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A DETAILED ANALYSIS OF THE SAFEGUARDS
CAPABILITIES OF MATERIAL BALANCE
ACCOUNTING SYSTEMS
IN THE LOW ENRICHED UO_2 CONVERSION
AND FABRICATION SECTORS
OF THE COMMERCIAL FUEL CYCLE

January 1970

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By

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January 1, 1970

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ABSTRACT

Material measurement errors limit the capabilities of material accounting to detect material losses when physical inventory quantities are periodically compared to accounting balances. The measurement uncertainties in typical material balance systems of the low enriched UO_2 manufacturing facilities are characterized in this report in the form of general performance and general capability models.

The safeguards capabilities of material accounting can be equated in terms of the probability of detecting a loss of material in MF when material diversion actually occurs. An assessment is made of the detection capabilities of typical material balance systems of the UO_2 manufacturing cycle.

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INTRODUCTION

The development of domestic and international safeguards programs for special nuclear materials and the rapid growth of a commercial fuel cycle for nuclear power reactors have aroused new interest in the control capabilities of material balance accounting. The protection of nuclear materials against diversion to nonpeaceful applications is the major objective of safeguards programs. Material accounting systems indirectly detect diversion as losses of material when physical inventory quantities are compared to accounting balances. These differences are usually referred to as Material Unaccounted For (MUF). The occurrence of a MUF is not prima facie evidence of diversion because there are many causes for material imbalances. A loss of material indicated by MUF must be carefully investigated for cause before the occurrence of diversion can be substantiated or disclaimed.

OBJECTIVES

Material accounting records are subject to errors beyond the usual financial accounting experience because all material measurements are subject to some error. These measurement errors are an inherent cause of material imbalances. Because material accounting procedures cannot distinguish material losses from measurement errors, statistical procedures must be employed to assess objectively the significance of measurement errors and to test for material losses in MUF. The

characterization of the measurement uncertainties of **MUF** in the material accounting systems of typical low-enriched UO_2 manufacturing facilities is a major objective of this report.

The safeguards capabilities of material balance accounting to detect diversion can be equated in terms of the probability of detecting diversion as a loss of material in **MUF** when diversion actually occurs. Statistical alarm criteria can be established to detect losses of material in **MUF** which exceed the normal measurement uncertainties of a material balance system. The probability that the critical values of these tests will be exceeded when diversion actually occurs can be determined by statistical procedures for different amounts of diversion. The assessment of these capabilities for the low enriched UO_2 manufacturing facilities is the second objective of this report.

STUDY PLAN

A systems approach of analysis was chosen for this study to focus attention on the functional relationships within material balance systems. Because **MUF** is the product of all the activities in a material balance system, it seemed appropriate that the components of the system be studied in their whole environment rather than as individual parts. Although this approach tends to oversimplify the general analysis problem, it does delineate the major subproblems of material balance accounting and promotes the optimization of measurement systems.

The material balance models in this report were developed from composite data selected to represent what is typical of the industry rather than any particular facility or manufacturing operation. One set of models was designed to typify the general material balance performance of current industrial operations and material control practices. A second series was prepared to illustrate the existing technical capabilities for designing

material balance systems in an industrial environment. The open literature was searched extensively to acquire the necessary modeling information on process descriptions, material flow patterns, physical measurement data, and material balance performance.

A nominal uranium thruput of one ton per day and a nominal Uranium-235 enrichment of 3.0% were chosen as representative material values for the UO_2 facilities now in operation or under construction. To provide an insight into both the short and long-term capabilities of material balance accounting, time intervals of 3, 6, and 12 months were selected for study. No attempt was made to incorporate nonmeasurement errors and the effects of operator mistakes into the general models of this study. These errors can best be treated on an individual facility basis as variances to standard operating procedures.

SUMMARY AND CONCLUSIONS

Measurement errors inherently limit the safeguards capabilities of material balance accounting to detect diversion as losses of material in MUF. The identification of small losses of material for even short periods of time is difficult with current measurement systems. Sizable losses can occur with little probability of detection for material balance spans of one year or greater. Current performance can be upgraded significantly through better quality control and the adoption of improved measurement methods and physical inventory practices.

MEASUREMENT UNCERTAINTIES

The measurement uncertainties in a material balance system naturally increase with time as the flow of materials and the number of measurements increase in a facility. The relative growth of measurement uncertainties is smaller than that of material thruput because of the random occurrence of some

types of measurement errors. From the summary data shown in Tables 1 and 2, it can be seen that the measurement uncertainties in the general performance cases are three to four times greater than those of the general capability models for similar time periods. The conversion facilities have a significant advantage in material balance capabilities because of relatively small inventories and the great accuracy of the measurements provided by the Government on UF_6 feed materials. The systematic errors in material transfers and the random errors in physical inventories are the major causes of measurement uncertainties in all the UO_2 manufacturing facilities.

TABLE 1. A Summary of the Uranium Material Balance Measurement Uncertainties in the Basic UO_2 Manufacturing Facilities of the Low-Enriched Uranium Fuel Cycle
95% Confidence Level

	UO_2 Conversion lb (%)	UO_2 Fabrication lb (%)	UO_2 Integrated ^(a) lb (%)
<u>General Performance</u>			
3 months	1,340 (0.7)	2,530 (1.4)	2,787 (1.5)
6 months	1,800 (0.5)	2,894 (0.8)	3,036 (0.8)
12 months	2,999 (0.4)	4,031 (0.6)	3,874 (0.5)
<u>General Capability</u>			
3 months	262 (0.1)	632 (0.4)	698 (0.4)
6 months	472 (0.1)	796 (0.2)	803 (0.2)
12 months	915 (0.1)	1,252 (0.2)	1,127 (0.2)

Plant Assumptions: Nominal U Thruput 1 ton per day

Note: All the relative percentage values are based on nominal thruputs.

a. "Integrated^N means a combination of conversion and fabrication operations.

TABLE 2. A Summary of the Uranium-235 Material Balance Measurement Uncertainties in the Basic UO_2 Manufacturing Facilities of the Low-Enriched Uranium Fuel Cycle
95% Confidence Level

	UO ₂ Conversion kg (%)		UO ₂ Fabrication kg (%)		UO ₂ Integrated kg (%)	
<u>General Performance</u>						
3 months	28.2	(1.1)	45.0	(1.9)	48.1	(2.0)
6 months	41.4	(0.8)	57.6	(1.2)	56.6	(1.2)
12 months	72.5	(0.7)	91.4	(0.9)	81.8	(0.8)
<u>General Capability</u>						
3 months	7.0	(0.3)	13.3	(0.5)	13.2	(0.5)
6 months	12.7	(0.3)	19.1	(0.4)	17.0	(0.3)
12 months	24.7	(0.3)	33.5	(0.3)	27.3	(0.3)
Plant Assumptions:	Nominal U Thruput		1 ton per day			
	U-235 Enrichment		3.0%			

Note: All the relative percentage values are based on nominal uranium thruputs.

Systematic Errors

The systematic errors in material transfers control the long-term material balance uncertainties of the UO_2 manufacturing facilities for periods of one year and greater. These errors are also significant, if not controlling, in the intermediate time spans. The laboratory analytical assays on UO_2 product samples are the major source of systematic errors in the uranium transfers of all UO_2 facilities. Systematic errors also dominate the measurement uncertainties in reactor cores, as illustrated in Table 3. Better instrument calibration and analytical standards programs are required to effect an improvement in these critical areas of safeguards control.

TABLE 3. A Summary of the Measurement Uncertainties in a 100-Ton Low-Enriched UO₂ Reactor Fuel Core

	Uranium lb (%)	Uranium-235 kg (%)
<u>General Performance</u>		
Systematic	560 (0.32)	14.0 (0.59)
Random	35 (0.02)	4.3 (0.18)
Total	561 (0.32)	14.6 (0.62)
<u>General Capability</u>		
Systematic	190 (0.11)	5.5 (0.23)
Random	18 (0.01)	1.0 (0.04)
Total	191 (0.11)	5.6 (0.23)
Assumption:	Uranium-235 enrichment.	3.0%

Random Errors

Random errors are particularly important to the determination of the short-term measurement capabilities of material balance systems. For time spans greater than one year, random errors become relatively insignificant to overall measurement performance. Physical inventories are the major source of random errors in material balance systems. The scrap inventories of the fabrication operations contribute greatly to the total inventory uncertainty of fabrication plants. Since relatively small quantities of scrap are generated in the ADU conversion operations, the in-process inventories are the major source of random errors at the conversion facilities. Some improvement can be achieved through the upgrading of sampling and analytical methods and practices. However, final success often depends upon the reduction of inventory size and the placement of materials in preferred physical forms and measurement locations.

DIVERSION DETECTION CAPABILITIES

The probability of detecting a loss of material by material balance accounting is dependent upon the size of the loss, the measurement uncertainty of MUF, and the risk assumed for mistaking measurement errors for material losses in the statistical test employed. High risks for the latter, large material losses, and small measurement uncertainties all enhance the probability of detecting material losses. The size of the measurement uncertainties of MUF determines the minimum threshold for detecting a loss of material under specified test conditions.

Detection Probabilities

Material balance systems can be designed under current technology to detect Uranium-235 losses of 15 kg with a sizable degree of certainty for a material accounting period of three months and 40 kg for a period of 12 months. However, material losses of twice these quantities cannot be detected with equivalent degrees of certainty through current material accounting systems. Examples of typical plant capabilities for detecting diversion as material losses are shown in Tables 4 and 5. The large variations in detection probabilities which are visible between the capability and performance models are attributable to the differences in measurement uncertainties displayed in Tables 1 and 2. The UO_2 conversion facilities have the greatest capability for detecting material losses because their measurement uncertainties are smallest. Only minor differences in detection capabilities are discernible between the fuel fabrication facilities and the larger integrated conversion-fabrication complexes.

Detection Thresholds

The growth of measurement uncertainties in time poses a serious safeguards problem because a series of small material

TABLE 4. The Probability of Detecting Diversion as Material Losses
in Low-Enriched UO_2 Manufacturing Facilities
Material Balance Span of One Year

<u>Amount of Diversion</u>	<u>General Performance Model</u>			<u>General Capability Model</u>		
	<u>Conversion Fabrication Integrated</u>			<u>Conversion Fabrication Integrated</u>		
	<u>Probability, %</u>			<u>Probability, %</u>		
<u>Uranium-235, kg</u>						
15	11	10	10	34	23	30
25	17	15	15	66	44	58
40	30	23	26	95	78	90
60	51	39	43	100	98	100
80	71	57	62	100	100	100
∞ <u>Total Uranium, 1b</u>						
1100	18	14	15	78	56	62
1800	34	23	24	99	89	94
2900	62	43	46	100	100	100
4400	91	71	74	100	100	100
5900	99	91	92	100	100	100

Probability levels greater than 99.5% are shown as 100%.

Assumptions: Nominal U Thruput 1 ton/day
 Nominal U-235 Enrichment 3%
 Risk of Type I Error 5%

TABLE 5. The Probability of Detecting Diversion as Material Losses
in Low-Enriched UO₂ Manufacturing Facilities
Material Balance Span of Three Months

<u>Amount of Diversion</u>	<u>General Performance Model</u>			<u>General Capability Model</u>		
	<u>Conversion</u>	<u>Fabrication</u>	<u>Integrated</u>	<u>Conversion</u>	<u>Fabrication</u>	<u>Integrated</u>
	<u>Probability, %</u>			<u>Probability, %</u>		
<u>Uranium-235, kg</u>						
15	29	17	17	100	74	75
25	57	31	29	100	98	99
40	88	56	52	100	100	100
60	100	84	81	100	100	100
80	100	97	96	100	100	100
<u>Total Uranium, lb</u>						
1100	50	22	20	100	96	94
1800	86	42	37	100	100	100
2900	99	74	68	100	100	100
4400	100	96	94	100	100	100
5900	100	100	100	100	100	100

Probability levels greater than 99.5% are shown as 100%.

Assumptions: Nominal U Throughput 1 ton/day
Nominal U-235 Enrichment 3%
Risk of Type I Error 5%

withdrawals can be made with little danger of detection through material accounting. Cumulatively, these removals can become a sizable diversion of material. In this regard, detection thresholds are often equated in terms of the smallest loss of material that can be detected at a given probability level. An example of the detection thresholds of typical material balance systems in the UO_2 manufacturing cycle is shown in Table 6. The relationships which were described in the previous paragraph are again apparent. The detection thresholds of current material balance systems can be lowered approximately 75% under general capability conditions. Nonetheless, withdrawals of approximately 5 kg of Uranium-235 per calendar quarter would still be possible with only a small probability of detection under these improved conditions.

The detection thresholds of the accounting systems for total uranium in terms of relative thruput are 20 to 50% lower than those of the Uranium-235 isotope. This greater detection sensitivity should be invaluable to the early detection and verification of Uranium-235 losses in facilities which operate within narrow isotopic ranges.

DISCUSSION

DESCRIPTION OF BASIC MATERIAL BALANCE CHARACTERISTICS

Most of the pressurized and boiling water reactors which are to be utilized for power generation within the United States during the next 10 years will be fueled with ceramic UO_2 pellets contained inside metallic fuel rods. The new pressurized water reactors will have uranium cores ranging from 50 to 100 tons of UO_2 while the boiling water reactors will have cores varying from 100 to 150 tons of UO_2 . Isotopic enrichments will vary from 2 to 5% for Uranium-235. At the present time, it appears that typical fuels manufacturing facilities will have annual production capacities ranging from 350 to

**TABLE 6. Thresholds for Detecting Uranium Losses
at Low-Enriched UO₂ Manufacturing
Facilities**

Probability Level of 80%

	UO ₂ Conversion	UO ₂ Fabrication	UO ₂ Integrated
	Uranium, lb (%) (a)		
<u>General Performance</u>			
3 months	1,700 (0.9)	3,100 (1.7)	3,500 (1.9)
6 months	2,200 (0.6)	3,500 (1.0)	3,800 (1.1)
12 months	3,700 (0.5)	5,000 (0.7)	4,800 (0.7)
<u>General Capability</u>			
3 months	300 (0.2)	800 (0.4)	900 (0.5)
6 months	600 (0.2)	1,100 (0.3)	1,000 (0.3)
12 months	1,100 (0.2)	1,500 (0.2)	1,400 (0.2)
	Uranium-235, kg (%)		
<u>General Performance</u>			
3 months	35 (1.4)	56 (2.3)	59 (2.4)
6 months	51 (1.0)	71 (1.5)	69 (1.4)
12 months	90 (0.9)	112 (1.2)	102 (1.0)
<u>General Capability</u>			
3 months	8 (0.3)	16 (0.7)	16 (0.7)
6 months	16 (0.3)	24 (0.5)	21 (0.4)
12 months	31 (0.3)	42 (0.4)	34 (0.3)
Assumptions:			
Nominal U Thruput	1 ton/day		
Nominal U-235 Enrichment	3%		
Risk of Type I Error	5%		

a. All the percentage values are related to plant material thruputs.

450 tons of uranium. Representative material flows, inventories, and measurement systems are described for the material balance systems of typical UO_2 production facilities in the power reactor fuel cycle.

Basic Manufacturing Processes

The ammonium diuranate (ADU) conversion and the sintered-pellet fabrication processes are expected to be used extensively for UO_2 fuels production. Material flow sheets for these processes are illustrated in Figures 1 and 2 and briefly described in the following paragraphs. Material losses are currently reported to be in the vicinity of 1.0% of uranium receipts for both processes. Approximately half of these losses can frequently be identified as measured waste discards. The other half is usually attributed to process losses of an unmeasured nature which appear as MUF in the material accounting system. In reality, unmeasured uranium holdup in plant equipment, and measurement biases in material transfers are common causes of material shortages in MUF.

The ADU Conversion Process

The ADU process which converts UF_6 to ceramic grade UO_2 powder is a semi-continuous train of unit operations including the following steps.

- Hydrolyze UF_6 in water or steam to produce uranyl fluoride (UO_2F_2).
- React uranyl fluoride with ammonia or ammonium hydroxide to form ADU.
- Centrifuge and/or filter the ADU.
- Calcine and chemically reduce the ADU to yield ceramic grade UO_2 powder.
- Mill and prepare the UO_2 for fabrication or offsite shipment.
- Recover useable scrap for recycle and dispose of unrecoverable waste.

FIGURE 1. A General Performance Flowsheet of the ADU Conversion Operation

FIGURE 2. A General Performance Flowsheet of the UO_2 Fabrication Operation

Occasionally, some uranyl fluoride solution and calciner powder may be withdrawn from the operation to fill special job orders. The ADU process also has potential application for the future production of mixed PuO_2 - UO_2 fuels for breeder reactors.

The UO_2 Fabrication Process

The production of ceramic UO_2 pellets can be characterized by the following unit operations:

- Prepare the UO_2 powder for cold pressing.
- Cold press the UO_2 powder into green pellets.
- Sinter the pellets in a furnace.
- Grind the pellets to dimensional specifications and dry.
- Inspect and prepare the UO_2 pellets for fuel rod loading or offsite shipment.

The loading and assembling of fuel rods into fuel bundles are integral steps in many, but not all, fabrication operations. These two operations are included in the basic models of this report.

Measurement Capabilities

All physical measurements are subject to errors because of variations in environmental conditions and operator performance. Some of these errors occur in a random manner while others vary in a systematic fashion. The variability incurred in reading an instrument is an example of random errors. This type of error can be estimated from the results of a series of repetitive measurements. Calibration errors are an example of systematic errors. This more persistent type of error can be determined accurately when reference standards are available for testing and controlling measurement performance. Because standards are seldom available for all the components of a measurement process, it is often necessary to estimate reasonable bounds for the systematic errors of some measurement components. The random and systematic errors of individual

material measurements can be combined statistically into statements of total measurement uncertainty for complete material balance systems. Based upon the detailed studies of this review, measurement systems are described for the typical UO_2 manufacturing processes and measurement uncertainties are characterized for individual measurement points.

