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*SNM Holdup Assessment of
Los Alamos Exhaust Ducts
Final Report*

Los Alamos
NATIONAL LABORATORY

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SNM HOLDUP ASSESSMENT OF LOS ALAMOS EXHAUST DUCTS, FINAL REPORT

by

Robert S. Marshall

ABSTRACT

Fissile material holdup in glovebox and fume hood exhaust ducting has been quantified for all Los Alamos duct systems. Gamma-based, nondestructive measurements were used to quantify holdup. The measurements were performed during three measurement campaigns. The first campaign, Phase I, provided foot-by-foot, semiquantitative measurement data on all ducting. These data were used to identify ducting that required more accurate (quantitative) measurement. Phase I data were used to estimate holdup on those ducts or sections of ducts that indicated fissile holdup of less than 50 g. Of the 280 duct systems receiving Phase I measurements, 262 indicated less than 50 g of fissile holdup and 19 indicated fissile holdup of 50 or more grams.

Seven duct systems were measured in a second campaign, called Series 1, Phase II. These measurements were performed with state-of-the-art instrumentation and methods. Holdup estimates on these ducts ranged from 421 g of ^{235}U in a duct servicing a shut-down uranium-machining facility to 39 g of ^{239}Pu in a duct servicing an active plutonium-processing facility.

Measurements performed in the second campaign proved excessively laborious, so a third (Series 2, Phase II) campaign was initiated that used more efficient instrumentation at some sacrifice in measurement quality. Holdup estimates for the 12 duct systems measured during this third campaign ranged from 70 g of ^{235}U in a duct servicing analytical laboratories to 1 g of ^{235}U and 1 g of ^{239}Pu in a duct carrying exhaust air to a remote filter building.

These quantitative holdup estimates support the conclusion made at the completion of the Phase I measurements that only ducts servicing shut-down uranium operations contain about 400 g of fissile holdup. No ventilation ducts at Los Alamos contain sufficient fissile material holdup to present a criticality safety concern.

1.0. Introduction

On 14 June 1990, the Los Alamos National Laboratory received a request from the Department of Energy's (DOE's) Los Alamos Area Office (LAAO) to determine the quantity of fissile material held up in all ducts that have been exposed to plutonium materials. The principal purpose for this determination was to ensure that fissile materials had not accumulated to a degree that could lead to a criticality event under any credible accident scenario.

The Laboratory provided LAAO and DOE's Albuquerque Operations Office (AL) with a two-phase measurement plan¹ on 6 July 1990, and the plan was approved by AL. This plan recommended a two-phase measurement program in which the first phase (Phase I) would provide survey-quality data on virtually every foot of glovebox exhaust ducting and allow estimation and stratification of holdup values for all ducting. Data from the Phase I measurements would be used to generate a graded sampling plan that would call for careful quantitative measurement of all "hot spots" and a statistical sampling of other duct locations indicating lesser holdup. The second phase of this plan (Phase II) would provide (1) accurate, quantitative measurements for selected duct segments, (2) a basis for bias-correcting any Phase I semiquantitative measurement results used, and (3) data needed for estimating Phase I and Phase II measurement uncertainties.

Phase I measurements began on 4 October 1990 and were completed on 23 January 1991. Follow-on measurements provided isotope identification, addressed a building not included in the June 1990 plan, and provided adequate-quality holdup estimates for ducting scheduled for removal. Phase I results were reported in Ref. 2.

An initial (Series 1) Phase II measurement campaign began on 28 April 1991 and was completed in December 1991. With these measurements, we quantified duct holdup for six Laboratory rooms that had been identified by Phase I measurements as candidates for having high levels of special nuclear material (SNM) holdup. A second (Series 2) Phase II measurement campaign began in June 1992 and ended in November 1992. These measurements provided duct holdup data for the remaining 12 "rooms" identified by the Phase I measurements as requiring quantitative holdup measurements. The term "rooms" refers to duct systems bounded by either a room or, in the case of ducts at TA-21, some duct systems having definitive boundaries such as a building wall or filter plenum.

This report addresses the Series 1 and 2 holdup measurement campaigns in two separate sections because different measurement strategies and instruments were employed. Some Laboratory technical areas received holdup measurements from both campaigns. In this report we describe holdup measurements, estimate fissile holdup, analyze holdup estimate uncertainties, and summarize the total holdup from a criticality safety perspective.

Throughout this document, the term "counting statistics" is used. This term refers to the combination of uncertainties in the counting data used to calculate a net, corrected peak area. The "counting statistic" for an accumulated count (a gross count, a background count, and so forth) is approximated by the square root of the accumulated count.

This report discusses at length the uncertainty (error) terms on duct holdup

estimates. Reports on holdup estimates typically contain very limited discussion on the source of uncertainty terms. This "omission" reflects the general lack of knowledge both of the identity of variables and of the effect of variables confounding all but the most simple holdup measurements. Our discussion of uncertainty terms attempts to identify major uncertainty components, to estimate numeric values for these components, and to combine these values to estimate the total uncertainty on duct holdup values. Although the treatments on individual uncertainty terms and the combination of these terms are likely to stimulate debate, the reader should recognize (1) the repeated application of conservative (worst case) assumptions to ensure that the uncertainty of stated duct holdup values are not underestimated and (2) that different treatments on individual uncertainty terms are not likely to appreciably change the total uncertainty statement for the holdup in each duct system.

Note also numerous conservative assumptions made in the determination of the stated holdup values. These assumptions were made to ensure that the Laboratory does not understate fissile holdup in any duct system. Because efforts have been made never to understate holdup and uncertainty estimates, in the interest of further safety enhancements, the reader is cautioned to avoid additional adjustments to the data.

2.0. Scope

The Phase I measurement program identified 19 Laboratory rooms at 5 technical areas requiring Phase II measurements. The criterion used to select these rooms was that the Phase I semiquantitative measurements indicated that the room contained more than 50 g of fissile holdup. This conservative value is far below the 400 g/duct criterion specified by DOE.³ It allows not only for very large uncertainties in the Phase I measurements but also for the remote possibility that all the duct holdup from contiguous rooms might accidentally accumulate at one location. The ducting specified under this criterion represents only 6% of the 32 400 ft of ducting surveyed under the Phase I program. Table I shows the location and Phase I holdup estimates for those areas requiring Phase II measurement or dismantlement and disposal (D&D).

This report addresses the Series 1 and 2, Phase II measurements on all but 3 of the 19 rooms listed in Table I. It describes the instrumentation and methodology used for Phase II measurements, discusses measurement uncertainties pertinent to these measurements, and states the probability that duct system fissile holdup exceeds 400 g.

One room listed in Table I, Technical Area (TA) -3/SM-66 Basement, does not require Phase II measurement or, in a sense, has already received Phase II measurements. Quantitative holdup measurements were completed on this room under a task separate from the Phase II effort. A description of this measurement effort is contained in the Phase I report.² The 91 g of ²³⁵U holdup listed in Table I for this room is final.

Table I. Rooms in Which Fissile Holdup > 50 g

Facility	Room	Phase I Holdup (g)
TA-3/SM-29	4023	535 U
TA-3/SM-29	7034	290 U
TA-21/DP	413	266 U
TA-21/DP	413 roof	227 U
TA-3/SM-29	5034	219 U
TA-3/SM-29	4034	193 U
TA-21/DP	408	157 U
TA-21/DP	313	85 U
TA-21/DP	W3 roof	89 Pu
TA-3/SM-66	Basement	91 U
TA-3/SM-29	7057A	67 U
TA-3/SM-29	7132	68 U
TA-3/SM-29	4095	63 U
TA-50	SM-69	61 U
TA-3/SM-29	2023	58 Pu
TA-55/PF-4	429	53 Pu
TA-21/DP	Outside	53 Pu
TA-48	Hot cells	NA ^a
TA-3/SM-102	Shop 13	NA ^b

^aNot available.^bMeasured by Group N-1 June 1992.

Three rooms listed in Table I are in locations in which nuclear activities have been suspended and are scheduled for D&D. Dismantlement of ducts in rooms 408 and 413 at TA-21 will be completed in 1993, the ducting at TA-3/SM-66 was dismantled in early 1993, and the TA-3/SM-102 ducting is scheduled for 1993 D&D. The ducting at TA-3/SM-102 was measured by members of the Laboratory's Safeguards Assay group as described in Sec. 5.5 and Appendix P.

3.0. Fissile Holdup—Criticality Safety Assessment

To facilitate criticality safety appraisals for each Los Alamos duct, we have estimated the probability that the actual fissile holdup could equal or exceed 400 g. The model used to estimate the probability is based on the assumption that repeated measurements of actual duct system holdup would generate a population of holdup values having Gaussian distribution and that the estimated measurement uncertainties are good approximations of the true measurement uncertainties. The model assumes that bias corrections have made. The quantity DELTA represents the number of standard deviation units; the quantity 400 g is above the measured holdup value:

$$\text{DELTA} = \frac{400 \text{ g} - \text{measured holdup in grams}}{1 \text{ standard deviation of the measured holdup}}$$

Once DELTA is determined, the probability that the duct holdup equals or exceeds 400 g can be determined from the Gaussian distribution. Appendix A contains a table used to determine the probability that the actual holdup is more than 400 g of fissile material.

For most of the duct systems, estimated holdup and holdup measurement uncertainties are sufficiently small that the calculated probability of the actual holdup exceeding 400 g is extremely small, about 10^{-10} to 10^{-15} . We have tried to assess all the major factors affecting holdup measurement uncertainty, but there are undoubtedly small factors that have not been addressed. These minor factors have little effect on the holdup uncertainty estimates stated but can have major effects on holdup probability estimates less than 10^{-6} . For this reason, if the calculated probability is less than 10^{-6} , we simply report $<10^{-6}$.

4.0. Series 1, Phase II Measurements

4.1. TA-21 Measurements

4.1.1. Room 313

4.1.1.1. Instrumentation. We conducted Phase I measurements using highly portable, simple-to-operate equipment. Highly efficient, rugged, low-cost, thallium-doped sodium iodide [NaI(Tl)] detectors 1 in. in both diameter and thickness were coupled with an Eberline Corp.* ESP-2 instrument with pulse height analyzer (PHA) option. The instrument was operated in the PHA mode with the threshold set at 150 keV and the window set to exclude gamma rays more energetic than 350 keV. The detector-photomultiplier package was collimated and shielded with 0.63 cm (0.25 in.) of lead. The "backside" of the phototube was covered with a 0.32-cm (0.125-in.) "washer" of lead. On the NaI detector end, the lead collimator-shield extended slightly (about 2 mm) beyond the face of the detector encapsulation, thereby providing the detector with a viewing angle somewhat less than 180° and protecting the detector from physical damage. The front of the NaI detector was covered with 0.030-in.-thick cadmium foil to reduce incident x-ray flux.

The Series 1, Phase II instrumentation used to perform holdup measurements at TA-21, room 313, was based on a compact, collimated, shielded NaI(Tl) detector developed at Los Alamos.⁴ The 1-in.-diam, 0.5-in.-thick NaI detector was coupled to a Davidson** Model 2056-4K portable multichannel analyzer (MCA). The cylindrical lead collimator was 1 in. in both diameter and depth. The net area of the 186-keV gamma-ray peak was obtained by subtraction of the counts in the continuum background region (241 to 291 keV) from counts in the peak region (161 to 211 keV). The low-resolution NaI detector option was acceptable for quantifying ^{235}U holdup at TA-21/DP because the ducting serviced areas dedicated to

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* Eberline Corp. 504 Airport Road, Santa Fe, NM 87501.

** D. S. Davidson Co., North Haven, Connecticut.

processing uranium that had a defined and limited range of isotopic composition. Examination of the digitized, low-resolution spectra acquired during these measurements confirmed the expected isotopic distributions.

We positioned the detector from below or from the sides of ducts using the "holdup tree" described in Appendix B. This robust, adjustable stand positioned the detector at heights ranging from 2 to 3.5 m above floor level. For measurements of ducting protruding through the roof of room 313, the detector was positioned manually, above the duct in most cases.

Finally, the thickness of the duct wall was determined with an ultrasonic thickness gauge (Panametrics,*** Model 5222).

4.1.1.2. Methodology

4.1.1.2.1. Holdup Model and Calibration. The holdup model and calibration used for Phase I measurements are described in Appendix C.

Phase II holdup measurements were performed consistent with a line-source model. We calibrated the instrument using the 186-keV gamma ray from an 8-g, highly enriched uranium reference disk (see Appendix D for details) in a point-source geometry. The calibration method entails first counting the source positioned in front of the detector (along the collimator axis) and then counting the source as it is moved through a series of lateral increments until it is beyond the detector/collimator field of view. The source-to-detector distance was large relative to the source dimension. This generalized-geometry calibration method is detailed in Appendix E.

4.1.1.2.2. Measurement Control. We checked the counting efficiency of the Phase I instrument at least twice daily by positioning a depleted uranium disk source on the face of the NaI detector and counting for 10 s. The count rate was compared with that observed for the source after initial energy calibration and remained within two relative standard deviations (~10%) of the initial measurement.

Measurement control checks were made on the Phase II instrumentation for both gain shift and bias. We checked gain shift using the 60-keV peak from a ^{241}Am source mounted on the detector and checked bias using a 0.5-g highly enriched uranium source counted at the time of calibration and again at least three times daily during the holdup measurement campaign. We also checked the gain shift on each spectrum acquired. Gain was adjusted if a shift exceeded one channel. Bias shift remained within three relative standard deviations (~3%) of the check source count rate.

4.1.1.2.3. Measurement Procedure and Data Reduction. We performed Phase I measurements at 1-ft intervals along the ducts by placing the shielded detector in contact with the duct and counting for 10 s. The shielded detector was clamped to a length of aluminum tubing so that adapters could be used to add additional lengths of tubing to position the detector on ducts up to 15 ft above floor level. For background measurements, we moved the detector laterally, "pointing" it at the

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*** Panametrics, Inc., Waltham, Massachusetts.

room ceiling, and counting for 10 s. If holdup seemed to vary appreciably between adjacent measurement locations, frequent background measurements were made. Background counts were subtracted from the total counts observed at applicable duct locations. Counts and location descriptions were recorded for each measurement. Assuming that the holdup was distributed as a narrow band along the inside bottom of the duct and that the detector "saw" a one-detector-diameter length (1 in.) of holdup, we converted the net counts observed to grams of ^{235}U in the 1-in. length of duct by dividing the counts by those observed during calibration from 1 g of ^{235}U as uranium oxide in a glass vial. We multiplied each gram-of-holdup-per-inch value by 12 to yield grams of holdup per foot and assumed that the holdup concentration was constant over 1-ft intervals. No duct attenuation corrections were necessary because the glass vial and the nominal 0.060-in. duct material attenuated the 186-keV gamma rays almost identically.

The Phase II measurement procedure and data reduction were predicated on generalizing the geometries of the duct holdup deposits as line sources. The detector was positioned so that the duct was centered in the detector's field of view and the total duct width was significantly less than half the full width of the field of view. The line-source measurement is subject to bias if a nonuniform deposit is measured in a single detector count at a single measurement location. To minimize this source of bias, three to nine contiguous locations were measured for each designated location, with the detector positioned to overlap the radial responses of adjacent measurements at the half maxima. Holdup deposits were assumed to be deposited on the bottoms of horizontal ducts and on all inner surfaces of vertical ducts. All assay results were corrected for the attenuation effects of the duct walls. Wall thickness was measured ultrasonically; wall thickness corrections varied from 10% to 20%. The calculated deposit thicknesses were sufficiently small that self-attenuation corrections were less than 1% and hence were not applied. The known radial response of the detector was used to correct the assay results (based on the infinitely-thin-line assumption) for an assumed finite width (one-half the duct width for horizontal ducts and the full duct width for vertical ducts) of the deposit. This correction, performed for each designated location, averaged approximately 1.2 because of the relatively large duct widths.

The region of interest for the 186-keV peak was 161 to 211 keV. We corrected this peak area for background continuum using integrated counts in the region 241–291 keV. We further corrected the resulting 186-keV peak count rate for room background using net background count rates measured every fourth duct measurement, on the average. To obtain the background count, we moved the detector laterally to view the room ceiling or walls but not the duct.

We converted the corrected, net 186-keV peak count rate for each measurement to grams of ^{235}U by multiplying the net count rate by the deposit-to-detector distance and by the line-source calibration constant derived from the generalized-geometry holdup calibration. We also corrected for the holdup deposit-width distribution and duct-wall attenuation. The resulting value for isotope mass per unit length for each contiguous measurement was averaged (with adjustments for end effects for the first and last of the contiguous measurements) and multiplied

by the length of duct between the first and last measurement to yield the mass of ^{235}U holdup for a length of duct containing the designated duct location.

4.1.1.3. Sampling Plan Phase I measurements were made at 1-ft intervals for all the ducting in room 313. A stratified sampling plan was used to select Phase I measurement locations with the goal of allocating the Phase II measurement resources in a cost-effective manner while providing adequate information to reduce total measurement uncertainty to well below the holdup estimate (that is, less than 100%). From purely a measurement accuracy standpoint, the best approach to estimating holdup is to measure carefully 100% of the ductwork with Phase II instrumentation and personnel. This approach is not cost effective, however, especially when operational history and Phase I data indicate that much of the ductwork contains very little material.

To stratify the Phase I measurement data, we selected identifiable "peaks" from the Phase I room 313 holdup profile (Appendix F). Five peaks, constituting about 50% of the indicated holdup, were selected as "high-holdup" strata. The remaining locations not included in the five peaks were identified as either "intermediate-holdup" or "low-holdup" strata. Eleven intermediate-strata and four low-strata locations were randomly selected. Based on the Phase I holdup estimates, the indicated holdup was as follows:

- low-holdup strata   <0.1 g/ft
- intermediate-holdup strata   0.1–1.0 g/ft
- high-holdup strata   >1 g/ft

These 20 locations were selected for Phase II measurement quantification. For those locations not selected (only intermediate- and low-holdup locations), holdup quantities were calculated from the Phase I measurement data after normalization. Normalization factors were calculated from ratios of the Phase II and Phase I measurement values for locations measured by both methods.

4.1.1.4. Phase II Results. As discussed in Sec. 4.1.1.3, the Phase II measurements were made not just at the 20 designated locations, but also at 3 to 9 Phase I locations contiguous with the selected Phase I location. The total of 75 Phase I locations were included in the Phase II measurements, which represents ~75 ft of the total ~315 ft of ducting associated with room 313. The Phase II ^{235}U measurements having favorable counting statistics (net, corrected 186-keV peak count rate at least 3 times the peak counting statistic) are detailed in Appendix G. The total estimated ^{235}U holdup for these measurements is 258 g.

4.1.1.5. Inclusion of Phase I Measurements. Approximately 240 ft of room 313 ducting received Phase I measurement only. All of this ducting is stratified as containing intermediate (0.1 to 1.0 g of ^{235}U per foot) or low (less than 0.1 g of ^{235}U per foot) holdup. By comparing the quantitative Phase II holdup values with the Phase I holdup values on duct segments measured by both methods, we were able to calculate a normalization factor (Phase II holdup/Phase I holdup) as described in

Sec. 4.1.1.7.1.3. This factor, 3.1, was used to normalize the 33.5 g of ^{235}U Phase I holdup for the 240 ft of ducting to 104 g of ^{235}U . Appendix G presents Phase I locations and measurement results.

4.1.1.6. Total Room Estimates. The total holdup estimate for room 313 is the sum of the holdup in the duct segments estimated from Phase I and Phase II measurements, as described in Secs. 4.1.1.4 and 4.1.1.5 above. This sum is 362 g of ^{235}U .

4.1.1.7. Uncertainty Estimates

4.1.1.7.1. Phase I

4.1.1.7.1.1. Counting statistics. The counting statistics on the Phase I net count rate, which includes the combined gross and background statistics, is a random error component that equals approximately 1% (at 1 standard deviation) of the total room holdup estimate.

4.1.1.7.1.2. Repeatability. Seven months after the initial Phase I measurements, a 10-ft section of decommissioned duct in room 313 was remeasured with the same Phase I instrumentation. This remeasurement of the duct section holdup agrees with the initial measurement to within 8%. This first-order estimate of Phase I repeatability includes both random and bias components. However, it appears that the 8% error is related mostly to the repositioning of the detector. As a result, we assume that the 8% uncertainty for the holdup calculated from the Phase I measurements is divided into a 6% random repositioning term and a 2% bias term. (The Phase I measurements were used to estimate holdup in several duct segments about 10 ft long, so the random component of this repeatability uncertainty term would be less than the 6% estimate for a single segment. However, because we lack more definitive information on this uncertainty term, we shall not reduce the 6% figure for estimating the uncertainty on the Phase I-based holdup estimate for those room duct segments for which holdup is estimated from Phase I measurements.)

4.1.1.7.1.3. Geometry/Model. The Phase I contact measurements assume that the holdup is located in a narrow band (1 to 2 cm wide) at the very bottom of the duct. The model also assumes that the holdup is uniform (that is, grams per unit length of duct) over 1-ft lengths of duct. Certainly this model is incorrect for many individual measurement locations as evidenced by some differences between Phase I and Phase II measurements. The modeling inaccuracies do seem to display some random attributes as the Phase I-Phase II comparisons (Table II) show Phase I location holdup estimates both higher and lower than the corresponding Phase II location holdup estimates. Theoretically, assuming the uncertainties in Phase II measurements are much less than those for Phase I measurements, we can estimate the Phase I geometry/model error terms by analyzing the difference between the Phase I and Phase II holdup estimates for duct segments measured by both methods. Table II lists Phase I and Phase II holdup estimates for commonly measured duct segments displaying intermediate and low holdup, wherein Phase I and Phase II measurement counting statistics were less than 3 times the net, corrected count rate.

Table II. Comparison of Phase I and Phase II Holdup Estimates on Duct Segments Displaying Intermediate and Low Holdup

Duct Segment Number	Phase II Holdup Est. Grams ²³⁵ U	Phase I Holdup Est. Grams ²³⁵ U	Phase II Est. Phase I Est.
62	29.3	4.7	6.2
73	3.0	1.2	2.5
92	5.5	1.2	4.6
150	27.1	4.5	6.0
181	0.86	0.49	1.8
231	8.8	3.6	2.4
258	4.1	4.4	0.93
268	15.5	21.2	0.73

The duct segment number refers to the location identified by the stratified location selection method. The more accurate Phase II estimate methodology required a series of contiguous Phase II measurements (three to nine), hence the term *duct segment*. Gram estimate values listed in columns 2 and 3 correspond to the Phase I and Phase II holdup estimated for the same segment, not simply the Phase I location.

The mean Phase II estimated/Phase I estimated value from Table II is 3.1. This value is used to bias-correct all Phase I holdup estimates for duct locations where Phase II measurements were not performed.

The uncertainty on the 3.1 bias correction factor cannot be definitively estimated from the standard deviation of the Phase II/Phase I estimates because the data do not display a normal distribution. Inspection of detailed Phase I and Phase II measurement data for all locations measured by both methods suggests that several variables are at play and that Phase I and Phase II comparative data are insufficient to isolate and evaluate these variables. For this reason, we recommend that a relative standard deviation (RSD) of 80% be used for the Phase I part of the room 313 holdup estimate. We further recommend that the 80% uncertainty estimate (1 RSD) be treated as a systematic uncertainty term. This recommendation is conservative (an overestimate) because the scatter in the Phase II/Phase I estimates listed in Table II suggests a sizable random component.

4.1.1.7.2. Phase II

4.1.1.7.2.1. Counting Statistics. Counting statistics for Phase II duct segment measurements varied from location to location but were less than 5% (1 relative standard deviation [1 RSD]) for high-holdup segments and in the 10% to 20% range in areas having poorer signal-to-noise properties. Because greater than 95% of the holdup estimated from the Phase II measurements resides in duct segments displaying high holdup, the contribution to the total Phase II holdup from counting statistics shall be estimated as 5% (1 RSD).

4.1.1.7.2.2. Repeatability. Measurements made at seven locations in room 313 on 29 April 1991 were repeated on 21 May 1991. The net, corrected count rates for these repeated measurements, listed in Table III, provide data from which the repeatability of Phase II measurements can be estimated. The measurements were made with the same instrumentation and were performed on locations identified with labels before the initial measurements.

Table III. Phase II Repeated Measurements			
Location No.	4/28 net cps	5/21 net cps	4/29 net cps
			5/21 net cps
150	7.27	6.8	1.07
62	4.82	4.1	1.18
73	15.43	17.4	0.89
268	10.13	11.1	0.91
231	2.07	1.7	1.21
258	5.22	6.8	0.77
181	0.73	1.0	0.73

From this limited data set, the mean and standard deviation calculated from the ratio of the count rate observed on the two different dates are 0.97 and 0.19, respectively. The mean value is not considered significantly different from unity.

The count-rate ratios differ from unity on both the high and low side, suggesting that the 0.19, 1σ estimate is predominately random in nature. The one standard deviation estimate for the repeatability term for a single measurement, in contrast to the ratio of two measurements, is $0.19/\sqrt{2} = 0.14$. By assuming that the seven individual measurements listed in Table III are equivalent to seven consecutive measurements on a single duct segment, we can approximate the repeatability term for a single Phase II duct measurement as 14%, 1 RSD.

The average number of Phase II measurements performed on a duct segment in Room 313, is five. The repeatability term for a duct with five measurements is about $14\%/\sqrt{5} = 6\%$.

The Phase II duct holdup estimate for room 313 was based on the sum of Phase II estimated holdup of 18 duct segments. We assume that the duct segment repeatability term acts principally as a random uncertainty. The relative repeatability term on the room total holdup estimates varies (approximately) with the inverse of the square root of the number of duct segments determined.

Therefore, the estimated repeatability uncertainty term for room 313 is $6\%/\sqrt{18} = 1.4\%$, 1 RSD.

4.1.1.7.2.3. Geometry/Model. Three factors introducing uncertainty relate to the difference between the modeled holdup distribution inside the ducts and the actual distribution. These factors are: (1) actual distance of deposit to the detector,

(2) effective width of the deposit and, (3) the deviation from linearity in the change in deposit concentration along the duct segment length. Because the holdup deposition is not actually known, the actual geometry/model uncertainty terms cannot be determined; however, upper bounds for these terms can be estimated. These upper bound effects of these three error sources are discussed below.

4.1.1.7.2.3.1. Detector-to-Deposit Distance. In the Phase II calculations, the detector-to-deposit distance is taken as the distance from the detector face to the duct midpoint for vertical ducts. This assumption is probably very good because deposition is probably uniformly distributed. In calculations for horizontal ducts, the detector-to-deposit distance is taken as the distance from the detector face to the duct bottom, which assumes the deposition to be located in the duct's bottom inside surface. Contact measurements of the horizontal ducts indicated highest holdup on the duct bottom and a rapid drop-off in holdup as the detector is raised above the duct bottom.

By assuming a worst case (but credible) holdup distribution over the lower quarter of horizontal ducts, one can estimate a worst case bias term. To calculate this estimate, we use the nominal room 313 duct diameter of 24 in. and nominal measurement distance of 36 in. We assume the holdup is in a thin layer covering one-fourth of the bottom of the duct with an effective center of mass located one-eighth of the duct diameter above the duct bottom. The effective deposit-to-detector distance is therefore 39 in. Because the line-source model takes holdup as an inverse-linear function of measurement distance, the difference between the nominal 36-in. distance used and the 39-in. effective distance introduces a worst case bias of -8%. We increase the Phase II estimate of room 429 duct holdup by this amount and assume the deposit-to-detector distance introduces an 8% random uncertainty to the Phase II holdup estimate.

4.1.1.7.2.3.2. Effective Width. Calculations of holdup in horizontal ducts include a "correction" for deposit width. This correction assumes the holdup to be distributed inside the duct with a deposit width equal to one-half the duct diameter. This assumption can introduce both positive and negative errors and is considered a source of random uncertainty. The actual effective deposit width is not known; however, upper bounds on this source of uncertainty can be estimated. The above-described nominal duct dimensions and measurement distance is used. We made deposit width corrections using the calibration data showing the detector count rate at various sideways movements of the point-calibration source. A plot of this lateral-displacement response curve is included as Appendix H. The correction factor compensates for count rate drop-off as the holdup deposit deviates from the theoretical infinitely thin line source to a deposit having finite width. For the nominal duct described, the correction factor is 1.18. From this factor, we conservatively estimate that the upper bound of the random uncertainty for the deposit width correction to be equal to the correction itself, that is, 18% relative at 1 standard deviation.

