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Performance Testing and Validation Plan of the Holdup Measurement System 4 for the K-25 East Side Process Gas Piping

A Thesis
Presented for The
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Mark Gregory Jadick

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DEDICATION

This thesis is dedicated to my wife, Emily, for being an unwavering source of strength and guidance throughout this process.

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ABSTRACT

This thesis addresses the calibration and testing of the Oak Ridge Institute for Science and Education's (ORISE) Holdup Measurement System 4 (HMS4) for use in quantifying U-235 holdup contained within the Process Gas Piping (PGP) of the K-25 Building. In addition to the calibration and testing performed the feasibility of measuring U-238 as a surrogate for U-235 quantification was conducted.

A Performance Testing and Validation Plan (PTVP) was developed for confirming the calibration of the system and collecting test data to qualify the HMS4 system for the intended application (ORISE 2009). Tests performed were in accordance with the PTVP and the results were documented in the Performance Testing and Validation Report (PTVR). In turn, the results have been examined to verify that the HMS4 system functions properly and can be used to reliably measure the residual U-235 in pipes.

Measurement parameters such as the Lower Level of Detection (LLD), the Minimum Detectable Activity (MDA), and the Total Measurement Uncertainty (TMU) have been determined and reported.

To support decommissioning activities, a rapid reliable radiation detection system is needed to assess the amount of residual U-235 within the PGP of the K-25 Building in Oak Ridge, Tennessee. The HMS4 system has been selected to make the required measurements. Verification measurements are considered necessary to assess the reliability and adequacy of the PGP characterization results to ensure criticality incredibility.

The purpose of this document is to evaluate the characteristics of the HMS4 system regarding its applicability for use on the east side of K-25. Additionally, to define the level of confidence that should be associated with each HMS4 measurement.

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ACRONYMS

DOE/ORO	U.S. Department of Energy's Oak Ridge Operations Office
DQO	Data Quality Objective
FOV	Field of View
GGH	Generalized Geometry Holdup
HEU	Higher Enriched Uranium
HMS4	Holdup Measurement System 4
IEAV	Independent Environmental Assessment and Verification
LaBr	Lanthanum Bromide
LANL	Los Alamos National Laboratory
LEU	Lower Enriched Uranium
LLD	Lower Limit of Detection
MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
MCA	Multi-Channel Analyzer
MDA	Minimum Detectable Activity
NaI	Sodium Iodide
NDA	Nondestructive Assay
OD	Outside Diameter
ORAU	Oak Ridge Associated Universities
ORISE	Oak Ridge Institute for Science and Education
ORNL	Oak Ridge National Laboratory
PGP	Process Gas Piping
PTVP	Performance Testing and Validation Plan
ROI	Region of Interest
RPD	Relative Percent Difference
RSD	Relative Standard Deviation
SNM	Special Nuclear Material
SS	Stainless steel
TMU	Total Measurement Uncertainty

Chapter 1

Introduction

1.1 Background

The U.S. Department of Energy's Oak Ridge Operations Office (DOE/ORO) is responsible for the oversight of the environmental management actions and has requested that the Independent Environmental Assessment and Verification Program (IEAV) of the Oak Ridge Institute for Science and Education (ORISE) conduct in-process inspections and verifications of the uranium hold-up deposits in the process gas piping (PGP) within the K-25 Building. To support decommissioning activities, a rapid, reliable radiation detection system is needed to assess the amount of residual U-235 within the PGP of the K-25 Building in Oak Ridge, Tennessee. The ORTEC Holdup Measurement System 4 (HMS4) has been selected to make the required measurements. The ORISE HMS4 verification measurements are necessary to assess the reliability and adequacy of the PGP characterization results to ensure criticality incredibility. Specifically, are procedures sufficiently robust to determine a conservative uranium hold-up gram quantity per unit length of PGP as well as to identify isolated hold-ups exceeding the allowable gram quantity per linear foot to maintain criticality incredibility?

The purpose of this thesis is to evaluate the characteristics of the HMS4 system regarding its applicability for use in measuring the PGP on the east side of K-25, as well as to define the level of confidence that should be associated with each HMS4 measurement. A *Performance Testing and Validation Plan (PTVP)* was developed for the evaluation of the HMS4[9]. It specifies a series of tests for evaluating the HMS4 system performance, along with the supporting rationale.

A *Performance Testing and Validation Report (PTVR)*[14] was developed outlining the results of the testing set forth in the PTVP[9]. The PTVR evaluates the various test results, specified later, to determine the adequacy of each test for the intended use of HMS4 at K-25. In addition, the test results are used define an equation for the Total Measurement Uncertainty (TMU) for the measurement of "grams U-235" using the HMS4 system. The TMU formula will be developed and calculated once measurements in the field of the PGP are obtained. This thesis is a combination of these PTVP and PTVR encompassing the entire process of planning and reporting the results of the HMS4 testing and calibration. A conclusion will be made as to the capability of the HMS4 for performing measurements of HEU and LEU on the east side of the K-25 building.

1.2 Non-Destructive Assay

Non-Destructive Assay (NDA) is a method used to quantify a given amount of radioactive material without physically damaging the sample[12]. Using a scintillation type detector, a Sodium-Iodide (NaI) or Lanthanum-Bromide (LaBr) in this case, photons from a given radioisotope of interest are detected. By measuring photons emitted by a given radioisotope is it possible to quantify the amount of material present. Incident photons from the radioisotope of interest along with non-source generated interfering background radiation interact in the crystal, resulting in the generation of photons in the crystal in the near visible region. A photomultiplier tube is utilized to convert the deposited photon energy into an output current pulse with an output proportional to the incoming photon energy.

The source material emits photons in all directions (4π). Only a certain fraction travel towards the detector as defined by its solid angle. Of this fraction, only a portion will be detected and registered as collected events in the energy spectrum. The remainder are eliminated

by several phenomena, including source self-attenuation, detector collimation, intervening materials, and detector efficiency. Where the full energy of the gamma ray is deposited in the detector, then a full energy peak event is registered. A partial deposition of energy results in the event being registered in a lower region of the energy spectrum.

The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM[2]) recommends that the Minimum Detectable Activity (MDA) in field NDA measurements be no more than 50% of a stated Data Quality Objective (DQO). In the K-25 decommissioning project a major DQO is the gram quantity of U-235 remaining in a given section of process gas piping. Testing and calibration will be tailored to meet this DQO, the limit set forth in MARSSIM will be followed if possible.

1.3 Generalized Geometry Holdup (GGH) Fundamentals

The GGH method was developed in order to simplify the quantitative analysis of holdup measurements performed using portable gamma-ray spectroscopy (Russo). The use and calibration of the HMS4 system is based upon the methodologies defined by Russo in reference LA-14206, 2005 [1]. Russo breaks down an infinite number of possibilities into three basic geometries for simplicity: point, line, and area. With respect to a given detectors field of view (FOV), a point source is simply a small point at the center of the detectors FOV, a line source is a narrow, uniform line through its center whose length extends beyond its width, and an area source is a uniform distribution whose length and width extend beyond the detector FOV . The GGH methodology, which encompasses attenuation correction algorithms and other modeling parameters, are combined in the HMS4 software package to provide a comprehensive tool for conducting in situ gamma-ray measurements of U-235.

The calibration of the HMS4 using the GGH method determines the relationship between the count rate of the measured gamma ray and the mass of the nuclide of interest[10,11]. Calibration for the assay of a point, line, or area deposit is accomplished with a point reference source. The response for each gamma-ray peak is measured with this source positioned on the detector axis at a known distance from the crystal. Measurements are also performed with the source displaced at fixed intervals from the crystal axis to obtain the two-dimensional radial response of the detector. These data are used to obtain the calibration for the assay of the specific isotope mass in a point, line, or area deposit.

1.3.1 Calibration Constants

The point calibration constant, K_p, for a point source is measured by counting a known point source placed on the extended centerline of the detector a known distance from the detector face. The line calibration constant, K_l, for a line source is measured by counting a known point source placed at several different locations along a line perpendicular to the extended detector centerline, intersecting the centerline at a known distance from the detector face. This produces a "radial response curve" that is integrated over the detector field of view to simulate the detector response to a line source. The area calibration constant, K_a, for an area source is calculated by integrating the line source response as the line is rotated 180° to simulate an area source completely filling the detector field of view. Formulas for obtaining these constants are shown below[11]:

$$K_p(g \cdot s \cdot cm^{-2}) = m_0 \div (C_0 \cdot r_0^2) \quad 1.1$$

$$K_l(g \cdot s \cdot cm^{-2}) = m_0 \div (L \cdot C_0 \cdot r_0) \quad 1.2$$

$$K_a(g \cdot s \cdot cm^{-2}) = m_0 \div (A \cdot C_0) \quad 1.3$$

Where,

C_0 = The axial response from the point calibration standard

r_0 = The distance between the calibration source and the crystal face (40cm)

m_0 = The mass of the calibration standard

Calibration constants for point, line, and area sources are derived during the calibration of the HMS4 system and are subsequently used to obtain the specific mass of the isotope measured for each generalized geometry[11]:

$$m_P\ (g) = K_{(p)} * C * r^2 \quad 1.4$$

$$m_L\ (g/cm) = K_{(l)} * C * r \quad 1.5$$

$$m_A\ (g/cm^2) = K_{(a)} * C * a \quad 1.6$$

Where,

C = Background-subtracted net count rate for the analysis peak

r = Distance from detector face to source

l = Associated length of deposit

a = Associated area of deposit

1.3.2 Correction Factors

The initial assay result is the specific isotope mass for a point, line or area deposit. Three additional corrections are required for equipment attenuation, finite-source dimensions, and the self attenuation of the deposit.

The specific mass of a point, line, or area deposit, m_P, m_L, or m_A is corrected for process piping and equipment attenuation effects using the formula:

$$CF_{EQ} = e^{\mu\rho x} \tag{1.7}$$

Where ρ and *x* are the density and thickness of the Process Gas Piping (PGP) or other intervening equipment. The corrected mass' point, line, and area sources are, respectively:

$$m_{P,EQ}(g) = m_P \bullet CF_{EQ} \tag{1.8}$$

$$m_{L,EQ}(g/cm) = m_L \bullet CF_{EQ} \tag{1.9}$$

$$m_{A,EQ}(g/cm^2) = m_A \bullet CF_{EQ} \tag{1.10}$$

The initial assumptions made about the geometry of a given holdup (point, line, or area) must be corrected since virtually no real world deposits will be precisely any of these three geometries. Real world geometries are often a blending of some combination of the three basic geometries. Hence, a correction factor is needed to take this knowledge into account and is referred to as the finite source correction[11]. It should be noted that a finite source correction is not needed for an area deposit since an area deposit should always encompass the entire FOV of the detector. The finite source correction is applied to a given specific mass which has already been corrected for equipment attenuation. The finite source correction will always be greater than one and is calculated using a six step process which begins defining the width, w, of a given finite deposit.

Choosing w is typically accomplished using a NaI detector coupled to a rate-meter and scanning the gamma-ray count across the area of interest to determine the extent of the deposit. Figure 1.1 depicts a non-descript holdup in a section of PGP. By scanning the pipe the field operator will determine the width of w by the observed count rates.

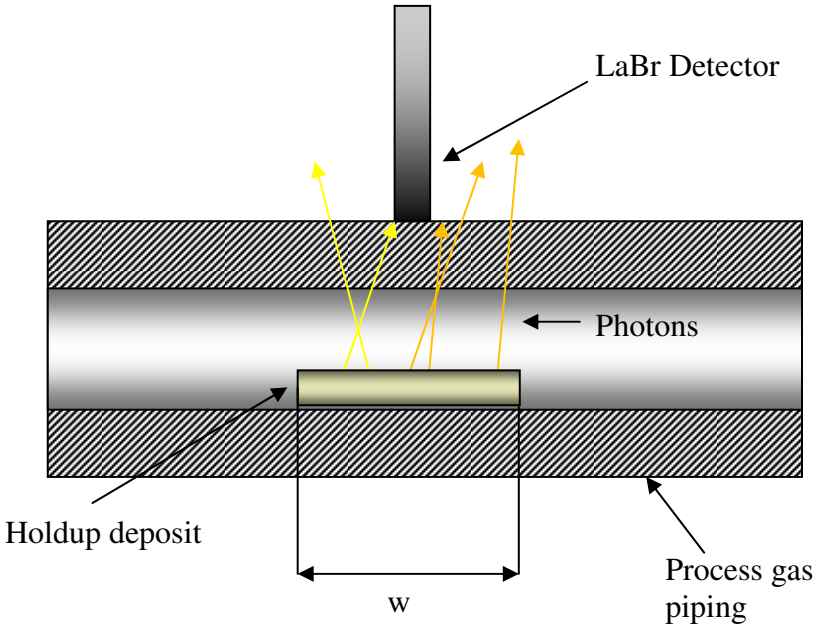

Figure 1.1 Non-descript holdup in process gas piping with width "w". The holdup emits photons which are attenuated by the process gas piping before depositing their energy in the detector crystal. The width of the deposit is determined in the field via scanning with a NaI detector coupled to a rate-meter.