UF₆ Receipt Measurements

The measurement of UF_6 in standard shipping containers has been thoroughly investigated at the AEC gaseous diffusion plants. Their findings are used extensively in the postulations made for UF_6 measurements in the study models. Complete verification of the AEC shipping data is uncommon at the UO_2 production facilities. Commercial processors frequently check-weigh the cylinders but none routinely verify the assay values.

Weighing Capabilities. Precisions of ± 1 lb and ± 2 lb are frequently quoted for weighing the large UF_6 cylinders at the AEC diffusion plants. Sophisticated scale maintenance and measurement quality control programs are required to achieve such levels of performance. Relative precisions in the range of 0.1 to 0.2% are more typical of the performance achieved at commercial facilities. Systematic errors below 0.1% are often quoted for weighing operations performed under controlled conditions.

Sampling. The sampling of UF_6 is a very specialized operation in which care must be exercised to avoid the loss of volatile impurities and to prevent foreign impurity contamination. Sampling errors are very small for pure UF_6 . When purity levels fall to 99.5%, or lower, sampling errors are reported to be as large as 0.1 to 0.15%. Systematic errors are normally maintained below 0.1%. The AEC diffusion plants frequently utilize composite sampling plans for cylinder shipments to commercial sites.

Uranium Assays. Total uranium is usually determined by conventional gravimetric methods having reported precisions ranging between 0.03 and 0.12% of assay values. Systematic errors as large as 0.15% are quoted in the literature. Isotopic assays are normally performed at the AEC sites with electron bombardment mass spectrometers. Precisions in the range of 0.04 to 0.15% are commonly reported for Uranium-235. Systematic errors are small.

Combined Capabilities. Conventional error propagation techniques are used to combine the weighing, sampling, and analytical components of error into estimates of total measurement capabilities, as summarized in Table 7. The Uranium-235 measurement uncertainties are always larger than those of total uranium because the errors of the latter are included in the determination of the Uranium-235 uncertainties.

TABLE 7. A Summary of the Basic Components of Error in a Typical UF₆ Cylinder Measurement, 95% Confidence Level

<u>-Component</u>	<u>General Performance</u>		<u>General Capability</u>	
	<u>Systematic,</u> <u>%</u>	<u>Random,</u> <u>%</u>	<u>Systematic,</u> <u>%</u>	<u>Random,</u> <u>%</u>
Net Weight	0.10	0.20	0.05	0.06
Sampling (Uranium)	0.10	0.12	0.02	0.07
Sampling (Uranium-235)	0.03	0.06	0.02	0.04
Uranium Assay	0.15	0.12	0.03	0.06
Uranium-235 Assay	0.30	0.50	0.08	0.11
Total Uranium	0.21	0.26	0.06	0.11
Total Uranium-235	0.36	0.56	0.10	0.15

UF₆ Heels

The strategy to be employed by commercial processors in the disposal of cylinder heels is not clear at the present time. The heels may be left in the cylinders for return to the diffusion plants. As another alternative, the heels may be washed from the cylinders and cycled to scrap recovery. Some form of measurement is required in either case. The material balance significance of the measurement errors is limited by the relatively small quantities of uranium in the heels.

Direct Measurement. The application of the uranium assay values of a cylinder to the net weight of the heel is the most direct approach of heel accounting. The representativeness of the assay values should be tested periodically because heels can become collection points for corrosion products and foreign impurities. The following measurement errors are considered to be typical of this measurement procedure:

	<u>General Performance</u>		<u>General Capability</u>	
	<u>Systematic,</u> <u>%</u>	<u>Random,</u> <u>%</u>	<u>Systematic,</u> <u>%</u>	<u>Random,</u> <u>%</u>
Total uranium	33	66	16	26
Uranium-235	33	66	16	26

Indirect Measurement. The measurement of the uranium contained in the cylinder wash water is an indirect approach of heel measurement. Undissolved solids are reported to be a problem in the sampling of the wash solutions. The following errors are typical of this measurement approach:

	<u>General Performance</u>		<u>General Capability</u>	
	<u>Systematic,</u> <u>%</u>	<u>Random,</u> <u>%</u>	<u>Systematic,</u> <u>%</u>	<u>Random,</u> <u>%</u>
Total Uranium	12	30	1.2	7.0
Uranium-235	12	30	1.3	7.0

UO₂ Measurements

Similar methods of measurement are used for the powder and the pellet forms of uranium dioxide. Lot sizes vary extensively between processing facilities. The measurement of UO₂ pellets is especially important to safeguards because it is the final direct measurement of uranium prior to fuel cladding and reactor irradiation.

Weighing Capabilities. Systematic and random errors smaller than 0.1% are frequently quoted for a single weight determination. Pellet weights are directly determined while net weight procedures are used for UO₂ powder in containers. Operator errors must be carefully controlled to achieve high standards of performance.

Sampling. No major sampling problems are encountered in the measurement of UO₂ product materials. This is especially true of the pellets for which sampling errors are considered to be negligible. Errors as large as 0.12% are reported for UO₂ powder samples.

Uranium Assay. Several analytical procedures are utilized within the industry for the determination of the uranium content of UO₂ products. The gravimetric and the chemical titration approaches of direct analysis are frequently employed to acquire the most accurate results. Both the systematic and random errors of these methods are reported to be no greater than 0.1% relative to the assay values. Another approach using O/U and metal impurity analyses to determine uranium indirectly on a by-difference basis is sometimes utilized in commercial facilities. Systematic errors may be as large as 0.3% and random errors 0.4% for this measurement approach.

Isotopic Assay. Both optical and mass spectrometry are commonly utilized for the isotopic analysis of uranium contained in UO₂ powders. The former is most frequently used for

process control purposes and the latter for special requests for high precision work. A third approach of using the isotopic values of UF_6 receipts to estimate the shipping values for UO_2 powder is also utilized. The precision differences of the two direct analytical methods are sizable. For Uranium-235 enrichments in the range of 2 to 5%, the precision of a single optical spectrometric result is frequently reported to fall within the range of 2 to 3% of the reported value. The precision of a mass spectrometric result is reported to be approximately 0.5%, using a surface ionization source unit. Biases should not exceed 0.2% for the mass spectrometric method and 0.5% for the optical method. No accuracy or precision data are readily available on the utilization of the UF_6 isotopic receipt data.

Reactor Core Capabilities. The individual components of error and the combined uncertainties of a UO_2 measurement are summarized in Table 8. On the basis of these capabilities, the relative measurement uncertainties of a reactor core containing 100 tons of uranium dioxide pellets are estimated to be as follows:

	<u>General Performance</u>		<u>General Capability</u>	
	<u>Systematic,</u> <u>%</u>	<u>Random,</u> <u>%</u>	<u>Systematic,</u> <u>%</u>	<u>Random,</u> <u>%</u>
Total Uranium	0.32	0.02	0.11	0.01
Uranium-235	0.59	0.18	0.23	0.04

The material significance of these values can best be seen when the relative errors are converted to absolute quantities of uranium. Assuming the basic isotopic enrichment of 3%, the following fuel core uncertainty estimates are obtained:

	<u>General Performance</u>		<u>General Capability</u>	
	<u>Systematic</u>	<u>Random</u>	<u>Systematic</u>	<u>Random</u>
Total Uranium, lb	560	35	190	18
Uranium-235, kg	14	4.3	5.5	1.0

The analytical assay uncertainties are the key factors in the determination of overall performance.

TABLE 8. A Summary of the Basic Components of Error in Typical UO₂ Product Measurements, 95% Confidence Level

<u>Component</u>	<u>General Performance</u>		<u>General Capability</u>	
	<u>Systematic,</u> <u>%</u>	<u>Random,</u> <u>%</u>	<u>Systematic,</u> <u>%</u>	<u>Random,</u> <u>%</u>
Net Weight (powder)	0.10	0.14	0.05	0.07
Net Weight (pellets)	0.10	0.10	0.05	0.05
Sampling (powder) ^(a)	0.07	0.10	0.05	0.06
Uranium Assay	0.30	0.40	0.09	0.08
Uranium-235 Assay	0.50	2.50	0.20	0.50
Total Uranium:				
Powder	0.32	0.43	0.11	0.12
Pellets	0.32	0.41	0.11	0.10
Total Uranium-235:				
Powder	0.59	2.53	0.23	0.51
Pellets	0.59	2.53	0.23	0.51

a. Sampling errors for UO₂ pellets are considered to be negligible.

Waste Measurements

The waste streams of the UO₂ production operations are grouped into three categories for measurement review, (1) liquid wastes, (2) process residues, and (3) solid wastes. The material balance significance of the relatively large measurement uncertainties associated with these materials is limited by the small quantities of uranium contained therein.

Volume Capabilities. Flowmeters and differential pressure instruments are utilized frequently to measure the volume of liquid wastes with precisions ranging from 0.5 to 9%. Systematic errors are reported to be in the range of 0.3 to 3.0%. Carefully maintained quality control programs are required to achieve the lower values.

Weighing Capabilities. Process residues are often weighed for accountability purposes with uncertainties ranging from 0.1 to 0.4%. The weighing of residues and solid wastes is unnecessary when nondestructive bulk measurement methods are employed for uranium.

Sampling. The heterogeneous nature of waste materials severely limits sampling capabilities. Because of the large relative errors in many waste assays, it is often impossible to distinguish between the sampling and analytical components of error. Random errors of sampling frequently fall in the range of 10 to 40% while systematic errors range between 5 and 15%.

Assay Capabilities. Various colorimetric methods of analysis are utilized to determine the uranium contents of waste samples. Fluorometric techniques are sometimes used for the analysis of trace quantities of uranium. Precisions in the range of 3 to 15% are reported for the colorimetric methods. Systematic errors as large as 5% are not uncommon.

The Uranium-235 content of wastes is seldom determined by direct sampling-analytical procedures but is usually estimated from isotopic compositions of parent process streams. These estimates are subject to extensive error when materials of more than one isotopic enrichment are simultaneously used on a production line. Analytical capabilities better than 0.6% are possible for direct assay methods.

Bulk Measurements. Bulk wastes are frequently scanned with gamma spectrometers to acquire accountability estimates

of the contained uranium. Precisions ranging from 25 to 100% and systematic errors ranging from 5 to 20% are often reported for this type of measurement.

Combined Capabilities. The waste measurement uncertainties which are used in the material balance models of this study are summarized in Table 9.

TABLE 9. Typical Waste Measurement Uncertainties in the Low-Enriched UO₂ Manufacturing Industry, 95% Confidence Level

	<u>General Performance</u>		<u>General Capability</u>	
	Systematic, %	Random, %	Systematic, %	Random, %
<u>Liquid Waste</u>				
Volume	2.0	7.0	0.3	0.3
Sampling	15	30	5	10
Uranium	5	12	2	4
Uranium-235	10	30	0.2	0.6
Total Uranium	16	33	5.4	11
Total Uranium-235	19	44	5.4	11
<u>Process Residue</u>				
Weight	0.2	0.4	0.1	0.2
Sampling	15	30	5	24
Uranium	10	40	5	24
Uranium-235	10	30	0.2	0.6
Total Uranium	18	50	7.1	26
Total Uranium-235	21	58	7.1	26
<u>Solid Waste</u>				
Bulk Uranium	20	70	10	30
Bulk Uranium-235	25	74	12	36

Atmospheric Losses

The small quantities of uranium regularly lost to the atmosphere do not warrant separate consideration in this report. Nonetheless, this type of loss can be sizable and significant if it is not carefully controlled through

monitoring programs. This is especially true at the initial operating phase of a facility.

PHYSICAL INVENTORIES

Composite physical inventory values are presented in the study models to complete the material balance cycle. Large variations occur in inventory quantities and measurement uncertainties between and within facilities. Inventory location, the physical nature of the material, and physical inventory procedures all contribute to the accuracy and precision of inventories. For the sake of simplicity, the same inventory quantities are used for both the beginning and ending inventories of a material balance.

Inventory Conditions

Inventory preparations frequently control the overall performance of physical inventories. The minimization of inventory quantities and the placement of materials in preferred measurement locations reduce the measurement uncertainties of physical inventories significantly. Shutdown-cleanout inventories are generally more accurate than those performed under regular operating conditions. For modeling purposes, a plant shutdown inventory with moderate preparation is utilized in the general performance models. A shutdown-cleanout inventory is used for the general capability models. Materials are assumed to be in shutdown locations for the general performance cases and in preferred measurement locations for the general capability cases.

Measurement Capabilities

Sizable portions of many physical inventories are recorded on the basis of prior process measurements. Verifications of gross weights are sometimes performed. The isotopic Uranium-235 contents of inventories are almost always determined from prior process measurements and engineering estimates. A semi-measured

inventory is employed in the general performance models and a measured inventory is presented in the general capability models. Typical physical inventory quantities and measurement uncertainties are summarized in Table 10 for the UO_2 processing facilities.

Scrap Accumulation

The measurement uncertainties associated with scrap inventories are almost always significant to the determination of the total uncertainty of physical inventories. Even though very moderate levels of accumulation and conservative estimates of error are postulated for the study models, the errors in scrap measurements are sizable. The conclusion is clear that the size of the scrap inventory and the accuracy of scrap measurements must be controlled carefully for the purpose of acquiring accurate physical inventory results.

THE MEASUREMENT UNCERTAINTIES OF MUF

The sensitivity of a material balance system to detect material losses is directly related to the measurement uncertainties in the system. From a safeguards viewpoint, these uncertainties indeed determine the threshold of detection below which the occurrence of material losses cannot be uncovered by the material accounting process. An understanding of the interrelationships of the components of error in MUF is essential to the design of optimum safeguards systems.

Basic Approach

Conventional Gaussian propagation techniques are used to combine the measurement errors of individual accounting points and physical inventories into overall statements of uncertainty for MUF. Complete independency of measurement errors is assumed for all the material accounting entries except those which are based upon item counts and prior measurements. In the latter instances, perfect correlation is assumed. Time periods of

TABLE 10. Typical Physical, Inventory Quantities and Measurement Errors
at the Low-Enriched UO_2 Manufacturing Facilities,
95% Confidence Level

		<u>General Performance</u>		<u>General Capability</u>	
		<u>U, lb</u>	<u>U-235, kg</u>	<u>U, lb</u>	<u>U-235, kg</u>
UF_6 Storage:	quantity	8,000	109	8,000	109
	systematic error	17	0.4	5	0.1
	random error	12	0.6	10	0.2
UF_6 - UO_2 Process:	quantity	30,000	408	30,000	408
	systematic error	440	7.3	42	1.0
	random error	640	12.6	60	1.4
Pellet Manufactur- ing:	quantity	30,000	408	6,000	82
	systematic error	390	6.4	29	0.5
	random error	810	14.4	76	1.4
Rods and Bundles:	quantity	120,000	1,633	150,000	2,041
	systematic error	380	9.6	165	4.7
	random error	44	3.8	12	0.8
Scrap Storage: (Conversion)	quantity	2,000	27	1,200	16
	systematic error	56	1.1	20	0.3
	random error	200	2.8	48	1.4
Scrap Storage: (Fabrication)	quantity	8,000	109	3,500	48
	systematic error	740	14.4	240	5.5
	random error	1,130	17.6	300	4.6
Scrap Processing:	quantity	2,000	27	500	7
	systematic error	56	1.0	25	0.5
	random error	160	2.6	80	1.4

3, 6, and 12 months are used for the study of the short, intermediate, and long-term effects of measurement uncertainties on the accuracy of material balance results.

Overall System Uncertainties

The measurement uncertainties in MUF for the low enriched UO_2 manufacturing facilities are summarized in Table 11 and described in detail in Appendix B. In all the UO_2 facilities, it can be seen that current material balance uncertainties are sizable and of safeguards significance. Present levels of performance can be improved several fold through the use of better inventory practices and measurement methods. Extraordinary action would be required to reduce significantly the uncertainties of a Uranium-235 material balance below 0.3% of material thruput. Since measurement uncertainties are related in time to material thruput, the overall uncertainty of material balance results can, to a degree, be controlled through the regulation of the time span between physical inventories.

Systematic and Random Error Comparisons

A deeper insight into measurement uncertainties can be acquired by splitting the overall material balance uncertainty values into their systematic and random components of error, as illustrated in Table 12. In absolute quantities of material, the systematic errors grow significantly and regularly with time while the random errors increase very slowly with time. Consequently, the growth of measurement uncertainties in MUF is caused primarily by systematic errors. Random errors affect the measurement uncertainties of MF significantly for material balance periods of short and intermediate time durations. For material balance spans of one year and more, the systematic errors completely dominate overall measurement performance.

