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IMPROVED MATERIAL ACCOUNTING FOR PLUTONIUM PROCESSING FACILITIES AND A ^{235}U - HTGR FUEL FABRICATION FACILITY

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1.0 INTRODUCTION

This report was prepared as part of the Special Safeguards tudy.(1) The major objective of the study was to: "provide a ystematic assessment of the safeguards measures identified in the raft Generic Environmental Statement on Mixed Oxide (GESMO) and evelop a safeguards plan for protection of plants and materials n the plutonium recycle and high-enriched uranium cycle." Studies ere initiated to investigate potential gains from the application f new technologies such as real-time material control. Simultaeously, studies were initiated to evaluate the potential gains rom carrying out existing safeguards measures. This study, titled Improved Material Accounting," deals with the latter.

Presently, all facilities licensed to process significant uantities of special nuclear materials must establish and maintain a system of nuclear materials control and accountability. As part of this system, limits of error based on the SNM measurement uncertainties must be established and, to within the limit of these uncertainties, all material must be accounted for.(2) This report describes the safeguards characteristics of a material accounting system and then describes the material accounting characteristics of future plutonium and ^{235}U - HTGR fuel fabrication facilities.

There are always some dangers associated with any attempt to model a facility which has yet to be built. It is impossible to project the influence of future technological developments. However, useful areas of future development can only be identified by applying present technology to future plants. If these areas are actually subject to future study and technological developments, the future facilities will have more favorable characteristics than those shown in this report.

The models shown in this report are not based on the operating characteristics of particular plants. However, when possible, data used in the models are referenced to the performance characteristics of material accounting equipment. This relevant experience is documented, thereby providing a basis for future study and improvement.

REFERENCES

1) Office of Special Studies, Special Safeguards Study - Scopes of Work, NUREG-75/060, US Nuclear Regulatory Commission, Washington, D. C., June 1975.

2) Code of Federal Regulations, Title 10 Part 70.58.

2.0 SUMMARY

This study described the general safeguards characteristics of a material measurement system and then describes typical accounting systems for a fuel reprocessing plant, a plutonium nitrate to oxide conversion facility, a LWR mixed oxide fuel fabrication facility, and a high-enriched uranium HTGR fuels plant. These facilities are commercial size, envisioned to be operating in the mid-1980s.

The measurement characteristics of the commercial size plants differ significantly from presently operating facilities. Present facilities tend to have large static inventories of material whereas future facilities are best characterized as having a high material throughput. Thus, many of the measurement problems associated with present facilities will be less significant in future facilities. Based on the models shown in this report, systematic errors will pose the greatest limit on measurement systems in future facilities. As a result, it is recommended that:

- the existing licensing review process for material accounting performance be initiated at the conceptual design stage and follow the progress of the equipment measurement system performance tests through startup;
- the present capability of measurement systems, particularly with regard to reducing the limit of error of calibrations, be throughly reviewed and the results of such studies be documented and available in the open literature;

- regulations governing cumulative LEMUF and series of MUFs be developed to supplement current LEMUF regulation for single accounting periods.

esent regulations require a measurement control program as part an accounting system. When used with the above recommendations, e material accounting characteristics of future facilities should greatly improved. In addition to these general findings, provements specific to a particular facility were also identified.

For the chemical separations plant, it is recommended that:

- formal material accounting periods be no less frequent than quarterly for the separations area;
- studies be initiated to demonstrate the accuracy and usefulness of "running inventory" measurements;
- formal material accounting periods be no less frequent than monthly for the plutonium nitrate storage area;
- daily weight factor (specific gravity times liquid height) readings to be taken on static plutonium nitrate storage tanks to ensure that no change has taken place.

For the plutonium oxide conversion facility, it is recommended that:

- formal material accounting periods be no less frequent than monthly;
- formal monthly inventory measurements be supplemented with informal inventory measurements whenever a process runout occurs.

For the mixed oxide fuel fabrication plant, it is recommended that:

- formal inventory reporting requirements be no less frequent than monthly;
- the PuO_2 storage area be formalized as a material balance area and that daily physical inventories using PuO_2 weight be performed over this area.

The above recommendations, if carefully followed, are envisioned to greatly improve the material accounting characteristics of future plutonium and high-enriched uranium processing facilities. In section 8.0, the benefits of an improved material accounting system are compared with the costs associated with the improvements. In most cases, the additional costs range from several thousands to several hundred thousand dollars per year. In one case, the requirement for a formal quarterly inventory over the separations area of a reprocessing plant, an annual lost production cost of $25M occurs. This is considered to be an extremely high penalty and it prevents reducing the formal inventory requirement from the present semiannual regulatory requirement. In all other cases, the cost-benefit relationship of the improvements is considered favorable.

3.0 IMPROVED MATERIAL ACCOUNTING

3.0 PURPOSE

The purpose of the task is to evaluate the improvements in the sensitivity and timeliness of loss detection that realistically can be achieved in currently planned or future plutonium processing facilities. Improvements in sensitivity and timeliness of loss detection depend upon evaluating the safeguards effectiveness of various material control practices and equipment design features that could be used to improve the performance of material accounting. Materials accounting is used in the broad sense as a safeguards function that provides deterrence and detection of diversion and assurance that diversion has not occurred.

3.2 FEATURES OF MATERIALS ACCOUNTING

3.2.1 Objectives of Materials Accounting

The objective of materials accounting measures is to identify the quantities, locations, and forms of nuclear material under a particular custodial responsibility. Under the broad objective, safeguards goals are to detect the absence of material from the accounting records and to identify the specific area of loss and those immediately responsible for the material.

Materials accounting is the cornerstone of safeguards assurance in that it provides quantitative evidence that the more timely measures for the prevention and detection of diversion have been effective. This quantitative check is the after-the-fact evidence that the nuclear material is indeed present and accounted for.

Materials accounting has the virtue of being independently verifiable. This feature has particular value to national or international safeguards authorities who can take advantage of their central position in the flow of materials accounting data to obtain independent verification of facility data. For example, advantage can be taken of shipper-receiver data in which two parties both testify to the presence of the stated quantity in the shipment.

3.2.2 Forms of Accounting

Two material accounting procedures are employed in nuclear processing facilities: item accounting and material balance accounting. Item accounting, as with the counting of money, is exact and can be repeated as frequently as desired. The sensitivity of material or mass balance accounting is inherently limited by measurement uncertainties in its power to detect loss. In addition, its timeliness is limited by the need to "close" a material balance, calling for a physical inventory to complete the balance.

Item accounting is used as a supplementary assurance measure to mass or quantity accounting to provide visual and immediate evidence that sealed containers, finished fuel rods, etc., are present and accounted for.

However, item accounting is not a fundamental assurance measure. The very nature of processing operations require that items lose their identity. In addition, the amount of material in finished items can be known only through measurements of each item. Thus, the certainty with which all material is ultimately accounted for is dependent on the accuracy of measured quantities.

Material balance accounts are taken over a specified period of time. The material balance is formed by adding all measured receipts to the initial measured physical inventory and subtracting away all measured removals. These additions to and subtractions from the initial measured inventory yield the so-called "book inventory" which is the amount of material that "should be" present. The measured physical inventory establishes what "is" present. The difference between the book inventory and the physical inventory is termed "material unaccounted for," abbreviated to "MUF."

3.2.3 Limitations in Sensitivity and Timeliness

Mass accounting's value as a safeguards measure is limited by its lack of sensitivity and its lack of timeliness to detect loss. The limitation in sensitivity is inherent in that there will always be some measurement uncertainties. Materials accounting is also "blind" in that it cannot determine whether a detected loss is due to diversion or some other cause.

The limitation in timeliness is more practical than inherent. Timeliness is limited by the frequency of physical inventory taking. In some instances, a loss could remain undiscovered until the time a physical inventory is taken. There are practical limitations on how often physical inventories can be taken. In many processing operations, there is a real economic need to operate the process on a continuous basis for a reasonable length of time, without shutting down the process in order to take a physical inventory.

Sensitivity

Because of the inherent measurement uncertainty, there is usually some difference between what "should be" and what "is" - between the book inventory and the physical inventory. Differences also may develop from unmeasured losses and buildup of material in process equipment. The sum of all such differences is expressed as MUF. Since MUF is derived from measurements and subject to measurement uncertainties, it may be treated as a statistic. As a statistic MUF has an expected value and a standard deviation. The expected value is the true loss or buildup of material in the process. The standard deviation reflects whether the difference between what "is" and what "should be" could be due solely to measurement uncertainties. The standard deviation of MUF associated with these measurement uncertainties is estimated by combining or propagating the measurement uncertainties associated with each quantity entering into the MUF equation. The standard deviation of MUF arising from measurement uncertainties is represented by the term σ_{MUF} (sigma MUF). In the Federal regulations dealing with materials accounting, the term "limit of error" of MUF, abbreviated to LEMUF, is used rather than σ_{MUF}. The limit of error of MUF, or LEMUF, is defined as twice the standard deviation of MUF, e.g.,

$$LEMUF = 2\sigma_{MUF}.^{*}$$

The value for LEMUF may be expressed in either absolute or relative units. It is expressed in absolute units in weight units of element or isotope, e.g., kilograms of plutonium. It is usually expressed in relative units as a percentage of the plant throughput.

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* The statistical basis for this equation is discussed in Appendix A. Basically, LEMUF, defined in this way, is taken to have the following significance. If no unmeasured losses have occurred, then 95 times out of 100 what "should be" and what "is" present is expected to differ by

The power to detect loss is roughly inversely proportional to the magnitude of LEMUF. The smaller the value of LEMUF is, the greater is the power of detection. For a given value of LEMUF, the probability of detecting loss is roughly directly proportional to the amount of loss; the greater the loss, the greater the probability of detection.

At this point, several generalizations about LEMUF are useful. On the one hand, absolute measurement uncertainties are always additive. Thus, for a given plant measurement system, the absolute value of LEMUF increases as the amounts of the measured quantities entering into the MUF calculation are increased. Similarly, for a constant flow process, the absolute value of LEMUF increases with the length of the accounting period simply due to the increase in quantities and their associated uncertainties.

By contrast, the relative value of LEMUF, when expressed as a percentage of throughput, tends to decrease with increasing throughput. This stems from two reasons, the measurement uncertainties represented by LEMUF have both random and systematic components. The random components decrease in a relative sense with replication or as the number of measured items entering into the MUF calculation increase. The systematic components of error, by contrast, tend to remain constant in a relative sense with replication. The second reason for the decrease in the relative value of LEMUF as throughput increases in that uncertainties arising from inventory measurements make a smaller contribution to LEMUF.

It is apparent from the above discussion that the magnitude of LEMUF, which is the index of the sensitivity of loss detection, is dependent on the length of the accounting period. This relationship between the sensitivity and timeliness of loss detection is explained more fully in the following discussion.

Timeliness

The timeliness with which a loss (MUF) can be detected is a function of both the frequency of inventory taking and the time required to make the measurements associated with closing the material balance. In general, the former is the predominant factor.

In considering the relationship betwen frequency of physical inventory taking and detection of loss, several aspects are important. These include:

- The promptness with which a diversion could be detected and action taken to recover the material.
- The probability with which a loss "event" could be detected.
- The probability with which a rate of loss could be detected.

A loss event is defined as a relatively large loss that occurs in a very short period of time and during a single accounting period. A rate of loss is defined as a relatively small loss (or buildup) that takes place continuously over a number of accounting periods.

From the standpoint of providing time for recovery and apprehension, frequent physical inventories are always of advantage. Obviously, the sooner a loss is detected, the sooner action can be taken to recover the material.

The probability that a loss event can be detected depends on the amount of loss and absolute value of LEMUF. As was noted earlier, the absolute limit of error can be reduced, thereby increasing the probability of detection in two basic ways: first, by improving the quality of measurements and secondly, by reducing the length of the accounting period, i.e., increasing the frequency of physical inventory taking. This latter approach, however, has practical and technical limitations.

Physical inventory taking can incur additional costs because of lost production and additional measurements. From a technical standpoint, a point of diminishing return is reached where the taking of more frequent physical inventories reduces the limit of error only slightly. This is the point where most of the contribution to LEMUF is due to inventory measurement uncertainty, with the uncertainty due to measurement of receipts and removals playing only a small part.

By contrast, the sensitivity with which a "rate of loss" can be detected generally increases with time. A small but constant loss or buildup occurring over a number of material balance periods is best detected by evaluation of the cumulative MUF. In this case, the contribution of the inventory error plays a less important role since only the beginning inventory of the first period and the ending inventory of the last period contribute to the measurement uncertainty of cumulative MUF. Since a constant or persistent loss accumulates in time, a point is reached where the ratio of the accumulated loss to the accumulated measurement uncertainty is optimum from a detection standpoint.

In summary, the best sensitivity for detecting a large single theft or loss event is obtained by taking frequent physical inventories. Whereas the best sensitivity for detecting a small continuous theft or a continuous loss occurring over a number of accounting periods is by the evaluation of cumulative MUF. In detecting a loss event, the observed MUF of an individual accounting period is evaluated against the measurement uncertainty of MUF for that period. For detecting a rate of loss, the cumulative MUF for a number of accounting periods is evaluated against the cumulative measurement uncertainty.

3.2.4 Historical Limitations of Physical Inventory Measurements

In certain process designs, the assurance that could be obtained from short accounting periods was limited by the exactness with which the in-process inventory could be measured. Often, large quantities of inventory were present at locations in which the quantities could be only crudely estimated or were in forms inherently difficult to measure. As a result of these difficulties, research and development efforts were initiated in recent years to provide equipment design guidelines for reducing those limitations.. The efforts have resulted in design guidelines$^{(1-4)}$ aimed at achieving the following objectives:

- The transfer of the bulk of the in-process inventory to locations where it can be measured with a high degree of exactness.
- The incorporation in the process design of systems for measuring the material in process vessels.
- The incorporation of process steps such as in-house scrap

recovery that convert difficult to measure materials to more readily measurable forms.

Currently designed processes are expected to include features that allow mass accounting to reach measurement sensitivities of loss detection approaching the state of the art.

3.3 INTERACTION WITH OTHER MATERIAL CONTROL AND ACCOUNTING MEASURES

Often the inherent limitations of mass balance accounting are assumed to apply to an entire facility. This tends to create the false impression that (1) a loss can be detected only after a physical inventory has been taken and (2) the sensitivity of detecting a loss is always limited by measurement uncertainty.

Normally, mass balance accounting is applied only to the processing activities. Item accounting is usually applied to materials held in storage awaiting processing, shipping, etc. This form of accounting can be very timely. If material can be properly sealed and contained, seals can be checked without measurement error.

Formal materials accounting is usually applied to a whole plant or over several process steps. Usually, the best state-of-art measurements are used for accountability purposes. These exact measurements are often fairly expensive and often require several days of analysis time. Less expensive measurements with shorter turnaround times are normally used for process control purposes. Because of the immediate and local nature of process control activities, most large loss events would be discovered quite promptly and the area of loss quickly identified. The staff expects that the RETIMAC concept, supplementing process control data with NDA instrumentation to obtain "Real Time Material Control," will provide eventually a major improvement in that form of theft detection.

As part of the evaluation of mass balance accounting, the possibility that individual process steps will be able to provide much faster response times than the overall process balance will be considered. If a weight balance is maintained around each process hood or separate step, even though it is not a part of the official accountability system, it does provide immediate assurance that materials have not been simply taken from the process area.

For some process steps, daily records of process yields are maintained. These can also provide a quick indication of the direct removal of material.

4.0 EXPECTED CAPABILITY OF MATERIALS ACCOUNTING IN FUTURE PLUTONIUM PROCESSING OPERATIONS

As described in Section 3.2, the estimation of the loss detection sensitivity of material balance accounting for a processing operation is a function of many parameters. All flows into and out of the process must be described in terms of batch size and the number of batches. These flow streams include not only the streams arriving and leaving the facility but also the internal flows. For each material transfer, the types of measurements made and the measurement accuracy must be known. The measurement accuracy should be expressed in terms of its random and systematic components since the behavior of the balance over time will depend on knowledge of both terms.

The ability of a given plant to obtain a material balance which is highly sensitive to loss will depend to some extent on the quality assurance procedures that are incorporated into the plant measurement system. The analysis presented here will assume that the quality of the measurement system is extremely good by today's standard. Since the evaluation is intended to look at the performance of plants presently being designed, standards which are high today should be commonplace a decade from now.

In order to evaluate the safeguards effectiveness of material balance accounting methods, three plants were chosen for evaluation. These are a LWR reprocessing plant with an associated plutonium nitrate storage and oxide conversion facility, a LWR plutonium fuel fabrication facility and an HTGR ^{235}U fuel fabrication plant. The LWR reprocessing plant was modeled after Barnwell,(5-6) the plutonium fuel fabrication facility after the Westinghouse Anderson Plant,(7) and the HTGR Fuel plant after the Youngsville Facility.(8) The HTGR fabrication plant which involved enriched uranium fuel fabrication was included only as an illustrative comparison of the plutonium and enriched uranium fuel cycle as discussed in Appendix C of this report.

Although the plant models are close to the design descriptions presented in license applications and SAR's submitted for these plants, the material balance data were developed using state-of-the-art measurement methods. The models obtained in this way are thought to represent what might be achievable within the next decade. Areas of uncertainty will be pointed out. In addition, based on the results, it will be possible to show which variables are most critical to obtaining highly sensitive material balances.

The material balance accounting capabilities of presently planned plutonium fuel cycle facilities are shown in Table 4.1. A current HTGR fuel fabrication facility is also shown for comparative purposes. The sensitivity with which loss can be distinguished from measurement uncertainty is shown by the LEMUF on Table 4.1.

The last three columns are the most important. Column 5 shows the absolute value of LEMUF in kilograms. Column 6 shows the relative values of LEMUF as a percentage of two forms of plant throughput - (1) feed plus inventory and (2) feed only. Column 7 shows current Regulatory requirements for relative LEMUF.

The values for LEMUF which are shown in Table 4.1 are based on state-of-the-art measurement quality and current Regulatory requirements for frequency of physical inventory taking. The detailed material balance models, the estimates used for random and systematic error of measurement, and the error propagation models are described in Appendixes A and B.

The values presented in Table 5.1 are for plants which are presently in the design stage or are being built. State of the art measurement techniques were used in propagating measurement uncertainties. Thus, except for HTGR fabrication plants, all plants exceed present regulatory requirements. The following sections will evaluate additional improvements in the effectiveness of material balance accounting which might be realized in future plants.

TABLE 4.1 Material Balance Accounting Capability of Current Processes

	#1	#2	#3	#4	#5	#6		#7
Process	Accounting Period	Special Nuclear Material	Feed kgs	Inventory Level kgs	LEMUF kgs	Present Capability %(Feed+Inv.)	%Feed	Regulatory Requirement,%
Separations	6 months	Plutonium	7568	5	54.4	0.72	0.72	1.0
$Pu(NO_3)$ Storage	Static	Plutonium	0	2000	5.16	0.26	--	0.5
$Pu(NO_3)$ Storage	2 months	Plutonium	2500	2000	17.38	0.39	0.70	0.5
Pu Nitrate-Oxide Conversion	2 months	Plutonium	2500	1.5	9.59	0.38	0.38	0.5
Plutonium Fuel Fab.	2 months	Plutonium	1190	772	3.67	0.19	0.31	0.5
HTGR Fuel Fab.(a)	2 months	^{235}U	1632	1520	36.82	0.86	2.25	0.5

(a) Shown for comparative purposes only.

5.0 DESCRIPTION AND EFFECTIVENESS OF POSSIBLE MATERIAL ACCOUNTING IMPROVEMENTS

The previous section illustrated material balance accounting capabilities for currently required inventory frequencies and state-of-the-art measurements. The material balance areas studied extended over an entire processing operation or the entire plant.

This section considers the possible increases in safeguards effectiveness which can be achieved by improvements in the material balance accounting methods used in plutonium fuel cycle facilities. To increase the safeguards effectiveness of material balance accounting four basic improvements are desired. These are:

- Improvement in the sensitivity of detecting loss events.
- Improvement in the timeliness of loss detection.
- Improvement in the sensitivity of detecting small losses (or buildups) which occur over a long period of time.
- Improvement in the extent to which loss detection is localized.

5.1 IMPROVED MATERIAL ACCOUNTING IN SEPARATION PLANTS

The reprocessing plant evaluation presented in Section 4 was based on a 5 MT/day plant using the Purex process. Because this process has been used by both government and private industry there is a wealth of experience concerning the plant's operating characteristics.

Basically, the plant is a highly integrated facility. This integration is required in order to obtain the desired amount of separation of the uranium and plutonium from the waste products. The plant is designed for continuous operation. Industry personnel have stated that it is highly desirable to run a reprocessing plant continuously for several months and then shut down for an extended maintenance period. Thus, plans for the AGNS plant at Barnwell contemplate continuous operation for 5 months followed by a 1-month shutdown period for maintenance and cleanout for inventory taking. This mode of operation was used in calculating the LEMUF values shown previously in Table 4.1.

The gains in safeguards effectiveness which can be achieved by increasing the frequency of inventory taking are shown in Table 5.1. The absolute values for LEMUF shown in Column 3 of Table 5.1 show the increased sensitivity for detecting a loss event which can be gained by increasing the frequency of inventory taking. The relative values for LEMUF shown in Column 4 reflect the sensitivity for detecting a rate of loss which is proportional to throughput.

Two plant conditions for inventory taking are shown in Table 5.1. First is a cleanout inventory which entails up to 2 weeks of flushing and cleanout. Second is a running inventory in which the plant is inventoried without a process shutdown. This second inventory method does, however, involve careful planning and operational adjustments to obtain the best conditions for measurement of the inventory.

As the data in Table 5.1 shows, a running inventory yields LEMUF values of about the same magnitude as those associated with a cleanout inventory. This comparison is misleading from the standpoint of safeguards assurance. The cleanout inventory includes all the plutonium in the process equipment.

TABLE 5.1 LEMUF Sensitivity to Inventory Frequency for the Separations Part of a 5 MT/Day Reprocessing Plant

	#1	#2	#3	#4
Accounting Period	Feed	Inventory Kilograms	LEMUF	$\frac{\text{LEMUF} \times 100}{\text{Feed}}$
		Cleanout Inventory	(kg of Pu)	
1 week	303	5	4.09	1.35
2 weeks	605	5	5.85	0.97
1 month	1251	5	10.07	0.80
2 months	2523	5	18.85	0.75
3 months	3784	5	27.8	0.73
6 months	7568	5	54.4	0.72
12 months	15136.5	5	107.8	0.71
		Running Inventory(a)		
1 week	303	222	5.61	1.85
2 weeks	605	222	6.99	1.16
1 month	1251	222	10.77	0.86
2 months	2523	222	19.24	0.76

(a) Running inventory includes only the plutonium present in liquid form. It does not include material firmly held on surfaces or soluble forms of plutonium adhering to surfaces above the normal liquid level of equipment.

By contrast, the running inventory includes only the plutonium present in process liquids. It does not include material firmly held on surfaces or material adhering to surfaces above the normal liquid level of equipment. Experience has shown that such accumulations can add up to 10-20 kilograms of plutonium.

As a consequence, there doesn't appear to be any practical substitute to periodic cleanout inventories entailing a fairly thorough cleanout. The running inventory does provide a rapid assurance check and is worth evaluating on a trial basis. However, it should not be used as a substitute for a cleanout inventory.

Improvements in the measurements themselves are expected to further enhance material accounting's value as an assurance measure. Definite improvements in measurement quality are expected to result from implementation of recent regulations calling for formal measurement control programs.(9) One result expected from implementation of such programs is a reduction in the long-term systematic errors of measurement. The effect of such a reduction is shown in Table 5.2 for cumulative LEMUF(10) taken over a number of accounting periods. The decreasing trend in relative LEMUF with time is due to a partial canceling of the systematic error of MUF. That is, some of the systematic errors from one accounting period have different directions than those from the next period and thus are cancelled.

Increasing the number of material balance areas within the separations part of a reprocessing was not considered beneficial. The current requirement of separating the plutonium product area from the separations part is considered sufficient for purposes of localizing losses and providing extra protection for attractive forms of material.

TABLE 5.2 Reduction of Relative Cumulative LEMUF with Time for the Separations Part of a 5 MT/Day Reprocessing Plant

Length of Accounting Period	Number of Periods	Years	Cumulative LEMUF, % Feed
6 months	1	0.5	0.72
"	2	1	0.54
"	4	2	0.37
"	8	4	0.29
"	16	8	0.20
3 months	1	0.25	0.73
"	2	0.50	0.52
"	3	0.75	0.43
"	4	1.0	0.38
"	5	1.25	0.34
"	6	1.50	0.31
"	7	1.75	0.29
"	8	2.0	0.28
"	12	3.0	0.23
"	16	4.0	0.21
"	20	5.0	0.19

5.2 IMPROVED MATERIAL ACCOUNTING IN NITRATE STORAGE

The plutonium nitrate storage area of the reprocessing plant consists of eight banks of slab tanks. These are used for receiving, storing, and mixing the plutonium nitrate product from the separations part of the process. The storage area receives feed as concentrated plutonium nitrate solutions from the separations MBA and ships plutonium nitrate solutions to the conversion process for converting nitrate to oxide.

The basic materials accounting objective for the nitrate storage area is to provide assurance that the plutonium credited to the storage account is present and accounted for. The exactness with which this objective can be met will depend on operational status of the various storage banks at any particular time.

Several operational conditions need to be considered. These are:

- Banks (of tanks) in static conditions where the solution volume (or weight) is essentially constant over the accounting period.
- Banks in which only internal mixing has taken place or from which only shipments (transfers out) were made during the accounting period.
- Banks in which solutions of a different plutonium concentration were received and mixed with previously stored material.

The timeliness and sensitivity of materials accounting assurance checks will be somewhat different for each of the above conditions.

For banks of tanks in a static condition, nearly continuous assurance is provided through in-place instrumentation which records the weight of solution in each tank (the weight of solution above the bottom dip-tube). Also, when only internal mixing takes place within a bank, a weight balance can readily be obtained on nearly a daily basis. Similarly, when a bank is used only for shipments, a daily volume balance is also possible.

By contrast, the least timely and least sensitive situation would be when a bank of tanks is used for receiving and mixing new material on a continuous basis. In this case, a material balance involving both solution weight and plutonium concentration would have to be formed around those banks. This balance is least timely because an accurate inventory is not possible until the tanks are completely mixed (a several-day operation). It is least sensitive because the physical inventory measurement includes both volume (or weight) and assay errors.