An area of interest will be chosen in one foot increments in order to meet the stated DQO's which are based on one foot pipe sections. Once w is chosen the following six steps are employed to determine the finite source correction factor as defined by Russo:

1. Plot the radial response data C_i for the analysis gamma ray (186 keV U-235 peak) measured with the point source at a predetermined number of positions (19) along a line fixed at a distance of r_0 (40cm) from the detector. Evaluate C(x) and fit the data to a normalized Gaussian G(x) which represents the shape of the radial response curve using the formula:

$$C(x) = G(x) = \exp[-0.5(2.354x/FWHM)^2] \quad 1.11$$

   Where x is defined as the displacement of the calibration source from the detector axis, 40cm in this case. The curve C(x) is used to obtain all corrections for the finite dimensions of the point or line deposits measured with the detector used.

2. Measurement of a holdup deposit at distance r with finite dimension w and using the ratio r/r_0 to adjust for the difference between r and the calibration distance r_0.

$$w_0 = w \cdot \left(r/r_0\right)^{-1} \quad 1.12$$

3. Determination of the normalized radial response $C(w_0/2)$ at the outer edge ($x = w_0/2$) of the line or point.

4. Obtain the average of C(w0/2), the normalized response at the center of the deposit to get the effective radial response for the source of finite dimension w.

$$C_{EFF} = \left[1 + C\left({}^{W_0}/_{2}\right)\right]/2 \quad 1.13$$

5. Compute the finite source correction factor for a line or point deposit.

   For a point deposit: $CF_{FIN,P} = (C_{EFF})^{-2}$ 1.14

   For a line deposit: $CF_{FIN,L} = (C_{EFF})^{-1}$ 1.15

6. Apply the finite source correction to the equipment attenuation corrected specific mass using the equations below:

   For a point deposit: $m_{P,FIN}(g) = m_{P,EQ} \bullet CF_{FIN,P}$ 1.16

   For a line deposit: $m_{L,FIN}(g/cm) = m_{L,EQ} \bullet CF_{FIN,L}$ 1.17

   For an area deposit: $m_{A,FIN}(g/cm^2) = m_{A,EQ}$ 1.18

The final correction factor needed takes into account source self-attenuation. One of the reasons for this complication is the fact that as the enrichment value changes throughout the PGP so does the correction factor for source-self attenuation. To further complicate the matter, this effect can become so pronounced for Lower Enriched Uranium (LEU) deposits that the measurement is no longer valid; an effect known as infinite thickness. As defined by Russo[11], LEU deposits are those which are composed of less than 20% U-235. Sufficiently large deposits of LEU can greatly attenuate the 186 keV gamma ray which is the energy used by the HMS4 in quantifying U-235.

The calculation of the self-attenuation correction factor is defined by Russo and is a six step process:

1. Convert the specific isotope mass of a point, line, or area source to the specific actinide (AC) mass:

   For a point deposit: $m_{P,FIN\ AC}(g) = m_{P,FIN} / \varepsilon$ 1.19

   For a line deposit: $m_{L,FIN\ AC}(g/cm) = m_{L,EQ\ FIN} / \varepsilon$ 1.20

   For an area deposit: $m_{A,FIN\ AC}(g/cm^2) = m_{A,EQ} / \varepsilon$ 1.21

Where ε is defined as:

$$\varepsilon = f_I \cdot f_E \quad 1.22$$

f_I being the fraction of the actinide isotope relative to the elemental total and f_E being the fraction of the element relative to the actinide total.

2. Convert the specific actinide mass to the measured actinide areal density:

   For a point deposit: $(\rho x)_{MEAS,P}(g/cm^2) = m_{P,FIN\ AC} / a$ 1.23

   For a line deposit: $(\rho x)_{MEAS,L}(g/cm^2) = m_{L,FIN\ AC} / w$ 1.24

   For an area deposit: $(\rho x)_{MEAS,P}(g/cm^2) = m_{A,FIN\ AC}$ 1.25

Where w is the experimental width parameter as defined previously, and a is the finite width of a point deposit.

3. Check and ensure that the previous equations for the measured actinide areal density do not approach 1. A measured actinide areal density approaching one signifies infinite thickness and subsequently and invalid measurement.

4. Calculate the areal density of the point, line, or area deposit corrected for self-attenuation.

For a point deposit: $(\rho x)_{,P} = -(1/\mu) \bullet \ln[1-\mu(\rho x)_{MEAS,P}]$ 1.26

For a line deposit: $(\rho x)_{,L} = -(1/\mu) \bullet \ln[1-\mu(\rho x)_{MEAS,L]}$ 1.27

For an area deposit: $(\rho x)_{,A} = -(1/\mu) \bullet \ln[1-\mu(\rho x)_{MEAS,A]}$ 1.28

5. Convert the corrected areal density to the respective specific mass for the point, line, or area actinide deposit, corrected for self-attenuation effects:

For a point deposit: $m_{P,SELF\ AC}(g) = a \bullet (\rho x)_P$ 1.29

For a line deposit: $m_{L,SELF\ AC}(g/cm) = w \bullet (\rho x)_L$ 1.30

For an area deposit: $m_{A,SELF\ AC}(g/cm^2) = (\rho x)_A$ 1.31

6. Convert the self-attenuation corrected specific actinide mass of the point, line, or area deposit to the respective corrected specific isotope mass:

For a point deposit: $m_{P,SELF}(g) = \varepsilon \bullet m_{P,SELF\ AC}$ 1.29

For a line deposit: $m_{L,SELF}(g/cm) = \varepsilon \bullet m_{L,SELF\ AC}$ 1.30

$$\text{For an area deposit: } m_{A,SELF}(g/cm^2) = \varepsilon \bullet m_{A,SELF\ AC} \qquad 1.31$$

If no correction for process piping and equipment attenuation is performed, the assay results will always be biased low[1]. An estimate of the equipment attenuation based on the best information available gives a result that may be high or low for individual measurements, but the overall result tends to be much better than ignoring the correction altogether.

1.4 Description of the Holdup Measurement System 4 (HMS4)

The concept underlying the HMS4 system was originated in the 1970s and has been in consistent use since then; HMS4 is the most current version. It is a NaI-based detector and software package used to automatically correct for various factors, such as those discussed in the previous section, in reporting the final measured result. The HMS4 has also been adapted to accommodate for a Lanthanum Bromide (LaBr) detector which is also addressed in this thesis. *Evaluation of an Integrated Holdup Measurement System Using the GGH Formalism with the M³CA* (Russo 1995)[10] and *Gamma Ray Measurements of Holdup Plant-Wide: Application Guide for Portable, General Approach* (Russo 2005)[1] describe the parent system as it existed in 1995 and more recently in 2005.

Figure 1.2 is a photo of the ORISE HMS4 system utilizing a LaBr detector. Figure 1.3 shows a schematic diagram of the LaBr detection element and its housing for the HMS4 system. The detector crystal is a 1.5 inch diameter by 1.5 inch thick scintillator.



Figure 1.2 The ORISE HMS4 System showing, from left to right, the ORTEC DigiDart field portable MCA, LaBr detector, and Intermec field controller.

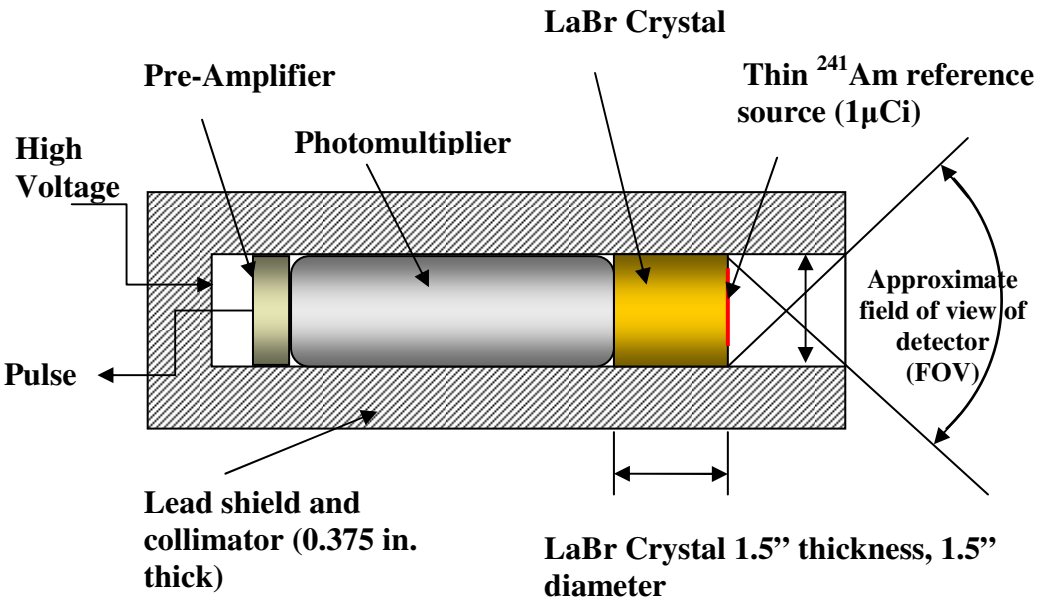

Figure 1.3 Shielded LaBr detector utilized in the ORISE HMS4. The Am-241 source is used for gain stabilization and is located within lead shielding depicted by the gray cross-hatched area in the figure.

On the far left of figure 1.2 is the ORTEC DigiDart Multi-Channel Analyzer (MCA), in the middle is the ORISE LaBr detector, and on the right is the Intermec field portable controller. When a photon is absorbed in the LaBr crystal, it is converted into visible light that strikes a photo-multiplier tube, which is then converted to an electrical signal. The magnitude of the electrical signal is then digitized and converted into channel numbers by the MCA. The field controller takes a given measurement from the MCA and assigns it to a pre-determined measurement location. Figure 1.3, is a depiction of the inside of the LaBr detector.

An Am-241 source is positioned on the anterior face of the crystal to provide a constant reference source of gamma-rays with an energy of approximately 60 keV. This peak provides a data quality check and an electronic gain stabilization signal for the electronics system. The presence of the Am-241 source produces a constant full-energy peak that does not interfere with the observation of a full energy deposition photon interaction of U-235 or U-238.

1.4.1 Regions of Interest

Regions of Interest (ROI) are specific ranges of channels, which are user defined, that the HSM4 software uses for its calculations. These ROI's represent a discrete number of channels corresponding to peaks of interest in the detection of a given radioisotope of interest. Eight ROI's were set up to capture the Am-241 source, U-235, U-238, and Bi-207.

Three windows were set up around the 60 keV peak of Am-241; one for the peak itself and two around it. These three peaks serve to inform the user if there has been a gain shift in the instrument. Should the peak centered on the 60 keV peak begin to bleed over into one of the peaks around it, a gain shift error message is displayed alerting the user of a potential gain shift. This feature also proved useful in diagnosing a failed cable.

Two windows were set up for the detection of U-235 focusing on its 186 keV peak. One peak was centered on the 186 keV peak, the second was set above the 186 keV to capture the Compton continuum from down scattering of higher energy gamma rays.

The final three peaks focused on the 1001 keV peak from Pa-234^{m}, for U-238 detection, and the 1064 keV peak for calibration using Bi-207. One peak centered on the 1001 keV peak, one was set up above the peak to capture the Compton continuum, and the final was set up around the 1064 keV peak for the purposes of calibration.

1.5 LEU Calibration

The end goal of the HMS4 holdup measurements is to quantify the amount of U-235 in process gas piping and equipment. When possible, direct measurement of the U-235 via the emitted 186 keV photons is preferred. However, for holdups of low enrichment (less than approximately 20% U-235 by weight) the self-absorption of the 186 keV photons within the U-238 matrix prohibits accurate, quantitative direct measurements using this photon energy. For cases where direct measurement of the 186 keV photon is not feasible, the mass of U-235 can be inferred by measuring U-238 via the 1001 keV photon emitted by the U-238 daughter, Pa-234^{m}, and inferring the U-235 mass based on analytical or process knowledge of the enrichment values. Figure 1.4 shows the pronounced U-238 peak of a LEU source.