4.1.1.7.2.3.3. Nonlinear Holdup Concentration Along Duct Segment. This effect could introduce error into that fraction of a duct segment holdup associated with the "end" or "first and last" measurements along the duct segment. This error could be appreciable if the holdup concentration is highest at an "end" measurement location and if the holdup concentration varies in a nonlinear manner within the "end" measurement full width at half maximum (FWHM) "zone." Because all Phase II measurements of high-holdup locations were centered around the portion of the duct segment having the highest holdup concentration, it is unlikely that this source of error introduces as much as a 5% bias to the high-strata duct segment holdup estimates. Furthermore, this source of error is likely to display random characteristics, that is, lead to over- and underestimates of individual duct segment holdup. Therefore, this source of error is considered negligible for the room 313 holdup estimate.

4.1.1.7.2.4. Calibration. Uncertainty in the calibration performed with a well-characterized uranium metal foil source is dominated by uncertainties in the foil areal density (0.447 g/cm^2), in the counting statistics incurred during the generalized-geometry holdup calibration, and in the measurement of the source-to-detector distance.

We determined the foil areal density from the measured diameter and mass of the foil source. Uncertainties on these measured values introduces a bias in the calibration factor of about 1%.

The counting statistics in the calibration constant is an estimated 2.4%. In the determination of the constant itself, this term is a random uncertainty; however, because the constant is multiplied by all Phase II measurements to convert counting data to mass of ^{235}U , the term behaves as a systematic uncertainty in the duct segment and total room holdup estimate.

The line-source calibration constant is expressed as count rate per gram of ^{235}U at a known detector-to-line source distance. The source-to-detector distance is measured during calibration and has an estimated uncertainty of 2 mm, which is 0.4% of the 500-mm measurement distance.

As the calibration constant is applied, these three uncertainty term exhibit systematic error properties. Though some of these systematic uncertainty terms may reasonably offset one another (introduce biases of opposite sign), we shall make the worst case assumption that they are additive and assign a systematic uncertainty to the Phase II calibration of 3.8%.

4.1.1.7.2.5. Other Components. Many additional sources of uncertainty exist; however, conditions were controlled (long count times, frequent instrument checks, adjustments as necessary, and so forth) to reduce to a negligible level the combined effect of all known additional sources of error.

4.1.1.7.3. Combined Phase I and Phase II Uncertainties. Uncertainties associated with the duct segment holdup estimated from Phase I and Phase II measurements are summarized in Table IV.

Table IV. Phase I and II Estimated Uncertainties, 1 RSD			
Phase	Source	Uncertainty	
		Systematic (%)	Random (%)
Phase I	Counting statistic	<1	1
	Repeatability	2	6
	Geometry/model	80	<1
Phase II	Counting statistic	<1	5
	Repeatability	<1	1.4
	Geometry/model		
	Distance	<1 ^a	8
	Width	<1	18
	Nonlinearity	<1	<1
	Calibration	3.8	<1
^a An 8% distance bias correction is applied to raise Phase II duct segment holdup from 258 g to 279 g of ²³⁵ U.			

The Phase I uncertainty terms listed in Table IV are applied to the duct segment holdup estimated from Phase I measurements (104 g of ²³⁵U). The Phase II uncertainty terms are applied to the duct segments having holdup estimated from Phase II measurements (279 g). The systematic uncertainty terms may be positive or negative; however, they are summed to represent a "worst case" situation. Random uncertainty terms are added in quadrature. The combined uncertainty estimates (as 1 standard deviation) for Phase I and Phase II holdup estimates are as follows:

- Systematic uncertainty on Phase I holdup estimate = 85 g of ²³⁵U
- Random uncertainty on Phase I holdup estimate = 6 g of ²³⁵U
- Systematic uncertainty on Phase II holdup estimate = 11 g of ²³⁵U
- Random uncertainty on Phase II holdup estimate = 57 g of ²³⁵U

In the "worst case" approach, the uncertainties for the Phase I and Phase II holdup estimates are combined as follows:

1. Systematic uncertainties are added, $85 + 11 = 96$.
2. Random uncertainties are added in quadrature, $(6^2 + 57^2)^{0.5} = 57$.
3. Combined systematic and random terms are added, $96 + 57 = 153$.

On this basis, the total room 313 estimated holdup of 385 g of ²³⁵U has a 1 standard deviation estimated uncertainty of 153 g of ²³⁵U.

4.1.2. Room 413R

4.1.2.1. Instrumentation. Instrumentation used for the Phase 1 and Phase 2 measurements are described in Sec. 4.1.1.1.

4.1.2.2. Methodology. The Phase I and II methodology used for room 413R ducts is the same as that described in Sec. 4.1.1.2. Duct wall attenuation corrections for Phase II results ranged from 20% to 30%.

4.1.2.3. Sampling Plan. Appendix F illustrates the holdup distribution for room 413R (ventilation ducts on the roof of room 413) as determined by Phase I measurements. The two "peaks" appear to contain about 50% of the holdup, and five Phase I locations were selected to direct Phase II measurements to cover all of these "hot spots." We randomly selected six locations to represent the medium-holdup locations and one location to represent the low-holdup locations. Furthermore, Phase II measurements were performed on 64 ft of duct that had not received Phase I measurements. These Phase II measurements covered 164 ft of the 290 ft of room 413R ducts.

4.1.2.4. Phase II Results. The 164 ft of duct measured by Phase II instrumentation contains an estimated 315 g of ^{235}U . The Phase II ^{235}U measurements with favorable counting statistics (estimate at least 3 times the 1σ counting statistic.) are detailed in Appendix G.

4.1.2.5. Inclusion of Phase I Data. The Phase I holdup estimate for 31 ft of ducting (defined by locations 1 to 130 in the Appendix F figure for room 413R) that did not receive Phase II measurements is 54 g of ^{235}U . Bias correction (Sec. 4.1.2.7.1.3) decreases this value to 22 g. The Phase I holdup estimate for locations 131 to 26, which are not estimated from Phase II data, is 22 g of ^{235}U . Bias correction increases this value to 45 g. Appendix G contains a listing of holdup estimates for room 413R based on Phase II measurements. The total bias-corrected Phase I-measured portion of the room 413R ducting is estimated to contain 67 g of ^{235}U .

4.1.2.6. Total Room Estimated Holdup. The sum of the holdup measured in duct segments by Phase I or Phase II methodology is the total room 413R duct estimated holdup: 381 g of ^{235}U .

4.1.2.7. Uncertainty Estimates

4.1.2.7.1. Phase I

4.1.2.7.1.1. Counting Statistics. The discussion on counting statistics in Sec. 4.1.1.7 for room 313 applies to room 413R.

4.1.2.7.1.2. Repeatability. The discussion on repeatability in Sec. 4.1.1.7 applies to room 413R.

4.1.2.7.1.3. Geometry/Model. The initial discussion of geometry/model for room 313 also applies to room 413R.

Table V lists Phase I and Phase II holdup estimates on duct segments measured by both Phase I and Phase II instrumentation and where Phase II measurement counting statistics were less than 3 times the net count rate.

Table V. Comparison of Phase I and Phase II Holdup Estimates			
Duct Segment Location Nos.	Phase II Holdup Est. Grams ²³⁵ U	Phase I Holdup Est. Grams ²³⁵ U	Phase II Est. Phase I Est.
21-32	10.4	17.7	0.58
36-41	9.7	22.2	0.43
41-49	1.4	9.9	0.14
61-66	2.3	5.1	0.45
141-149	3.8	1.7	2.2
158-165	2.5	5.7	0.43
172-190	70.4	23.3	3.0
191-202	42.2	15.9	2.7
203-213	27.5	15.7	1.8
213-221	96.2	47.7	2.0

The last column in Table V suggests two populations of ratios. Examination of the Phase I records shows that the measurements made on 4 October 1990, corresponding to measurement location numbers 1 through 140, were made with the single-channel analyzer window "open," whereas the remaining measurements were made on 5 October 1990 with the window engaged. With the exception of measurements corresponding to the segment at locations 158 through 165, bias correction factors seem to be different for measurements taken with different single-channel analyzer window setting. From the Table V data, a mean Phase I bias correction factor of 0.40 is calculated for measurements on locations 1 through 140 and a factor of 2.0 for measurement locations 141 through 221. Even though the instrument setting variable can be identified, as with room 313, a number of other variables are probably at play, and comparative measurement data are insufficient to establish definitive geometry/model uncertainty values for the Phase I measurements. We therefore recommend a relative standard deviation of 80% be used for the Phase I part of the room 413R holdup estimate. We further recommend that the 80% error estimate (1 RSD) be treated as a systematic error term. This recommendation is probably quite conservative (an overestimate) because scatter in the Table V data used to calculate the bias correction factors suggest a sizable random component.

4.1.2.7.2. Phase II

4.1.2.7.2.1. Counting Statistics. Counting statistics for Phase II measurements varied from location to location but were less than 5% (1 RSD) for high-holdup segments and in the 10% to 20% range in areas having poorer signal-to-noise properties. Because greater than 95% of the holdup estimated from the Phase II measurements resides in duct segments displaying high holdup, the contribution to the total Phase II holdup from counting statistics shall be estimated as 5% (1 RSD).

4.1.2.7.2.2. Repeatability. The discussion in Sec. 4.1.1.7 for calculating the relative repeatability uncertainty for the holdup in the Phase II-measured duct segments

applies. Because Phase II measurements were performed on 21 duct segments, the estimated uncertainty term for repeatability for room 413R is $6\% / \sqrt{21} = 1.3\%$, 1 RSD.

4.1.2.7.2.3. Geometry/Model. The discussion in Sec. 4.1.1.7 on geometry/model uncertainty terms generally apply to measurements made on the room 413R ducting. The 413R ducts containing about 95% of the holdup were smaller in diameter than room 313 ducts; hence, uncertainty values relating to detector-to-deposit distance and deposit width are recalculated.

4.1.2.7.2.3.1. Detector-to-Deposit Distance. Most of the 413R holdup was in square cross-section ducts. These ducts are located outside the building, and the holdup deposits were very likely affected by condensation within the ducts, which would transport the deposits to the bottom of the ducts. For this reason, we assume that the holdup deposits are located entirely on the duct bottom and that the effective detector-to-deposit distance is the distance from the detector to the duct bottom used to calculate holdup. This distance has some measurement uncertainty. The nominal measurement distance of 33 in. has an estimated random uncertainty of 1 in., which introduces a random uncertainty in holdup estimates of about 6%, 1 RSD.

4.1.2.7.2.3.2. Effective Deposit Width. The discussion in Sec. 4.1.1.7 on this source of uncertainty applies to the 413R measurements; however, for the 413R nominal duct, the correction factor is 1.21, and a random uncertainty of 21% (1σ) is assumed for this correction.

4.1.2.7.2.4. Calibration. The calibration uncertainties discussed in Sec. 4.1.1.7 apply to the 413R measurements.

4.1.2.7.3. Combined Phase I and Phase II Uncertainties. Uncertainties associated with the room 413R Phase I and II measurement-based estimates of holdup are summarized in Table VI. The Phase I uncertainty terms listed in Table VI are applied to the duct segment holdup estimated from Phase I measurements (66 g of ^{235}U). The Phase II uncertainty terms are applied to the duct segments having holdup estimated from Phase II measurements (315 g). The systematic uncertainty terms may be positive or negative; however, they are summed to represent a "worst case" situation. Random uncertainty terms are added in quadrature. The combined uncertainty estimates (as 1 standard deviation) for Phase I and Phase II holdup estimates are as follows:

• Systematic uncertainty on Phase I holdup estimate	= 57 g of ^{235}U
• Random uncertainty on Phase I holdup estimate	= 1 g of ^{235}U
• Systematic uncertainty on Phase II holdup estimate	= 12 g of ^{235}U
• Random uncertainty on Phase II holdup estimate	= 71 g of ^{235}U

Table VI. Phase I and II Estimated Uncertainties, 1 RSD			
Phase	Source	Uncertainty	
		Systematic (%)	Random (%)
Phase I	Counting statistic	<1	1
	Repeatability	6	2
	Geometry/model	80	<1
Phase II	Counting statistic	<1	5
	Repeatability	<1	1.3
	Geometry/model		
	Distance	<1	6
	Width	<1	21
	Nonlinearity	<1	<1
	Calibration	3.8	<1

In the "worst case" approach, the uncertainties for the Phase I and Phase II holdup estimates are combined as follows:

1. Systematic uncertainties are added, $57 + 12 = 68$.
2. Random uncertainties are added in quadrature, $(12 + 71^2)^{0.5} = 71$.
3. Combined systematic and random terms are added, $68 + 71 = 139$.

On this basis, the total room 413R estimated holdup of 381 g of ^{235}U has a 1 standard deviation estimated uncertainty of 139 g of ^{235}U .

4.2. TA-55, PF-4 Measurements

The comprehensive Phase I duct survey of TA-55 indicated that only one room contained more than 50 g of fissile material holdup. This room, room 429, received Phase II measurements to quantify duct holdup.

4.2.1. Instrumentation. Instrumentation used to perform the Phase I measurements was identical to that used at TA-21 and described in Sec. 4.1.1.1.

The Phase II instrumentation used to perform holdup measurements in room 429 at TA-21 was a collimated, shielded, low-resolution NaI(Tl) detector coupled to a Davidson Model 2056-4K portable MCA. The 1-in. (2.54-cm)-diam, 2-in. (5.08-cm)-thick detector was collimated with a tungsten sleeve 1 in. (2.5 cm) in depth and diameter. Lead shielding around the detector was 1 in. (2.5 cm) thick. The low-resolution NaI detector option was acceptable for ^{239}Pu holdup quantification in room 429 because the ducting serviced gloveboxes dedicated to processing weapons-grade plutonium. Examination of the digitized, low-resolution spectra acquired during these measurements confirmed the expected freedom from isotopic interferences.

We positioned the detector from below or from the sides of ducts using a "holdup tree" (Appendix B). This robust, adjustable stand positioned the detector at heights ranging from 2 to 3.5 m above floor level.

Finally, an ultrasonic thickness gauge (Panametrics, Model 5222) was used to determine duct wall thickness.

4.2.2. Methodology

4.2.2.1. Holdup Model and Calibration. The holdup model and calibration used for Phase I measurements are described in Appendix C.

Phase II measurements performed were consistent with a far-field, line-source model. We performed a generalized-geometry holdup assay calibration (Appendix E) using the well-characterized MT-52 plutonium standard SPH-1 described in Appendix D.

4.2.2.2. Measurement Control. We checked the Phase I instrument counting efficiency at least twice daily by positioning a depleted uranium disk source on the face of the NaI detector and counting for 10 s. The count rate was compared with that observed for the source after initial energy calibration and remained within four standard deviations of the initial measurement counting statistics.

Phase II measurement control consisted of bias and precision checks using a ^{137}Cs check source and a ^{239}Pu reference source, both of which were characterized at the time of calibration. Both sources were measured before, during, and after the holdup measurements on each day. The ^{137}Cs 662-keV gamma-ray peak was also used frequently to monitor the electronic gain because the signals from holdup deposits were too weak to produce well-defined peaks in the assay spectra.

4.2.2.3. Measurement Procedure and Data Reduction. We performed Phase I measurements at 1-ft intervals along the ducts by placing the shielded detector in contact with the duct and counting for 10 s. The shielded detector was clamped to a length of aluminum tubing so that adapters could be used to add additional lengths of tubing to position the detector on ducts up to 15 ft above floor level. Background measurements were made by moving the detector laterally, "pointing" it at the room ceiling, and counting for 10 s. If holdup seemed to vary appreciably between adjacent measurement locations, frequent background measurements were made. Counts and location description was recorded for each measurement. Assuming that the holdup was distributed as a narrow band along the inside bottom of the duct and that the detector "saw" a one-detector-diameter length (1 in.) of holdup, we converted the net counts observed to grams of ^{239}Pu in the 1-in. length of duct by dividing the counts by those observed during calibration from 1 g of ^{239}Pu as PuO_2 in a glass vial. We multiplied each gram-holdup-per-inch value by 12 to yield grams of holdup per foot and assumed that the holdup concentration was constant over 1-ft intervals. No duct attenuation corrections were necessary because the glass vial and the nominal 0.060-in.-thick duct material attenuated the 208-keV gamma almost identically.

For the Phase II measurements, we used the same instrumentation and methodology described in Secs. 4.1.1.1 and 4.1.1.2. The region of interest for the

^{239}Pu peak was 375 to 450 keV, and the high-energy Compton continuum background region of interest was from 475 to 550 keV. The measurements were performed at distances such that the duct geometry in the detector field of view can be approximated by a (relatively narrow) line across its center. The spacings between adjacent measurements of the ducts were chosen equal to the FWHM of the detector's radial response at the measurement distance to minimize sensitivity to deposit nonuniformities. The measurement distances were taken to be the distances from the detector to the bottom of the duct for horizontal ducts and from the detector to the center of the duct for vertical ducts. Room backgrounds were measured at all assay locations by displacement of the detector to just exclude the duct from the field of view.

Assay and background measurements were performed in 100-s count periods, and spectra acquired for measurement control were obtained in 300-s counts. All spectra were stored on tape for future retrieval.

The measured net count rates in the assay region were corrected for duct attenuation of the gamma-rays and for the finite widths of the (line-source) deposits. We corrected for duct attenuation using duct thicknesses that were measured ultrasonically. These effects were 12% to 14%. The deposit widths were assumed to be one-half the duct width for horizontal ducts and the full duct width for vertical ducts. The finite-deposit-width corrections varied from 1% to 10%.

We converted the corrected net count rates to mass of ^{239}Pu per unit length of duct by multiplying by the line-source calibration constant (in grams of ^{239}Pu s/counts-cm²) and by the assay distance (centimeters). The average value of the mass per unit length for a continuous measured length of duct was multiplied by the length of duct segment measured (in centimeters) to give the total mass of ^{239}Pu in the measured length.

4.2.3. Sampling Plan

The stratified sampling plan described in Sec. 4.1.1.3 was used to select all high-holdup plus randomly selected intermediate- and low-holdup locations indicated by the Phase I survey measurements. Appendix F shows the room 429 duct holdup profile. The high strata were for Phase I peaks indicating greater than 1 g of ^{239}Pu per foot, intermediate strata for holdup between 0.1 and 1 g/ft, and low strata for holdup less than 0.1 g/ft. Locations 106 through 120 were selected to ensure comprehensive Phase II measurements across this duct segment for which Phase I measurements indicated the highest holdup level for the room ducts.

4.2.4. Phase II Results. The 97 Phase II measurements performed quantified holdup in 78 ft of the total 418 ft of ducting in room 429. The quantity of ^{239}Pu estimated from the Phase II measurements on the duct segments selected was 9 g.

4.2.5. Inclusion of Phase I Measurements. The duct segments represented by the 340 ft of ducting not selected for Phase II measurements were all characterized from Phase I measurements as containing intermediate or low levels of holdup. By using the Phase II/Phase I normalization factor (2.0) discussed in Sec. 4.1.2.7.1.3, we

increased the 15-g Phase I value for the 301 ft of intermediate- and low-holdup ducting to a "final" value of 30 g of ^{239}Pu .

4.2.6. Total Room Estimate. The total room 429 holdup estimate is the sum of the Phase I and Phase II estimates described in Secs. 4.2.4 and 4.2.5. **This sum is 39 g of ^{239}Pu .**

4.2.7. Uncertainty Estimates

4.2.7.1. Phase I. The counting statistics and repeatability components of the Phase I measurement uncertainties discussed in Sec. 4.1.1.7.1 apply to the measurements in room 429 at TA-55.

The stratified sampling for room 429 was designed to allow determination of a bias correction factor for the Phase I measurements by comparing the grams-of- ^{239}Pu -per-foot values estimated from both Phase I and II measurements on the same duct segments. Few data are useful for this comparison because most of these duct segments contained holdup levels below the measurement limit of detection for the measurement methods. Only five of the duct segments had holdup measured above the Phase I and/or Phase II limits of detection. The measurement results for these five segments are listed in Table VII.

Table VII. Comparison of Phase I and Phase II Holdup Estimates for Room 429 Duct Segments

Duct Segment Location No.	Phase II Holdup Est. Grams ^{235}U	Phase I Holdup Est. Grams ^{235}U	Phase II Est. Phase I Est.
5	1.6	0.9	1.8
11	3.2	1.8	1.8
120	1.9	29	0.07
302	0.6	0.37	1.6
70	0.5	2.2	0.2

The Phase II/Phase I comparison for duct segment 120 deserves comment. This duct segment crosses over a conveyor and several gloveboxes known to contain holdup levels much higher than the glovebox exhaust ducts (the exhaust air leaving each glovebox passes through a high-energy particulate air [HEPA] filter before entering the exhaust ventilation system). We suspect that the Phase I detector, having relatively "thin" shielding compared with the Phase II detector, was subject to background bias effects and severely overstated the duct holdup. The comparison value 0.07 is considered invalid. (This assumption is used in a direction to increase, not decrease, duct segment holdup estimates based on the less certain Phase I measurement values.) Even with the location 120 comparison value, comparison data from room 429 are inadequate to calculate a reliable Phase I bias correction factor. The Table VII data seem, with the exception of the suspect segment 120

comparison, to be reasonably consistent with the Phase II/Phase I ratios presented in Table V for room 313 at TA-21, which yielded a bias correction factor of 2.0.

The 2.0 factor is larger than any of the Phase II/Phase I ratios listed in Table VII and hence probably leads to an overestimate of room 429 holdup. However, because so little Phase II/Phase I comparison data exist for room 429, we recommend that an 80%, 1 RSD uncertainty be applied to the bias correction and that this uncertainty be considered a systematic error term. This error term embraces the geometry/model and calibration uncertainties for the Phase I based holdup estimates for room 429 duct segments.

4.2.7.2. Phase II Estimate Uncertainties

4.2.7.2.1. Counting Statistics. The counting statistics for Phase II measurements varied as a function of holdup level and were higher than those for TA-21 because the duct location count rates observed in room 429 were never more than 5 times the background levels. Counting statistics for duct segments containing holdup significantly above background (greater than 2 standard deviations above background) were approximately 25% (1 RSD); however, because of the large number of Phase II measurements performed, the counting statistics uncertainty on the 9 g of ^{239}Pu holdup determined for the Phase II-measured duct segments is 0.8 g. We calculated this random uncertainty value by summing the net count rate variances of all Phase II-measured duct segments.

4.2.7.2.2. Repeatability. Measurement repeatability depends principally on our ability to return to a designated duct segment and repeat the detector orientation for both the duct and background count. The discussion and the uncertainty estimate methodology presented in Sec. 4.1.1.7.1.2 allow us to estimate the repeatability uncertainty (a random error term) as 4% relative or 0.4 g on the 9-g ^{239}Pu holdup determined for the 23 Phase II-measured duct segments.

4.2.7.2.3. Geometry/Model. Two factors introducing uncertainty relate to the difference between the modeled holdup distribution inside the ducts and the actual distribution. These factors are (1) the actual detector-to-deposit distance and (2) the effective width of the deposit. Because the holdup deposition is not actually known, the true geometry/model uncertainty terms cannot be determined; however, upper bounds for these terms may be estimated. The upper bound effects of these two error sources are discussed below.

4.2.7.2.3.1. Detector-to-Deposit Distance. In the Phase II calculations, the detector-to-deposit distance for vertical ducts is taken as the distance from the detector face to the duct midpoint. This assumption is probably very good because deposition is likely to be uniformly distributed when averaged over many feet of vertical ducting. The calculations for horizontal ducts used the distance from the detector face to the duct bottom, which assumes that the deposition is on the duct bottom inside surface. Contact measurements on the horizontal ducts indicated highest holdup on the duct bottom and a rapid drop-off in holdup as the detector is raised above the duct bottom.

By assuming a worst case (but credible) holdup distribution over the lower one-fourth of horizontal ducts, one can estimate a worst case bias term. To make this estimate, we use the nominal room 429 duct diameter of 6.7 in. and nominal measurement distance of 39 in. We assume the holdup is in a thin layer covering one-fourth of the bottom of the duct with a effective center of mass one-eighth of the duct diameter above the duct bottom. The effective detector-to-deposit distance is therefore 39.9 in. Because the line-source model used to calculate holdup has holdup as a inverse-linear function of measurement distance, the difference between the nominal 39-in. distance used and the 39.9-in. effective distance introduces a worst case bias of -2.3%. We will increase the Phase II estimate of room 429 duct holdup by this amount and assume the detector-to-deposit distance introduces a 2.3% random uncertainty to the Phase II holdup estimate.

4.2.7.2.3.2. Effective Width. The discussion in Sec. 4.1.1.7.2.3 on this source of uncertainty applies to the room 429 measurements; however, for the room 429 nominal duct, the correction factor is 1.12. From this factor, we conservatively estimate the upper bound of the random uncertainty for the deposit width correction to be equal to the correction itself, that is, 12% relative at 1 standard deviation.

4.2.7.2.3.3. Calibration. The calibration uncertainties discussed in Sec. 4.1.1.7.2.4 apply to the room 429 measurements.

4.2.7.3. Combined Phase I and Phase II Uncertainties. Uncertainties associated with the room 429 Phase I and Phase II measurement-based estimates of holdup are summarized in Table VIII.

Table VIII. Phase I and II Estimated Uncertainties, 1 RSD			
Phase	Source	Uncertainty	
		Systematic (%)	Random (%)
Phase I	Counting statistic	<1	1
	Repeatability	6	2
	Geometry/model	80	<1
Phase II	Counting statistic	<1	9
	Repeatability	<1	4
	Geometry/model		
	Distance	<1	2.3
	Width	<1	12
	Calibration	3.8	<1

The Phase I uncertainty terms listed in Table VIII are applied to the duct segment holdup estimated from Phase I measurements (30 g of ²³⁹Pu). The Phase II

uncertainty terms are applied to the duct segments having holdup estimated from Phase II measurements (9 g of ^{239}Pu). The systematic uncertainty terms may be positive or negative; however, they are summed to represent a "worst case" situation. Random uncertainty terms are added in quadrature. The combined uncertainty estimates (as 1 standard deviation) for Phase I and Phase II holdup estimates are as follows:

- Systematic uncertainty on Phase I holdup estimate = 26 g of ^{239}Pu
- Random uncertainty on Phase I holdup estimate = 1 g of ^{239}Pu

- Systematic uncertainty on Phase II holdup estimate = 0 g of ^{239}Pu
- Random uncertainty on Phase II holdup estimate = 2 g of ^{239}Pu

In a "worst case" approach, the uncertainties for the Phase I and Phase II holdup estimates are combined as follows:

1. Systematic uncertainties are added, $26 + 0 = 26$.
2. Random uncertainties are added in quadrature, $(1^2 + 2^2)^{0.5} = 2$.
3. Combined systematic and random terms are added, $26 + 2 = 28$.

On this basis, the total room 429 estimated holdup of 39 g of ^{239}Pu has a 1 standard deviation estimated uncertainty of 28 g of ^{239}Pu .

4.3. TA-3, SM-29 (CMR Building) Measurements

4.3.1. Instrumentation. We performed Phase I measurements using the NaI-based instrumentation described in Appendix C.

The Phase II assay instrumentation employed at TA-3 was a computer-controlled, high-resolution gamma-ray, holdup measurement system consisting of the following components:

- portable, 2.5 in $\times$ 2.5 cm, coaxial, HpGe detector (EG&G Ortec) with tungsten shield and collimator.
- portable MCA (Davidson Model 2056-4K)
- laptop computer (Compaq SLT386)
- printer (Kodak Diconix 150+)
- equipment stands ("trees")
- ultrasonic thickness gauge (Panametric model 5222)
- automated software package (Los Alamos design)

This holdup measurement system is described more completely in Appendix B.