The timeliness and sensitivities of the various kinds of material balances which may be used for safeguards assurance at the plutonium nitrate storage facility are shown in Table 5.3. The sensitivities for loss detection are shown by the LEMUF values. As the data show, the smallest LEMUF values are for material in a static condition whereas the largest values correspond to the situation where material is received and mixed on a continuous basis.

The values for LEMUF shown in Table 5.3 should be regarded as illustrative of the various operational conditions which may exist in the storage area. [illegible]

TABLE 5.3 Typical LEMUF Values for the Plutonium Nitrate Storage Facility in a 5 MT/Day Reprocessing Plant

Accounting Period	Operational Conditions	Feed	Inventory	LEMUF
		Kilograms		
1 day	Static	0	1000	3.46
1 day	Static	0	2000	4.89
1 day	Internal Mixing	0	1000	3.65
1 day	Internal Mixing	0	2000	5.16
1 day	Shipping-Receiving and Mixing	50	1000	5.85
1 week	Shipping-Receiving and Mixing	300	1000	6.15
2 weeks	Shipping-Receiving and Mixing	600	1000	7.47
3-4 weeks	Shipping Receiving and Mixing	1000	1000	10.15
2 months	Shipping-Receiving and Mixing	2500	2000	17.38

that a mixture of conditions will exist, e.g., some tanks will be static, some under internal circulation, and some in which shipping, receiving and mixing are taking place.

5.3 IMPROVED MATERIAL ACCOUNTING IN NITRATE-TO-OXIDE CONVERSION

The sensitivity and timeliness of the material balance performed over the nitrate-to-oxide conversion process using oxalate precipitation was evaluated in a manner which parallels the analyses performed for the other processes. The results are shown in Table 5.4.

Two levels of inventory holdup are shown in the table. One is for a cleanout inventory in which the entire process is cleaned out, including the calciner. The second case is for a draindown inventory which involves a nitric acid flush of all the equipment except the calciner. In the draindown inventory, the calciner holdup is reduced to a minimum level, but the furnace is not flushed. The draindown inventory requires about a one-day process shutdown and the cleanout inventory requires about four days of process shutdown.

A running inventory was also considered but is not shown in the table. The uncertainties associated with this type of inventory were too large to be of safeguards value. These large uncertainties stem mainly from the large quantities of plutonium in difficult to measure forms such as highly hydrated precipitates and powders. In addition, there are large quantities present in piping and in the calciner. In these locations amounts can be estimated only crudely.

As the data in Table 5.4 show, both the timeliness of detection and the sensitivity to detect a "loss event" are improved by increasing the frequency of inventory taking. This is contrasted by the relative values for LEMUF which show that the sensitivity for detecting a rate of loss increases with time.

TABLE 5.4 LEMUF Sensitivity to Inventory Level and Inventory Frequency for a Plutonium Nitrate-to-Oxide Conversion Facility

Accounting Period	Feed	Inventory	LEMUF	LEMUF
	kilograms			% of Feed
1 week	300	1.5	1.798	0.599
1 week	300	4.0	3.119	1.040
2 weeks	600	1.5	2.730	0.455
2 weeks	600	4.0	3.735	0.622
1 month	1225	1.5	4.922	0.401
1 month	1225	4.0	5.543	0.452
2 months	2500	1.5	9.589	0.384
2 months	2500	4.0	9.998	0.400

The improvement in long-term assurance which is expected to result from current requirements for formal measurement control programs is shown by the cumulative LEMUF values given in Table 5.5. The values shown should be interpreted as illustrative of the expected trend rather than interpreted in an absolute sense.

TABLE 5.5 Reduction of Relative Cumulative LEMUF with Time for the Plutonium Nitrate-to-Oxide Conversion Facility

Length of Accounting Periods	Number of Periods	Years	Cumulative LEMUF, % Feed
2 months	1	0.166	0.384
2 months	3	0.5	0.234
2 months	6	1.0	0.179
2 months	12	2.0	0.144
2 months	18	3.0	0.131

5.4 IMPROVED MATERIAL ACCOUNTING IN FUEL FABRICATION

The timeliness and sensitivity of material balance accounting for the plutonium fabrication facility was evaluated in the same manner as was derived for the other processes. The sensitivity of LEMUF to inventory level and inventory frequency is shown in Table 5.6.

As the data show, both the timeliness and sensitivity for detecting a loss event are improved as the frequency of inventory taking is increased. As was noted previously, the sensitivity for detecting a rate of loss which is proportional to throughput increases with time.

Two inventory levels are considered in the analysis. One is for a draindown inventory in which the in-process inventory is reduced to 6 kilograms. The other is for a similar draindown inventory of material in difficult to measure locations, but includes over 500 kilograms in weigh tanks

TABLE 5.6 LEMUF Sensitivity to Inventory Level and Inventory Frequency for a 200 MT/Year Mixed Oxide Fabrication Plant

Accounting Period	Feed	Inventory	LEMUF	LEMUF % of Feed
	Kilograms			
1 week		9	1.649	1.10
1 week	150	772	2.264	1.51
2 weeks	300	9	1.775	0.59
2 weeks	300	772	2.357	0.79
1 month	595	9	2.180	0.37
1 month	595	772	2.276	0.45
2 months	1190	9	3.324	0.28
2 months	1190	772	3.886	0.31

which allow the accurate measurement of the inventory. This illustrates one of the design features being incorporated in future plants which improves materials accounting capability. As the data in Table 5.6 show, there is only a slight difference in the LEMUF values for the two inventory levels.

The draindown procedures for inventory taking are estimated to require a process shutdown of about 8 hours or one full shift.

The improvement in long-term assurance which is expected to result from formal measurement control programs is shown in Table 5.7 for cumulative LEMUF.

To enhance the loss detection of highly attractive materials, a separate material balance for the PuO_2 storage area was evaluated. This balance is based on forming a "weight" balance around the PuO_2 storage area. In this area all of the PuO_2 is stored in "weigh" hoppers so that a continuous

TABLE 5.7 Reduction of Relative Cumulative LEMUF with Time for a 200 MT/Year Mixed Oxide Fabrication Plant

Length of Accounting Periods	Number of Periods	Years	Cumulative LEMUF, % Feed
2 months	1	0.166	0.31
2 months	3	0.5	0.18
2 months	6	1.0	0.14
2 months	12	2.0	0.12
2 months	18	3.0	0.11

record of PuO_2 weight is obtained. The sensitivity of such a material balance to detect losses of PuO_2 as a loss in weight is shown in Table 5.8. As the data show, LEMUF values ranging from 1 to 2.7 kilograms can be obtained for accounting periods ranging from 1 day to 2 months.

TABLE 5.8 Sensitivity of Loss Detection in PuO_2 Storage Area of a 200 MT/Year Mixed Oxide Fabrication Plant

Accounting Period	Feed	Inventory	LEMUF$^{(a)}$
	Kilograms		
8 hours	7	290	1.0
1 day	21	290	1.0
1 week	150	290	1.3
2 weeks	300	290	1.9
4 weeks	600	290	2.2
8 weeks	1200	290	3.0

(a) LEMUF values are based on a material balance using weight of PuO_2 as the only measurement uncertainty. Assurance that substitution has not occurred is obtained through regularly scheduled assays for element content.

6.0 COSTS OF MATERIAL ACCOUNTING IMPROVEMENTS

Improvement in material accounting can result in lost production and increased operating costs. Lost production costs are difficult to assess. However, if the facility is shut down to take a physical inventory, then it is conservative to attribute all the lost revenue to the additional inventory requirement. If the facility is down for other reasons, a lost production cost is assessed against the inventory measurement only if the inventory measurement extends the length of the outage. In this case the penalty assessed against material accounting is only for the additional downtime.

The lost production cost assessment, described above, assumes facilities are independent. Facilities do interact. A reactor cannot use plutonium that was not separated or was not converted or was not fabricated into fuel. The assumption will be made that the facilities can be decoupled enough so that one facility is not solely dependent on the other. Care still must be exercised when comparing facility costs if plants are not sized to process the same amount of plutonium. This occurs in this analysis because the 1500 MT/yr reprocessing plant produces approximately 50 kg of plutonium per day, whereas the conversion plant has a peak capacity of 100 kg/day and a 200 MT/year mixed oxide fuel fabrication plant is expected to require only 21 kg/day of plutonium. In the cost analysis, the conversion plant will be arbitrarily held to the 50 kg/day plutonium recovery rate from separations. The fabrication plant size will not be changed but it will be noted in any comparisons that about two reference-size fabrication plants will be required to use the plutonium separated in the reference-size reprocessing plant.

The costs of additional labor and analytical measurements are summarized in Table 6.1. The measurement costs were based on an evaluation performed by Brouns and Roberts.(11) These costs were estimated from information obtained from ERDA contractors and from a private laboratory which performs measurement services for licensees. A $150/day chargeout rate was used for the cost

TABLE 6.1 Summary of Lost Production and Additional Measurement and Labor Costs for Material Accounting

Units Costs for Measurement Control Operations

Operation	$/Measurement
Chemical Assay	
Pu in MO	40
Pu in PuO_2	35
Pu in Aqueous Samples	30
Pu in Waste (α counting)	30
Isotopic Analyses	
Pu in MO	125
Pu in PuO_2	[illegible]
NDA	
Weighing	
Standards	2
Process Items	5
Volume Determination	15
Sampling	
Mixing required	20
No mixing	6

Unit Cost of Labor — $150/man day

Unit Cost of Lost Production

Separation	$180/kg of HM[a] reprocessed
Conversion	$400/kg of Plutonium
Fabrication	$250/kg of HM fabricated

[a] Heavy Metal

of a man-day of labor. These are 1975 costs and include all the charges necessary for full cost recovery. The lost production costs for reprocessing and fabrication were based on economic data presented at an AIF-sponsored fuel cycle conference held in Atlanta, Georgia on March 19-21, 1975.(12) The lost production $1/gm cost for the conversion facility quoted at the conference was reduced to $0.40/gm to represent the conversion cost attainable by a 50 kg/day facility.

6.1 COSTS ASSOCIATED WITH IMPROVED MATERIALS ACCOUNTING IN SEPARATIONS PLANTS

Three material accounting improvements were considered in Section 5. These were more frequent physical inventories, performing running inventories, and improvements in long-term measurements in long-term measurement quality. The costs of each of these improvements will be evaluated in the following subsection.

6.1.1 More Frequent Physical Inventories

Because of the highly integrated operation of a separations facility, physical inventory measurements more frequent than once in 6 months, are difficult to accomplish without significant production losses.

Using the Barnwell Plant as a representative facility, it is designed for an annual throughput of 1500 MT/day. Based on the 6 MT/day dissolver capacity, the plant must operate for 250 days to process 1500 MT/year. Thus, shutdown periods which total longer than 115 days would result in lost production. An average rate of 5 MT/day over 300 days allows for rework of off-standard material and for minor process upsets. The remaining 65 days allows for two one-month periods for scheduled plant maintenance and a complete physical inventory.

So long as there are no lost production costs, the major direct cost penalty associated with additional physical inventories is the labor costs of process operators working in the plant. Of the approximately 150 people employed in the plant, the job assignments of 50 people may be affected during the outage. At $150/day/man for 14 days, the assigned manpower cost of each outage is $105,000. If 1 day's production is lost, the revenue from five MT of fuel at $180,000/MT(12) is lost. Thus, the lost production penalty is $900,000 per day.

Using the assumptions in the above paragraphs, Table 6.2 has been prepared to summarize the cost penalties associated with more frequent physical inventories in a separations plant. A physical inventory was taken during each 30-day outage as a base case. Incremental inventory-taking costs were charged when the sole reason for the outage was a physical inventory requirement. This calculational procedure results in a maximum charge for taking additional inventories. If, as an example, minor maintenance could be performed during inventory shutdowns such that the scheduled 30-day maintenance period could be shortened, then the dollar cost (production loss) assessed against inventory taking would be decreased. No such credits were taken for inventory frequencies shorter than semiannual.

The lost production cost must be taken as a direct penalty to the nuclear economy since additional capacity would have to be installed elsewhere. The effect on Barnwell must be addressed relative to their revenue. Thus, for quarterly inventory periods the 140 MT of lost annual capacity represents a 9.3 percent decrease in revenue.

TABLE 6.2 Maximum Incremental Costs of Inventory Frequencies Shorter than 6 Months

Number Inventory Periods/Year	Annual Maintenance Requirement (Days)	Incremental Physical Inventory Requirement (Days)	Annual Production Loss		Incremental Physical Inventory Cost (millions)	Total Incremental Cost of More Frequent Inventories (millions)
			Days[a]	Cost[b] (millions)		
2	65	0	0	0	0	0
4	65	28	28	25.2	0.2	25.4
6	65	56	56	50.4	0.4	50.8
10	65	112	112	101	0.8	102
12	65	140	140	126	1.0	127

(a) Base case, two planned 30-day outages with one inventory taken for each outage.
(b) The time required for a physical inventory is assumed to be 14 days. Any decrease or increase in this assumption directly affects these cost figures.

Note: (1) Total plant income is assumed at (1500) (180,000) = $270 million/yr.

6.1.2 Costs of Performing A Running Inventory

The previous analysis looked at the costs of performing a good physical inventory check more frequently than once per 6 months. Flushing and decontamination procedures were used both to bring the heldup material to measurement locations and to minimize the remaining physical inventory in the facility. This procedure is time consuming and costly.

As was described in Section 4, the running inventory can account for most of the material present in flowing streams. The costs of taking a running inventory are associated with the additional measurements, sampling and analyses required. A computer software package and data collection procedure must be developed.

Although the software package is a one-time charge, estimated to cost $40,000 initially, changes in plant operating procedures and improved measurement systems will probably make this program obsolete in a few years. Thus, a fixed cost of $20,000/year will be used to develop and update the analysis routine. This cost represents an average annual cost. In some years, there may be no charges; in other years, major costs will be incurred.

Taking a running inventory requires additional data collection, sampling and analyses. For each running inventory, six nonroutine samples must be drawn and analyzed. Assuming isotopic dilution procedures must be used on all the samples, the analysis cost is estimated to be $200 per sample. Process data collection and evaluation would take an estimated two man-days at a charge rate of $150/day. Based on these costs, each running inventory is estimated to cost $1500.

Table 6.3 summarizes these costs as the frequency of taking running inventories is increased. In this table, formal draindown inventories are assumed to be taken semi-annually. Formal draindown inventory measurements supplant the need for taking a running inventory.

TABLE 6.3 Additional Costs Incurred for Taking Running Inventories in a Separations Plant

Inventory Frequency	Number of Running Inventory/ Year[a]	Total Shutdown Days Required	Total Annual Costs
Quarterly	2	0	$ 23,000
Bimonthly	5	0	27,500
Monthly	8	0	32,000
Biweekly	18	0	47,000
Weekly	38	0	77,000
Daily	248	0	392,000

(a) Basis:
10 months of production/year
40 weeks of production/year
250 days of production/year

6.1.3 Costs Resulting from Improved Measurement Control

Measurement control programs have been instituted to improve the accuracy and precision of material accounting measurements. One improvement expected from such programs is a reduction in the long-term systematic errors in flow measurements. As described in section 5, reductions in long-term systematic errors can be realized through periodic recalibration of equipment and by instituting improved, statistically based, tests of sampling and measurement procedures.

The cost of such a program is estimated to be approximately \$200,000/year for a plutonium fuel fabrication plant.(11) The costs are expected to be in the same range for the separations part of an LWR reprocessing plant. Since the program is part of current regulations, there is no incremental cost penalty associated with improved measurement control.

6.2 COSTS OF IMPROVED MATERIAL ACCOUNTING IN PLUTONIUM NITRATE STORAGE FACILITIES

Two improvements in material accountability were considered for the plutonium nitrate storage facility. First, the costs associated with increasing the frequency of physical inventory measurements will be considered. More frequent inventory measurements result in improved timeliness to detect loss. Secondly, the costs of calibrating and using process control data to estimate running inventories will be considered.

6.2.1 Costs of More Frequent Physical Inventories

The problems of material accounting of liquid plutonium nitrate solutions can be minimized by minimizing the amount of material being stored and by attempting to keep most of the inventory static during an accounting period. Thus, the operating strategy can have a large effect on the accuracy of physical inventory measurements.

The operating requirements vary tremendously over the course of a year. In spite of the variability during the year, there will be times when the storage inventory is low, there will be periods when many of the storage tanks are static. At these times, taking a material inventory minimizes measurement uncertainties. Full advantage of these conditions should be taken.

From the standpoint of costs, it is important to consider how frequently these favorable material inventory periods might occur. The costs are also minimized over these intervals.

Favorable periods are likely to occur quite frequently. Many tanks are likely to be static for a week; essentially no tank will be static for a year. The optimum inventory time interval corresponds to the time it takes to empty or fill a storage tank. At Barnwell, which is expected to be representative of future facilities, the optimum frequency would therefore be in the range of from 10 to 30 days.

During this period one bank might be filling, another emptying, and the remaining six could be kept static and locked out. Thus, only two sets of measurements rather than the complete set of eight would be required. As the period lengthens, more and more banks of tanks must be inventoried. Every 2 months, as many as four banks might have been used. For longer periods, it is likely that transfers or withdrawals from all of them would have occurred.

The cost of obtaining an estimate of a physical inventory in one bank of tanks is about $150. The cost breakdown is: $90 for the six weight-factor measurements, $30 for sampling and $30 for determining the plutonium content in the sample. Thus, cost is incurred only if transfers to or from the bank have occurred during the accounting period. Based on the cost per bank it is now possible to estimate the annual inventory cost for several inventory periods and then obtain the incremental cost difference from the standard 2-month base inventory period. These costs are shown in Table 6.4.

TABLE 6.4 Estimated Annual Costs for Performing Physical Inventories in a Plutonium Nitrate Storage Facility

Inventory Frequency	Measurement Cost Per Inventory Period	Total Annual Cost	Incremental Cost from Base 2-month Period
1 day[a]	$ 300	$ 110,000	$ 106,000
1 week	300	16,000	12,000
2 weeks	300	7,800	4,200
20 days[b]	300	4,500	900
2 months	600	3,600	0
6 months	1200	2,400	-1,200
1 year	1200	1,200	-2,400

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a) Because the storage Facility is a buffer between the separations and conversion facilities, additions or withdrawals may occur 365 days/year.

b) Based on 15, 1 MT Pu storage batches/year.

6.2.2 Running Inventory Costs for a Plutonium Nitrate Storage Facility

Instrumentation to continuously monitor liquid levels in nitrate storage tanks will be required for process control information. These instruments may not be more than one percent accurate without calibration. It is estimated that these instruments could be calibrated so that volume (or weight) could be measured more accurately. Such a calibration is not expected to cost more than $1000 annually.

The costs of taking a running inventory are quite small, taking 2 to 3 man-hours or about $50/inventory check. This inventory check is on the weight factor (liquid level and specific gravity) no samples are taken. As such, it is just a supplement to the formal balance discussed previously. Table 6.5 summarizes the annual costs associated with taking a running inventory.

TABLE 6.5 Estimated Annual Costs for Performing a Running Inventory in a Plutonium Nitrate Storage Facility

Inventory Frequency	Total Annual[(a)] Measurement Cost
1 day	$19000
1 week	2900
2 weeks	2000
1 month	1300

(a) Assumes a formal inventory measurement period of 2 months.

6.3 COSTS OF IMPROVED MATERIAL ACCOUNTING IN PLUTONIUM NITRATE-TO-OXIDE CONVERSION FACILITIES

Four improvements in material accountability were considered for the plutonium nitrate-to-oxide conversion facility. First, the costs associated with increasing the frequency of physical inventory measurements will be considered. More frequent inventories result in improved timeliness to detect loss. Secondly, the costs associated with process draindown will be considered. Third, the costs of calibrating and using process control data to estimate running inventories will be considered. The final case considers the cost of the measurement control program.

6.3.1 Costs of More Frequent Physical Inventories

The base case reported in section 5 performed a formal physical inventory every 2 months. It is estimated that the process would require days to minimize and measure the physical inventory of material in the process.

There are two types of incremental costs associated with more frequent inventories. One is the direct cost and the second is the cost of any lost production. The direct cost is estimated to be $3000/inventory period. The major cost is the estimated 20 man-days of labor at a charge rate of $150/day.

At a throughput rate of 50 kg/day, a 1000 kilogram lot of plutonium from the storage area would be converted to oxide in 20 days. Since the next lot would be expected to have different isotopics, normal operations would dictate a runout of plutonium before the next batch starts. Thus, formal physical inventories, taken after 20 days of full production may impose a minimum stress on facility operations. For a reprocessing plant producing 15,000 kilograms of plutonium per year, there could be as many as 15 formal inventory periods each year. The incremental annual cost, at $3,000 per inventory period, would be $27,000. The downtime for the additional nine physical inventories is 45 days. The total annual lost production cost for a facility converting 50 kg/day at a cost of $400/kg is $900,000. The incremental annual costs associated with a monthly inventory period would be $18,000 and $600,000 for additional operating and lost product costs, respectively.

6.3.2 Costs of Inventories Obtained by Process Draindown

Rather than a complete cleanout between each batch, a runout of the inventory in the process may be sufficient. In this case the six formal inventory periods could be supplemented by nine draindown inventories. The formal inventory measurements are assumed to be taken between batches of plutonium. The costs associated with the nine draindown inventory measurements are estimated to be $600 each 4 man-days of labor. Thus, the incremental costs of draindown inventories is $5400 annually. The annual lost production cost, based on one shift of production lost/inventory, totals $40,000 annually.

6.3.3 Costs of Running Inventories

Running inventories would supplement the 15 draindown or cleanout inventories taken during the year. The major costs associated with running inventories result from the additional calibrations and analyses required. Since NDA methods are probably the only convenient means for surveying the inventory in process equipment and since the instrumentation is isotopic dependent, periodic recalibrations are required, probably preceding the conversion of each new 1 MT/batch of plutonium.

The calibration procedure is expected to take 1 man-day of labor and measurements with five process standards for each of the two parallel process lines. The total calibration cost is therefore $400 per batch or $6000 per year. The cost for each running inventory measurement, based on the measurement and labor costs presented in Table 6.6 is $200. It is assumed that each running inventory measurement will require 10 NDA readings at $10 each, two volume determinations at $15 each and approximately 4 hours of staff labor at $75. Table 6.6 gives the incremental annual costs associated with supplementing formal inventory measurements with more frequent, running inventory measurements.

TABLE 6.6 Costs of Supplementing Formal Material Balances with Running Inventories in the Oxide Conversion Facility

Running Inventory Frequency	Incremental Annual Cost Calibration	 Inventory	 Total
Monthly	$ 3600	$ 2,400	$ 6,000
Biweekly (25 periods/year)	5000	5,000	10,000
Weekly (50 weeks/year)	6000[(a)]	10,000	16,000
Daily (300 days/year)	6000	60,000	66,000

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a) Based on one calibration every one MT of plutonium processed.

6.3.4 Costs Resulting from Improved Measurements Control

The measurement control program has been instituted to improve the accuracy and precision of material accounting measures. The measurement control program for the oxide conversion plant would be administered by the same staff responsible for the separations plant control program. Indeed the integration of data obtained from the combined plant inventory measurements would greatly aid the program. Thus, the costs cannot be separated from the $200,000 annual cost estimate prepared for the separations plant control program. Because this program is part of current regulations, there is no incremental cost penalty associated with improved measurement control.

6.4 COSTS OF MATERIAL ACCOUNTING IMPROVEMENTS IN A 200 MT/YEAR MIXED OXIDE FUEL FABRICATION FACILITY

This section will summarize the incremental costs of the four fuel fabrication material accounting improvements described in Section 5.4. The improvements were: more frequent physical inventory measurements, more frequent inventory checks on highly attractive material forms, taking a running inventory and improved measurement quality.

6.4.1 Costs of Obtaining More Frequent Physical Inventories

There are periods during the course of a year when physical inventory of material in the process is at a minimum. The costs of performing a physical inventory at such times is minimal.

Using the proposed Westinghouse Anderson plant as a guide, each of the three input storage silos can hold up to 150 kilograms of plutonium. At a production rate of 200 MT/year, 150 kg of feed plutonium are used in 7 days of full production.

During that time the one silo has been drained, a full one is on standby and the third is being filled.

The silos containing recovered scrap are designed similarly. In seven days, one has been emptied, another filled and a third on standby. Based on these storage capacities, a formal weekly inventory, timed to correspond to the switch from one input tank to another, appears to represent a minimum cost condition. In addition, since the completion of one input batch is frequently going to be the signal for a plutonium isotopic change, runout of the process line is likely to be required. For this analysis, physical inventories taken once a week are assumed to correspond to both the switch from one input silo to another and the runout of the pellet line.

At this time all material in process is weighed and the analytical factor corresponding to its respective PuO_2 or MO_2 batch is applied to get the plutonium content. In addition, at that time all scrap cans, irrespective of their contents, are sent to scrap recovery.

The costs are estimated by determining the number of measurements required to obtain the physical inventory level, and then multiplying by the costs summarized in Table 6.1. At the end of each period, there could be 58 green pellet boats 135 sintered pellet storage boats and as many as 888 inspected pellet trays in storage. As many as 18 cans of clean scrap, dirty scrap and waste might be sent to their respective treatment locations. Assuming an average inventory of material in the process, about 500 weighings would be required. The cost, based in the cost estimates in Table 6.1 would be $2500. The evaluation of the 18 waste and scrap cans at $30 each would cost $500. Thus the incremental cost associated with taking more frequent physical inventories, at a frequency as high as once a week, is estimated to cost $3000.

Labor costs must also be included. It is estimated to require one shift to clean up the process equipment in preparation for each physical inventory. Assuming as many as 20 process operators would be used, the labor cost would be another $3000. Thus, the total incremental costs associated with each inventory period is $6000. This assumes the physical inventories occur no more frequently than once a week and, therefore, result in no net loss in production. Table 6.7 summarizes the incremental costs of physical inventory measurements taken more frequently than once every 2 months.

For each physical inventory required the facility will experience one shift of lost production. Based on a fabrication cost of $250/kg of heavy metal, the revenue lost by the fabricator is approximately $45,000. This lost revenue cost must be multiplied by the number of additional physical inventories required annually. These are shown in the last column in Table 6.7.