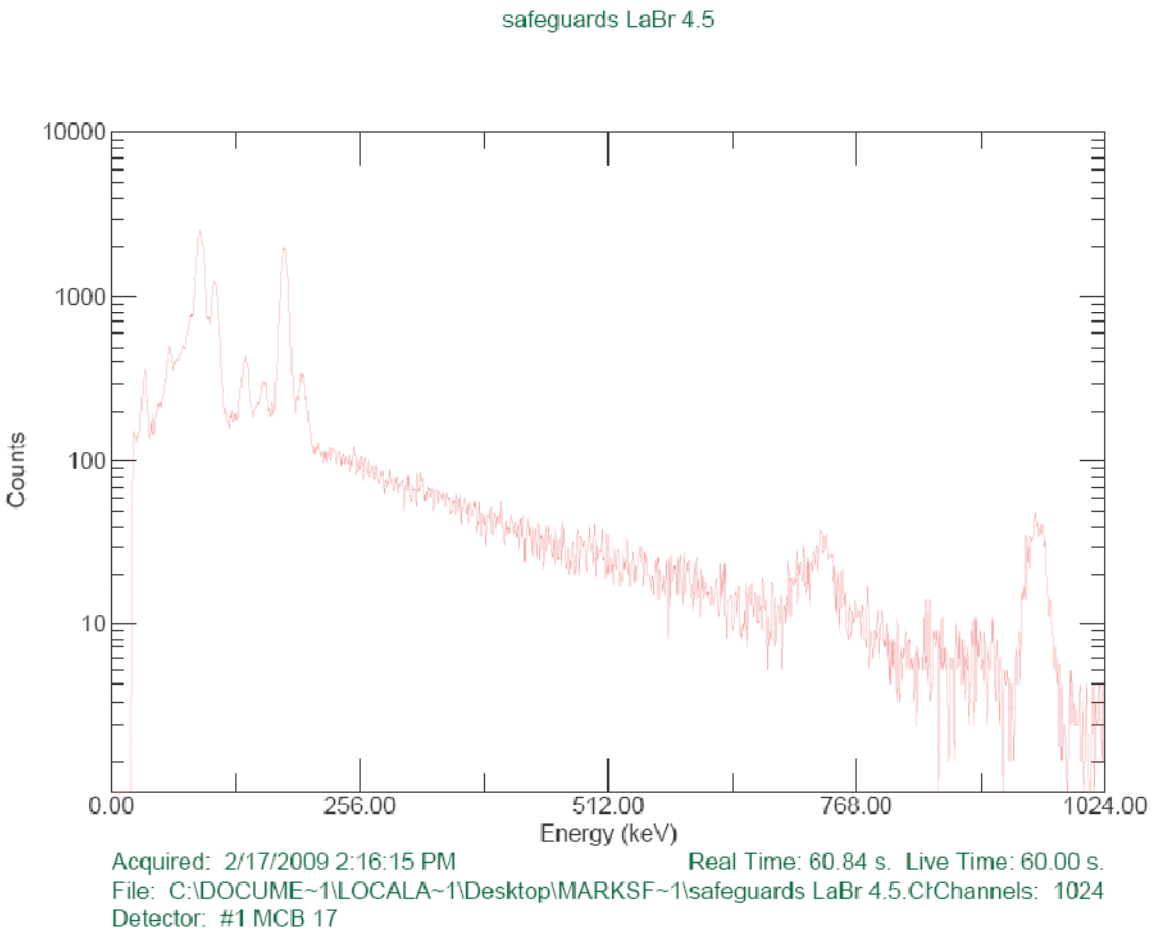

Figure 1.4 Measurement of LEU source showing the pronounced 1001 keV peak.

No significant U-238 source was available to calibrate the HMS4 system, so a surrogate 1.35 μCi Bi-207 source was used in its place. This source was chosen due to its availability, being a well characterized source, and its 1064 keV gamma which closely resembles the desired 1001 keV gamma from U-238. The approach used was to replace the number of counts per second for U-238 with the counts per second from the Bi-207 source. This number of counts was used to determine the equivalent gram quantity of U-238 represented by 1.35 μCi of Bi-207. Using this process it was calculated that 1.35 μCi of Bi-207 was equivalent to approximately 352 grams of U-238.

1.6 Efficiency Determination

The use of the HMS4 will result in full energy peaks in the energy spectrum representing the U-235 186 keV photon and the U-238 1001 keV photon. Measurement of these peaks will result in a determined value of the peak intensity either as counts per unit time or counts collected over time. If the relationship is known between the counts measured and the source – detector geometry for that measurement, then the amount of U-235 or U-238 can be calculated.

Ψ is defined as the conversion factor for detector efficiency (calibration), source self-attenuation, matrix and geometric attenuation, and finite point or line source dimensions and is calculated as:

$$\Psi = \frac{A}{B} = K \cdot CF_{sa} \cdot CF_{fw} \cdot CF_{ma} \qquad 1.32$$

Where,

A = Net (background subtracted) counts per unit time measured in the U-235 or U-238 full energy peak observed with the HMS4. The background ROI should be

as wide as the U-235 peak for simplicity and to obtain good precision on the background measurement.)

B = Grams of U-235 or U-238 in the source material being measured.

K = Detector calibration coefficient (counts / sec • g $^{235/238}$U).

CF_{sa} = Correction factor for source self attenuation (unit less).

CF_{fin} = Correction factor for finite source width (point or line) (unit less).

CF_{eq} = Correction factor for matrix attenuation caused by materials between the source and the detector (unit less).

Figure 1.5 is a schematic diagram of the HMS4 measuring a source of interest. Note that this is a conceptual diagram. The source material emits photons in all directions (4π); only a certain fraction travel towards the detector as defined by its solid angle. Of this fraction, only a portion will be detected and registered as collected events in the energy spectrum. The remainder are eliminated by several phenomena, including source self attenuation, detector collimation, intervening materials, and detector efficiency. When the full energy of the gamma ray is deposited in the detector, then a full energy peak event is registered. A partial deposition of energy results in the event being registered in a lower region of the energy spectrum.

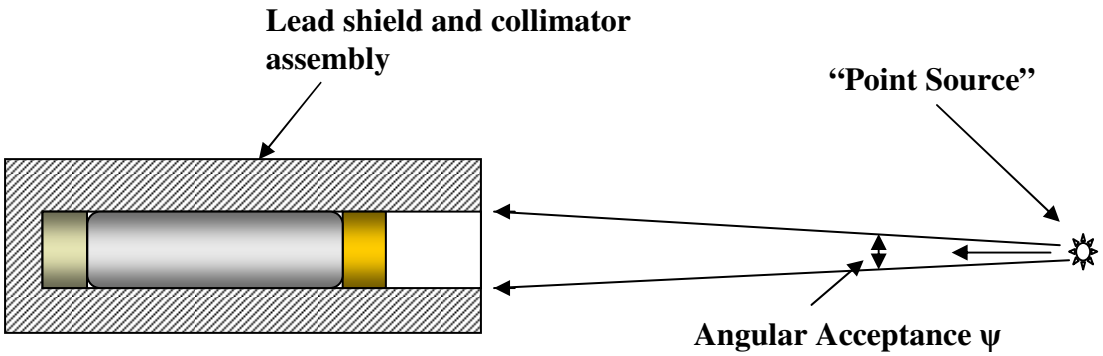

Figure 1.5 Measurement geometry for absolute efficiency of detection showing a point source geometry.

Determination of the source activity requires that the source geometry must be accounted for along with accounting for all absorbing media between the source material and the detector. Additionally, interfering background counts from scatter and background sources must also be subtracted from the peak ROI.

1.7 Point Source and Extended Source Measurement

As depicted in figure 1.6, any extended source can be closely approximated by successively measuring a point source at multiple locations to simulate that extended geometry; in this depiction a line source. This methodology has been adapted at Los Alamos National Laboratory (LANL) to GGH measurements with the HMS4 system in order to closely approximate the three pertinent measurement geometries: point, line, and area[1,10,11]. The HMS4 system considers a point as an infinitely small point source, a line as an infinitely thin source whose lateral extent completely covers the detector field of view), and an area source as one whose lateral extent completely covers the detectors field of view).

For this work, a calibration method is used where a known small geometry source is measured in multiple locations to effectively cover the extended geometry of interest (line or area), as shown in figure 1.7.

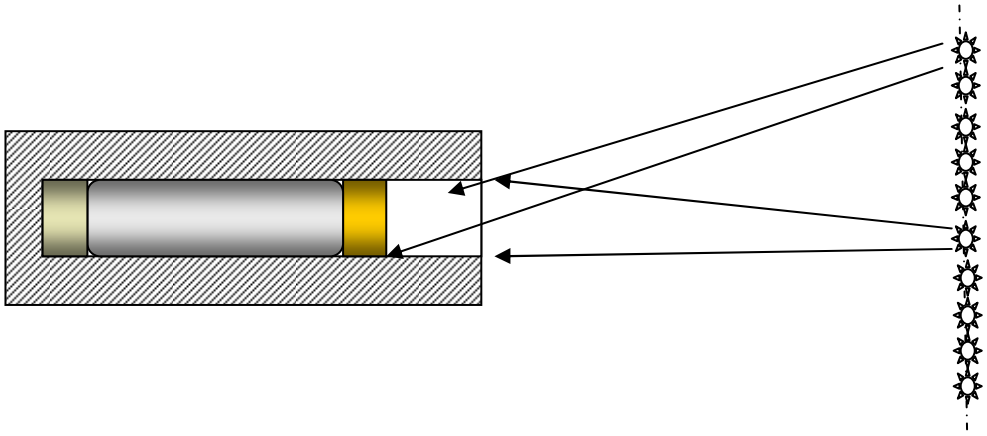

Figure 1.6 Integration of measurements at multiple locations to simulate a line source. For test measurements the detector will be physically moved to simulate the extended geometry of a line source.



Figure 1.7 Depiction of point, line, and area source during calibration. Area source measurements are approximated by integrating the line source geometry 180°. This integration is performed automatically by the HMS4 software when the appropriate geometry is entered.

The detector efficiency, K_P, for a point source is measured by counting a known point source placed on the extended centerline of the detector a known distance from the detector face.

The detector efficiency, K_L, for a line source is measured by counting a known point source placed at several different locations along a line perpendicular to the extended detector centerline, intersecting the centerline at a known distance from the detector face. This produces a "radial response curve" that is integrated over the detector field of view to simulate the detector response to a line source.

The detector efficiency, K_A, for an area source is calculated by integrating the line source response as the line is rotated 180° to simulate an area source completely filling the detector field of view. This integration is automatically performed by the HMS4 software when measurements are made.

1.8 Objective of this thesis

The objective of this thesis is to determine if the HMS4 system coupled to a LaBr detector is both capable and properly calibrated to perform holdup measurements of the PGP on the east side of K-25. By performing the tests set forth in this thesis, a clear demonstration of the systems capability will be determined for both HEU and LEU. A secondary objective of this thesis is to determine if the HMS4 system is capable of performing LEU measurements at all. Detection of LEU with the HMS4 system is not typically performed, and has not been conducted by ORISE, so the feasibility of LEU measurements will be tested in this thesis.

1.9 Organization of this thesis

The first section of this thesis will set forth the test parameters and criteria required for determining the feasibility of using the HMS4 system for holdup measurements on the East side of K-25. The feasibility of measuring HEU and LEU using a LaBr detector will be analyzed. Next, the results of the testing and a determination of the HMS4's suitability to perform PGP measurements will be shown. The results will specify which geometry is the most suitable for conducting measurements in the field and the error associated with them. Following the results will be a conclusion and future results section.

Chapter 2

Testing Parameters

2.1 Data Quality Objectives

Data quality objectives are in essence goals which are set forth before the commencement of a project. Their purpose is to clearly establish what the purpose of the project is and help guide it. For the Independent Verification (IV) performed by ORISE on the east side of the K-25 building, the Data Quality Objective (DQO) is to ensure that there is no more than a specified value of U-235 per linear foot of Process Gas Piping (PGP). These criteria are specific to a given pipes outside diameter (OD) and are: less than 7 grams per foot of U-235 for PGP with an OD of 3-inches to 4-inches, 10 grams per foot of U-235 for PGP with an OD of 4-inches to 6-inches, 14 grams per foot of U-235 for PGP with an OD of 6-inches to 10-inches, and 22 grams per foot U-235 for PGP with an OD of greater than 10-inches. For the verification effort on the east side of K-25 all of the pipes are greater than 10-inches in diameter.

2.2 LLD and MDA Calculations

The Lower Limit of Detection (LLD) is defined as the net signal level above which an observed signal may be reliably recognized as detected, whereas the Minimum Detectable Activity (MDA) is dependent upon ambient interferences in the location of measurement. LLD and MDA are inextricably linked since LLD defines, for lack of a better word, system "noise" while MDA defines ambient "noise" that is above the identified "noise" indigenous to the instrument. In a stable environment LLD and MDA would be expected to be identical; however,

field measurements are complicated by ambient factors that cannot be specifically ascribed to material holdup in the measurement location. A predominant influence on the MDA is ambient background. For a typical NDA measurement, a background measurement is performed in the general area of the component without including the deposit being assayed. This is done to determine the contribution of gamma rays present within the detector FOV not ascribed to the deposit. NDA background measurements are not performed by removing the component or by removing the deposition of radioactive material from the component. Current NDA measurements are performed in the K-25 building where there is a sizeable background contribution due to the distribution of material holdup.

A widely accepted approach for determining the LLD and MDA is based on Currie's 1968 paper, "Limits for Qualitative Detection and Quantitative Determination."[3] A Martin Marietta Energy Systems position paper entitled "Standardized Statistical Techniques for Radiological Measurements[3]" published in 1993 was strongly based on the Currie's statistical techniques and is commonly used. See also J.C. Lochamy, “The Minimum Detectable Activity Concept” 1981[5] and G.V. Walford et. al. 1971[6] and EG&G Application Note 17 by J.C. Lochamy 1981.[6]

From the position paper and the above references, two principal limiting levels are defined:

1. Decision Level or Critical Level (L_C)—the net signal level above which an observed signal may be reliably recognized as detected.

2. Lower Level of Detection (L_D)—the lowest practical *quantity* that the instrument can routinely and reliably detect. "Routine detection means that if the activity is equal to the

detection limit, the instrument will report a detected result at least 95% of the time, but not necessarily equal to the detection limit."

For a 95% confidence level for one-tailed statistics, the probability of incorrect positive assumption (Type I error, α) and an incorrect non-detection (Type II error, β) are set equal to 5%. The decision or critical level equation is based on the maximum allowable value for α and the standard deviation of the net signal when its limiting mean is zero. The equation for the decision level is given by:

$$L_C = k_\alpha \cdot \sigma_0 \qquad 2.1$$

Where,

k_α = abscissa of the standardized normal distribution corresponding to the probability level 1-α for the 95% confidence interval and one-tailed statistics, k = 1.645.

σ_0 = standard deviation when the limiting mean of the net signal is zero.