TABLE 11. A Summary of the Material Balance Measurement Uncertainties in Typical Low-Enriched UO₂ Manufacturing Facilities, (a)
95% Confidence Level

	UO ₂ <u>Conversion</u>	UO ₂ <u>Fabrication</u>	UO ₂ <u>Integrated</u>
	<u>Uranium, lb (%)</u>		
<u>General Performance</u>			
3 months	1,340 (0.7)	2,530 (1.4)	2,790 (1.5)
6 months	1,800 (0.5)	2,890 (0.8)	3,040 (0.8)
12 months	3,000 (0.4)	4,030 (0.6)	3,870 (0.5)
<u>General Capability</u>			
3 months	260 (0.1)	630 (0.4)	700 (0.4)
6 months	470 (0.1)	800 (0.2)	800 (0.2)
12 months	920 (0.1)	1,250 (0.2)	1,130 (0.2)
	<u>Uranium-235, kg (%)</u>		
<u>General Performance</u>			
3 months	28 (1.1)	45 (1.9)	48 (2.0)
6 months	41 (0.8)	58 (1.2)	57 (1.2)
12 months	72 (0.7)	91 (0.9)	82 (0.8)
<u>General Capability</u>			
3 months	7 (0.3)	13 (0.5)	13 (0.5)
6 months	13 (0.3)	19 (0.4)	17 (0.3)
12 months	25 (0.3)	34 (0.3)	27 (0.3)

() All parenthetical percentages are related to plant thruput.

a. Assumptions: Nominal uranium thruput 1 ton/day
Nominal U-235 enrichment 3%

TABLE 12 A Comparison of the Systematic and Random Components of Measurement Error in MUF at the Low-Enriched UO₂ Manufacturing Facilities, (a)
95% Confidence Level

	UO ₂ <u>Conversion</u>		UO ₂ <u>Fabrication</u>		UO ₂ <u>Integrated</u>	
	<u>Systematic</u>	<u>Random</u>	<u>Systematic</u>	<u>Random</u>	<u>Systematic</u>	<u>Random</u>
<u>Uranium, 1b</u>						
<u>General Performance</u>						
3 Months	940	960	1,440	2,080	1,550	2,320
6 Months	1,520	970	2,010	2,080	1,960	2,320
12 Months	2,830	980	3,450	2,030	3,100	2,330
<u>General Capability</u>						
3 Months	240	110	440	450	460	520
6 Months	460	120	660	450	610	520
12 Months	910	130	1,170	450	990	520
<u>Uranium-235, 1d</u>						
<u>General Performance</u>						
3 months	20	20	30	34	30	37
6 months	35	21	46	35	42	38
12 months	68	24	84	36	72	39
<u>General Capability</u>						
3 months	6	3	11	7	10	acorn
6 months	12	3	18	7	15	
12 months	24	4	33	8	26	

a. Assumptions: Nominal uranium thruput 1 ton/day
Nominal U-235 enrichment 3%

Physical Inventory and Material Transfer Comparisons

The inventory uncertainties of MUF remain relatively static in time because each material balance contains solely a beginning and an ending inventory, regardless of the time span of the accounting period. In contrast, the measurement uncertainties of material transfers grow progressively in time as the number of transactions increase during a material balance period. Because of this relationship, the relative importance of inventory uncertainties naturally decreases with time, as illustrated in Table 13. Measurement uncertainties in physical inventories frequently play a major role in the determination of measurement performance for material balances of short time spans or small material thruputs. The measurement uncertainties of the long-term material balance position of a facility are usually dominated by the cumulative errors in material transfer measurements.

Physical Inventories

Most of the random errors in the material balance of a UO_2 production facility are generated in physical inventory measurements and estimates, as illustrated in Table 14. Physical inventory errors usually affect the fabrication sites of the low enriched UO_2 fuel cycle more than the conversion plants because inventory quantities are larger. The evidence is clear that significant reductions in the random errors of MUF can only be implemented through the improvement of physical inventory performance. As the time span between physical inventories is reduced, more attention must be directed to the control of inventory errors.

Major Locations of Error

Scrap inventories are usually the largest source of measurement error in physical inventories. The in-process inventories are normally the second largest source of error. A

TABLE 13. The Comparative **Material** Balance Significance of Measurement Errors in Physical Inventories and Material Transfers, Relative Percent

	UO_2 <u>Conversion</u>		UO_2 <u>Fabrication</u>		UO_2 <u>Integrated</u>	
	<u>Inventory</u>	<u>Transfer</u>	<u>Inventory</u>	<u>Transfer</u>	<u>Inventory</u>	<u>Transfer</u>
<u>Uranium</u>						
<u>General Performance</u>						
3 months	72	28	90	10	94	6
6 months	40	60	68	32	79	21
12 months	14	86	35	65	48	52
<u>General Capability</u>						
3 months	24	76	81	19	89	11
6 months	7	93	51	49	67	33
12 months	2	98	21	79	34	66
<u>Uranium-235</u>						
<u>General Performance</u>						
3 months	57	43	75	25	86	14
6 months	26	74	47	53	62	38
12 months	9	91	19	81	30	70
<u>General Capability</u>						
3 months	21	79	64	36	77	23
6 months	6	94	31	69	47	53
12 months	2	98	10	90	18	82

Note: Percentage values represent fractional parts of the total measurement variance.

TABLE 14. The Relative Contribution of Physical Inventory Errors to the Total Random Component of Variance of MUF, Relative Percent

	UO ₂		UO ₂		UO ₂	
	<u>Conversion</u>		<u>Fabrication</u>		<u>Integrated</u>	
	<u>U</u>	<u>U-235</u>	<u>U</u>	<u>U-235</u>	<u>U</u>	<u>U-235</u>
<u>General Performance</u>						
3 months	98	85	100	94	100	98
6 months	97	74	100	89	99	96
12 months	94	58	99	80	99	91
<u>General Capability</u>						
3 months	92	89	100	96	99	98
6 months	85	78	100	94	99	95
12 months	72	65	99	89	98	93

Note: All percentages are rounded to the nearest whole number.

reversal of this ranking is occasionally observed when the scrap generation rate of a unit operation is small. Both types of inventories are dominated by random errors. The feed storage inventories seldom contribute errors in significant quantities to materially affect the final outcome of MUF. When the intermediate and final product inventories contain extremely large quantities of material, the systematic errors of measurement are sizable and sometimes of significance to the determination of overall material balance uncertainty. In contrast to the scrap and the in-process inventories, the random errors of the product storage inventories are relatively small and inconsequential.

Inventory Taking

Physical inventories in the processing and the scrap storage areas of the manufacturing facilities are regularly subject to extensive error because of execution mistakes and the inaccessibility and incompatibility of the material to physical

measurement. The implementation of measurement programs to cover these areas adequately are frequently considered to be impractical. Better inventory planning, scheduling, and preparation are required.

The standardization of inventory procedures and the proper training of personnel are important to the control of errors attributable to item omissions, counting mistakes, identification and recording errors, and the improper application of measurement procedures and factors. In a different sense, the standardization of inventory procedures enhances the by-difference cancelling of measurement biases which are common to both the beginning and the ending inventories of a material balance. Consistency in inventory-taking plays an important role in inventory performance.

Preferred Inventory Position

The location of material on inventory directly affects measurement uncertainties in physical inventories because sampling and measurement capabilities vary widely between process vessels, storage containers, and material forms. The best inventory measurements are usually acquired at the routine product measurement and process control points in the processing system. In the inventory models of this report, the measurement uncertainty of a physical inventory can be varied several fold by changing the locations of material. Thus, the positioning of material in preferred measurement locations is an important factor in the determination of the measurement uncertainty of physical inventories.

Inventory Size

A reduction of inventory size is frequently required to attain the desired control of measurement uncertainties in physical inventories and MUF. This is especially true for those portions of the in-process and scrap inventories which

are not readily accessible or amenable to good measurements. The emptying and cleaning of process vessels, equipment, and hoods can often alleviate the in-process problems. The fast recovery and recycling of scrap materials are important to the reduction of inventory uncertainties. In the study models, approximately 70% of the reduction in inventory uncertainties between the general performance and capability cases is the result of reductions in inventory size. The measurement uncertainties of scrap in the fabrication shops are much larger than those of the conversion plants because the scrap generation and accumulation rates of the fabrication processes are larger. The control of the inventory size of scrap is especially important to the control of inventory uncertainties in the fabrication operations.

Inventory Form

The conversion of scrap to measurable forms of material for storage may be required in some instances to achieve necessary levels of control. A several-fold improvement in measurement accuracy and precision can often be achieved through this procedure.

Material Transfers

The systematic errors which dominate the long-term measurement uncertainties of material accounting are associated primarily with material transfer measurements, as illustrated in Table 15. The control of systematic errors in the external material transactions of nuclear facilities is also necessary to prevent the shifting of MUF's from one facility to another in multi-facility complexes.

TABLE 15. The Relative Contribution of Measurement Errors in Material Transfers to the Total Systematic Component of Variance of MUF, Relative Percent

	UO_2		UO_2		UO_2	
	<u>Conversion</u>		<u>Fabrication</u>		<u>Integrated</u>	
	<u>U</u>	<u>U-235</u>	<u>U</u>	<u>U-235</u>	<u>U</u>	<u>U-235</u>
<u>General Performance</u>						
3 months	55	72	31	45	20	32
6 months	83	91	65	77	50	65
12 months	95	98	88	93	80	88
<u>General Capability</u>						
3 months	92	94	40	50	25	35
6 months	98	98	72	80	57	69
12 months	99	100	91	94	84	90

Note: All percentages are rounded to the nearest whole number.

Locations of Error

A breakdown of the systematic components of error in material transfers shows clearly that the measurement of UO_2 product materials is the key factor in the control of these errors, as illustrated in Table 16. Furthermore the detailed measurement statistics of this review indicate that the analytical components of error are the major sources of systematic error in the UO_2 measurements. Thus, the control of systematic errors in the laboratory analysis of UO_2 product materials is vital to safeguards control programs.

The systematic errors in the UF_6 transfer measurements are significant but of secondary importance to the overall control of systematic errors in material transfers. The small quantities of uranium measured in waste discards limit the relative importance of the systematic errors in waste measurements. Nonetheless, biases in these measurements must still be controlled carefully to avoid systematic material balance losses of material.

TABLE 16. The Relative Contribution of the Major Transfer Measurements to the Total Systematic Error in Material Transfers

	<u>UF</u> Receipts		<u>UO₂</u> Powder		<u>UO₂</u> Pellets		Waste Discards	
	<u>U</u>	<u>U - 235</u>	<u>U</u>	<u>U - 235</u>	<u>U</u>	<u>U - 235</u>	<u>U</u>	<u>U - 235</u>
<u>UO₂ Conversion Plant</u>								
General Performance, %	30	27	68	72			2	1
General Capability, %	23	15	76	84			1	1
<u>UO₂ Fabrication Plant</u>								
General Performance, %			49	50	49	49	2	1
General Capability, %			50	50	49	50	1	<1
<u>UO₂ Integrated Plant</u>								
General Performance, %	30	27			68	72	2	1
General Capability, %	22	15			75	84	3	1

Internal scrap recovery is assumed for the models of this study. Should major portions of the fabrication scrap be transferred **offsite** for recovery, the systematic errors in these measurements and material estimates can become a significant factor in the control of systematic errors in material transfers and MUF.

DIVERSION DETECTION CAPABILITIES

The safeguards capabilities of a material balance system can be equated in terms of the probability of detecting diversion, when it occurs. In material accounting, diversion is detected as a loss of material in MUF. If the material balance data were entirely free of error, each MUF quantity would have to be considered a real loss or gain of material. Since the actual data are known to contain measurement errors, the significance of MUF must be evaluated in the light of these uncertainties. In many instances, measurement errors alone can account for the entire quantity of material unaccounted for in a material balance. The sensitivity and the probability of detecting diversion in the presence of measurement errors are discussed in this report on the basis of the study models.

Decision Risks

Two types of error are encountered in making decisions regarding the significance of MUF in the presence of measurement errors. In one case, the occurrence of MUF may be interpreted as a loss of material when in reality no loss occurs and MUF is merely the result of measurement errors (Type 1 error). This kind of error is sometimes referred to as a false alarm. In another instance, a MUF may be interpreted as a natural reflection of measurement errors when in reality a loss of material actually occurs (Type 2 error). In other words, the hypothesis of no loss of material is accepted when

in fact a real loss occurs. It is impossible to choose between the two alternatives without risk of error. The suitability of these risks depends upon the consequences of making such errors.

Type 1 Errors

The probability of calling a MUF a loss of material when in reality there is no loss, is defined in a statistical sense as the level of significance of the test, or the risk of making a Type 1 error. Because of the interplay of the effects of measurement errors on material balance results, there is always some possibility, no matter how remote, that an improbable MUF is solely the product of measurement errors. What has to be decided is how large a risk is an organization willing to take in mistaking measurement errors for material losses. The decision is made by selecting a desired level of significance for the test. A choice of a 5% level of risk, for example, simply means that an organization decides to place under suspicion the MUF values which fall in the lower 5% region of the probability distribution function for the measurement errors in the system. This does not mean that the chance of making a correct decision regarding material losses and measurement errors is 95% because Type 2 errors can also be incurred. The price paid for a low false-alarm rate is a reduced sensitivity for detecting real losses of material.

Type 2 Errors

Safeguards studies should be especially concerned with this type of error in which a real loss of material is considered to be a normal reflection of measurement uncertainties. The risk of making Type 2 errors can be equated in terms of the probability of accepting the hypothesis that no loss of material occurs when in fact a real loss does occur. However, safeguards is more directly interested in the complementary function of this test, the probability of detecting a real loss of

material. When the probability of detecting diversion is plotted against the magnitude of the loss, the resulting curve is statistically known as the power function of the test. Thirty-six sets of curves for the study models are presented in Appendix C for central reference. These curves can be utilized directly to estimate the probability of detecting the diversion of different quantities of uranium in material systems similar to those of the study cases.

Probability of Detection

The probability of detecting a real diversion as a loss of material through MUF is dependent upon the quantity of material diverted, the cumulative measurement uncertainty of MUF, and the level of significance of the test employed. To facilitate the review of these relationships, a limited number of study tables are provided in Appendix D. Standard statistical procedures for determining the power function of the test of a hypothesis are used for the determination of the detection probability functions.

Magnitude of Diversion

Large quantities of diversion are easier to detect than small quantities of diversion under the same test conditions for a given material balance. This relationship can be readily observed in Tables 17, 18, and 19 when the probability values in the vertical columns are related to quantities of diversion. In viewing the probability changes in the horizontal rows, it is apparent that the probability of detecting the diversion of a given quantity of material decreases as the time span of a material balance is lengthened.

Measurement Uncertainties

The most important parameter in the determination of detection probabilities is the cumulative measurement uncertainty of a material balance. To generalize, the probability

TABLE 17. The Probability of Detecting Diversion as a Uranium Loss in a Material Balance of a Low-Enrichment UO_2 Conversion Plant, (a)
Type 1 Error of 5%

<u>Amount of Diversion</u>	<u>General Performance Model</u>			<u>General Capability Model</u>		
	<u>3 months</u>	<u>6 months</u>	<u>12 months</u>	<u>3 months</u>	<u>6 months</u>	<u>12 months</u>
<u>Uranium-235, kg</u>	<u>Probability, %</u>			<u>Probability, %</u>		
15	29	19	11	100	78	34
25	57	35	17	100	99	66
40	88	62	30	100	100	95
60	100	90	51	100	100	100
80	100	99	71	100	100	100
<u>Total Uranium, lb</u>						
1,100	50	34	18	100	100	78
1,800	86	64	34	100	100	99
2,900	99	94	62	100	100	100
4,400	100	100	91	100	100	100
5,900	100	100	99	100	100	100

Note: All values are rounded to the nearest percent.

a. Assumptions: Nominal U Thruput 1 ton/day
Nominal U-235 Enrichment 3%

TABLE 18. The Probability of Detecting Diversion as a Uranium Loss in a Material Balance of a Low-Enrichment UO_2 Fabrication Plant, (a)
Type 1 Error of 5%

<u>Amount of Diversion</u>	<u>General Performance Model</u>			<u>General Capability Model</u>		
	<u>3 months</u>	<u>6 months</u>	<u>12 months</u>	<u>3 months</u>	<u>6 months</u>	<u>12 months</u>
<u>Uranium-235, kg</u>	<u>Probability, %</u>			<u>Probability, %</u>		
15	17	14	10	74	48	23
25	31	22	15	98	84	44
40	56	41	23	100	100	78
60	84	68	39	100	100	98
80	97	88	57	100	100	100
<u>Total Uranium, 1b</u>						
1,100	22	20	14	96	87	36
1,800	42	36	23	100	100	99
2,900	74	66	43	100	100	100
4,400	96	92	71	100	100	100
5,900	100	99	91	100	100	100

Note: All values are rounded to the nearest percent.

a. Assumptions: Nominal U Thruput 1 ton/day
Nominal U-235 Enrichment 3%

TABLE 19. The Probability of Detecting Diversion as a Uranium Loss in a Material Balance of a Low-Enrichment UO_2 Conversion-Fabrication Plant, (a)
Type 1 Error of 5%

Amount of Diversion	General Performance Model			General Capability Model		
	3 months	6 months	12 months	3 months	6 months	12 months
<u>Uranium-235 , kg</u>	<u>Probability, %</u>			<u>Probability, %</u>		
15	17	14	10	75	56	30
25	29	23	15	99	91	58
40	52	42	26	100	100	90
60	81	69	43	100	100	100
80	96	89	62	100	100	100
<u>Total Uranium, lb</u>						
1,100	20	18	15	94	87	62
1,800	37	33	24	100	100	94
2,900	68	61	46	100	100	100
4,400	94	90	74	100	100	100
5,900	100	99	92	100	100	100

Note: All values are rounded to the nearest percent.

a. Assumption: Nominal U Thruput 1 ton/day
Nominal U-235 Enrichment 3%

of detecting the loss of a given quantity of material decreases as measurement uncertainties increase. Because the measurement uncertainties of a facility grow cumulatively with material throughput and time, the probability of detecting a given loss of material decreases with throughput and time. As a result of this relationship, the shortening of time spans between physical inventories is often encouraged for improving short-term detection capabilities. For the same reason, the detection of the continuous removal of small quantities of uranium is a more serious problem than the detection of the same total quantity of material withdrawn at one time.

Significance Level of the Test

The probability of detecting material losses is significantly enhanced as higher risks are accepted for making Type 1 errors. The final size of the critical region for testing the significance of a loss of material in MF is actually determined by the level of significance selected for the test. In Table 20, it is noted that significant improvement in detection capabilities can be achieved by raising the risk level from 1 to 5%. Additional gains can be obtained by accepting a risk level of 10%. There are, of course, practical limitations to the false alarm levels which an organization can assume effectively. In selecting the preferred level of risk for an individual facility, the consequences of false alarms must be equated against the strategic and operating importance of having improved capabilities for detecting material losses.