6.4.2 Costs of Frequent Inventories of Highly Attractive Material Forms

The proposed Westinghouse Anderson plant design was used to evaluate the costs associated with supplementing the plantwide physical inventory measurements with more frequent measurements on materials in attractive form. The PuO_2 powder input and storage area was evaluated. Unpackaged cans under item control can be checked in about an hour, costing $20. Measurement of the weight of material in the storage silos costs $15, a calibration check may cost another $15; thus, the total cost of inventoring the plutonium oxide storage area is approximately $50. Table 6.8 summarizes the incremental costs of physical inventories taken more frequently than once every 2 months for the plutonium oxide feed storage area . The time intervals shown in Table 6.8 are nominal times. The plant is assumed to be operating during each of the 12 months of the year. During the year, 47 PuO_2 input batches weighing 170 kg will have been processed. The weekly inventory frequency is based on the completion of one input batch per 7 days of operation. The number of operating shifts is assumed to be 1000 per year. Slightly different assumptions would not significantly affect the costs shown in Table 6.8.

TABLE 6.7 Incremental Costs of Plutonium Fabrication Plant Physical Inventory Measurements taken more Frequently than Bimonthly

Inventory Frequency	Number of Supplemental Balances	Total Incremental Annual Cost	Total Lost Production Annual Cost
Monthly	6	$ 36,000	$ 270,000
Biweekly	18	108,000	800,000
Weekly	41	246,000	1,800,000

TABLE 6.8 Incremental Costs of Performing Physical Inventory Measurements more Frequently than Bimonthly over the PuO_2 Feed Storage Area of a Plutonium Fuel Fabrication Plant

Inventory Frequency	Number of Supplemental Balances	Total Incremental Costs
Monthly	6	$ 300
Biweekly	18	900
Weekly	41	2050
Daily	323	16100
Each Shift	994	49700

6.4.3 Costs of Obtaining a Running Inventory

Except for the pellet line, essentially all the processes are batch operation. In addition, based on the Anderson Plant design, which is thought to be representative of future plants, a process computer will be used for process evaluation and control. This means that for much of the process a running inventory analysis will be available. For the pellet line, because of the holdup in feed and surge tanks, information will not be available except by difference. A runout of inventory, while considered possible, would require an average of 3 hours and a maximum of 6 hours. This could not be done any more frequently than once a week, a case which has already been analyzed. Thus, one must turn to real time material control techniques, to get running physical inventory measurements.

6.4.4 Costs Resulting From Improved Measurement Control

The measurement control program has been instituted to improve the accuracy and precision of material accounting measurements. Although it is estimated to cost approximately \$200,000(11) it brings present plants into compliance with present regulations.(9) Thus, there is no incremental cost associated with this accounting improvement.

7.0 NONECONOMIC ACCEPTANCE FACTORS OF MATERIAL ACCOUNTING IMPROVEMENTS

7.1 SOCIAL IMPLICATIONS

Employees and the general public accept the requirement that a company be able to account for all the material in its custody. Thus, there is total acceptance of improvements in material accountability.

7.2 ENVIRONMENTAL IMPLICATIONS

Based on past history, the best evidence that material losses are occurring in a process facility has been obtained from material accounting records. Losses via unexpected pathways were occurring and were not being detected by other means. The existence of unexplained losses initiated an investigation which located the loss path to the environment. Thus, improvements in material accounting will provide assurance that the environmental insult from the facility is below established limits.

7.3 INSTITUTIONAL IMPLICATIONS

Material accounting places requirements on operating companies which is unique to the nuclear industry. As such, many companies may hesitate to work in the nuclear industry because of the possibility of bad publicity as a result of poor performance.

Governmental involvement is high. At the same time, material accounting criteria have been written by both national and international organizations. Thus, improved material accounting fits easily into the existing structure of these governing bodies. The impact would therefore be very small.

7.4 LEGAL IMPLICATIONS

Material accounting regulations are presently administered by NRC. The legal bases for such a requirement, in the interests of material security, have never been seriously questioned. Any changes to material accounting would have a minimum impact on the existing structure of regulatory agencies, and the way they presently function.

8.0 CONCLUSIONS AND RECOMMENDATIONS

In sections 4 through 7, improvements in material accountability were evaluated both in terms of their benefits - improved timeliness and sensitivity - and their costs. In this section, the benefits and the costs will be compared. Based on this comparison subsequent sections will recommend 1) improvements to present material accounting techniques and 2) will recommend areas of research which appear to have the most potential to further improve material accounting timeliness and sensitivity.

8.1 BENEFIT-COST EVALUATION

The benefit of improvements in material accounting are measured as increased sensitivity and timeliness to detect a loss. The costs are measured by the increased economic burden imposed on the facility.

Table 8.1 summarizes the estimated benefits of the proposed improvements to materials accounting. Improvements are judged as minor if the change in the sensitivity or timeliness of loss detection is less than a factor of 2, moderate if they result in changes ranging from 2 to 10, and substantial if they result in changes in loss detection sensitivity which are greater than a factor of 10. This scale is rather subjective, but does judge the relative benefits of suggested material accounting improvements. Based on this scale Table 8.1 summarizes the benefits and costs of material accounting improvements suggested by the results of earlier sections.

The recommendations presented in the next two sections are based on the data summarized in Table 8.1.

TABLE 8.1 Benefit-Cost Table of Proposed Material Accounting Improvements for Plutonium Processing Facilities

	Benefit		Costs(c)	
Proposed Improvement in Material Accounting	Improved Timeliness	Improved Sensitivity	Additional Annual Operating	Lost Production
1) Reprocessing Plant Material Accounting				
a. Formal Quarterly Inventory	Moderate	Moderate	$200,000	$25 million
b. Weekly Running Inventory	Substantial	Substantial	77,000	None
c. Measurement Control Program	No change	Moderate[a]	None[b]	None
2) Plutonium Nitrate Storage Area				
a. Formal Inventory	Moderate	Moderate	900	None
b. Daily Inventory of all Static Tanks	Substantial	Moderate	19,000	None
3. Plutonium Nitrate-Oxide Conversion Facility				
a. Formal Monthly Inventory	Moderate	Minor-Moderate	18,000	600,000
b. Informal MUF Estimate at Times when Equipment Drained	Moderate	Moderate	5,400	40,000
c. Measurement Control Program	No change	Moderate[a]	None	None
4. Plutonium Fuel Fabrication Facility[d]				
a. Formal Monthly Inventory	Moderate	Minor	36,000	270,000
b. Daily Balance over PuO_2 Storage Area	Substantial	Substantial	16,000	None
c. Measurement Control Program	No Change	Moderate	None	None

(a) Sensitivity to detect losses occurring at a slow rate is improved.

(b) Estimated to cost $200,000, presently part of regulations.

(c) All non-economic costs are insignificant.

(d) Approximately 2 fabrication plants are required to utilize all the plutonium obtained from reprocessing. This factor should be included in any comparison.

8.2 RECOMMENDATIONS FOR IMPROVEMENTS IN MATERIAL ACCOUNTING

Based on the evaluations presented in this report, the staff makes the following general recommendations:

- That the existing licensing review process of material accounting performance be initiated at the conceptual-design stage and follow the progress of equipment measurement system performance tests up through startup.

  Initiating the license review at the conceptual-design stage can provide the best assurance that those design features which improve the ease and exactness with which nuclear materials can be measured will be incorporated into future facilities. These features include the measurement of physical inventories and material flows. Further, by continuing the review process through the startup phase, pilot plant experience can be used to evaluate process holdup and measurement-system performance at a stage where improvements can be made. Lastly, pre-startup calibration data and measurement tests can be used as a basis for demonstrating that the system will meet safeguards specifications for materials accounting.

- That the present capability of measurement systems be the subject of a thorough review and that the results of such studies be documented and available in the open literature. At the present time, there is not a complete listing of the present capability of all measurement systems used in material accounting. As a result, designers are not always able to choose the measurement systems which will provide the most acceptable performance.

The following recommendations are made for specific facilities:

- Chemical Separations: The staff recommends that the formal material accounting periods be no less frequent than quarterly.

  Quarterly periods give increased assurance that all material processed can be accounted for. In addition, quarterly inventory periods allow for more frequent equipment calibration checks. Thus, sensitivity to detect accumulations or losses occurring at a slow rate is much improved. The semiannual inventory requirement simply allows too much material to flow through the system between measurement system calibrations.
- The staff also recommends that studies be initiated to demonstrate the accuracy of running inventory measurements in a separations facility.

  Based on the analyses presented here, much of the inventory in the separations facility is present in accumulator tanks between processing steps and as such,can be measured periodically without process shutdown. An actual demonstration is needed because between inventory periods plutonium has been known to deposit on the walls of process vessels and, as a result, be "lost" until the equipment is flushed. In current designs such "losses" are thought to be small but this must be demonstrated.

- Plutonium nitrate storage facilities. The staff recommends the formal material accounting period be no less frequent than monthly.

At any time, plutonium nitrate solution may be held in static or active tanks. Static tanks are being held for future use and are locked out. Active tanks are those to which material has been added or withdrawn or in which material is being mixed. Because of the impossibility to account for plutonium in incompletely mixed tanks, a running inventory on the facility is impossible in spite of its simplicity. Thus, a requirement for a monthly inventory will restrict operations to the extent that tank uniformity must be obtained quite often. At the same time, the monthly reporting requirement makes it highly advantageous to lock out as many tanks as possible for that monthly period. While it is recognized that the monthly reporting requirement may somewhat reduce the flexibility of the operations, reduced flexibility is very advantageous from the standpoint of material accountability.

- Plutonium Nitrate Storage. The staff recommends that the static tanks be checked daily to insure that the weight factor (specific gravity times liquid height) has not changed.

The static plutonium nitrate storage tanks may be locked out of the process for several accounting periods. Although it is not felt that sampling for plutonium content is required, a daily check of the weight factor for each tank would appear to be a minimum requirement.

- Plutonium Nitrate to Oxide Conversion. The staff recommends that formal inventory reporting requirements be no less frequent than monthly.

  Based on the analyses of this process, presented earlier, sensitive running inventories of this process are not possible. At the same time, monthly cleanouts are not extremely time consuming and appear to be a reasonable alternative.

- Plutonium Nitrate to Oxide Conversion. The staff recommends that the formal monthly inventory be supplemented with informal inventory measurements wherever a process runout occurs.

  Process runouts occur to get a clean separation between batches or to do preventive maintenance. In either case, such runouts provide a convenient time to take an inventory. The results are only slightly less sensitive than the formal inventory.

- Plutonium Fuel Fabrication. The staff recommends that formal inventory reporting requirements be no less frequent than monthly.

  Future plutonium fabrication plants have very small quantities of material in difficult-to-measure forms. In addition,process runouts are likely to occur several times a month. Thus, providing several opportunities a month for process inventory measurements.

Measurements at such times should be encouraged since they represent what are likely to be ends of accounting frames for other facilities. In this way, cross-checks between facilities may be available.

- Plutonium Oxide Storage. The staff recommends that the PuO_2 storage area be formalized as a material balance area and that daily physical inventories using PuO_2 weight be performed over this area. Because of the attractive nature of this material, which is present in loose form or in sealed containers, the staff believes that daily weight balances and item counts should be performed. Losses from other areas require the extraction of much larger quantities of material, amounts which are likely to be noticed. This is not the case with a PuO_2 storage area if it is only inventoried with the frequency of the balance of the plant.

8.3 RECOMMENDATIONS FOR FUTURE RESEARCH

The following general recommendations for future research topics is made:

- Cumulative LEMUF. The staff recommends that Regulations for Cumulative LEMUF be developed for plutonium fuel cycle facilities to supplement current Regulation for LEMUF for single accounting periods.

  At the present time, Regulations for measurement quality expressed in terms of LEMUF, apply to only single and fairly short accounting periods. They do not fully address the problem of long-term assurance and the problem of long-term material control. In some respects, much better assurance can be obtained by evaluating materials accounting data from the standpoint of the cumulative MUF and its associated limit of error, CUMLEMUF, than by evaluating the MUF for a single accounting period.

  To develop realistic limits for cumulative MUF, development efforts are required in two areas. First, statistical procedures must be developed for the propagation of cumulative measurement errors. Second, studies of current state of the art measurements and their uncertainties must be carried out to provide a realistic basis for the CUMLEMUF values to be used in the Regulations.

- Safeguards Assurance of Material Accounting. The staff recommends that formal materials accounting using the best state-of-the art measurements be fostered and improved as a means of providing positive assurance that diversion has not occurred. Further, it is recommended that R&D programs aimed at improving the timeliness and sensitivity of materials accounting be continued and expanded as appropriate.

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APPENDIX A

MATERIAL ACCOUNTING METHODS

As discussed in section 3, material accounting methods are used to provide assurance that the nuclear material being processed through a facility can be accounted for. This assurance is accomplished by breaking each facility into a number of discrete material balance areas (MBA's). All material transfers into or out of each area must be measured and recorded. Since all parts of the facility which could contain special nuclear material must be included in a material balance area, a facility balance can always be formed by combining the results of the individual areas.

In this appendix, the methods employed to evaluate the effects of improved accounting techniques will be described. Appendix B applies these techniques, the results of which are summarized in section 3. This appendix will be divided into three sections. This appendix will begin with a general description of the MUF concept. This will be followed by a fairly detailed description of the statistical models used to obtain the confidence limits on the value of MUF. The final part develops the detailed equations used to model possible improvements in the sensitivity accounting methods.

A.1 THE MUF CONCEPT

MUF is an acronym for Material Unaccounted For. It is calculated by taking the difference between the book inventory (the material which is supposed to be present in the inventory) and the physical inventory (the amount of material which is either measured or estimated to be present). In the absence of measurement, sampling and bookkeeping errors, a positive MUF indicates an unaccounted loss of material and a negative MUF indicates an unaccounted for gain.

The book inventory at the end of an accounting period is obtained by taking the quantity of material present at the beginning of the accounting period and adding to it all measured receipts and subtracting all measured removals. Thus, if F denotes the total amount of feed, R all the removals and BI the beginning inventory, then the ending book inventory, EBI, can be expressed as:

$$EBI = BI + F - R. \tag{1}$$

If EI is the measured or estimated ending inventory, then MUF is expressed as:

$$MUF = EBI - EI = BI - EI + F - R. \tag{2}$$

In general, the inventory, feed and removal terms are made up of the sum of many items. MUF can be evaluated for many accounting periods. If in the <u>tth</u> period there are n_t batches of feed, ℓ_t removal batches, and "k" categories of material on beginning and ending inventory, then:

$$MUF_t = \sum_i^k (I_{t-1,i} - I_{t,i}) + \sum_i^{n_t} F_{t,i} - \sum_j^{\ell_t} R_{t,j}. \tag{3}$$

This expression is for a single material balance area. All flows, receipts or removals, from the area are included in the MUF equation. If the MUF's from each area are added up, then the facility MUF is obtained. This occurs because the inventory term for the entire facility equals the sum of the inventory in its parts and any transfers between MBA's cancel out. On the books, all internal transfers are described by entering an R_j term into the records of the MBA shipping material and an identical F_i term in the MBA receiving the material. When the MUF's for these two areas are summed, since the removals from both areas are subtracted from the feeds from both areas, the terms representing the internal transfer cancel. By definition, feeds or removals from the facility have no such cor-

If the length of the accounting period is very long, then the values for n_t and ℓ_t in equation (3) can become very large. The number of categories of material on inventory is not influenced by the length of the accounting frame. In addition it is only the inventory levels at the beginning and end of the accounting frame that enter into MUF. This is easily shown by summing the MUF calculations for two successive periods.

$$MUF_t + MUF_{t+1} = \sum_i^K \left[(I_{t-1,i} - I_{t,i}) + (I_{t,i} - I_{t+1,i}) \right] + \sum_i^{n_t} F_{t,i} + \sum_i^{n_{t+1}} F_{t+1,i} - \sum_j^{\ell_t} R_{t,j} - \sum_j^{\ell_{t+1}} R_{t+1,j}. \tag{4}$$

When the two MUF's are summed the intermediate inventory estimate, $I_{t,i}$, cancels out. The feed term in the sum of all the feed batches for both periods and the removal term is also the sum of the removals from both periods. Thus, in addition to evaluating an entire facility from smaller material balance areas, it is also possible to combine short material balance periods into longer ones.

If the MUF's from N consecutive accounting periods are summed, this cumulative material unaccounted for estimate is designated by the acronym CUMMUF. When N accounting periods are summed, equation (3) becomes:

$$CUMMUF_N = \sum_i^k (I_{0,k} - I_{N,k}) + \sum_t^N \sum_i^{n_t} F_{t,i} - \sum_t^N \sum_j^{\ell_t} R_{t,j}. \tag{5}$$

In the above equation the subscript "t" represents the tth accounting period. The term $I_{0,i}$ represents a physical inventory term at the start of the first accounting period over which MUF's are accumulated. If the cumulative MUF calculation begins with a new, clean facility, then $I_{0,i}$ is zero for all "i."

In the following sections, equations (3) and (5) will be used to develop equations for evaluating the statistical confidence limits that can be placed on a given value for MUF.

A.2 STATISTICAL MODELS FOR EVALUATING MUF SIGNIFICANCE

The amount of material in a batch can never be measured exactly. Even the amount of material under item accounting is uncertain to the extent that the amount of material contained in each item cannot be known exactly. Placing items under item control does not improve the precision of the inventory measurement; it does simplify and quicken the inventory measurement procedures.

Recognizing that no measurement can be made without error, the following paragraphs will take estimated errors in basic measurements and show their effect on the certainty of the MUF and CUMMUF terms.

The basic measures of dispersion and uncertainty in a given measurement are the variance and the standard deviation. These measures of the certainty of a given measurement are described below.

The variance of a random variable x is defined by the equation

$$\sigma^2(x) = \int_{-\infty}^{\infty} (x-\mu)^2 f(x)dx,$$

where μ is defined as the mean or expected value of x, and f(x) is the density function and is a measure of the frequency with which x will assume a value in the small interval dx about x. Then σ is defined as the standard deviation. If R values are randomly chosen from the distribution, then

$$\overline{x} = \sum_{i}^{R} x_i/R \tag{6A}$$

and

$$\sigma^2(x) = \sum_{i}^{R} (x_i-\overline{x})^2/R-1 \tag{6B}$$

are unbiased estimates of μ and σ^2 respectively. For a normal distribution about two-thirds fall within one standard deviation of the mean and 95

If two measurements are independent, the variance of a series of measurements equals the sum of the individual measurement variance. Thus, the equation for the tth accounting period becomes:

$$\sigma_t^2(\mathrm{MUF}) = \sigma^2(EI_{t-1} - EI_t) + \sigma^2(F_t) + \sigma^2(R_t). \qquad (7)$$

In this equation, the beginning inventory term for the tth accounting period has been replaced by its equivalent, the ending inventory for the previous accounting period. The F and R terms represent the sum of all feed and removal terms for the accounting period. The variance of the inventory terms has not been broken up because the assumption of independence may not be valid. This is particularly true if the length of the accounting period is very short.

The variance of CUMMUF for N accounting periods can be obtained by a parallel development. The result is :

$$\sigma_N^2(\mathrm{CUMMUF}) = \sigma^2(BI_1 - EI_N) + \sigma^2\left(\sum_t^N F_t\right) + \sigma^2\left(\sum_t^N R_t\right). \qquad (8)$$

Once again the variance of the inventory measurement has not been separated because the measurements may not be independent.

Equations (7) and (8) can be applied to a single material balance area of to an entire facility. It should be noted that although MUF for the entire facility is the sum of the MUF's for the individual MUF's, the relationship is not true for the variance of MUF. To be correct, the variance associated with internal transfers must not be included in the facility calculation. If equations (7) and (8) as applied to MBAs were added together, errors associated with internal transfers would not cancel but instead would be counted twice.

The values of MUF and CUMMUF obtained by closing the material balance can be considered as random variables with a mean and a standard deviation. The central limit theorem would indicate that since MUF and CUMMUF are the sum of many distributed variables, where no individual values tend to be dominating, the values of MUF and CUMMUF will tend to be normally distributed about the expected value of MUF (or CUMMUF). The expected value of MUF is the value that MUF would have in the absence of measurement errors.

If the expected value of MUF (or CUMMUF) is zero, then the absolute value of MUF_t (or CUMMUF) is expected to deviate from zero by less than $2\sigma(MUF)$ or $2\sigma(CUMMUF)$ 95 times out of 100.

Because of the statistical significance frequently attached to the 95 percent confidence interval, twice the standard deviation of MUF has been given the acronym LEMUF for Limit of Error MUF. LEMUF is usually used as a control point, i.e., an investigation is initiated whenever MUF exceeds LEMUF for an accounting period. In this way, assurance is gained that all material processed through the MBA or the facility has been accounted for.

The normal distribution of calculated values of MUF about zero, under controlled conditions, can be used as the basis for several statistical tests. First, if the calculated value of MUF exceeds LEMUF five times out of 100 no unmeasured losses have occurred but measurement errors have combined in such a way that the absolute value of MUF deviates from zero by a value greater than LEMUF. When this occurs it is called a type I error. Note that if the expected MUF is zero MUF is just as likely to be more negative than -LEMUF as to be more positive than +LEMUF. Any time MUF exceeds LEMUF an investigation is usually required. For this reason the region outside the interval [-LEMUF,LEMUF] is defined as the critical region. (See Mood, page 247.)(1)

Suppose there is a loss ϵ, then MUF will be distributed around ϵ with a standard deviation of σ_{MUF}. There is some probability that the loss will not be detected because measurement errors hide the loss. This is called a type II error. The probability that a loss ϵ will not be detected can be obtained from the following equation.

$$P(\epsilon) = 1 - \left\{F\left(\frac{\mathrm{LEMUF}-\epsilon}{\sigma_{MUF}}\right) - F\left(\frac{-\mathrm{LEMUF}-\epsilon}{\sigma_{MUF}}\right)\right\}, \tag{11}$$

where F(x) is the cumulative distribution function of the zero mean, unit variance, and normal distribution. Values of F(x) for a given x can be obtained from any standard set of statistical tables.$^{(2)}$ Figure (1) shows the value of $P(\epsilon)$ as a function of ϵ for the case where the expected value of MUF is zero and $\sigma(\mathrm{MUF}) = 1.0$.

Equation (11) can be simplified if $\epsilon > \mathrm{LEMUF}$. In this case:

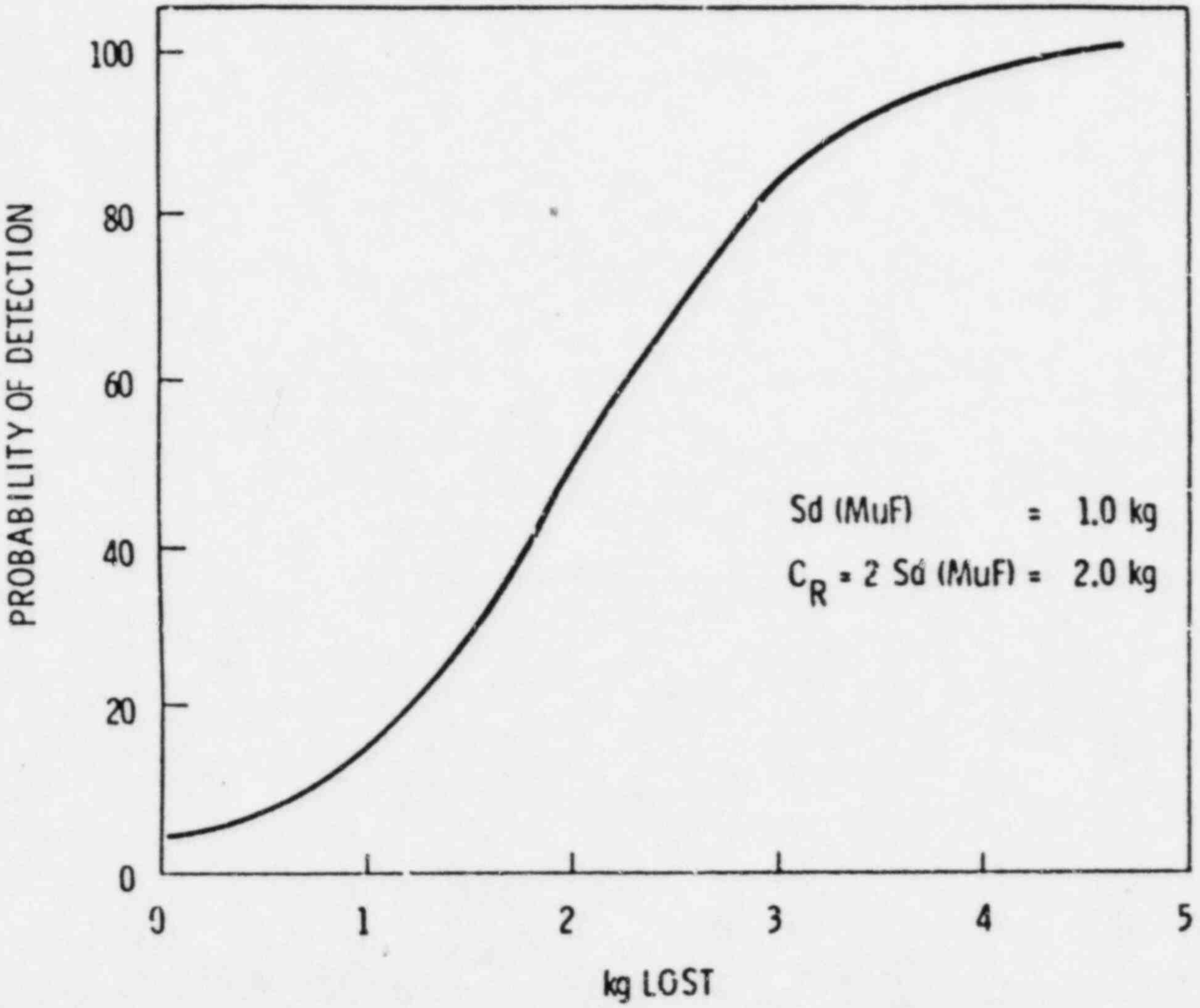
$$P(\epsilon) = 1 - F\left(\frac{\mathrm{LEMUF}-\epsilon}{\sigma_{MUF}}\right) = F\left(\frac{\epsilon-\mathrm{LEMUF}}{\sigma_{MUF}}\right) = F\left(\frac{\epsilon}{\sigma_{MUF}} - 2\right). \tag{12}$$

A similar development can also be carried out for multiple diversions using the expression for $\sigma_N(\mathrm{CUMMUF})$. If an amount ϵ is lost during each accounting period, then as shown by Stewart,$^{(3)}$ the probability of detecting the cumulative loss $N\epsilon$ is given by:

$$P(N\epsilon) = 1 - \left\{F\left(\frac{2\sigma_N(\mathrm{CUMMUF})-N\epsilon}{\sigma_N(\mathrm{CUMMUF})}\right) - F\left(\frac{-2\sigma_N(\mathrm{CUMMUF}-N\epsilon)}{\sigma_N(\mathrm{CUMMUF})}\right)\right\}. \tag{13}$$

If $N\epsilon > 2\sigma_N(\mathrm{CUMMUF})$ then equation (13) is approximated by:

$$P(N\epsilon) = F\left(\frac{N\epsilon-2\sigma_N(\mathrm{CUMMUF})}{\sigma_N(\mathrm{CUMMUF})}\right) = F\left(\frac{N\epsilon}{\sigma_N(\mathrm{CUMMUF})} - 2\right). \tag{14}$$



<u>FIGURE A.1</u> Sample Power Curve

Stewart[3] presents the rationale for using equation (12) to detect single diversions and equation (14) for the detection of multiple diversions. Equation (14) is insensitive for single losses because the variance terms associated with the flows for N accounting periods are included in the calculation. At the same time, since Nc can be expressed as a fraction of the throughput, the detection probability using σ(CUMMUF) increases with time. For short accounting periods, the variance terms associated with inventory limit the detection capability. After many accounting periods the variances associated with flow become dominant and unmeasured flow losses become more susceptible to detection by statistical methods.

