-1
10	ε CONCENTRATION - Pu STRIPPER FEED	1.00-2	1.00-2	2.82-2	2.82-2	4.28-6
11	ε INVENTORY - Pu STRIPPER	2.51-2	1.00-1	1.42-1	1.42-1	2.99
12	ε VOLUME - Pu CONCENTRATOR	6.10-3	3.00-2	1.64-1	1.64-1	3.92
13	ε CONCENTRATION - Pu CONCENTRATOR	4.21-3	1.00-2	1.13-1	1.13-1	1.38
14	ε VOLUME - Pu CATCH TANK	3.00-2	3.00-2	0.00	0.00	5.05-5
15	ε CONCENTRATION - Pu CATCH TANK	1.00-2	1.00-2	0.00	0.00	7.90-5
16	ε FLOW RATE - 2A FEED TANK INPUT	1.14-3	2.50-2	4.87-2	3.19-1	2.08+1
17	η FLOW RATE - 2A FEED TANK INPUT	3.88-5	1.50-2	3.02-2	1.29	3.86+2
18	θ FLOW RATE - 2A FEED TANK INPUT	2.75-5	5.00-3	2.14-2	9.18-1	1.81+2
19	ε CONCENTRATION - 2A FEED TANK INPUT	8.63-4	1.00-2	3.67-2	2.40-1	1.06+1
20	η CONCENTRATION - 2A FEED TANK INPUT	2.75-5	5.00-3	2.14-2	9.19-1	1.81+2
21	θ CONCENTRATION - 2A FEED TANK INPUT	2.05-5	2.00-3	1.60-2	6.84-1	9.66+1
22	ε VOLUME - Pu SAMPLE TANK OUTPUT	1.95-4	3.00-3	4.05-2	2.65-1	1.44+1
23	η VOLUME - Pu SAMPLE TANK OUTPUT	1.69-5	1.00-3	1.31-2	5.63-1	5.83+1
24	θ VOLUME - Pu SAMPLE TANK OUTPUT	1.62-5	1.00-3	1.26-2	5.42-1	6.06+1
25	ε CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.97-4	3.00-3	4.09-2	2.68-1	1.43+1
26	η CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.03-5	2.00-3	1.58-2	6.77-1	9.75+1
27	θ CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.87-5	2.00-3	1.46-2	6.25-1	1.06+2

TABLE E-XXXIV

MEASUREMENT UNCERTAINTIES: UPAA 3, GOAL 3, DAILY RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - 2A FEED TANK	2.35-3	3.00-2	3.69-1	3.69-1	1.18+1
2	ε CONCENTRATION - 2A FEED TANK	1.75-3	1.00-2	2.75-1	2.75-1	4.71
3	ε INVENTORY - 2A COLUMN	3.12-2	5.00-2	1.32-1	1.32-1	6.01-1
4	ε INVENTORY - 2B COLUMN	3.32-2	5.00-2	1.41-1	1.41-1	5.06-1
5	ε VOLUME - 3A FEED TANK	9.56-3	3.00-2	1.76-1	1.76-1	2.14
6	ε CONCENTRATION - 3A FEED TANK	6.94-3	1.00-2	1.28-1	1.28-1	4.41-1
7	ε INVENTORY - 3A COLUMN	3.19-2	5.00-2	1.35-1	1.35-1	5.70-1
8	ε INVENTORY - 3B COLUMN	3.04-2	5.00-2	1.29-1	1.29-1	6.43-1
9	ε VOLUME - Pu STRIPPER FEED	2.90-2	3.00-2	8.20-2	8.20-2	3.30-2
10	ε CONCENTRATION - Pu STRIPPER FEED	1.00-2	1.00-2	2.82-2	2.82-2	4.96-5
11	ε INVENTORY - Pu STRIPPER	3.18-2	1.00-1	1.80-1	1.80-1	2.14
12	ε VOLUME - Pu CONCENTRATOR	7.48-3	3.00-2	2.01-1	2.01-1	3.01
13	ε CONCENTRATION - Pu CONCENTRATOR	5.52-3	1.00-2	1.48-1	1.48-1	8.11-1
14	ε VOLUME - Pu CATCH TANK	3.00-2	3.00-2	0.00	0.00	7.62-5
15	ε CONCENTRATION - Pu CATCH TANK	1.00-2	1.00-2	0.00	0.00	5.52-6
16	ε FLOW RATE - 2A FEED TANK INPUT	1.56-3	2.50-2	6.65-2	4.36-1	1.50+1
17	η FLOW RATE - 2A FEED TANK INPUT	3.52-4	1.50-2	1.04-1	6.79-1	4.16+1
18	θ FLOW RATE - 2A FEED TANK INPUT	3.63-5	5.00-3	2.83-2	1.21	1.37+2
19	ε CONCENTRATION - 2A FEED TANK INPUT	1.12-3	1.00-2	4.77-2	3.12-1	7.91
20	η CONCENTRATION - 2A FEED TANK INPUT	2.49-4	5.00-3	7.35-2	4.81-1	1.91+1
21	θ CONCENTRATION - 2A FEED TANK INPUT	2.68-5	2.00-3	2.09-2	8.94-1	7.37+1
22	ε VOLUME - Pu SAMPLE TANK OUTPUT	2.65-4	3.00-3	5.51-2	3.61-1	1.03+1
23	η VOLUME - Pu SAMPLE TANK OUTPUT	2.16-5	1.00-3	1.68-2	7.19-1	4.54+1
24	θ VOLUME - Pu SAMPLE TANK OUTPUT	2.15-5	1.00-3	1.68-2	7.18-1	4.54+1
25	ε CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.62-4	3.00-3	5.44-2	3.56-1	1.05+1
26	η CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.80-4	2.00-3	5.30-2	3.47-1	1.01+1
27	θ CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.66-5	2.00-3	2.07-2	8.87-1	7.43+1