The detection limit is based on the value determined for L_C, the maximum allowable value for a Type II error (β), and the standard deviation of the net signal when the limiting mean is equal to L_D. The detection limit equation is defined as:

$$L_D = L_C + k_\beta \cdot \sigma_D \qquad 2.2$$

Where,

k_β = abscissa of the standardized normal distribution corresponding to the probability level 1-β for the 95% confidence interval and one-tailed statistics, k = 1.645.

σ_D = standard deviation when the limiting mean of the net signal is L_D.

For the case in which the background is much greater than the net signal, the variations in the standard deviations from a net signal of zero to L_D are slight. Therefore, the standard deviation of the net signal can be assumed constant, i.e. $\sigma_D = \sigma_0 = \sigma$.

For the variance of a net signal given by:

$$\sigma^2 = \sigma_{S+B}^2 + \sigma_B^2 \quad (2.3)$$

Where,

σ_{S+B}^2 = variance of the "sample + blank" signal (2.4)

σ_B^2 = variance of the blank signal (2.5)

This assumption results in the variance being equal to twice the blank variance or

$$\sigma^2 = 2 \cdot \sigma_B^2 \quad (2.6)$$

If the standard deviation of the blank has been made negligible due to multiple observations as in the case of HMS4, the variance of the net signal is simply equal to the variance of the blank. For paired observations where the background is not known, the standard deviation will differ from the case of the well known blank by the square root of two.

If the risk of 5% for a Type I or Type II error is acceptable (95% confidence interval for one-tailed statistics), the following equations for the decision and detection limits are valid for active measurements in HMS4[5]:

$$L_C = 1.645 \cdot \sqrt{2 \cdot \sigma_B} \quad (2.7)$$

$$L_D = 1.645^2 + 2 \cdot L_C \quad (2.8)$$

The lower level of detection LLD is the counts measured by the detector which are statistically measurable above the background counts. The LLD is dependent on the background measurement used for each location. The sum of the analysis peak and the continuum from the background spectrum is used to calculate the LLD using the following equation:

$$\mathrm{LLD} = \mathrm{k}^2 + 2\mathrm{k}\sqrt{2 \cdot (\mathrm{B_{ROI4}} + \mathrm{B_{ROI5}})} \quad 2.9$$

Where,

k = 1.645 which corresponds to a 95 % confidence level

B_{ROI4} = Value of the analysis peak in background spectrum

B_{ROI5} = Value of the continuum in the background spectrum

Note also that in the case of component measurements using the area source algorithm, the background measurements must be corrected for the attenuation of the target component before the LLD is calculated. For LEU measurements ROI 4 will be replaced with ROI 6 and ROI 5 will be replaced with ROI 7.

The MDA is calculated using the LLD calculated above, the count time, and the correction factor for the attenuation of the container wall. Using the following equation,

$$\text{For a point source: } \mathrm{MDA} = \frac{\mathrm{LLD} \cdot \mathrm{K_x} \cdot \mathrm{CF_{EQ}} \cdot \mathrm{r}^2}{\mathrm{T}} \quad 2.10$$

$$\text{For a line source: } \mathrm{MDA} = \frac{\mathrm{LLD} \cdot \mathrm{K_x} \cdot \mathrm{CF_{EQ}} \cdot \mathrm{r}}{\mathrm{T}} \quad 2.11$$

$$\text{For an area source: } \mathrm{MDA} = \frac{\mathrm{LLD} \cdot \mathrm{K_x} \cdot \mathrm{CF_{EQ}}}{\mathrm{T}} \quad 2.12$$

Where,

K_x = Calibration constant for a point, line or area source

T = Counting time in seconds

CF_{EQ} = Equipment attenuation correction factor

r = Detector standoff

The following procedures shall be used to establish the Lower Limit of Detection for the HMS4 as defined previously:

Perform "blank" measurements:

1. Utilizing an appropriate detector holder or hardware apparatus set up a surrogate component that is representative of actual measurement configuration for which the HMS4 measurements are anticipated to be applied. Model the measurements as a point source.
2. Position the HMS4 detector to emulate standard holdup measurement protocols.
3. Perform five replicate measurements of the surrogate configuration.
4. Calculate and report the measured value.
5. Reanalyze measurements modeling as a line and then an area.
6. Calculate and report the measured value for both line and area models.
7. Calculate L_C and L_D as described previously.
8. Report instrument LLD and use calculations from the previous section to calculate MDA.

2.2 Total Measurement Uncertainty

2.2.1 Sources of Measurement Uncertainty

Random and systematic measurement uncertainties are propagated to derive a Total Measurement Uncertainty (TMU). Systematic error in a measurement is a consistent and repeatable bias or offset from the true value[15]. Random and pseudo-random errors in a measurement are the identifiable variations between successive measurements made under apparently identical measurement conditions and may include counting uncertainties as well as errors related to ill-defined data reduction parameters, errors in physical measurements, inhomogeneities, matrix interferences, and variations in chemical composition of deposits which may not be defined directly by holdup measurements results.

Pseudo-random errors can create either positive or negative bias, and do not display a significant predominance of one type of bias or the other. TMU is determined using both empirical data collected during tests of the instrument measurement capabilities influenced by ambient conditions and modeled performance data that extrapolates for measurement conditions that cannot be readily simulated. Random and pseudo-random error components are added in quadrature[15]. Systematic error components which may create a negative bias on the computed U-235 values are added to the overall estimate arithmetically. A systematic error bias that creates only a positive bias on the computed U-235 values is ignored in the calculation of TMU for confidence level determinations (e.g. “95% confidence”).

The contributing uncertainties can be large and numerous. The listing below summarizes uncertainty contributions in a somewhat subjective order of decreasing importance.

1. Unknown material distribution or location, which affects the source-to-detector distance and the validity of the chosen physical model algorithm, either a point, line, or area source calibration and data reduction.
2. Self-absorption in the deposit material or its matrix.
3. Gamma-ray attenuation by intervening matrix materials.
4. Background interference from distant line-of-sight objects or from adjacent unresolved material.
5. Detector instability or improper calibration.
6. Unrepresentative calibration standards.
7. Counting statistics.
8. Uncertainty of holdup material isotopic composition.
9. Deviation of actual measurement geometry from the calibration geometry.

Many potential sources of measurement error in application of the HMS4 system have been identified. Each of these must be addressed in one of the following ways:

1. The error is significant and random (e.g. counting statistics), and will be computed and added in quadrature to the TMU[15].

2. The error is significant and pseudo-random and will be computed and added in quadrature to the TMU[15].

3. The error may have a systematic negative bias on the measurement of U-235 results (e.g. use of process gas enrichments late in the life of the cascade, which

would represent the highest possible enrichment deposits and thus the lowest self-attenuation calculations), and a reasonable conservative bounding assumption can be made and utilized in the measurements and data reduction. In this case, the bounding assumption is contained in the nominal measured value and will not be added to TMU.

4. The error may have a systematic positive bias on the measurement of U-235 results (e.g. neglecting corrosion and erosion of pipe wall thickness in the calculation of matrix attenuation), and will be ignored as this represents a bounding conservative assumption in the calculation of U-235 mass as described in item (3) above.

5. The error may have a random or systematic negative bias on the measurement of U-235 results, but evaluation of the magnitude of possible errors demonstrates that the error is negligible in the HMS4 application in the K-25 and K-27 buildings.

6. The error may have a systematic negative bias on the measurement of U-235 results, and a reasonable calculation of the potential error can be accomplished for each measurement. This systematic error will be added arithmetically to the TMU for the measurement[15].

7. The error may be systematic and significant, but will be detected in calibration or field measurements, and the causal factor(s) will be corrected and the measurement repeated.

2.2.2 Calibration Uncertainty

Source positioning error can result from the requirement that the base measurement must be made with the source on the extended axis of the detector/collimator assembly, and the radial measurements must be made at known intervals to the "left" and "right" of the axis of the detector/collimator assembly along a line perpendicular to that axis. If any of these requirements are violated with any significance, a non-symmetric radial response will result. If a non-symmetric radial response is observed, the geometry of the calibration setup shall be corrected, and the calibration re-performed. Therefore, source positioning errors are not included as contributors to the TMU since it will be obvious from the observed radial response that an error was made.

Instabilities in instrument gain and linearity are monitored by evaluating the signal from the resident Am-241 source integral to the detector. Any instability will be revealed as part of each measured gamma-ray spectrum. Thus, errors due to instrument instability will be remediated in process, and are ignored in this treatment of TMU.

Calibration counting statistics for foreground and background measurements will be computed using standard statistical methods and propagated in quadrature with other random and pseudo-random errors.

2.2.3 Errors in Specification of Enrichment Level

The calculation of holdup source self attenuation by the HMS4 system is most sensitive to the specification of the enrichment level of the deposit. As discussed in Russo[1], source self-attenuation is mostly caused by the heavy uranium nucleus due to its very high mass attenuation coefficient. Total uranium content is determined by dividing the U-235 measured mass by the enrichment. Thus, for highly enriched uranium, the total uranium content in the holdup source may be only about 1.09 times the U-235 mass, while at the lowest enrichments, the total uranium mass may by 100 times the U-235 mass. Moreover, the effect of self-absorption is not linear, but exponential with the inverse of enrichment[1,11].

Russo[1] calculates that self-absorption is negligible below total uranium areal densities of about 0.2 g/cm^2. At very high enrichment, this areal density results in U-235 amounts above the DQOs (and thus the action levels) for U-235 in pipe and other components measured by HMS4. At low enrichments, however, DQO levels of U-235 in pipe result in massive amounts of self-absorption.

Deposits laid late in the life of the cascade would be expected to be at enrichment levels characteristic of process gas late in the life of the cascade. Consumption deposits which may have occurred continuously over the life of the cascade would have an average enrichment equal to the mass flow averaged enrichment at that point in the cascade over the life of the cascade. Deposits laid early in the life of the cascade would have enrichment characteristic of process gas early in the life of the cascade.

Periodic cleaning of process piping and equipment would tend to cause deposits to be at the higher end of enrichment possibilities. Since a majority of the deposits that HMS4 is utilized to detect probably occurred continuously over the life of the cascade, the appropriate nominal

assumption might be to use the mass flow averaged enrichment at any point in the cascade. However, this assumption would still be subject to measurement uncertainty since any given deposit could have been laid earlier in the life of the cascade, and remained undisturbed thereafter. There appear to be two choices here. The first would be to compute a custom-tailored measurement uncertainty for each measurement location. This would introduce field operational complexities that are unjustifiable in light of the precision benefit realized. Alternatively, a bounding conservative assumption could be utilized for the deposit enrichment at any point in the cascade for the nominal U-235 mass calculation. To account for deposits that may not be representative of continuous consumption over the life of the cascade, and might have been laid, at least partially, early in the life of the cascade, the assumed deposit enrichment at any point in the cascade will be taken as 50% of the mass flow averaged process gas enrichment over the life of the cascade at a given measurement point in the cascade. For this component of TMU, the uncertainty is embodied in the nominal calculation, so no contribution to TMU will be calculated.

2.2.4 Gamma-Ray Attenuation by Materials between the Source and the Detector

The material configurations originally installed in items that are measured by the HMS4 system are well characterized and known. The major error contribution is expected to be material corrosion and erosion over time that has reduced the attenuation compared to the model used in the HMS4 data reduction algorithm. This creates a positive bias on measured U-235 amounts. Thus, this effect will be ignored in the computation of TMU for HMS4 measurements.

2.2.5 Gamma-Ray Self-Attenuation by the Deposit

Unlike measurements on the west side of K-25, the east side contains deposits well below 20% enrichment which may result in an infinite thickness result on the HMS4 output report. Typical holdup deposits tend to be thin leading to an average self-attenuation effect as large as a few percent; this effect will always be biased low. While a bias of several percent is generally not important for an individual measurement point, a several-percent bias propagated throughout the total holdup in the K-25 building is a serious problem. The magnitude of the effect of gamma-ray self-attenuation for a measured holdup deposit can be determined if the areal density of the deposit, uncorrected for self-attenuation (but corrected for room-background, equipment-attenuation and finite-source effects), is known[1].

2.2.6 Holdup Source Location and Distribution

The large majority of HMS4 measurements at K-25 are carried out on piping systems. It is generally expected that undisturbed holdup deposits will be uniformly distributed. However, if the deposit has been exposed to moist air, oxidation and hydration of the deposit have been observed to occur, with the hydrated oxides becoming loose and falls to the bottom of the pipe in question. Since all HMS4 measurements (either area source measurements or finite line source measurements) assume uniform deposits on the inner surface of a pipe, an error can be introduced if this "oxidation-hydration-separation" phenomenon has occurred. The bias created by this error can be either positive or negative, depending on the measurement technique utilized and the source-detector geometry for a specific measurement. This potential error is mitigated by the vent, purge, and drain program in which the interior of the pipe is visually observed via bore scope, and piping segments with visible deposits are removed from the system.

Tests are specified in this document to define the effect of the source being concentrated in the bottom of the pipe. The results of those tests will be used to define a contribution to total measurement error to be attributed to this phenomenon. The exact nature of this model variability error parameter, denoted σ_{mv}, will be defined after the test results are known.

2.2.7 Background Measurement Errors

NDA measurements of holdup material can be significantly influenced by ambient background emanating from other sources in the area, or sources external to the building[1]. HMS4 protocols require that, where possible, the geometric configuration of a measurement be executed in such a way as to minimize background contributions from obvious adjacent sources (pipes and equipment). Moreover, attenuation of background by the target matrix is accounted for in the HMS4 data reduction algorithm.