4.3.2. Methodology

4.3.2.1. Phase I Measurements. The Phase I measurement calibration and methodology described in Appendix C pertain to the Phase I measurements performed in TA-3/SM-29.

4.3.2.2. Series 1, Phase II Measurements

4.3.2.2.1. Holdup Model and Calibration. The ducting at TA-3 is configured in a manner suitable for line-source model measurements. Measurements were performed at distances such that the duct geometry in the detector field of view can be approximated by a relatively narrow line across its center. To minimize sensitivity to deposit nonconformities, the spacing between adjacent measurement points along continuous runs of ducting (segments) were chosen to be equal to the FWHM of the detectors radial response at the measurement distance. The measurement distance was taken to be the distance from the detector to the bottom surface of the duct. On vertical duct segments, the holdup deposit was assumed to be uniformly distributed, hence with effective width equal to the duct diameter. On horizontal ducts, the holdup was assumed to be deposited on the bottom inside surface of the duct with a width equal to one-half the duct diameter. The holdup estimate for the one duct segment found to contain fissile material (0.8 g of ^{239}Pu) was corrected for effective width according to the method described in Sec. 4.1.1.7.2.3. Attenuation corrections were made for duct material, but the one holdup deposit observed was so dispersed that self-attenuation corrections would have been less than 1 %.

We calibrated Phase II instruments using the plutonium standard SPH-1 and uranium standard 9-000 described in Appendix D. The general-geometry calibration methodology described in Appendix E was used.

4.3.2.2.3. Measurement Control. Bias checks were periodically made with a ^{137}Cs source (661-keV peak) mounted in a highly reproducible geometry before and after each measurement session (at least daily). For all measurements, spectrum quality and energy calibration were monitored with a ^{109}Cd (88-keV peak) source attached to the face of the detector.

Before determining peak areas, the software performs an energy calibration from the centroid of the 88- and 661-keV peaks and adjusts the region of interest (channel values) as gain shifts occur. The peak positions remained constant throughout the measurements, indicating a very stable system.

4.3.2.2.4. Phase II Measurement Procedure and Data Reduction. We performed Phase II measurements by attaching the detector to the portable "tree" about 2 duct diameters away from the duct and accumulating gamma spectra for varying times depending on the signal strength. All horizontal duct segments were measured with the detector directed upward at the duct bottom surface. Vertical ducts were measured with the detector oriented horizontally. A series of measurements were made on each duct segment with the detector located to provide adjacent measurements overlapping at the FWHM of the detector field of view. We measured room backgrounds at all measurement locations by displacing the detector laterally to exclude the duct from the field of view. Duct wall thickness was measured ultrasonically. Location, duct diameter, detector-face-to-duct-surface distance, and duct thickness, were recorded. We determined continuum background for peaks used for holdup quantification by counting energy regions slightly above the peak of interest.

The computer program performed the following calculations:

- Normalize the continuum background to the number of channels under the associated assay peak.
- Subtract the normalized continuum background.
- Subtract the room background.
- Correct for duct attenuation.
- Apply the line-source calibration factor and assay distance to calculate the mass of isotope per unit length of duct.
- Calculate the counting statistics uncertainty.

4.3.2.3. Sampling Plan. Phase I measurements were performed at 1-ft intervals on all ducting; however, in most of the basement rooms of the building, long segments of ducting displayed tens of feet of duct exhibiting consistent, low-gamma activity. For these duct segments, Phase I measurement intervals were increased to 2 ft and remained so until the duct or background activity increased significantly.

The three-strata sampling procedure described for TA-21 Phase II measurements (Sec. 4.1.1.3) was used to select 22 measurement locations in room 5034, the first TA-3/SM-29 room scheduled for Phase II measurements. After performing lengthy measurements at selected locations, it became apparent that the activity associated with the low- and intermediate-holdup locations was too low to obtain significant count rates in the fissile isotope peak energy regions. As can be seen in Appendix F, illustrating the Phase I holdup profile for the three TA-3/SM-29 rooms receiving Phase II measurements, the gamma activity observed during the Phase I measurements is highly concentrated in a few feet of ducting. To adapt to the highly concentrated holdup characteristic of all the building rooms measured (5034, 4023, and 4034), the stratified sampling approach was abandoned and Phase II measurements performed on the locations displaying sufficient activity to allow Phase II quantification of fissile holdup in these locations.

4.3.2.4. Phase II Results

4.3.2.4.1. Room 4023. Three Phase I locations (791, 1046, and 1067) were designated to identify duct segments requiring Phase II measurements. The segments correspond to the three highest peaks shown in the Appendix F holdup profile diagram. Sixteen Phase II measurements were performed over 12 ft of ducting corresponding to location 1046. No ^{235}U or ^{239}Pu peaks were observed above the background continuum. Similarly, on the four Phase II measurements made on 4 ft of duct corresponding to location 791 and the 5 ft of duct corresponding to location 1067, no ^{235}U or ^{239}Pu peaks were distinguishable above background. Several peaks were observed for both duct segments corresponding to ^{228}Th and its daughter products. The high activity observed for these segments during the Phase I measurements was caused by counting Compton continuum and full-energy gamma rays from isotopes in the ^{228}Th decay series. Appendix I shows the gamma spectral interference caused by the ^{228}Th decay series isotopes. The cross-hatched area illustrates the energy region included in the Phase I measurements.

Based on the premise that the Phase II measurements could have detected ^{235}U and ^{239}Pu holdup at two standard deviations above background, the limit of detection, based on the continuum counting statistics at the location with the least favorable absolute counting statistics, was 0.22 g of ^{235}U per foot and 0.26 g of ^{239}Pu per foot. Making the worst case assumption that this limit of detection represents the fissile holdup for the total length of duct segment (duct origin to joining with another duct segment), we calculate the duct segment holdup listed in Table IX.

Table IX. Maximum Holdup Estimates For Phase II Measured Locations

Phase I Location No.	Total Segment Length (ft)	Limit of Detection (g/ft)		Calc. Holdup (g)	
		^{235}U	^{239}Pu	^{235}U	^{239}Pu
791	22	0.22	0.26	5	6
1046	33	0.22	0.26	7	9
1067	10	0.22	0.26	<u>2</u>	<u>3</u>
Totals:				14	18

Duct segments represented by the locations 791, 1046, and 1067 account for 81% of all the room 4023 Phase I counts. These duct segments represent about 3% of the total duct length in room 4023.

4.3.2.4.2. Room 4034. Phase II measurements were performed on the duct segments corresponding to the two large, broad peaks shown in the Appendix F holdup profile. These two duct segments correspond to Phase I locations 402 and 460. All Phase II measurements (10) made in these duct segments demonstrated peaks from ^{228}Th and its daughter products but no distinguishable peaks from ^{235}U or ^{239}Pu .

Based on the premise that the Phase II measurements could have detected ^{235}U and ^{239}Pu holdup at two standard deviations above background, the limit of detection, based on the location with the least favorable absolute counting statistics, was 0.73 g of ^{235}U per foot and 0.90 g of ^{239}Pu per foot. Making the worst case assumption that this limit of detection represents the fissile holdup for all room 4034 duct segment, we calculate the duct segment holdup listed in Table X.

Duct segments represented by locations 402 and 460 account for 94% of all the room 4023 Phase I counts. These duct segments represent about 9% of the total duct length in room 4034.

Table X. Maximum Holdup Estimates For Phase II Measured Locations

Phase I Location No.	Total Segment Length (ft)	Limit of Detection (g/ft)		Calc. Holdup (g)	
		²³⁵ U	²³⁹ Pu	²³⁵ U	²³⁹ Pu
402	25	0.73	0.90	18	23
460	29	0.73	0.90	<u>21</u>	<u>26</u>
Totals:				39	49

4.3.2.4.3. Room 5034. Duct segments at seven Phase I locations in room 5034 received Phase II measurements. None of the 35 Phase II measurements displayed a ²³⁵U peak discernible above background. The counting statistic on the location with the highest Compton background (that is, poorest absolute counting statistic) corresponded to a ²³⁵U holdup concentration of about 0.0086 g per centimeter or 0.26 g per foot of duct.

One duct segment (location 150) displayed ²³⁹Pu peaks above background. The duct segment spanning Phase I locations 147 through 154 was estimated to contain 0.8 g of ²³⁹Pu at 0.1-g uncertainty, 1 standard deviation. The remaining locations displayed no ²³⁹Pu peaks above background. The least favorable counting statistic for background at these locations corresponds to 0.0037 g of ²³⁹Pu per centimeter or 0.11 g per foot of duct. Assuming that the Phase II measurements could have detected ²³⁵U and ²³⁹Pu holdup at two standard deviations above background, we determined that the limit of detection, based on the duct segment displaying the worst absolute counting statistics, was 0.5 g of ²³⁵U per foot and 0.22 g of ²³⁹Pu per foot. Making the worst case assumption that this limit of detection represents the fissile holdup for all the room duct segments estimated with Phase II measurement data, we calculated the duct segment holdup listed in Table XI.

Duct segments represented by locations 147 through 154 and those listed in Table XI account for 96% of all the room 5034 Phase I counts. These duct segments represent about 20% of the total duct length in room 5034.

4.3.2.5. Inclusion of Phase I Measurements

4.3.2.5.1. Room 4023. Phase II measurements addressed locations representing 80.6% of the gamma activity counted during Phase I measurements. Additional measurements on a vacuum line immediately above duct location 1163 demonstrated that virtually all the Phase I counts ascribed to locations 1162 through 1166 were from this high-background source. The activity from locations 1162 through 1166 equals 3.3% of the total Phase I activity. Furthermore, 10 ft of duct was removed between the times the Phase I and Phase II measurements were made. This duct segment contributed 5.4% to the total Phase I integrated counts. After correcting the 19.4% of the integrated counts not covered by Phase II measurements

Table XI. Maximum Holdup Estimates For Phase II Measured Locations

Phase I Location No.	Total Segment Length (ft)	Limit of Detection (g/ft)		Calc. Holdup (g)	
		²³⁵ U	²³⁹ Pu	²³⁵ U	²³⁹ Pu
59	8	0.52	0.22	4	2
104	30	0.52	0.22	15	7
140	12	0.52	0.22	6	3
150	8	0.52	NA ^a	4	0.8
170	14	0.52	0.22	7	3
230	10	0.52	0.22	5	2
238	3	0.52	0.22	<u>2</u>	<u>1</u>
Totals:				43	18.8

^aDirectly measured.

by the sum of the counts from locations 1162 through 1166 and locations 779 through 788, we find that the Phase I activity requiring quantification is 10.7%. If this 10.7% of the integrated Phase I counts is assumed to be generated by ²³⁵U or ²³⁹Pu, the Phase I holdup estimates for locations not covered by Phase II measurements are 315 g of ²³⁵U or 15 g of ²³⁹Pu. Because the Phase II measurements could identify only ²²⁸Th and daughter products as the source of gamma activity, the ²³⁵U or ²³⁹Pu estimates based on Phase I measurements probably greatly overstate the actual fissile holdup.

4.3.2.5.2. Room 4034. Phase II measurements were performed on duct segments accounting for 94.3% of the integrated Phase I counts for room 4034. If the remaining 5.7% of the integrated counts are assumed to be from ²³⁵U or ²³⁹Pu, the Phase I-based holdup estimates for ducts not covered by Phase II measurements are 31 g of ²³⁵U or 1 g of ²³⁹Pu. Because the Phase II measurements could identify only ²²⁸Th and daughter products as the source of gamma activity, the ²³⁵U or ²³⁹Pu estimates based on Phase I measurements probably greatly overstate the actual fissile holdup.

4.3.2.5.3. Room 5034. As discussed in Sec. 4.3.2.4.3, 96% of the Phase I-counted gamma activity associated with room 5034 ducts was quantified by Phase II measurements. The remaining 4% of the activity was contained in 248 ft of ducts displaying relatively low gamma count rates. Based on the Phase I instrument calibration versus uranium and plutonium oxides (Appendix B), this remaining activity corresponds to 25 g of ²³⁵U or 1 g of ²³⁹Pu. This conservative estimation assumes that the gamma activity counted is from ²³⁵U or ²³⁹Pu, not the more likely

activity from nonfissile isotopes causing the high Compton background consistently observed in the Phase II measurements.

4.3.2.6. Total Room Estimated Holdup. Table XII lists the total estimated fissile holdup for each of the three TA-3/SM-29 rooms receiving Phase II holdup measurements.

Table XII. Total Fissile Material Holdup In Ducts

Room Nos.	Duct Holdup (g)						Max 239Pu	Max. Fissile ^a
	Phase I		Phase II			Total		
	235U	or 239Pu	235U	239Pu	Max. 235U			
4023	315	15	14	16	329	31	345	
4034	31	1	39	49	70	50	119	
5034	25	1	44	19	69	20	88	

^aMax. fissile = Phase I grams of ²³⁵U + Phase II (grams of ²³⁵U + grams of ²³⁹Pu). Phase I fissile estimates are either ²³⁵U or ²³⁹Pu, but not both.

4.3.2.7. Uncertainty Estimates

4.3.2.7.1. Phase I. Phase I instrumentation and methodology applied at TA-21 and described in Appendix C, were employed at TA-3/SM-29. The Phase I uncertainty estimates for counting statistics and repeatability described in Sec. 4.1.1.7.1 also apply to TA-3/SM-29. However, the geometry/model uncertainty term for this facility has a dominant source of bias not characteristic of the TA-21 measurements reported in Sec. 4.1. This source of bias was observed for *all* duct segments at TA-3/SM-29 measured with Phase II instrumentation and is assumed to have affected all the Phase I measurements made in rooms 4023, 4034, and 5034. The bias is caused by gamma radiation from nonfissile isotopes (principally ²²⁸Th and daughter products) that interfered with the Phase I measurements either directly, through gamma peaks within the broad 150- to 350-keV energy window, or indirectly, through Compton continuum spanning the entire energy range of this window. This source of bias was not observed in the rooms receiving Phase I or II measurements at TA-21 or TA-55 because the holdup deposits did not include appreciable gamma-emitting isotopes other than those introduced by the uranium or plutonium materials processed in those rooms.

Table XIII shows the magnitude and direction of bias that the nonfissile isotope holdup introduced into the ²³⁵U holdup estimates made on the duct segments receiving both Phase I and Phase II measurements. It is apparent from Table XIII that the Phase I estimates of ²³⁵U holdup much less than 100 g agree to within a few grams with the Phase II *upper limit* values. For duct segments having Phase I estimated holdup greater than 100 g, the Phase I estimates greatly exceed the Phase II *upper limit* values. In essentially all cases in which the Phase I

Table XIII. Phase I and Phase II ^{235}U Holdup Estimates for Duct Segments

Duct Segment Location		Phase I Holdup	Phase II Holdup
Room	Number	Estimate (g ^{235}U)	Estimate (g ^{235}U)
4023	791	204	4
"	1046	452	8
"	1067	527	2
4034	402	287	18
"	460	185	21
5034	59	2	4
"	104	13	15
"	140	16	6
"	150	392	4
"	170	102	7
"	230	7	5
"	238	0	2
"	289	0	1

measurements indicated gamma activity greater than background (holdup estimated greater than 1 g), Phase I estimates are biased high. On this basis, we recommend that the geometry/model, which assumes lack of interference from nonfissile isotopes uncertainty for the TA-3/SM-29 duct segment holdup estimated from Phase I measurements, be considered free of negative bias (never understating the actual holdup) but with variable and unknown positive bias.

4.3.2.7.2. Phase II. The counting statistic, repeatability, and geometry/model uncertainty components for the Phase II measurements for the three TA-3/SM-29 rooms are essentially the same as those described in Sec. 4.1.1.7.2. However, these uncertainty estimates apply fully only to the one duct segment in room 5034 where ^{239}Pu peaks were observed (location 150) and the calculated holdup was 0.8 g. All the remaining duct segment holdup estimated from Phase II measurements was determined from limits of detection because fissile peaks were not observed. These limits of detection were based on the 2 standard deviation estimates of the gamma background underlying the gamma energy regions corresponding to the isotopes ^{235}U and ^{239}Pu . Furthermore, the room duct limits of detection were calculated for the Phase II measurement of the duct segment showing the *worst* absolute counting statistics that lead to the *highest* limit of detection value. A rigorous discussion of systematic and random uncertainty terms for the Phase II upper limit values listed in Tables IX through XI is meaningless because these values are the product of two worst case assumptions. If the uncertainty on these values must be expressed in statistical terms, one can state that (1) the stated holdup values have zero negative bias (do not understate the actual holdup) and undefined-but-likely-large positive

bias and (2) the random uncertainty (at two standard deviations) is contained *within* the upper holdup estimates. In other words, the total uncertainties have already been incorporated in the upper limit holdup values expressed in Tables IX through XI.

4.3.2.7.3. Combined Phase I and Phase II Uncertainties. The total holdup estimates presented in Table XII have zero negative and undefined-but-likely-large positive bias. The upper range of random uncertainty components for the Phase I measurements are already embraced by the conservative Phase I assumption that all gamma counts are from fissile isotopes (no nonfissile isotope interference). Duct segment holdup estimated from Phase II measurements was based on duct holdup limits of detection calculated from measurements under worst case conditions (leading to an overestimate of holdup) and applied to all duct segments.

To illustrate the consistent conservatism (overstated holdup) incorporated into the Phase I and II holdup estimates, consider the two following examples from room 5034 measurements.

Example 1. Phase I measurements were used to estimate holdup in duct segments that did not display high gamma activity. However, in room 5034 six duct segments exhibiting low gamma activity were measured by both Phase I and II methods (Table XIII). The Phase I estimated holdup for these segments was 38 g of ^{235}U , whereas the Phase II holdup *upper limit* was estimated at 33 g.

Example 2. Phase II measurements on the duct segments are listed in Table XIII. A limit of detection value of 0.52 g of ^{235}U was used for *all* duct segments. This value was calculated from the duct segment displaying the worst absolute counting statistic (highest theoretical fissile holdup concentration). Had we calculated duct segment holdup using *individual* duct segment counting statistics, the Phase II maximum holdup for these segments would have been 32 g instead of the 44 g declared.

We therefore recommend that the room holdup values listed in Table XII be considered upper limits of holdup with uncertainty terms already added in.

5.0. Series 2, Phase II Measurements

5.1. Measurement Program

5.1.1. Measurement Strategy. At the completion of the Series 1, Phase II measurement campaign, it became apparent that the level of effort required to produce the best quality holdup data was excessive for the low levels of holdup associated with the ducts requiring further fissile holdup quantification. DOE/AL and Laboratory management agreed that a graded measurement strategy would be used to measure holdup in the remaining ducts. The highest quality (and most resource-intensive) holdup measurements would be reserved for those ducts thought to, or found to, contain fissile material holdup levels that might be of criticality safety concern. Less resource-intensive and more flexible measurement

methods would be used for ducts containing lesser quantities of fissile material. Following this more cost-effective measurement strategy, we quantified duct holdup in 11 of the 12 rooms measured in the Series 2 campaign using less laborious methods and measured only one room using the highest quality method.

5.1.2. Instrumentation. The Phase I semiquantitative measurements on some ducts at TA-21 and TA-3/SM-29 indicated fissile holdup levels that might have been of criticality safety concern. However, interviews with operating personnel revealed that gloveboxes associated with these exhaust ducts had been used for research on nonfissile isotopes that probably biased the Phase I measurements. A high-resolution detector would be required to resolve the interfering peaks. A high-efficiency, high-purity germanium (HPGe) detector was purchased for the remaining Phase II measurements.

An HPGe detector had been used for the CMR Building Series 1, Phase II measurements; however, the relative small detector and associated collimation required lengthy measurement times to attain the sensitivities required to ensure the measured ducting contained much less than 200 g of fissile holdup. Furthermore, relatively small detectors, with concomitant relatively modest efficiency for high-energy gamma rays, suffer from a somewhat high Compton background interference when one attempts to measure the ^{235}U , 186-keV gamma peak in the presence of isotopes producing higher energy gamma peaks.

The HPGe detector selected for the Series 2, Phase II measurements was high efficiency both in terms of cross section and collection efficiency for high-energy gamma rays. Specifically, the selected HPGe detector was 3 in. in diameter and 4 in. thick and had a collection efficiency of 100% at 1.33 Mev relative to a 3-in.-thick NaI(Tl) detector. The HPGe detector used for the Series 1, Phase II CMR Building measurements was of 1-in. diameter and approximately 30% efficiency.

The large HPGe detector required a heavy (about 10-kg.) lead collimator. Because it was impractical to manually hold the detector in place during measurement, a camera tripod was modified to hold the detector and support the massive collimator.

Because many of the Series 2, Phase II measurements would be made on difficult-to-reach ducting (TA-21 rooftop and outside ducting), a highly portable instrumentation package was ordered. This instrumentation included an EG&G-Ortec Nomad®* portable MCA operated through a laptop personal computer (PC), and a battery power supply. The PC also provided storage for the spectra obtained. Peak areas for fissile peaks or other isotopes of interest were obtained and recorded in the field. Being able to store the spectra allowed us to perform additional peak identification and evaluation upon return to the laboratory. The MCA and PC plus the battery power supplies were packaged in an aluminum "suitcase" that was relatively easy to transport. Figure 1 shows the large detector-collimator assembly mounted on the tripod. The MCA-PC mounted in the lower half of the suitcase is located on a wheeled cart. A 20-ft-long bundle of three coaxial cables connect the two instrument components.

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* EG&G ORTEC, Oak Ridge, Tennessee.

Fig. 1. Detector collimator assembly.

5.1.3. Holdup Model and Calibration. A far-field, line-source measurement model was used for the Series 2, Phase II measurements. Measurements were configured to determine holdup linear concentration (grams of fissile material per unit length of duct).

Rather than use the generalized-geometry calibration method used for the Series 1, Phase II measurements, we calibrated the instrumentation using a mock-up of the expected holdup deposition in ducts. We prepared this mock-up by inserting, nose-to-tail, six long, narrow, thin enriched uranium foil standards into a 6-in.-diam, 0.125-in.-thick-wall, stainless steel pipe. A full description of the foil standards is found in Appendix J. This arrangement of uranium foil standards gave a relatively uniform holdup distribution 8.9 ft (2.7 m) long by 1.5 in. (3.8 cm) wide and having an effective linear density of 6.2 g of ^{235}U per foot of duct (0.201 g of ^{235}U per centimeter of duct). The pipe was suspended 8 ft above floor level and the detector-collimator oriented as shown in Fig. 1 and positioned directly beneath the mock-up duct. We made multiple counts of the ^{235}U , 186-keV peak using three detector-to-duct distances (91.5, 119, and 146 cm). Using the far-field, line-source

premise that count rate varies inversely with distance, we normalized the mean count rates for each distance to 100 cm and averaged. The average count rate was corrected for the duct attenuation (32%). By dividing this count rate by the effective linear density of ^{235}U , we obtained a calibration expressed as counts per minute at 186 keV, corresponding to 1 g of ^{235}U per foot of duct.

A similar calibration constant was obtained for ^{239}Pu . Because similar thin-foil plutonium standards were not available, we performed the calibration by counting point-source standards for both ^{235}U and ^{239}Pu (standards 9-000 and SPH-1, see Appendix D). Both the ^{235}U , 186-keV count rate and the ^{239}Pu , 414-keV count rate were corrected for self-attenuation and the corrected count rates divided by the respective grams of fissile isotope. We obtained a ^{239}Pu linear density calibration constant by finding the ratio of the ^{239}Pu cpm/g source value to the ^{235}U cpm/g source value and multiplying this ratio by the ^{235}U linear density calibration constant.

A second calibration constant was derived for the ^{239}Pu gamma peak at 129 keV. We calculated this constant by multiplying the above ^{239}Pu linear calibration constant by the ratio of the 129-keV count rate to the 414-keV count rate of a ^{239}Pu standard.

5.1.4. Measurement Control. A depleted uranium disk source was counted for 10 min shortly after the initial calibration ^{235}U foil standards. This initial disk source count rate was recorded and the source counted at least daily throughout the Series 2, Phase II measurement campaign. This measurement control check monitored the counting efficiency of entire instrument package. The pass-fail criterion for each check was that the count rate observed must not differ from the initial count rate by more than three standard deviations. On the two or three occasions that this check failed to pass, we found that the MCA energy calibration had shifted a few channels. An energy recalibration restored the instrument to a "pass" status.

The EG&G-Ortec software for the MCA provides peak stabilization that ensures that a reference peak centroid corresponds to a specified energy. The peak selected was the 186-keV peak because the disk source was always counted first, each day that holdup measurements were performed. During the first month of operation, the MCA-PC shutdown sequence caused the instrument energy calibration to be erased, which in turn led to the source check failures discussed above. In consultation with the manufacture, we identified the problem. After a correct shutdown procedure was established, no further source check failures occurred.

5.1.5. Measurement Procedure and Data Reduction. We performed the vast majority of the Series 2, Phase II measurements by positioning the detector-collimator below the duct segment and "pointing" the detector upward at the duct as shown in Fig. 1. Some measurements had to be made with the detector positioned horizontally because there was not adequate space beneath the duct segment to permit vertical "viewing." Measurement time was typically 1 min unless interfering Compton radiation from higher energy peaks added unacceptable

uncertainty to the fissile isotope peaks. Longer counting times were occasionally used to improve measurement precision.

During each holdup measurement, we recorded the measurement location, detector-to-duct distance, count time, peak energy, duct material and thickness, and net peak area. The net peak area was calculated from the observed spectra by the EG&G-Ortec Maestro® software through the laptop PC. The net peak area algorithm uses regions of interests on either side of the peak of interest to extrapolate the under-peak background and then to subtract this background from the gross peak area. The background correction algorithm is found in Appendix K.

To convert the observed net peak area to linear density, the net peak area is first corrected for duct attenuation, normalized to a 100-cm detector-to-duct distance, converted to counts per minute if the count time was not 1 min, and then multiplied by the linear density calibration constant to yield grams of fissile material per foot of duct. We calculated the grams of fissile material for that duct segment by multiplying the length of duct represented by the measurement. Finally, the grams of fissile material for all duct segments were summed to yield the total fissile holdup for the duct.

Because many of the ducts segments measured in the Series 2, Phase II program contained very low concentrations of fissile material, many of the measurements produced zero or even negative net counts. This observation is consistent with the statistical nature of counting data. Because concerted efforts were made to omit all sources of negative bias (underestimate of actual holdup), negative net counts are valid data, and total duct holdup is calculated by algebraically summing the holdup calculated for all duct segments. We calculated the ^{235}U holdup using the 186-keV peak. Calculation of the holdup values for ^{239}Pu involved both the 129-keV and 414-keV peaks, and the peak yielding the most precise linear ^{239}Pu density (most favorable counting statistic) was selected to represent each segment.

Series 2, Phase II measurements were spaced such that adjacent measurements overlapped slightly to ensure that no localized deposits would be completely missed. No bias was introduced by this slight overlap because the measurements produced linear density holdup values for each segment and the linear density values were multiplied by the exact length of duct, that is, the sum of the duct segment lengths equaled the actual total duct length. Typically, measurements were spaced at 100-cm intervals and collected the duct gamma emissions from 100-cm duct segments.

5.1.6. Sampling Plan. The Series 2, Phase II measurements at TA-21, TA-48, and TA-50 were made at intervals encompassing the entire duct systems; hence, we used a 100% sampling plan. At TA-3/SM-29, the Series 2, Phase II measurements were taken on those duct segments identified by the Phase I measurements as "hot spots." The holdup for those segments not included in the "hot spots" was calculated from the Phase I measurements as described in Appendix C.

5.2. Uncertainty Estimates

5.2.1. Counting Statistics. Counting precision values for each measurement are calculated by the EG&G-Ortec Maestro® software using the algorithm detailed in Appendix B. Because the Series 2, Phase II measurements were directed at ducts typically containing very small holdup, the counting precision was usually large relative to the net count. The counting precision for each measurement is propagated for each duct system according to the following model:

$$S_{\text{duct holdup}} = \left[\sum s_i^2 (\text{segment length}_i)^2 \right]^{0.5},$$

where

$S_{\text{duct holdup}}$ = the one standard deviation estimate of the total duct holdup counting precision term expressed in grams and

s_i = the estimate of the counting precision for the linear holdup density at measurement location i and is expressed as grams of fissile isotope per foot.