By using equations (7) through (14) it is possible to determine the power curves for a given set of feed, removal and inventory variance measurements. The following section will look at the detailed error structure of these terms and describe how basic errors in measurement, sampling and analysis are combined to obtain the accuracy of a given flow or inventory measurement.

A.3 MATHEMATICAL MODELLING OF FLOW AND INVENTORY MEASUREMENT ERRORS

The previous section started with the measurement error variances in flow and inventory, and propagated these variances to variances in MUF and CUMMUF. Measurement errors associated with various flow and inventory terms are generally statistically independent so that the propagation technique is fairly straightforward. Obtaining the variance term for specific flow and inventory terms is not as straightforward because the assumption of independence is in general not valid. This section will develop the techniques which have been used to obtain the individual flow and inventory variance terms in equations (7) and (8).

There are two factors which make the development of flow and inventory variance terms somewhat complicated. First, the material balance considers a single element or isotope but often the measurements are made on mixtures of elements and isotopes. Thus, a single measurement on each flow or inventory component cannot be used. A weight or volume measurement of the entire flow or inventory component must be supplemented by an analysis of a sample of the material balance component. Thus, the errors in measuring a flow or inventory component must consider errors in analysis, sampling and weight or volume measurements.

The second complicating factor is the existence of random, short-term systematic and long-term systematic measurement errors. Random errors in measurements are independent errors whereas systematic errors show various degrees of dependency on each other. For example, if a scale is miscalibrated for an entire accounting period, then every reading taken during the period is in error by a constant amount. Such an error, since it would not be expected to persist for many accounting periods, would be classified as a short-term systematic error. Long-term systematic errors are assumed to persist indefinitely. It is easy to see that when a whole series of measurements are dependent on a single calibration, the assumption of independence is not valid.

Although the two complicating factors are somewhat related, they will be treated separately. The key assumption will be that it is possible to break each measurement system into random short-term systematic and long-term systematic components. Then all random, short- and long-term systematic errors will be treated separately when determining their influence on a flow or inventory component of the material balance.

To demonstrate how the individual flow or inventory measurement variance terms are determined, take the feed term

$$F_i = W_i \cdot X_i, \tag{15}$$

where F_i is the total weight of the element in the ith feed batch, i.e., kg of plutonium,

W_i is the total weight of the feed batch (kg),

X_i is the concentration of the element over which the material balance is being taken (kg of Pu/kg of feed).

Statistical proofs$^{(4)}$ are available to show that an approximation for the variance of the term F_i is:

$$\sigma^2_{F_i} = (W_i \cdot X_i)^2 \left[\frac{\sigma^2_W}{W^2} + \frac{\sigma^2_X}{X^2}\right] \tag{16}$$

$$= (F_i^2)\left[\frac{\sigma^2_W}{W^2} + \frac{\sigma^2_X}{X^2}\right] \tag{17}$$

The terms σ^2_W/W^2 and σ^2_X/X^2 are the relative error variances associated with weighing and determining the concentration of the material balance element or isotope in the feed batch, respectively. The subscript has been left off the W and X because the relative errors are assumed to be independent of the batch weights and concentrations.

Equation (17) will be used to describe the behavior of the random and long- and short-term systematic errors. For random errors, the ratio of σ_W^2/W^2 will be denoted by r_W^2, for short-term systematic errors, the ratio will be denoted by p_W^2, and for long-term systematic errors the ratio will be denoted by q_W^2. The equation for the random error variance of the feed term becomes:

$$\sigma_r^2(F_i) = F_i^2 \left[r_W^2 + r_X^2\right]. \tag{18}$$

Because there can be random and systematic errors associated with sampling as well as analysis, the term r_X^2, equation (18) is frequently expanded to the form:

$$\sigma_r^2(F_i) = F_i^2\left[r_W^2 + r_S^2 + r_A^2\right] . \tag{19}$$

Similar equations could be written for σ_S^2 and σ_q^2.

Equation (19) is valid for the case where the random error in F_i is obtained from one weighing, one sampling and one analysis. There are some cases where multiple weighings, samplings, or analyses are performed. In such cases, equation (19) is not a valid representation of σ_r^2. If R_W weighings, R_S samples, and R_A analyses are performed, it can be shown that:

$$\sigma_r^2(F_i) = F_i^2 \left[\frac{r_W^2}{R_W} + \frac{r_S^2}{R_S} + \frac{r_A^2}{R_A}\right]. \tag{20}$$

Equation (20) is valid for evaluating the variance associated with the random error component. Since multiple weighings, samplings or analyses have no effect on the systematic error component, equation (19) remains valid for the propagation of both long- and short-term systematic errors.

Equations (19) and (20) are used for the propagation of systematic and random errors associated with individual flow or inventory terms. The material balance requires a summation of flow and inventory terms. The propagation of systematic and random error variances through these summations are described in the following paragraphs. The behavior of the flow terms will be derived first. This will be followed by an evaluation of the inventory terms.

The analysis of the flow terms considers a generalized flow term denoted by Y_i.

Let

$$Y_i = \mu + \varepsilon_i + O_i. \tag{21}$$

Where μ is the true amount being measured

ε_i is the random error made in the measurement of μ, and

Oi is the systematic error made in the measurement of μ.

During the mth accounting period, assume n batches associated with the flow component "Y." In addition, during the "m" accounting period assume the systematic error term O is a constant for all n. No distinction between long-and short-term systematic errors will be made at this time. If the sum of all Y_i is a measurement which is part of the material balance for the accounting period, then:

$$\sum_i^n Y_i = \sum_i^n \mu + \sum_i^n \varepsilon_i + \sum_i^n O. \tag{22}$$

Since μ and O are the same for all n,

$$\sum_{i}^{n} Y_i = n\mu + n\Theta + \sum_{i}^{n} \varepsilon_i. \tag{23}$$

The variance of a constant times a random variable is equal to the variance of the variable times the constant squared. For statistically independent variables the variance of a sum is equal to the sum of the variances. The variance of a random variable plus a constant is equal to the variance of the random variable. Thus:

$$\sigma^2\left(\sum_{i}^{n}(Y_i)\right) = n\sigma_\varepsilon^2 + n^2\sigma_\Theta^2. \tag{24}$$

The variance of all ε_i has been expressed as σ_ε^2 and the variance of θ has been denoted by σ_θ^2. From this equation it can be seen that if only one batch of material is associated with the accounting period, then there is no distinction between random and systematic error. On the other hand, as the number of batches included in an accounting period becomes large, since σ_ε and σ_θ usually differ by less than a factor of ten, then the contribution of the systematic error term far exceeds the contribution of the random error term.

Historically systematic errors don't persist indefinately. Let θ in equation (23) be broken into two components, θ_p and θ_q, representing short-term and long-term systematic errors in measurement respectively. Let θ_q persist indefinitely but let the value θ_p for the m<u>th</u> accounting period be taken from a distribution with a mean of zero and a standard deviation of σ_{θ_p}. Then by analogy to the previous development, the total flow variance for m periods, each with n batches becomes:

$$\sigma^2\left(\sum_{j}^{m} \sum_{i}^{n} Y_{j,i}\right) = (nm)^2\, \sigma_{\Theta_q}^2 + mn^2\sigma_{\Theta_p}^2 + mn\sigma_\varepsilon^2. \tag{25}$$

When the σ's are expressed as relative errors, the equation for the feed term becomes:

$$\frac{\sigma^2\left(\sum_{j}^{m}\ \sum_{i}^{n} F_{j,i}\right)}{(mn\bar{F})^2} = \left(q_F^2 + \frac{p_F^2}{m} + \frac{r_F^2}{mn}\right) \tag{26}$$

The term $\bar{F}$ is the average amount of accountable material in a feed batch. Thus, the product $mn\bar{F}$ is the total quantity of material feed into the material balance area during m accounting periods.

The numerator on the left side of equation (26) is one of the flow terms in equation (8) for σ^2(CUMMUF). Similar expressions can be derived for each feed and removal stream entering into the variance calculation.

From equation (26) it can be seen that the effect of the short-term systematic error component on CUMMUF can be treated as if m values for the short-term systematic error were randomly chosen from a distribution with a mean of zero and a relative variance equal to p_F^2. Thus, for one accounting period σ(CUMMUF) is unaffected by the fraction of the error that is short-term. It follows that σ(MUF) is unaffected also. However σ(CUMMUF) is influenced if m becomes large. The product mn can be considered as a time term for a facility operating at a constant throughput. Over a fixed time interval, since mn is constant, the term q^2+r^2/mn is constant. However, the term p^2/m becomes smaller as m increases. Thus, over a fixed time period σ(CUMMUF)/mm is minimized by maximizing m.

The tradeoff's between m and n will be demonstrated in Appendix B for a 6-month and 3-month inventory in a reprocessing plant. Over an interval of 2 years, the same total number of batches of material flow through the facility. In each case, however, recalibrations are assumed to occur whenever an inventory measurement is made. Thus, if an inventory measurement is made every 6 months there are only four calibrations in 2 years, whereas for the 3-month case there are eight recalibrations. It will also be shown in Appendix B that p^2 is large relative to q^2+r^2/mn. Thus, there is a strong incentive for maximizing the value of m in order to minimize the value of σ(CUMMUF).

The variance term associated with the inventory terms in the MUF equation will initially parallel the development used for developing the variance equations associated with the flow terms. First, the variance term for the inventory term in equations (7) and (8) will be broken into random and systematic error components. The distinction between long- and short-term systematic errors need not be made because MUF and CUMMUF contain only estimates of the beginning and ending inventory levels. In both the σ^2(MUF) and σ^2(CUMMUF) equations, the inventory variance term will be described by:

$$\sigma^2(BI\text{-}EI) = \sigma_r^2(I_B-I_E) + \sigma_p^2(I_B-I_E). \tag{27}$$

The terms in parentheses in equation (27) should be taken symbolically and not algebraically. Thus, $\sigma_r^2(I_B-I_E)$ is taken as the random error variance of the inventory term in the MUF equation. The subscript p denotes the systematic error variance of the inventory component.

Equation (27) is used to describe the inventory contribution to the variance of MUF and CUMMUF. It may be argued that the "q" subscript, denoting a long-term systematic error variance, should be used in the equation for σ^2(CUMMUF), such a distinction will not be used in this evaluation.

There may be many categories of material on inventory, if there are k categories, all are assumed to be independent, thus

$$\sigma_r^2(I_B-I_F) = \sum_i^k \sigma_r^2\ (I_{B_i}-I_{E_i}). \tag{28}$$

A similar expression can be written for the systematic error component.

The behavior of the measurement error variances associated with inventory measurement cannot be summarized in a form which is as simple as the flow variances. Random errors propagate in a straightforward manner but systematic errors must be handled on a case by case basis. Assume there are k categories of material on inventory at the beginning and end of the accounting period. The inventory level in one of the k categories may be best described by either an inventory level or an item count times the average amount of accountable material in each item. These two inventory categories show a different error structure as developed in the following paragraphs.

For the case where the inventory level is best defined as a total quantity of accountable material, let I_{B_i} and I_{E_i} represent the amount of accountable material in the ith inventory category at the beginning and end of the accounting period respectively. Then the random error variance term can be expressed in the form:

$$\sigma_r^2(I_{B_i}-I_{E_i}) = (I_{B_i}^2 + I_{E_i}^2)\, r_{I_i}^2 \,. \qquad (29)$$

The systematic error term will be assumed to have the following form:

$$\sigma_p^2(I_{B_i}-I_{E_i}) = (I_{B_i}-I_{E_i})^2 p_{I_i}^2 = (\Delta I_i)^2 p_{I_i}^2. \qquad (30)$$

Equation (30) assumes the relative systematic error is proportional to the change in inventory level rather than to the absolute inventory level in the storage vessel.

For the case where the inventory is present as countable items in an inventory category, let $\bar{I}_i$ be the average amount of material in the ith category and C_{B_i} and C_{E_i} be the number of items on beginning and ending inventory in the ith category. Then the following expressions are used for the random and systematic error variances associated with inventory.

$$\sigma_r^2(I_{B_i}-I_{E_i}) = (C_{B_i} + C_{E_i})\, \bar{I}_i^2 r_{I_i}^2 \tag{31}$$

$$\sigma_p^2\, (I_{B_i}-I_{E_i}) = (C_{B_i}^2 + C_{E_i}^2)\, \bar{I}_i^2 \rho_{I_i}^2 \;. \tag{32}$$

In this case, the systematic errors associated with material present on ending inventory are assumed to not cancel with the systematic errors of measurement made at the beginning of the period. This is a conservative assumption since some cancellation is likely to occur, particularly for short accounting intervals.

For each of the k categories of material on inventory, either equations (29) and (30) or equations (31) and (32) are used to propagate inventory errors. Equations (30) and (32) are very different. The evaluations performed in Appendixs B and C assumes that equation (32) is the proper form whenever the inventory can be represented as batches of material which turn over during an accounting period. Green pellets which have not been fired fall into this category. During an accounting period, it is highly unlikely that green pellets present at the beginning of the accounting period will not be processed and replaced by new batches of unfired pellets during the period. Equation (30) is assumed to be the proper form whenever the inventory is present as a large batch of material. A storage tank containing several hundred kilograms of plutonium is placed in this category. If a small amount of material is withdrawn or if the tank is emptied and filled back up to approximately the same level, then it is believed that the systematic error component is proportional to the difference rather than the absolute inventory of material present.

Equations (29) and (30) are applied to containers which are under item control and undergo processing during the accounting period. Items that are on inventory and do not undergo processing are included in the MUF equation but not in the estimate of the σ(MUF). Any errors made in estimating the amount of accountable material in these items cancel out since they are present in both I_{B_i} and I_{E_i}.

The estimate of σ^2(MUF) and σ^2(CUMMUF) require a summation of the k categories of material on inventory. For each category, a decision is made as to whether equations (29) and (30) or (31) and (32) are applicable. For each class the variance term is calculated and then the variance of all categories is summed to get the random and short- and long-term systematic error inventory variances. These inventory variances are then summed to get the inventory variance term in equation (27).

A.4 SUMMARY OF NUCLEAR MATERIAL ACCOUNTING EQUATIONS

The following equations are used to evaluate the sensitivity of nuclear material accounting methods.

1) $\mathrm{MUF} = \mathrm{BI} + \mathrm{EI} + F - R$

2) $\mathrm{LEMUF} = 2 \cdot \sigma(\mathrm{MUF})$

3) $\sigma(\mathrm{MUF}) = \sqrt{\sigma^2(\mathrm{MUF})}$

4) $\sigma^2(\mathrm{MUF}) = \sigma^2(\mathrm{BI}-\mathrm{EI}) + \sigma_F^2 + \sigma_R^2.$

For n feed batches during the accounting period

5) $\sigma_F^2 = \overline{F}^2 \left[n\, r_F^2 + n^2(p_F^2 + q_F^2) \right].$

For ℓ removal batches during the accounting period

5) $\sigma_R^2 = \overline{R}^2 \left[\ell r_R^2 + \ell^2(p_R^2 + q_R^2) \right].$

If there are more than one feed or one removal stream then equations (5) and (6) must be developed for each stream.

The variance of the beginning and ending inventory term is broken down into k categories of material for each category, a decision is made as to whether or not it is describable as an absolute inventory level or as a series of discrete items. If the first h of the k categories is defined by a total inventory level and the rest by an item count, then

$$7)\quad \sigma^2(BI-EI) = \sigma_r^2(I_B-I_E) + \sigma_p^2(I_B-I_E),$$

and

$$8)\quad \sigma_R^2(I_B-I_E) = \sum_{i=1}^{h} (I_{B_i}^2+I_{E_i}^2)r_{I_i}^2 + \sum_{i=n+1}^{k}(C_{B_i}+C_{E_i})\bar{I}_i^2 r_{I_i}^2$$

$$9)\quad \sigma_p^2(I_B-I_F) = \sum_{i-1}^{h} \Delta I_i^2 r_{I_i}^2 + \sum_{i=n+1}^{k} (C_{B_i}^2+C_{E_i}^2)\bar{I}_i^2 p_{I_i}^2.$$

The equations for CUMMUF parallel equations (2) through (9). Equations (5) and (6) must now consider the effect of m accounting periods. They become:

$$5R)\ \sigma_F^2(\text{CUMMUF})\text{s}\ \bar{F}^2\left[mnr_F^2 + n^2mp_F^2 + n^2m^2q_F^2\right]$$

$$6R)\ \sigma_R^2\ (\text{CUMMUF}) = \bar{R}^2\left[mnr_R^2 + n^2mp_R^2 + n^2m^2q_R^2\right].$$

All other equations remain the same.

Equations (1) through (9) are used in Appendix B to quantify the effect of possible improvements in material accounting. The results of these analyses have been summarized in Section 3 of this report.

REFERENCES

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3) K. B. Stewart, "Statistical Techniques for Enhancing the Role of Material Balance Accounting in Safeguards," BNWL-1386, Battelle-Northwest, Richland, Washington, May 1970.

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APPENDIX B

SAFEGUARDS MATERIAL ACCOUNTING CAPABILITIES OF FUTURE PLUTONIUM PROCESSING FACILITIES

This appendix will describe the detailed measurement uncertainty calculations performed to evaluate the sensitivity of future plutonium processing plants to detect material losses. Two processing plants will be evaluated; a 1500 MT/yr LWR reprocessing operation and a 200 MT/yr mixed-oxide fuel fabrication facility. Because of the vast differences in material accounting characteristics within a reprocessing plant, the model will individually consider the accounting characteristics of separations area, the plutonium nitrate storage area, and the plutonium nitrate-to-oxide conversion area. This evaluation will treat each area as individual facilities. A discussion will be limited to the plutonium material accounting capabilities of these four facilities. It should be recognized that the reprocessor must also account for the uranium processed through the plant.

This appendix will completely develop the material accounting capability of each of the four plutonium processing facilities before introducing the next one. Each facility will be introduced by a brief description of its operating characteristics. This will be followed by a discussion of the accuracy of accounting measurements performed for the facility. A final section will describe the material accounting capability of the facility. In general, the last section will develop the quantitative relationship which exists between the operating state of the facility and the timeliness and sensitivity of the accounting records. The mathematical models described in Appendix A will be used to obtain the material accounting capability of each facility.

B.1 MATERIAL ACCOUNTING CAPABILITY OF THE SEPARATIONS FACILITY OF A 1500 MT/YR LWR REPROCESSING PLANT

As described in the previous paragraphs, the reprocessing plant has been divided into three separate facilities, a separations facility, a plutonium nitrate storage facility, and a plutonium nitrate to oxide conversion facility. This section will discuss the material accounting characteristics of the separations facility. The other facilities will be the major subject of subsequent sections.

The separations facility operation is remote, performed behind many feet of concrete. This analysis will be modeled after the 1500 MT/yr Barnwell Plant being constructed by Allied General Nuclear Services (AGNS). The facility description will be taken from the Safety Analysis Report(1) prepared by AGNS personnel. It is thought to be representative of future separations facilities.

Although the separations operation properly begins when the spent fuel is unloaded from the large shipping casks, from the standpoint plutonium accountability, the accountability tank which receives feed from the dissolver is the start of the separations process. The rationale for starting the plutonium accountability with the dissolver solution is rather straightforward. All plutonium in this stream is potentially usable material and will be feed into subsequent processes. Thus, it is properly the start of plutonium safeguards concerns. In addition, up until the fuel is dissolved, its plutonium content is only known through calculations. Thus one works backwards from the dissolver solution to the plutonium content in the fuel assemblies used to make up the dissolver solution.

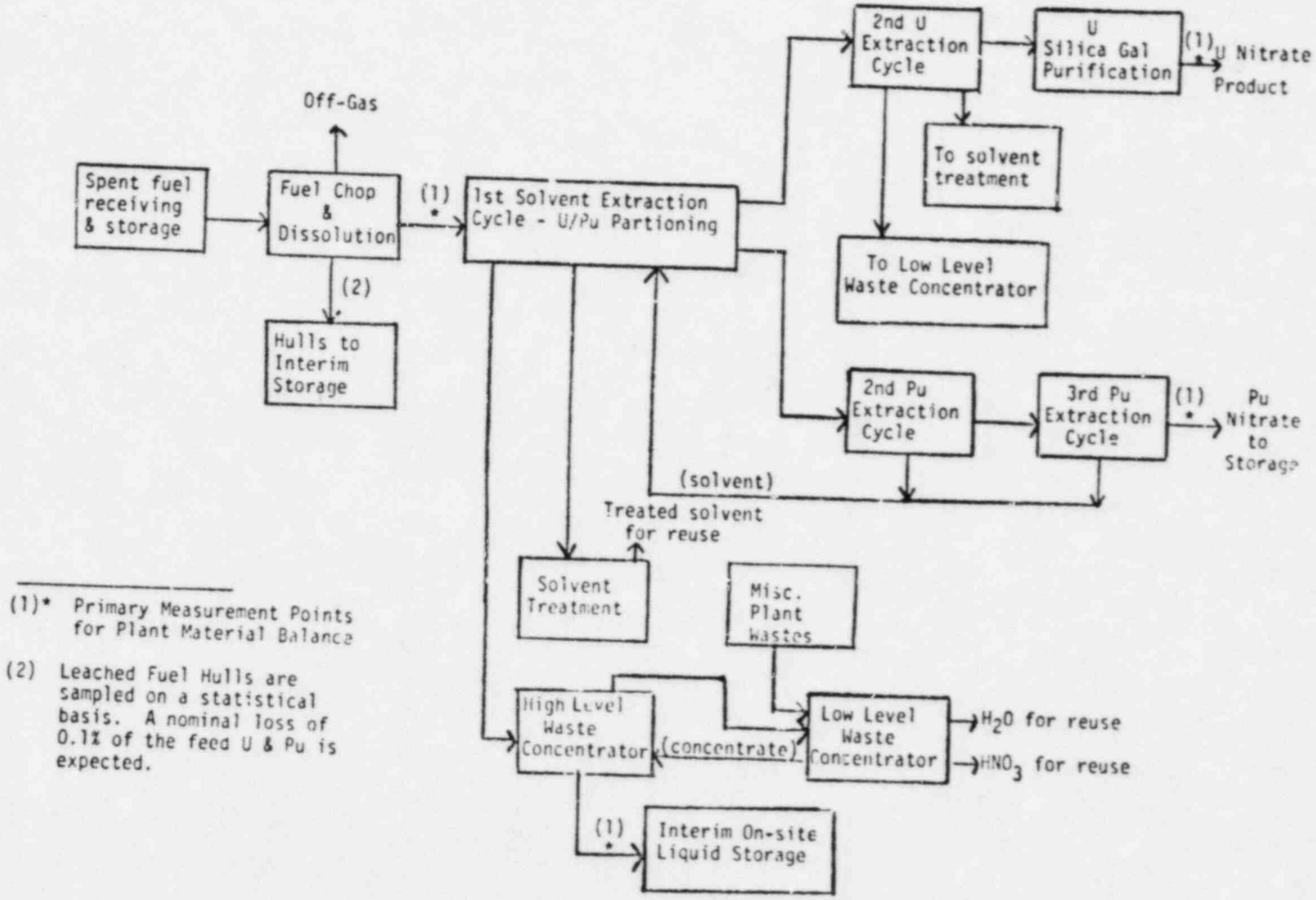
By starting with dissolver solution, one potential plutonium stream is not considered in the plutonium accountability calculation. This is the plutonium associated with the clad hulls. Since the hulls are presently considered to be a waste stream and undergo no further processing to recover the traces of uranium and plutonium present, the amount of plutonium, although of safeguards concern, has no impact on the amount of plutonium which must be accounted for after it is processed through the separations facility.

The input accountability tank represents the first point in the operation where the uranium to plutonium ratio can be accurately determined. The uranium content is known quite accurately from knowledge of the initial uranium content in the fresh fuel and the subsequent fuel exposure level attained at reactor discharge.

The dissolver solution from one of the three dissolvers is batched into the accountability tank and then jetted into the feed tank for the first column in the separations procedure. Once the solution is transferred from the account tank it becomes part of a continuous process and batch identity is effectively lost.

The Purex separation process is shown schematically in Figure B.1. All chemical processing activities beginning with the transfer of material from the dissolver accountability measurement tank and ending with the transfer of product material to the storage area are included in one material balance area.

There seems to be little incentive to divide the area into more than one material balance area. First of all, except for the final concentration and storage steps all operations are remote. In addition, all flows are continuous or semicontinuous with recycle and backcycle being used extensively to obtain the desired product purity. Thus multiple material balance areas bounded by reliable material measurements would be difficult to



(1)* Primary Measurement Points for Plant Material Balance

(2) Leached Fuel Hulls are sampled on a statistical basis. A nominal loss of 0.1% of the feed U & Pu is expected.