Detection Thresholds

The sensitivity of a material balance system to detect material losses is an important measure of safeguards effectiveness because statistical tests cannot distinguish material losses from measurement errors completely. Below detection

TABLE 20. **The Effects of Varying the Risk Levels for Type 1 Errors on the Probability of Detecting Uranium-235 Diversion as a Material Loss at an Integrated UO₂ Facility (a)**

<u>Risk Level</u> <u>Type 1 Errors</u>	<u>Amount of Diversion</u>			
	<u>15 kg</u>	<u>25 kg</u>	<u>40 kg</u>	<u>60 kg</u>
<u>General Performance, %</u>	<u>Probability of Detection, %</u>			
-1	4	8	19	42
-5	14	23	42	69
-10	29	48	74	95
<u>General Capability, %</u>				
-1	30	74	99	100
-5	56	91	100	100
-10	86	100	100	100

Note: All values are rounded to the nearest percent.

a. Assumptions: *Nominal Uranium Thruput* *1 ton/day*
 Nominal U-235 Enrichment *3%*
 Material Balance Span *6 months*

thresholds, material can be diverted with little danger of detection through material accounting. When detection probabilities are utilized as safeguards criteria, detection thresholds are often equated in terms of the smallest loss of material that can be detected at a given probability level. Detection thresholds can be determined from the power functions of the tests employed. A limited number of summary tables showing threshold values of detection as absolute quantities of material and relative percentages of thruput are presented in Appendix E.

In using detection probabilities as safeguards criteria, it is important to consider the capabilities of systems to detect small losses of material. The measurement uncertainties in a system may be too large to permit the detection of small,

but strategically significant, losses of material with the desired level of protection. As an example of existing safeguards capabilities, threshold quantities for the 80% probability level are listed in Table 21 for the study cases. Losses of material smaller than the threshold values cannot be detected with the desired level of probability unless the measurement uncertainties in MUF are reduced or the risk of making Type 1 errors is increased. The reduction of measurement uncertainties is the most effective procedure for lowering threshold levels.

Present Capabilities

Current material accounting systems, as exemplified by the general performance models, have little sensitivity for detecting diversion below 30 kg of Uranium-235 at the UO_2 conversion sites and 40 kg at the fabrication facilities. For the longer production spans, sizable losses of material must occur before high degrees of detection probability are attainable under general performance conditions. For time spans of a year or more, the detection thresholds frequently exceed 100 kg. A detailed summary of current capabilities can be obtained from Tables 22, 23, and 24. In the study of detection thresholds and probabilities, it is significant to note that the detection capabilities of the large integrated UO_2 production facilities are nearly as great as those of the separated fabrication units for short periods of time and actually better than the separated units for time periods greater than nine months. This favorable comparison can be primarily attributed to superior capabilities for measuring the UF_6 input to the integrated facilities as compared to the UO_2 input to the separated fabrication units.

Capabilities for detecting diversion are 20 to 50% better for gross uranium than for the isotope Uranium-235. These

TABLE 21. Thresholds for Detecting Uranium Losses
at Low-Enriched UO₂ Manufacturing Facilities,
Probability Level of 80%

	UO ₂ <u>Conversion</u>	UO ₂ <u>Fabrication</u>	UO ₂ <u>Integrated</u>
	<u>Uranium, lb (%)(a)</u>		
<u>General Performance</u>			
3 months	1,700 (0.9)	3,100 (1.7)	3,500 (1.9)
6 months	2,200 (0.6)	3,500 (1.0)	3,800 (1.1)
12 months	3,700 (0.5)	5,000 (0.7)	4,800 (0.7)
<u>General Capability</u>			
3 months	300 (0.2)	800 (0.4)	900 (0.5)
6 months	600 (0.2)	1,100 (0.3)	1,000 (0.3)
12 months	1,100 (0.2)	1,500 (0.2)	1,400 (0.2)
	<u>Uranium-235, kg (%)</u>		
<u>General Performance</u>			
3 months	35 (1.4)	56 (2.3)	59 (2.4)
6 months	51 (1.0)	71 (1.5)	69 (1.4)
12 months	90 (0.9)	112 (1.2)	102 (1.0)
<u>General Capability</u>			
3 months	8 (0.3)	16 (0.7)	16 (0.7)
6 months	16 (0.3)	24 (0.5)	21 (0.4)
12 months	31 (0.3)	42 (0.4)	34 (0.3)
Assumptions:	Nominal U Thruput		1 ton/day
	Nominal U-235 Enrichment		3.0%
	Risk of Type 1 Error		5%

a. All the percentage values are related to plant material thruputs.

TABLE 22. Detection Thresholds for Uranium Losses
at a Low-Enriched UO₂ Conversion Facility
Type 1 Error of 5%

		Probability of Loss Detection			
		50%	70%	80%	90%
		<u>Uranium, lb (%)</u>			
<u>General Performance</u>					
3 months		1,100 (0.6)	1,400 (0.8)	1,700 (0.9)	2,000 (1.1)
6 months		1,400 (0.4)	1,900 (0.5)	2,200 (0.6)	2,600 (0.7)
12 months		2,400 (0.3)	3,200 (0.4)	3,700 (0.5)	4,300 (0.6)
<u>General Capability</u>					
3 months		200 (0.1)	300 (0.2)	300 (0.2)	400 (0.2)
6 months		400 (0.1)	500 (0.1)	600 (0.2)	600 (0.2)
12 months		700 (0.1)	1,000 (0.1)	1,100 (0.2)	1,400 (0.2)
		<u>Uranium-235, kg (%)</u>			
<u>General Performance</u>					
3 months		23 (0.9)	30 (1.2)	35 (1.4)	41 (1.7)
6 months		34 (0.7)	45 (0.9)	51 (1.0)	60 (1.2)
12 months		49 (0.6)	79 (0.8)	90 (0.9)	106 (1.1)
<u>General Capability</u>					
3 months		6 (0.2)	7 (0.3)	8 (0.3)	10 (0.4)
6 months		10 (0.2)	14 (0.3)	16 (0.3)	18 (0.4)
12 months		20 (0.2)	26 (0.3)	31 (0.3)	36 (0.4)

Note: All percentage values are related to plant throughput

TABLE 23. Detection Thresholds for Uranium Losses
at a Low-Enriched UO₂ Fabrication Facility,
Type 1 Error of 5%

		Probability of Loss Detection			
		50%	70%	80%	90%
		<u>Uranium, lb (%)</u>			
<u>General Performance</u>					
3 months		2,000 (1.1)	2,800 (1.6)	3,100 (1.7)	3,700 (2.1)
6 months		2,300 (0.6)	3,000 (0.8)	3,500 (1.0)	4,200 (1.2)
12 months		3,000 (0.4)	4,400 (0.6)	5,000 (0.7)	5,900 (0.8)
<u>General Capability</u>					
3 months		500 (0.3)	700 (0.4)	800 (0.4)	900 (0.5)
6 months		600 (0.2)	900 (0.3)	1,000 (0.3)	1,200 (0.3)
12 months		1,000 (0.1)	1,400 (0.2)	1,500 (0.2)	1,900 (0.3)
		<u>Uranium-235, kg (%)</u>			
<u>General Performance</u>					
3 months		36 (1.5)	44 (1.8)	56 (2.3)	65 (2.7)
6 months		47 (1.0)	61 (1.3)	71 (1.5)	84 (1.7)
12 months		73 (0.7)	97 (1.0)	112 (1.2)	142 (1.5)
<u>General Capability</u>					
3 months		10 (0.4)	14 (0.6)	16 (0.7)	19 (0.8)
6 months		16 (0.3)	20 (0.4)	24 (0.5)	28 (0.6)
12 months		27 (0.3)	36 (0.4)	42 (0.4)	49 (0.5)

Note: All percentage values are related to plant thruput.

TABLE 24. Detection Thresholds for Uranium Losses
at a Low-Enriched Conversion-Fabrication Facility,
Type 1 Error of 5%

		Probability of Loss Detection			
		50%	70%	80%	90%
		<u>Uranium, lb (%)</u>			
<u>General Performance</u>					
3 months		2,200 (1.2)	3,000 (1.7)	3,500 (1.9]	4,000 (2.2)
6 months		2,500 (0.7)	3,300 (0.9)	3,800 (1.1]	4,400 (1.2)
12 months		3,200 (0.4)	4,200 (0.6)	4,800 (0.7]	5,600 (0.8)
<u>General Capability</u>					
≤ months		600 (0.3)	800 (0.4)	900 (0.5)	1,000 (0.6]
≤ months		700 (0.2)	900 (0.3)	1,000 (0.3)	1,200 (0.3]
1≥ months		900 (0.1)	1,200 (0.2)	1,400 (0.2)	1,700 (0.2]
		<u>Uranium-235, kg (%)</u>			
<u>General Performance</u>					
3 months		39 (1.6)	52 (2.1]	59 (2.4)	70 (2.9)
6 months		46 (0.9)	61 (1.2]	69 (1.4)	83 (1.7)
12 months		57 (0.6)	88 (0.9]	102 (1.0)	120 (1.2)
<u>General Capability</u>					
3 months		11 (0.4)	14 (0.6)	16 (0.7)	19 (0.8)
6 months		14 (0.3)	18 (0.4)	21 (0.4)	25 (0.5)
12 months		22 (0.2)	29 (0.3)	34 (0.3)	40 (0.4)

Note: All percentage values are related to plant thruput.

differences are primarily induced by measurement uncertainties associated with the performance of isotopic assays. In facilities which operate within relatively narrow ranges of isotopic composition, the earlier detection capabilities of the total uranium systems should be invaluable to the safeguarding of Uranium-235. However, the status of one account does not necessarily guarantee a like position for the other. Experience has shown that the separate accounting for Uranium-235 is necessary for effective materials management and safeguards control.

Technical Capabilities

The general capability models of this study indicate that the current capabilities of material accounting programs to detect diversion can be improved several fold through the utilization of better measurement systems and the improvement of inventory control practices. No new technology is required to attain the levels of capability projected in the general capability models. For the UO_2 conversion sites, detection thresholds for Uranium-235 can be reduced from 30 kg to 8 kg for short material balance spans. In a similar fashion, the thresholds of the fabrication sites can be reduced from 40 kg to 16 kg. Reductions of thresholds from the vicinity of 100 kg to approximately 35 kg can be achieved in all these facilities for time periods of one year. Improvements beyond these capabilities must come primarily through reductions in the systematic errors which occur in the measurement of UO_2 powder and pellets. Better calibration and analytical standards programs are needed to effect such action. Any improvement of material balance detection capabilities to levels below 0.1% of plant material throughput will require an extraordinary commitment to safeguards.

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APPENDIX A

TABLES

BASIC MODEL DESCRIPTIONS

TABLE A-1. A Summary of the Basic Material Flows and Measurement Errors of a Typical Low Enriched UO_2 Conversion Facility

	<u>General Performance</u>		<u>General Capability</u>	
	<u>U</u>	<u>U-235</u>	<u>U</u>	<u>U-235</u>
UF ₆ Input:				
Daily Thruput	2,000 lb	27.2 kg	2,000 lb	27.2 kg
Measurement Unit	16,000 lb	217.6 kg	3,200 lb	43.5 kg
Systematic Error	0.21%	0.36%	0.06%	0.10%
Random Error (2 σ)	0.16%	0.52%	0.11%	0.15%
UO ₂ Output:				
Daily Thruput	1,980 lb	26.9 kg	1,990 lb	27.0 kg
Measurement Unit	2,200 lb	29.9 kg	880 lb	12.0 kg
Systematic Error	0.32%	0.59%	0.11%	0.23%
Random Error	0.40%	2.53%	0.11%	0.51%
Liquid Waste:				
Daily Thruput	4 lb	55 g	2 lb	27 g
Measurement Unit	2 lb	27 g	1 lb	14 g
Systematic Error	16%	19%	5.4%	5.4%
Random Error	33%	44%	11%	11%
Process Residue:				
Daily Thruput	4 lb	55 g	2 lb	27 g
Measurement Unit	4 lb	55 g	2 lb	27 g
Systematic Error	18%	21%	7.1%	7.1%
Random Error	50%	58%	26%	26%
Solid Scrap:				
Daily Thruput	2 lb	27 g	2 lb	27 g
Measurement Unit	14 lb	190 g	14 lb	190 g
Systematic Error	20%	25%	10%	12%
Random Error	70%	74%	30%	36%
Physical Inventory:				
Units/Inventory	40,000 lb	544 kg	39,200 lb	533 kg
Systematic Error	458 lb	7.5 kg	56 lb	1.4 kg
Random Error	672 lb	13.5 kg	78 lb	2.0 kg

TABLE A-2. A Summary of the Basic Material Flows and Measurement Errors of a Typical Low Enriched UO₂ Fabrication Facility

	General Performance		General Capability	
	U	U-235	U	U-235
UO₂ Input:				
Daily Thruput	1,980 lb	26.9 kg	1,990 lb	27.0 kg
Measurement Unit	2,200 lb	29.9 kg	880 lb	12.0 kg
Systematic Error	0.32%	0.59%	0.11%	0.23%
Random Error (2σ)	0.40%	2.53%	0.11%	0.51%
UO₂ Output:				
Daily Thruput	1,960 lb	26.6 kg	1,980 lb	26.9 kg
Measurement Unit	880 lb	12.0 kg	880 lb	12.0 kg
Systematic Error	0.32%	0.59%	0.11%	0.23%
Random Error	0.40%	2.53%	0.10%	0.51%
Liquid Waste:				
Daily Thruput	2 lb	27 g	2 lb	27 g
Measurement Unit	2 lb	27 g	1 lb	14 g
Systematic Error	16%	19%	5.4%	5.4%
Random Error	33%	44%	11%	11%
Process Residue:				
Daily Thruput	4 lb	55 g	2 lb	27 g
Measurement Unit	4 lb	55 g	2 lb	27 g
Systematic Error	18%	21%	7.1%	7.1%
Random Error	50%	58%	26%	26%
Solid Scrap:				
Daily Thruput	4 lb	55 g	2 lb	27 g
Measurement Unit	14 lb	190 g	14 lb	190 g
Systematic Error	20%	25%	10%	12%
Random Error	70%	74%	30%	36%
Physical Inventory:				
Units/Inventory	160,000 lb	2,177 kg	160,000 lb	2,177 kg
Systematic Error	921 lb	185 kg	294 lb	7.3 kg
Random Error	1,469 lb	232 kg	318 lb	5.0 kg

TABLE A-3. A Summary of the Basic Material Flows and Measurement Errors of a Typical Low Enriched UO₂ Conversion-Fabrication Facility

	General Performance		General Capability	
	U	U-235	U	U-235
UF₆ Input:				
Daily Thruput	2,000 lb	27.2 kg	2,000 lb	27.2 kg
Measurement Unit	1,600 lb	217.6 kg	3,200 lb	43.5 kg
Systematic Error	0.21%	0.36%	0.06%	0.10%
Random Error (2 σ)	0.16%	0.52%	0.11%	0.15%
UO₂ Output:				
Daily Thruput	1,978 lb	26.9 kg	1,988 lb	27.0 kg
Measurement Unit	880 lb	12.0 kg	880 lb	12.0 kg
Systematic Error	0.32%	0.59%	0.11%	0.23%
Random Error	0.40%	2.53%	0.10%	0.51%
Liquid Waste:				
Daily Thruput	4 lb	55 g	2 lb	27 g
Measurement Unit	2 lb	27 g	1 lb	14 g
Systematic Error	16%	19%	5.4%	5.4%
Random Error	33%	44%	11%	11%
Process Residue:				
Daily Thruput	4 lb	55 g	2 lb	27 g
Measurement Unit	4 lb	55 g	2 lb	27 g
Systematic Error	18%	21%	7.1%	7.1%
Random Error	50%	58%	26%	26%
Solid Scrap:				
Daily Thruput	4 lb	55 g	4 lb	55 g
Measurement Unit	14 lb	190 g	14 lb	190 g
Systematic Error	20%	25%	10%	12%
Random Error	70%	74%	30%	36%
Physical Inventory:				
Units/Inventory	200,000 lb	2,722 kg	200,000 lb	2,722 kg
Systematic Error	1,050 lb	20.1 kg	330 lb	7.4 kg
Random Error	1,637 lb	26.5 kg	372 lb	5.9 kg

TABLE A-4. A Summary of the Basic Material Quantities and Measurement Errors of a Typical Physical Inventory at a Low Enriched UO₂ Conversion Facility

	<u>General Performance</u>		<u>General Capability</u>	
	<u>U, lb</u>	<u>U-235, kg</u>	<u>U, lb</u>	<u>U-235, kg</u>
UF ₆ Storage:				
Quantity	8,000	109	8,000	109
Systematic Error	17	0.4	5	0.1
Random Error (2σ)	12	0.6	10	0.2
UF ₆ - UO ₂ Process:				
Quantity	10,000	136	2,000	27
Systematic Error	450	7.3	42	1.0
Random Error	640	12.6	60	1.4
UO ₂ Powder storage:				
Quantity	20,000	272	28,000	381
Systematic Error	64	1.6	31	0.9
Random Error	46	4.0	6	0.4
Scrap Recovery:				
Quantity	2,000	27	1,200	16
Systematic Error	56	1.1	20	0.3
Random Error	200	2.8	48	1.4
Total Inventory:				
Quantity	40,000	544	39,200	533
Systematic Error	458	7.5	56	1.4
Random Error	672	13.5	78	2.0
Total Measurement Error	813	15.4	96	2.4

TABLE A-5. A Summary of the Basic Material Quantities and Measurement Errors of a Typical Physical Inventory at a Low Enriched Fabrication Facility

	<u>General Performance</u>		<u>General Capability</u>	
	<u>U, lb</u>	<u>U-235, kg</u>	<u>U, lb</u>	<u>U-235, kg</u>
Powder				
Preparation:				
Quantity	10,000	136	2,000	27
Systematic Error	310	5.1	18	0.3
Random Error (2σ)	800	11.8	68	1.0
Pellet				
Processing:				
Quantity	20,000	272	4,000	54
Systematic Error	240	3.8	23	0.4
Random Error	450	8.2	34	1.0
Rods and Bundles:				
Quantity	120,000	1,633	150,000	2,041
Systematic Error	380	9.6	165	4.7
Random Error	44	3.8	12	0.8
Scrap Storage:				
Quantity	8,000	109	3,500	48
Systematic Error	740	14.4	240	5.5
Random Error	1,130	17.6	300	4.6
Scrap Processing:				
Quantity	2,000	27	500	7
Systematic Error	56	1.2	25	0.5
Random Error	190	3.0	70	1.2
Total Inventory:				
Quantity	160,000	2,177	160,000	2,177
Systematic Error	921	18.5	294	7.3
Random Error	1,469	23.2	318	5.0
Total Measurement Error	1,734	29.9	433	8.8