The corrected count rate for observation of a pipe or other object in an area measurement is

$$cCR_B=(A_4 - A_5)/T_A - (B_4 - B_5)/(T_B*tt) \quad 2.13$$

Where,

cCR_B = Corrected count rate in region of interest 4

A_4 = Total (foreground plus background) counts in ROI 4

A_5 = Total (foreground plus background) counts in ROI 5

B_4 = Background counts in ROI 4

B_5 = Background counts in ROI 5

T_A = Counting time for the total counts

T_B = Background counting time

tt = Correction factor for attenuation by materials that attenuated the background during the foreground measurement (e.g. two pipe wall thicknesses).

The variance of the corrected count rate is:

$$\sigma^2_{cCRB} = (A_4 + A_5)/T_A^2 + B/(tt*T_B)^2 + (B_4 + .0225B_4^2 + B_5 + .0225B_5^2) / (tt*T_B)^2 \qquad 2.14$$

This error will be propagated with other random/pseudo-random errors to define the TMU contribution from background measurements.

2.2.8 Computation of the Total Measurement Uncertainty

The variance in the calculated value for U-235 will be the sum of the variances of all the contributing parameters with random and pseudo-random errors.

$$TMU = \sigma_{U235} = |\sigma_{MV}| + \sqrt{\sigma_{OP}^2 + \Psi^2 \sigma_{cCRB}^2} \qquad 2.15$$

Where,

$\sigma_{U\text{-}235}$ = Standard deviation of the measured U-235 value.

σ_{MV} = Absolute value of the worst-case bias introduced by model variability as determined in the model variability testing.

σ_{OP} = Uncertainty introduced by the single operator variability.

Ψ = Conversion factor from net counts per unit time to grams of U-235, including detector efficiency, matrix attenuation, self-absorption, and finite width point or line source correction.

Note that this formulation assumes that counting statistics during calibration are negligible. The 95% confidence level result will be the nominal measurement plus 1.645 times the TMU to get 95% confidence in one-tailed statistics.

2.3 Precision and Accuracy

Precision is a measure of the reproducibility of the system and is determined through replicate counting of an item with a known quantity of radioactive material of interest. For the purposes of this study, precision is expressed as the percent Relative Standard Deviation (RSD) for a set of replicate measurements and is calculated as follows:

$$\%RSD = (\sigma / \bar{x}) * 100 \quad 2.16$$

Where,

σ = Standard deviation.

$\bar{x}$ = Average of the replicate measured U-235 or U-238 values.

Accuracy, or bias, is the degree of agreement between measured concentration or activity values and the true or known values. Accuracy is determined by replicate counting of containers with standards of known U-235 or U-238 content. For this study, accuracy is expressed as relative percent difference, (%RPD), and is calculated as follows:

$$\%RPD = (C_m - C_{srm})/ C_{srm} * 100 \quad 2.17$$

Where,

C_m = Average of the replicate measured U-235 or U-238 values.

C_{srm} = "true" or certified value.

2.4 Instrument Qualification

All calibration, calibration verification, and calibration confirmation measurements are to be executed utilizing current and applicable ORISE procedures. Calibration activities will be performed at Oak Ridge National Laboratory's (ORNL) Safeguards Laboratory National User Facility (SL) in order to utilize their well-characterized calibration sources. Calibration is conducted using a single point source standard of known attenuation and is applicable to point, line, and area measurements[10,11].

2.4.1 Instrument Set-Up

The instrument must be prepared for routine operation by creating requisite software and hardware parameters such as the applicable gain, standoff, and connections between the hardware. The connection between the Multi-Channel Analyzer (MCA) and the Lanthanum Bromide (LaBr) detector has not been used by ORISE in the past and will require particular attention. The performance check source used will be an 11g 93% enriched U-235 standard as well as a well characterized 1.35 μCi Bi-207 source. The measurements themselves will be conducted as follows:

1. Place the identified performance check source on or near (specify in results) the HMS4 detector.
2. Establish and record optimum operational (setup) parameters for the instrument hardware and software.
3. Perform a background measurement before introducing the calibration source into the detector environment.

Figure 2.1 shows an ideal energy spectrum obtained from a successful set up using a U-235 check source. The full energy peak from the 186 keV photon is observed together with the full energy peak from the Am-241 60 keV check source installed as part of the HMS4. ROI's are also identified that are used to assess and subtract background events.

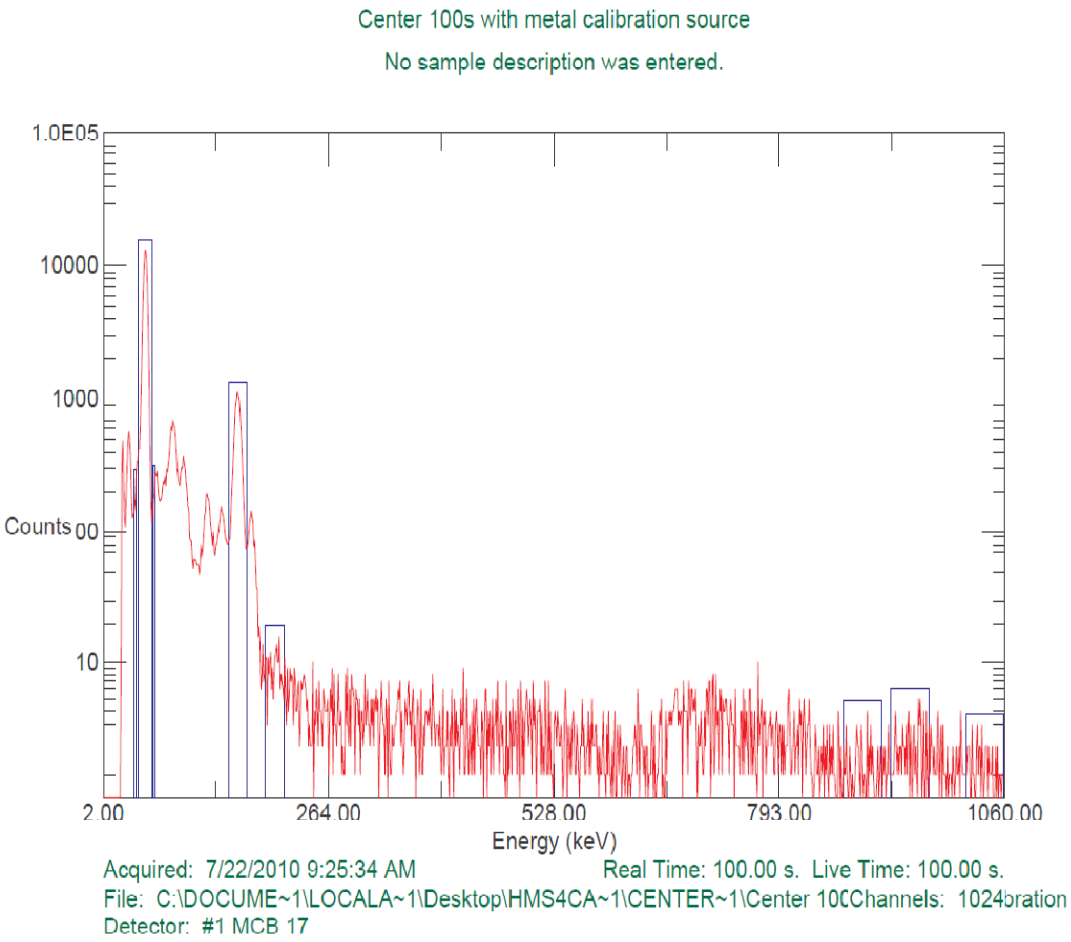

Figure 2.1 Typical Spectrum with Assigned Regions of Interest (ROI) Obtained After Successful Set-up. This measurement was made using a 93% enriched source.

2.4.2 Chi-Squared Test

In order to confirm that the detector is operating in response to random events, a chi-squared test (χ^2) will be performed on six replicate measurements with the source on the axis of the detector positioned at 40 cm from the face of the detector. The counting time is arbitrary, except that there should be about 400 counts in the peak ROI for each measurement[13]. The source-geometry configuration will not be touched or disturbed in any way between these six measurements.

The chi-squared test equation is:

$$X^2 = (1/x_{mean}) \sum_{i=1}^{6} (x_i - x_{mean})^2 \qquad 2.18$$

Where,

x_{mean} = Mean counts (no background subtraction of the six raw χ^2 test measurements.)

x_i = Counts for the individual raw X^2 test measurements.

Acceptable values of X^2 for six measurements must fall within the range from 1.145 to 11.071[13]. Outside this range, there is more than a 90% chance that extraneous non-random events are being counted. If the value is outside this range, the problem must be diagnosed and rectified before proceeding to re-perform the X^2 test[11]. The first step in the diagnosis should be to re-perform the X^2 test twice. If both tests are within the acceptable limits, the first test was probably a statistical outlier. If one or both fail, proceed to diagnose the problem.

2.4.3 Calibration

The steps required to perform a χ^2 test and the basic calibration steps for are shown below:

1. Utilizing the ORNL calibration fixture, place an 11g 93% enriched U-235 calibration standard in a fixed position, horizontally centered on the detector axis and 40 cm from LaBr crystal front face.

2. Perform six measurements of the source. Do not touch or disturb the source or detector between these measurements. The counting time is arbitrary, except that there should be about 400 counts in the peak region of interest (ROI 4) for each measurement. Background subtraction should not be performed.

3. Using these six measurements, perform the chi-squared test described previously.

Next, perform Radial Response Measurements for the initial calibration: Perform radial response measurements to determine point, line, and area calibration constants.

1. Utilizing the ORNL calibration fixture, place the 11g 93% enriched U-235 standard in a fixed position, horizontally centered on the detector axis and 40 cm from the LaBr crystal front face. Collect a measurement.

2. Perform nine successive measurements by moving the standard in 5 cm increments off the centerline to the right and then nine measurements to the left of the detector.

3. Tabulate the measurement data for entry into the HMS4 calibration software.

Since no adequately characterized LEU or U-238 source was available at the Safeguards Laboratory, an adequately characterized Bi-207 source was used to simulate the 1001 keV photon from U-238 for the purposes of determining LEU calibration factors. Bi-207 emits gamma rays at approximately 1064 keV versus the 1001 keV emitted by U-238 (actually emitted by the $Pa\text{-}234^{m}$ progeny of U-238). Prior to performing the LEU calibration test, an ROI for the 1064 keV peak shall be added centered on the 1064 KeV peak. Using the radiological characteristics of U-238 and Bi-207, the Bi-207 activity and gamma yield can be correlated to an equivalent mass of U-235.

The first step in this process was determining the number of gammas per second given off by 1.35 μCi of Bi-207 knowing that the intensity of the 1064 keV Bi-207 peak is 74.60%:

$$A_{Bi207} = 1.35\mu Ci \cdot \frac{3.7x10^{10} Bq}{1\ Ci} = 49{,}950\ Bq = 49{,}950\ dps$$

$$A_{Bi207} = 0.7460 \cdot 49{,}950\ dps = 37{,}263\ dps$$

This number of disintegrations per second will now be used for $Pa\text{-}234^{m}$ to determine an equivalent amount of U-238. The disintegrations for $Pa\text{-}234^{m}$ will be used for U-238 since it is assumed that they will be nearly identical. The knowledge that the intensity of the 1001 keV is 0.842 percent will also be used in the calculation.

$$A_{Pa234} = A_{U238} = \frac{A_{Bi207}}{0.00842} = 4{,}425{,}499 \text{ dps}$$

Finally, the number obtained above will be used with the specific activity of U-238 in order to determine a gram quantity of U-238:

$$SA_{U238} = \left(\frac{T_{1/2}\, Ra_{226}}{T_{1/2}\, U_{238}}\right) \cdot \left(\frac{226}{238}\right) = 3.4\text{x}10^{-7} \text{ Ci/g}$$

$$A_{U238} = 4{,}425{,}499 \text{ dps} \cdot \left(\frac{1 \text{ Ci}}{3.7\text{x}10^{10} \text{ dps}}\right) = 120 \text{ µCi } U_{238}$$

$$m_{U238} = \frac{120 \text{ µCi}}{3.4\text{x}10^{-7} \text{ Ci/g}} = 352 \text{ g } U_{238}$$

This mass represents an equivalent gram quantity of U-238 produced by the Bi-207 source.

2.4.4 Calibration Verification

As previously stated, valid holdup measurement with the HMS4 in field deployment demands that the HMS4 usage complies with the calibration geometries. Therefore, verification of calibration geometries is a critical aspect of the calibration process.

Modeling of the equipment is based on how the item is positioned relative to the detector's field-of-view (FOV). The methods to be validated are for a point, line, or area source. The following describes the item positioning required for each method[10].

- A point source simulates a small, localized deposit that is completely inside the detector's FOV. A point source should occupy 5% or less of the diameter of the detector FOV but can be modeled as a "finite point" until it occupies enough of the FOV to make an area measurement more feasible.
- A line (simulating small pipe deposition) source is a narrow source that extends beyond the detector's FOV in one dimension. A line source fills the FOV from one side to the other while occupying 5% or less in the other dimension but can be modeled as a "finite line" until it occupies enough of the FOV to make an area measurement more feasible.
- An area source (simulating large duct, pipe, floor, etc.) extends beyond the detector FOV in all directions.