The segment length is in units of feet.

5.2.2. Repeatability. The Series 1 and 2 Phase II duct measurements were both subject to the same repositioning variables that dominate the uncertainty of repeating a duct measurement at a given location. The repeatability discussion of Sec. 4.1.1.7.2.2 applies to the Series 2, Phase II measurements and the single measurement repeatability uncertainty estimate of 14%, 1 RSD, is used for each Series 2, Phase II duct holdup uncertainty estimate. Because this uncertainty term is random, the repeatability 1 RSD for a duct system with n measured segments is $14\% / \sqrt{n}$.

5.2.3. Geometry/Model. The line model for holdup estimation assumes that the detector face-to-deposit distance is known, the deposit width is a thin line, and the deposit is uniformly distributed along the duct segment being measured. Uncertainties associated with these three sources of uncertainty are discussed below.

5.2.3.1. Detector-to-Deposit Distance. Although we used a meter stick to measure the distance from the detector face to the bottom of the duct, in many cases exact distances could not be maintained because equipment and machinery interfered or, in the case of outside ducting, because of irregular terrain. The estimated variation of about 10% in the detector-to-deposit distance introduces a random uncertainty of about 20% to each holdup measurement. Because this uncertainty is random, the distance 1 RSD for a duct system having n measured segments is $20\% / \sqrt{n}$.

5.2.3.2. Deposit Width Effects. No appreciable bias or random uncertainties are assigned to deposit width effects for the following reasons: (1) Almost all of the ducts measured in the Series 2, Phase II program were subject to internal

condensation (TA-21) or a periodic spray-wash down (TA-3/SM-29); hence, it is a reasonable approximation that the holdup measured was at the bottom of the duct. (2) The large-diameter detector-collimator is characterized by a somewhat "flat" response to an off-axis displacement of a point source as can be seen in the lateral displacement response curve in Appendix L. A lateral offset of 10 cm produces virtually no change in count rate with the large-diameter detector-collimator for measurements made at a 1-m detector-face-to-source distance.

5.2.3.3. Nonuniform Holdup Concentration Along Duct Segment. Highly localized holdup deposits, "hot spots," can introduce both positive and negative bias to the Series 2, Phase II measurements. These measurements were typically made at 1-m intervals over long lengths (many meters) of duct. If a "hot spot" was concentrated between two adjacent measurements, the holdup quantity estimated for that duct segment would be biased low. Conversely, if a Series 2, Phase II measurement was centered on a "hot spot," the holdup estimate for that segment would be biased high. We used Phase I counting data to identify localized "hot spots," and the Series 2, Phase II measurement for that segment (typically of 1-m length) were centered on the "hot spot." The probability that a "hot spot" would fall between adjacent Series 2, Phase II measurements was minimized to the degree that the Phase I measurements (spaced at 1-ft intervals) located all the "hot spots." For the large number of measurements made for each duct system, these positive and negative biases partially offset each other. Any residual bias is likely to be positive (that is, holdup is overstated) because of our conscious practice of centering measurements on "hot spots."

The random uncertainty associated with nonuniform holdup was estimated from the lateral-displacement response curve illustrated in Appendix L. By assuming that the holdup within a segment is localized within a 10-cm length of duct, we can estimate the measurement system's response compared with the same amount of isotope uniformly distributed as a theoretical line source. Consider Fig. 2, which illustrates the system response to holdup located in a series of 10-cm-long "bands" between two adjacent Series 2, Phase II measurements located 1 m apart at locations A and B. The two measurements overlap so that detectors located at both A and B "see" counts from holdup in the same band. To estimate the system response to holdup located in bands of 10-cm width, we sum the height of the response curve at the band center for response to detectors located at A and B, that is, at the two adjacent measurement locations. The summed responses are listed in Table XIV.

Because each band has equal probability of containing the holdup, the mean response is 64, one standard deviation is 28, and one RSD is 44%. We will use this RSD value as an estimate of the random uncertainty associated with nonuniform holdup as it affects a single Series 2, Phase II measurement. We shall assume that all "hot spots" in a duct are approximately the same, that is, contain about the same mass of fissile material. Because multiple measurements, n , are made for a duct system, the 1-RSD uncertainty on the entire duct system holdup is $44\% / \sqrt{n}$.

Fig 2. System response to holdup in a series of "bands" between two adjacent Series 2, Phase II measurements.

5.2.3.4. Calibration Uncertainty. Calibration uncertainties were related to (1) the uncertainty in the mass of ^{235}U in the foil standards, (2) errors made in measuring the distance between the detector face and the source, and (3) counting statistics. The files containing the initial preparation documentation for the uranium foil standards can no longer be located, but the foils were undoubtedly prepared from high-purity uranium metal that had been assayed by standard analytical chemistry methods. A typical uncertainty associated with the assay of uranium metal has a 1 RSD of about 0.2 % and a bias of less than 0.1%. A second uncertainty in the

Table XIV. System Response to Offset Holdup^a

Band	A + B Response
1	100 + 0 = 100
2	88 + 0 = 88
3	63 + 0 = 63
4	40 + 2 = 42
5	20 + 8 = 28
6	8 + 20 = 28
7	2 + 40 = 42
8	0 + 63 = 63
9	0 + 88 = 88
10	0 + 100 = 100

^a $n = 10, \bar{x} = 64, s = 28, 1 \text{ RSD} = 0.44.$

preparation of the uranium foils is a weighing error. A typical weighing error is a 1 RSD of 0.2% and a bias of 0.1%. We do not have comprehensive documentation on the fabrication of the foils, so we will conservatively assume that the random uncertainty estimates for the assay and weighing terms act additively to generate a bias of $\pm 0.4\%$.

The detector-to-source distance was measured with a meter stick. The largest uncertainty in this measurement is caused by the plastic-wrapped foils not lying exactly flat in the stainless steel pipe used to simulate a duct. This uncertainty to the 100-cm distance was about 1 cm and, based on the line-source calibration method, introduces a random uncertainty of about 1% to the calibration constant.

Finally, the count rate at the 100-cm detector-to-source distance was measured 10 times; twice each at a different location along the uranium foil constructed line source. Because each point is considered equally representative, the standard deviation of 63 or 1.5% RSD is the random error term on the mean count rate of 4083 cpm.

The calibration constant for ^{239}Pu was calculated from the ^{235}U calibration constant as described in Sec. 5.1.3. This calculation involved counting the ^{239}Pu standard SPH-1 and ^{235}U standard 9-000 (Appendix D) at the same detector-to-source distance and calculating ^{239}Pu -to- ^{235}U peak area ratios for both the 129-keV and 414-keV peaks of ^{239}Pu . The mass and attenuation for these two standards are well known and contribute negligible uncertainty to the calibration constants. Similarly, the uncertainty in the measurement distance is negligible.

The 1 RSD counting statistics terms for counting the plutonium and uranium standards were as follows:

- 3.9% for the ^{239}Pu 129-keV peak,
- 3.3% for the ^{239}Pu 414-keV peak, and
- 0.4% for the ^{235}U 186-keV peak.

Because plutonium/uranium peak ratios are determined and then multiplied by the ^{235}U calibration constant, the counting statistic terms for the two standards and the foil counts are combined in quadrature yielding the following:

- ^{239}Pu , 129-keV peak, 1 RSD = $[(0.039)^2 + (0.004)^2 + (0.015)^2]^{0.5} = 0.043$ or 4.2%
- ^{239}Pu , 414-keV peak, 1 RSD = $[(0.033)^2 + (0.004)^2 + (0.015)^2]^{0.5} = 0.036$ or 3.6%

The three uncertainty terms for calibration (isotope mass, measured distance, counting statistics) can act in the same "direction"; that is, all concurrently have positive or negative value. We shall make the conservative assumption that they do and are therefore additive. The combined uncertainty terms for the three isotope peaks of interest are as follows:

- ^{235}U , 186-keV peak, $1 \text{ RSD} = 0.4\% + 1.0\% + 1.5\% = 2.9\%$
- ^{239}Pu , 129-keV peak, $1 \text{ RSD} = 0.4\% + 1.0\% + 4/2\% = 5.7\%$
- ^{239}Pu , 414-keV peak, $1 \text{ RSD} = 0.4\% + 1.0\% + 3.6\% = 5.0\%$

5.3. TA-21 Measurements

5.3.1. Wing 3-North Roof. Glovebox and fume hood exhaust ducts exit the west side of wing 3-north upward into a horizontal exhaust duct that runs north-south along the building roof. The Phase I measurements showed high gamma activity at the extreme south end of this duct (Appendix E). The areas of highest activity correspond to locations where vertical duct headers exit the building and join the horizontal duct. The Phase I measurements showed quite low gamma activity for all locations along the ducting on the east side of wing 3-north.

5.3.1.1. Series 2, Phase II Measurement Results. Measurements made *inside* wing 3-north (west side) on the ducts that lead to the vertical header that penetrates the roof and meets the west-side horizontal duct showed many gamma peaks from ^{243}Am and the daughter product ^{239}Np . The spectra showing these peaks is presented in Appendix M. These same peaks were observed in the wing 3-west roof measurements. No measurements of peak areas corresponding to the fissile isotopes ^{235}U or ^{239}Pu were observed to exceed *two* standard deviation precision on the peak; however, a few measurements produced peak areas corresponding to about one standard deviation of the peak area precision. The 15 measurements made on this duct system are tabulated in Appendix N. **Fissile holdup corresponding to these measurements over the 56-ft length of ducting was 1 g of ^{235}U and -0.1 g of ^{239}Pu .** The quantity of americium and neptunium contained in the wing 3 roof ducts was estimated to be 0.2 g of ^{243}Am and 0.07 g of ^{239}Np .

5.3.1.2. Inclusion of Phase I Results. The 56 ft of ducting on the east side of the wing 3-north roof displayed very low count rates for all the Phase I measurements. The Phase I holdup estimate for this ducting is 0.4 g of ^{239}Pu . If we apply the 2.0 bias correction described in Sec. 4.1.2.7.1.3, the wing 3-east duct holdup estimate based on Phase I measurements is 1 g of ^{239}Pu . Process history indicates that no ^{235}U was handled in gloveboxes associated with this duct; hence, no ^{235}U holdup is assigned to this ducting.

5.3.1.3. Total Wing 3-North Roof Holdup Estimate. Summing the Phase I holdup estimates for the wing 3-east ducting and the Series 2, Phase II holdup estimates for the wing 3-west ducting, we arrive at an total holdup estimate of 1 g of ^{235}U and 1 g of ^{239}Pu .

5.3.1.4. Measurement Uncertainties. Uncertainty estimates for the wing 3-north roof duct measurements are listed in Table XV.

Table XV. Phase I and II Estimated Uncertainties, 1 RSD			
Phase	Source	Uncertainty	
		Systematic (%)	Random (1%)
Phase I	Counting statistic	<1	1 %
	Repeatability	6	2 %
	Geometry/model	80	<1 %
Phase II	Counting statistic ^a	<1	0.7 g ²³⁵ U 0.4 g ²³⁹ Pu
	Repeatability	<1	3.2 %
	Geometry/model		
	Distance	<1	5.2 %
	Width	<1	<1 %
	Nonuniformity	<1	11 %
	Calibration		
	²³⁵ U	2.9	<1 %
	²³⁹ Pu	5.0	<1 %
^a The random uncertainty is presented in absolute terms as propagated from the counting statistics for each individual measurement.			

The Phase I uncertainty terms listed in Table XV are applied to the duct segment holdup estimated from Phase I measurements (wing 3-east duct, 1 g of ²³⁹Pu). The Series 2, Phase II uncertainty terms in Table XV are applied to the duct segments containing holdup estimated from Series 2, Phase II measurements (wing 3-west duct, 1 g of ²³⁵U, less than 1 g of ²³⁹Pu). The systematic uncertainty terms may be positive or negative; however, they are summed to represent a "worst case" situation. Random uncertainty terms are added in quadrature. The combined uncertainty estimates (as one standard deviation) for Phase I and Series 2, Phase II holdup estimates as follows:

- Systematic uncertainty on Phase I holdup estimate = < 1 g ²³⁵U
1 g ²³⁹Pu
- Random uncertainty on Phase I holdup estimate = <1 g ²³⁵U
<1 g ²³⁹Pu
- Systematic uncertainty on S 2,P II holdup estimate = <1 g ²³⁵U
<1 g ²³⁹Pu
- Random uncertainty (1 RSD) on Phase II holdup estimate = 1 g ²³⁵U
<1 g ²³⁹Pu

In a worst case approach, we combine the uncertainties for the Phase I and Series 2, Phase II holdup estimates as follows:

1. Systematic uncertainties are added, $<0 \text{ g } ^{235}\text{U}$ and $1 \text{ g } ^{239}\text{Pu}$.
2. Random uncertainties are added in quadrature, $(0^2 + 1^2)^{0.5} = 1 \text{ g } ^{235}\text{U}$
 $(0^2 + 0^2)^{0.5} = 0 \text{ g } ^{239}\text{Pu}$.
3. Combined systematic and random terms are added, $0 + 1 = 1 \text{ g } ^{235}\text{U}$
 $(1 + 0) = 1 \text{ g } ^{239}\text{Pu}$.

On this basis the total wing 3-north roof duct estimated ^{235}U holdup of 1 g of ^{235}U has a 1 standard deviation, total estimated uncertainty of 1 g of ^{235}U . The total wing 3-north roof duct estimated ^{239}Pu holdup of 1 g has a 1 standard deviation, total estimated uncertainty of 1 g of ^{239}Pu .

5.3.1.5. Duct Holdup Probability Assessment. The probability that the wing 3-north roof ducting contains 400 g or more of ^{235}U or ^{239}Pu is less than 10^{-6} .

5.3.2. Outside Ducting. The term "outside ducting" refers to the ducting that leaves the roofs of the various TA-21 processing buildings and goes to the filter building. This entire 380 ft of ducting is mounted on stanchions about 5.5 m above ground level. The Series 2, Phase II measurements were performed on the entire duct system with the up-looking detector on a tripod; the detector-to-duct distance was 4.4 m . A total of 70 measurements were performed with the detector placed at 6-ft (1.8-m) intervals. Because of the large-diameter, high-efficiency HPGe detector, 1-min measurement times provided adequate sensitivity.

5.3.2.1. Series 2, Phase II Measurement Results. We extended the count times from 1 min to 5 min for a few measurements for which the initial count indicated that a peak might have been present (that is, the net peak area was greater than two standard deviations counting uncertainty). Nevertheless, no spectral peaks were observed for fissile isotopes in any of the duct measurements. In the few locations where any gamma peaks were discernible on the multichannel analyzer, only small peaks corresponding to ^{241}Am , ^{243}Am , and ^{239}Np were observed.

We calculated the fissile holdup for this duct system by summing the mass of ^{235}U and ^{239}Pu measured in each duct segment as listed in Appendix N.

5.3.2.2. Total TA-21 Outside Duct Holdup. The total fissile holdup determined from the Series 2, Phase II measurements of the TA-21 outside duct system is 14 g of ^{235}U and 7 g of ^{239}Pu .

5.3.2.3. Measurement Uncertainties. Uncertainty estimates for the TA-21 outside duct system holdup are listed in Table XVI.

Table XVI. Estimated Measurement Uncertainties for TA-21 Outside Duct Holdup, 1 RSD

Source	Uncertainty	
	Systematic (%)	Random (1%)
Counting Statistic ^a	<1	9.8 g. ²³⁵ U 5.0 g. ²³⁹ Pu
Geometry / model		
Distance	<1	2.4%
Width	<1	<1%
Nonuniformity	<1	5.3%
Repeatability	<1	1.7%
Calibration		
²³⁵ U	2.9	<1%
²³⁹ Pu	5.7	<1%

^aThe random uncertainty is presented in absolute terms as propagated from the counting statistics for each individual measurement.

The uncertainty terms listed in Table XVI are applied to the Series 2, Phase II measured fissile holdup of 14 g of ²³⁵U and 7 g of ²³⁹Pu. Systematic uncertainties may be either positive or negative; however, they are summed to represent a "worst case" situation. Random uncertainty terms are added in quadrature. The combined uncertainty estimates (as one standard deviation) for the holdup estimates are as follows:

- Systematic uncertainty on the Phase II holdup estimate = 1 g ²³⁵U
= 0 g ²³⁹Pu
- Random uncertainty on the Phase II holdup estimate = 10 g ²³⁵U
= 5 g ²³⁹Pu

In a worst case approach, the systematic and random uncertainties are summed to yield an total uncertainty estimate:

- Total uncertainty estimate (1 standard deviation) = 11 g ²³⁵U and 5 g ²³⁹Pu

On this basis the total TA-21 outside duct estimated ²³⁵U holdup of 14 g has an total estimated 1 standard deviation uncertainty of 11 g of ²³⁵U. The estimated ²³⁹Pu holdup of 7 g has an total estimated 1 standard deviation uncertainty of 5 g.

5.3.2.4. Duct Holdup Probability Assessment. The probability that the TA-3 outside ducting contains 400 g or more of ²³⁵U or ²³⁹Pu is less than 10⁻⁶.

5.4. TA-3, SM-29 (CMR Building) Measurements

5.4.1. Room 4023. Ducting in this basement room of wing 4 of the CMR Building received Series 1, Phase II measurements. The results of these measurements are reported in Sec. 4.3.2. The measurements were directed at the "hot spots" identified during the Phase I measurements. As described in Sec. 4.3.2.5, holdup estimates from the Phase I measurements were used for those sections of duct not included in the Series 1, Phase II measurements. The combined measurements provided an unacceptably high ^{235}U holdup estimate of 345 g, a value driven by the 315-g contribution from the Phase I measurements. All indicators suggested that the Phase I measurements were biased by nonfissile isotopes in the ducting, but further high-resolution measurements were needed to provide a more accurate holdup estimate. On this basis, Series 2, Phase II measurements were performed on an additional 370 ft of this extensive duct system.

5.4.1.1. Series 2, Phase II Measurement Results. The high gamma counts observed in the low-resolution, Phase I measurements were driven by widely distributed holdup of microgram quantities of the nonfissile isotopes ^{212}Pb and ^{208}Tl (Appendix O). Although these isotopes contributed a Compton continuum background to the Series 2, Phase II measurements, the very high efficiency HPGe detector was ideally suited to minimize the background contribution in the energy regions used to quantify the fissile isotope peak areas. Series 2, Phase II measurement were made on the entire duct system on the south side of room 4023. Phase I gamma activity for this duct section is illustrated in Appendix F. Of the 112 segments measured, no peaks were observed for fissile isotopes, no net peak areas for fissile isotopes were observed to equal the three standard deviations of the net area. The segment-by-segment holdup estimates and counting precision estimates are listed in Appendix N. The fissile holdup estimated from the Series 2, Phase II measurements on the 370 ft of Room 4023 ducts are 11 g of ^{235}U and 3 g of ^{239}Pu .

5.4.1.2. Inclusion of Phase I Results. The Series 2, Phase II measurements covered the ducting located on the south side of room 4023. This portion includes one-half of the room 4023 ducting. The north-side ducting demonstrated very low Phase I counts, and its holdup is estimated from the Phase I measurements. The Phase I estimated holdup for the north-side ducting is 0.3 g of ^{235}U . Applying the 2.0 bias correction described in Sec. 4.1.2.7.1.3, the ^{235}U holdup in room 4023 north-side ducting is estimated at 1 g. Process history indicates no plutonium handling in the gloveboxes serviced by this ducting; had the observed Phase I counts been from plutonium isotope emissions, the plutonium holdup would have been much less than 1 g.

5.4.1.3. Total Room 4023 Holdup Estimate. Summing the Phase I holdup estimate for the room 4023 north-side ducting and the Series 2, Phase II holdup estimates for the south-side ducting yields a total room holdup estimate of 12 g of ^{235}U and 3 g of ^{239}Pu .

5.4.1.4. Measurement Uncertainties. Uncertainty estimates for the room 4023 holdup estimates are listed in Table XVII below:

Table XVII. Phase I and II Estimated Uncertainties, 1 RSD			
Phase	Source	Uncertainty	
		Systematic (%)	Random (1%)
Phase I	Counting statistic	<1	1%
	Repeatability	6	2%
	Geometry/model	80	<1%
Phase II	Counting statistic ^a	<1	5 g ²³⁵ U 5 g ²³⁹ Pu
	Repeatability	<1	1.7%
	Geometry/model		
	Distance	<1	2.4%
	Width	<1	<1%
	Nonuniformity	<1	4.7%
	Calibration		
	²³⁵ U	2.9	<1%
	²³⁹ Pu	5.7	<1%
^a The random uncertainty is presented in absolute terms as propagated from the counting statistics for each individual measurement.			

The Phase I uncertainty terms listed in Table XVII are applied to the Phase I measured fissile holdup estimates of 1 g of ²³⁵U. The Series 2, Phase II uncertainty terms listed in Table XVII are applied to the Series 2, Phase II measured fissile holdup of 11 g of ²³⁵U and 3 g of ²³⁹Pu. Systematic uncertainties may be either positive or negative; however, they are will be summed to represent a "worst case" situation. Random uncertainty terms are added in quadrature. The combined uncertainty estimates (as one standard deviation) for the holdup estimates are as follows:

- Systematic uncertainty on the Phase I holdup estimate = 1 g ²³⁵U
- Systematic uncertainty on the Series 2, Phase II holdup estimate = 0 g ²³⁵U
= 0 g ²³⁹Pu
- Random uncertainty on the Phase II holdup estimate = 6 g ²³⁵U
= 5 g ²³⁹Pu

In a worst case approach, the systematic and random uncertainties are summed to yield an total uncertainty estimate:

- Total uncertainty estimate (1 standard deviation) = 7 g ^{235}U and 5 g ^{239}Pu .

On this basis the total room 4023 estimated ^{235}U holdup of 12 g has an total estimated 1 standard deviation uncertainty of 7 g of ^{235}U . The estimated ^{239}Pu holdup of 3 g has an total estimated 1 standard deviation uncertainty of 5 g.

5.4.1.5. Duct Holdup Probability Assessment. The probability that the room 4023 ducting contains 400 g or more of ^{235}U or ^{239}Pu is less than 10^{-6} .

5.4.2. Room 7034. The Phase I measurements indicated that Room 7034 ducting contained 371 g of holdup as ^{235}U . Series 2, Phase II measurements were performed on those duct segments identified with high gamma activity as illustrated by the "peaks" in Appendix F, diagram CMR - ROOM 7034. Recent decontamination operations in this room indicated that the high gamma activity observed during the Phase I measurements may have been caused by localized deposits of plutonium in drain lines or pumps. The Series 2, Phase II measurements were performed on 89 of the 459 ft of ducting. This 89 ft of ducting contributed 90% of the Phase I counted activity.

5.4.2.1. Series 2, Phase II Measurement Results. A total of seven Series 2, Phase II measurements were made spanning duct segments varying in length from 3.4 to 24 ft. The measurement quality was somewhat limited because of plutonium holdup in drains and sumps. Also, decontamination activities limited the access needed to perform more precise measurements. These limitations are reflected in what appears to be a negative bias in the ^{235}U estimates and in the relatively high uncertainty in the ^{235}U estimate. Tables in Appendix N list the measurement results and uncertainties. In summary, the duct segments receiving Series 2, Phase II measurements contain an estimated -9 g of ^{235}U and 7 g of ^{239}Pu .

5.4.2.2. Inclusion of Phase I Results. Phase I measurement data are used to estimate holdup in the 330 ft of ducting, containing 10% of the total Phase I counted activity. The Phase I estimated holdup for these duct segments is 17 g of ^{235}U and 1 g of ^{239}Pu . Applying the 2.0 bias correction described in Section 4.1.2.7.1.3., the room 7034 ducting holdup associated with these Phase I measurements is 34 g of ^{235}U and 2 g of ^{239}Pu .

5.4.2.3. Total Room 7034 Holdup Estimate. Summing the Series 2, Phase II (the negative Series 2, Phase II value for ^{235}U holdup will be considered a zero-gram value to ensure that we do not understate the actual holdup) and Phase I measurement-based holdup estimates yields a total holdup estimate for the 459 ft of ducting of 34 g of ^{235}U and 9 g of ^{239}Pu .

5.4.2.4. Measurement Uncertainties. Uncertainty estimates for the room 7034 duct measurements are listed in Table XVIII below:

Table XVIII. Phase I and II Estimated Uncertainties, 1 RSD			
Phase	Source	Uncertainty	
		Systematic (%)	Random (1%)
Phase I	Counting statistic	<1	1 %
	Repeatability	6	2 %
	Geometry/model	80	<1 %
Phase II	Counting statistic ^a	<1	5 g ²³⁵ U 1 g ²³⁹ Pu
	Repeatability	<1	1.7 %
	Geometry/model		
	Distance	<1	2.4 %
	Width	<1	<1 %
	Nonuniformity	<1	17 %
	Calibration		
	²³⁵ U	2.9	<1 %
	²³⁹ Pu	5.7	<1 %
^a The random uncertainty is presented in absolute terms as propagated from the counting statistics for each individual measurement.			

The Phase I uncertainty terms listed in Table XVIII are applied to the Phase I measured fissile holdup estimates of 34 g of ²³⁵U and 2 g of ²³⁹Pu. The Series 2, Phase II uncertainty terms in Table XVIII are applied to the Series 2, Phase II measured fissile holdup of 0 g of ²³⁵U (as discussed above, the actual -9 g of ²³⁵U estimate from the Series 2, Phase II measurements will be considered 0 g of ²³⁵U) and 7 g of ²³⁹Pu. Systematic uncertainties may be either positive or negative, however, they are will be summed to represent a "worst case" situation. Random uncertainty terms are added in quadrature. The combined uncertainty estimates (as one standard deviations) for the holdup estimates are as follows:

- Systematic uncertainty on the Phase I holdup estimate = 29 g ²³⁵U
= 2 g ²³⁹Pu
- Systematic uncertainty on the Series 2, Phase II holdup estimate = <1 g ²³⁵U
= 1 g ²³⁹Pu
- Random uncertainty on the Phase I holdup estimate = 1 g ²³⁵U
= <1 g ²³⁹Pu
- Random uncertainty on the Series 2, Phase II holdup estimate = 5 g ²³⁵U
= 2 g ²³⁹Pu

In a worst case approach, the systematic and random uncertainties are summed to yield an total uncertainty estimate:

- Total uncertainty estimate (1 standard deviation) = 35 g of ^{235}U and 5 g of ^{239}Pu .

On this basis the total room 7034 estimated ^{235}U holdup of 34 g has an total estimated 1 standard deviation uncertainty of 35 g of ^{235}U . The estimated ^{239}Pu holdup of 9 g has an total estimated 1 standard deviation uncertainty of 5 g.

5.4.2.5. Duct Holdup Probability Assessment. The probability that the ducting contains 400 g or more of ^{235}U or ^{239}Pu is less than 10^{-6} .

5.4.3. Room 7057A Holdup. The Phase I measurements indicated that the ducting in room 7057A contained 87 g of ^{235}U . A few feet of ducting contained about 50% of the gamma activity observed in the Phase I measurements (Appendix F, CMR ROOM 7057A). These duct segments received Series 2, Phase II measurements.

5.4.3.1. Series 2, Phase II Measurement Results. The Series 2, Phase II high-resolution gamma spectra on those segments having the highest gamma activity showed a predominant peak at 662 keV that corresponds to ^{137}Cs . Peaks were also observed at 301 and 313 keV. These latter peaks would have been credited to ^{235}U when the low-resolution Phase I measurements were made. The isotope generating these peaks have not been identified, but the peak energies do not correspond to those of known fissile isotopes. The results of seven Series 2, Phase II measurement are listed in Appendix N. No peaks were observed corresponding to fissile isotopes. In summary, the estimated holdup in the 24 ft of room 7057A ducting receiving Series 2, Phase II measurements is less than 1 g of ^{235}U and less than 1 g of ^{239}Pu .