TABLE A-6. A Summary of the Basic Material Quantities and Measurement Errors of a Typical Physical Inventory at an Integrated UO₂ Conversion-Fabrication Facility

	<u>General Performance</u>		<u>General Capability</u>	
	<u>U, lb</u>	<u>U-235, kg</u>	<u>U, lb</u>	<u>U-235, kg</u>
UF ₆ Storage:				
Quantity	8,000	109	8,000	109
Systematic Error	17	0.4	5	0.1
Random Error (2σ)	12	0.6	10	0.2
UF ₆ - UO ₂ Operation:				
Quantity	30,000	408	30,000	408
Systematic Error	440	7.3	42	1.0
Random Error	640	12.6	60	1.4
Pellet Manufacturing:				
Quantity	30,000	408	6,000	82
Systematic Error	390	6.4	29	0.5
Random Error	810	14.4	76	1.4
Rods and Bundles:				
Quantity	120,000	1,633	150,000	2,041
Systematic Error	380	9.6	165	4.7
Random Error	44	3.8	12	0.8
Scrap Storage:				
Quantity	10,000	136	5,500	75
Systematic Error	780	14.7	280	5.6
Random Error	1,260	17.8	350	5.3
Scrap Processing:				
Quantity	2,000	27	500	7
Systematic Error	56	1.0	25	0.5
Random Error	160	2.6	80	1.4
Total Inventory:				
Quantity	200,000	2,722	200,000	2,722
Systematic Error	1,050	20.1	330	7.4
Random Error	1,637	26.5	372	5.9
Total Measurement Error	1,945	33.3	497	9.5

APPENDIX B
TABLES
MATERIAL BALANCE MEASUREMENT UNCERTAINTIES

TABLE B-1. A Synthesized General Performance Model of the Uranium Material Balance for a Low-Enriched UO_2 Conversion Facility

	Three-Month Period				Fraction of Total Variance, %
	Quantity, lb	Measurement Systematic, lb	Errors Random, lb	(95CL) Total, lb	
Beginning Inventory	40,000	458	672	813	36.2
UF_6 Receipts	180,000	378	83	387	8.4
UO_2 Shipments	178,200	570	79	575	18.5
Waste Discards:					
Liquid	360	58	9	59	0.2
Process Residue	360	65	19	68	0.3
Solid Scrap	180	36	35	50	0.2
Ending Inventory	40,000	458	672	813	36.2
Material Unaccounted For	900	937	958	1,340	
(Percent of Thruput)	0.5%	0.5%	0.5%	0.7%	

TABLE B-2. A Synthesized General Performance Model of the Uranium-235 Material Balance for a Low-Enriched UO₂ Conversion Facility

Three Month Period					
	Quantity, kg	Measurement Systematic, kg	Errors (95CL) Random, kg	Total, kg	Fraction of Total Variance, %
Beginning Inventory	544	7.5	13.5	15.4	28.4
UF ₆ Receipts	2,448	8.8	3.7	9.5	11.4
UO ₂ Shipments	2,424	14.3	6.8	15.8	31.4
Waste Discards:					
Liquid	5	1.0	0.2	1.0	0.1
Process Residue	5	1.1	0.3	1.1	0.2
Solid Scrap	2	0.6	0.5	0.8	0.1
Ending Inventory	544	7.5	13.5	15.4	28.4
Material Unaccounted For	12	19.9	20.0	28.2	
(Percent of Thruput)	0.5%	0.8%	0.8%	1.1%	

TABLE B-3. A Synthesized General Performance Model of the Uranium Material Balance for a Low-Enriched UO₂ Conversion Facility

Six-Month Period					
	Quantity, lb	Measurement Errors (95CL)			Fraction of Total Variance, %
		Systematic, lb	Random, lb	Total, lb	
Beginning Inventory	40,000	458	672	813	20.0
UF ₆ Receipts	360,000	756	120	765	18.2
UO ₂ Shipments	356,400	1,140	112	1,145	40.7
Waste Discards:					
Liquid	720	115	14	116	0.4
Process Residue	720	130	27	133	0.5
Solid Scrap	360	72	49	87	0.2
Ending Inventory	40,000	458	672	813	20.0
Material Unaccounted For	1,800	1,519	966	1,800	
(Percent of Thruput)	0.5%	0.4%	0.3%	0.5%	

TABLE B-4. A Synthesized General Performance Model of the Uranium-235 Material Balance for a Low-Enriched UO₂ Conversion Facility

Six-Month Period					
	Quantity, kg	Measurement Systematic, kg	Errors (95CL) Random, kg	Total, kg	Fraction of Total Variance, %
Beginning Inventory	544	7.5	13.5	15.4	13.1
UF ₆ Receipts	4,896	17.6	5.3	18.4	19.9
UO ₂ Shipments	4,847	28.6	9.7	30.2	53.2
Waste Discards:					
Liquid	10	1.9	0.2	1.9	0.2
Process Residue	10	2.1	0.4	2.1	0.4
Solid Scrap	5	1.2	0.7	1.4	0.1
Ending Inventory	544	7.5	13.5	15.4	13.1
Material Unaccounted For	24	35.3	21.4	41.4	
(Percent of Thruput)	0.5%	0.7%	0.4%	0.8%	

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TABLE B-5. A Synthesized General Performance Model of the Uranium Material Balance for a Low-Enriched UO₂ Conversion Facility

One-Year Period					
	Quantity, lb	Measurement Errors (95CL)			Fraction of Total Variance, %
		Systematic, lb	Random, lb	Total, lb	
Beginning Inventory	40,000	458	672	813	7.2
UF ₆ Receipts	720,000	1,512	172	1,522	25.8
UO ₂ Shipments	712,800	2,281	158	2,286	58.1
Waste Discards:					
Liquid	1,440	230	18	231	0.6
Process Residue	1,440	259	38	262	0.8
Solid Scrap	720	144	70	160	0.3
Ending Inventory	40,000	458	672	813	7.2
Material Unaccounted For	3,600	2,834	982	2,999	
(Percent of Thruput)	0.5%	0.4%	0.1%	0.4%	

TABLE B-6. A Synthesized General Performance Model of the Uranium-235 Material Balance for a Low-Enriched UO₂ Conversion Facility

One-Year Period					
	Quantity, kg	Measurement Systematic, kg	Errors (95CL) Random, kg	Total, kg	Fraction of Total Variance, %
Beginning Inventory	544	7.5	13.5	15.4	4.3
UF ₆ Receipts	9,792	35.2	7.6	36.0	24.7
UO ₂ Shipments	9,694	57.2	13.7	58.8	65.8
Waste Discards:					
Liquid	20	3.8	0.3	3.8	0.3
Process Residue	20	4.2	0.6	4.2	0.5
Solid Scrap	10	2.5	1.0	2.7	0.1
Ending Inventory	544	7.5	13.5	15.4	4.3
Material Unaccounted For	48	68.3	24.2	72.5	
(Percent of Thruput)	0.5%	0.7%	0.2%	0.7%	

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TABLE B-7 A Synthesized General Capability Model of the Uranium Material Balance
for a Low-Enriched UO₂ Conversion Facility

	Three-Month Period				Fraction of Total Variance, %
	Quantity, lb	Measurement Systematic, lb	Errors (95CL) Random, lb	Total, lb	
Beginning Inventory	39,200	56	78	96	12.1
UF ₆ Receipts	180,000	108	27	111	18.4
UO ₂ Shipments	179,090	197	14	197	56.2
Waste Discharges:					
Liquid	180	10	1	10	0.2
Process Residue	180	13	5	14	0.3
Solid Scrap	180	18	15	23	0.7
Ending Inventory	39,200	56	78	96	12.1
Material Unaccounted For	370	235	115	262	
(Percent of Thruput)	0.2%	0.1%	0.1%	0.1%	

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TABLE B-8. A Synthesized General Capability Model of the Uranium-235 Material Balance for a Low-Enriched UO₂ Conversion Facility

Three-Month Period					
	Quantity, kg	Measurement Errors (95CL)			Fraction of Total Variance, $\frac{b}{a}$
		Systematic, kg	Random, kg	Total, kg	
Beginning Inventory	533	1.4	2.0	2.4	10.7
UF ₆ Receipts	2,448	2.4	0.5	2.5	12.6
UO ₂ Shipments	2,435	5.6	0.9	5.7	65.6
Waste Discards:					
Liquid	3	0.1	<0.1	0.1	<0.1
Process Residue	3	0.2	0.1	0.2	0.1
Solid Scrap	2	0.3	0.2	0.4	0.3
Ending Inventory	533	1.4	2.0	2.4	10.7
Material Unaccounted For	5	6.3	3.0	7.0	
(Percent of Thruput)	0.2%	0.3%	0.1%	0.3%	

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TABLE B-9. A Synthesized General Capability Model of the Uranium Material Balance for a Low-Enriched UO₂ Conversion Facility

	Six-Month Period				Fraction of Total Variance, %
	Quantity, 1b	Measurement Errors (95CL)			
		Systematic, 1b	Random, 1b	Total, 1b	
Beginning Inventory	39,200	56	78	96	3.7
UF ₆ Receipts	360,000	216	38	220	21.8
UO ₂ Shipments	358,170	394	18	394	69.6
Waste Discards:					
Liquid	360	19	2	19	0.2
Process Residue	360	25	7	26	0.3
Solid Scrap	360	36	21	41	0.7
Ending Inventory	39,200	56	78	96	3.7
Material Unaccounted For	750	457	120	472	
(Percent of Thruput)	0.2%	0.1%	<0.1%	0.1%	

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TABLE B-10. A Synthesized General Capability Model of the Uranium-235 Material Balance for a Low-Enriched UO₂ Conversion Facility

Six-Month Period					
	Quantity, kg	Measurement Errors (95CL)			Fraction of Total Variance, %
		Systematic, kg	Random, kg	Total, kg	
Beginning Inventory	533	1.4	2.0	2.4	3.2
UF ₆ Receipts	4,896	4.9	0.7	4.9	14.7
UO ₂ Shipments	4,871	11.2	1.3	11.3	78.4
Waste Discards:					
Liquid	5	0.3	<0.1	0.3	0.1
Process Residue	5	0.4	0.1	0.4	0.1
Solid Scrap	5	0.6	0.3	0.7	0.3
Ending Inventory	533	1.4	2.0	2.4	3.2
Material Unaccounted For	10	12.3	3.2	12.7	
(Percent of Thruput)	0.2%	0.3%	0.1%	0.3%	

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TABLE B-11. A Synthesized General Capability Model of the Uranium Material Balance for a Low-Enriched UO₂ Conversion Facility

One- Year Period					
	Quantity, 1b	Measurement Errors (95CL)			Fraction of Total Variance, %
		Systematic, 1b	Random, 1b	Total, 1b	
Beginning Inventory	39,200	56	78	96	1.0
UF ₆ Receipts	720,000	432	53	435	22.8
UO ₂ Shipments	716,340	788	28	788	74.0
Waste Discards:					
Liquid	720	39	3	39	0.2
Process Residue	720	50	10	51	0.3
Solid Scrap	720	72	30	78	0.7
Ending Inventory	39,200	56	78	96	1.0
Material Unaccounted For	1,500	906	130	915	
(Percent of Thruput)	0.2%	0.1%	<0.1%	0.1%	

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TABLE B-12. A Synthesized General Capability Model of the Uranium-235 Material Balance for a Low-Enriched UO₂ Conversion Facility

One-Year Period

	Quantity, kg	Measurement Systematic, kg	Errors (95CL) Random, kg	Total, kg	Fraction of Total Variance, %
Beginning Inventory	533	1.4	2.0	2.4	0.9
UF ₆ Receipts	9,792	9.8	1.0	9.8	15.7
UO ₂ Shipments	9,742	22.4	1.7	22.5	82.1
Waste Discards:					
Liquid	10	0.5	<0.1	0.5	<0.1
Process Residue	10	0.7	0.1	0.7	0.1
Solid Scrap	10	1.2	0.5	1.3	0.3
Ending Inventory	533	1.4	2.0	2.4	0.9
Material Unaccounted For	20	24.5	3.5	24.7	
(Percent of Thruput)	0.2%	0.3%	<0.1%	0.3%	

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FABLE B-13. A Synthesized General Performance Model of the Uranium Material Balance
for a Low-Enriched UO_2 Fabrication Facility

Three-Month Period					
	Quantity, 1b	Measurement Errors (95CL)			Fraction of Total Variance, %
		Systematic, 1b	Random, 1b	Total, 1b	
Beginning Inventory	160,000	921	1,469	1,734	44.8
UF_6 Receipts	178,200	570	79	575	5.2
UO_2 Shipments	176,400	564	50	566	5.0
Waste Discards:					
Liquid	180	29	7	30	<0.1
Process Residue	360	65	20	68	0.1
Solid Scrap	360	72	49	87	0.1
Ending Inventory	160,000	921	1,469	1,734	44.8
Material Unaccounted For	900	1,440	2,080	2,530	
(Percent of Thruput)	0.5%	0.8%	1.2%	1.4%	

TABLE B-14. A Synthesized General Performance Model of the Uranium-235 Material Balance for a Low-Enriched UO₂ Fabrication Facility

Three-Month Period					
	Quantity, kg	Measurement Errors (95CL)			Fraction of Total Variance, %
		Systematic, kg	Random, kg	Total, kg	
Beginning Inventory	2,177	18.5	23.2	29.9	37.7
UO ₂ Receipts	2,424	14.3	6.8	15.8	13.0
UO ₂ Shipments	2,400	14.2	4.3	14.8	11.4
Waste Discards:					
Liquid	2	0.5	0.1	0.5	<0.1
Process Residue	5	1.1	0.3	1.1	0.1
Solid Scrap	5	1.3	0.7	1.5	0.1
Ending Inventory	2,177	18.5	23.2	29.9	37.7
Material Unaccounted For	12	30.1	33.5	45.0	
(Percent of Thruput)	0.5%	1.2%	1.4%	1.9%	

TABLE B-15. A Synthesized General Performance Model of the Uranium Material Balance for a Low-Enriched UO₂ Fabrication Facility

Six-Month Period					
	Quantity, 1b	Measurement Systematic, 1b	Errors (95CL) Random, 1b	Total, 1b	Fraction of Total Variance, %
Beginning Inventory	160,000	921	1,469	1,734	34.2
UO ₂ Receipts	356,400	1,140	112	1,145	15.8
UO ₂ Shipments	352,800	1,129	71	1,131	15.2
Waste Discards:					
Liquid	360	58	9	59	0.1
Process Residue	720	130	27	133	0.2
Solid Scrap	720	144	71	161	0.3
Ending Inventory	160,000	921	1,469	1,734	34.2
Material Unaccounted For	1,800	2,009	2,083	2,894	
(Percent of Thruput)	0.5%	0.6%	0.6%	0.8%	

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TABLE B-16. **A Synthesized General Performance Model of the Uranium-235 Material Balance for a Low-Enriched UO₂ Fabrication Facility**

Six-Month Period					
	Quantity, kg	Measurement Errors (95CL)			Fraction of Total Variance, %
		Systematic, kg	Random, kg	Total, kg	
Beginning Inventory	2,177	18.5	23.2	29.9	23.5
UO ₂ Receipts	4,847	28.6	9.7	30.2	27.4
UO ₂ Shipments	4,798	28.3	6.1	28.9	25.2
Waste Discards:					
Liquid	5	0.9	0.2	0.9	<0.1
Process Residue	10	2.1	0.4	2.1	0.2
Solid Scrap	10	2.5	1.0	2.7	0.2
Ending Inventory	2,177	18.5	23.2	29.9	23.5
Material Unaccounted For	24	46.2	34.5	57.6	
 (Percent of Thruput)	0.5%	0.9%	0.7%	1.2%	

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TABLE B-17. A Synthesized General Performance Model of the Uranium Material Balance
for a Low-Enriched UO₂ Fabrication Facility

One-Year Period					
	Quantity, lb	Measurement Errors (95CL)			Fraction of Total Variance, %
		Systematic, lb	Random, lb	Total, lb	
Beginning Inventory	160,000	921	1,469	1,734	17.6
UO ₂ Receipts	712,800	2,281	158	2,286	32.2
UO ₂ Shipments	705,600	2,258	99	2,260	31.5
Waste Discards:					
Liquid	720	115	13	116	0.1
Process Residue	1,440	259	38	262	0.4
Solid Scrap	1,440	288	100	305	0.6
Ending Inventory	160,000	921	1,469	1,734	17.6
Material Unaccounted For	3,600	3,448	2,089	4,031	
(Percent of Thruput)	0.5%	0.5%	0.3%	0.6%	

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TABLE B-18. A Synthesized General Performance Model of the Uranium-235 Material Balance for a Low-Enriched UO₂ Fabrication Facility

One-Year Period					
	Quantity, kg	Measurement Errors (95CL)			Fraction of Total Variance, %
		Systematic, kg	Random, kg	Total, kg	
Beginning Inventory	2,177	18.5	23.2	29.9	9.3
UO ₂ Receipts	9,694	57.2	13.7	58.8	41.5
UO ₂ Shipments	9,596	56.6	8.6	57.2	39.3
Waste Discards:					
Liquid	10	1.9	0.2	1.9	0.1
Process Residue	20	4.2	0.6	4.2	0.2
Solid Scrap	20	4.9	1.4	5.1	0.3
Ending Inventory	2,177	18.5	23.2	29.9	9.3
Material Unaccounted For	48	83.8	36.4	91.4	
(Percent of Thruput)	0.5%	0.9%	0.4%	0.9%	

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TABLE B-19. A Synthesized General Capability Model of the Uranium Material Balance for a Low-Enriched UO₂ Fabrication Facility