FIGURE B.1 Conceptual Flowsheet Purex Processing Plant

B.1.1 Description of Important Material Accounting Characteristics of a Separations Facility

The material accounting characteristics can be strongly influenced by whether the plant is maintained by remote or contact maintenance. Directly maintained equipment must be designed to be thoroughly decontaminated. This aids material accountability. At the same time, the requirement for decontamination lengthens the downtime. A minimum outage would probably be 10 - 14 days. Maintenance outages would probably last at least 30 days. This means that although the facility can be almost flushed clean, a requirement for frequent material accountings would probably result in lost production.

This analysis will follow the Barnwell design philosophy. All but the head-end operations are assumed to be maintained using contact maintenance. Formal material accounts will be assumed to require thorough flushing to remove the major portion of the plutonium from the remote process equipment.

Present regulations for separations facilities require material accountings be taken at least once every 6 months. Table B.1 shows a typic material balance for a 6 month period. The plutonium content in the feed stream was assumed to be 10 kg/tonne of initial uranium in the fresh fuel. This is above the expected concentration expected in discharged uranium fuel but below the concentration expected if recycled plutonium fuel assemblies are being processed. The plutonium losses in the high-level waste stream represent 0.9% of the feed plutonium. Lower losses are expected in practice, a high value insures that the estimated measurement errors for the waste stream will be conservative.

Although the data presented in Table B.1 are for a specific accounting period, different accountability intervals are easily obtained from Table B.1

TABLE B.1 Material Flow for a Single Campaign at a Purex Processing Plant
(Basis: 750 Metric Tons Fuel Input, 6-Month Operation)

Material Balance Component	Batch Size kg.	No. of Batches	Total Material[(a)] in Campaign, kg.
Total Input			
Pu	20.182	375	6743.25
U	1998	375	749,250.00
Total Product[(b)]			
Pu	25.0	300	6682.5
U	7425	100	742,500
Waste			
Pu	0.273	250	60.75
U	27.0	250	6750.00
In-Process Inventory[(c)]			
Pu	0.5	10	5
U	5.0	10	50

a) For this example, it is assumed that the concentration of Pu is 9kg/ton of U. In actual operation, this value can be expected to range from 5 to 10kg/ton of U. A nominal 0.1% loss with the leached hulls is assumed.

b) Pu at 200 g/ℓ; U at 1.5 molar.

c) Inventory assumed for a "clean" plant. Small amounts of U & Pu in process are transferred to tanks where measurements can be made. The inventory in a "clean" plant is expected to be nearly constant at each 6 month inventory period.

by applying a fixed ratio to the column specifying the numbered batches processed. This procedure will be followed to evaluate the relationship between sensitivity and timeliness of material accountings for a separations facility. This information is developed in section B.1.3 of this appendix. This section is preceded by an evaluation of the accuracy of present measurement techniques to determine the quantity of plutonium in each stream entering or leaving the separations facility plutonium material balance area.

B.1.2 Measurement Uncertainties for the Separations Facility Plutonium Accountability Measurements

Measurement uncertainties for two types of accountability measurements will be developed in this section. First, the measurement uncertainties associated with what are considered to be the best formal accounting measurements will be described. Then the estimated accuracy of running inventory measurements will be described.

There are many years of experience with formal material accounting methods for plutonium accountability in a Purex-type separations facility. Performance data from facilities in this country and in Europe can be used. As a result, the present capability of measurement systems and techniques has been extensively documented.(2-7) Table B.2 represents a composite summary of estimated measurement errors. These numbers should be considered to be representative of present performance. They represent measurement errors associated with what are thought to be the most accurate measurement methods. Analysis of the plutonium content in the input accountability tank is obtained using isotopic dilution techniques to get the uranium to plutonium ratio. The uranium content can be accurately determined from knowledge of the initial uranium content and discharge exposure

TABLE B.2 Estimates of Random and Systematic Error for Separations Facility Plutonium Accountability Measurements

Material Balance Component	Relative Percent Standard Deviation of a Single Measurement		
	Volume	Sampling	Analytical
Plutonium Input			
Random	0.3	0.30	1.0
Short-Term Systematic	0.18	0.10	0.20
Long-Term Systematic	0.02	0.02	0.02
Plutonium Product			
Random	0.3	0.1	0.2
Short-Term Systematic	0.1	0.1	0.1
Long-Term Systematic	0.02	0.02	0.02
Plutonium Waste			
Random	2.0	6.0	20.0
Short-Term Systematic	3.0	6.0	10.0
Long-Term Systematic	1.0	1.0	1.0
Plutonium Holdup			
Random/Vessel	5.0	5.0	5.0

of each fuel assembly in the dissolver batch. The plutonium content in the product is determined by coulometry and in the waste by TTA extraction-alpha counting. These analytical methods when used in conjunction with good volume calibrations and sampling techniques provide the best estimate of the capability of future separations facility measurement methods. It is fully recognized that some facilities will exceed the measurement accuracies reported in Table B.2; others will not quite meet them. A factor of two deviation from the accuracies is possible but larger deviations are thought to be unlikely.

The systematic error term has been divided into a short-term and long-term error component. At present, no studies have been performed to quantify how much of the systematic error term will be reduced by the measurement control program. The 0.02% long-term systematic error represents that fraction of the systematic error that may persist over many accounting periods. As shown in Appendix A, the distinction between long-term and short-term systematic errors does not affect σ(MUF) but it does become important in evaluating σ(CUMMUF).

Table B.2 summarized the accuracy of present formal material accounting measurement methods. Because shutdowns for physical inventory measurements require 10 - 14 days at a minimum, running physical inventories must be considered to be a serious alternative.

Based on the Barnwell design, which is thought to be representative of future designs, most of the inventory is present in feed or accumulator tanks. Column 2 of Table B.3 presents a compilation of the estimated average inventory of plutonium present in the flowing streams during normal operations. The estimated accuracy of measuring these inventories is shown in subsequent columns in the table. The accuracy of inventories in the separations columns was taken to be 10%. The actual inventory level and measurement accuracy in an operating plant would be obtained by experience.

TABLE B.3 Running Inventory Measurement Uncertainties for the Separations Facility of a 1500 MT/Year LWR Reprocessing Plant

Process Component	No. of Components	Plutonium Component Inventory kg	Estimated Measurement Accuracy ± Volume	Sampling	Analytical
Fuel Dissolution					
Accountability tank	1	23.13	Random 0.3	0.3	0.1
Accountability tank	1	23.13	Systematic 0.18	0.1	0.20
Centrifuge	1	1.5		10[a]	
HA Feed Tank	1	21.5	1	3	0.17
Flush Accum. Tank	1	6	1	3	0.17
U-Pu Co-decontamination Cycle					
HA Column	1	1		10	
HS Column	1	1.2		10	
1B	1	0.5		10	
1BX Column	1	0		10	
Secondary Recovery	3	<<0.1	1	5	0.17
Plutonium Purification					
1 BP Feed Tank	1	1.7	1	5	0.17
2A Column	1	0.5	1	10	
3A Column	1	1.3		10	
3B Column	1	1.3		10	
2 PS Column	1	20		10	
2 P Column	1	11 0		10	
Plutonium Catch Tank	1	7	1	5	0.17
Plutonium Rework Tank	1	0[b]		25	
Plutonium Collection & Storage					
Pu Sample Tank	1	21	0.32	0.14	0.22
Pu Temp. Storage Tanks	3	42	Random 0.3	0.10	0.20
			Systematic 0.1	0.10	0.10
Pu Temp. Storage Tanks	3	42	Random 0.3	0.10	0.20
			Systematic 0.1	0.10	0.10
Pu Measurement tanks	1	11	0.32	0.14	0.22

a) If only one error term presented, that value indicates the total measurement error used.

b) Rachig Ring Filled Tank (Capacity 200 kg of Pu) assumed not used during accounting period.

The values are thought to be typical. The biggest error associated with the running inventory measurement is the inability to guarantee that a sample taken from an accumulator tank is representative of the plutonium concentration in the tank. Sampling errors below 5% may be impossible to realize in practice.

The inventory levels shown in Table B.3 are based on the plutonium concentration in the flowing streams. In the high-acid Purex flowsheet, plutonium deposition from solution onto the walls of process equipment is not thought to be a major problem. This fact must be demonstrated in practice.

B.1.3 Capability of Material Balance Accounting Systems for Plutonium in a 1500 MT/Yr Separations Facility

Based on the results presented in the previous sections of this appendix, it is now possible to use the error propagation models described in Appendix A to obtain the capability of material balances performed over a separations facility.

Three cases will be considered. First, the effect of the accounting interval on the value of LEMUF will be evaluated. This will be followed by the results of the running inventory evaluation. The third case will evaluate the possible effect of the measurement control program on the long-term reduction in systematic errors.

The variation of LEMUF with the frequency of the formal material accounting interval is shown in Table B.4. This table clearly demonstrates the behavior of LEMUF with throughput as discussed in the introduction to section 3. Although the value of LEMUF increases as the throughput increases, the value of LEMUF, expressed as a percentage of the feed, decreases. The former term is a criterion for evaluating whether a single large loss has occurred whereas the latter is a criterion for evaluating whether small frequent losses are occurring.

Although the table shows formal accounting intervals as short as

TABLE B.4 Measurement Uncertainty Evaluation for the Separations Area of a 1500 MT/Year LWR Reprocessing Plant

	Length of Material Accounting Period						
	1 Week	2 Weeks	1 Month	2 Months	3 Months	6 Months	1 Year
	Measurement Error Variances						
Feed - 20.18 kg's of Pu							
No of Batches	15.0	30	62	125	187.5	375	750
Random Error Variance - kg²	.72	1.44	2.98	6.01	9.0	18.02	36.0
Systematic Error Variance - kg²	.77	3.07	13.10	53.27	119.9	479.41	1917.7
Total Variance - Feed - kg²	1.49	4.51	16.08	59.28	128.9	497.43	1953.7
Product - 25 kg							
No of Batches	12.5	25	50	100	150	300	600
Random Error Variance - kg²	0.11	0.22	0.44	0.88	1.31	2.6	5.2
Systematic Error Variance - kg²	0.29	1.17	4.69	18.75	42.19	168.8	675.0
Total Variance - Product - kg²	0.40	1.39	5.13	19.63	44.50	171.4	680.2
Waste 0.273 kg							
No of Batches	10	20	41.3	83.3	125.00	250	500
Random Error Variance - kg²	0.03	0.07	0.14	0.27	0.41	0.82	1.64
Systematic Error Variance - kg²	0.11	0.43	1.85	7.50	16.89	67.54	270.17
Total Variance - Waste - kg²	0.14	0.50	1.99	7.77	17.30	68.36	271.81
Total Variance - Flow kg²	2.03	6.40	23.20	86.68	190.7	737.2	2905.7
Total Variance - Inventory - kg²	2.16	2.16	2.16	2.16	2.2	2.2	2.2
Total Variance	4.19	8.56	25.36	88.84	192.9	739.4	2907.9
Sd(MUF) - kg	2.05	2.92	5.04	9.43	13.9	27.2	53.9
LEMUF - kg	4.09	5.85	10.07	18.85	27.8	54.4	107.8
LEMUF x 100/Feed -%	1.35	0.97	0.80	0.75	0.73	0.72	0.71

weekly, running a plant for a week followed by a 2-week shutdown for a physical inventory measurement is not economically feasible. They are shown to compare with the running inventory evaluation developed in Tables B.5 and B.6.

Table B.5 presents the estimated accuracy for a single running inventory in the separations facility. The accuracy of this running inventory can be used in two calculations. Assume the accounting period is bounded on one end by inventory obtained using formal inventory techniques, then the uncertainty associated with that inventory measurement is very small; half the value used for the inventory term in Table B.4. The other inventory uncertainty value is associated with a running inventory. The second case assumes the accounting period is bounded on both sides by a running-inventory estimate. Table B.6 compares these two cases with the best formal balance estimate. Based on this comparison, it can be seen that running-inventory material accounting techniques may provide the most acceptable assurance that all the material feed into the system can be accounted for at intermediate times during a formal material accounting period.

The running inventory is not thought to be a substitute for a formal accounting material balance. When the plant is shut down and relatively clean, it will be convenient to check the calibrations of the various measurement systems. This is required as part of current regulations.(9) The major effect of this measurement quality control program is to randomize some components of the systematic error. It will never be possible to completely randomize the systematic error between accounting periods. Tables B.7 and B.8 show the effect of randomizing the short-term systematic errors shown in Table B.2. They are randomized by assuming new calibrations are used for each accounting period. Table B.7 shows the effect of recalibrations

TABLE B.5 Running Inventory Measurement Uncertainty Evaluation for the Separations Area in a 1500 MT/Year LWR Reprocessing Plant

Process Component	No. of Components	Plutonium Component Inventory kg	Estimated Measurement Accuracy %	Total Measurement Error Variance kg^2
Fuel Dissolution				
Accountability tank	1	23.13	Random 1.1	0.063
Accountability tank	1	23.13	Systematic 0.26	0.004
Centrifuge	1	1.5	10.0	0.023
HA Feed Tank	1	21.5	5.0	1.156
Flush Accum. Tank	1	6	5.0	0.090
				1.386
U-Pu Co-decontamination Cycle				
HA Column	1	1	10.0	0.015
HS Column	1	1.2	10.0	0.015
1B Column	1	0.5	10.0	0.003
1BX Column	1	0	10.0	0.00
				0.028
Secondary Recovery	3	<<0.1	10.0	0.000
Plutonium Purification				
1 BP Feed Tank	1	1.7	5.0	0.007
2A Column	1	.5	10	0.010
3A Column	1	1.3	10	0.017
3B Column	1	1.3	10	0.017
2PS Column	1	20	10	0.040
2P Column	1	11.0	10	1.210
Plutonium Catch Tank	1	7	5	0.122
Plutonium Rework Tank	1	0(a)	--	0.000
				1.426
Plutonium Collection & Storage				
Pu Sample Tank	1	21	0.41	0.008
Pu Temp. Storage tanks	3	42	Random 0.37	0.074
Pu Temp. Storage tanks	3	42	Systematic 0.17	0.047
Pu Measurement tanks	1	11	0.41	0.002
				0.131
TOTALS		238.6		2.921

a) In Barnwell -200 kg's of plutonium could be stored in this Rachig Ring Filled Column. No additions or withdrawals are assumed during the running inventory period.

TABLE B.6 Comparison of LEMUF Sensitivity to Frequency and the Type of Physical Inventory Performed to Obtain the Material Balance for a 5 MT/day Separations Facility

		LEMUF	
Accounting Period	Formal Accounting Period	Formal Inventory Period on One Size of Accounting Interval	Running Inventory on Both Sides of Accounting Interval
1 Week	4.09	4.91	5.61
2 Weeks	5.85	6.44	6.99
1 Month	10.07	10.43	10.77
2 Months	18.85	19.04	19.24

at 6-month intervals and Table B.8 shows the effect of a 3-month recalibration interval. This program has the greatest potential for increasing the sensitivity of material accounts to detect small, frequent, undetected losses, measured as the ratio of LEMUF to feed on the last line in the tables. Gains in sensitivity are significant when recalibrations occur every 3 months instead of every 6 months. This shows one, perhaps unexpected, advantage of material accounting intervals more frequent than the present 6 month reporting requirement for separations facilities.

B.2 MATERIAL ACCOUNTING MODELS FOR THE PLUTONIUM NITRATE STORAGE FACILITY

The plutonium obtained from the separation facility can be stored as nitrate or sent to the oxide conversion facility. In this evaluation, all the plutonium nitrate is assumed to be sent through the storage facility even though economic, safety and safeguards concerns may suggest otherwise. Two overriding reasons may result in the extensive use of the facility. First of all, there is an advantage to the fabricator to obtain plutonium having the same isotopics in fairly large batch sizes. It greatly simplifies scrap recovery operations and, as a result, the fuel is much more homogeneous. The possibility of removing americium from plutonium nitrate solutions is the second reason why plutonium might be stored as nitrate. Both the reactor operator and the fabricator like the plutonium assemblies to be low in americium. The fabricator because of the ^{241}Am dose to workers and the reactor operator because ^{241}Am is a nuclear poison. For both these reasons, fair amounts of plutonium nitrate might be stored.

The Barnwell plutonium nitrate storage facility is thought to be representative of future facilities of this type. At Barnwell, 1 tonne of plutonium can be stored in six interconnected slab tanks. The present

TABLE B.7 Effect of the Measurement Control Program on the Long-Term Measurement Errors for Semi-Annual Inventory Periods Over the Separations Area of a 1500 MT/Year LWR Reprocessing Plant

	Elapsed Time from Initiation of the Control Program				
	6 Months	1 Year	2 Years	4 Years	8 Years
Number of Inventory Periods	1	2	4	8	16
	Cumulative Measurement Error Variances				
Feed - 20.182 kg's of Pu					
No of Batches - 375					
Random Error Variance - kg²	18.02	36.05	79.09	144.2	288.4
Short Term Systematic Error Variance - kg²	472.54	945.08	1080.18	4628.9	7560.8
Long Term Systematic Error Variance - kg²	6.87	27.49	109.97	439.9	1759.6
Total Variance - Feed - kg²	497.43	1008.62	1269.24	5265.0	9608.8
Product - 25 kg					
No. of Batches - 300					
Random Error Variance - kg²	2.6	5.2	10.5	21	42
Short Term Systematic Error Variance - kg²	162.0	324.0	648.0	1296	2592
Long Term Systematic Error Variance - kg²	6.8	27.0	108.0	432	1728
Total Variance - Product - kg²	171.4	356.2	766.5	1749	4362
Waste 0.273 kg					
No of Batches - 250					
Random Error Variance - kg²	0.82	1.6	3.3	6.6	13.1
Short Term Systematic Error Variance - kg²	66.14	132.3	264.6	529.2	1058.3
Long Term Systematic Error Variance - kg²	1.39	5.6	22.4	89.4	357.7
Total Variance - Waste - kg²	68.35	139.5	290.2	625.2	1429.1
Total Flow Variance	737.2	1468.5	3137.0	7647.2	15400
Inventory Variance	2.2	2.2	2.2	2.2	2.2
Total Variance	739.4	1670.5	3139.2	7649.4	15402
Sd(MUF) - kg	27.2	40.9	56.0	87.5	124.1
LEMUF - kg	54.4	81.7	112.0	174.9	248.2
(LEMUF x 100)/Feed-%	0.72	0.54	0.37	0.29	0.20

TABLE B.8 Effect of the Measurement Control Program on the Long-Term Measurement Errors for Quarterly Inventory Periods Over the Separations Area of a 1500 MT/Year LWR Reprocessing Plant

	Elapsed Time from Initiation of the Control Program										
Number of Inventory Periods	3 Months 1	6 Months 2	9 Months 3	12 Months 4	15 Months 5	18 Months 6	21 Months 7	2 years 8	3 years 12	4 Years 16	5 Years 20
	Cumulative Measurement Error Variance										
Feed - 20.18 kg Batches											
No of Batches/Inventory Period - 187.5											
Random Error Variance - kg²	9.011	18.02	27.033	36.94	45.06	54.07	63.07	72.08	108.13	144.17	180.22
Short Term Systematic Error Variance - kg²	118.14	236.28	354.42	472.56	590.70	708.84	826.98	945.12	1417.68	1890.24	2362.80
Long Term Systematic Error Variance - kg²	1.718	6.87	15.46	27.49	42.95	61.85	84.18	109.95	247.39	439.81	687.20
Total Variance - Feed kg²	128.87	261.17	396.91	536.04	678.71	824.75	974.23	1127.15	1773.20	2474.22	3230.22
Product - 25 kg Batches											
No. of Batches/Inventory Period -150											
Random Error Variance - kg²	1.312	2.624	3.936	5.246	6.56	7.87	9.18	10.49	15.74	20.99	26.24
Short Term Systematic Error Variance - kg²	40.50	81.00	121.50	162.00	202.50	243.00	283.50	324.0	486.0	648.0	810.00
Long Term Systematic Error Variance - kg²	1.687	6.75	15.18	26.94	42.17	60.73	82.66	107.97	242.93	431.87	674.80
Total Variance - Product kg²	43.499	90.37	140.62	194.24	251.23	311.60	375.34	442.46	744.67	1100.86	1511.04
Waste - 0.273 kg Batches											
No. of Batches/Inventory Period - 125											
Random Error Variance - kg²	0.409	0.818	1.227	1.636	2.04	2.45	2.86	3.27	4.90	6.54	8.18
Short Term Systematic Error Variance - kg²	16.54	33.08	49.62	66.16	82.70	99.24	115.78	132.32	198.48	264.64	330.80
Long Term Systematic Error Variance - kg²	0.34	1.36	3.06	5.44	8.50	12.24	16.66	21.76	48.96	87.04	136.00
Total Variance - Waste kg²	17.29	35.25	53.91	73.24	93.24	113.93	135.30	157.35	252.34	358.22	474.98
Total Variance - Flow - kg²	189.66	386.79	591.44	803.57	1023.13	1250.29	1484.87	1726.96	2770.21	3933.3	5216.24
Total Inventory Variance - kg²	2.16 →										
Total Variance - kg²	191.82	288.95	593.60	805.73	1025.34	1252.45	1487.03	1729.12	2772.37	3935.5	5218.4
Sd(MUF) - kg	13.85	19.72	24.36	28.39	32.02	35.39	38.56	41.58	52.65	62.73	72.24
LEMUF - kg	27.70	39.44	48.73	56.77	64.04	70.78	77.12	83.17	105.31	125.47	144.48
(LEMUF x 100/Feed) %	0.732	0.521	0.429	0.375	0.338	0.311	0.291	0.27	0.232	0.207	0.19

storage facility contains four banks of six tanks each. Thus up to 4 tonnes of plutonium as nitrate solution could be on inventory at any time. Future expansion could double the capacity so that 8 tonnes of plutonium might be on inventory in the facility. The 8-tonne capacity represents the entire production of the separation facility for 7 months. As such, it does not represent an excessively large surge capacity between the separations and conversion facilities.

B.2.1 Description of Important Material Accounting Features of a Plutonium Nitrate Storage Facility

Based on the 1 tonne plutonium capacity of each bank, several modes of operation are suggested. These are:

- Banks of tanks in static condition where solution volume (or weight) is essentially constant over the accounting period.
- Banks in which only interval mixing has taken place or from which only shipments (transfers out) were made during the accounting period.
- Banks in which solutions of a different plutonium concentration were received and mixed with previously stored material.

The timeliness and sensitivity of materials accounting checks will be somewhat different for each of the above conditions. The next section will present the basic measurement uncertainty data for each of the above cases. This will be followed by a section quantifying the sensitivity of the accounting methods in the actual storage facility being considered.

B.2.2 Measurement Uncertainty Estimates for the Plutonium Nitrate Storage Facility

The plutonium nitrate storage facility is considering only one material form. As such the relative errors for receipts, removals and stored material are identical. It is assumed that the measurement techniques are the same as those used for the plutonium nitrate product solution from the separations facility. These are the same measurement errors already presented in Table B.2 and are used for all flow measurements in the storage facility.

The inventory measurement error associated with material stored in the six connected tanks is obtained by assuming that one sample and one analysis is performed for each bank. However, the weight-factor (volume times specific gravity) reading for each of the six tanks is used to get the estimate of the quantity of plutonium solution in the tank. The effect of this procedure is to reduce the volume error associated with stored material by $\sqrt{6}$. Table B.9 summarizes the random and systematic errors used for the plutonium nitrate storage facility accountability measurements.

B.2.3 Capability of Material Balance Accounting Systems for a Plutonium Storage Facility

The material accounting capability of storage facility can be obtained by combining the uncertainties associated with the various operating modes which exist during an accounting period. The longer the accounting period the greater the complexity of operations and, as a result, the greater the total uncertainty of the measurements. Thus there is truly an incentive for relatively short material accounting periods since the operations are relatively simple.

The first set of cases will consider one to four banks static throughout the entire material accounting period. The second set of cases will consider the cases where 1000 to 4000 kg of plutonium is being mixed in the facility. The third set of cases will evaluate the effect of shipping and receiving from 50 to 2500 kg of plutonium as nitrate. If less than 1000 kg is shipped or received, only two banks must be active. All four are assumed to be active for the case where 2500 kg is shipped and received during an accounting period.

TABLE B.9 Estimates of Random and Systematic Error for the Accountability Measurements of the Plutonium Nitrate Storage Facility

Material Balance Component	Relative Percent Standard Deviation of a Single Measurement		
	Volume	Sampling	Analytical
$Pu(NO_3)_4$			
Random	0.3	0.1	0.2
Systematic	0.1	0.1	0.1
$Pu(NO_3)_4$			
Random	0.12	0.1	0.2
Systematic	0.1	0.1	0.1
$Pu(NO_3)_4$ Input to Oxide Conv.			
Random	0.3	0.1	0.2
Systematic	0.1	0.1	0.1
Material Heldup in Empty Tanks Random Error/Tank	50		

Case 1: Material Balance Capability of Static Tanks

If tanks are static, the sensitivity to detect loss is independent of the time interval between accounting periods. There are no measured flows. In this case, the volume (or weight) in each tank is checked at the beginning and end of the accounting period. No samples or analyses need be performed. Thus the variance of the resultant inventory measurement is only affected by the variance of the volume readings. For each tonne, six readings (one for each tank in the bank) are taken at the beginning of the accounting period and six are taken at the end. The accuracy of each reading is taken to be 0.3%. The error is all random, with no systematic component. Table B.10 shows the resultant sensitivity of LEMUF for static storage of from 1000 to 4000 kilograms of plutonium.

TABLE B.10 Measurement Uncertainty Evaluation for a Static Plutonium Nitrate Storage Facility

Number of Banks Inventoried	1	2	3	4
Plutonium Inventory/Bank (kg of Pu)	1000	1000	1000	1000
Total Plutonium Inventory (kg of Pu)	1000	2000	3000	4000
	Measurement Error Variances			
Random Error Variance kg^2	1.5	3.0	4.5	6.0
Systematic Error Variance kg^2	0	0	0	0
Total Variance/Inventory kg^2	1.5	3.0	4.5	6.0
Total Variance (Beginning and End) kg^2	3.0	6.0	9.0	12.0
Sd (MUF) kg	1.73	2.45	3.00	3.46
LEMUF kg	3.46	4.90	6.00	6.93

Case 2: Active Mixing in the Storage Facility

In this case, as in case 1, no sampling or analysis is performed, thus the only contribution to the material balance variance is the volume (or weight) measurement error variances.