5.4.3.2. Inclusion of Phase I Results. Phase I measurement data will be used to estimate the fissile holdup in the 579 ft of ducting that did not receive Series 2, Phase II measurements. Process history provided definitive information that allowed us to identify those duct segments that had been exposed to plutonium but not to ^{235}U . Hence, Phase I gamma counts on those segments were ascribed to ^{239}Pu . The remaining duct segment gamma counts were ascribed to ^{235}U even though some of the activity could have been from the more active isotope ^{239}Pu . Those duct segments in room 7057A that did not receive Series 2, Phase II measurements have holdup estimated as 31 g of ^{235}U and 0.4 g of ^{239}Pu . Applying the 2.0 bias correction described in section 4.1.2.7.1.3., the room 7057A ducting holdup associated with these Phase I measurements is 62 g of ^{235}U and 1 g of ^{239}Pu .

5.4.3.3. Total Room 7057A Holdup Estimates. Summing the Phase I and Series 2, Phase II holdup estimates yields a total room 7057A holdup estimates of 62 g of ^{235}U and 1 g of ^{239}Pu .

5.4.3.4. Measurement Uncertainties. Uncertainty estimates for the Room 7057A duct measurements are listed in Table XIX below:

Table XIX. Phase I and II Estimated Uncertainties, 1 RSD			
Phase	Source	Uncertainty	
		Systematic (%)	Random (1%)
Phase I	Counting statistic	<1	1 %
	Repeatability	6	2 %
	Geometry/model	80	<1 %
Phase II	Counting statistic ^a	<1	0.3 g ²³⁵ U 0.2 g ²³⁹ Pu
	Repeatability	<1	1.7 %
	Geometry/model		
	Distance	<1	2.4 %
	Width	<1	<1 %
	Nonuniformity	<1	17 %
	Calibration		
	²³⁵ U	2.9	<1 %
	²³⁹ Pu	5.7	<1 %

^aThe random uncertainty is presented in absolute terms as propagated from the counting statistics for each individual measurement.

The Phase I uncertainty terms listed in Table XIX are applied to the Phase I measured fissile holdup estimates of 62 g of ²³⁵U and 1 g of ²³⁹Pu. The Series 2, Phase II counting uncertainty terms in Table XIX are less than 1 g and the Series 2, Phase II holdup is less than 1 g for both isotopes; hence, the Series 2, Phase II measurement uncertainties do not contribute at the gram level to the room holdup estimate. Systematic uncertainties may be either positive or negative, however, they are summed to represent a "worst case" situation. Random uncertainty terms are added in quadrature. The combined uncertainty estimates (as one standard deviations) for the holdup estimates are as follows:

- Systematic uncertainty on the Phase I holdup estimate = 53 g ²³⁵U
= 1 g ²³⁹Pu
- Random uncertainty on the Phase I holdup estimate = 2 g ²³⁵U
= <1 g ²³⁹Pu

In a worst case approach, the systematic and random uncertainties are summed to yield an total uncertainty estimate:

- Total uncertainty estimate (1 standard deviation) = 55 g of ²³⁵U and 1 g of ²³⁹Pu.

On this basis the total room 7057A estimated ^{235}U holdup of 62 g has an total estimated 1 standard deviation uncertainty of 55 g of ^{235}U . The estimated ^{239}Pu holdup of 1 g has an total estimated 1 standard deviation uncertainty of 1 g.

5.4.3.5. Duct Holdup Probability Assessment. The probability that the room 7057A ducting contains 400 g or more of ^{235}U or ^{239}Pu is less than 10^{-6} .

5.4.4. Room 7132 Duct Holdup. Phase I measurements indicated a room 7132 duct holdup of 67 g of ^{235}U . Although the room ducting services gloveboxes that are used to prepare plutonium samples, historical data show that some enriched uranium had been handled in these boxes; hence, the observed gamma activity was ascribed to ^{235}U . The gamma activity observed during the Phase I measurements was concentrated in 22 ft of the 87 ft total of ducting (Appendix F, CMR ROOM 7132).

5.4.4.1. Series 2, Phase II Measurement Results. The Series 2, Phase II measurement spectra showed gamma peaks from ^{239}Pu and ^{241}Am plus some unknown isotopes. No gamma peaks at 186 keV were actually observed for ^{235}U . However 1.7 g of ^{235}U holdup is calculated from the summed net peak areas. The four Series 2, Phase II measurement results are listed in Appendix N. In summary, the Series 2, Phase II measurements showed a duct holdup of 2 g of ^{235}U and 13 g of ^{239}Pu .

5.4.4.2. Inclusion of Phase I Results. As mentioned above, the gamma activity observed in the Phase I measurements was concentrated in the 22 ft of ducts that received Series 2, Phase II measurements. Phase I counts summed for the remaining ducting was -238 out of a room total of 22 863. This negative sum reflects the low but highly variable net count rates observed for most of the ducting. Many of the Phase I measurements had large background corrections caused by multigram ^{239}Pu inventories in gloveboxes immediately above the ducting. Less than 1 g of fissile holdup is credited to the ducting that received only Phase I measurements.

5.4.4.3. Total Room 7132 Duct Holdup Estimate. The total fissile material holdup in the room 7132 ducting is estimated at 2 g of ^{235}U and 13 g of ^{239}Pu .

5.4.4.4. Measurement Uncertainties. Measurement uncertainties for the Series 2, Phase II measurements used to estimate the room holdup are summarized in Table XX. The uncertainty terms listed in Table XX are applied to the Phase II measured fissile holdup estimates of 2 g of ^{235}U and 13 g of ^{239}Pu . Systematic uncertainties may be either positive or negative, however, they are summed to represent a "worst case" situation. Random uncertainty terms are added in quadrature.

Table XX. Estimated Measurement Uncertainties, 1 RSD		
Source	Uncertainty	
	Systematic (%)	Random (1%)
Counting Statistic ^a	<1	1.1 g. ²³⁵ U 0.8 g. ²³⁹ Pu
Geometry/model		
Distance	<1	2.4%
Width	<1	<1%
Nonuniformity	<1	22%
Repeatability	<1	1.7%
Calibration		
²³⁵ U	2.9	<1%
²³⁹ Pu	5.7	<1%

^aThe random uncertainty is presented in absolute terms as propagated from the counting statistics for each individual measurement.

The combined uncertainty estimates (as one standard deviation) for the holdup estimates are as follows:

- Systematic uncertainty on the holdup estimate = <1 g ²³⁵U
= 1 g ²³⁹Pu
- Random uncertainty on the holdup estimate = 1 g ²³⁵U
= 3 g ²³⁹Pu

In a conservative, worst case approach, the systematic and random uncertainties are summed to yield an total uncertainty estimate:

- Total uncertainty estimate (1 standard deviation) = 1 g ²³⁵U and 4 g ²³⁹Pu.

On this basis the total room 7132 estimated ²³⁵U holdup of 2 g has an total estimated 1 standard deviation uncertainty of 1 g of ²³⁵U. The estimated ²³⁹Pu holdup of 13 g has an total estimated 1 standard deviation uncertainty of 4 g.

5.4.4.5. Duct Holdup Probability Assessment. The probability that the room 7132 ducting contains 400 g or more of ²³⁵U or ²³⁹Pu is less than 10⁻⁶.

5.4.5. Room 4095 Duct Holdup. The Phase I measurements indicated a room 4095 duct holdup of 63 g of ²³⁵U. Most of the gamma activity was confined to 24 ft of the total 156 ft of ducting, as illustrated in Appendix F, diagram CMR ROOM 4095, locations 85 through 110. Series 2, Phase II measurements were made on the high-activity, 24 ft of ducting.

5.4.5.1. Series 2, Phase II Measurement Results. The Series 2, Phase II measurement spectra showed gamma peaks for ^{212}Pb and ^{208}Tl but no observable fissile isotope peaks. The eight Series 2, Phase II measurement results are listed in Appendix N. In summary, the duct segments receiving Series 2, Phase II measurements are estimated to contain 1 g of ^{235}U and 1 g of ^{239}Pu .

5.4.5.2. Inclusion of Phase I Results. Holdup in the 132 ft of ducting indicating lower holdup is estimated from the Phase I measurements. Holdup in ducting that received only Phase I measurements is estimated as less than 1 g of ^{235}U and less than 1 g of ^{239}Pu .

5.4.5.3. Total Room 4095 Duct Holdup Estimate. The holdup estimate for room 4095 ducting is 1 g of ^{235}U and 1 g of ^{239}Pu .

5.4.5.4. Measurement Uncertainty. Because only those duct segments receiving Series 2, Phase II measurements indicated holdup equal to or greater than 1 g, uncertainties in the estimated holdup are related to Series 2, Phase II measurement uncertainties as listed in Table XXI below:

Table XXI. Estimated Measurement Uncertainties, 1 RSD		
Source	Uncertainty	
	Systematic (%)	Random (1%)
Counting Statistic ^a	<1	1.0 g. ^{235}U 0.8 g. ^{239}Pu
Geometry/model		
Distance	<1	2.4%
Width	<1	<1%
Nonuniformity	<1	15.5%
Repeatability	<1	1.7%
Calibration		
^{235}U	2.9	<1%
^{239}Pu	5.7	<1%

^aThe random uncertainty is presented in absolute terms as propagated from the counting statistics for each individual measurement.

The uncertainty terms listed in Table XXI are applied to the Series 2, Phase II measured fissile holdup estimates of 1 g of ^{235}U and 1 g of ^{239}Pu . Systematic uncertainties may be either positive or negative; however, they are summed to represent a "worst case" situation. Random uncertainty terms are added in quadrature. The combined uncertainty estimates (as one standard deviation) for the holdup estimates are as follows:

- Systematic uncertainty on the holdup estimate = <1 g ^{235}U
= <1 g ^{239}Pu
- Random uncertainty on the holdup estimate = 1 g ^{235}U
= 1 g ^{239}Pu

In a conservative, worst case approach, the systematic and random uncertainties are summed to yield an total uncertainty estimate:

- Total uncertainty estimate (1 standard deviation) = 1 g ^{235}U and 1 g ^{239}Pu .

On this basis the total room 4095 estimated ^{235}U holdup of 1 g has an total estimated 1 standard deviation uncertainty of 1 g of ^{235}U . The estimated ^{239}Pu holdup of 1 g has an total estimated 1 standard deviation uncertainty of 1 g.

5.4.5.5. Duct Holdup Probability Assessment. The probability that the room 4095 ducting contains 400 g or more of ^{235}U or ^{239}Pu is less than 10^{-6} .

5.4.6. Room 2023. The Phase I measurements indicated a room 2023 holdup of 58 g of ^{239}Pu . More than half of this activity was confined to 40 ft of ducting; indeed, one in-line filter in this ducting contributed about 20 g to the total holdup. The Appendix F diagram for CMR ROOM 2023 illustrates the highly localized gamma activity where the Series 2, Phase II measurements were concentrated.

5.4.6.1. Series 2, Phase II Measurement Results. We measured 26 ft of room 2023 ducting in the Series 2, Phase II campaign. The measurements included the filter mentioned above. The filter contained only about 3 g of ^{239}Pu , suggesting that the filter had been changed since the Phase I measurements had been made. This filter will be omitted from the duct holdup estimates because it is likely to retain the contained plutonium during accident scenarios that would transport holdup to a common location. Gamma spectra in the 300- to 340-keV region was observed in duct segments associated with high Phase I holdup estimates. Although the observed peaks did not correspond to fissile isotope peaks, they would have added a positive bias to the low-resolution Phase I measurements. The Series 2, Phase II measurement results are listed in Appendix N. **In summary, the holdup estimate of those duct segments receiving Series 2, Phase II measurements are less than 1 g of ^{235}U and 2 g of ^{239}Pu .**

5.4.6.2. Inclusion of Phase I-Measured Ducting. Very low gamma activity was observed during the Phase I campaign on the 1786 ft of ducting not measured by Series 2, Phase II measurements. Based on the Phase I measurement results on these duct segments, the holdup is 2.8 g of ^{239}Pu . Process history clearly states that no uranium processing had been performed in the gloveboxes serviced by this ducting; therefore, no ^{235}U holdup is credited to room 2023 ducting. **Applying the**

2.0 bias correction described in Sec. 4.1.2.7.1.3., the room 2023 ducting holdup estimated from Phase I measurements, is 6 g of ^{239}Pu .

5.4.6.3. Total Room 2023 Duct Holdup Estimate. Total duct holdup is determined by adding the holdup for duct segments measured Phase I methods to those measured by Series 2, Phase II methods. The total estimated duct holdup for room 2023 is 8 g of ^{239}Pu .

5.4.6.4. Measurement Uncertainty. Uncertainty estimates for the room 2023 duct measurements are listed in Table XXII below:

Table XXII. Phase I and II Estimated Relative Uncertainties, 1 RSD			
Phase	Source	Uncertainty	
		Systematic (%)	Random (1%)
Phase I	Counting statistic	<1	1%
	Repeatability	6	2%
	Geometry/model	80	<1%
Phase II	Counting statistic ^a	<1	0.3 g ^{235}U 0.3 g ^{239}Pu
	Repeatability	<1	1.7%
	Geometry/model		
	Distance	<1	2.4%
	Width	<1	<1%
	Nonuniformity	<1	18%
	Calibration		
	^{235}U	2.9	<1%
	^{239}Pu	5.7	<1%
^a The random uncertainty is presented in absolute terms as propagated from the counting statistics for each individual measurement.			

The Phase I uncertainty terms listed in Table XXII are applied to the Phase I measured fissile holdup estimates of 6 g of ^{239}Pu . The Series 2, Phase II uncertainty terms in Table XXII are applied to the Series 2, Phase II measured fissile holdup of 2 g of ^{239}Pu . Systematic uncertainties may be either positive or negative; however, they are summed to represent a "worst case" situation. Random uncertainty terms are added in quadrature. The combined uncertainty estimates (as one standard deviations) for the holdup estimates are as follows:

- Systematic uncertainty on the Phase I holdup estimate = 5 g ^{239}Pu
- Systematic uncertainty on the Series 2, Phase II holdup estimate = <1 g ^{239}Pu

- Random uncertainty on the Phase I holdup estimate = <1 g ²³⁹Pu
- Random uncertainty on the Series 2, Phase II holdup estimate = <1 g ²³⁹Pu

In a worst case approach, the systematic and random uncertainties are summed to yield an total uncertainty estimate:

- Total uncertainty estimate (1 standard deviation) = 5 g ²³⁹Pu.

On this basis the total room 2023 estimated ²³⁹Pu holdup of 8 g has an total estimated 1 standard deviation uncertainty of 5 g.

5.4.6.5. Duct Holdup Probability Assessment. The probability that the room 2023 ducting contains 400 g or more of ²³⁹Pu is less than 10⁻⁶.

5.5. TA-3, SM-102, Shop 13 Measurements. Because to an oversight, the exhaust ducting in shop 13 was not measured during the Phase I measurement campaign. Quantitative measurements were performed on the 350-ft-long duct system in June 1992 by the Laboratory's Safeguards Assay group. Because the ducting had only serviced operations using one fissile material (²³⁵U), and to gain adequate measurement sensitivity, a low-resolution NaI detector was used in conjunction with a portable multichannel analyzer. The generalized-geometry holdup method was used (Appendix E) and the instrument was calibrated with ²³⁵U source 9-000 (Appendix D).

Appendix P contains a description of the duct system, instrumentation, measurement method, sample plan, calibration, measurement control, data reduction, and uncertainty estimation.

5.5.1. Phase II Measurement Results. Data for each of the measurements are listed in Appendix P. In summary, the shop 13 duct system contained an estimated 421 g of ²³⁵U as holdup.

5.5.2. Uncertainty Estimate. Appendix P quotes estimated errors (measurement uncertainties) of 50% for total holdup estimates. This is probably an overstatement of the actual uncertainty. However, because the ducting is being removed, no further efforts will be made to refine this uncertainty statement. Therefore, the shop 13 estimated holdup of 421 g is assigned an total, 1 standard deviation uncertainty of 211 g.

5.6. TA-48 Measurements

5.6.1. Building 1, Hot Cell Exhaust Ducting. The Building 1 hot cells exhaust air travels downward into an inaccessible below-ground duct that connects to a demister chamber in a basement room. The exhaust air then travels through ducting to a ground-level room containing HEPA filters. The exhaust air is then vented to the atmosphere through a tall exhaust stack. The Phase I measurements performed on this ducting indicated the high gamma counts one expects from the

activation products associated with the hot cell operations; hence, no Phase I estimates were made on the fissile holdup.

5.6.2. Duct Holdup Estimates. The length of ducting from the demister chamber to the exhaust stack, excluding the HEPA filter chambers, is about 220 ft. Twenty-two Series 2, Phase II measurements were performed on this ducting. The measurements were complicated by the presence of ^{75}Se gamma peaks and associated Compton background. This isotope is present because the hot cells are used to produce medical isotopes from reactor-activated materials.

Compton background from the ^{75}Se added relatively large uncertainties to those energy regions common to fissile isotopes. However, by extending the Series 2, Phase II counting times to 300 s, we obtained adequate sensitivity to fissile holdup. No fissile peaks were observed; hence, the holdup estimates stated are probably statistical artifacts of high Compton background rather than actual holdup.

Measurement results totaling an estimated holdup of 11 g of ^{235}U and -2 g of ^{239}Pu for the 22 measurements are listed in Appendix N.

5.6.3. Measurement Uncertainties. The measurement uncertainties typical to the Series, Phase II measurements are listed in Table XXIII. However, the measurements for ^{239}Pu gave predominately negative peak areas (16 out of 22 measurements), suggesting a source of negative bias. This observation is common to ^{239}Pu measurements at either 129 or 414 keV. The bias is probably quite small (largest negative value for any segment was 1.1 g) and is probably adequately "covered" by the total 1 standard deviation measurement uncertainty estimated as 3.3 g of ^{239}Pu .

Table XXIII. Estimated Measurement Uncertainties, 1 RSD		
Source	Uncertainty	
	Systematic (%)	Random (1%)
Counting Statistic ^a	<1	13 g. ^{235}U 3.3 g. ^{239}Pu
Geometry/model		
Distance	<1	2.4%
Width	<1	<1%
Nonuniformity	<1	9.4%
Repeatability	<1	1.7%
Calibration		
^{235}U	2.9	<1%
^{239}Pu	5.7	<1%
^a The random uncertainty is presented in absolute terms as propagated from the counting statistics for each individual measurement.		

The uncertainty terms listed in Table XXIII are applied to the Series 2, Phase II measured fissile holdup estimates of 11 g of ^{235}U and -2 g of ^{239}Pu . Systematic uncertainties may be either positive or negative, however, they are summed to represent a "worst case" situation. Random uncertainty terms are added in quadrature. The combined uncertainty estimates (as one standard deviations) for the holdup estimates are as follows:

- Systematic uncertainty on the holdup estimate = <1 g ^{235}U
= <1 g ^{239}Pu
- Random uncertainty on the holdup estimate = 13 g ^{235}U
= 3 g ^{239}Pu

In a conservative, worst case approach, the systematic and random uncertainties are summed to yield an total uncertainty estimate:

- Total uncertainty estimate (1 standard deviation) = 13 g ^{235}U and 3 g ^{239}Pu .

On this basis the total TA-48, hot cell ducting estimated ^{235}U holdup of 11 g has an total estimated 1 standard deviation uncertainty of 13 g of ^{235}U . The estimated ^{239}Pu holdup of -2 g has an total estimated 1 standard deviation uncertainty of 3 g.

5.6.5. Duct Holdup Probability Assessment. The probability that the TA-48, hot cell ducting contains 400 g or more of ^{235}U or ^{239}Pu is less than 10^{-6} .

5.7. TA-50, Building 69 (Size-Reduction Facility) Measurements

5.7.1. TA-50, Building 69 Ducting. The Size-Reduction facility has one large glovebox complex where gloveboxes and other large equipment are disassembled for efficient, final packaging. The glovebox complex is service by a single, 52-ft-long duct system. Phase I measurements indicated a fissile material holdup of 61 g of ^{235}U .

5.7.2. Series 2, Phase II Duct Holdup Estimates. The entire 52 ft of ducting was measured using the Series 2, Phase II methods. Although gamma peaks from the ^{137}Cs were observed, no gamma peaks corresponding to fissile isotopes were observed. Thirteen Series 2, Phase II measurements were made on the duct system (Appendix N). From the sum of the Series 2, Phase II measurements on the duct segments, the holdup is estimated as less than 1 g of ^{235}U and 2.6 g of ^{239}Pu .

5.7.3. Measurement Uncertainty. Measurement uncertainties for the TA-50, Building 69 ducting are detailed in Table XXIV below:

Table XXIV. Measurement Uncertainty Summary for TA-50, Building 69 Ducts, 1 RSD

Source	Uncertainty	
	Systematic (%)	Random (1%)
Counting Statistic ^a	<1	4.2 g. ²³⁵ U 2.7 g. ²³⁹ Pu
Geometry/model		
Distance	<1	2.4%
Width	<1	<1%
Nonuniformity	<1	12%
Repeatability	<1	1.7%
Calibration		
²³⁵ U	2.9	<1%
²³⁹ Pu	5.7	<1%

^aThe random uncertainty is presented in absolute terms as propagated from the counting statistics for each individual measurement.

The uncertainty terms listed in Table XXIV are applied to the Series 2, Phase II measured fissile holdup estimates of less than 1 g of ²³⁵U and 3 g of ²³⁹Pu. Systematic uncertainties may be either positive or negative, however, they are summed to represent a "worst case" situation. Random uncertainty terms are added in quadrature. The combined uncertainty estimates (as one standard deviations) for the holdup estimates are as follows:

- Systematic uncertainty on the holdup estimate = <1 g ²³⁵U
= <1 g ²³⁹Pu
- Random uncertainty on the holdup estimate = 4 g ²³⁵U
= 3 g ²³⁹Pu

Using a conservative, worst case approach, the systematic and random uncertainties are summed to yield an total uncertainty estimate:

- Total uncertainty estimate (1 standard deviation) = 4 g ²³⁵U and 3 g ²³⁹Pu.

On this basis the total TA-50, Building 69 estimated ²³⁵U holdup of less than 1 g has an total estimated 1 standard deviation uncertainty of 4 g of ²³⁵U. The estimated ²³⁹Pu holdup of 3 g has an total estimated 1 standard deviation uncertainty of 3 g.

5.7.4. Duct Holdup Probability Assessment. The probability that the TA-50, size-reduction ducting contains 400 g or more of ²³⁵U or ²³⁹Pu is less than 10⁻⁶.

6.0. Conclusion

Duct systems in 16 rooms at 6 Los Alamos facilities were identified during preliminary semiquantitative holdup survey measurements as requiring quantitative holdup measurement. We remeasured these duct systems using quantitative holdup measurement methods. The quantitative measurements were made in two campaigns: a Series 1, Phase II campaign wherein state-of-the-art measurements were performed, and a Series 2, Phase II campaign where more cost-effective, adequate-quality, measurements were performed. The primary purpose of these quantitative measurements was to adequately quantify the duct systems fissile holdup to ensure criticality safety for all in-service duct systems.

Two duct systems that are out of service and either in the process of, or scheduled for, removal were also measured during the Phase II campaigns. Additionally, duct systems for two buildings were measured apart from the Phase II campaigns but with measurements adequately quantified to determine fissile holdup for their respective duct-removal programs. Table XXV summarizes the holdup estimates derived from these quantitative measurement campaigns.

Table XXV. Estimated Duct Holdup and Holdup Uncertainties

Estimated Holdup and Uncertainty						
TA/Bldg.	Room No.	Grams of		Grams of		Duct Status
		²³⁵ U	1σ	²³⁹ Pu	1σ	
21/4S	408	157	na ^a	<1	na ^a	D&D
21/4S	413	266	na ^a	<1	na ^a	D&D
21/4S	413R	381	139	<1	<1	D&D
21/3S	313	385	153	<1	<1	D&D
21/3N	W3 roof	1	1	1	1	active
21	Outside	14	10	7	6	active
3/29	4023	12	7	3	5	active
3/29	7034	34	35	9	2	active
3/29	7057A	62	55	1	1	active
3/29	7132	2	1	13	5	active
3/29	4095	1	1	1	1	active
3/29	2023	<1	<1	8	6	active
3/29	5034	69	61	20	17	active
3/29	4034	70	62	50	44	active
50/69	Size redn.	<1	4	3	3	active
48/1	Hot cell	11	14	<1	12	active
55/PF-4	429	<1	<1	39	28	active
3/102	Shop 13	421	211	<1	<1	D&D
3/66	Basement	91	na	<1	<1	D&D

^ana = not available. See Section 2.0.

Note that all the duct systems *in active use* have fissile holdup estimates far below the 400-g fissile limit suggested by former DOE Secretary Admiral Watkins.³ Note also that the measurement uncertainties estimated for these ducts are sufficiently small that the holdup estimates *plus* their associated uncertainties are also far below the 400-g limit.

We have performed probability assessments on each duct system to assist in the criticality safety assessment for each duct system. With the exception of six duct systems associated with out-of-service operations and scheduled for D&D, all of the Los Alamos ducts have a probability of 400 g or more of fissile holdup of 10^{-6} (one in a million).

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I wish to thank John Chamberline of INC-DO for his capable assistance while the Series 2, Phase II measurements were performed at TA-21 (DP Site). Nelson Stalnaker of CLS-1 wrote the specifications for, ordered, and set up the high-efficiency HPGe detector and portable MCA used for all the Series 2, Phase II measurements. Nelson Stalnaker and Cynthia Mills generously provided training and troubleshooting assistance for the portable MCA operation. Thanks to Donna Hofmann of CLS-1 for preparing the extensive Series 2, Phase II tables in Appendix N. Special thanks to Barry Burton of IS-1 for his courteous and professional assistance as the technical editor of this lengthy report.

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APPENDIX A

HOLDUP PROBABILITY

The procedure for determining the holdup probability is based on the following assumptions:

- Measurement-based duct holdup estimates have Gaussian characteristics.
- Uncertainties on holdup estimates are well estimated.
- Holdup estimates are corrected for bias.

Follow this procedure to estimate the probability that the actual holdup exceeds a quantity X :

1. Determine the holdup quantity X_0 from measurement data.
2. Estimate the uncertainty, σ , on the holdup quantity.
3. Compute DELTA as follows:

$$\text{DELTA} = \frac{X - X_0}{\sigma} .$$

4. Use Table A-I to estimate the probability that the actual holdup exceeds the quantity X .

Table A-I. DELTA Versus Probability that Holdup Exceeds X	
DELTA	Probability
0	0.500×10^0
1	0.159×10^0
2	0.228×10^{-1}
3	0.135×10^{-2}
4	0.317×10^{-4}
5	0.287×10^{-6}
6	0.987×10^{-9}
7	0.128×10^{-11}
8	0.666×10^{-15}

APPENDIX B

**EXCERPT FROM "EVALUATION OF HIGH-RESOLUTION GAMMA-RAY
METHODS FOR DETERMINATION OF SOLID PLUTONIUM HOLDUP IN HIGH-
THROUGHPUT BULK-PROCESSING EQUIPMENT,"
LOS ALAMOS NATIONAL LABORATORY REPORT
LA-11729-MS January 1990**

by

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II. EQUIPMENT AND SOFTWARE

The hardware used for the holdup measurements at Rocky Flats is pictured in Fig. 1. A commercial photographic stand with a tripod wheel base and a

Fig. 1. Hardware for the portable holdup measurements. The shielded HPGe detector is mounted on the counterweighted arm of the movable stand (top). Below it are the printer, personal computer, and portable multichannel analyzer, each on a movable shelf. All units can operate with battery power.

counterweighted arm capable of more than 2 m of vertical travel supports the detector, portable multichannel analyzer (PMCA), laptop personal computer, and printer. The PMCA, personal computer, and printer are mounted on separate, movable, custom-designed trays.