Three-Month Period					
	Quantity, lb	Measurement Errors (95CL)			Fraction of Total Variance, %
		Systematic, lb	Random, lb	Total, lb	
Beginning Inventory	160,000	294	318	433	40.4
UO ₂ Receipts	179,090	197	14	197	9.5
UO ₂ Shipments	178,180	196	12	196	9.5
Waste Discards:					
Liquid	180	10	1	10	<0.1
Process Residue	180	13	5	14	0.1
Solid Scrap	180	18	15	23	0.1
Ending Inventory	160,000	294	318	433	40.4
Material Unaccounted For	370	444	450	632	
(Percent of Thruput)	0.2%	0.2%	0.3%	0.4%	

TABLE B-20. A Synthesized Capability Model of the Uranium-235 Material Balance
for a Low-Enriched UO₂ Fabrication Facility

Three-Month Period					
	Quantity, kg	Measurement Systematic, kg	Errors (95CL) Random, kg	Total, kg	Fraction of Total Variance, %
Beginning Inventory	2,177	7.3	5.0	8.8	31.9
UO ₂ Receipts	2,435	5.6	0.9	5.7	18.4
UO ₂ Shipments	2,423	5.6	0.9	5.7	17.8
Waste Discards:					
Liquid	2	0.1	<0.1	0.1	<0.1
Process Residue	2	0.2	0.1	0.2	<0.1
Solid Scrap	3	0.2	0.2	0.3	<0.1
Ending Inventory	2,177	7.3	5.0	8.8	31.9
Material Unaccounted For	5	11.2	7.2	13.3	
(Percent of Thruput)	0.2 %	0.5 %	0.3 %	0.5 %	

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TABLE B-21. A Synthesized General Capability Model of the Uranium Material Balance
for a Low-Enriched UO₂ Fabrication Facility

Six-Month Period					
	Quantity, lb	Measurement Errors (95CL)			Fraction of Total Variance, %
		Systematic, lb	Random, lb	Total, lb	
Beginning Inventory	160,000	294	318	433	25.7
UO ₂ Receipts	358,170	394	19	394	24.3
UO ₂ Shipments	356,340	392	18	392	23.9
Waste Discards:					
Liquid	360	19	2	19	0.1
Process Residue	360	25	7	26	0.1
Solid Scrap	360	36	21	42	0.2
Ending Inventory	160,000	294	318	433	25.7
Material Unaccounted For	750	656	451	796	
(Percent of Thruput)	0.2 %	0.2 %	0.1 %	0.2 %	

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TABLE B-22. A Synthesized General Capability Model of the Uranium-235 Material Balance **for** a Low-Enriched UO₂ Fabrication Facility

	Six-Month Period				Fraction of Total Variance,
	Quantity, kg	Measurement Errors (95CL)			
		Systematic,	Random,	Total,	
		kg	kg	kg	
Beginning Inventory	2,177	7.3	5.0	8.8	15.4
UO ₂ Receipts	4,871	11.2	1.3	11.3	34.9
UO ₂ Shipments	4,846	11.1	1.2	11.2	34.2
Waste Discards :					
Liquid	5	0.3	0.1	0.3	<0.1
Process Residue	5	0.3	0.1	0.3	<0.1
Solid Scrap	5	0.6	0.3	0.7	0.1
Ending Inventory	2,177	7.3	5.0	8.8	15.4
Material Unaccounted For	10	17.7	7.3	19.1	
(Percent of Thruput)	0.2%	0.4%	0.2%	0.4%	

TABLE B-23. A Synthesized General Capability Model of the Uranium Material Balance for a Low-Enriched UO₂ Fabrication Facility

One-Year Period					
	Quantity, lb	Measurement Errors (95CL)			Fraction of Total Variance, %
		Systematic, lb	Random, lb	Total, lb	
Beginning Inventory	160,000	294	318	433	10.4
UO ₂ Receipts	716,340	788	27	789	39.6
UO ₂ Shipments	712,680	784	25	784	38.9
Waste Discards:					
Liquid	720	38	3	38	0.1
Process Residue	720	50	7	50	0.2
Solid Scrap	720	72	30	78	0.4
Ending Inventory	160,000	294	318	433	10.4
Material Unaccounted For	1,500	1,168	452	1,252	
(Percent of Thruput)	0.2%	0.2%	0.1%	0.2%	

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TABLE B-24. A Synthesized General Capability Model of the Uranium-235 Material Balance for a Low-Enriched UO₂ Fabrication Facility

One-Year Period					
	Quantity,	Measurement Errors (95CL)			Fraction
	kg	Systematic,	Random,	Total,	of Total
		kg	kg	kg	Variance,
					%
Beginning Inventory	2,177	7.3	5.0	8.8	5.0
UO ₂ Receipts	9,742	22.4	1.7	22.5	45.0
UO ₂ Shipments	9,692	22.3	1.7	22.4	44.7
Waste Discards:					
Liquid	10	0.5	<0.1	0.5	<0.1
Process Residue	10	0.7	0.1	0.7	0.1
Solid Scrap	10	1.2	0.5	1.3	0.2
Ending Inventory	2,177	7.3	5.0	8.8	5.0
Material Unaccounted For	20	32.6	7.5	33.5	
(Percent of Thruput)	0.2%	0.3%	0.1%	0.3%	

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TABLE B-25. A Synthesized General Performance Model of the Uranium Material Balance for an Integrated Low-Enriched UO₂ Manufacturing Facility

Three-Month Period					
	Quantity, lb	Measurement Systematic, lb	Errors (95CL) Random, lb	Total, lb	Fraction of Total Variance, %
Beginning Inventory	200,000	1,050	1,637	1,945	46.8
UF ₆ Receipts	180,000	378	83	387	2.0
UO ₂ Shipments	178,020	570	50	572	4.2
Waste Discards:					
Liquid	360	58	9	59	<0.1
Process Residue	360	65	19	68	0.1
Solid Scrap	360	72	50	88	0.1
Ending Inventory	200,000	1,050	1,637	1,945	46.8
Material Unaccounted For	900	1,547	2,318	2,787	
(Percent of Thruput)	0.5%	0.9%	1.3%	1.5%	

TABLE B-26. A Synthesized General Performance Model of the Uranium-235 Material Balance for an Integrated Low-Enriched UO₂ Manufacturing Facility

Three-Month Period					
	Quantity, kg	Measurement Errors (95CL)			Fraction of Total Variance, %
		Systematic, kg	Random, kg	Total, kg	
Beginning Inventory	2,722	20.1	26.5	33.3	43.2
UF ₆ Receipts	2,448	8.8	3.7	9.5	3.9
UO ₂ Shipments	2,421	14.3	4.3	14.9	9.5
Waste Discards:					
Liquid	5	0.9	0.2	0.9	<0.1
Process Residue	5	1.1	0.3	1.1	0.1
Solid Scrap	5	1.2	0.7	1.4	0.1
Ending Inventory	2,722	20.1	26.5	33.3	43.2
Material Unaccounted For	12	30.1	37.5	48.1	
(Percent of Thruput)	0.5%	1.2%	1.5%	2.0%	

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TABLE B-27. A Synthesized General Performance Model of the Uranium Material Balance for an Integrated Low-Enriched UO₂ Manufacturing Facility

	Six-Month Period				Fraction of Total Variance, %
	Quantity, 1b	Measurement Systematic, 1b	Errors (95CL) Random, 1b	Total, 1b	
Beginning Inventory	200,000	1,050	1,637	1,945	39.5
UF ₆ Receipts	360,000	756	120	765	6.3
UO ₂ Shipments	356,040	1,139	71	1,141	14.1
Waste Discards:					
Liquid	720	115	13	116	0.1
Process Residue	720	130	27	133	0.2
Solid Scrap	720	144	70	160	0.3
Ending Inventory	200,000	1,050	1,637	1,945	39.5
Material Unaccounted For	1,800	1,958	2,320	3,036	
(Percent of Thruput)	0.5%	0.5%	0.6%	0.8%	

TABLE B-28. A Synthesized General Performance Model of the Uranium-235 Material Balance for an Integrated Low-Enriched UO₂ Manufacturing Facility

Six-Month Period					
	Quantity, kg	Measurement Systematic, kg	Errors (95CL) Random, kg	Total, kg	Fraction of Total Variance, %
Beginning Inventory	2,722	20.1	26.5	33.3	31.2
UF ₆ Receipts	4,896	17.6	5.3	18.4	10.6
UO ₂ Shipments	4,842	28.6	6.1	29.2	26.5
Waste Discards:					
Liquid	10	1.9	0.2	1.9	0.1
Process Residue	10	2.1	0.4	2.1	0.2
Solid Scrap	10	2.5	1.0	2.7	0.2
Ending Inventory	2,722	20.1	26.5	33.3	31.2
Material Unaccounted For	24	42.0	37.9	56.6	
(Percent of Thruput)	0.5%	0.9%	0.8%	1.2%	

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TABLE B-29. A Synthesized General Performance Model of the Uranium Material Balance for an Integrated Low-Enriched UO_2 Manufacturing Facility

	One – Year Period				Fraction of Total Variance, %
	Quantity, lb	Measurement Errors (95CL)			
		Systematic, lb	Random, lb	Total, lb	
Beginning Inventory	200,000	1,050	1,637	1,945	24.2
UF ₆ Receipts	720,000	1,512	172	1,522	15.4
UO ₂ Shipments	712,080	2,279	100	2,281	34.7
Waste Discards:					
Liquid	1,440	230	18	231	0.4
Process Residue	1,440	259	38	262	0.5
Solid Scrap	1,440	288	99	305	0.6
Ending Inventory	200,000	1,050	1,637	1,945	24.2
Material Unaccounted For	3,600	3,098	2,326	3,874	
(Percent of Thruput)	0.5%	0.4%	0.3%	0.5%	

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TABLE B-30. A Synthesized General Performance Model of the Uranium-235 Material Balance for an Integrated Low-Enriched UO₂ Manufacturing Facility

One-Year Period

	Quantity, <u>kg</u>	Measurement Errors (95CL) <u>Systematic,</u> <u>kg</u>	<u>Random,</u> <u>kg</u>	<u>Total,</u> <u>kg</u>	Fraction of Total Variance, <u>%</u>
Beginning Inventory	2,722	20.1	26.5	33.3	14.9
UF ₆ Receipts	9,792	35.2	7.6	36.0	19.4
UO ₂ Shipments	9,684	57.1	8.6	57.7	49.9
Waste Discards:					
Liquid	20	3.7	0.3	3.8	0.2
Process Residue	20	4.2	0.6	4.2	0.3
Solid. Scrap	20	4.9	1.4	5.1	0.4
Ending Inventory	2,722	20.1	26.5	33.3	14.9
Material Unaccounted For	48	72.0	38.8	81.8	
(Percent of Thruput)	0.5%	0.7%	0.4%	0.8%	

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TABLE B-31. A Synthesized General Capability Model of the Uranium Material Balance for an Integrated Low-Enriched UO₂ Manufacturing Facility

Three-Month Period					
	Quantity, lb	Measurement Errors (95CL)			Fraction of Total Variance, %
		Systematic, lb	Random, lb	Total, lb	
Beginning Inventory	200,000	330	372	497	44.5
UF ₆ Receipts	180,000	108	27	111	2.6
UO ₂ Shipments	178,910	197	13	197	8.1
Waste Discards:					
Liquid	180	10	1	10	<0.1
Process Residue	180	13	5	14	<0.1
Solid Scrap	360	36	21	42	0.3
Ending Inventory	200,000	330	372	497	44.5
Material Unaccounted For	370	458	527	698	
(Percent of Thruput)	0.2%	0.3%	0.3%	0.4%	

TABLE B-32. A Synthesized General Capability Model of the Uranium-235 Material Balance for an Integrated Low-Enriched UO₂ Manufacturing Facility

Three-Month Period					
	Quantity,	Measurement Errors (95CL)			Fraction
	kg	Systematic,	Random,	Total,	of Total
		kg	kg	kg	Variance,
					%
Beginning Inventory	2,722	7.4	5.9	9.5	38.7
UF ₆ Receipts	2,448	2.4	0.5	2.5	3.6
UO ₂ Shipments	2,433	5.6	0.9	5.7	18.7
Waste Discards:					
Liquid	2	0.1	0.1	0.1	<0.1
Process Residue	3	0.2	0.1	0.2	<0.1
Solid Scrap	5	0.6	0.3	0.7	0.3
Ending Inventory	2,722	7.4	5.9	9.5	38.7
Material Unaccounted For	5	10.2	8.3	13.2	
(Percent of Thruput)	0.2%	0.4%	0.3%	0.5%	

TABLE B-33. A Synthesized General Capability Model of the Uranium Material Balance for an Integrated Low-Enriched UO₂ Manufacturing Facility

Six-Month Period					
	Quantity, lb	Measurement Errors (95CL)			Fraction of Total Variance, %
		Systematic, lb	Random, lb	Total, lb	
Beginning Inventory	200,000	330	372	497	33.4
UF ₆ Receipts	360,000	216	38	220	7.7
UO ₂ Shipments	357,810	394	18	394	24.4
Waste Discards:					
Liquid	360	19	2	19	0.1
Process Residue	360	25	7	26	0.1
Solid Scrap	720	72	30	78	0.9
Ending Inventory	200,000	330	372	497	33.4
Material Unaccounted For	750	605	529	803	
(Percent of Thruput)	0.2%	0.2%	0.1%	0.2%	

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TABLE B-34. A Synthesized General Capability Model of the Uranium-235 Material Balance for an Integrated Low-Enriched UO₂ Manufacturing Facility

Six-Month Period					
	Quantity, kg	Measurement Systematic, kg	Errors (95CL) Random, kg	Total, kg	Fraction of Total Variance, %
Beginning Inventory	2,722	7.4	5.9	9.5	23.4
UF ₆ Receipts	4,896	4.9	0.7	4.9	8.3
UO ₂ Shipments	4,866	11.2	1.3	11.3	44.3
Waste Discards:					
Liquid	5	0.3	<0.1	0.3	<0.1
Process Residue	5	0.3	0.1	0.3	<0.1
Solid Scrap	10	1.2	0.5	1.3	0.6
Ending Inventory	2,722	7.4	5.9	9.5	23.4
Material Unaccounted For	10	14.8	8.4	17.0	
(Percent of Thruput)	0.2%	0.3%	0.2%	0.3%	

TABLE B-35. A Synthesized General Capability Model of the Uranium Material Balance for an Integrated Low-Enriched UO₂ Manufacturing Facility

One-Year Period					
	Quantity, lb	Measurement Errors (95CL)			Fraction of Total Variance, %
		Systematic, lb	Random, lb	Total, lb	
Beginning Inventory	200,000	330	372	497	16.9
UF ₆ Receipts	720,000	432	53	435	15.1
UO ₂ Shipments	715,620	787	25	787	49.1
Waste Discards:					
Liquid	720	39	3	39	0.1
Process Residue	720	50	10	51	0.2
Solid Scrap	1,440	144	43	150	1.7
Ending Inventory	200,000	330	372	497	16.9
Material Unaccounted For	1,500	994	531	1,127	
(Percent of Thruput)	0.2%	0.1%	0.1%	0.2%	

TABLE B-36. A Synthesized General Capability Model of the Uranium-235 Material Balance for an Integrated Low-Enriched UO₂ Manufacturing Facility

One-Year Period					
	Quantity, kg	Measurement Errors (95CL)			Fraction of Total Variance, %
		Systematic, kg	Random, kg	Total, kg	
Beginning Inventory	2,722	7.4	5.9	9.5	9.0
UF ₆ Receipts	9,792	9.8	1.0	9.8	13.0
UO ₂ Shipments	9,732	22.4	1.8	22.5	68.1
Waste Discards:					
Liquid	10	0.5	<0.1	0.5	<0.1
Process Residue	10	0.7	0.1	0.7	0.1
Solid Scrap	20	2.4	0.7	2.5	0.8
Ending Inventory	2,722	7.4	5.9	9.5	9.0
Material Unaccounted For	20	25.9	8.5	27.3	
(Percent of Thruput)	0.2%	0.3%	0.1%	0.3%	

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APPENDIX C
PROBABILITY CURVES
FOR DETECTING URANIUM DIVERSION

FIGURE C-1. Probability Curves for Detecting Uranium Diversion in Low-Enriched UO_2 Conversion Facilities for a Material Balance Span of Three Months, General Performance Model

FIGURE C-2. Probability Curves for Detecting Uranium-235 Diversion in Low-Enriched UO_2 Conversion Facilities for a Material Balance Span of Three Months, General Performance Model

FIGURE C-3. Probability Curves for Detecting Uranium Diversion in Low-Enriched UO_2 Conversion Facilities for a Material Balance Span of Six Months, General Performance Model

FIGURE C-4. Probability Curves for Detecting Uranium-235 Diversion in Low-Enriched UO₂ Conversion Facilities for a Material Balance Span of Six Months, General Performance Model

FIGURE C-5. Probability Curves for Detecting Uranium Diversion in Low-Enriched UO₂ Conversion Facilities for a Material Balance Span of One Year, General Performance Model

FIGURE C-6. Probability Curves for Detecting Uranium-235 Diversion in Low-Enriched UO₂ Conversion Facilities for a Material Balance Span of One Year, General Performance Model

FIGURE C-7. Probability Curves for Detecting Uranium Diversion in Low-Enriched UO_2 Conversion Facilities for a Material Balance Span of Three Months, General Capability Model

FIGURE C-8. Probability Curves for Detecting Uranium-235 Diversion in Low-Enriched UO₂ Conversion Facilities for a Material Balance Span of Three Months, General Capability Model

FIGURE C-9. Probability Curves for Detecting Uranium Diversion in Low-Enriched UO_2 Conversion Facilities for a Material Balance Span of Six Months, General Capability Model

FIGURE C-10. Probability Curves for Detecting Uranium-235 Diversion in Low-Enriched UO_2 Conversion Facilities for a Material Balance Span of Six Months, General Capability Model

FIGURE C-11. Probability Curves for Detecting Uranium Diversion in Low-Enriched UO_2 Conversion Facilities for a Material Balance Span of One Year, General Capability Model