2.4.5 Calibration Verification Requirements

After performing all of the following steps for verification of the HEU calibration, repeat the steps using appropriate LEU sources to verify the LEU calibration. Also, a second point source measurement should be conducted to confirm linearity.

Perform "point source" verification

1. Utilizing the ORNL calibration fixture or appropriate detector holders or hardware place a well-characterized “point source” standard in a fixed position, horizontally centered on the detector, and at a distance from the detector face which conforms to the requirements for a point source.

2. Perform three replicate measurements of the standard (one minute count time).

3. Tabulate the measurement data.

4. Use the appropriate “point source” calibration constants to determine the U-235 mass of the measured standard.

5. Calculate and report the measured accuracy and precision for the “point source” verification measurement.

6. Repeat steps 1-5 using a well-characterized source of a different mass of U-235 than first used in step 1 to check for linearity of the calibration.

Perform “line source” verification:

1. Utilizing the calibration fixture or appropriate detector holders or hardware place a well-characterized “line source” standard in a fixed position, horizontally centered on the detector from the detector face at a distance which conforms to the requirements of a line source.

2. Perform three replicate measurements of the standard (one minute count time).

3. Tabulate the measurement data.

4. Use the appropriate HMS4 “line source” calibration constants to determine the U-235 mass of the measured standard.

5. Calculate and report the measured accuracy and precision for the “line source” verification measurement.

Perform “area source” verification:

1. Utilizing the calibration fixture or appropriate detector holders or hardware place a well-characterized “area source” standard in a fixed position horizontally centered on the detector at a distance which conforms to the requirements of an area source.

2. Perform three replicate measurements of the standard.

3. Tabulate the measurement data.

4. Use the appropriate HMS4 “area source” calibration constants to determine the U-235 mass of the measured standard.

5. Calculate and report the measured accuracy and precision for the "area source" verification measurement.

In the point, line, and area source tests described, three replicate measurements are made for each source type. The accuracy of each is defined by the following equations:

$$m_{mean} = (m_1 + m_2 + m_3)/3 \qquad 2\text{-}19$$

Where,

m_{mean} = Mean measured U-235 or U-238 mass in grams.

m_1 , m_2 , m_3 = U-235 or U-238 mass results from the three measurements.

The relative percent difference of the measurements is defined as:

$$\%RPD = 100\ ((m_{mean} - m_{source}) / m_{source}) \qquad 2\text{-}20$$

Where,

m_{source} = Known mass of the calibration standard.

The precision for each three-replicate test is defined by the relative standard deviation as:

$$\%RSD = 100\ [\{\ (m_{mean} - m_1)^2 + (m_{mean} - m_2)^2 + (m_{mean} - m_3)^2\}/2]^{1/2} /\ m_{mean} \qquad 2\text{-}21$$

The success criterion for this test is:

$$|\%RPD| + \%RSD < 25\% \qquad 2\text{-}22$$

If this inequality is violated, the test should be re-performed at least twice (six additional measurements) and the %RPD and %RSD recomputed on the basis of the available nine measurements. If the inequality is still violated, it is very likely that a systematic error of some

nature is present in the calibration or calibration verification measurements. In this case, the problem must be diagnosed and remedied, and the calibration and/or calibration verification measurements re-performed.

2.4.6 Calibration Confirmation

The fundamental qualification of the HMS4 system is to demonstrate the ability of the instrument and its associated analysis algorithms to report a measured value of U-235 within the value given for a known sample. The following tests will be conducted to determine the consistent repeatability (precision) of the detector with items similar to those for which the detector will be used. The instrument accuracy reflects the degree to which the measured quantity can be algorithmically treated to render a calculated value that matches a known value. Both accuracy and precision characteristics, given the measuring instrument and standard methodology, are essential to establish the abilities and limitations of the instrument to perform a certain task.

Perform the following calibration confirmation tests twice, once for HEU using appropriate HEU sources, and once for LEU using appropriate LEU source. The purpose of these tests are to demonstrate the capability of the HMS4 calibration algorithms to correctly report known material content in surrogates that are representative of actual material holdup configurations. A large round duct will be used at a 40cm standoff distance. The material of the pipe is stainless steel, schedule 40, with a 12 inch diameter.

Perform “point source” confirmation:

1. Place a well-characterized “point source” standard in a material matrix that is representative of material configurations for HMS4 measurements.

2. Model and measure the point source.
3. Perform three replicate measurements of each of the surrogate configurations (one minute count times).

Perform "line source" confirmation:

1. Place a well-characterized "line source" standard in a material matrix that is representative of material configurations for HMS4 measurements.
2. Model and measure the "line source".
3. Perform three replicate measurements of each of the surrogate configurations (one minute count times).

Perform "area source" confirmation:

1. Place a well-characterized U-235 "area source" standard in a material matrix that is representative of material configurations for HMS4 measurements.
2. Model and measure the "area source".
3. Perform three replicate measurements of each of the surrogate configurations (one minute count times).

In the point, line, and area source tests described above, three replicate measurements are made for each source type. The accuracy of each is defined by the following equations:

$$m_{mean} = (m_1 + m_2 + m_3)/3 \qquad 2\text{-}23$$

Where,

m_{mean} = Mean measured U-235 or U-238 mass in grams.

m_1 , m_2 , m_3 = U-235 or U-238 mass results from the three measurements.

The relative percent difference of the measurements is defined as

$$\%RPD = 100 ((m_{mean} - m_{source}) / m_{source}) \quad 2\text{-}24$$

Where,

m = Known mass of the calibration standard.

The precision for each three-replicate test is defined by the relative standard deviation as

$$\%RSD = 100 [\{ (m_{mean} - m_1)^2 + (m_{mean} - m_2)^2 + (m_{mean} - m_3)^2\}/2]^{1/2}]/ m_{mean} \quad 2\text{-}25$$

The success criterion for this test is

$$|\%RPD| + \%RSD < 25\% \quad 2\text{-}26$$

If this inequality is violated, the test should be re-performed at least twice (six additional measurements) and the %RPD and %RSD recomputed on the basis of the available nine measurements. If the inequality is still violated, it is very likely that a systematic error of some nature is present in the calibration or calibration verification measurements and/or data reduction. In this case, the causal factor(s) must be diagnosed and remedied, and the calibration and/or calibration verification measurements re-performed.

2.5 Model Variability

Model variability testing is used to determine the measurement uncertainty or bias introduced by modeling the three fundamental geometries (point, line, and area). Incorrect geometries will

intentionally be input into the HMS4 software and then measured to test how well the system will respond to a particular geometry. For example, an area source will be input into the HMS4 software when in actuality a point source will be measured. For each test shot, the user performing the testing will be aware of the exact source position within the large round duct and every effort will be made to aim the detector directly at the appropriate location (not "blind" testing). The specific measurements to be performed are shown in Table 2.1.

Table 2.1 HMS4 Model Variability Test Shots

*Each test measurement will be performed three times.

Test No.*	Actual Source Geometry	Modeled Input Geometry	Detector Offset (cm)	Enrichment Level
1	Point	Point	Contact	93%
2	Point	Line	Contact	93%
3	Point	Area	Contact	93%
4	Point	Point	50cm	93%
5	Point	Line	50cm	93%
6	Point	Area	50cm	93%
7	Point	Point	1/2 Pipe Scan	93%
8	Point	Line	1/2 Pipe Scan	93%
9	Point	Area	1/2 Pipe Scan	93%
10	Point	Point	Top Scan	93%
11	Point	Line	Top Scan	93%
12	Point	Area	Top Scan	93%
13	Line	Point	Contact	93%
14	Line	Line	Contact	93%
15	Line	Area	Contact	93%
16	Line	Point	50cm	93%
17	Line	Line	50cm	93%
18	Line	Area	50cm	93%
19	Line	Point	1/2 Pipe Scan	93%
20	Line	Line	1/2 Pipe Scan	93%
21	Line	Area	1/2 Pipe Scan	93%
22	Line	Point	Top Scan	93%
23	Line	Line	Top Scan	93%
24	Line	Area	Top Scan	93%

Table 2.1 Continued

*Each test measurement will be performed three times.

Test No.*	Actual Source Geometry	Modeled Input Geometry	Detector Offset (cm)	Enrichment Level
25	Area	Point	Contact	93%
26	Area	Line	Contact	93%
27	Area	Area	Contact	93%
28	Area	Point	50cm	93%
29	Area	Line	50cm	93%
30	Area	Area	50cm	93%
31	Area	Point	1/2 Pipe Scan	93%
32	Area	Line	1/2 Pipe Scan	93%
33	Area	Area	1/2 Pipe Scan	93%
34	Area	Point	Top Scan	93%
35	Area	Line	Top Scan	93%
36	Area	Area	Top Scan	93%

In piping systems, due to gravity, it is probable that undetected point or line source deposits will fall to the bottom of the pipe. If this is the case, area source algorithm measurements made from the side of the pipe may not detect some or all of deposits in the bottom of the pipe. This geometric configuration will also cause under-prediction of the attenuation of 186 keV gamma rays from U-235, which will cause a negative bias in the U-235 mass measurement. (The track length of a gamma ray coming from a deposit in the bottom of the pipe to a detector placed at the side of the pipe is noticeably greater than the thickness of the pipe wall.) For these reasons, HMS4 will be positioned above or below the pipe during piping measurements.

2.6 Operator Variability

Operator variability testing is used to determine the measurement variability introduced between a single operator performing multiple measurements of the same configuration, as well as variability of different operators measuring the same configurations. For each test shot, the user performing the testing will not be aware of the exact source position within the equipment. The user will determine the probable source location by scanning, and will perform the measurement "blindly" as they would in the field. Only HEU sources will be used in the operator variability tests since it is assumed that human performance will not vary based on enrichment levels. Since piping measurements are usually carried out in one foot sections at K-25, the operator will determine a one foot section of pipe to measure with the HMS4.

This test requires 5 operators to each perform 14 replicate measurements of the same section of pipe where a known-mass area source has been placed on the inner surface of the pipe. The purpose of this test is to quantify the variance in measurement techniques between operators. The primary data of interest are the gross counts in ROI 4 which represents the 186 keV photon produced by U-235.

The background will be ignored in the statistical analysis since the test environment is a low background area and we are looking for variability in the gross (foreground plus background) measurements. The following tests aim to determine the variability in measurement results due to the variability in measurement due to operator repeatability and technique.

Perform area source comparison:

1. Position the HMS4 detector to emulate standard holdup measurement protocols.
2. Place a well characterized area source standard in a surrogate 12" diameter pipe. Model the measurements as an area source by following ORISE procedures.
3. Operators 1 through 5 shall perform a measurement applied from the top of the pipe.
4. Calculate and report the measured value. Include the ROI report for full evaluation of the data.

   Note: Operators 1 through 5 shall perform individual and independent measurements of the same surrogate configuration in sequence.
5. Repeat steps 2 through 5 until each operator has made 14 measurements.

2.6.1 Single Operator Variability for Area Source Measurements

To determine a representative measurement uncertainty for a single operator's use of the HMS4 system, the variance of each operator will be calculated, and summed in quadrature to obtain an average variance for all five operators.

$$x_{i\,mean} = \left(\frac{1}{N}\right)\sum_{k=1}^{N_i} x_{ik} \qquad 2\text{-}27$$

Where,

$x_{i,mean}$ = Mean counts for operator i.

$N_i = 14$.

x_{ik} = Individual replicate counts for operator i.

The variance of operator i's counting over 14 replicates is:

$$\sigma^2_{so,i} = \left\{\frac{1}{(N_i-1)}\right\} \sum_{k=1}^{N_i} (x_{ik} - x_{i\,mean})^2 \qquad 2\text{-}28$$

The single operator variance over all 5 operators in the test is:

$$\sigma^2_{so} = \left(\frac{1}{4}\right) \sum_{i=1}^{5} \sigma^2_{so,I} \qquad 2\text{-}29$$

Where the quadrature is divided by four since we will use up one degree of freedom in calculating the mean of all the observations as:

$$x_{mean} = \left(\frac{1}{5}\right) \sum_{i=1}^{5} x_{i,mean} \qquad 2\text{-}30$$

The percent relative standard deviation over all operators is then

$$\%RSD = 100\ \sigma_{so} / x_{mean} \qquad 2\text{-}31$$

The contribution of the variance of measurements by a single operator to TMU for an HMS4 field measurement is:

$$\sigma^2_{so}\,(\text{grams U-235}) = \%RSD\ (m_{meas})/100 \qquad 2\text{-}32$$

Where,

m_{meas} = U-235 mass value in the field HMS4 measurement.

2.6.2 Inter-Operator Variability

In order to determine whether or not the techniques of the 5 operators are statistically different, the t-Test will be utilized. Each operator will be tested against each of the other four operators resulting in a total of 10 tests for significance of difference between the replicate populations.