TABLE E-XXXV

MEASUREMENT UNCERTAINTIES: UPAA 3, GOAL 4, NO RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - 2A FEED TANK	8.18-4	3.00-2	1.28-1	1.28-1	3.57+1
2	ε CONCENTRATION - 2A FEED TANK	6.93-4	1.00-2	1.09-1	1.09-1	1.34+1
3	ε INVENTORY - 2A COLUMN	1.22-2	5.00-2	5.16-2	5.16-2	3.11
4	ε INVENTORY - 2B COLUMN	1.43-2	5.00-2	6.08-2	6.08-2	2.49
5	ε VOLUME - 3A FEED TANK	4.57-3	3.00-2	8.41-2	8.41-2	5.57
6	ε CONCENTRATION - 3A FEED TANK	3.27-3	1.00-2	6.02-2	6.02-2	2.06
7	ε INVENTORY - 3A COLUMN	1.29-2	5.00-2	5.45-2	5.45-2	2.89
8	ε INVENTORY - 3B COLUMN	1.44-2	5.00-2	6.12-2	6.12-2	2.46
9	ε VOLUME - Pu STRIPPER FEED	1.37-2	3.00-2	3.87-2	3.87-2	1.19
10	ε CONCENTRATION - Pu STRIPPER FEED	9.57-3	1.00-2	2.70-2	2.70-2	4.49-2
11	ε INVENTORY - Pu STRIPPER	1.41-2	1.00-1	7.97-2	7.97-2	6.09
12	ε VOLUME - Pu CONCENTRATOR	3.38-3	3.00-2	9.10-2	9.10-2	7.87
13	ε CONCENTRATION - Pu CONCENTRATOR	1.94-3	1.00-2	5.22-2	5.22-2	4.16
14	ε VOLUME - Pu CATCH TANK	3.00-2	3.00-2	0.00	0.00	1.08-5
15	ε CONCENTRATION - Pu CATCH TANK	1.00-2	1.00-2	0.00	0.00	8.45-5
16	ε FLOW RATE - 2A FEED TANK INPUT	7.32-4	2.50-2	1.18-2	1.44-1	3.32+1
17	η FLOW RATE - 2A FEED TANK INPUT	2.62-5	1.50-2	2.91-3	4.37-1	5.72+2
18	θ FLOW RATE - 2A FEED TANK INPUT	2.60-5	5.00-3	2.90-3	4.35-1	1.91+2
19	ε CONCENTRATION - 2A FEED TANK INPUT	5.24-4	1.00-2	8.43-3	1.03-1	1.81+1
20	η CONCENTRATION - 2A FEED TANK INPUT	2.25-5	5.00-3	2.51-3	3.76-1	2.21+2
21	θ CONCENTRATION - 2A FEED TANK INPUT	1.85-5	2.00-3	2.06-3	3.09-1	1.07+2
22	ε VOLUME - Pu SAMPLE TANK OUTPUT	1.31-4	3.00-3	1.03-2	1.26-1	2.20+1
23	η VOLUME - Pu SAMPLE TANK OUTPUT	1.27-5	1.00-3	1.42-3	2.12-1	7.75+1
24	θ VOLUME - Pu SAMPLE TANK OUTPUT	1.42-5	1.00-3	1.58-3	2.37-1	6.95+1
25	ε CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.25-4	3.00-3	9.84-3	1.21-1	2.30+1
26	η CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.72-5	2.00-3	1.91-3	2.87-1	1.15+2
27	θ CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.54-5	2.00-3	1.71-3	2.57-1	1.29+2