FIGURE C-12. Probability Curves for Detecting Uranium-235 Diversion in Low-Enriched UO₂ Conversion Facilities for a Material Balance Span of One Year, General Capability Model

FIGURE C-13. Probability Curves for Detecting Uranium Diversion in Low-Enriched UO_2 Fabrication Facilities for a Material Balance Span of Three Months, General Performance Model

FIGURE C-14. Probability Curves for Detecting Uranium-235 Diversion in Low-Enriched UO_2 Fabrication Facilities for a Material Balance Span of Three Months, General Performance Model

FIGURE C-15. Probability Curves for Detecting Uranium Diversion in Low-Enriched UO_2 Fabrication Facilities for a Material Balance Span of Six Months, General Performance Model

FIGURE C-16. Probability Curves for Detecting Uranium-235 Diversion in Low-Enriched UO_2 Fabrication Facilities for a Material Balance Span of Six Months, General Performance Model

FIGURE C-17. Probability Curves for Detecting Uranium Diversion in Low-Enriched UO_2 Fabrication Facilities for a Material Balance Span of One Year, General Performance Model

FIGURE C-18. Probability Curves for Detecting Uranium-235 Diversion in Low-Enriched UO₂ Fabrication Facilities for a Material Balance Span of One Year, General Performance Model

FIGURE C-19. Probability Curves for Detecting Uranium Diversion in Low-Enriched UO₂ Fabrication Facilities for a Material Balance Span of Three Months, General Capability Model

FIGURE C-20. Probability Curves for Detecting Uranium-235 Diversion in Low-Enriched UO_2 Fabrication Facilities for a Material Balance Span of Three Months, General Capability Model

FIGURE C-21. Probability Curves for Detecting Uranium Diversion in Low-Enriched UO_2 Fabrication Facilities for a Material Balance Span of Six Months, General Capability Model

FIGURE C-22. Probability Curves for Detecting Uranium-235 Diversion in Low-Enriched UO_2 Fabrication Facilities for a Material Balance Span of Six Months, General Capability Model

FIGURE C-23. Probability Curves for Detecting Uranium Diversion in Low-Enriched UO_2 Fabrication Facilities for a Material Balance Span of One Year, General Capability Model

FIGURE C-24. Probability Curves for Detecting Uranium-235 Diversion in Low-Enriched UO_2 Fabrication Facilities for a Material Balance Span of One Year, General Capability **Model**

FIGURE C-25. Probability Curves for Detecting Uranium Diversion in Low-Enriched UO_2 Conversion-Fabrication Facilities for a Material Balance Span of Three Months, General Performance Model

FIGURE C-26. Probability Curves for Detecting Uranium-235 Diversion in Low-Enriched UO_2 Conversion-Fabrication Facilities for a Material Balance Span of Three Months, General Performance Model

FIGURE C-27. Probability Curves for Detecting Uranium Diversion in Low-Enriched UO₂ Conversion-Fabrication Facilities for a Material Balance Span of Six Months, General Performance Model

FIGURE C-28. Probability Curves for Detecting Uranium-235 Diversion in Low-Enriched UO₂ Conversion-Fabrication Facilities for a Material Balance Span of Six Months, General Performance Model

FIGURE C-29. Probability Curves for Detecting Uranium Diversion in Low-Enriched UO_2 Conversion-Fabrication Facilities for a Material Balance Span of One Year, General Performance Model

FIGURE C-30. Probability Curves for Detecting Uranium-235 Diversion in Low-Enriched UO_2 Conversion-Fabrication Facilities for a Material Balance Span of One Year, General Performance Model

FIGURE C-31. Probability Curves for Detecting Uranium Diversion in Low-Enriched UO₂ Conversion-Fabrication Facilities for a Material Balance Span of Three Months, General Capability Model

FIGURE C-32. Probability Curves for Detecting Uranium-235 Diversion in Low-Enriched UO_2 Conversion-Fabrication Facilities for a Material Balance Span of Three Months, General Capability Model

FIGURE C-33. Probability Curves for Detecting Uranium Diversion in Low-Enriched UO₂ Conversion-Fabrication Facilities for a Material Balance Span of Six Months, General Capability Model

FIGURE C-34. Probability Curves for Detecting Uranium-235 Diversion in Low-Enriched UO₂ Conversion-Fabrication Facilities for a Material Balance Span of Six Months, General Capability Model

FIGURE C-35. Probability Curves for Detecting Uranium Diversion in Low-Enriched UO_2 Conversion-Fabrication Facilities for a Material Balance Span of One Year, General Capability Model

FIGURE C-36. Probability Curves for Detecting Uranium-235 Diversion in Low-Enriched UO₂ Conversion-Fabrication Facilities for a Material Balance Span of One Year, General Capability Model

APPENDIX D
SELECTED PROBABILITY TABLES
FOR DETECTING URANIUM DIVERSION

TABLE D-1 The Probability of Detecting Diversion as Material
Losses in a Low-Enriched UO₂ Conversion Plant

Type 1 Error of 10%

Amount of Diversion Uranium-235, kg	General Performance Model			General Capability Model		
	3 Months	6 Months	12 Months	3 Months	6 Months	12 Months
	Probability, %			Probability, %		
15	42	29	19	100	86	48
25	69	48	27	100	100	77
40	94	74	43	100	100	98
60	99	95	64	100	100	100
80	100	100	82	100	100	100
Total Uranium, lb						
1100	64	48	30	100	100	82
1800	92	76	48	100	100	99
2900	100	98	74	100	100	100
4400	100	100	94	100	100	100
5900	100	100	100	100	100	100

Assumptions: Nominal U Thruput 1 ton/day
 Nominal U-235 Enrichment 3%

All probability values are rounded to the nearest percent.

TABLE D-2 The Probability of Detecting Diversion as Material
Losses in a Low-Enriched UO₂ Fabrication Plant

Type 1 Error of 10%

Amount of Diversion Uranium-235, kg	General Performance Model			General Capability Model		
	3 Months	6 Months	12 Months	3 Months	6 Months	12 Months
	Probability, %			Probability, %		
15	27	23	18	84	62	35
25	44	35	25	99	91	59
40	69	55	34	100	100	87
60	91	79	52	100	100	99
80	99	94	69	100	100	100
Total Uranium, lb						
1100	35	30	23	99	93	68
1800	56	50	35	100	100	95
2900	84	78	57	100	100	100
4400	99	96	82	100	100	100
5900	100	100	93	100	100	100

Assumptions: Nominal ω Throughput 1 ton/day
 Nominal ω -235 Enrichment 3%

All probability values are rounded to the nearest percent.

TABLE D-3. The Probability of Detecting Diversion as Material Losses
in a Low-Enriched UO₂ Conversion-Fabrication Plant

Type 1 Error of 10%

Amount of Diversion Uranium-235, kg	General Performance Model			General Capability Model		
	3 Months	6 Months	12 Months	3 Months	6 Months	12 Months
	Probability, %			Probability, %		
15	26	23	18	85	69	43
25	41	35	25	100	96	71
40	65	56	38	100	100	96
60	89	80	57	100	100	100
80	98	94	75	100	100	100
Total Uranium, lb						
1100	31	28	25	98	93	74
1800	55	46	37	100	100	97
2900	79	74	59	100	100	100
4400	97	95	84	100	100	100
5900	100	100	96	100	100	100

Assumptions: Nominal U Thruput 1 ton/day
Nominal U-235 Enrichment 3%

All probability values are rounded to the nearest percent.

TABLE D-4 The Probability of Detecting Diversion as Material
Losses in a Low-Enriched UO₂ Conversion Plant

Type 1 Error of 5%

Amount of Diversion Uranium-235, kg	General Performance Model			General Capability Model		
	3 Months	6 Months	12 Months	3 Months	6 Months	12 Months
	Probability, %			Probability, %		
15	29	19	11	100	78	34
25	57	35	17	100	99	66
40	88	62	30	100	100	95
60	100	90	51	100	100	100
80	100	99	71	100	100	100
Total Uranium, lb						
1100	50	34	18	100	100	78
1800	86	64	34	100	100	99
2900	99	94	62	100	100	100
4400	100	100	91	100	100	100
5900	100	100	99	100	100	100

Assumptions: Nominal U Thruput 1 ton/day
 Nominal U-235 Enrichment 3%

All probability values are rounded to the nearest percent.

TABLE D-5. The Probability of Detecting Diversion as Material Losses in a Low-Enriched UO₂ Fabrication Plant

Type 1 Error of 5%

Amount of Diversion Uranium-235. kg	General Performance Model			General Capability Model		
	3 Months	6 Months	12 Months	3 Months	6 Months	12 Months
	Probability, %			Probability, %		
15	17	14	10	74	48	23
25	31	22	15	98	84	44
40	56	41	23	100	100	78
60	84	68	39	100	100	98
80	97	88	57	100	100	100
Total Uranium, lb	3 Months	6 Months	12 Months	3 Months	6 Months	12 Months
1100	22	20	14	96	87	56
1800	42	36	23	100	100	89
2900	74	66	43	100	100	100
4400	96	92	71	100	100	100
5900	100	99	91	100	100	100

Assumptions: Nominal U Thruput 1 ton/day

Nominal U-235 Enrichment 3%

All probability values are rounded to the nearest percent.

TABLE D-6 The Probability of Detecting Diversion as Material Losses
in a Low-Enriched UO₂ Conversion-Fabrication Plant

Type 1 Error of 5%

Amount of Diversion Uranium-235, kg	General Performance Model			General Capability Model		
	3 Months	6 Months	12 Months	3 Months	6 Months	12 Months
	Probability, %			Probability, %		
15	17	14	10	75	56	30
25	29	23	15	99	91	58
40	52	42	26	100	100	90
60	81	69	43	100	100	100
80	96	89	62	100	100	100
Total Uranium, lb						
1100	20	18	15	94	87	62
1800	37	33	24	100	100	94
2900	68	61	46	100	100	100
4400	94	90	74	100	100	100
5900	100	99	92	100	100	100

Assumptions: Nominal U Thruput 1 ton/day
 Nominal U-235 Enrichment 3%

All probability values are rounded to the nearest percent.

TABLE D-7. The Probability of Detecting Diversion as Material Losses in a Low-Enriched UO₂ Conversion Plant

Type 1 Error of 1%

Amount of Diversion Uranium-235, kg	General Performance Model			General Capability Model		
	3 Months	6 Months	12 Months	3 Months	6 Months	12 Months
	p r o b a b i l i t y , %			P r o b a b i l i t y , %		
15	10	6	3	98	53	13
25	29	14	6	100	95	39
40	69	35	12	100	100	82
60	97	72	25	100	100	100
80	100	94	45	100	100	100
Total Uranium, 1b						
1100	26	14	6	100	100	54
1800	64	37	13	100	100	95
2900	98	81	35	100	100	100
4400	100	100	73	100	100	100
5900	100	100	95	100	100	100

Assumptions: Nominal U Thruput 1 ton/day
 Nominal U-235 Enrichment 3%

All probability values are rounded to the nearest percent.

TABLE D-8. The Probability of Detecting Diversion as Material Losses in a Low-Enriched UO₂ Fabrication Plant

Type 1 Error of 1%

Amount of Diversion Uranium-235, kg	General Performance Model			General Capability Model		
	3 Months	6 Months	12 Months	3 Months	6 Months	12 Months
	Probability, %			Probability, %		
15	5	4	3	49	23	8
25	11	8	4	93	62	21
40	29	18	8	100	97	53
60	62	41	16	100	100	90
80	89	68	30	100	100	100
Total Uranium, lb						
1100	8	7	4	86	67	32
1800	19	15	8	100	99	70
2900	49	38	20	100	100	99
4400	89	77	45	100	100	100
5900	99	96	73	100	100	100

Assumptions: Nominal U Thruput 1 ton/day
 Nominal U-235 Enrichment 3%

All probability values are rounded to the nearest percent.

**TABLE D-9. The Probability of Detecting Diversion as Material Losses
in a Low-Enriched UO₂ Conversion-Fabrication Plant**

Type 1 Error of 1%

Amount of Diversion Uranium-235, kg	General Performance Model			General Capability Model		
	3 Months	6 Months	12 Months	3 Months	6 Months	12 Months
	Probability, %			Y r o b a b i l i t y , %		
15	5	4	3	48	30	11
25	11	8	5	93	74	31
40	26	19	9	100	99	73
60	58	42	20	100	100	98
80	85	70	36	100	100	100
Total Uranium, lb	3 Months	6 Months	12 Months	3 Months	6 Months	12 Months
1100	6	6	5	81	67	35
1800	16	13	8	100	99	80
2900	40	34	21	100	100	100
4400	80	72	48	100	100	100
5900	98	94	77	100	100	100

Assumptions: Nominal U Thruput 1 ton/day
Nominal U-235 Enrichment 3%

All probability values are rounded to the nearest percent.

APPENDIX E

TABLES

DETECTION THRESHOLDS FOR URANIUM LOSSES

TABLE E-1. Minimum Thresholds for Detecting Uranium-235 Losses with a Probability of 90% at Typical Low-Enriched UO_2 Production Facilities

Type 1 Error of 10%

		UO_2 Conversion kg (%)		UO_2 Fabrication kg (%)		UO_2 Conversion- Fabrication kg (%)	
<u>General Performance</u>							
3 Months		36	(1.4)	58	(2.4)	60	(2.5)
6 Months		53	(1.1)	72	(1.5)	72	(1.5)
12 Months		92	(0.9)	114	(1.2)	104	(1.1)
<u>General Capability</u>							
3 Months		9	(0.4)	17	(0.7)	16	(0.6)
6 Months		16	(0.3)	24	(0.5)	22	(0.4)
12 Months		32	(0.3)	42	(0.4)	34	(0.3)
Assumptions:	Nominal U Thruput			1 ton/day			
	Nominal U-235 Enrichment			3%			

All percentage values are related to plant thruput.

TABLE E-2. Minimum Thresholds for Detecting Uranium-235 Losses with a Probability of 90% at Typical Low-Enriched UO_2 Production Facilities

Type 1 Error of 5%

		UO_2 Conversion kg (%)		UO_2 Fabrication kg (%)		UO_2 Conversion- Fabrication kg (%)	
<u>General Performance</u>							
3 Months		41	(1.7)	65	(2.7)	70	(2.9)
6 Months		60	(1.2)	84	(1.7)	83	(1.7)
12 Months		106	(1.1)	142	(1.5)	120	(1.2)
<u>General Capability</u>							
3 Months		10	(0.4)	19	(0.8)	19	(0.8)
6 Months		18	(0.4)	28	(0.6)	25	(0.5)
12 Months		36	(0.4)	49	(0.5)	40	(0.4)
Assumptions:	Nominal U Thruput			1 ton/day			
	Nominal U- 235 Enrichment			3%			

All percentage values are related to plant thruput.

TABLE E-3. Minimum Thresholds for Detecting Uranium-235 Losses with a Probability of 90% at Typical Low-Enriched UO₂ Production Facilities

Type 1 Error of 1%							
		UO ₂ Conversion		UO ₂ Fabrication		UO ₂ Conversion Fabrication	
		kg	(%)	kg	(%)	kg	(%)
<u>General Performance</u>							
3 Months		51	(2.0)	82	(3.3)	66	(2.6)
6 Months		74	(1.5)	104	(2.1)	100	(2.0)
12 Months		131	(1.3)	164	(1.6)	148	(1.5)
<u>General Capability</u>							
3 Months		12	(0.4)	24	(0.9)	24	(0.9)
6 Months		23	(0.4)	34	(0.6)	30	(0.6)
12 Months		44	(0.4)	60	(0.6)	49	(0.5)
Assumptions:	Nominal U Thruput			1 ton/day			
	Nominal U-235 Enrichment			3%			

All percentage values are related to plant thruput.

TABLE E-4. Minimum Thresholds for Detecting Uranium-235 Losses with a Probability of 80% at Typical Low-Enriched UO₂ Production Facilities

Type 1 Error of 10%							
		UO ₂ Conversion		UO ₂ Fabrication		UO ₂ Conversion Fabrication	
		kg	(%)	kg	(%)	kg	(%)
<u>General Performance</u>							
	3 Months	30	(1.2)	48	(2.0)	50	(2.0)
	6 Months	44	(0.9)	60	(1.2)	60	(1.2)
	12 Months	76	(0.7)	96	(1.0)	88	(0.9)
<u>General Capability</u>							
	3 Months	8	(0.3)	14	(0.6)	14	(0.6)
	6 Months	14	(0.3)	20	(0.4)	18	(0.4)
	12 Months	26	(0.3)	36	(0.4)	28	(0.3)
Assumptions:	Nominal U Thruput			1 ton/day			
	Nominal U-235 Enrichment			3%			

All percentage values are related to plant thruput.

TABLE E-5. Minimum Thresholds for Detecting Uranium-235 Losses with a Probability of 80% at Typical Low-Enriched UO₂ Production Facilities

Type 1 Error of 5%

	UO ₂ Conversion kg (%)		UO ₂ Fabrication kg (%)		UO ₂ Conversion- Fabrication kg (%)	
<u>General Performance</u>						
3 Months	35	(1.4)	56	(2.3)	59	(2.4)
6 Months	51	(1.0)	71	(1.5)	69	(1.4)
12 Months	90	(0.9)	112	(1.2)	102	(1.0)
<u>General Capability</u>						
3 Months	8	(0.3)	16	(0.7)	16	(0.7)
6 Months	16	(0.3)	24	(0.5)	21	(0.4)
12 Months	31	(0.3)	42	(0.4)	34	(0.3)

Assumptions: Nominal U Thruput 1 ton/day

Nominal U-235 Enrichment 3%

All percentage values are related to plant thruput.