Within the last several years, portable HPGe detectors have demonstrated improved performance and reliability in laboratory and field applications. A recently available, commercial, custom-designed HPGe detector features a significantly reduced total weight (for the collimated shielded detector) despite substantial shielding requirements for plutonium holdup measurements. The detector includes both a 2.5-cm-thick tungsten backshield inside the cryostat directly behind the coaxial HPGe crystal and a stepped-down end cap diameter (from 7 cm to 4 cm) at the crystal location, minimizing the weight of the external tungsten shield. Figure 2 shows the detector and the external shield, which provides a 1.6-cm thickness of tungsten around the crystal with a 2-cm-diam by 2.5-cm-deep cylindrical collimator. The total mass of this equipment

Fig. 2. Custom-designed commercial HPGe detector (left) is shown with cadmium end cap (front, center), external tungsten shield (back, center) and external source (right). Detector is shown fitted with hardware for mounting purposes.

(including the external shield) with a full (24-h holding capacity) liquid nitrogen dewar is 11.3 kg; the mass of the external shield is 4.5 kg. Previous in-plant experience in plutonium holdup measurements² has demonstrated the need for the 1.6-cm thickness of tungsten, and yet the total weight of this shielded detector (roughly that of a standard lead brick) makes possible a rapid sequence of measurements at different arbitrary locations in the plant. This shielded detector is shown in Fig. 1 mounted on the counter weighted arm of the movable holdup equipment stand. The mounting device includes a ball pivot for flexibility of detector positioning.

Because reducing and analyzing the data from multiple-energy gamma-ray spectra is complex, automation is essential in using HPGe detectors for multiple-energy holdup assay. A prototype software package, developed for field use in portable gamma-ray holdup assays, was used to automate the Rocky Flats calciner holdup measurements. The software controls the PMCA to automatically acquire, reduce, and analyze the gamma-ray spectral data. Use of the code in on-line applications requires an IBM-PC-compatible computer, a PMCA, a printer, and a cylindrically collimated [HPGe or NaI(Tl)] gamma-ray detector. Off-line, the PMCA gamma-ray spectral data stored on floppy diskette or PMCA data tape can be analyzed by the software.

The software tests the quality of each gamma-ray spectrum by evaluating deviations from expected photopeak centroids, photopeak widths, and count rates for each acquisition. The photopeak and background regions of interest (ROIs) can be defined either by channel number or by energy. The ROIs defined by energy are set according to a unique energy calibration for each spectrum based on the measured centroids of designated photopeaks, thus eliminating concerns about long-term drifts in electronic gain.

The code accesses a designated file of parameters (from multiple stored parameter files) that defines the PMCA setup values, ROIs, photopeak identifications, photopeak and spectrum quality requirements, measurement control criteria, calibration constants, attenuation factors, calibration geometries, and default variables associated with the data acquisition cycles. The availability of multiple parameter files enables (1) the equipment to be used with various detectors and collimation geometries, (2) the assays to be performed for various isotopes, and (3) the measurements to be applied to various sets of process equipment, simply by assigning the (new) appropriate parameter file

before running the software. The automated hardware setup at startup or restart of the software requires about 1 min, after which data acquisition can begin.

In the background option, the software acquires and reduces a background spectrum. The net count rate results for the photopeak energy region are stored for subtraction as background from count rates obtained from all subsequent spectra. Precharacterized standards are measured in the accuracy check option, and the results are compared to stored values. In the assay option, the code reduces the spectral data and applies the appropriate calibration to give quantitative results for holdup. In all options, multiple gamma-ray peaks can be analyzed.

The assay option requires the operator to define the holdup source geometry ("point," "line," or "area") in the detector field of view and the source-to-detector distance for other than area sources. The subsequent assay results are computed in units of g, g/cm, or g/cm² for the three geometries (respectively) where the mass is the isotope mass. When known, the effects of equipment attenuation can be included. The multiple-energy assay corrected for equipment attenuation flags self-attenuation effects when deposits are large. A separate (transmission) measurement should be performed to measure these effects. Otherwise, the flagged assay result at the highest photopeak energy is a lower limit on the actual holdup. In a separate option, the software also automates a point source calibration procedure to determine and store the calibration constants for each of the three holdup geometries. With multiple assay photopeaks, the complexity of the calibration requires that this procedure be automated. The calibration and assay formalism used in this software has been described previously.²

APPENDIX C

**EXCERPT FROM "SNM HOLDUP MEASUREMENTS FOR LOS ALAMOS
EXHAUST DUCTS, PHASE I REPORT,"
LOS ALAMOS NATIONAL LABORATORY REPORT
LA-12231-MS February 1992**

by

Robert S. Marshall

III. PHASE I MEASUREMENTS

Methods and Equipment

It was recognized early on that completion of Phase I measurements in a timely manner (by end of calendar year 1990) would require rapid measurements using highly portable, simple to operate equipment. Highly efficient, rugged, low-cost, thallium-activated sodium iodide detectors were an obvious selection and several brands of battery-powered, portable, single-channel analyzers were considered. Based on recommendations from Los Alamos health physics staff, an Eberline Corp. ESP-II instrument with a single channel analyzer option was evaluated and found to be satisfactory and four instruments purchased. Both one-inch diameter, one-inch thick, and two-inch diameter, two-inch thick NaI detectors were collimated with lead, fitted with thin cadmium shielding and evaluated. The first instrument package was calibrated in early-September, a team of four persons trained, and initial duct holdup measurements made in the TA-55 Plutonium Facility on 9-14-90. Modifications were made to enhance measurement speed and portability, and the final instrument configuration evaluated at TA-55 on 10-2-90.

In this final configuration, the detector/photomultiplier package was collimated and shielded with 0.63 cm (0.25 inches) of lead. The "backside" of the phototube was covered with a 0.32 cm (0.125 inch) "washer" of lead. On the NaI detector end, the lead collimator/shield extended slightly (~ 2 mm) beyond the face of the detector encapsulation, thereby providing the detector with a somewhat-less-than 180 degree viewing angle and protecting the detector from physical damage.

Using a variety of radioisotope sources, the counting energy region was adjusted to approximately 150-350 keV. This region was selected to provide a high detection sensitivity for both ^{235}U and ^{239}Pu with a single instrument setting. The ^{239}Pu is indirectly measured through the ^{237}U daughter of ^{241}Pu . The ^{241}Pu -to- ^{239}Pu ratio varies by about a factor of two in the low-to-medium burnup Pu isotopes handled at the Lab, and the ^{237}U , alpha-branch decay product is characterized by a prolific 208 keV peak. A factor of 2 uncertainty in the Phase I survey measurements was considered acceptable for the survey and semiquantitative usage of the Phase I data. The relatively broad-energy range was subject to bias from counting Compton continuum or some gamma peaks from nonfissile isotopes. This bias caused many Phase I measurements to overestimate the quantity of fissile material present.

To provide daily assurance of instrument performance, a depleted uranium disk-source was counted and corrective measures taken if the source check differed from the count rate determined at calibration by more than three standard deviations from the theoretical counting statistics. The instruments proved very stable, in part because the wide energy band selected was relatively insensitive to typical variations in temperature or from mechanical shock. Power consumption proved very low; no battery replacement was required over a 5-month measurement period.

To provide maximum sensitivity and relative ease of detector placement at selected duct locations, all measurements were made by placing the detector at contact with the duct surface. Wherever practical, measurements were made on the underside of duct assuming that if deposits were not evenly distributed over the duct inner surface, they would tend to be deposited on the duct bottom surface. Ducting located on the roofs of buildings at TA-21 were measured from the topside. These counts were corrected by using a correction factor determined by measuring some locations along the ducts from both the top and undersides. Background measurements were made by moving the detector laterally a few feet away from the duct, "pointing" at an area with no suspected holdup, and counting.

The detectors were clamped to lengths of thin-wall, 3.8 cm (1.25 in.) aluminum tubing, and wooden adaptors were fabricated to allow up to 3 lengths of tubing to be coupled together. This arrangement allowed measurement of ducts as high as 5.2 m (17 feet) above floor/ground level.

Twenty-foot of RG 58 CU coaxial cable with HVN connectors carried the high voltage and counting signals between the detector/phototube and the ESP-II instrument.

Measurements were made at nominal one-foot intervals. On a small fraction of the ducts, holdup was found to be essentially constant over several tens-of-feet and spacing between measurements was increased to two feet. A measurement time of 10 seconds was used for all measurements and provided a sensitivity of approximately 0.02 g ²³⁵U/ft and 0.001 g ²³⁹Pu/ft. In areas of high background, measurement sensitivity suffered by as much as ten-fold from these values.

To add semiquantitative value to the Phase I measurements, small glass vials containing about one gram of U₃O₈ or PuO₂ prepared in a glovebox and positioned in front of the detectors at contact through the glovebox glove. By counting for 10 second periods, a rough calibration constant was obtained which allowed conversion of duct counts/10 sec. to approximate gram SNM values. These values were used to stratify the duct holdup for the Phase II sampling plans.

APPENDIX D

STANDARDS USED FOR PHASE II CALIBRATIONS

Standards Used for Phase II Calibrations			
Standard ID	SPH-1	9-000	7-000
Material	plutonium metal	uranium metal	uranium metal
Isotope mass (g)	5.00 (^{239}Pu)	20.02 (^{235}U)	8.438 (^{235}U)
Shape	Sphere	Disk	Disk
Diameter (cm)	0.805	5.08	5.08
Density (g/cm ³)	19.6	NA	NA
Mass/surface area (g/cm ²)	NA	1.060	0.447
μ at stated energy (g/cm ²)	0.29 (400 keV) 0.27 (414 keV)	1.46 (186 keV)	1.46 (186 keV)

APPENDIX E

**SECTION M OF THE WORKBOOK FOR THE UNITED STATES
DEPARTMENT OF ENERGY SAFEGUARDS TECHNOLOGY TRAINING
PROGRAM COURSE, "NONDESTRUCTIVE ASSAY OF SPECIAL
NUCLEAR MATERIALS HOLDUP," PRESENTED AT THE LOS ALAMOS
NATIONAL LABORATORY ON FEBRUARY 4-8, 1991, THE COURSE
WAS CONDUCTED BY THE LOS ALAMOS NATIONAL LABORATORY
SAFEGUARDS RESEARCH AND DEVELOPMENT GROUP, N-1.**

Safeguards Technology Training Program

Los Alamos
Los Alamos National Laboratory

Nondestructive Assay of Nuclear Materials Holdup

Derivation of the SNM Holdup Generalized Geometry Calibrations

Introduction

Special Nuclear Materials (SNM) can be distributed in process equipment in a wide variety of ways. When measuring SNM holdup, it is necessary to interpret radiation data in the context of an assumed (or known) material distribution in order to convert the measurements to grams of holdup. The three most basic source distributions are:

- a small, localized deposit that can be treated as a point source,
- a long, narrow deposit (e.g., in a pipe) that can be treated as a line source of uniform linear mass density, and
- an extended deposit (e.g., on the floor of a glovebox, over the bottom of a large-area duct, in a concrete spill basin, etc) that can be treated as an area source of uniform areal mass density.

It is rare when a holdup deposit conforms strictly to one of these ideal distribution geometries. However, practical measurements and analysis may dictate assuming one or more of these distributions in order to get a usable number in a finite amount of time.

In some cases, the holdup deposit may be distributed in such a way that assumption of only one of these distributions introduces unacceptable uncertainty and/or bias to the final results. In those cases, it may be advisable to interpret the measurement data with two or all three of the ideal distributions and average the results. The scatter in the individual results compared to the average may then serve to indicate the magnitude of the uncertainty on the true result.

Some holdup measurements may not lend themselves even to this hybrid approach. Such cases may require a specially designed measurement procedure, with unique analysis algorithms. Every effort should be made, however, to minimize the number of such "custom" measurement tasks in a holdup measurement campaign, if only in the interests of cost effectiveness. In many such demanding cases, resorting to the simpler analyses associated with the basic source geometries may provide an equally uncertain — but equally good — result that is more defensible and will be more understandable by others who may be required to deal with the same measurement later.

The objective of this section is to describe how a single calibration check source can be used to generate appropriate calibration expressions for all three basic geometries. This approach is attractive because it requires only a small check source (rather than a host of SNM standards) to equip the measurement system for a variety of measurement scenarios.

To carry this simpler approach further, applying it to the source geometries encountered (but sometimes not fully known) in real facilities, requires experience and creativity on the part of the measurement team, as well as a strong dose of practicality and a sense of proportion.

The Point Source Geometry

This geometry follows the classic inverse-square-law dependence for the count rate as a function of source-to-detector distance. It is applicable when the source is small compared with the diameter of the detector/collimator field of view.

Let a standard SNM (point) mass m_0 be placed at a distance r_0 from the detector, resulting in a gamma-ray count rate of C_0 . (See Figure 1.) If an unknown point SNM mass, m is placed at the same distance from the detector, the count rate (C) will scale

Figure 1. Collimated gamma detector placed at distance r_0 from point source of m_0 grams of SNM.

with mass and be given by

$$C(r_0) = C_0 [m/m_0].$$

If the detector is placed at an arbitrary distance (r) from the unknown source, then the measured count rate will be governed by the inverse-square law:

$$C(r) = C_0 [m/m_0] [r_0/r]^2.$$

The unknown point SNM mass is thus expressed in terms of the source-to-detector distance (r) and the measured count rate $C(r)$ as

$$m \text{ (grams holdup)} = \left[\frac{m_0}{C_0 r_0^2} \right] C(r) r^2 = K_p C(r) r^2,$$

the point-source calibration constant K_p being given by:

$$K_p = \left[\frac{m_0}{C_0 r_0^2} \right] \text{ g-s/cm}^2.$$

The Linear Source Geometry

The point source can also be used to construct a calibration for a linear distribution of SNM. This geometry is applicable when the SNM is distributed along a line whose length extends well beyond the detector/collimator field of view and whose width is small compared to the diameter of that field of view. The use of a point source to establish the calibration for a linear source distribution is illustrated in Figure 2. The point source of mass m_0 is placed at the distance r_0 , and the count rate C_0 is measured, as with the point source calibration. Then the point source is moved (in regular

Figure 2. Geometry for use of point source to establish linear source calibration. The computed effective source length parameter is also indicated.

intervals of length s) transverse to the detector axis, and count rates C_i are measured for each position (i) of the source. In effect, the point source is used to simulate (one segment at a time) the linear distribution of SNM and the count rate the full linear source would produce (see Figure 3).

Figure 3. Illustration of the segmented extended linear source simulated by the discrete source placements in the linear calibration measurement. The linear SNM density (λ_0) is effectively m_0/s .

The effective linear mass density of SNM over the path along which the source is moved is $m_0/s = \lambda_0$, where s is the spacing of the source positions for which the count rates C_i are measured. The total count rate from this linear source is given by the sum of the measured count rates over the full range of observable source positions:

$$\text{Total Count Rate} = C_c = \sum_{i=-\infty}^{i=+\infty} C_i = 2 \sum_{i=0}^{i=+\infty} C_i - C_0,$$

where the detector response for negative values of i (i.e., left of the central source position) are assumed to be the same as for their positive counterparts. This is a good assumption if the detector/collimator system has right-left symmetry in its response and if the count rate C_0 is measured with the point source centered exactly on the detector axis. [See Figure 4.]

Figure 4. Illustration of the measured radial response of a collimated ("real") detector to a point source placed at several equally spaced positions, as described in the text and in Figure 2. Also depicted is the response of an ideal detector whose on-axis response at distance r_0 to the point source is C_0 counts/s. The ideal detector's response to all source positions in its field of view along the line that is a perpendicular distance r_0 from the detector is C_0 counts/s.

It is convenient to define the effective length of a uniform linear source (of linear mass density λ_0) that would give the same total count rate with an ideal detector† as that obtained in the calibration measurement. Since C_0 is the response from a length s (at distance r_0), then the total count rate C_c would be the result of L/s such responses and is therefore expressed in terms of C_0 as follows:

$$C_c = C_0 L/s = \lambda_0 C_0 L/m_0.$$

Thus, we can express this effective source length in terms of the measured data:

$$\text{Effective Source Length} = L = \frac{sC_c}{C_0} = \sum_{i=-\infty}^{i=+\infty} s \frac{C_i}{C_0} = 2s \sum_{i=0}^{i=+\infty} \frac{C_i}{C_0} - s.$$

Since the radial detector response falls off with increasing source displacement from the central position, the parameter, L , is less than the diameter of actual geometric field of view of the detector (note this is indicated in figures 2 and 5).

Now consider another linear source of mass density λ , viewed from the same perpendicular distance by the same detector. (See Figure 5.) The total count rate (C)

Figure 5. Measurement of unknown linear holdup source with linear mass density λ . At the same perpendicular distance as that used in the calibration, the detector has the same field of view and effective source length parameter, L .

observed from this source would simply scale with λ , compared to λ_0 at calibration:

$$C = C_c \lambda / \lambda_0 = (C_0 L / m_0) \lambda.$$

The count rate in a detector from a line source of radiation decreases with increasing perpendicular distance (r) of the detector from the source. As the source-to-detector distance increases, the source length viewed by the detector *increases* in proportion to r ,

† For our purposes, an ideal detector is one that responds with a constant measured count rate (C_0 in this case) for all source positions that are within its field of view and with zero response for sources outside its field of view. [See Figure 4.]

but the contribution from all points along the viewed length *decreases* with the usual $1/r^2$ dependence. As long as the linear source fills the detector field of view, the detector response to this source therefore varies inversely with r . Thus, if the perpendicular distance (r) is varied, the measured count rate is expressed by:

$$C(r) = \left[\frac{C_0 L}{m_0} \right] \lambda \left(\frac{r_0}{r} \right).$$

The linear mass density of an unknown holdup deposit measured at a distance r under the above calibration is therefore given by:

$$\lambda(\text{grams holdup/centimeter}) = \left[\frac{m_0}{C_0 r_0 L} \right] C(r) r = K_1 C(r) r,$$

the linear source holdup calibration constant being given by:

$$K_1 = \left[\frac{m_0}{C_0 r_0 L} \right] \text{g-s/cm}^2.$$

The Area Source Geometry

The line source calibration data can be used to construct a calibration for area sources of SNM. To see this, we consider Figure 6, which shows the line-source calibration setup from the area source perspective. Only the "positive" source

Figure 6. Line source calibration setup, from the areal source perspective. Each position of the calibration source of mass m_0 defines an annular region over which a uniform distribution of such sources is visualized. The detector is still placed at a perpendicular distance r_0 from the central source position, to give the central count rate of C_0 , as before.

position indices are used, since each source position corresponds to a full annular region centered on the central source position, and this annulus includes the corresponding negative source positions.

To construct the areal calibration, we visualize (at a given source location along the line) successive placements of the calibration source around the corresponding annular area. In the linear calibration exercise, we considered each source position as a linear segment of unit length s with SNM mass m_0 . In the areal calibration, we consider the source m_0 to be situated on a unit area α , giving an areal SNM mass density (ρ_0) of:

$$\rho_0 = m_0/\alpha \text{ (grams SNM per cm}^2\text{)}.$$

We then visualize the successive placement of m_0 in unit areas α around the annulus as depicted in Figure 7.

Figure 7. Illustration of the visualized successive placements of m_0 grams of SNM around one of the annular regions defined by the linear source position to simulate a uniform areal distribution of SNM of areal density m_0/α .

Each annulus at source position i has an area a_i given by:

$$a_i = 2\pi s^2 \text{ [except } a_0 = \pi s^2/4],$$

where s is still the length of the linear segments defined by each source position. If the detector response does not vary as the detector is rotated about its axis, then each visualized placement of the source around the annular area a_i will give a count rate C_i . The entire annulus would therefore contribute $(a_i/\alpha)C_i$ to the total count rate, and the total count rate (C_c) that would be realized from many sources of SNM of mass m_0 spread uniformly over all of the areas would be:

$$C_c = \sum_{i=1}^{i=\infty} \frac{a_i}{\alpha} C_i + \frac{a_0}{\alpha} C_0,$$

where C_i and C_0 have the same definitions as in the previous calibration exercises, and the symmetry of the detector response with respect to rotation about its axis (mentioned above) is also assumed.

It is also convenient to define an effective source area (A) that corresponds to a uniform area source (of areal mass density ρ_0) that would give the same total count rate with an ideal detector[†] as that obtained in the calibration measurement. Since C_0 is the detector response from the area α (at a distance r_0), then the count rate C_c would be the result of A/α such responses and is therefore expressed in terms of C_0 as follows:

$$C_c = \frac{A C_0}{\alpha} = \frac{\rho_0 A C_0}{m_0}.$$

Thus, we can express this effective source area in terms of the measured data:

$$\text{Effective source area} = A = \frac{\alpha C_c}{C_0} = \sum_{i=1}^{i=\infty} a_i \frac{C_i}{C_0} + a_0 = \pi s^2 \left[2 \sum_{i=1}^{i=\infty} i \frac{C_i}{C_0} + 1/4 \right].$$

Since the radial detector response falls off with increasing source displacement from the central position, the parameter, A , is less than the area of the actual geometric field of view of the detector.

At the same r_0 , a different areal density ρ gives a count rate (C) that simply scales with the areal density (ρ), compared with the calibration density (ρ_0):

$$C = C_c \frac{\rho}{\rho_0} = \frac{\rho A C_0}{m_0}.$$

As the source-to-detector distance (r) increases, the area viewed by the detector *increases* in proportion to r^2 , but the contribution from each point in the viewed areal SNM distribution *decreases* with the same inverse- r^2 dependence. Thus, as long as the area source fills the detector field of view, there is no r -dependence to the measured count rate. This results in the areal calibration of:

$$\rho(\text{grams holdup/cm}^2) = \left[\frac{m_0}{A C_0} \right] C = K_a C,$$

with the areal calibration constant being given by:

$$K_a = \left[\frac{m_0}{A C_0} \right] \text{g-s/cm}^2.$$

[†] For our purposes, an ideal detector is one that responds with a constant measured count rate (C_0 in this case) for all source positions that are within its field of view and with zero response for sources outside its field of view. [See Figure 4.]

Summary

It is possible to calibrate the measurement system for the three basic source geometries (point, line, area) using a single point calibration source and a set of measurements on that source. In the calibration exercise, the quantities that are recorded prior to measurement are:

- m_0 , the mass of the point calibration source,
- r_0 , the perpendicular distance between the point source and the detector face, along the detector axis [also the perpendicular distance between the detector face and the line along which the calibration measurements are made], and
- s , the spacing between successive placements of the calibration source along the line.

The basic count rates that must be measured are:

- C_0 , the calibration source net count rate with the calibration source a distance r_0 from the detector face and on the detector axis, and
- C_i , the count rates from the calibration source located at several successive positions along a line transverse to the detector axis and a perpendicular distance r_0 from it.

Finally, two parameters must be calculated from the recorded and measured data:

- L , the effective line source length parameter, and
- A , the effective area source area parameter.

From this information, the generalized geometry calibrations can be computed, and these are summarized in the table below.

Geometry	Effective Dimension Parameter	Holdup Relation	Calibration Constant [g-s/cm ²]
Point	n/a	$m(\text{grams holdup}) = K_p C(r) r^2$	$K_p = \left[\frac{m_0}{C_0 r_0^2} \right]$
Line	$L = \sum_{i=-\infty}^{i=+\infty} s \frac{C_i}{C_0} = 2s \sum_{i=0}^{i=+\infty} \frac{C_i}{C_0} - s$	$\lambda(\text{grams holdup/cm}) = K_l C(r) r$	$K_l = \left[\frac{m_0}{C_0 r_0 L} \right]$
Area	$A = \sum_{i=1}^{i=\infty} a_i \frac{C_i}{C_0} + a_0 = \pi s^2 \left[2 \sum_{i=1}^{i=\infty} i \frac{C_i}{C_0} + 1/4 \right]$	$\rho(\text{grams holdup/cm}^2) = K_a C$	$K_a = \left[\frac{m_0}{A C_0} \right]$

APPENDIX F
HOLDUP INDICES

DP - ROOM 313

DP - ROOM 413R

TA-55 - ROOM 429

5 LOCATIONS PER CELL

CMR - ROOM 4023

CMR - ROOM 4034

5 LOCATIONS PER CELL

CMR - ROOM 5034

5 LOCATIONS PER CELL

DP - W3 ROOF

5 LOCATIONS PER CELL

DP - OUTSIDE

5 LOCATIONS PER CELL

CMR - ROOM 7034

CMR - ROOM 7057A

10 LOCATIONS PER CELL

CMR; ROOM 4095

CMR – ROOM 2023

10 LOCATIONS PER CELL

TA-50 - SM-69

APPENDIX G

PHASE I AND PHASE II ²³⁵U HOLDUP ESTIMATES FOR TA-21

Phase I and Phase II ²³⁵ U Holdup Estimates for TA-21, Room 313 Ducts			
Phase I Locations	Phase II est. grams	Phase I est. grams	Bias-Corrected Phase I grams
1-55	NA ^a	1.2	3.7
55-72	103.4	NA	NA
72-79	67.1	NA	NA
79-9	NA	5.0	15.4
91-92	5.5	NA	NA
92-149	NA	15.1	46.9
149-157	29.2	NA	NA
157-180	NA	3.5	10.9
180-183	0.9	NA	NA
183-231	NA	0.0	0.0
231-235	8.8	NA	NA
235-257	NA	2.3	7.2
257-261	4.0	NA	NA
261-264	NA	2.0	6.2
264-270	32.0	NA	NA
270-285	NA	3.8	11.8
285-288	4.1	NA	NA
288-292	NA	0.1	0.3
292-297	2.6	NA	NA
297-315	NA	0.5	1.5
Total:	258	Total:	104
		Grand total:	362 g ²³⁵ U

^a NA = not applicable.

Phase I and Phase II ^{235}U Holdup Estimates for TA-21, Room 413 Ducts			
Phase I Locations	Phase II est. grams	Phase I est. grams	Bias-Corrected Phase I grams
1-21	NA ^a	9.7	3.9
21-32	10.7	NA	NA
32-36	NA	11.1	4.4
36-41	9.7	NA	NA
41-49	1.4	NA	NA
49-61	NA	2.0	0.9
61-66	2.3	NA	NA
66-131	NA	31.3	12.5
131-141	NA	4.1	8.2
141-149	3.8	NA	NA
149-158	NA	4.5	9.0
158-165	2.5	NA	NA
165-172	NA	10.4	20.4
172-191	70.4	NA	NA
191-202	41.2	NA	NA
202-212	27.5	NA	NA
212-221	96.2	NA	NA
221-226	NA	3.4	6.8
1000-1002	49.3	NA	NA
Total:	315.0	Total:	66.1
		Grand total:	381 g ^{235}U

^a NA = not applicable.

APPENDIX H

LATERAL DISPLACEMENT RESPONSE CURVE OF THE DETECTOR COUNT RATE

APPENDIX I

GAMMA-RAY SPECTRAL INTERFERENCE CAUSED BY THORIUM-228 DECAY SERIES ISOTOPES

APPENDIX J
CHARACTERIZATION OF ENRICHED URANIUM FOILS

TO: N-1 Staff

DATE: August 11, 1992

FROM: Eric Piquette & ⁶⁴³Greg Sheppard

MAILSTOP/TELEPHONE: E540/7-6599

SYMBOL: N-1-92-529

SUBJECT: **Characterization of Enriched Uranium Foils**

During the summer of 1991, an effort was made to characterize the thickness and uniformity of the thin, plastic-laminated, enriched uranium foils. This memorandum documents that activity.

Abstract

The uranium foils characterized in this experiment frequently are arranged to simulate linear or planar sources of radiation in generalized-geometry gamma-ray measurements. Since the foils are intended to represent uniform lines and planes, it is useful to know how homogeneous they are individually. Two independent nondestructive gamma-ray methods were used to characterize the foils. In the first, generalized geometry assumptions were employed and the areal densities of the foils were found by passively counting ^{235}U gamma rays at five different points along each of the foils. In the second characterization, a thickness map for each of the foils was generated by measuring the attenuation of a full-energy peak from a transmission source at points on a 1.27-cm-square grid. The average areal density and the relative uniformity of the foils were determined.

Introduction

It is becoming common to employ generalized geometry assumptions in the gamma-ray nondestructive assay of special nuclear materials. If suitable line- or area-source standards are unavailable, calibrations are performed by measuring a point source at multiple positions to generate a detector response curve and to compute point-, line-, and area-calibration constants. Line and area standards make calibration much simpler, as only one measurement is required. Such standards also provide a means to verify the generalized geometry calibrations made with point sources.