TABLE E-XXXVI

MEASUREMENT UNCERTAINTIES: UPAA 3, GOAL 4, DAILY RECALIBRATION

NO.	DESCRIPTION	MEASUREMENT ERRORS CALCULATED (1σ)	CURRENT (1σ)	MATERIALS BALANCE σ 1 DAY (Kg Pu)	6 MONTHS (Kg Pu)	RELATIVE COST
1	ε VOLUME - 2A FEED TANK	1.18-3	3.00-2	1.85-1	1.85-1	2.45+1
2	ε CONCENTRATION - 2A FEED TANK	8.16-4	1.00-2	1.28-1	1.28-1	1.12+1
3	ε INVENTORY - 2A COLUMN	1.55-2	5.00-2	6.56-2	6.56-2	2.24
4	ε INVENTORY - 2B COLUMN	1.55-2	5.00-2	6.57-2	6.57-2	2.23
5	ε VOLUME - 3A FEED TANK	4.91-3	3.00-2	9.03-2	9.03-2	5.11
6	ε CONCENTRATION - 3A FEED TANK	3.46-3	1.00-2	6.26-2	6.26-2	1.94
7	ε INVENTORY - 3A COLUMN	1.55-2	5.00-2	6.56-2	6.56-2	2.24
8	ε INVENTORY - 3B COLUMN	1.55-2	5.00-2	6.56-2	6.56-2	2.23
9	ε VOLUME - Pu STRIPPER FEED	1.70-2	3.00-2	4.81-2	4.81-2	7.60-1
10	ε CONCENTRATION - Pu STRIPPER FEED	1.00-2	1.00-2	2.82-2	2.82-2	1.34-5
11	ε INVENTORY - Pu STRIPPER	1.60-2	1.00-1	9.07-2	9.07-2	5.24
12	ε VOLUME - Pu CONCENTRATOR	3.79-3	3.00-2	1.02-1	1.02-1	6.91
13	ε CONCENTRATION - Pu CONCENTRATOR	2.64-3	1.00-2	7.10-2	7.10-2	2.79
14	ε VOLUME - Pu CATCH TANK	3.00-2	3.00-2	0.00	0.00	8.44-6
15	ε CONCENTRATION - Pu CATCH TANK	1.00-2	1.00-2	0.00	0.00	9.33-6
16	ε FLOW RATE - 2A FEED TANK INPUT	9.51-4	2.50-2	1.53-2	1.87-1	2.53+1
17	η FLOW RATE - 2A FEED TANK INPUT	2.19-4	1.50-2	2.44-2	2.99-1	6.74+1
18	θ FLOW RATE - 2A FEED TANK INPUT	2.87-5	5.00-3	3.19-3	4.79-1	1.73+2
19	ε CONCENTRATION - 2A FEED TANK INPUT	6.98-4	1.00-2	1.12-2	1.37-1	1.33+1
20	η CONCENTRATION - 2A FEED TANK INPUT	1.52-4	5.00-3	1.70-2	2.08-1	3.18+1
21	θ CONCENTRATION - 2A FEED TANK INPUT	2.11-5	2.00-3	2.35-3	3.53-1	9.36+1
22	ε VOLUME - Pu SAMPLE TANK OUTPUT	1.62-4	3.00-3	1.27-2	1.56-1	1.75+1
23	η VOLUME - Pu SAMPLE TANK OUTPUT	1.68-5	1.00-3	1.87-3	2.80-1	5.86+1
24	θ VOLUME - Pu SAMPLE TANK OUTPUT	1.68-5	1.00-3	1.86-3	2.80-1	5.86+1
25	ε CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.62-4	3.00-3	1.27-2	1.56-1	1.75+1
26	η CONCENTRATION - Pu SAMPLE TANK OUTPUT	1.12-4	2.00-3	1.25-2	1.53-1	1.68+1
27	θ CONCENTRATION - Pu SAMPLE TANK OUTPUT	2.11-5	2.00-3	2.35-3	3.52-1	9.37+1