The t-Test parameter between operator i and operator j is:

$$t = (x_{i,mean} - x_{j,mean}) / (\sigma^2_{so,i}/N_i + \sigma^2_{so,j}/N_j)^{1/2} \quad 2\text{-}33$$

In this case, N_i and N_j are both 14, and $x_{i,mean}$, $x_{j,mean}$, $\sigma^2_{so,i}$, and $\sigma^2_{so,j}$ have been defined previously. For this test, values of $t > 1.71$ indicate that there is at least a 90% chance that the difference between the two operator measurement populations are statistically significant.
If all operators pass all of the t-Tests, then this contribution to total measurement uncertainty will be ignored. If not, then the variance between operators will be calculated in quadrature as

$$\sigma^2_{op} = \left(\frac{1}{4}\right) \sum_{i=1}^{5} \left(x_{j,mean} - x_{mean}\right)^2 \quad 2\text{-}34$$

The percent relative standard deviation (counts) due to variability between operators is then

$$\%RSD_{op} = 100\ \sigma_{op} / x_{mean} \quad 2\text{-}35$$

The contribution to total measurement uncertainty is:

$$\sigma_{op}\ (\text{grams U-235}) = \%RSD_{op}\ (m_{meas})/100 \quad 2\text{-}36$$

Where m_{meas} is the U-235 mass determined in an HMS4 field measurement.

Chapter 3

Test Results

3.1 Chi-Square (χ^2) Test

The chi-squared test is a method for confirming that the counting variability in a detection system is consistent, and in response to, the random nature of radioactive decay, which can be predicted according to probability. More specific, when multiple counts of a radioactive sample (or natural background) are made, the results should approximate a Poisson distribution. The chi-squared test is a method to compare the variability of the results to the predicted variability from a true Poisson distribution. If the system results are too consistent (little variability) or too excessive (large variability), then the system may not be performing properly.

3.1.1 Requirements

To confirm that the HMS4 was operating in response to random events (rather than white noise or bleed-over from system power or electronics), a chi-squared test was performed. The chi-squared test was broken up into two distinct parts; the first for high enriched uranium (HEU) and the second for low enriched uranium (LEU). The LEU measurements end goal is quantification of the U-238 in the PGP, which can then be related back to U-235. A U-238 standard of sufficient activity was not available, therefore a well characterized surrogate, Bi-207, was used. A calibration fixture was used to position a 10.984 g U-235 standard horizontally centered on the detector axis 40 cm from the LaBr crystal face for HEU verification. For LEU, a 1.35 μCi Bi-207 source was used in the same manner with the Bi-207 standard centered on the detector axis 40 cm from the center of the LaBr crystal. Six replicate measurements of the

source were to be performed without disturbing the source or detector between these measurements.

Acceptable values of χ^2 for the six measurements range from 1.145 to 11.071[13]. If the resulting value fell outside the acceptable range, an investigation was required to determine if there was an instrument problem or the measurement result was a statistical outlier. The first diagnostic step would be to repeat the chi-squared test two more times. If both additional tests were determined to be within the acceptable limits, the first test would be considered a statistical outlier.

3.1.2 Performance

At a 40 cm source-to-detector standoff, measured counts in the Region of Interest (ROI) 4 were collected using a 10.984g U-235 source for HEU measurements. The average number of counts in ROI 4 was 5,945. The data collected for the chi-squared test for HEU are given in Table 3.1. The result for the chi-squared test using data collected from Table 3.1 is 7.149.

Measurements for LEU used ROI 7; this ROI was centered on the 1,065 keV peak emitted from Bi-207. A 1.35 μCi source of Bi-207 was placed at a 40 cm source-to-detector standoff. The average number of counts in ROI 7 was 751. The data collected for the chi-squared test for LEU are given in Table 3.2. The result for the chi-squared test using the data collected in Table 3.2 is 9.848.

The chi-squared test equation is:

$$\chi^2 = (1/x_{mean}) \sum_{i=1}^{6} (x_i - x_{mean})^2 \qquad 3\text{-}1$$

Table 3.1 Chi-squared test data for HEU

	Source + Background (Counts)		Background (Counts)		$(x_i - x_{mean})^2$
Measurement	**ROI 4**	**ROI 5**	**ROI 4**	**ROI 5**	
1	6,015	155	185	104	4,923
2	5,989	139	172	104	1,951
3	6,025	158	208	91	6,427
4	5,969	132	190	116	584
5	5,787	137	210	118	24,911
6	5,884	137	187	95	3,701
Mean	5,945	143	192	105	

Table 3.2 Chi-squared test data for LEU

	Source + Background (Counts)		Background (Counts)		$(x_i - x_{mean})^2$
Measurement	**ROI 7**	**ROI 8**	**ROI 7**	**ROI 8**	
1	794	152	104	132	1,849
2	696	169	119	131	3,025
3	717	138	127	133	1,156
4	772	133	112	103	441
5	781	152	143	141	900
6	746	140	132	138	25
Mean	751	147	123	130	

3.1.3 Evaluation

The values for both HEU and LEU, 7.149 and 9.848, fell within the acceptable range of 1.145 to 11.071. The chi-squared test was performed successfully on the first attempt for both tests.

3.2 Radial Response Measurements

The HMS4 uses the Generalized Geometry Holdup (GGH) Assay Method that was developed to simplify the quantitative analysis of holdup measurements performed with portable gamma-ray spectroscopy[1,10,11]. The calculations in the HMS4 software simplify the measuring process by reducing the large number of possible geometries to only three: point, line, and area. The analysis of holdup data using GGH requires the following constraints:

1. Radiation shielding is used on the back and sides of the crystal.
2. A cylindrical collimator is installed on the front of the crystal.
3. The detector is positioned so that the deposit can be approximated as:
    a. a small point at its center, or
    b. a narrow, uniform line through its center whose length exceeds its width, or
    c. a uniform distribution that fills it (area deposit).
4. Measurements are performed at a known distance *r* between the detector and the deposit.

The calibration of the HMS4 using the GGH method determines the relationship between the count rate of the measured gamma ray and the mass of the nuclide of interest. Calibration for the assay of a point, line, or area deposit is accomplished with a point reference source. The response for each gamma-ray peak is measured with this source positioned on the detector axis at

a known distance from the crystal. Measurements are also performed with the source displaced at fixed intervals from the crystal axis to obtain the two-dimensional radial response of the detector. These data are used to obtain the calibration for the assay of the specific isotope mass in a point, line, or area deposit.

The initial assay result is the specific isotope mass for a point, line or area deposit. Three additional corrections are required for equipment attenuation, finite-source dimensions, and the self attenuation of the deposit[10].

The correction factor for process piping and equipment attenuation effects are given by:

CF_{SA} = Correction factor for source self-attenuation

CF_{FIN} = Correction factor for finite source width (finite point or line)

CF_{EQ} = Correction factor for matrix attenuation caused by materials between the source and the detector (i.e. piping).

If no correction for process piping and equipment attenuation is performed, the assay results will always be biased low[1]. An estimate of the equipment attenuation based on the best information available gives a result that may be high or low for individual measurements, but the overall result tends to be much better than ignoring the correction altogether.

3.2.1 Requirements

The specific performance tests and measurements are divided for HEU and LEU measurements. The specific guidance for HEU called for positioning a 10.894g U-235 standard horizontally centered on the detector axis 40 cm from the LaBr crystal front face using a

calibration fixture. Successive measurements were to be made by moving the standard in 5-cm increments, collecting nine measurements off the centerline to the right and then nine measurements off the centerline to the left. These radial response measurements were to be used to calculate the calibration constants for point, line, and area. The same procedure was accomplished using the LaBr detector calibrating for HEU measurements. For LEU measurements, the LaBr was used along with a 1.35 μCi Bi-207 source and its activity related back to an equivalent U-238 mass.

3.2.2 Performance

A 3.37 cm diameter uranium point source (10.894 g at 93.16% enrichment) was placed 40 cm from the face of the crystal, centered on the detector axis, and counted for 1200s. Eighteen additional measurements were taken by moving the source off the centerline (in 5-cm increments) to the right and to the left of the axis and measuring for 200s at each location. The results were entered into the HMS4 computer software where appropriate calibration and radial response data were generated. The radial response curve that was generated during calibration is provided in Fig. 3.1.

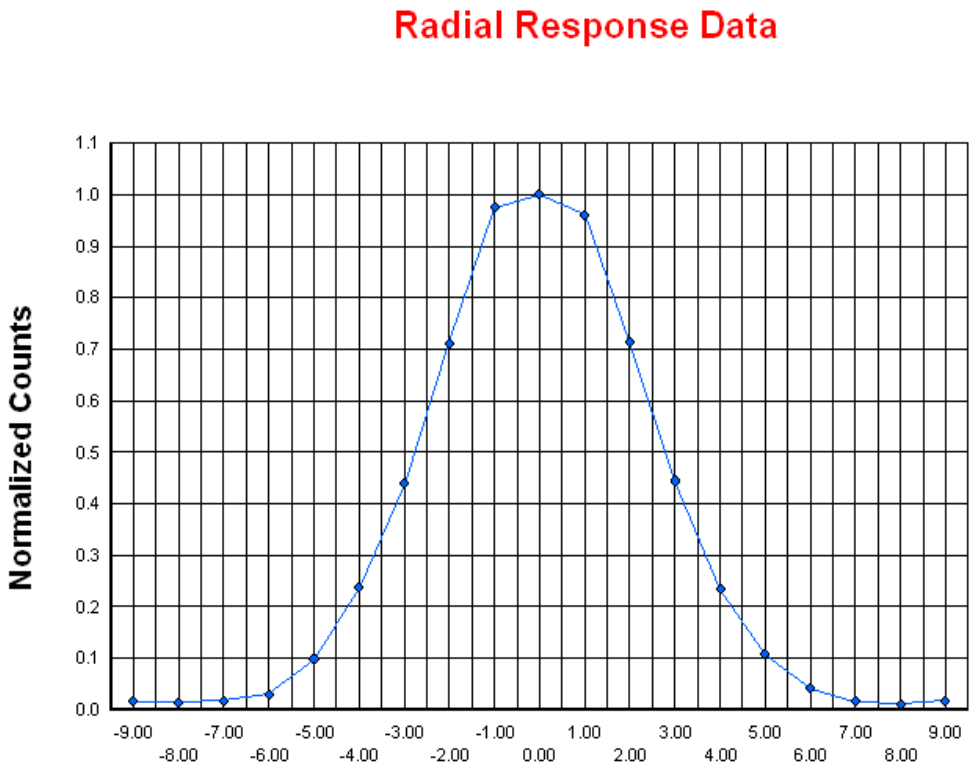

Figure 3.1 Radial response curve using an HEU source.
Values along the abscissa represent positions from the centerline in increments of 5cm.

Radial response measurements were performed on the HMS4 for LEU measurement using a LaBr detector. A 6.5 cm diameter Bi-207 point source (1.35 μCi) was placed 40 cm from the center of the crystal, centered on the detector axis, and counted for 1200s. Eighteen additional measurements were taken by moving the source off the centerline (in 5-cm increments) to the right and to the left of the axis. The results were entered into a spreadsheet mimicking GGH calculations for LEU where appropriate; calibration and radial response data were generated using this spreadsheet. The radial response curve that was generated during calibration is provided in Fig. 3.2.

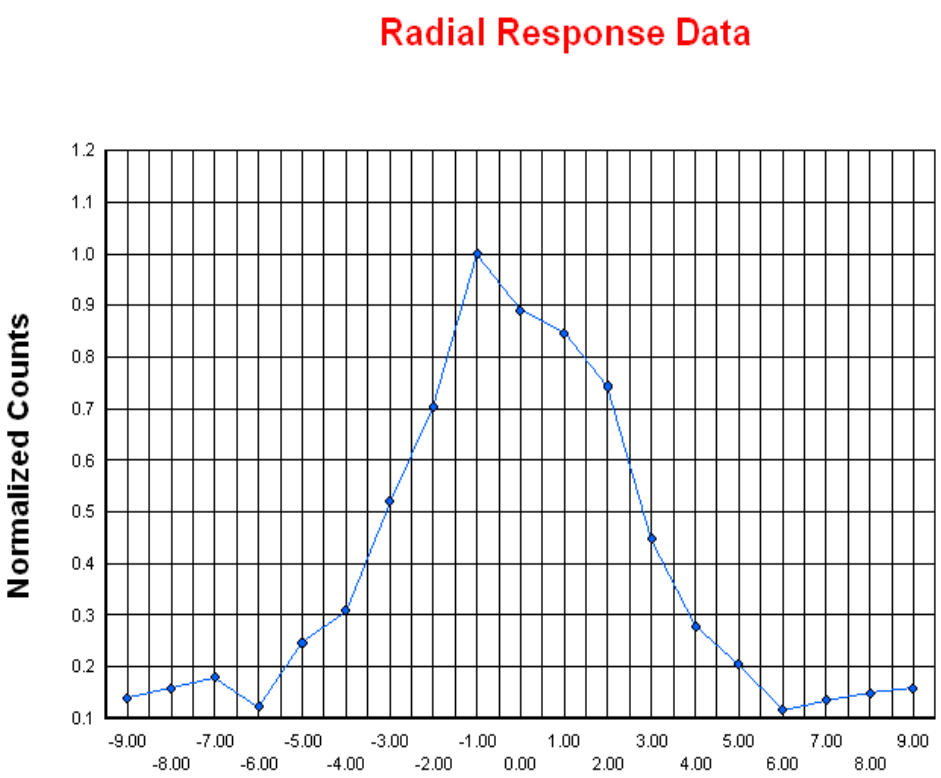

Figure 3.2 Radial response curve using an LEU source.
Values along the abscissa represent positions from the centerline in increments of 5cm.