There are no large changes in tank level during the mixing operation. It is then reasonable to assume that the systematic errors, if any, are randomized by the number of tanks being mixed. Table B.11 shows the resulting sensitivity of LEMUF for mixing from 1000 to 4000 kilograms of plutonium using a systematic error component randomized by the number of tanks being mixed. It can be seen that because of the mixing, the sensitivity to detect a loss is slightly poorer than the static case.

Case 3, the third set of cases looks at the effect of additions and withdrawals on the value of LEMUF. Transfers representing a 1-day, 1-week, 2-week, 1-month, and 2-month accounting period will be evaluated. Two banks are assumed to be active whenever additions and withdrawals are being made. It is assumed that one bank would be receiving material, and withdrawals would occur from another bank of tanks whic [illegible] been completely mixed. If there are more than 1000 kg [illegible] transferred during the accounting period, then it is assumed that four of the banks are active and must be assayed. Table B.12 summarizes the measurement uncertainty evaluation for an active storage area. In this table, two calculations are shown for each accounting period, one calculation representing the least insensitive situation: one bank full and the other empty. The other calculation represents an optimum case, one which occurs when both banks are half full.

TABLE B.11 Measurement Uncertainty Evaluation for a Plutonium Nitrate Storage Facility with Internal Mixing

Number of Banks Inventoried	1	2	3	4
Plutonium Inventory/Bank (kg of Pu)	1000	1000	1000	1000
Total Plutonium Inventory (kg of Pu)	1000	2000	3000	4000
	Measurement Error Variances			
Random Error Variance kg^2	1.5	3.0	4.5	6.0
Systematic Error Variance kg^2	0.17	0.33	0.5	0.67
Total Variance/Inventory kg^2	1.67	3.33	5.0	6.67
Total Variance (Beginning and End) kg^2	3.33	6.67	10.0	13.33
Sd (MUF) kg	1.83	2.58	3.16	3.65
LEMUF kg	3.65	5.16	6.32	7.30

TABLE B.12 Measurement Uncertainty Evaluation for the Plutonium Nitrate Storage Area in a 1500 MT/Year LWR Reprocessing Plant

	Length of Accounting Period							
	1 Day		1 Week		2 Week		3 Weeks	2 Months
Feed[a] - 25 kgs of Pu								
No of Batches	2		12		24		40	100
Random Error Variance kg^2	0.0175		0.105		0.21		.85	0.88
Systematic Error Variance kg^2	0.0175		0.27		1.08		3.00	18.75
Total Variance - Feed kg^2	0.025		0.375		1.29		3.35	19.62
Total Flow Variance[a] kg^2	0.05		0.75		2.58		6.70	39.25
Inventory Cases								
No of Active banks	2		2		2		2	4
Beginning Bank Inventories kg^2	(1000, 0)[b]	(475, 525)	(1000, 0)	(650, 350)	(1000, 0)	(800, 200)	(1000, 0)	(1000, 1000, 0,0)
Random Error Variance kg^2	6.54	3.25	6.54	3.54	6.54	4.42	6.54	13.08
Ending Bank Inventories kg^2	(950, 50)	(525, 475)	(700, 300)	(350, 650)	(400, 600)	(200, 800)	(0, 1000)	(0, 500, 500, 1000)
Random Error Variance kg^2	5.88	3.25	3.77	3.54	3.38	4.42	6.54	9.75
Systematic Error Variance kg^2	0.02	0.02	0.54	0.54	2.16	2.16	6.0	13.50
Total Variance - Inventory kg^2	12.43	6.53	10.85	7.62	12.08	11.0	19.08	36.30
Average Total Inventory Variance kg^2	8.50		8.70		11.36		19.08	36.30
Total Variance kg^2	8.55		9.45		13.94		25.78	75.55
Sd(MUF) kg	2.92		3.07		3.73		5.08	8.69
LEMUF kg	5.85		6.15		7.47		10.15	17.38
LEMUF x 100/Feed-%	11.7		2.05		1.24		1.02	0.70

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a) Product and Feed Streams Identical.

b) Brackets Enclose Individual Bank Inventories.

Since the behavior of the variance is quadratic as a tank is emptied, the average variance can be obtained through integration. The mean sensitivity obtained in this manner is shown at the bottom of the table.

Included in the variance calculation for an empty tank is a holdup uncertainty which can be associated with one kilogram of plutonium. It is estimated that this much material could be held up on the large wall areas in the bank. Flushing between storage batches was not considered.

Table B.12 shows an addition and a withdrawal equivalent to a 1-day accounting period. Since uniformity in the storage bank is required before it can be inventoried, the minimum inventory period is determined by the mixing time. If several days are required to obtain a uniform plutonium solution in a bank, then the 1-day accounting period is impossible. Since there has been no experience mixing 1000-kilogram lots of plutonium, the mixing time is unknown, it might be significantly larger than a day.

B.3 MATERIAL ACCOUNTING CAPABILITY OF THE PLUTONIUM NITRATE-TO-OXIDE CONVERSION FACILITY IN A 1500 MT/YR REPROCESSING PLANT

The plutonium nitrate-to-oxide conversion operation is modeled after the proposed Barnwell conversion facility.(10) It is shown schematically in Figure B.2 and represents what can be considered to be a typical conversion operation.

Plutonium nitrate solution is withdrawn from either the plutonium storage facility or the product storage area in the separations facility and pumped into one of two conversion facility feed preparation tanks. Each tank can contain up to

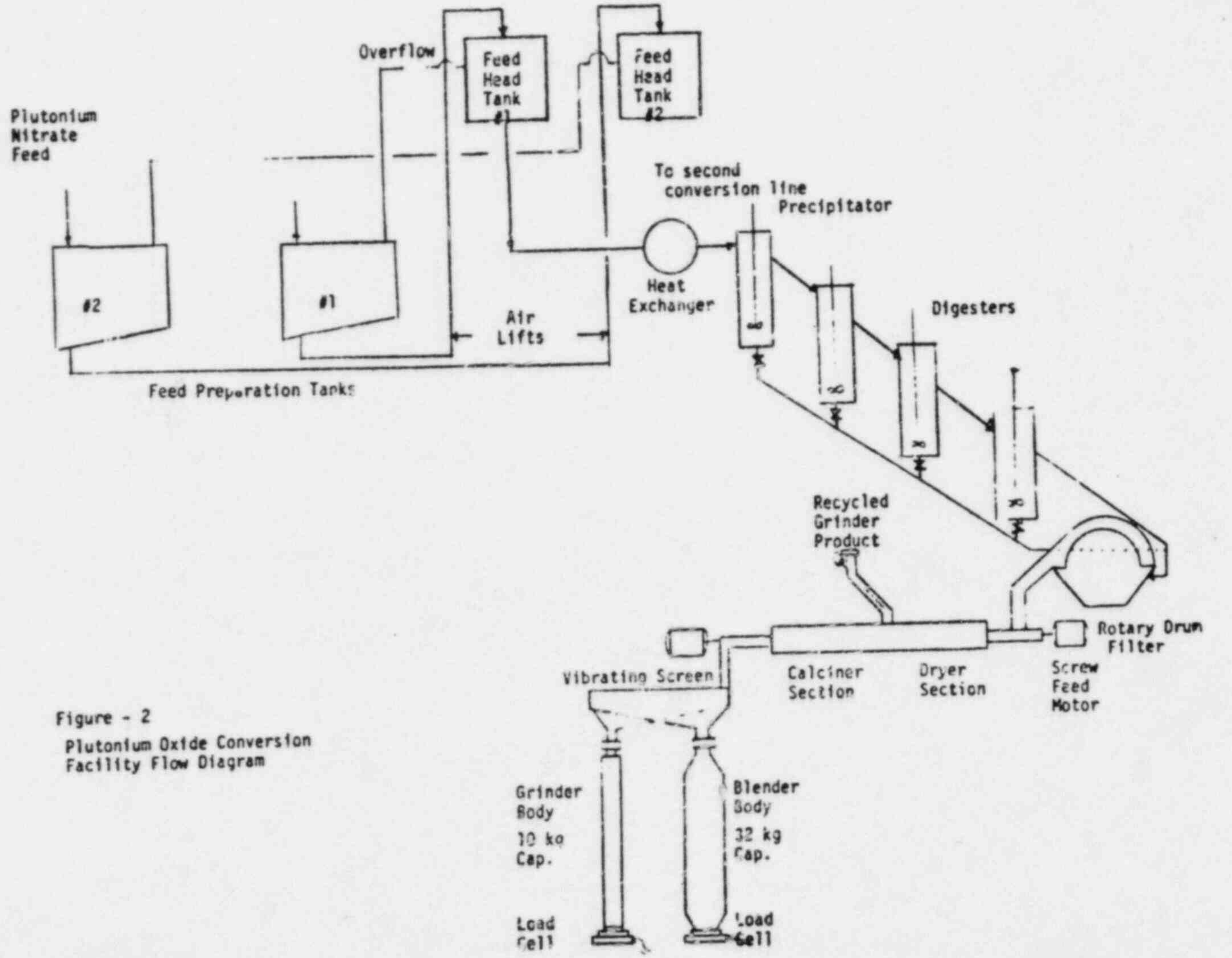

FIGURE B.2 Plutonium Oxide Conversion Facility Flow Diagram

50 kg of plutonium, enough for 12 hours of operation.

After the transfer is complete, the solution in the feed preparation tank is thoroughly mixed, the volume or weight measured and a sample taken for analysis of the plutonium content. The tank solution is then prepared for conversion by adjusting the acid content, diluting the plutonium solution to the proper concentration, and adding chemicals to insure that all the plutonium is in the plus four chemical valence state. During the time the solution in one tank is being prepared to be fed to the conversion operation, the contents of the alternate feed tank are being transferred to the precipitators.

The prepared solution in the input tanks is pumped into one of two feed-head tanks. These tanks are kept at a constant level by allowing any excess solution to drain back to the feed tank. Output from a head tank is split into two parallel streams each feeding a separate conversion line.

The solution from a head tank flows through a heat exchanger and then into the precipitation tank where oxalic acid is added to precipitate plutonium oxalate. The resultant slurry leaves the precipitator as an overflow stream and cascades down through a series of three digesters which age the precipitate to improve filterability. The slurry finally flows into a rotary-drum filter which separates the precipitate from the filtrate. A knife edge scrapes the drum removing the wet filter cake which then falls into a screw feed dryer-calciner. The output from the calciner is high-fired plutonium oxide. This material is screened to remove large chunks of powder and then blended to obtain uniform 32 kg PuO_2 batches which are then canned into 8 kg containers for storage or shipment offsite. The large chunks of powder are collected in a grinder assembly. When the grinder contains the proper amount of plutonium oxide, the grinder assembly is disconnected from the conversion line. The chunks are then broken up into a fine powder which is then recycled back through the calciner.

B.3.1 Description of Important Material Accounting Design Features Except for the Input and Output Batch Operations

All the nitrate-to-oxide conversion operations operate continuously. This mode of operation parallels the way a separations facility operates. Physical inventories can be taken by draining, flushing, and cleaning equipment or an attempt can be made to perform a running inventory. Both will be considered .

The conversion facility at Barnwell is designed to convert 25,000 kilograms of plutonium from nitrate to oxide every year. However, the separations area is expected to obtain less than 15,000 kg of plutonium annually. In this analysis, it will be assumed that the conversion facility feed rate exactly matches the rate of plutonium output from the separations facility. It should be noted that the major effect of the assumption is to reduce the amount of material flowing through the plant during a fixed accounting interval. Other throughput levels during the accounting period are easily simulated by simply changing the accounting period to reflect the new throughput .

Table B.13 shows the input and output data for a typical 2-month accounting period. In subsequent sections, the effect of varying the length accounting will be evaluated by simply changing the number of batches of input and output to reflect a shorter or longer accounting period. These evaluations will be presented in section B.3 of this appendix. Prior to that, the accuracy of present measurement techniques to determine the amount of plutonium entering or leaving the conversion facility will be discussed.

B.3.2 Measurement Uncertainties for the Plutonium Conversion Facility Accountability Measurements

Measurement uncertainties for three types of accountability measurements will be developed in this section. First, the measurement uncertainties associated with what are considered to be the best formal accounting measurements will be described. Then the estimated accuracy of inventory or inventory obtained by just draining and flushing the wet side of the process will be evaluated. Finally, the possibility of performing a running inventory measurement will be discussed.

The nitrate-to-oxide conversion facility occupies a central place in the utilization of plutonium in oxide fuel assemblies. In this analysis, the measurement errors for the nitrate will be identical to those used in the separations facility. In like manner, the measurement errors for the oxide will be the same as those used in the fabrication plant. Table B.14 represents a composite summary of measurement uncertainty evaluations(4,5,7,8) relavant to a plutonium nitrate to oxide conversion facility.

TABLE B.13 Flow for a Single Campaign in a Plutonium Conversion Facility for a 2-Month Accounting Period

Material Balance Component	Batch Size (kg of Pu)	No. of Batches	Total Material in Campaign (kg of Pu)
Input			
Plutonium Nitrate	25	100	2500
Output			
Plutonium Oxide Product	7.058	353.92	2498
Waste[a]	0.025	80	2

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a) Sent back to separations plant for treatment and possible recovery.

TABLE B.14 Estimates of Random and Systematic Error for Plutonium Conversion Facility Accountability Measurements

Material Balance Component	Relative Percent Standard Deviation of a Single Measurement		
	Volume	Sampling	Analytical
Plutonium Nitrate Input			
Random	0.3	0.1	0.2
Short-Term Systematic	0.1	0.1	0.1
Long Term Systematic	0.02	0.02	0.02
Plutonium Oxide Product			
Random	0.070	0.1	0.25
Short-Term Systematic	0.035	--	0.046
Long-Term Systematic	0.020	0.02	0.02
Plutonium Waste			
Random	2	3	10
Short-Term Systematic	1	--	10
Long-Term Systematic	1	1	1

The systematic errors have been divided into short-term and long-term errors. In one accounting period both contribute to the variance equally. Over many accounting periods, the short-term systematic error is treated as a random variable with a sample size equal to the number of accounting periods. The 0.02% . residual long-term systematic error is not based on any evaluations but is thought to simulate the behavior of that portion of the systematic error that persists from one accounting period to the next. The values shown in Table 6.14 will be used in the next section to evaluate the effect of formal accounting period length on LEMUF. The effect of the measurement control program, simulated by randomizing the short-term systematic error component between accounting periods, will also be described.

The formal accounting procedure assumes that an attempt has been made to minimize the amount of material held up in the process. The wet side of the process is drained and flushed to remove almost all the plutonium held up. The dryer-calciner is cycled several times in an attempt to dislodge plutonium oxide caked on the walls and in the screw. This process requires 4 to 5 days of downtime.

As a result of this operation, the total amount of plutonium in the system is estimated to be 1.5 kg held up in three places. One half a kilogram in each dryer-calciner and one-half kg in the plutonium oxide loadout facility equipment.

An alternate to this procedure is a draindown inventory measurement. As was the case with the formal inventory period, the wet end is runout drained and flushed. This operation takes about a day. However, no attempt is made to cleanout the calciner. In this case, an estimated 4.5 kg of plutonium is held up in five places. There is one kilogram in each of the dryer-calciners and one kilogram held up in each of the drum filters. The remaining one-half kilogram is in the plutonium oxide loadout equipment.

The running inventory evaluation is based heavily in the facility description provided in the SAR on the plutonium conversion facility at Barnwell. (10) Table B.15 was prepared to summarize the inventory measurements required to perform a running inventory. The measurement error uncertainties are based on two factors. The first and most important is the possible variation in holdup which is likely to be experienced during operation. The second is the estimated accuracy of monitoring normal process variances.

Unfortunately there are several pieces of equipment which could experience a large holdup variation. The partially full input piping, the filter and the dryer-calciner are the largest sources of process variance. In addition, in each of the above cases, the geometry of the held up material is difficult to predict. Unfortunately, geometry plays an important role in determining holdup using NDT techniques. Thus, fairly large measurement uncertainties were placed on several process measurements. The next section will apply those measurement accuracies

TABLE B.15 Running Inventory Measurement Uncertainties for the Plutonium Nitrate to Oxide Conversion Facility of a 1500 MT/Year Reprocessing Plant

Process Component	No. of Components	Component Plutonium Inventory kg		Estimated Measurement Accuracy %		
				Volume	Sampling	Analytical
Nitrate Preparation						
Feed Tanks	2	37.5	Random	0.3	0.1	0.2
Feed Tanks	2	37.5	Systematic	0.1	0.1	0.1
Feed preparation Tanks	2	0.6			10[(a)]	
Heat Exchangers	2	0.7			10	
Pump	1	0.2			10	
Feed Piping	2	5.1			25	
Precipitation						
Precipitation Tanks	2	0.53			10	
Digester Tanks	6	0.53			10	
Vacuum Filters	2	3.5			50	
Powder Preparation						
Dryer-Calciners	2	4.0			50	
Vibrating Screen	2	0.25			50	
Screw Feeder	2	0.40			10	
Grinder Assemblies	4	10.0			1[(b)]	
Blender Assemblies	2	16.0			1[(b)]	

(a) If only one error term presented, that valve indicates the total measurement error used.

(b) Assemblies on load cells.

to estimate the sensitivity of running inventories to detect losses.

B.3.3 Capability of Material Balance Accounting System for a Plutonium Nitrate-to-Oxide Conversion Facility

Based on the material accountability information presented on the last few pages it is now possible to describe the capability of material balances performed over a conversion facility. Four cases will be considered. First, the effect of the accounting period length on LEMUF will be evaluated. This will be followed by the results of the draindown inventory and then running-inventory evaluation. The last topic will be the possible improvement in loss sensitivity which is expected from the improvements in measurement control.

The variation of LEMUF with the frequency of the formal material accounting interval is shown in Table B.16. In effect there is a factor of two uncertainty in the length of the accounting period for a given throughput level. If both conversion lines are operating, 1000 kg of plutonium can be processed in 10 days. Twenty days would be required if the plant was operated so that it just kept up with the rate of plutonium production in the separation facility.

The formal, draindown and running inventory analyses have the same flow measurement variances but different inventory variances. The variance calculation for a running inventory measurement is shown in Table B.17. Table B.18 shows the effect of the inventory variance on LEMUF. It can be seen that the running-inventory measurement uncertainties are too large to be of much value even when the inventory period is bounded on one end by an inventory measurement with a low variance.

TABLE B.16 Measurement Uncertainty Evaluation for the Plutonium Nitrate-to-Oxide Conversion Area in a 1500 MT/Year LWR

Period	6 days(a)	12 days(a)	20 days(a)	1 Month	2 Months	6 Months	1 Year
Feed							
No. of Batches	12	24	40	49	100	300	600
Batch Size-25 kg of pu							
Random Error Variance - kg^2	0.105	0.21	0.35	0.429	0.875	2.625	5.25
Systematic Error Variance kg^2	0.270	1.08	3.00	4.502	18.75	168.75	675
Total Variance - Feed - kg^2	0.375	1.29	3.35	4.931	19.625	171.38	680.25
Product							
No. of Batches	42.47	84.94	141.57	173.42	353.92	1061.77	2123.55
Batch Size-7.058 - kg of Pu							
Random Error Variance - kg^2	0.016	0.033	0.055	0.067	0.136	0.409	0.819
Systematic Error Variance - kg^2	0.041	0.162	0.449	0.674	2.808	25.272	101.088
Total Variance Product - kg^2	0.057	0.195	0.504	0.741	2.944	25.681	101.907
Waste							
No. of Batches	10	20	32	40	80	240	480
Batch Size-(0.025) kg of Pu							
Random Error	7×10^{-5}	1.4×10^{-4}	2.2×10^{-4}	2.8×10^{-4}	5.6×10^{-4}	.002	0.003
Systematic .0101	6×10^{-4}	0.003	0.006	0.010	0.04	0.364	1.454
Total Variance - Waste - kg^2	.001	0.003	0.007	0.010	0.041	0.366	1.457
Total Flow Variance - kg^2	0.433	1.488	3.861	5.682	22.61	197.427	783.514
Inventory Variance - kg^2	0.375	0.375	0.375	0.375	0.375	0.375	0.375
Total Variance - kg^2	0.808	1.863	4.236	6.057	22.99	197.62	783.80
Sd(MUF) - kg	0.899	1.365	2.050	2.461	4.80	14.06	28.00
LEMUF - kg	1.798	2.7308	4.116	4.923	9.59	28.12	55.99
LEMUFx100/Feed	0.599	0.455	0.412	0.401	0.384	0.375	0.373

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a) Period could be shorter by a factor of two if both conversion lines running at design capacity.

TABLE B.17 Running Inventory Measurement Uncertainty Evaluation for the Plutonium Nitrate to Oxide Conversion Area in a 1500 MT/Year Reprocessing Plant

Process Component	No. Of Components	Component Plutonium Inventory kg	Estimated Measurement Accuracy %	Total Measurement Error Variance kg²
Nitrate Preparation				
Feed tanks	2	37.5	Random 0.37	0.039
Feed tanks	2	37.5	Systematic 0.17	0.017
Feed preparation tanks	2	0.6	10	0.007
Heat Exchangers	2	0.7	10	0.009
Pump	1	0.2	10	0.000
Feed Piping	2	5.1	25	3.251
				3.324
Precipitation				
Precipitation tanks	2	0.53	10	0.006
Digester Tanks	6	0.53	10	0.017
Vacuum Filters	2	3.5	50	6.125
				6.148
Powder Preparation				
Dryer-Calciners	2	4.0	50	8.000
Vibrating Screen	2	0.25	50	0.031
Screw Feeder	2	0.40	10	0.003
Grinder Assemblies	4	10.0	1(a)	0.040
Blender Assemblies	2	16.0	1(a)	0.051
				8.125
TOTALS		180.44		17.597

a) Assemblies on load cells.

TABLE B.18 Comparison of LEMUF Sensitivity to Frequency and the Type of Physical Inventory Performed to Obtain the Material Balance for a Plutonium Conversion Facility

	LEMUF				
	Formal Accounting Inventory Measurement on One Side of the Accounting Period				
Accounting Period	Formal on Second Side	Draindown on Second Side	Running on Second Side	Draindown Inventory On Both Sides of the Accounting Period	Running Inventory on Both Sides of the Accounting Period
6 days[(a)]	1.80	2.59	8.53	3.20	11.94
12 days[(a)]	2.73	3.31	8.78	3.80	12.11
20 days[(a)]	4.12	4.52	9.30	4.89	12.50
1 Month	4.92	5.27	9.68	5.59	12.79
2 Months	9.59	9.76	12.71	9.95	15.21

a) Could be shorter by a factor of two if both conversion lines operating.

The tradeoff between draindown and formal inventory measurement sensitivities is much smaller. Indeed, supplementing the formal accounting records with intermediate draindown inventory analyses would appear to be worthwhile. Especially, since operational requirements may require draindown inventories to separate batches for various customers.

The effect of the measurement control program on the long-term sensitivity of the plant to detect small continuous or semi-continuous losses is shown in Table B.18. Large gains in sensitivity as measured by the decrease in the term (LEMUF x 100/Feed) can be realized from the measurement control program.

B.4 CAPABILITY OF MATERIAL BALANCE ACCOUNTING SYSTEMS FOR PLUTONIUM IN A 200 MT/YEAR MIXED OXIDE LWR FUEL FABRICATION PLANT

The description of a 200 MT/year mixed-oxide LWR fuel fabrication plant is based on a model developed by E. Bain, et al.(11) The material balance data taken from this report is shown in Figure 3.3. It should be recognized that one 1500 MT/year reprocessing plant separates enough plutonium for a mixed oxide fabrication plant having a capacity of approximately 400 MT/year. This factor should be included wherever a comparison of plant types is made.

The organization of this section will parallel that of previous sections. Following a description of the important material accounting features of the facility, subsections will be devoted to an evaluation of measurement uncertainties and finally, a summary of material accounting capabilities.