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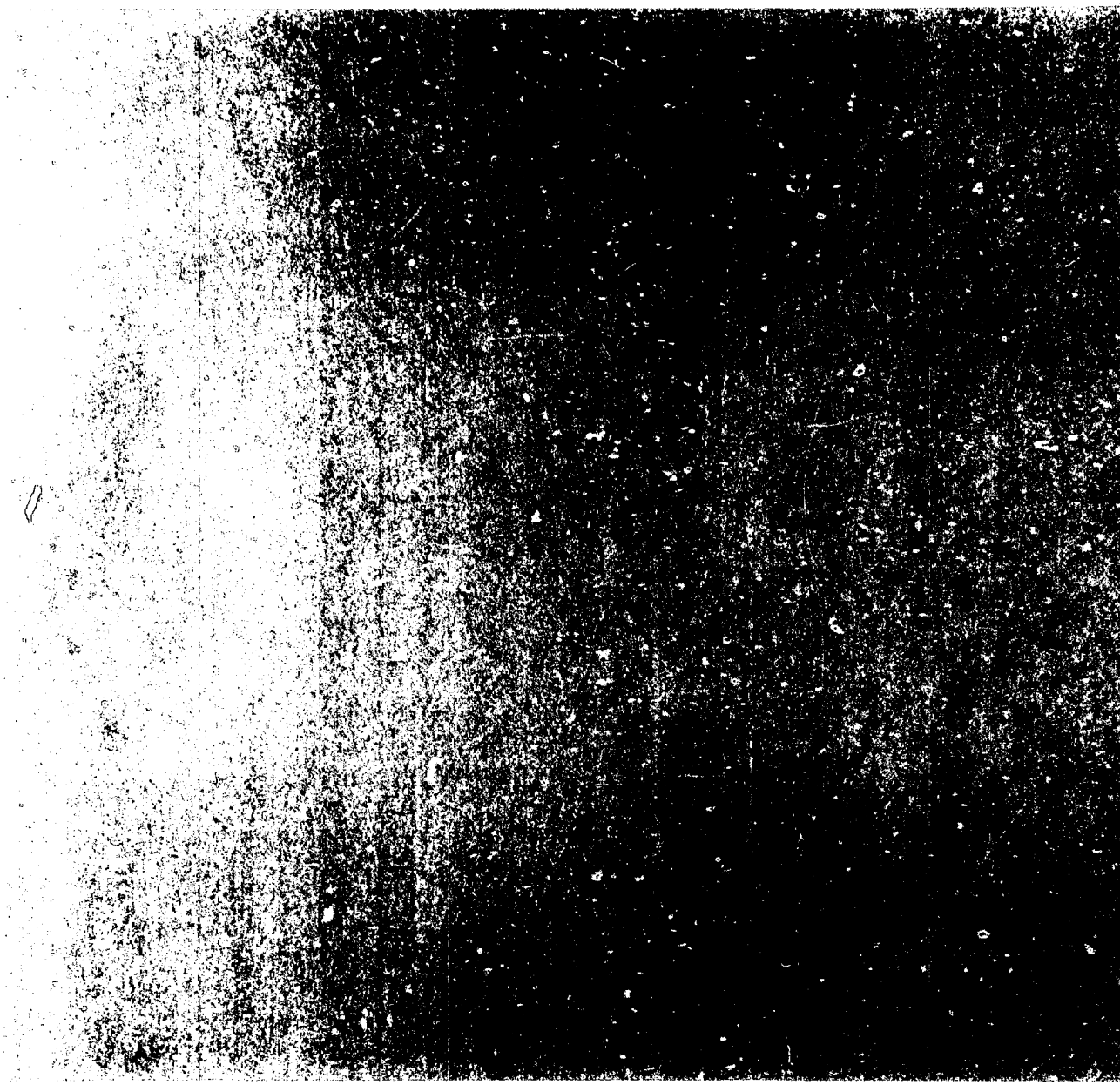

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