Description of the Foils

There are ten uranium foils, all enriched to 93.15% ^{235}U . Each is thin enough that self-attenuation is very small. Foils #1-4 are approximately 7.6 cm wide by 45.7 cm long, and foils #5-10 measure approximately 46.0 cm by 3.8 cm (see Table 1). The "book" thicknesses were obtained by dividing the masses of the foils by their respective areas (product of length and width). At the time of the experiment, the foils were encapsulated in a plastic laminate of 0.008 cm (0.003 in) thickness on each side. Attenuation through the laminate had a small effect on the thickness data, and was accounted for in the calculations.

GS:EP/gjm

Cy: N-1 Files (Author) ⁶⁴⁶GHE

Table 1. Foil Dimensions

Foil ID#	Mass of Foil (g)	Length (cm)	Width (cm)	"Book" Thickness (g/cm ² ²³⁵ U)
1	12.5	45.72	7.62	0.03342
2	9.3	45.72	7.62	0.02486
3	9.3	45.72	7.62	0.02486
4	12.4	45.72	7.70	0.03281
5*	9.4	46.00	3.81	0.05146
6	9.3	46.10	3.81	0.04932
7	9.4	46.10	3.81	0.04985
8	8.6	42.35	3.81	0.04965
9	9.2	46.00	3.81	0.04890
10	9.0	45.95	3.81	0.04789

* Foil 5 has a ragged edge; this is approximately accounted for in the "book thickness" computation.

Repackaging of the Foils

Some time after this experiment was completed, a small hole was discovered in the laminate covering of Foil #1. Subsequently, the entire set of foils was repackaged for better protection and control of contamination. The repackaging consisted of affixing an additional layer of plastic laminate identical to the foils' original covering. Hence, the total laminate thickness on each side of the foils is presently 0.015 cm.

Passive Measurement

A Bicron Model 1M.5/1LP-X shielded, collimated NaI detector and a Davidson Model 2056-4K PMCA were used to acquire spectral data. The NaI crystal is 2.54 cm in diameter and 1.27 cm deep. The detector is rigidly mounted inside the lead collimator-shield. The collimator depth and diameter are both 2.54 cm. A highly enriched uranium disk standard (#9-000) was used to measure the detector response and to normalize it. The calculated effective source area at the 53.54-cm calibration distance was $1215.5 \pm 10.1 \text{ cm}^2$.

At contact (source-to-detector distance equals 2.54 cm, the collimator depth), even the narrow foils fill the detector field of view and meet the area source criterion. A foil was laid flat on a counter top, the detector/collimator assembly was placed on top of the foil along its longitudinal centerline, and a passive spectrum was acquired and analyzed. This was repeated at each of five positions along its length (1", 5", 9", 13", and 17" from left edge of foils, except Foil #8, which was counted at 1", 5", 9", 13", and 15 3/4"), and the process was repeated for each foil. The mean and standard deviation of the net 186-keV count rate were determined for each foil. Then the area source calibration constant, $k_A = 2.237 \times 10^{-4} \pm 2.4 \times 10^{-6} \text{ g-s/cm}^2$, was applied to compute the foil thickness. Results are shown in Table 2.

Table 2. Results of Passive Characterization

Foil ID#	Self-attenuation Correction Factor (CF _{att})	Mean Net Count Rate (cps)	Mean Measured Thickness $\pm 1\sigma$ (g/cm ² ²³⁵ U)
1	1.025	138.8 $\pm$ 11.3	0.0318 $\pm$ 0.0026
2	1.019	107.9 $\pm$ 2.2	0.0246 $\pm$ 0.0006
3	1.019	110.4 $\pm$ 6.5	0.0252 $\pm$ 0.0015
4	1.025	139.1 $\pm$ 10.0	0.0319 $\pm$ 0.0023
5	1.034	186.4 $\pm$ 2.6	0.0431 $\pm$ 0.0008
6	1.035	196.3 $\pm$ 1.0	0.0454 $\pm$ 0.0005
7	1.035	197.3 $\pm$ 4.2	0.0457 $\pm$ 0.0011
8	1.033	183.4 $\pm$ 2.8	0.0424 $\pm$ 0.0008
9	1.035	195.5 $\pm$ 2.0	0.0453 $\pm$ 0.0007
10	1.035	193.5 $\pm$ 3.9	0.0448 $\pm$ 0.0010

Transmission Measurement Setup

A collimated ⁵⁷Co source was positioned so that its beam axis was coincident with that of the upward-looking planar high purity germanium detector. A 0.15-cm thick cadmium filter and a detector collimator measuring 0.95 cm in diameter and 5 cm in depth were used. Spectral data were acquired with a Canberra Genie MCA and net peak areas were calculated by the MCA software. A 500-second spectrum was acquired from the ⁵⁷Co source and the net area of the unattenuated 122-keV peak (I₀) was recorded. Similar measurements of I₀ were made at the conclusion of each foil characterization and also at the halfway point for each of the wide foils, in order to assure measurement control.

Transmission Measurement Procedure

Transmission data were acquired using a real time preset of 30 seconds. The foils were positioned one-at-a-time on a piece of 15 cm x 92 cm plexiglas on which a grid of 1.27-cm units was drawn. A 2.5-cm hole in the plexiglas was aligned with the source and detector collimator axes. A foil was placed on the grid so that the beam penetrated it at the first measurement position. A spectrum was then acquired and the net 122-keV peak area for the point was recorded. Then the foil was repositioned to the next coordinates, a transmission spectrum was acquired, and the net 122-keV peak area was recorded. This was repeated until each foil was mapped on the 1.27-cm grid. Narrow foils were mapped with 3x36 measurement points (except Foil #8, which was 3x33) and the wide foils were characterized with a 6x36 transmission map.

Calculation of Thicknesses and Errors

Gamma-ray attenuation through matter is described by the familiar relation:

$$I/I_0 = \exp(-\mu\rho x) \quad (1)$$

where I is the intensity of the transmitted beam, I₀ is the intensity of the incident beam, μ is the linear attenuation coefficient, ρ is the density of the attenuating material, and x is its thickness. The attenuation coefficient, μ_U , for uranium at 122-keV is 4.081 cm²/g.³ When attenuation by the plastic laminate covering the foils is included in the calculations, the attenuation equation becomes

$$I/I_0 = \exp(-\mu_U\rho_U x_U - \mu_P\rho_P x_P) \quad (2)$$

where $\mu_L = 0.16 \text{ cm}^2/\text{g}$ is the linear attenuation coefficient for plastic at 122-keV, and $\rho_L x_L$ is the areal density of the laminate, found to be 0.03085 g/cm^2 .

Equation (2) can be solved for $\rho_U x_U$, the areal density of uranium, to obtain:

$$\rho_U x_U = (1/\mu_U) \cdot \ln(I_0/I) - (\mu_L/\mu_U) \rho_L x_L \quad (3)$$

The second term here is the equivalent thickness of the laminate, and is a constant, analogous to $0.0012 \text{ g/cm}^2 \text{ U}$. Using equation (3), areal densities were determined for all measured points on the foils. Then the mean areal density and its standard deviation were computed for each foil (see Table 3).

By comparing the actual measured standard deviation to the standard deviation of a uniform foil of the same average thickness, one gains a sense of its relative non-uniformity. The variance in measurements of an ideally "flat" foil would be due only to random error components:

$$\sigma_{\text{flat}}^2 = (1/\mu_U)^2 ((\sigma_I/I)^2 + (\sigma_{I_0}/I_0)^2) \quad (4)$$

Table 3. Transmission Measurements Results Summary

Foil ID#	Mean Measured Thickness $\pm 1\sigma$ (g/cm ²)	"Flat" σ_{flat} (g/cm ²)	Ratio of Measured σ to σ_{flat}
1	0.0323 $\pm$ 0.00296	0.00138	2.14
2	0.0244 $\pm$ 0.00190	0.00136	1.40
3	0.0242 $\pm$ 0.00168	0.00136	1.24
4	0.0318 $\pm$ 0.00245	0.00138	1.78
5	0.0440 $\pm$ 0.00177	0.00143	1.24
6	0.0459 $\pm$ 0.00182	0.00143	1.27
7	0.0465 $\pm$ 0.00169	0.00144	1.17
8	0.0434 $\pm$ 0.00221	0.00140	1.58
9	0.0463 $\pm$ 0.00153	0.00143	1.07
10	0.0455 $\pm$ 0.00160	0.00144	1.11

Results and Conclusions

After all thicknesses were calculated, a FORTRAN routine was used to render an exaggerated three dimensional thickness profile of the foils. These plots, shown in Figures 1 and 2, permit a qualitative estimate of the relative uniformity of the foil thicknesses. A T-test, performed at each transmission measurement point, revealed thickness extremes.

One method of testing the uniformity of the foils is to compare the standard deviation of the thickness measurement distribution with the standard deviation for an ideally "flat" foil of the same average thickness (equation 4). If the ratio of the measured standard deviation to the "flat" standard deviation is near unity, then the foil can be considered satisfactorily uniform. Using an arbitrary figure of merit of 1.4, it was concluded that all foils were flat except numbers 1, 4, and 8. This agrees well with the graphical analysis.

In a third check of foil flatness, the raw 122-keV net peak areas for all the measurement points on each foil were charted on a frequency diagram, and Gaussian

curves were fit to the resulting histograms. The normality of the data was gauged by performing chi-squared tests on these distributions. Table 4 shows the results of the curve fittings, and gives chi-squared and residuals data.

Table 4. Histogram Curve Fitting Residuals and Goodness-of-Fit

Foil ID#	Sum of Squares of Residuals	Chi-Squared and Degrees of Freedom	Probability of Fit
1	275.	23.5 2	0%
2	77.8	3.97	5%
3	113.	2.37 4	65%
4	242.	4.78 3	20%
5	34.1	1.47 5	92%
6	48.5	0.66 1	45%
7	72.3	5.56 4	25%
8	104.	0.65 1	45%
9	6.2	0.71 5	98%
10	131.	3.38 3	35%

When the foils were packaged originally, it was observed that some of them were highly oxidized. Prior to the lamination process, the majority of the oxide was removed from foils #1-4. No oxide was removed from foils #6-10. Any uranium oxide present in the foils would add weight to them, but would not have a significant effect on the transmission or passive measurements. In the worst case, where a foil is pure U_3O_8 , it is 15% oxygen by weight. This may account for the difference in areal density values between the "book thickness" and the results of the experiments (see Table 5). Even with pure uranium oxide, attenuation by the oxygen alters the calculated thickness by less than one percent, and thus is considered negligible here.

Table 5. Foil Thickness Measurements Summary

Foil ID#	"Book" Thickness (g/cm ² ²³⁵ U)	Passive Mean Measured Thickness $\pm 1\sigma$ (g/cm ² ²³⁵ U)	Transmission Mean Measured Thickness $\pm 1\sigma$ (g/cm ² ²³⁵ U)
1	0.0334	0.0318 $\pm$ 0.0026	0.0323 $\pm$ 0.0030
2	0.0249	0.0246 $\pm$ 0.0006	0.0244 $\pm$ 0.0019
3	0.0249	0.0252 $\pm$ 0.0015	0.0242 $\pm$ 0.0017
4	0.0328	0.0319 $\pm$ 0.0023	0.0318 $\pm$ 0.0024
5	0.0515	0.0431 $\pm$ 0.0008	0.0440 $\pm$ 0.0018
6	0.0493	0.0454 $\pm$ 0.0005	0.0459 $\pm$ 0.0018
7	0.0498	0.0457 $\pm$ 0.0011	0.0465 $\pm$ 0.0017
8	0.0496	0.0424 $\pm$ 0.0008	0.0434 $\pm$ 0.0022
9	0.0489	0.0453 $\pm$ 0.0007	0.0463 $\pm$ 0.0015
10	0.0479	0.0448 $\pm$ 0.0010	0.0455 $\pm$ 0.0016

Useful information was gained about the less "flat" foils, as well. For instance, Foil #1 has a thick spot on one end, but the rest of the foil appears to be relatively even.

Knowing this, the bad end of the foil could be shielded or corrected for in an experiment.

Using the Foils as Line and Area Sources

A primary purpose of this standards characterization was to determine the uniformity of the foils and the limits of their use in generalized geometry calibrations. The foils may be laid end to end or side by side to create line or area sources, respectively. Since the narrow foils (#5-10) are almost the same thickness, they lend themselves most readily to this application. The six narrow foils differ in thickness by about 4%. Only very near the line or plane of foils could these differences be detected, however. As the detector is withdrawn from the foil, nonuniformity error drops rapidly. From these computed error graphs we conclude that the foils are uniform when configured for use under generalized geometry assumptions. Best results would be obtained with Foils #6, 7, 9, and 10, which are the same thickness to within about 1%.

Table 6 gives effective areal densities for the foils, corrected for self-attenuation at 186 keV. Effective ^{235}U mass is also given as the effective areal density times the measured area of the foils. As an example, the effective linear mass density of a line source constructed from foils 6, 7, 9, and 10 would be

$$\frac{(7.78 + 7.87 + 7.83 + 7.68)}{(46.1 + 46.1 + 46.0 + 45.95)} = 0.169 \text{ g/cm } ^{235}\text{U}$$

Table 6. Effective Density Values For Use in Passive Generalized Geometry Experiments at 185 keV

Foil ID#	Thickness, Total U (g/cm ²)	Self-Attenuation Coefficient	Effective Density (g/cm ² ^{235}U)	Effective ^{235}U Mass (g)
1	.0347	.975	.0315	11.0
2	.0262	.981	.0239	8.33
3	.0261	.981	.0238	8.24
4	.0341	.975	.0310	10.9
5	.0472	.966	.0425	7.52
6	.0493	.965	.0443	7.78
7	.0499	.964	.0448	7.87
8	.0466	.967	.0419	6.76
9	.0497	.964	.0447	7.83
10	.0489	.965	.0439	7.68

REFERENCES

1. G. A. Sheppard, et al, "Models for Gamma-Ray Holdup Measurements at Duct Contact," presented at the Institute of Nuclear Materials Management 32nd Annual Meeting, New Orleans, Louisiana, July 28-31, 1991, Los Alamos National Laboratory report LA-UR-91-2507 (July 1991).
2. N. Ensslin and H. A. Smith, Jr., "Attributes and Semi-quantitative Measurements," Chapter 20 in Passive Nondestructive Assay of Nuclear Materials, NUREG/CR-5550, T. D. Reilly, N. Ensslin, and H. A. Smith, Jr., Eds., Los Alamos National Laboratory document LA-UR-90-732 (1991).
3. Values for μ were taken from the ATTEN computer code. ATTEN is based on cross section data from Nuclear Data Tables A7, 565-681(1970), E. Storm and H. Israel, "Photon Cross Section from 1 keV to 100 MeV for Elements Z=1 to Z=100."

Figure 1. Exaggerated 3-D Thickness Profiles of Wide Foils.

Figure 2. Exaggerated 3-D Thickness Profiles of Narrow Foils.

APPENDIX K

MAESTRO II OPERATOR'S MANUAL

Calculate

< Alt C >

Peak Area

< Alt A >

Figure 59. Peak Area

This command (see Figure 59) displays the net area, gross area, and the error of the net area for the ROI peak that is marked.

The background on the low channel side of the peak is the average of the first three channels of the ROI (see Figure 60). The channel number for this background point is the middle channel of the three points. The background on the high channel side of the peak is the average of the last three channels of the ROI. The channel number for this background point is also the middle channel of the three points. These two pairs of points on each side of the peak are the end points of the straight-line background.

Figure 60. Background Calculation

The background is given by the following:

$$B = \left(\sum_{i=l}^{l+2} C_i + \sum_{i=h-2}^h C_i \right) \frac{h-l+1}{6}$$

where

- B is the background area
- l is the ROI low limit
- h is the ROI high limit
- C_i is the contents of channel i
- 6 is the number of data channels used (3 on each end)

The gross area is the sum of all the channels marked by the ROI according to the following:

$$A_g = \sum_{i=l}^h C_i$$

where

A_g is the gross counts in the ROI
 l is the ROI low limit
 h is the ROI high limit
 C_i is the contents of channel i

The adjusted gross area is the sum of all the channels marked by the ROI but not used in the background according to the following:

$$A_{ag} = \sum_{i=l+3}^{h-3} C_i$$

where

A_{ag} is the adjusted gross counts in the ROI
 l is the ROI low limit
 h is the ROI high limit
 C_i is the contents of channel i

The net area is the adjusted gross area minus the adjusted calculated background, as follows:

$$A_n = A_{ag} - \frac{B(h-l-5)}{(h-l+1)}$$

The error in the net area is the square root of the sum of the squares of the errors in the adjusted gross area and the weighted error of the adjusted background. The background error is weighted by the ratio of the adjusted peak width to the number of channels used to calculate the adjusted background. Therefore, net peak area error is given by:

$$\sigma_{An} = \sqrt{A_{ag} + \left(\frac{h-l-5}{6} \right) \left(\frac{h-l-5}{h-l+1} \right) B}$$

where

A_{ag} is the adjusted gross area
 A_n is the net area
 B is the background area
 C_i is the contents of channel i
 l is the ROI low limit
 h is the ROI high limit
 σ_{An} is the error in the net area

APPENDIX L

LATERAL DISPLACEMENT RESPONSE CURVE

APPENDIX M

GAMMA SPECTRA FROM TA-21 WING 3-NORTH DUCTS

TYPE = -1 MCA # 01 SEGMENT # 01 SEQUENCE # 0
 REALTIME = 671.00 SECONDS, LIVETIME = 600.00 SECONDS
 DATA COLLECTED AT 15:39:32 ON 06-JUL-92

7692-1.CHN

APPENDIX N

Table N-1. TA-21, Wing 3 North, Roof (West Side)

Segment Length (ft)	²³⁵ U (g/ft)	σ (g/ft)	²³⁵ U (g)	(σ · ft) ²	²³⁹ Pu (g/ft)	σ (g/ft)	²³⁹ Pu (g)	(σ · ft) ²
3.3	-0.09	0.05	-0.3	0.03	0.02	0.03	0.07	0.010
3.3	0.04	0.04	0.1	0.02	-0.05	0.03	-0.2	0.010
3.3	-0.03	0.03	-0.1	0.01	<0.01	0.03	<0.03	0.010
3.3	<0.01	0.05	<0.03	0.03	0.02	0.02	0.07	0.004
3.3	0.04	0.04	0.1	0.02	-0.05	0.03	-0.2	0.010
3.3	-0.04	0.04	-0.1	0.02	0.01	0.02	0.03	0.004
3.3	0.04	0.04	0.1	0.02	-0.02	0.03	-0.07	0.010
3.3	0.04	0.03	0.1	0.01	<0.01	0.02	<0.03	0.004
3.3	0.01	0.03	0.03	0.01	0.01	0.02	0.03	0.004
3.3	-0.01	0.03	-0.03	0.01	0.01	0.02	0.03	0.004
3.3	0.03	0.02	0.1	0.00	0.02	0.02	0.07	0.004
3.3	0.08	0.05	0.3	0.03	<0.01	0.02	<0.03	0.004
3.3	<0.01	0.06	<0.03	0.04	-0.01	0.02	-0.03	0.004
3.3	0.02	0.05	0.1	0.03	-0.01	0.02	-0.03	0.004
9.9	0.02	0.05	<u>0.2</u>	<u>0.25</u>	0.01	0.02	<u>0.10</u>	<u>0.039</u>
SUM			0.60	0.53			-0.12	0.125
√SUM				0.7				0.35

Table N-2. TA-21, Outside Duct

Segment Length (ft)	²³⁵ U (g/ft)	σ (g/ft)	²³⁵ U (g)	(σ · ft) ²	²³⁹ Pu (g/ft)	σ (g/ft)	²³⁹ Pu (g)	(σ · ft) ²
6	-0.01	0.05	-0.1	0.09	<0.01	0.04	<0.1	0.06
6	0.07	0.05	0.4	0.09	0.02	0.04	0.1	0.06
6	0.07	0.05	0.4	0.09	0.04	0.03	0.2	0.03
6	-0.47	0.30	-2.8	3.2	0.02	0.04	0.1	0.06
6	0.18	0.10	1.1	0.36	0.06	0.08	0.4	0.2
6	0.20	0.11	1.2	0.44	0.04	0.09	0.2	0.3
6	0.02	0.13	0.1	0.61	-0.01	0.09	-0.1	0.3
6	-0.17	0.14	-1.0	0.71	0.03	0.09	0.2	0.3
5	0.28	0.21	1.4	1.1	0.15	0.11	0.8	0.3
6	-0.23	0.26	-1.4	2.4	-0.01	0.12	-0.1	0.5
6	-0.16	0.25	-1.0	2.3	0.06	0.09	0.4	0.3
6	0.20	0.19	1.2	1.3	0.1	0.08	0.6	0.2
6	0.10	0.19	0.6	1.3	-0.01	0.09	<0.1	0.3
6	0.17	0.20	1.0	1.4	<0.01	0.09	0.06	0.3
6	0.05	0.18	0.3	1.2	0.05	0.07	0.3	0.2
6	0.02	0.22	0.1	1.7	0.04	0.1	0.2	0.4
6	-0.07	0.21	-0.4	1.6	-0.11	0.11	-0.7	0.4
6	0.26	0.16	1.6	0.92	0.1	0.1	0.6	0.4
6	0.02	0.24	0.1	2.1	-0.01	0.09	-0.1	0.3
6	0.30	0.16	1.8	0.92	0.06	0.08	0.4	0.2
6	0.08	0.22	0.5	1.7	-0.1	0.2	-0.6	1.4
6	0.37	0.18	2.2	1.2	0.01	0.09	0.1	0.3
6	0.02	0.22	0.1	1.7	0.08	0.08	0.5	0.2
6	-0.15	0.24	-0.9	2.1	0.19	0.08	1.1	0.2
6	-0.4	0.26	-2.4	2.4	<0.01	0.1	<0.1	0.4
6	0.39	0.17	2.3	1.0	0.04	0.09	0.2	0.3
6	-0.02	0.20	-0.1	1.4	0.01	0.09	0.1	0.3
6	-0.03	0.22	-0.2	1.7	0.07	0.07	0.4	0.2
6	-0.06	0.21	-0.4	1.6	<0.01	0.09	<0.1	0.3
6	0.11	0.21	0.7	1.6	0.01	0.1	0.1	0.4
6	0.13	0.48	0.8	8.3	0.08	0.08	0.5	0.2
6	0.12	0.16	0.7	0.92	<0.01	0.07	<0.1	<0.1
6	0.18	0.18	1.1	1.2	<0.01	0.1	<0.1	0.4
6	-0.09	0.20	-0.5	1.4	0.01	0.08	0.1	0.2
8	-0.14	0.21	-1.1	2.8	-0.08	0.09	-0.6	0.5

6	0.18	0.09	1.1	0.3	<0.01	0.22	<0.1	1.7
6	0.08	0.17	0.5	1.0	0.02	0.08	0.1	0.2
6	-0.36	0.23	-2.2	1.9	-0.02	0.08	-0.1	0.2
6	0.09	0.16	0.5	0.92	0.03	0.08	0.2	0.2
6	0.09	0.18	0.5	1.2	0.04	0.07	0.2	0.2
6	0.22	0.14	1.3	0.71	0.02	0.08	0.1	0.2
6	0.15	0.16	0.9	0.92	-0.03	0.08	-0.2	0.2
6	0.01	0.08	0.1	0.23	<0.01	0.03	<0.1	0.03
6	0.09	0.18	0.5	1.2	-0.04	0.08	-0.2	0.2
6	0.03	0.23	0.2	1.9	0.07	0.06	0.4	0.1
8	-0.07	0.19	-0.6	2.3	0.02	0.07	0.2	0.3
6	0.15	0.15	0.9	0.81	-0.05	0.09	-0.3	0.3
6	0.10	0.15	0.6	0.81	0.07	0.07	0.4	0.2
6	-0.15	0.21	-0.9	1.6	-0.05	0.08	-0.3	0.2
6	0.27	0.18	1.6	1.2	-0.08	0.08	-0.5	0.2
6	0.19	0.16	1.1	0.92	0.05	0.06	0.3	0.1
6	0.17	0.16	1.0	0.92	-0.02	0.08	-0.1	0.2
6	<0.01	0.19	<0.1	1.3	<0.01	0.08	<0.1	0.2
6	0.14	0.15	0.8	0.81	0.01	0.08	0.1	0.2
6	-0.36	0.22	-2.2	1.7	0.02	0.06	0.1	0.1
6	0.24	0.12	1.4	0.52	-0.04	0.08	-0.2	0.2
6	-0.15	0.19	-0.9	1.3	0.03	0.08	0.2	0.2
6	0.10	0.27	0.6	2.6	-0.01	0.08	-0.1	0.2
6	-0.26	0.22	-1.6	1.7	0.04	0.06	0.2	0.1
6	0.13	0.16	0.8	0.92	<0.01	0.03	<0.1	0.03
6	-0.23	0.21	-1.4	1.6	-0.17	0.32	-1.0	3.7
6	<0.01	0.17	<0.1	1.0	0.06	0.06	0.4	0.1
6	0.07	0.16	0.4	0.92	-0.05	0.08	-0.3	0.2
6	-0.07	0.20	-0.4	1.4	-0.02	0.08	-0.1	0.2
6	0.20	0.21	1.2	1.6	-0.01	0.08	-0.1	0.2
6	0.13	0.16	0.8	0.92	0.23	0.30	1.4	3.2
6	-0.04	0.19	-0.2	1.3	-0.02	0.08	-0.1	0.2
6	0.03	0.08	0.2	0.23	0.01	0.03	0.1	0.03
6	-0.13	0.20	-0.8	1.4	0.19	0.08	1.1	0.2
6	0.06	0.18	<u>0.4</u>	<u>1.2</u>	-0.01	0.07	<u>-0.1</u>	<u>0.2</u>
SUM			13.6	96.11			7.26	24.70
$\sqrt{\text{SUM}}$				9.8				5.0

Table N-3. TA-3, SM-29, Room 4023

Segment Length (ft)	²³⁵ U (g/ft)	σ (g/ft)	²³⁵ U (g)	(σ · ft) ²	²³⁹ Pu (g/ft)	σ (g/ft)	²³⁹ Pu (g)	(σ · ft) ²
3.3	0.02	0.05	0.07	0.03	-0.06	0.04	-0.2	0.017
3.3	0.03	0.05	0.1	0.03	0.03	0.03	0.1	0.010
3.3	-0.03	0.06	-0.1	0.04	0.02	0.02	0.07	0.004
3.3	-0.03	0.07	-0.1	0.05	0.02	0.04	0.07	0.017
3.3	0.03	0.05	0.1	0.03	-0.02	0.02	-0.07	0.004
3.3	0.06	0.05	0.2	0.03	<0.01	0.02	<0.03	0.004
3.3	0.04	0.06	0.1	0.04	-0.07	0.05	-0.2	0.027
3.3	0.02	0.06	0.07	0.04	0.05	0.03	0.2	0.010
3.3	-0.01	0.06	-0.03	0.04	0.01	0.03	0.03	0.010
3.3	<0.01	0.06	<0.03	0.04	<0.01	0.03	<0.03	0.010
3.3	-0.07	0.06	-0.2	0.04	0.03	0.03	0.1	0.010
3.3	-0.05	0.06	-0.2	0.04	<0.01	0.03	<0.03	0.010
3.3	-0.03	0.06	-0.1	0.04	-0.02	0.03	-0.07	0.010
5.0	0.03	0.09	0.2	0.20	0.02	0.05	0.1	0.063
6.6	0.12	0.09	0.79	0.35	0.05	0.05	0.3	0.109
3.3	-0.02	0.06	-0.07	0.04	-0.07	0.05	-0.2	0.027
3.3	<0.01	0.06	<0.03	0.04	0.03	0.03	0.1	0.010
3.3	0.01	0.06	0.03	0.04	-0.02	0.04	-0.07	0.017
3.3	<0.01	0.06	<0.03	0.04	0.02	0.04	0.07	0.017
3.3	0.06	0.06	0.2	0.04	-0.02	0.04	-0.07	0.017
3.3	<0.01	0.06	<0.03	0.04	-0.02	0.04	-0.07	0.017
3.3	-0.03	0.07	-0.1	0.05	<0.01	0.04	<0.03	0.017
3.3	0.05	0.07	0.2	0.05	0.03	0.04	0.1	0.017
3.3	-0.02	0.07	-0.07	0.05	0.02	0.04	0.07	0.017
3.3	-0.13	0.09	-0.43	0.09	-0.05	0.04	-0.2	0.017
3.3	-0.09	0.09	-0.3	0.09	0.03	0.04	0.1	0.017
3.3	0.04	0.11	0.1	0.13	0.05	0.06	0.2	0.039
3.3	-0.04	0.07	-0.1	0.05	-0.02	0.04	-0.07	0.017
3.3	-0.03	0.08	-0.1	0.07	-0.02	0.04	-0.07	0.017
3.3	<0.01	0.09	<0.03	0.09	0.07	0.04	0.2	0.017
3.3	0.13	0.08	0.43	0.07	-0.02	0.06	-0.07	0.039
3.3	0.12	0.08	0.40	0.07	-0.02	0.06	-0.07	0.039
3.3	0.03	0.09	0.1	0.09	-0.10	0.07	-0.33	0.053
5.0	-0.02	0.16	-0.1	0.64	0.06	0.09	0.3	0.203
5.0	0.09	0.08	0.5	0.16	<0.01	0.06	<0.05	0.090