TABLE B.19 Effect of the Measurement Control Program on the Long-Term Measurement Errors for the Plutonium Nitrate-to-Oxide Conversion Area for a 1500 MT/Year LWR Reprocessing Plant

	Elapsed Time from Initiation of Control Program									
	2 Months	6 Months	1 Year	2 Years	3 Years	4 Years	5 Years	6 Years	8 Years	10 Years
Number of Inventory Periods	1	3	6	12	18	24	30	36	48	60
	Cumulative Measurement Error Variances									
Feed - 25 kg Batches										
No. of Batches/Inventory Period - 100										
Random Error Variance - kg^2	.875	2.625	5.25	10.5	15.75	24.875	26.25	31.5	42	52.5
Short Term Systematic Error Variance kg^2	18	54	108	216	324	432	540	648	864	1080
Long Term Systematic Error Variance kg^2	.75	6.75	27	108	243	432	675	972	1728	2700
Total Variance Feed kg^2	19.625	63.375	140.25	334.5	582.75	888.875	1241.25	1651.5	2634	3832.5
Product - 7.058 kg Batches										
No of Batches/Inventory Period - 353.92										
Random Error Variance -kg^2	.136	0.409	0.819	1.638	2.456	3.275	4.094	4.913	6.550	8.188
Short Term Systematic Error Variance - kg^2	2.059	6.177	12.35	24.71	37.06	49.42	61.77	74.13	98.84	123.55
Long Term Systematic Error Variance kg^2	0.748	6.739	26.96	107.82	242.61	431.30	673.90	970.42	1725.19	2695.61
Total Variance - Product kg^2	2.943	13.325	40.13	134.17	282.13	464.00	739.76	1049.46	1830.58	2827.25
Waste - 0.025 kg Batches										
No. of Batches/ Inventory Period - 80										
Random Error Variance kg^2	0.001	0.002	0.003	0.007	0.010	0.014	0.017	0.020	0.027	0.034
Short Term Systematic Error Variance kg^2	0.040	0.12	0.24	0.48	0.72	0.96	1.20	1.44	1.92	2.40
Long Term Systematic Error Variance kg^2	0.001	0.011	0.043	0.173	0.389	0.691	1.08	1.55	2.765	4.32
Total Variance - Waste kg^2	0.042	0.133	0.286	0.66	1.119	1.665	2.297	3.01	4.712	6.754
Total Flow Variance - kg^2	22.61	76.833	180.67	469.33	866.00	1374.54	1983.3	2703.97	4469.3	6666.5
Inventory Variance - kg^2	0.375									
Total Measurement Error Variance	22.99	77.21	181.05	469.7	866.38	1374.96	1983.7	2704.4	4469.7	6666.9
Sd(MUF) - kg	4.795	8.79	13.45	21.67	29.43	37.08	44.54	52.00	66.85	81.65
LEMUF - kg	9.59	17.57	26.90	43.34	58.86	74.15	89.07	104.00	133.71	163.30
LEMUFx100/Feed	0.384	0.234	0.179	0.144	0.131	0.123	0.119	0.116	0.111	0.109

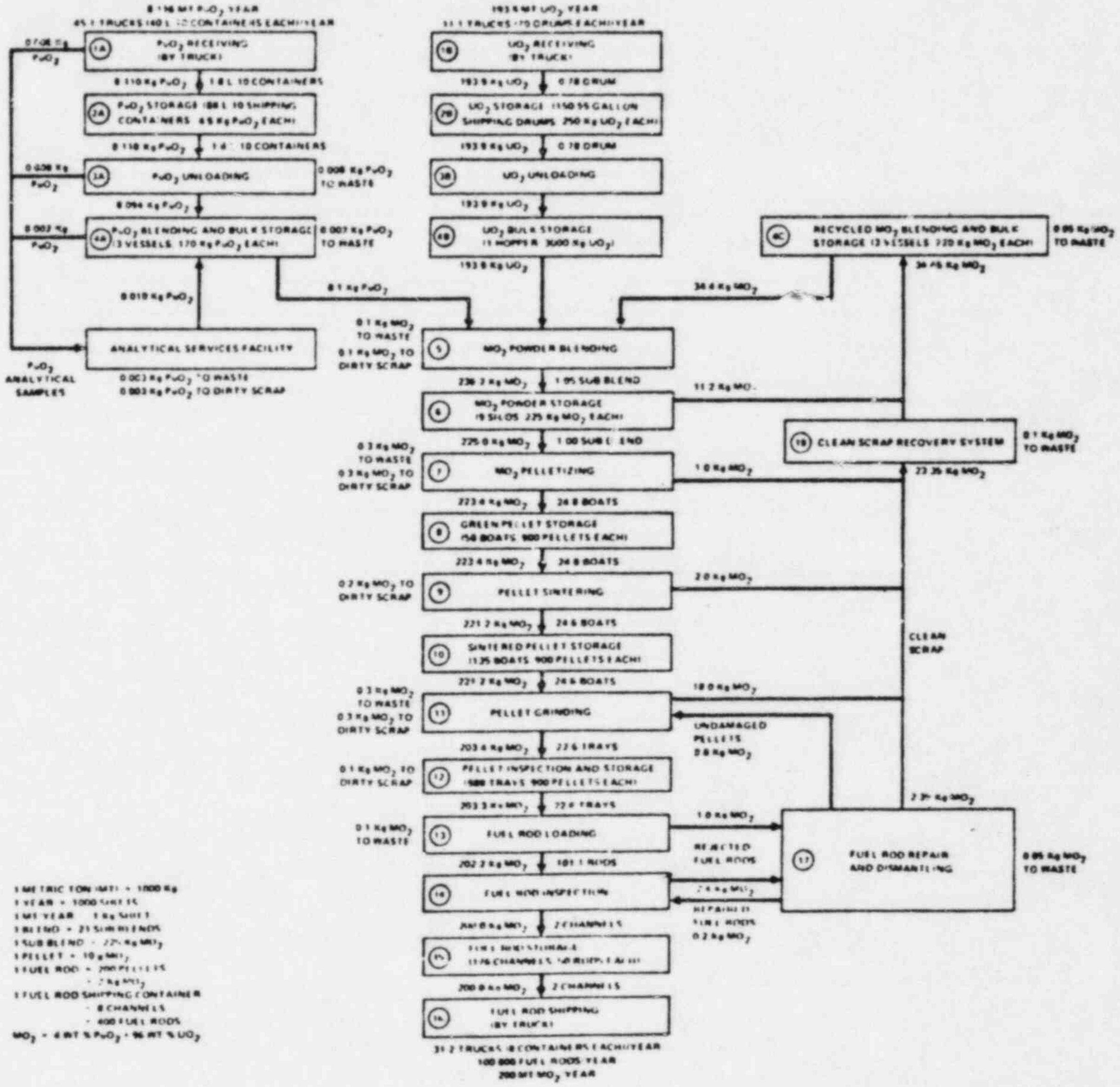

FIGURE B.3 Average Material Flow Per 8-Hour Shift for MO_2 Fuel Plant

B.4.1 Description of Important Material Accounting Design Features

The fuel fabrication plant described in Reference (11) incorporates many of the design features suggested in regulatory guides$^{(12-14)}$ for improved materials accounting. The following paragraphs highlight those features.

Regulatory Guide 5.8 discusses design considerations to minimize holdup in drying and fluidized-bed operations. The PuO_2 input powder, the MO_2 blended powder and the MO_2 recovered scrap are all stored in fluidized bed silos. Based on experience with blowback filters,$^{(16)}$ a PuO_2 input storage silo may hold up from 500 grams to 3.5 kg of plutonium. A value of 1.3 kg was used in this analysis. The valve at the bottom of the silo may also hold up some PuO_2 powder. However, the entire assembly including the outlet valve is on a weigh cell. Thus, the holdup level can be monitored.

Regulatory Guide 5.8 also discusses the problem of caking in fluidized beds. Both the PuO_2 and mixed oxide are very stable chemically and by closely controlling the moisture, something essential for criticality safety, there should be no caking problem. Once again, since the entire silo is on a weigh cell, material held up can be weighed very accurately.

Regulatory Guide 5.25 discusses design criterion for wet-process operations. Except for the lab, there are no wet processes. Thus, the design criteria in 5.25 are automatically met.

Regulatory Guide 5.26 discusses material balance areas and item control areas. The proposed plant contains a process computer that monitors the tare weights, gross weights and locations of all in-process pellet trays. Most transfers are computer controlled. Scrap transfers are done remotely. Thus transfers between MBA's or ICA's cannot occur without being monitored by the process computer. Even though some areas do not physically separate material in difficult balance areas, such areas are in remote canyons and there is no way to transfer materials from one area to another.

Regulatory Guide 5.42 discusses design criterion for dry-process operations. The facility places heavy reliance on pneumatic transfers. Storage hoppers have conical-shaped bottoms and PuO_2 is non-reactive with the materials of construction of process equipment. Moisture content, a potential problem, is monitored and must be controlled for criticality safety. Based on the regulatory guide, the above design characteristics are highly desirable. The only apparent deficiency is the inability to measure the amount of material held up as feed to the slug, granulator and pellet machines. These feeding hoppers must be run out, a process taking 3 to 6 hours, before an accurate inventory estimate can be made.

The above paragraphs briefly describe how the design described in Reference (11) meets or exceeds most of the regulatory design criteria applicable to fuel fabrication facilities. Subsequent sections will discuss measurement uncertainties and the expected material accounting capability of the facility.

B.4.2 Measurement Uncertainties for Mixed Oxide Fabrication Plant Plutonium Accountability Measurements

The measurement uncertainties associated with what are considered to be the best formal accounting measurements will be described in this section. The uncertainties associated with running-inventory type accounting systems has been discussed earlier, under the topic Real Time Material Control and Accounting Systems.

As was the case with the reprocessing plant, there are many years of experience with material accounting in a mixed oxide fabrication plant. Performance data from this country and abroad is available.(2,3,4,6,7) Table B.20 represents a composite summary of the estimated present capability of fabrication plant measurement systems. There have been no studies to date which break the systematic error term up into long-term and short-term components. As a result, a long-term systematic component of 0.2% was selected to represent the fraction of the systematic error that might persist for many years. The short-term component is simply the difference between the systematic error component estimated from past studies and the long-term systematic error term. Since the long- and short-term components must be squared and then added to get the total systematic error, some of the short-term errors are presented as two place decimals. This was done solely to make the total systematic error come out as a single digit number.

TABLE B.20 Estimates of Random and Systematic Error for Fabrication Plant Plutonium Accountability Measurements

Material Balance Component	Relative Percent Standard Deviation of A Single Measurement		
	Weighing	Sampling	Analytical
Input			
Plutonium Oxide			
Random	0.07	0.10	0.25
Short-Term Systematic	0.035	--	0.046
Long-Term Systematic	0.020	0.02	0.02
Products			
Plutonium Output (Finished Pellets)			
Random	0.07	0.10	0.30
Short-Term Systematic	0.035	--	0.046
Long-Term Systematic	0.020	0.02	0.020
Plutonium Waste			
Random	2.0	3.0	10.0
Short-Term Systematic	--	--	10.0
Long-Term Systematic	1.0	1.0	1.0
Dirty Scrap			
Random	0.1	5.0	5.0
Short-Term Systematic	--	--	5.0
Long-Term Systematic	0.1	1.0	1.0
In-process Storage			
Mixed Oxide Powder Blends (inc. recovered clean scrap)			
Random	0.07	0.10	0.30
Short-Term Systematic	0.035	--	0.08
Long-Term Systematic	0.020	0.02	0.02
Mixed Oxide Scrap Can			
Random	0.07	0.20	0.30
Short-Term Systematic	0.035	--	0.08
Long-Term Systematic	0.02	0.02	0.02
Green Pellet Store			
Random	0.07	0.15	0.30
Short-Term Systematic	0.035	--	0.08
Long-Term Systematic	0.02	0.02	0.02
Sintered Pellet Store			
Random	0.07	0.10	0.30

B.4.3 Capability of Material Balance Accounting Systems for Plutonium in a 200 MT/Year Mixed Oxide Fuel Fabrication Facility

From the standpoint of material accounting, major emphasis has been placed on overall plant performance. When discussing overall performance, measurement errors associated with internal transfers are not included. Intermediate materials, present as in-process inventories do enter into the inventory term. Thus, in-process inventories, if they are present in well characterized forms, do not seriously degrade the sensitivity of the accounting system.

Tables B.21 and B.22 have been prepared to summarize the estimated contribution of in-process material to the overall plant accounting system variance. Table B.21 produces a tabulation of the measurement variance for material held up in the process vessels. The holdup-level estimates have been based on a facility decommissioning study.(16) Table B.22 provides a tabulation of the variance for material held up as well characterized in-process inventories. These inventory variances are combined with the flow variance terms for several accounting periods to obtain the sensitivity of LEMUF to inventory level and inventory frequency.

Table B.23 shows the results of combining the high inventory-level variances with the flow variances for several accounting periods. Table B.24 compares the value of LEMUF obtained for the high inventory case with a case where the well-characterized in-process inventory level is small. The gain in sensitivity of loss detection is very small.

TABLE B.21 Inventory Measurement Uncertainty Evaluation for Material Held Up in Process Equipment in a 200 MT/Year Mixed Oxide Fuel Fabrication Facility

Process Component	No. Of Components	Plutonium Holdup per Component kg's	Measurement Accuracy %	Total Measurement Error Variance kg^2
PuO_2 Powder Unloading and Transfer	3	0.2	50	0.03
PuO_2 Storage Silos	3	1.3	0.29	4.2×10^{-5}
PuO_2 Blender Feed System	1	1.0	50	0.25
MO_2 Storage Silos	9	0.05	0.29	1.9×10^{-7}
MO_2 Blender Feed System	1	0.1	50	2.5×10^{-3}
Blend, Mill	1	0.05	50	6.25×10^{-4}
Slug, Granulate, Press	3	0.05	50	1.875×10^{-3}
Grind	2	0.05	50	1.25×10^{-3}
Pellet Inspection	1	0.1	50	2.5×10^{-3}
Lab	36	0.05	50	0.0225
Defect Rod Unloading	1	0.1	50	2.5×10^{-3}
Clean Scrap Recovery	4	0.06	50	3.6×10^{-3}
Misc. Waste Treatment	11	0.05	50	6.8×10^{-3}
Clean Scrap Storage	3	0.05	0.29	1.9×10^{-7}
TOTALS		9.25		0.3187

TABLE B.22 Beginning Plus Ending Inventory Measurement Uncertainty Evaluation for Well-Measured In-Process Inventories in a 200 MT/Year Mixed Oxide Fuel Fabrication Facility

Process Inventory Item	No. of Items	Plutonium Content Per Item (kg of Pu)	Total Random Error Variance kg^2	Total Systematic Error Variance kg^2	Total Error Variance kg^2
PuO_2 Powder Silos	2	150	0.348	0.020	0.368
(a) PuO_2 Powder Silos	1	150	0.174	0	0.174
MO_2 Powder Silos	5	7.94	0.0047	0.0013	0.0060
Clean Scrap Silos	2	25.41	0.0100	0.0012	0.0112
(a) Clean Scrap Silo	1	25.41	0.0050	0	0.0050
(b) Green Pellet trays	29	0.3176	3.0×10^{-5}	7.0×10^{-5}	(0.0001)2
(b) Sintered Pellet trays		0.3176	7.0×10^{-5}	3.8×10^{-4}	(0.0004)2
(b) Finished Pellet trays	444	0.3176	4.7×10^{-4}	1.7×10^{-2}	(0.0172)2
(b) Clean Scrap cans	36	0.7058	2.0×10^{-4}	5.0×10^{-4}	(0.0007)2
Subtotal - if some silos inactive for accounting period					0.4280
TOTAL		762.8			0.6020

a) Not applicable for accounting periods where when one silo remains inactive for accounting period.

b) Different batches are assumed present at beginning and end of inventory period. Thus, total variance must be multiplied by two.

TABLE B.23 Measurement Uncertainty Evaluation for a 200 MT/Year Mixed Oxide Fuel Fabrication Facility

	Length of Material Accounting Period					
	7 Days	15 Days	1 Month	2 Months	6 Months	12 Months
	Measurement Error Variances					
Feed - 7.052 kg's of Pu						
Number of Batches	21.25	42.5	84.3	168.7	506	1012
Random Error Variance - kg^2	0.0082	0.0164	0.0325	0.0650	0.195	0.390
Systematic Error Variance - kg^2	0.0101	0.0405	0.1594	0.6378	5.740	22.958
Total Variance - Feed - kg^2	0.0183	0.0569	0.1919	0.7028	5.935	23.348
Product - 0.3176 kg's						
Number of Batches	466.62	933.2	1852	3703.7	11.111	22.222
Random Error Variance - kg^2	0.0005	0.0010	0.0020	0.004	0.012	0.024
Systematic Error Variance - kg^2	0.0184	0.0738	0.2906	1.162	10.461	41.844
Total Variance - Product - kg^2	0.0189	0.0748	0.2926	1.166	10.473	41.868
Dirty Scrap - 0.106 kg						
Number of Batches	8.39	16.8	33.2	66.4	199	398
Random Error Variance - kg^2	0.0005	0.0009	0.0019	0.004	0.011	0.022
Systematic Error Variance - kg^2	0.0020	0.0079	0.0309	0.124	1.113	4.453
Total Variance - D. Scrap kg^2	0.0025	0.0088	0.0338	0.127	1.124	4.475
Misc. Waste 0.1882 kg						
Number of Batches	4.72	9.45	18.7	37.4	112.1	224.3
Random Error Variance - kg^2	0.006	0.0013	0.0025	0.005	0.015	0.030
Systematic Error Variance - kg^2	0.0020	0.0079	0.0309	0.124	1.113	4.453
Total Variance Waste kg^2	0.0026	0.0092	0.0334	0.129	1.128	4.483
Total Variance - Flow kg^2	0.042	0.150	0.551	2.125	18.661	74.174
Total Variance - Inventory kg^2	1.239					
Total Variance - kg^2	1.281	1.389	1.790	3.364	19.90	75.413
Sd(MUF) - kg	1.132	1.178	1.338	1.834	4.46	8.68
LEMUF - kg	2.26	2.36	2.68	3.67	8.92	17.4
LEMUF*100/Feed-%	1.50	0.79	0.45	0.31	0.25	0.24

TABLE B.24 Comparison of LEMUF Sensitivity to Frequency and Amount of-Well Measured In-Process Material Included in the Material Balance for a 200 MT/Year Fuel Fabrication Plant

Accounting Period	No In-process Materials other than Quantities Held up in Process Equipment	Large Amount of In-Process Material (762 kg's of Pu) in Addition to Quantities Held up in Process Equipment
	kg	kg
1 Week	1.649	2.264
2 Weeks	1.775	2.357
1 Month	2.180	2.676
2 Months	3.324	3.668

The same data used to develop the results shown in Table B.25 can also be used to show the effect of randomizing the short-term systematic error from one accounting period to the next. It is believed that this randomization will be a result of the measurement control program.(9) As shown in Table B.24, randomizing a component of the systematic error results in a significant reduction in the rate of LEMUF/Feed. As discussed in the introduction to section 3, this ratio is a measure of the detection sensitivity of the plant against small continuous or semicontinuous losses of material.

The previous paragraphs discussed the behavior of the overall plant balance. Based on the error terms in Table B.20 it can be seen that intermediate process flows can be measured with essentially the same accuracy as the input and final product measurements. This means that material balances taken over small pieces of the process may be timely, sensitive loss detectors. Table B.26 shows the results of a material balance taken over the plutonium oxide powder storage area. Since the input is weighed and analyzed as part of the plant balance, this term is identical to the input term in Table B.23 The storage silos are on weigh cells and can be measured accurately. The output is batched into the PuO_2 blender input hopper which is also on a weigh cell. Thus, all the flows and inventories can be determined and monitored in an essentially continuous manner. Based on the results, shown in Table B.26,

TABLE B.25 Effect of the Measurement Control Program on the Long-Term Measurement Errors for a 200 MT/Year Mixed Oxide Fuel Fabrication Facility

	Elapsed Time from Initiation of Control Program									
	2 Months	6 Months	1 Year	2 Years	3 Years	4 Years	5 Years	6 Years	3 Years	10 Years
No. Of Inventory Periods	1	3	6	12	18	24	30	36	48	60
	Cumulative Measurement Error Variances									
Feed - 7.058 kg Batches No of Batches/Inventory Period - 168.67										
Random Error Variance - kg²	.065	.195	.390	.780	1.17	1.56	1.95	2.34	3.12	3.90
Short Term Systematic Error Variance - kg²	.468	1.403	2.806	5.612	8.42	11.22	14.03	16.84	22.45	28.06
Long Term Systematic Error Variance - kg²	.170	1.531	6.122	24.490	55.10	97.96	153.06	220.41	391.83	612.24
Total Variance - Feed - kg²	.703	3.129	9.318	30.882	64.69	110.74	169.04	239.59	417.4	644.2
Product - 0.3176 kg Batches No of Batches/Inventory Period 3703.7										
Random Error Variance - kg²	0.004	0.012	0.024	0.047	0.071	0.094	0.118	0.270	0.188	0.235
Short Term Systematic Error Variance - kg²	0.996	2.989	5.978	11.956	17.933	23.911	29.889	35.867	47.832	59.778
Long Term Systematic Error Variance - kg²	0.166	1.494	5.978	23.911	53.800	95.645	149.445	215.202	382.581	597.783
Total Variance - Product - kg²	1.166	4.495	11.98	35.914	71.804	119.65	174.452	251.339	430.592	657.796
Dirty Scrap - 0.106 kg Batches No of Batches/Inventory Period - 66.36										
Random Error - Variance - kg²	0.004	0.011	0.022	0.045	0.067	0.089	0.111	0.134	0.179	0.224
Short Term Systematic Error Variance - kg²	0.109	0.327	0.653	1.306	1.959	2.612	3.266	3.919	5.275	6.531
Long Term Systematic Error Variance - kg²	0.015	0.134	0.534	2.138	4.809	8.550	13.359	19.238	34.200	53.437
Total Variance - Dirty Scrap kg²	.128	0.472	1.209	3.489	6.835	11.251	16.736	23.291	39.654	60.192
Waste - 0.1802 kg Batches No. of Batches/Inventory Period - 37.38										
Random Error Variance - kg²	0.005	0.015	0.030	0.060	0.091	0.121	0.151	0.181	0.241	0.302
Short Term Systematic Error Variance - kg²	0.109	0.327	0.653	1.306	1.959	2.612	3.266	3.919	5.225	6.531
Long Term Systematic Error Variance - kg²	0.015	0.134	0.534	2.138	4.809	8.550	13.359	19.238	3 34.20	53.437
Total Variance - Waste kg	0.129	0.476	1.217	3.504	6.859	11.283	16.776	23.338	39.666	60.270
Total Variance - Flow - kg²	2.126	8.572	23.73	73.79	150.19	252.92	382.00	537.59	927.26	1422.5
Total Variance - Inventory - kg²	1.239									
Total Variance kg²	3.365	9.811	24.97	75.03	151.43	254.16	383.2	538.8	928.5	1423.7
Sd(MUF) - kg	1.834	3.132	4.997	8.662	12.31	15.94	19.57	23.21	30.47	37.73
LEMUF - kg	3.669	6.265	9.990	17.323	24.61	31.88	39.15	46.43	60.94	75.46
(LEMUF x 100/Feed) %	0.308	0.175	0.140	0.121	0.114	0.111	0.110	0.108	0.107	0.106

TABLE B.26 Measurement Uncertainty Evaluation for the PuO_2 Power Storage Area in a 200 MT/Year Fuel Fabrication Plant

Time Period	Batch	8 Hours	Day	Week	2 Weeks	1 Month	2 Months
Flow Terms							
Feed Component							
No. of Batches	1	1.012	3.036	2.25	42.5	84.3	168.6
Batch Size (kg or Pu)	7.058						
Random Error Variance kg^2	3.86×10^{-4}	3.90×10^{-4}	1.17×10^{-3}	0.008	0.016	0.033	0.065
Systematic Error Variance kg^2	2.24×10^{-5}	2.30×10^{-3}	2.06×10^{-4}	0.010	0.040	0.159	0.678
Total Error Variance kg^2	--	4.13×10^{-4}	1.38×10^{-3}	0.018	0.057	0.192	0.703
Product Component							
No of Batches	1	1	3	21	42	83.3	166.6
Batch Size (kg of Pu)	7.142						
Random Error Variance kg^2	3.86×10^{-4}	3.86×10^{-4}	1.18×10^{-3}	0.009	0.017	0.034	0.066
Systematic Error Verlance kg^2	2.24×10^{-5}	2.24×10^{-5}	2.06×10^{-4}	0.010	0.040	0.159	0.638
Total Error Variance kg^2	--	4.08×10^{-4}	1.39×10^{-3}	0.019	0.057	0.193	0.704
Flow Total	--	8.21×10^{-4}	2.77×10^{-3}	0.037	0.114	0.384	1.407
Inventory Terms							
PuO_2 Storage Silos							
No. of Active Silos	--	--	2	2	3	3	3
Beginning Inventory kg (Silo 1, Silo 2, Silo 3)	--	(120, 30)	(120, 30)	(150, 0)	(150, 150, 0)	(150, 150,0)	(150, 150, 0)
Ending Inventory kg (Silo 1, Silo 2 Silo 3)	--	(113, 37)	(100, 50)	(0, 150)	(150, 0, 150)	(150, 0, 150)	(150, 0, 150)
Random Error Variance	--	.2278	.2152	0.3483	0.6966	0.6965	0.6966
2ΔT Systematic Error Variance	4.58×10^{-5}	4.58×10^{-5}	1.37×10^{-4}	0.0206	0.0206	0.0206	0.0206
Total Error Variance	--	.2279	.2153	0.3689	0.7172	0.7172	0.7172
Holdup Inventory							
No. of Location	--	2	2	2	3	3	3
Amt/Loc (kg)	--	0.2	0.2	0.2	0.2	0.2	0.2
BI Random Error Variance kg^2	--	0.02	0.02	0.02	0.03	0.03	0.03
EI Random Error Variance kg^2	--	0.02	0.02	0.02	0.03	0.03	0.03
Total Error Variance kg^2	--	0.04	0.04	0.04	0.06	0.06	0.06
Total Inventory Error Variance kg^2	--	0.2679	0.2553	0.4089	.7772	.7772	.7772
Total Error Variance kg^2	--	0.269	0.258	.450	.891	1.161	2.184
Sd(MUF) kg	--	0.52	0.51	0.67	.94	1.08	1.48
LEMUF kg	--	1.0	1.0	1.3	1.9	2.2	3.0
LEMUFx100/Feed %	--	14.5	4.7	.89	.63	.36	.25

the loss sensitivity of this area is very high, exceeding the capability of the plant. In addition, because of the weigh cell design, the material balance can be very timely. Since much less PuO_2 must be diverted than MO_2, a formal material balance over this area appears both possible and highly desirable.

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APPENDIX C

HTGR FUEL FABRICATION PLANT MODEL

The plant model for initial and reload core-fuel fabrication is based on information provided by the General Atomic Corporation in support of their license application for the proposed Youngsville, North Carolina, plant.(1)

The Youngsville plant is designed to handle highly enriched ^{235}U feed and cannot fabricate recycle fuels. The plant is capable of fabricating six fuel cores/year. Initially, essentially all their production will be initial cores. In time, the requirement for replacement cores will increase. In this analyses it will be assumed that the facility will fabricate five initial cores and four one-fourth core reloads in the year being analyzed. This condition may be expected to exist in the late 1980's.

The fuel management of these reactors is complicated by the requirement for no fuel shuffling. The standard fuel element shown in Figure 1, is a hexagonal block of graphite. In a 1170 MWe plant, these blocks are stacked eight high and are refueled seven stacks at a time.(2) Heat generation rates are controlled by varying the amount of ^{235}U in a fuel assembly. Thus, in a core there could be many enrichments. For this analysis, typical amounts of ^{235}U and thorium used in an initial core assembly and in a reload assembly will be used.

The following sections describe the fuel assemblies and then the fuel assembly fabrication process.

C.1 HTGR FUEL ELEMENT DESCRIPTIONS

The standard fuel element for the commercial HTGR is shown in Figure C.1. It is a hexagonal block of graphite into which vertical coolant and fuel holes are drilled. The fuel holes are filled with rods composed of fuel particles (up to about 60 volume percent) bonded together by a graphite matrix. A standard fuel element into which control rods can be inserted is shown in Figure C.2.