TABLE E-6. Minimum Thresholds for Detecting Uranium-235 Losses with a Probability of 80% at Typical Low-Enriched UO₂ Production Facilities

Type 1 Error of 1%

	UO ₂ Conversion		UO ₂ Fabrication		UO ₂ Conversion- Fabrication	
	kg	(%)	kg	(%)	kg	(%)
<u>General Performance</u>						
3 Months	45	(1.8)	72	(3.0)	76	(3.1)
6 Months	66	(1.3)	91	(1.9)	89	(1.8)
12 Months	116	(1.2)	144	(1.5)	130	(1.3)
<u>General Capability</u>						
3 Months	11	(0.4)	21	(0.9)	21	(0.9)
6 Months	20	(0.4)	30	(0.6)	27	(0.6)
12 Months	39	(0.4)	53	(0.5)	43	(0.4)

Assumptions: Nominal U Thruput 1 ton/day

Nominal U-235 Enrichment 3%

All percentage values are related to plant thruput.

TABLE E-7. Minimum Thresholds for Detecting Uranium-235 Losses with a Probability of 70% at Typical Low-Enriched UO₂ Production Facilities

Type 1 Error of 10%

		UO ₂ conversion		UO ₂ Fabrication		UO ₂ Conversion- Fabrication	
		kg	(%)	kg	(%)	kg	(%)
<u>General Performance</u>							
3 Months		26	(1.1)	40	(1.7)	44	(1.8)
6 Months		37	(0.7)	52	(1.1)	50	(1.0)
12 Months		66	(0.6)	81	(0.8)	74	(0.7)
<u>General Capability</u>							
3 Months		6	(0.2)	12	(0.5)	12	(0.5)
6 Months		12	(0.2)	17	(0.3)	16	(0.3)
12 Months		22	(0.2)	30	(0.3)	24	(0.2)
Assumptions:	Nominal U Thruput			1 ton/day			
	Nominal U-235 Enrichment			3%			

All percentage values are related to plant thruput.

TABLE E-8. Minimum Thresholds for Detecting Uranium-235 Losses with a Probability of 70% at Typical Low-Enriched UO₂ Production Facilities

Type 1 Error of 5%

	UO ₂ Conversion		UO ₂ Fabrication		UO ₂ Conversion- Fabrication	
	kg	%	kg	(%)	kg	(%)
<u>General Performance</u>						
3 Months	30	(1.2)	44	(1.8)	52	(2.1)
6 Months	45	(0.9)	61	(1.3)	61	(1.2)
12 Months	79	(0.8)	97	(1.0)	88	(0.9)
<u>General Capability</u>						
3 Months	7	(0.3)	14	(0.6)	14	(0.6)
6 Months	14	(0.3)	20	(0.4)	18	(0.4)
12 Months	26	(0.3)	36	(0.4)	29	(0.3)
Assumptions:	Nominal U Thruput		1 ton/day			
	Nominal U-235 Enrichment		3%			

All percentage values are related to plant thruput.

TABLE E-9. Minimum Thresholds for Detecting Uranium-235 Losses with a Probability of 70% at Typical Low-Enriched UO₂ Production Facilities

Type 1 Error of 1%

	UO ₂ Conversion		UO ₂ Fabrication		UO ₂ Conversion- Fabrication	
	kg	(%)	kg	(%)	kg	(%)
<u>General Performance</u>						
3 Months	40	(1.6)	64	(2.6)	68	(2.7)
6 Months	59	(1.2)	81	(1.6)	80	(1.6)
12 Months	104	(1.0)	130	(1.3)	116	(1.1)
<u>General Capability</u>						
3 Months	10	(0.4)	18	(0.7)	19	(0.7)
6 Months	18	(0.3)	27	(0.5)	24	(0.4)
12 Months	35	(0.3)	48	(0.4)	38	(0.3)

Assumptions: Nominal U Thruput 1 ton/day
 Nominal U-235 Enrichment 3%

All percentage values are related to plant thruput.

TABLE E-10. Minimum Thresholds for Detecting Uranium-235 Losses with a Probability of 50% at Typical Low-Enriched UO₂ Production Facilities

Type 1 Error of 10%

	UO ₂ Conversion		UO ₂ Fabrication		UO ₂ Conversion- Fabrication	
	kg	(%)	kg	(%)	kg	(%)
<u>General Performance</u>						
3 Months	18	(0.7)	28	(1.2)	30	(1.2)
6 Months	26	(0.5)	36	(0.7)	36	(0.7)
12 Months	47	(0.4)	57	(0.6)	52	(0.5)
<u>General Capability</u>						
3 Months	5	(0.2)	8	(0.3)	8	(0.3)
6 Months	8	(0.2)	12	(0.2)	11	(0.2)
12 Months	16	(0.2)	22	(0.2)	18	(0.2)

Assumptions: Nominal U Thruput 1 ton/day
 Nominal U-235 Enrichment 3%

All percentage values are related to plant thruput.

TABLE E-11. Minimum Thresholds for Detecting Uranium-235 Losses with a Probability of 50% at Typical Low-Enriched UO_2 Production Facilities

Type 1 Error of 5%

	UO_2 Conversion		UO_2 Fabrication		UO_2 Conversion- Fabrication	
	kg	(%)	kg	(%)	kg	(%)
<u>General Performance</u>						
3 Months	23	(0.9)	36	(1.5)	39	(1.6)
6 Months	34	(0.7)	47	(1.0)	46	(0.9)
12 Months	59	(0.6)	73	(0.7)	67	(0.7)
<u>General Capability</u>						
3 Months	6	(0.2)	10	(0.4)	11	(0.4)
6 Months	10	(0.2)	16	(0.3)	14	(0.3)
12 Months	20	(0.2)	27	(0.3)	22	(0.2)
Assumptions:	Nominal U Thruput		1 ton/day			
	Nominal U-235 Enrichment		3%			

All percentage values are related to plant thruput.

TABLE E-12. Minimum Thresholds for Detecting Uranium-235 Losses with a Probability of 50% at Typical Low-Enriched UO_2 Production Facilities

Type 1 Error of 1%

	UO_2 Conversion		UO_2 Fabrication		UO_2 Conversion- Fabrication	
	kg	(%)	kg	(%)	kg	(%)
<u>General Performance</u>						
3 Months	33	(1.3)	52	(2.1)	56	(2.2)
6 Months	48	(0.9)	66	(1.3)	66	(1.3)
12 Months	84	(0.8)	105	(1.1)	96	(0.9)
<u>General Capability</u>						
3 Months	8	(0.3)	15	(0.6)	15	(0.6)
6 Months	14	(0.3)	22	(0.4)	20	(0.4)
12 Months	28	(0.3)	39	(0.4)	32	(0.3)
Assumptions:	Nominal U Thruput		1 ton/day			
	Nominal U-235 Enrichment		3%			

All percentage values are related to plant thruput.

TABLE E-13. Minimum Thresholds for Detecting Uranium Losses with a Probability of 90% at Typical Low-Enriched UO₂ Production Facilities

Type 1 Error of 10%

	UO ₂ Conversion		UO ₂ Fabrication		UO ₂ Conversion- Fabrication	
	lb	(%)	lb	(%)	lb	(%)
<u>General Performance</u>						
3 Months	1700	(0.9)	3200	(1.8)	3500	(2.0)
6 Months	2300	(0.6)	3700	(1.1)	3900	(1.1)
12 Months	3800	(0.5)	5200	(0.7)	5000	(0.7)
<u>General Capability</u>						
3 Months	300	(0.2)	800	(0.4)	900	(0.5)
6 Months	600	(0.2)	1000	(0.3)	1000	(0.3)
12 Months	1200	(0.2)	1600	(0.2)	1400	(0.2)
Assumptions:	Nominal U Thruput		1 ton/day			
	Nominal U-235 Enrichment		3%			

All percentage values are related to plant thruput.

TABLE E-14. Minimum Thresholds for Detecting Uranium Losses with a Probability of 90% at Typical Low-Enriched UO₂ Production Facilities

Type 1 Error of 5%

	UO ₂ Conversion		UO ₂ Fabrication		UO ₂ Conversion- Fabrication	
	lb	(%)	lb	(%)	lb	(%)
<u>General Performance</u>						
3 Months	2000	(1.1)	3700	(2.1)	4000	(2.2)
6 Months	2600	(0.7)	4200	(1.2)	4400	(1.2)
12 Months	4300	(0.6)	5900	(0.8)	5600	(0.8)
<u>General Capability</u>						
3 Months	400	(0.2)	900	(0.5)	1000	(0.6)
6 Months	600	(0.2)	1200	(0.3)	1200	(0.3)
12 Months	1400	(0.2)	1900	(0.3)	1700	(0.2)
Assumptions:	Nominal U Thruput		1 ton/day			
	Nominal U-235 Enrichment		3%			

All percentage values are related to plant thruput.

TABLE E-15. Minimum Thresholds for Detecting Uranium Losses with a Probability of 90% at Typical Low-Enriched UO₂ Production Facilities

Type 1 Error of 1%

	UO ₂ Conversion lb (%)	UO ₂ Fabrication lb (%)	UO ₂ Conversion- Fabrication lb (%)
<u>General Performance</u>			
3 Months	2400 (1.3)	4600 (2.5)	5000 (2.7)
6 Months	3200 (0.9)	5100 (1.4)	5400 (1.5)
12 Months	5400 (0.7)	7200 (1.0)	7000 (0.9)
<u>General Capability</u>			
3 Months	500 (0.3)	1100 (0.6)	1200 (0.6)
6 Months	800 (0.2)	1400 (0.4)	1400 (0.4)
12 Months	1700 (0.2)	2200 (0.3)	2000 (0.3)

Assumptions: Nominal U Thruput 1 ton/day
 Nominal U-235 Enrichment 3%

All percentage values are related to plant thruput.

TABLE E-16. Minimum Thresholds for Detecting Uranium Losses with a Probability of 80% at Typical Low-Enriched UO₂ Production Facilities

Type 1 Error of 10%

	UO ₂ Conversion lb (%)	UO ₂ Fabrication lb (%)	UO ₂ Conversion- Fabrication lb (%)
<u>General Performance</u>			
3 Months	1400 (0.8)	2600 (1.5)	3000 (1.7)
6 Months	1900 (0.5)	3000 (0.8)	3200 (0.9)
12 Months	3000 (0.4)	4200 (0.6)	4000 (0.6)
<u>General Capability</u>			
3 Months	300 (0.2)	700 (0.4)	700 (0.4)
6 Months	500 (0.1)	800 (0.2)	800 (0.2)
12 Months	1000 (0.1)	1300 (0.2)	1200 (0.2)

Assumptions: Nominal U Thruput 1 ton/day
 Nominal U-235 Enrichment 3%

All percentage values are related to plant thruput.

TABLE E-17. Minimum Thresholds for Detecting Uranium Losses with a Probability of 80% at Typical Low-Enriched UO_2 Production Facilities

Type 1 Error of 5%

	UO_2 Conversion lb (%)	UO_2 Fabrication lb (%)	UO_2 Conversion- Fabrication lb (%)
<u>General Performance</u>			
3 Months	1700 (0.9)	3100 (1.7)	3500 (1.9)
6 Months	2200 (0.6)	3500 (1.0)	3800 (1.1)
12 Months	3700 (0.5)	5000 (0.7)	4800 (0.7)
<u>General Capability</u>			
3 Months	300 (0.2)	800 (0.4)	900 (0.5)
6 Months	600 (0.2)	1000 (0.3)	1000 (0.3)
12 Months	1100 (0.2)	1500 (0.2)	1400 (0.2)

Assumptions: Nominal U Thruput 1 ton/day

Nominal U-235 Enrichment 3%

All percentage values are related to plant thruput.

TABLE E-18. Minimum Thresholds for Detecting Uranium Losses with a Probability of 80% at Typical Low-Enriched UO_2 Production Facilities

Type 1 Error of 1%

	UO_2 Conversion lb (%)	UO_2 Fabrication lb (%)	UO_2 Conversion- Fabrication lb (%)
<u>General Performance</u>			
3 Months	2100 (1.2)	4000 (2.2)	4400 (2.3)
6 Months	2900 (0.8)	4600 (1.2)	4700 (1.3)
12 Months	4800 (0.6)	6400 (0.9)	6200 (0.9)
<u>General Capability</u>			
3 Months	400 (0.2)	1000 (0.6)	1100 (0.6)
6 Months	800 (0.2)	1300 (0.4)	1300 (0.4)
12 Months	1400 (0.2)	2000 (0.3)	1800 (0.3)

Assumptions: Nominal U Thruput 1 ton/day

Nominal U-235 Enrichment 3%

All percentage values are related to plant thruput.

TABLE E-19. Minimum Thresholds for Detecting Uranium Losses with a Probability of 70% at Typical Low-Enriched UO₂ Production Facilities

Type 1 Error of 10%

	UO ₂ Conversion lb (%)	UO ₂ Fabrication lb (%)	UO ₂ Conversion- Fabrication lb (%)
<u>General Performance</u>			
3 Months	1200 (0.6)	2400 (1.3)	2600 (1.4)
6 Months	1700 (0.4)	2600 (0.7)	2700 (0.8)
12 Months	2700 (0.4)	3600 (0.5)	3400 (0.5)
<u>General Capability</u>			
3 Months	200 (0.1)	600 (0.3)	600 (0.3)
6 Months	400 (0.1)	700 (0.2)	700 (0.2)
12 Months	800 (0.1)	1100 (0.2)	1000 (0.1)
Assumptions:	Nominal U Thruput 1 ton/day		
	Nominal U-235 Enrichment 3%		

All percentage values are related to plant thruput.

TABLE E-20. Minimum Thresholds for Detecting Uranium Losses with a Probability of 70% at Typical Low-Enriched UO₂ Production Facilities

Type 1 Error of 5%

	UO ₂ Conversion lb (%)	UO ₂ Fabrication lb (%)	UO ₂ Conversion- Fabrication lb (%)
<u>General Performance</u>			
3 Months	1400 (0.8)	2800 (1.6)	3000 (1.7)
6 Months	1900 (0.5)	3000 (0.8)	3300 (0.9)
12 Months	3200 (0.4)	4400 (0.6)	4200 (0.6)
<u>General Capability</u>			
3 Months	300 (0.2)	700 (0.4)	800 (0.4)
6 Months	500 (0.1)	900 (0.3)	900 (0.3)
12 Months	1000 (0.1)	1400 (0.2)	1200 (0.2)
Assumptions:	Nominal U Thruput 1 ton/day		
	Nominal U-235 Enrichment 3%		

All percentage values are related to plant thruput.

TABLE E-21. Minimum Thresholds for Detecting Uranium Losses with a Probability of 70% at Typical Low-Enriched UO₂ Production Facilities

Type 1 Error of 1%

	UO ₂ Conversion lb (%)	UO ₂ Fabrication lb (%)	UO ₂ Conversion- Fabrication lb (%)
<u>General Performance</u>			
3 Months	1900 (1.0)	3600 (2.0)	4000 (2.2)
6 Months	2600 (0.7)	4200 (1.2)	4300 (1.2)
12 Months	4200 (0.5)	5800 (0.8)	5500 (0.8)
<u>General Capability</u>			
3 Months	400 (0.2)	900 (0.5)	1000 (0.5)
6 Months	700 (0.2)	1100 (0.3)	1100 (0.3)
12 Months	1300 (0.2)	1800 (0.3)	1600 (0.2)
Assumptions:	Nominal U Thruput 1 ton/day		
	Nominal U-235 Enrichment 3%		

All percentage values are related to plant thruput.

TABLE E-22. Minimum Thresholds for Detecting Uranium Losses with a Probability of 50% at Typical Low-Enriched UO₂ Production Facilities

Type 1 Error of 10%

	UO ₂ Conversion lb (%)	UO ₂ Fabrication lb (%)	UO ₂ Conversion- Fabrication lb (%)
<u>General Performance</u>			
3 Months	900 (0.5)	1600 (0.9)	1800 (1.0)
6 Months	1200 (0.3)	1800 (0.5)	1900 (0.5)
12 Months	1900 (0.3)	2600 (0.4)	2400 (0.3)
<u>General Capability</u>			
3 Months	200 (0.1)	400 (0.2)	400 (0.2)
6 Months	300 (0.1)	500 (0.1)	500 (0.1)
12 Months	600 (0.1)	800 (0.1)	700 (0.1)
Assumptions:	Nominal U Thruput 1 ton/day		
	Nominal U-235 Enrichment 3%		

All percentage values are related to plant thruput.

TABLE E-23. Minimum Thresholds for Detecting Uranium Losses with a Probability of 50% at Typical Low-Enriched UO₂ Production Facilities

Type 1 Error of 5%

	UO ₂ conversion lb (%)	UO ₂ Fabrication lb (%)	UO ₂ Conversion- Fabrication lb (%)
<u>General Performance</u>			
3 Months	1100 (0.6)	2000 (1.1)	2200 (1.2)
6 Months	1400 (0.4)	2300 (0.6)	2500 (0.7)
12 Months	2400 (0.3)	3000 (0.4)	3200 (0.4)
<u>General Capability</u>			
3 Months	200 (0.1)	500 (0.3)	600 (0.3)
6 Months	400 (0.1)	600 (0.2)	700 (0.2)
12 Months	700 (0.1)	1000 (0.1)	900 (0.1)
Assumptions:	Nominal U Thruput 1 ton/day		
	Nominal U-235 Enrichment 3%		

All percentage values are related to plant thruput.

TABLE E-24. Minimum Thresholds for Detecting Uranium Losses with a Probability of 50% at Typical Low-Enriched UO₂ Production Facilities

Type 1 Error of 1%

	UO ₂ Conversion lb (%)	UO ₂ Fabrication lb (%)	UO ₂ Conversion- Fabrication lb (%)
<u>General Performance</u>			
3 Months	1600 (0.9)	2900 (1.6)	3200 (1.7)
6 Months	2000 (0.5)	3400 (0.9)	3500 (0.9)
12 Months	3400 (0.4)	4600 (0.6)	4500 (0.6)
<u>General Capability</u>			
3 Months	300 (0.2)	700 (0.4)	800 (0.4)
6 Months	500 (0.1)	900 (0.2)	900 (0.2)
12 Months	1000 (0.1)	1400 (0.2)	1300 (0.2)
Assumptions:	Nominal U Thruput 1 ton/day		
	Nominal U-235 Enrichment 3%		

All percentage values are related to plant thruput.

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