3.3	0.11	0.09	0.36	0.09	<0.01	0.06	<0.03	0.039
3.3	0.02	0.12	0.07	0.16	0.02	0.08	0.07	0.070
3.3	-0.11	0.14	-0.36	0.21	-0.03	0.09	-0.1	0.088
3.3	0.03	0.12	0.1	0.16	0.09	0.07	0.3	0.053
3.3	0.12	0.12	0.40	0.16	<0.01	0.07	<0.03	0.053
3.3	-0.06	0.11	-0.2	0.13	0.08	0.08	0.3	0.070
3.3	0.18	0.10	0.59	0.11	0.05	0.08	0.2	0.070
3.3	-0.01	0.17	-0.03	0.31	-0.05	0.10	-0.2	0.109
3.3	-0.02	0.19	-0.07	0.39	<0.01	0.11	<0.03	0.132
3.3	-0.13	0.19	-0.43	0.39	0.11	0.11	0.36	0.132
3.3	-0.06	0.18	-0.2	0.35	<0.01	0.99	<0.03	10.67
3.3	0.09	0.18	0.30	0.35	0.14	0.08	0.46	0.070
6.6	0.54	0.40	3.6	6.97	-0.04	0.26	-0.3	2.945
3.3	0.17	0.15	0.56	0.25	-0.13	0.09	-0.4	0.088
3.3	0.01	0.13	0.03	0.18	<0.01	0.08	<0.03	0.070
3.3	0.18	0.11	0.59	0.13	-0.04	0.08	-0.1	0.070
3.3	0.07	0.11	0.2	0.13	0.03	0.06	0.1	0.039
3.3	0.24	0.10	0.79	0.11	0.04	0.06	0.1	0.039
3.3	-0.12	0.12	-0.40	0.16	0.10	0.08	0.3	0.070
5.0	0.21	0.13	1.1	0.42	0.11	0.08	0.55	0.160
6.6	<0.01	0.34	<0.07	5.04	0.07	0.13	0.5	0.736
3.3	0.04	0.10	0.13	0.11	<0.01	0.06	<0.03	0.039
3.3	0.03	0.10	0.10	0.11	0.05	0.06	0.2	0.039
3.3	0.17	0.09	0.56	0.09	0.03	0.06	0.1	0.039
3.3	<0.01	0.09	<0.03	0.09	0.11	0.05	0.36	0.027
3.3	-0.03	0.10	-0.1	0.11	0.03	0.06	0.1	0.039
3.3	-0.01	0.09	-0.03	0.09	-0.02	0.06	-0.07	0.039
6.6	0.11	0.16	0.73	1.12	-0.03	0.11	-0.2	0.527
3.3	-0.04	0.07	-0.1	0.05	0.02	0.06	0.07	0.039
5.0	-0.09	0.16	-0.4	0.64	0.14	0.11	0.70	0.303
6.6	0.28	0.15	1.8	0.98	<0.01	0.10	<0.07	0.436
3.3	0.06	0.09	0.2	0.09	0.04	0.06	0.1	0.039
3.3	-0.15	0.10	-0.50	0.11	-0.02	0.06	-0.07	0.039
3.3	-0.11	0.10	-0.36	0.11	0.09	0.05	0.30	0.027
3.3	-0.22	0.12	-0.73	0.16	0.03	0.06	0.1	0.039
3.3	0.16	0.09	0.5	0.09	-0.11	0.07	-0.36	0.053
3.3	-0.06	0.09	-0.2	0.09	-0.03	0.06	-0.1	0.039
6.6	0.04	0.15	0.26	0.98	0.05	0.09	0.3	0.353
3.3	0.06	0.10	0.2	0.11	0.02	0.06	0.07	0.039
3.3	-0.07	0.09	-0.2	0.09	<0.01	0.06	<0.03	0.039

3.3	0.07	0.08	0.2	0.07	0.05	0.05	0.2	0.027
3.3	0.05	0.08	0.2	0.07	0.04	0.06	0.1	0.039
3.3	0.15	0.09	0.50	0.09	-0.05	0.07	-0.2	0.053
3.3	-0.13	0.11	-0.43	0.13	-0.02	0.07	-0.07	0.053
3.3	-0.06	0.14	-0.2	0.21	0.01	0.24	0.03	0.627
3.3	-0.21	0.12	-0.69	0.16	-0.06	0.07	-0.2	0.053
3.3	0.12	0.11	0.40	0.13	0.04	0.08	0.1	0.070
3.3	0.03	0.13	0.10	0.18	-0.10	0.08	-0.3	0.070
3.3	0.20	0.16	0.66	0.28	0.13	0.10	0.43	0.109
3.3	0.06	0.17	0.2	0.31	-0.17	0.11	-0.56	0.132
3.3	0.02	0.14	0.07	0.21	-0.02	0.09	-0.07	0.088
3.3	-0.16	0.14	-0.53	0.21	-0.17	0.24	-0.56	0.627
3.3	0.17	0.10	0.56	0.11	0.04	0.07	0.1	0.053
5.0	-0.02	0.14	<u>-0.10</u>	<u>0.49</u>	-0.09	0.09	<u>-0.5</u>	<u>0.203</u>
SUM			11.42	27.05			2.79	21.19
$\sqrt{\text{SUM}}$				5.2				4.6

Table N-4. TA-3, SM-29, Room 7034

Segment Length (ft)	^{235}U (g/ft)	σ (g/ft)	^{235}U (g)	$(\sigma \cdot \text{ft})^2$	^{239}Pu (g/ft)	σ (g/ft)	^{239}Pu (g)	$(\sigma \cdot \text{ft})^2$
8.1	-0.04	0.09	-0.3	0.53	0.07	0.02	0.6	0.03
3.3	0.02	0.05	0.07	0.03	0.01	0.02	0.03	0.004
3.3	0.05	0.05	0.2	0.03	0.04	0.02	0.1	0.004
11	-0.25	0.21	-2.8	5.3	0.17	0.04	1.9	0.19
7.0	-0.06	0.14	-0.4	0.96	0.07	0.04	0.5	0.08
7.0	-0.05	0.15	-0.4	1.1	0.13	0.04	0.91	0.08
24	-0.22	0.18	<u>-5.3</u>	<u>18.7</u>	0.13	0.04	<u>3.1</u>	<u>0.92</u>
SUM			-8.92	26.65			7.14	1.308
$\sqrt{\text{SUM}}$				5.2				1.1

Table N-5. TA-3, SM-29, Room 7057A

Segment Length (ft)	²³⁵ U (g/ft)	σ (g/ft)	²³⁵ U (g)	(σ · ft) ²	²³⁹ Pu (g/ft)	σ (g/ft)	²³⁹ Pu (g)	(σ · ft) ²
3.0	0.04	0.03	0.12	0.008	0.02	0.02	0.06	0.004
4.0	0.04	0.03	0.16	0.014	-0.01	0.02	-0.04	0.006
4.0	<0.01	0.03	<0.04	0.014	0.01	0.02	0.04	0.006
3.0	-0.01	0.03	-0.03	0.008	0.01	0.02	0.03	0.004
3.0	0.05	0.05	0.15	0.023	-0.01	0.03	-0.03	0.008
3.0	<0.01	0.02	<0.03	0.004	-0.01	0.01	-0.03	0.001
3.0	0.01	0.02	<u>0.03</u>	<u>0.004</u>	<0.01	0.01	<u><0.03</u>	<u>0.001</u>
SUM			0.43	0.075			0.03	0.030
√SUM				0.27				0.17

Table N-6. TA-3, SM-29, Room 7132

Segment Length (ft)	²³⁵ U (g/ft)	σ (g/ft)	²³⁵ U (g)	(σ · ft) ²	²³⁹ Pu (g/ft)	σ (g/ft)	²³⁹ Pu (g)	(σ · ft) ²
2.0	-0.02	0.02	-0.04	0.00	0.039	0.010	0.08	0.00
6.0	-0.01	0.09	-0.06	0.29	1.45	0.070	8.7	0.18
6.0	0.18	0.07	1.1	0.18	0.41	0.059	2.5	0.13
8.0	0.09	0.11	<u>0.72</u>	<u>0.77</u>	0.25	0.076	<u>2.0</u>	<u>0.37</u>
SUM			1.72	1.24			13.28	0.68
√SUM				1.1				0.82

Table N-7. TA-3, SM-29, Room 4095

Segment Length (ft)	²³⁵ U (g/ft)	σ (g/ft)	²³⁵ U (g)	(σ · ft) ²	²³⁹ Pu (g/ft)	σ (g/ft)	²³⁹ Pu (g)	(σ · ft) ²
3.3	-0.06	0.07	-0.2	0.05	0.15	0.04	0.50	0.02
3.3	0.02	0.09	0.07	0.09	<0.01	0.08	<0.03	0.07
3.3	0.05	0.10	0.2	0.11	0.07	0.09	0.2	0.09
2.2	0.02	0.09	0.04	0.04	0.01	0.08	0.02	0.03
2.2	0.12	0.09	0.26	0.04	0.06	0.07	0.1	0.02
3.3	-0.07	0.13	-0.2	0.18	-0.05	0.11	-0.2	0.13
3.3	-0.12	0.15	-0.40	0.25	0.11	0.12	0.36	0.16
3.3	0.35	0.14	<u>1.2</u>	<u>0.21</u>	0.01	0.12	<u>0.03</u>	<u>0.16</u>
SUM			0.97	0.97			1.04	0.68
√SUM				1.0				0.82

Table N-8. TA-3, SM-29, Room 2023

Segment Length (ft)	²³⁵ U (g/ft)	σ (g/ft)	²³⁵ U (g)	$(\sigma \cdot \text{ft})^2$	²³⁹ Pu (g/ft)	σ (g/ft)	²³⁹ Pu (g)	$(\sigma \cdot \text{ft})^2$
4.4	0.01	0.02	0.04	0.01	0.06	0.02	0.3	0.01
3.3	-0.01	0.03	-0.03	0.01	0.12	0.03	0.40	0.01
3.3	0.04	0.02	0.13	0.00	0.03	0.02	0.10	0.00
5.5	-0.01	0.04	-0.06	0.05	0.24	0.04	1.3	0.05
4.4	-0.05	0.02	-0.22	0.01	0.02	0.02	0.09	0.01
3.3	-0.04	0.02	-0.13	0.00	-0.03	0.02	-0.10	0.00
SUM			-0.26	0.08			2.07	0.08
$\sqrt{\text{SUM}}$				0.28				0.28

Table N-9. TA-50, Building 69

Segment Length (ft)	²³⁵ U (g/ft)	σ (g/ft)	²³⁵ U (g)	$(\sigma \cdot \text{ft})^2$	²³⁹ Pu (g/ft)	σ (g/ft)	²³⁹ Pu (g)	$(\sigma \cdot \text{ft})^2$
8	-0.17	0.41	-1.4	10.8	0.05	0.23	0.4	3.4
8	0.07	0.29	0.56	5.4	0.01	0.22	0.08	3.1
3.3	-0.12	0.09	-0.40	0.09	0.06	0.06	0.2	0.04
3.3	0.03	0.08	0.1	0.07	0.14	0.05	0.46	0.03
3.3	-0.06	0.12	-0.2	0.16	-0.04	0.08	-0.1	0.07
3.3	-0.05	0.12	-0.2	0.16	0.13	0.08	0.43	0.07
3.3	0.10	0.12	0.33	0.16	0.02	0.09	0.07	0.09
3.3	0.10	0.15	0.33	0.25	0.05	0.10	0.17	0.11
3.3	0.23	0.15	0.76	0.25	0.08	0.11	0.26	0.13
3.3	0.08	0.11	0.3	0.13	0.08	0.08	0.26	0.07
3.3	-0.11	0.11	-0.36	0.13	0.03	0.08	0.1	0.07
3.3	-0.04	0.11	-0.13	0.13	0.03	0.07	0.1	0.05
3.3	-0.16	0.11	-0.53	0.13	0.04	0.07	0.13	0.05
SUM			-0.83	17.86			2.56	7.28
$\sqrt{\text{SUM}}$				4.2				2.7

Table N-10. TA-48 Hot Cell Exhaust System

Segment Length (ft)	²³⁵ U (g/ft)	σ (g/ft)	²³⁵ U (g)	(σ · ft) ²	²³⁹ Pu (g/ft)	σ (g/ft)	²³⁹ Pu (g)	(σ · ft) ²
7.8	-0.19	0.21	-1.5	2.7	-0.05	0.06	-0.4	0.22
5.9	0.09	0.14	0.5	0.68	-0.04	0.05	-0.2	0.09
5.9	0.22	0.18	1.3	1.1	-0.05	0.06	-0.3	0.13
5.9	-0.19	0.21	-1.1	1.5	0.01	0.06	0.06	0.13
5.9	0.09	0.18	0.5	1.1	-0.01	0.06	-0.06	0.13
5.9	0.23	0.20	1.4	1.4	-0.07	0.06	-0.4	0.13
5.9	0.25	0.18	1.5	1.1	-0.09	0.06	-0.5	0.13
3.3	0.10	0.11	0.3	0.13	-0.02	0.03	-0.1	0.01
3.3	0.07	0.15	0.2	0.25	-0.04	0.04	-0.1	0.02
3.3	0.03	0.16	0.1	0.28	-0.04	0.04	-0.1	0.02
4.9	0.36	0.23	1.8	1.27	-0.10	0.06	-0.49	0.09
3.3	0.29	0.13	1.0	0.18	0.03	0.04	0.1	0.02
2.5	0.06	0.17	0.2	0.18	-0.13	0.05	-0.3	0.02
2.5	0.20	0.19	0.5	0.23	-0.02	0.05	-0.05	0.02
3.9	0.28	0.27	1.1	1.11	0.09	0.08	0.4	0.10
5.2	0.37	0.37	1.9	3.70	0.01	0.10	0.05	0.27
7.5	-1.55	0.70	-11.6	27.6	-0.15	0.17	-1.1	1.63
6.5	1.03	1.37	6.70	79.3	0.28	0.34	1.8	4.9
6.5	-0.56	0.63	-3.6	16.8	0.03	0.15	0.2	0.95
2.6	0.31	0.38	0.81	0.98	-0.03	0.09	-0.08	0.05
9.75	0.84	0.49	8.2	22.8	-0.04	0.12	-0.4	1.37
6.5	0.11	0.26	<u>0.7</u>	<u>2.86</u>	0.02	0.06	<u>0.1</u>	<u>0.15</u>
SUM			10.91	167.2			-1.86	10.58
√SUM				12.9				3.3

APPENDIX O

GAMMA-RAY SPECTRAL INTERFERENCE CAUSED BY THALLIUM-208 AND LEAD-212

Appendix O: Gamma-Ray Spectral Interference Caused by Thallium-208 and Lead-212

APPENDIX P

TA-3, SM-102, HOLDUP MEASUREMENTS

TO: George Hagedorn, MEC-1, MS D471

DATE: June 15, 1992

THRU: Norbert Ensslin, N-1, MS E540 ^{NE}

MAILSTOP/TELEPHONE: E540/7-3250

FROM: ^{BL} Bob Likes & ^{EA} Ed Adams, N-1, MS E540

SYMBOL: N-1-92-392

SUBJECT: Measurement of Fissile 235U at TA-3, SM102, Shop 13-June1992

In mid March, 1992 Group N-1 received a request from MEC-1 to perform hold-up measurements for fissile material (235U) in the exposed exhaust ducting in shop-13 of SM-102. These measurements were conducted during the week of June 1, 1992 by Ed Adams and Bob Likes.

The ducting to be measured consisted of approximately 350 linear feet of exposed duct located in the shop and the connecting basement area. We divided the ducting to be measured into four distinct measurement areas: (1) the ducting running along the north shop wall; (2) the ducting running along the southeast and south wall; (3) the ducting running along the southwest wall; and (4) the ducting in the basement area. An initial gross gamma survey was conducted on June 2, 1992 for the purpose of identifying "hot spots" and for guidance as to how to proceed with measurements within the identified areas.

The measurement procedure used for these measurements was the Generalized Geometry Hold-up Method (GGH) using the Davidson PMCA and associated low resolution NaI detector calibrated for the assay of 235U. The calibration of the system occurred during the last week of May, 1992 using the standard GGH procedure with uranium disc standard 9-000 (20.02 g 235U) serving as the calibration standard. This calibration procedure gave rise to the establishment of the necessary point, line and area calibration constants.

The 60 kev gamma peak from 241-Am was used to monitor bias and system gain and the calibration was checked against a 235-U check foil each morning and again at noon during the period of the measurements. The calibration data is summarized at the end of the report in table 5. The tabulated errors are derived from counting statistics only. However, total holdup measurement errors are typically in the range of +/-50% when other uncertainty components are considered, and we will quote estimated errors of 50%.

MEASUREMENT AREA (1)-NORTH SIDE OF SHOP-13

The duct running across the north side of the shop consisted of approximately 107 linear feet of pipe connected to 9 individual water separator filter housings. The gross gamma survey indicated very small and uniform amounts of gamma activity

along the entire length of pipe and within the water separators. This information led to the establishment of our measurement plan for this area. We divided the entire length of ducting into 9 separate sections, each of which were associated with an individual water separator and about 15 feet of pipe following the connection of the water separator to the main duct. Because of the small and uniform gamma activity we performed two area source measurements on the bottom of each water separator and three to four randomly-selected line source measurements along the duct corresponding to each section. An ultra-sonic thickness gage was used to determine the thickness of the ducting and water separator material for the material attenuation correction necessary for each measurement point. These measurements resulted in the establishment of an estimated g/cm^2 hold-up value for each water separator and an estimated g/cm hold-up for the associated ducting of each section. Total grams 235U hold-up per section was determined from these values and total 235U hold-up for this measurement area was estimated as the sum of the results for the 9 sections. The water separators are estimated to contain 4.6 ± 2.3 g-235U and the ducting is estimated to contain 0 ± 0.9 g-235U. Measurement results for each section are presented individually on the attached measurement summary as Table 1.

MEASUREMENT AREA (2) - SOUTHEAST SIDE OF SHOP-13

The exposed ducting in measurement area (2) began on the east end of shop-13 about 10 feet from the southeast corner of the room and continued along the south wall of the room for approximately 95 feet to the place where it went through the wall to join the basement ducting. Interspaced along the south wall section were 9 smaller capped Y's entering the main duct. The gamma survey of this line showed varied degrees of activity above room background and a high degree of non-uniformity of potential hold-up deposits. The measurement plan adopted for this section was a series of continuous overlapping line source measurements at one foot intervals along the entire length of ducting. Because the diameter of the line increased in size at the intersection of each of the Y's, we further divided the line into measurement sections corresponding to the location of the Y's. This subdivision resulted in 28 separate measurement runs with total hold-up values determined for each. Total measurement area (2) hold-up is the sum of the 28 sectional results. The corrections that were applied to those results that indicated small amounts of material present were those that are necessary for wall material attenuation effects. For those points that indicate moderate to high levels of material deposits additional corrections were applied for self-attenuation, material distribution and detector response effects. The total hold-up in measurement area (2) is 410 ± 205 g-235U. Results for and identification of, each individual measurement section are summarized in Table 2.

MEASUREMENT AREA (3) - SOUTHWEST SIDE OF SHOP-13

Measurement area (3) was located in the southwest region of the shop and consisted of approximately 30 linear feet of exposed ducting. The initial gamma survey again indicated a fairly small and uniform activity along the entire length of duct. The subsequent measurement plan involved a series of line source measurements along the length of the duct to determine an average value of hold-up in grams 235U / cm, which when applied to the entire duct length resulted in the determination of the total estimated hold-up in this area. Each measurement result was corrected for wall material attenuation and since the response per measurement point was very small, no self-attenuation, material distribution or detector response corrections were applied.

The total hold-up estimate for this measurement area is 0.3 +/- 0.1 g-235U. A summary of the individual measurement points for this area is attached as Table 3.

MEASUREMENT AREA (4) - BASEMENT UNDER SHOP-13

Measurement area 4 was located in a basement area under shop-13 and consisted of approximately 50 linear feet of larger diameter (2 feet) duct into which the lines located in shop-13 fed. Again the initial gamma survey indicated small and uniform activity and the measurement plan involved a series of line source measurements along the 50 foot length. Measurements were made at 4 foot intervals for the determination of the average g/cm 235U hold-up. All individual measurements were corrected for wall material attenuation and a correction factor for geometric consideration of the larger diameter ducting was applied. The total hold-up estimate for this measurement area is 6.4 +/- 3.2 g-235U. An area measurement summary of individual results is attached as Table 4.

EA:BL/gjm

Cy: Robert Marshall, CLS-1, MS G728
George Eccleston, N-1, MS E540
Norbert Ensslin, N-1, MS E540
Charlie Hatcher, N-1, MS E540
Chris Bjork, N-1, MS E540
Phyllis Russo, N-1, MS E540
Steve Smith, N-1, MS E540
N-1 Files (2) *he*

TABLE 1

AREA 1 (NORTH SIDE OF SHOP-13)

<u>SECTION</u>	<u>235-U (GM)</u>	<u>ERROR statistical (only)</u>	
SEPARATOR #1	1.3	0.1	
DUCT FROM SEPARATOR #1 TO SEPARATOR #2	0.0	0.1	
SEPARATOR #2	0.2	0.1	
DUCT FROM SEPARATOR #2 TO NIPPLE #2	-0.8	0.1	
SEPARATOR #3	0.9	0.1	
DUCT FROM SEPARATOR #3 TO NIPPLE #3	-0.7	0.1	
SEPARATOR #4	0.6	0.1	
DUCT FROM SEPARATOR #4 TO NIPPLE #4	-1.7	0.1	
SEPARATOR #5	0.4	0.2	
DUCT FROM SEPARATOR #5 TO NIPPLE #5	-0.8	0.1	
SEPARATOR #6	0.1	0.1	
DUCT FROM SEPARATOR #6 TO NIPPLE #6	-1.0	0.1	
SEPARATOR #7	0.8	0.1	
DUCT FROM SEPARATOR #7 TO NIPPLE #7	0.7	0.1	
SEPARATOR #8	0.1	0.1	
DUCT FROM SEPARATOR #8 TO NIPPLE #8	0.6	0.1	
SEPARATOR #9	0.2	0.1	
DUCT FROM SEPARATOR #9 TO FLOOR	0.2	0.1	
<u>TOTAL SEPARATORS</u>	<u>4.6</u>	<u>2.3</u>	TOTAL ERROR
<u>TOTAL DUCTS</u>	<u>0.0</u>	<u>0.9</u>	TOTAL ERROR

NOTE: SEPARATORS ARE NUMBERED FROM EAST TO WEST. NIPPLES ARE NUMBERED TO CORRESPOND WITH THE SEPARATOR TO ITS EAST.

NOTE: NEGATIVE HOLDUP NUMBERS ARE DUE TO STATISTICAL FLUCTUATION WHEN SIGNAL TO BACKGROUND RATIO IS SMALL.

TABLE 2

AREA 2 (SOUTHEAST SIDE OF SHOP-13)

<u>SECTION</u>	<u>235-U (GM)</u>	<u>ERROR STATISTICAL (ONLY)</u>	
DUCT EAST WALL	0.3	0.1	
DUCT FROM EAST WALL TO 1ST "Y"	0.7	0.2	
1ST "Y"	0.3	0.1	
DUCT 1ST "Y" TO 2ND "Y"	2.8	0.2	
2ND "Y"	0.7	0.1	
DUCT 2ND "Y" TO NIPPLE #2	7.1	0.2	
NIPPLE #2 TO 3RD "Y"	1.7	0.1	
3RD "Y"	0.3	0.1	
DUCT 3RD "Y" TO NIPPLE #3	0.2	0.1	
NIPPLE #3 TO 4TH "Y"	15.6	0.2	
4TH "Y"	6.5	0.1	
DUCT 4TH "Y" TO NIPPLE #4	3.3	0.1	
NIPPLE #4 TO 5TH "Y"	34.6	1.9	
5TH "Y"	4.9	0.1	
DUCT 5TH "Y" TO NIPPLE #5	5.8	0.1	
NIPPLE #5 TO 6TH "Y"	15.7	0.2	
6TH "Y"	2.6	0.1	
DUCT 6TH "Y" TO NIPPLE #6	6.0	0.2	
NIPPLE #6 TO 7TH "Y"	172.9	5.8	
7TH "Y"	0.4	0.1	
DUCT 7TH "Y" TO NIPPLE #7	18.9	1.8	
NIPPLE #7 TO 8TH "Y"	18.5	0.2	
8TH "Y"	0.1	0.1	
DUCT 8TH "Y" TO TOP OF BEND	72.9	2.3	
TOP BEND TO 9TH "Y"	6.1	0.1	
9TH "Y" TO THE WALL	8.5	0.1	
9TH "Y"	0.8	0.1	
LARGE PIPE NIPPLE AT WALL	1.8	0.1	
<u>TOTAL "Y"s</u>	<u>16.6</u>	<u>8.3</u>	TOTAL ERROR
<u>TOTAL DUCTS</u>	<u>393.4</u>	<u>196.7</u>	TOTAL ERROR
<u>TOTAL 235-U (GM)</u>	<u>410.0</u>	<u>205.0</u>	TOTAL ERROR

NOTE: "Y"s ARE NUMBERED FROM EAST TO WEST. NIPPLES ARE NUMBERED TO CORRESPOND WITH THE "Y" TO IT'S EAST.

NOTE: NEGATIVE HOLDUP NUMBERS ARE DUE TO STATISTICAL FLUCTUATION WHEN SIGNAL TO BACKGROUND RATIO IS SMALL.

TABLE 3**AREA 3 (SOUTHWEST SIDE OF SHOP-13)**

<u>SECTION</u>	<u>235-U (GM)</u>	<u>ERROR STATISTICAL (ONLY)</u>
ALL 30 FEET OF DUCTING	0.3	0.1

TABLE 4**AREA 4 (BASEMENT)**

<u>SECTION</u>	<u>235-U (GM)</u>	<u>ERROR STATISTICAL (ONLY)</u>
DUCTING EAST WALL	4.2	0.1
DUCTING SOUTHEAST WALL	-0.1	0.1
DUCTING SOUTH WALL	0.8	0.1
<u>TOTAL 235-U (GM)</u>	<u>4.9</u>	<u>2.5</u> TOTAL ERROR
<u>TOTAL 235-U (GM)</u>		
<u>DUCT SIZE CORRECTED</u>	<u>6.4</u>	<u>3.2</u>

NOTE: NEGATIVE HOLDUP NUMBERS ARE DUE TO STATISTICAL FLUCTUATION WHEN SIGNAL TO BACKGROUND RATIO IS SMALL.

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