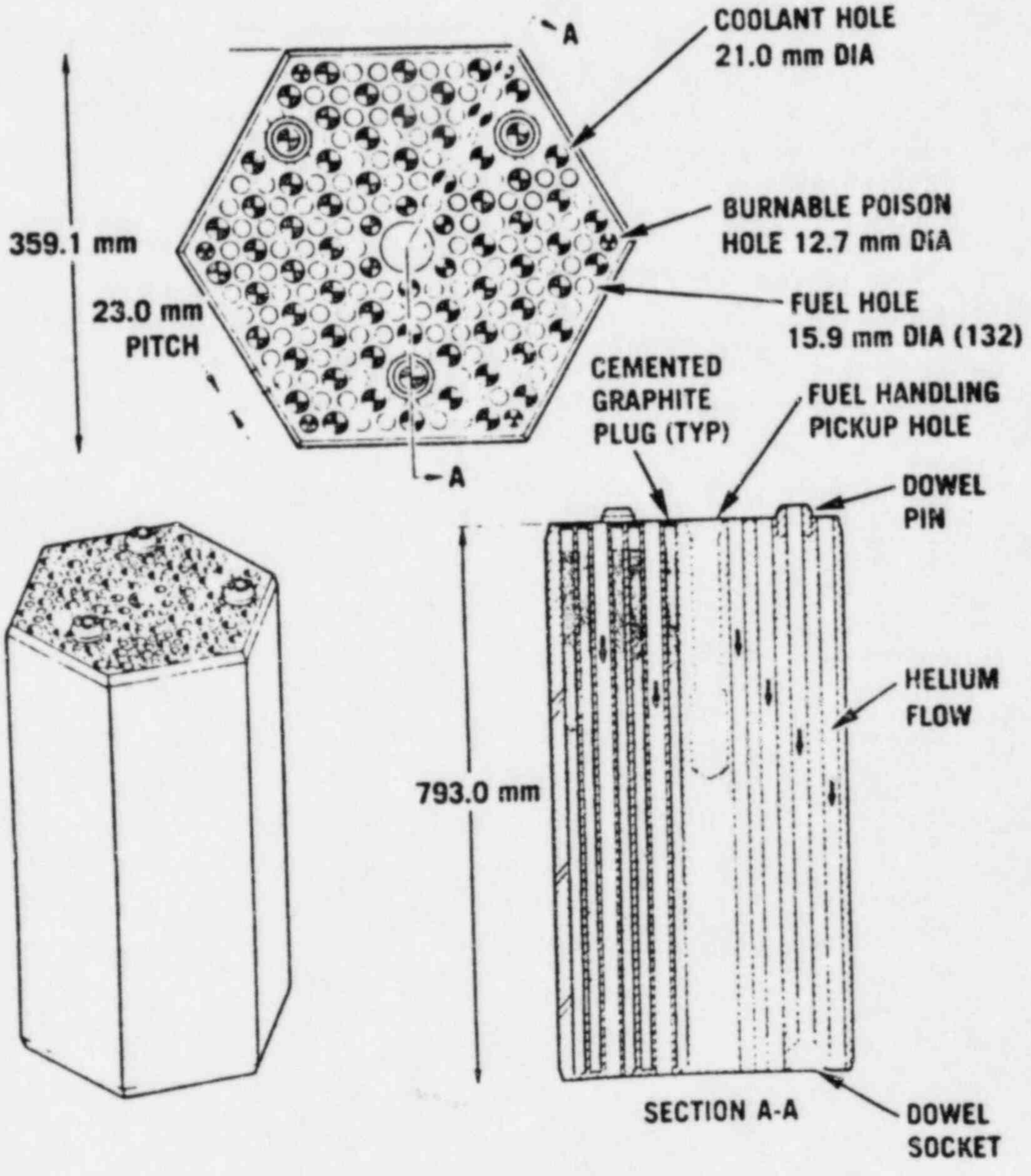

FIGURE C.1 HTGR Standard Fuel Element

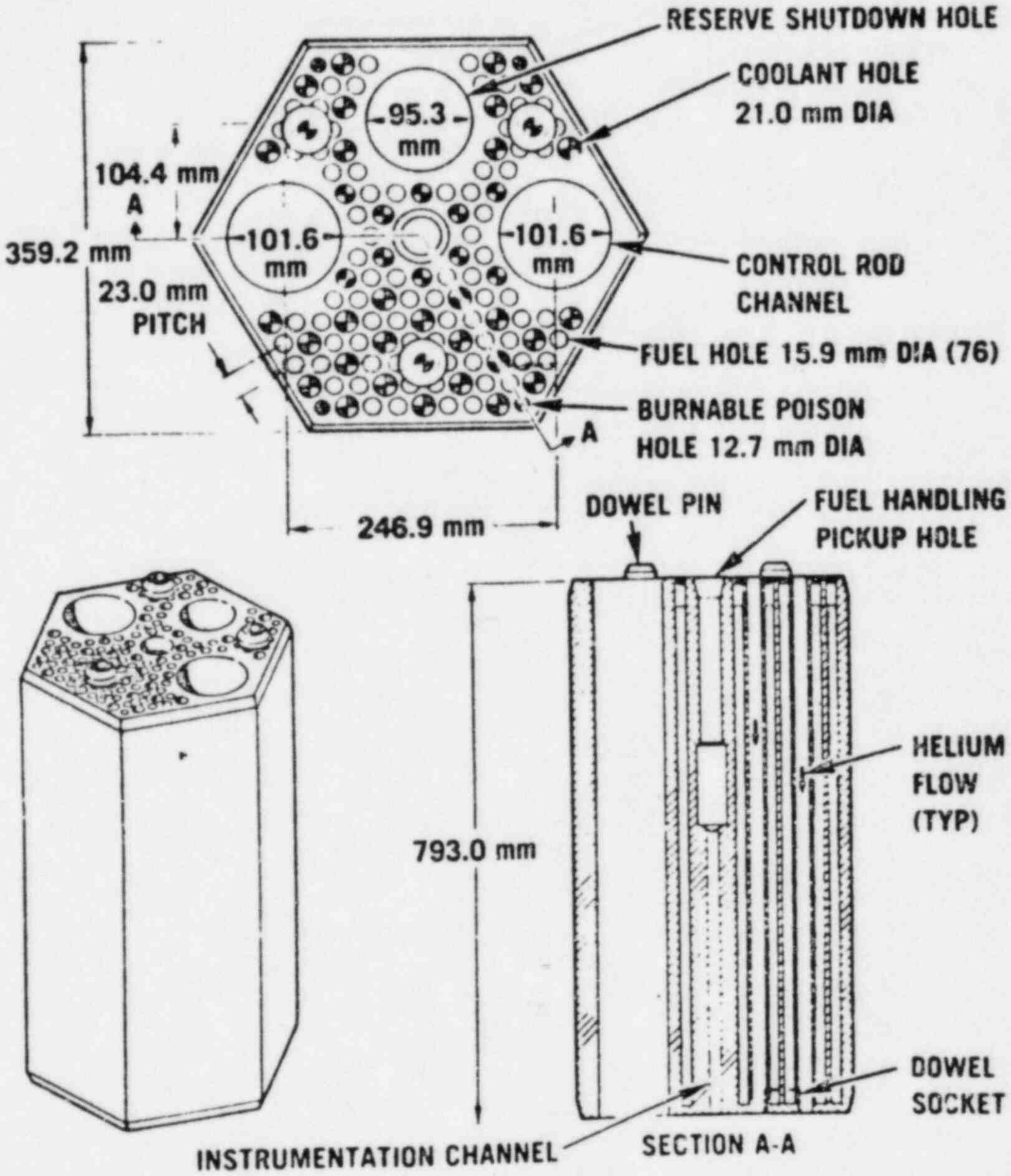

FIGURE C.2 HTGR Control Fuel Element

The initial core is fueled with thorium oxide and 93% enriched ^{235}U as uranium dicarbide. Subsequent reloads could either be enriched with ^{235}U, recycled ^{235}U or ^{233}U bred from the ^{232}Th. This analysis is not considering the ^{235}U recycle and ^{233}U streams.

As currently envisioned the UC_2 is encapsulated in TRISO particles and the ThO_2 is encapsulated in BISO particles. A microphotograph of the particles is shown in Figure 3. The TRISO particle consists of the inner fuel particle followed by successive layers of buffer carbon, pyrolytic carbon, silicon carbide and pyrolytic carbon. The BISO particle does not have a SiC layer. Table C.1 shows the fuel particle size and the thicknesses of the various layers. The densities of the various compounds making up the BISO and TRISO particles are shown in Table C.2. These density values are based on data presented

TABLE C.1 HTGR TRISO and BISO Particle Dimensions

Particle Characteristic	BISO Particle	TRISO Particle
Fuel	ThO_2	UC_2
	Particle Dimensions	(microns)
Fuel Particle Diameter	500	200
Buffer Carbon Thickness	85	85
Inner Pyrolytic Carbon Thickness	--	25
SiC Thickness	--	25
Outer Pyrolytic Carbon Thickness	75	25

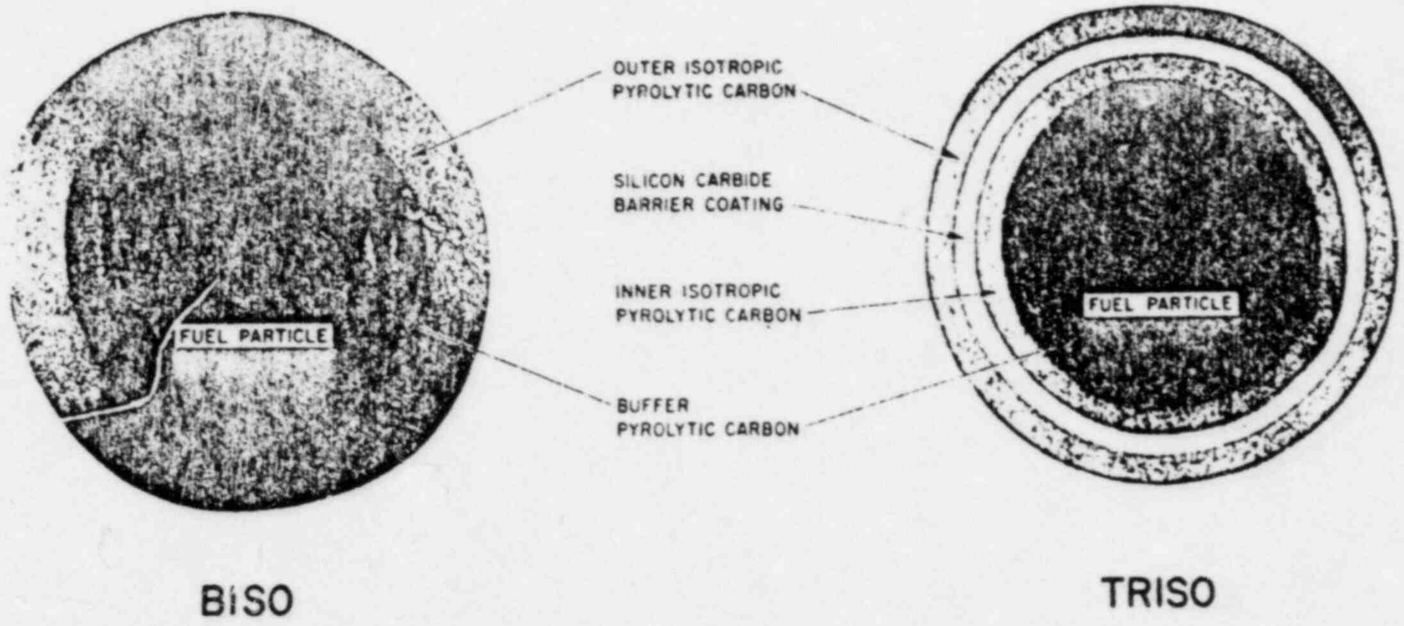

FIGURE C.3 GA Coated Particles

TABLE C.2 Density of Materials Used in BISO and TRISO Particles

Material	Density (gms/Cm^3)
UC_2	11.446
ThO_2	9.829
Buffer Carbon	1.1
SiC	3.2
Pyrolytic Carbon	2.0

by P. R. Kasten et al.(3) The fuel particle density is based on a density which is 93% of the theoretical density. Based on these densities, the volume and mass fraction occupied by the various materials are shown in Table C.3.

TABLE C.3 BISO and TRISO Particle Volume and Weight Fraction Data

	BISO Particle		TRISO Particle	
	Volume Fraction	Mass Fraction	Volume Fraction	Mass Fraction
Fuel Particle	0.2267	0.6448	0.0508	0.2345
Buffer Carbon	0.3188	0.0922	0.2709	0.1117
Inner Pyrolytic Carbon	--	--	0.1488	0.1227
Silicon Carbide	--	--	0.1888	0.2495
Outer Pyrolytic Carbon	0.4545	0.2630	0.3407	0.2816
Total Volume (Cm^3)	2.887×10^{-4}	--	8.245×10^{-5}	--
Total Mass (gms)	--	9.978×10^{-4}	--	1.997×10^{-4}

The BISO and TRISO particles described in the previous paragraphs are mixed with a binder and graphite powder and extruded into fuel sticks which are 2.48 inches long and 0.614 inches in diameter. Table C.4 describes the makeup of a typical fuel stick, standard fuel assembly and control element fuel assembly for both a total initial core loading and for a typical one-fourth core reload. This information forms the

TABLE C.4 Description of Core Compositions for a 1160 MWe HTGR

Component Description	Initial Core Composition	Reload Core Composition (4-1/4 Core Reloads)
Fuel Sticks		
Length - in	2.48	2.48
Diameter - in	0.614	0.614
Th Content - gms	6.414	5.774
ThO_2 Content - gms	7.299	6.570
^{233}U Content - gms	0.277	0.499
UC_2 Content - gms	0.330	0.593
Vol % BISO	27.2	24.5
Vol % TRISO	4.8	8.7
Vol % Matrix	68.0	66.8
Total Wt - gms	21.73	21.560
Std. Fuel Assembly		
Number/Core	3360	3360
Fuel Sticks/ Assembly	1581	1581
ThO_2 - kgs	11.540	10.387
UC_2 - kgs	0.521	0.938
SiC - kgs	0.542	0.988
Burnable Poison - kgs	0.907	0.907
Carbon Coatings - kgs	8.005	7.790
Fuel Stick Binder - kgs	14.230	13.980
Graphite Block - kgs	83.550	83.550
Total wt - kgs	119.295	118.540
Controlled Fuel Assembly		
Number/Core	548	548
No. of Fuel Sticks/Assembly	909(681)[a]	909(681)
ThO_2 - kgs	6.644	5.980
UC_2 - kgs	0.300	0.541
SiC - kgs	0.312	0.568
Burnable Poison - Kgs	0.605	0.605
Carbon Coating - kgs	4.609	4.485
Fuel Stick Binder - kgs	8.137	8.037
Graphite Block - kgs	81.246	81.246
Total wt - kgs	101.896	101.462
Total Core		
Thorium (kgs)	37,486	33,739
^{235}U (kgs)	1,617	2,913

a) Bottom Fuel Assembly in Control Rod Stack (73 total) basis for the material accounting evaluation of the fuel fabrication plant shown in the following section.

The next section will present an abbreviated descritpion of a material balance taken over the fabrication plant. This will be followed by sections on measurement uncertainties and finally a section summarizing the results of the material accounting calculations.

C.2 MATERIAL BALANCE MODEL FOR AN HTGR FUEL FABRICATION PLANT

The fabrication of HTGR fuel is basically a batch process. Criticality requirements limit inventories at most locations to a few kilograms of contained ^{235}U. Batch processing is one of the most straightforward ways of controlling inventories in the facility. In most processing areas, the batch size is limited to 3.6 kg of ^{235}U. Most conversion steps require that a batch be transferred out before another can be transferred in.

The abbreviated description of the plant flows is shown in Figure C.4. Based on the data provided in the previous section and the Youngsville license application information, the material balance is summarized in Table C.5. The scrap generated during the inventory period is assumed to be held over into the next period. This scrap includes furnace liners which are one of the major sources of measurement uncertainty.

TABLE C.5 HTGR Material Balance - 2-Month Accounting Period
Initial Core Campaign

Flow Component	Batch Size kg ^{235}U	No. of Batches	Total kg
UF_6 to Converter	15.55	105.185	1632.465
UO_2F_2	3.6	453.35	1632.074
Fresh UO_2 Feed	3.6	452.51	1629.028
Recovered UO_2 (from scrap)	3.6	133.41	480.289
Mix Line	0.72	2929.0	2109.317
UC_2 Convert	0.72	2844.4	2047.973
UC_2 Sperodize	3.6	552.4	1988.529
Buffer Seal Inner LTI Coat	3.6	538.4	1938.748
SiC Coat	3.6	520.69	1874.489
Outer LTI Coat	3.6	505.55	1819.948
Blend	3.6	475.69	1712.492
Green Rod	0.277 gms	6,182,282	1712.492
Carbonize	0.277 gms	6,007,282	1664.017
Final Product	0.277 gms	5,832,282	1615.542
Element Product	0.4092	3944	1613.905

C.3 ESTIMATED MEASUREMENT UNCERTAINTIES FOR AN HTGR FUEL FABRICATION PLANT

For the plutonium processing facilities, there was a wealth of data from independent sources which were used to obtain estimated measurement uncertainties. Because of the unique characteristics of the HTGR fuel, there is much less relevant data. Table C.6 presents a summary of the estimated capability of HTGR measurement systems. The categories CU-1 through CR-14 designate streams shown in Figure C.4. This information was obtained by personnel communication with GGA personnel.

The designation short-term and long-term systematic error needs some clarification. Although the definitions correspond to the usage described in Appendix A, the short-term error is based on weekly recalibrations. Thus, in order to get the systematic error component associated with a 2-month period, the methods developed in Appendix A must be used. For the evaluation of the capability of an HTGR fuel processor to account for the processed ^{235}U in a 2-month accounting period, the short-term systematic error component will be combined with the random error term.

In addition to the well measured, in-process inventories, holdup and measurement uncertainties associated with scrap recovery must also be considered. Table C.7 presents an evaluation of the estimated levels of holdup in equipment and these estimated measurement accuracies. At the present time the processes to be used for scrap recovery are incompletely specified. As a result, the data presented in Table C.7 are considered to be

TABLE C.6 HTGR Fuel Error Components

Category	Method	Random Error %	Short Term Syst. %	Long Term Syst. %
$U_3O_8 - UO_2$	Gravimetric	.01	-	.03
	Mass Spec	.02	-	.01
UThOxide	XRF	2.25	0.4	0.3
	Mass Spec	.02	-	.01
CU-1	XRF	2.75	0.4	0.3
CU-2	XRF	2.6	0.4	0.3
CU-3 (Comp)	XRF	1.0	0.4	0.3
CU-4	XRF	4.0	0.4	0.3
CU-5	XRF	2.6	0.5	1.03
CU-6	XRF	3.0	0.5	1.03
CU-7 (Comp)	XRF	1.0	0.5	1.03
CR-9 - 13	XRF	2.0	0.5	1.03
CR-14	Delayed Neutron Activation Analysis	2.0	0.5	1.04
Scrap-Liquid	XRF	2.75	0.4	0.3
Scrap-Solid	Gamma Count	4.0	1.0	2.8
Waste Barrels	Gamma Count	6.0	2.8	24.
Duct Holdup	Gamma Count	5.0	NA	20.
Filters	Gamma Count	6.0	NA	53.

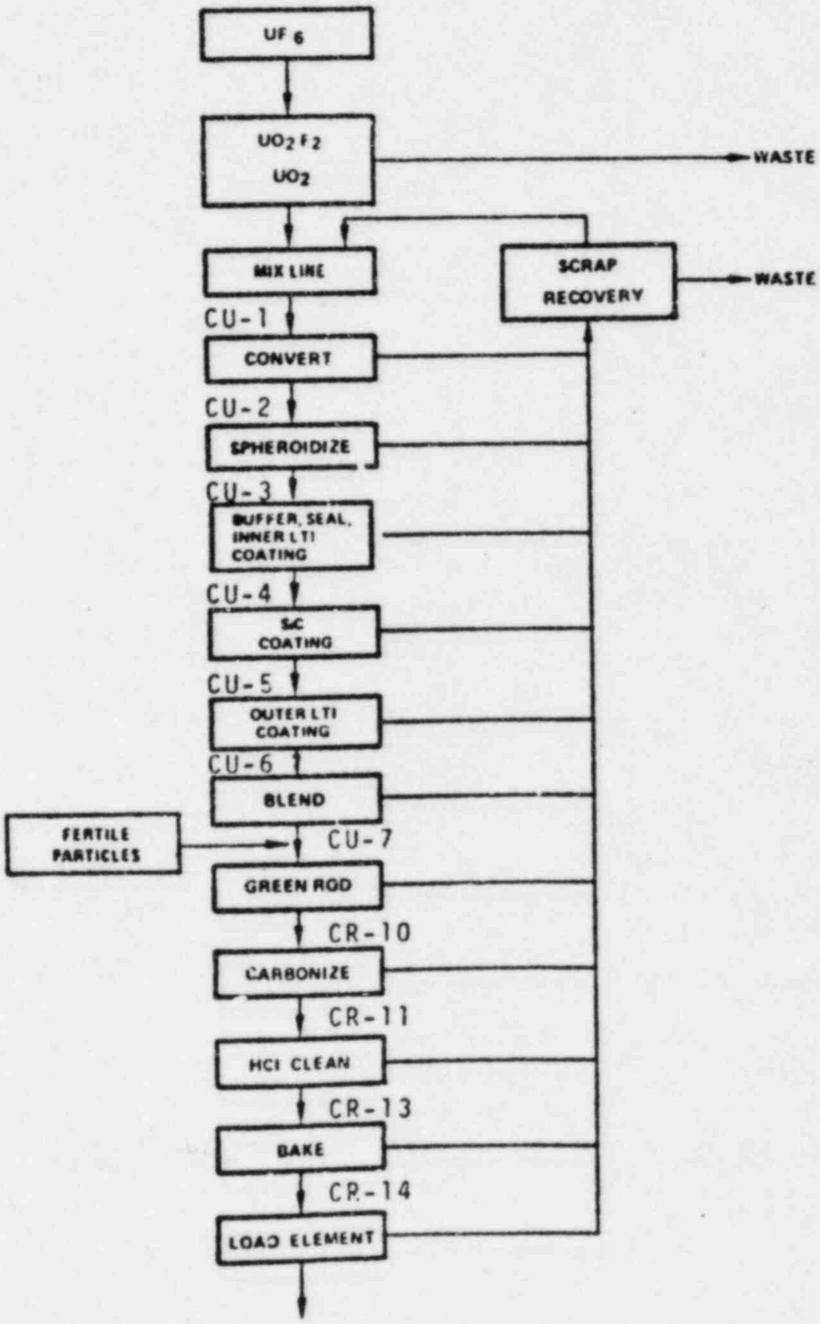

FIGURE C.4 Fissile Production Sequence Summary

TABLE C.7 Inventory Levels and Estimated Measurement Errors

Component	Number of Components (or Batches)	Estimate Inventory ^{235}U Per Component (gms)	Measurement Accuracy Random %	Systematic %
In-process Equipment				
UO_2 Conversion Units	4	3600	10	--
UO_2-C Blending	6	360	50	--
UC_2 Conversion	18	36	50	--
UC_2 Spherodizing	9	300	50	--
Screens	3	250	50	--
Coaters	36	20	50	--
Stick Fabrication	50	<1	50	--
Failed Equipment				
Coater Liners	400	20	20	--
Conversion Units	3	300	20	--
Misc. Equipment	100	100	20	--
Scrap				
Fast Scrap	45	3600	2.8	--
Off Speck Particles	88	3600	4.0	--
Defective Elements	15	409	2.3	--
Off Speck Fuel Sticks	500,000	0.277	2.3	--
Green Fuel Sticks	500,000	0.277	2.3	--
In-Process Materials				
UO_2	60	3600	0.02	0.01
UO_2 -C Blends	50	720	3.0	0.3
UC_2 Powder	60	3600	2.8	0.3
UC_2 Particles	50	3000	1.3	0.3
LTI Coat	10	3600	4.0	0.3
SiC Coat	20	3600	2.9	1.03
Triso Inspect	60	3600	3.3	1.03
Triso Blend	28,800	0.277	1.7	1.03
Stick Fab	86,400	0.277	2.4	1.04

order of magnitude estimates only; they are probably conservative. These estimates were based on studies of plutonium holdup and also from available descriptions of HTGR processing facilities.

C.4 MATERIAL ACCOUNTING CAPABILITY OF A ^{235}U HTGR FUELS PLANT

The previous sections have provided all the information required to evaluate the capability of material accounting in a high enriched ^{235}U-HTGR fuels plant. The variance calculation for the inventory term at the beginning or end of a 2-month period is shown in Table C.8. There may be material that was not processed during the 2-month period, such material was not included in the variance calculation. The inventory variance is included with the flow variance term in Table C.9 to obtain σ(MUF) and LEMUF estimates.

These estimates were used to provide a basis for comparison of HTGR facilities with plutonium processing facilities. This comparison is shown in Table 4.1.

The base case, 2-month accounting period was studied. Improvements in sensitivity and timeliness were beyond the scope of this study. Such an evaluation would require a much more detailed description of the scrap recovery operation.

TABLE C.8 Summary of Inventory Uncertainty Calculations

Inventory Component	^{235}U Content kg's	Variance kg^2
In-Process Inventories		
UO_2 Prep	212	0.034
UC_2 Prep	432	1.427
Triso Particles	324	5.407
Fuel Sticks	32	0.029
Total in-Process	1000	6.897
Scrap Recovery Inventories		
Failed Equipment	20	6.594
Coated Particle Scrap	320	1.825
Uncoated Particle Scrap	160	0.457
	500	8.876
Equipment Holdup	20	0.968
TOTAL INVENTORY	1520	16,741

TABLE C.9 Summary of Variance Calculation for an HTGR ^{235}U Fuel Fabrication Plant for a 2-Month Accounting Period

Component	Component Variance kg^2
Feed - 15.52 kg's of ^{235}U	
No. of Batches 105.184	
Random Error Variance	0.073
Systematic Error Variance	8.634
Total Variance - Feed	8.708
Product - 0.277×10^{-3} kg's	
No. of Batches - 583.2282	
Random Error Variance	0.0003
Systematic Error Variance	276.892
Total Variance - Product	276.893
Waste - 7.4×10^{-3} kg's	
No of Batches - 2500	
Random Error Variance	0.0009
Systematic Error Variance	19.842
Total Variance - Waste	19.843
Total Flow Variance	305.4
Inventory - 1520 kg's	
Inventory Variance (Beg. & End)	33.5
Total Variance - kg^2	338.9
sd(MUF) - kg's	18.4
LEMUF - kg's	36.8
LEMUFx100/Feed	2.25
LEMUFx100/(Feed+Inv)	0.86

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