3.2.3 Evaluation

The radial response curve was acceptable and the calibration constants that were derived from their calibration are:

HEU:

$K_{(p)} = 0.0000271958$ (gm-sec/cm^2)

$K_{(l)} = 0.0000387825$ (gm-sec/cm^2)

$K_{(a)} = 0.0000628614$ (gm-sec/cm^2)

LEU:

$K_{(p)} = 0.105811$ (gm-sec/cm^2)

$K_{(l)} = 0.150891$ (gm-sec/cm^2)

$K_{(a)} = 0.244575$ (gm-sec/cm^2)

3.3 Verification of Calibration

3.3.1 Point Source Calibration Verification

The detector calibration constant, $K_{(p),}$ for a point source was determined for the HMS4 system during calibration and evaluated. Successful verification of the calibration constant demonstrates the ability of the HMS4 system to measure the grams of U-235 or U-238 in a point source of known mass.

3.3.2 Requirements

Verification of the applicability of the $K_{(p)}$ determined is required to ensure its validity. The prescribed method of verification, as specified in the ORISE PTVP, required the measurement of two point sources or at least a secondary standard of U-235. The sources were to be measured at a fixed distance from the detector face, which conforms to the requirements for a point source. Three replicate measurements are required for each source measured. The resulting success criterion which is the absolute value of the Relative Percent Difference |%RPD| + % Relative Standard Deviation (RSD) must be within +/- 25% of the standard value for HEU measurements.

Testing for LEU measurements do not fall within this +/- 25% criteria due to the MDA of point measurements made on LEU being, on average, 381g U-238. No standard above the MDA was available for testing, nor is it expected that deposits of this magnitude will be encountered. For LEU measurements a first order approximation of the gram quantity of U-238 can be made though accurate measurement, within +/- 25%, will not be possible. Should measurements in the field show a deposit, which is infinitely thick, an approximation will be made as to the gram quantity of U-235 calculated from the amount of U-238 measured and the enrichment. After the approximate gram quantity is calculated criticality safety will be notified of the location for pipe removal.

3.3.3 Performance

The verification of the point source calibration was performed using the calibration fixture to position the sources horizontally centered on the detector axis crystal face. The two sources used

contained 2.387g and 10.894g of U-235 and the measurements were made at a distance of 40 cm. Table 3.3 summarizes the results of the measurements.

Table 3.3 Point source calibration verification results for HMS4 system HEU

Distance (cm)	Source (grams)	Measured grams (mean)	% RSD	%RPD	Success (±25%)
40	10.894	11.583	4.38	6.32	10.7
40	2.387	2.77	1.37	16.05	17.42

The relative percent difference, %RPD, and is calculated as follows:

$\%RPD = (C_m - C_{srm})/ C_{srm} * 100$

Where,

C_m is the average of the replicate measured U-235 values.
C_{srm} is the "true" or certified value.

3.3.4 Evaluation

The %RPD values, which are the percent differences from the true gram quantity values, were excellent at less than +/-17%. A review of the summarized results shows that all of the measurements meet the required success criterion of within +/- 25%. Verification of the point calibration constant demonstrated the ability of the HMS4 system to measure the grams of U-235 in a point source of known mass.

3.3.5 Performance

The verification of the point source calibration was performed using the calibration fixture to position the sources horizontally centered on the detector axis crystal face. The two sources used

contained 169g and 230g of U-238 and the measurements were made at a distance of 40 cm. Table 3.4 summarizes the results of the measurements.

Table 3.4 Point source calibration verification results for HMS4 system LEU

Distance (cm)	Source (grams)	Measured grams (mean)	% RSD	%RPD	Total Error
40	169	402.87	12.22	138.38	150.6
40	230	382.6	24.99	66.35	91.34

The relative percent difference, %RPD, and is calculated as follows:

$\%RPD = (C_m - C_{srm})/ C_{srm} * 100$

Where

C_m is the average of the replicate measured U-235 values.

C_{srm} is the "true" or certified value.

3.3.6 Evaluation

The %RPD values, which are the percent differences from the true gram quantity values, were +/-138.8% and +/-66.35%. A review of the summarized results shows that all of the measurements were overly conservative which is more desirable from a criticality safety standpoint. Verification of the point calibration constant for LEU demonstrated the ability of the HMS4 system to make a first order approximation of the gram quantity of U-238 in a point source of known mass.

3.4 Line Source Calibration Verification

The detector calibration constant, $K_{(l)}$, for a line source was determined for the HMS4 system during calibration and evaluated in Section 2. Successful verification of the calibration constant demonstrates the ability of the HMS4 system to measure the grams U-235 in a line source of known mass per unit length.

3.4.1 Requirements

Verification of the applicability of the $K_{(l)}$ value determined is required to ensure its validity. The prescribed method of verification, as specified in ORISE PTVP, required the measurement of a line source standard in a fixed position horizontally centered on the detector face at a distance, which conforms to the requirements for a line source. Three replicate measurements are required for the source. The resulting success criterion for HEU which is the absolute value of the %RPD + %RSD must be within +/- 25% of the standard value.

Testing for LEU measurements do not fall within this +/- 25% criteria due to the MDA of line measurements made on LEU being, on average, 404g U-238. No standard above the MDA was available for testing, nor is it expected that deposits of this magnitude will be encountered. For LEU measurements a first order approximation of the gram quantity of U-238 can be made though accurate measurement, within +/- 25%, will not be possible. Should measurements in the field show a deposit, which is infinitely thick, an approximation will be made as to the gram quantity of U-235 calculated from the amount of U-238 measured and the enrichment. After the approximate gram quantity is calculated criticality, safety will be notified of the location for pipe removal.

3.4.2 Performance

The verification of the line source calibration for HEU was performed using the calibration fixture to position the source horizontally centered on the detector axis crystal face. The line source used contained 1.55 g of U-235 and the measurements were made at a distance of 40 cm. Table 3.5 summarizes the results of the measurements.

Table 3.5 Line source calibration verification results for HMS4 system

Distance (cm)	Source (grams)	Measured grams (mean)	% RSD	%RPD	Success (±25%)
40	1.55	1.38	3.94	-11.2	15.14

3.4.3 Evaluation

The %RPD value, which is the percent difference from the true gram quantity value, was excellent at less than +/-12%. A review of the summarized results shows that the measurements meet the required success criterion of within +/- 25%. Verification of the line calibration constant demonstrated the ability of the HMS4 system to measure the grams of U-235 in a line source of known mass.

3.4.4 Performance

The verification of the line source calibration for LEU was performed using the calibration fixture to position the source horizontally centered on the detector axis crystal face. The line source used contained 198.468 g of U-238 and the measurements were made at a distance of 40 cm. Table 3.6 summarizes the results of the measurements.

Table 3.6 Line source calibration verification results for HMS4 system

Distance (cm)	Source (grams)	Measured grams (mean)	% RSD	%RPD	Total Error
40	198.468	340.09	7.9	73.88	81.78

3.4.5 Evaluation

The %RPD value, which is the percent difference from the true gram quantity value, was +/- 73.88%. A review of the summarized results shows that all of the measurements were overly conservative which is more desirable from a criticality safety standpoint. Verification of the line calibration constant for LEU demonstrated the ability of the HMS4 system to make a first order approximation of the gram quantity of U-238 in a line source of known mass.

3.5 Area Source Calibration Verification

The detector calibration constant, $K_{(a)}$, for an area source was determined for the HMS4 system during calibration and evaluated in Section 2. Successful verification of the calibration constant demonstrates the ability of the HMS4 system to measure the grams U-235 in a plane source of known mass per unit area.

3.5.1 Requirements

Verification of the applicability of the $K_{(a)}$ value determined is required to ensure its validity. The prescribed method of verification required the measurement of an area source standard in a fixed position horizontally centered on the detector face at a distance, which conforms to the requirements for an area source. Three replicate measurements are required for the source. The

resulting success criterion which is the absolute value of the %RPD + %RSD must be within +/- 25% of the standard value for HEU.

Testing for LEU measurements do not fall within this +/- 25% criteria due to the MDA of area measurements made on LEU being, on average, 749g U-238. No standard of this size was available for testing, nor is it expected that deposits of this magnitude will be encountered. For LEU measurements a first order approximation of the gram quantity of U-238 can be made though accurate measurement, within +/- 25%, will not be possible. Should measurements in the field show a deposit which is infinitely thick an approximation will be made as to the gram quantity of U-235 calculated from the amount of U-238 measured and the enrichment. After the approximate gram quantity is calculated criticality, safety will be notified of the location for pipe removal.

3.5.2 Performance

The verification of the area source calibration was performed by laying a card source on a table and collecting the measurements centered on the card from above. The source "card" was made by dusting Special Nuclear Material (SNM) over an adhesive surface and sealing it with another layer of plastic. The total amounts of U-235 on the cards were consistent, however based on measurements by ORNL; there was considerable variation in the distribution of the uranium over the different areas on all their source cards.

The source card used contained a total of 11.113 g of U-235 and the measurements were made at a distance of 40 cm. Table 3.7 summarizes the results of the measurements.

Table 3.7 Area source calibration verification results for HMS4 system

Distance (cm)	Source (grams)	Measured grams (mean)	% RSD	%RPD	Success (±25%)
40	11.113	11.678	1.41	5.09	6.5

3.5.3 Evaluation

The %RPD value, which is the percent difference from the true gram quantity value, was excellent at less than +/-6%. A review of the summarized results shows that the measurements meet the required success criterion of within +/- 25%. Verification of the area calibration constant demonstrated the ability of the HMS4 system to measure the grams of U-235 in an area source of known mass, even with variation in the distribution of the uranium in the source.

3.6 Source Calibration Confirmation

3.6.1 Point Source Calibration Confirmation For HEU

This section assesses the measurement ability of the HMS4 system in a situation similar to one in which the detector is to be used (i.e. measurements of sources within pipes). Compliance with standards for precision and accuracy must be demonstrated.

3.6.2 Requirements

Three replicate static measurements of a known point source were to be made with the source in a material matrix representative of the expected in-field application (i.e. within a pipe). The measurements were to be taken with a known source inside of a stainless steel (SS) pipe with a diameter of greater than 30 cm. The resulting success criterion which is the absolute value of the %RPD + %RSD must be within +/- 25% of the standard value.

3.6.3 Performance

The three replicate static measurements were made at a distance of 40 cm from the source that was placed in a 30 cm diameter SS pipe with a wall thickness of 0.279 cm. The point source used contained 2.38 g of U-235. Table 3.8 summarizes the results of the measurements.

Table 3.8 Point source calibration confirmation results for HMS4 system

Distance (cm)	Source (grams)	Measured grams (mean)	% RSD	%RPD	Success (±25%)
40	2.38	1.97	4.19	-17.57	21.76

3.6.4 Evaluation

The %RPD value, which is the percent difference from the true gram quantity value, was acceptable at less than +/-18%. A review of the summarized results shows that the measurements meet the required success criterion of within +/- 25%. This test serves to further confirm the point source calibration constant and demonstrates the ability of the HMS4 system to measure the grams of U-235 in a point source of known mass within a pipe as expected during in-field application.

3.7 Line Source Calibration Confirmation for HEU

3.7.1 Requirements

Three replicate static measurements of a known line source are to be made with the source in a material matrices representative of the expected in-field application (i.e. within a pipe). The measurements were to be taken with a known source inside of a stainless steel pipe with a diameter of 30 cm. The resulting success criterion which is the absolute value of the %RPD + %RSD must be within +/- 25% of the standard value.

3.7.2 Performance

The three replicate static measurements were made at a distance of 40 cm from the source that was placed in a 30 cm diameter SS pipe with a wall thickness of 0.279 cm. The point source used contained 1.55 g of U-235. Table 3.9 summarizes the results of the measurements.

Table 3.9 Line source calibration confirmation results for HMS4 system

Distance (cm)	Source (grams)	Measured grams (mean)	% RSD	%RPD	Success (±25%)
40	1.55	1.21	3.09	22.26	25.35

3.7.3 Evaluation

The %RPD value, which is the percent difference from the true gram quantity value, was acceptable at less than +/-23%. A review of the summarized results shows that the measurements meet the required success criterion of within +/- 25%. This test serves to further confirm the line source calibration constant and demonstrates the ability of the HMS4 system to measure the grams of U-235 in a line source of known mass within a pipe as expected during in-field application.

3.8 Area Calibration Confirmation for HEU

3.8.1 Requirements

Three replicate static measurements of a known area source were to be made with the source in a material matrices representative of the expected in-field application (i.e. within a pipe). The measurements are to be taken with a known source inside of a stainless steel pipe with a diameter of 30cm. The resulting success criterion which is the absolute value of the %RPD + %RSD must be within +/- 25% of the standard value.

3.8.2 Performance

Two separate tests were conducted for the area calibration confirmation as described below. For the first test, a small card source was placed in a 30 cm diameter stainless steel (SS) pipe with a wall thickness of 0.279 cm. The source card used contained 11.113 g of U-235. The source card did cover approximately the bottom half of the pipe. Table 3.10 summarizes the results of the measurements.

Table 3.10 Area source calibration confirmation results for HMS4 system

Distance (cm)	Source (grams)	Measured grams (mean)	% RSD	%RPD	Success (±25%)
40	11.113	13.28	1.08	20.84	21.91

3.8.3 Evaluation

The %RPD values, which are the percent differences from the true gram quantity values, were acceptable at less than +/-21%. However, the larger diameter pipe with the source wrapped completely around the inner diameter of the pipe produced much better results. A review of the summarized results shows that all of the measurements meet the required success criterion of within +/- 25%. This test serves to further confirm the area source calibration constant and demonstrates the ability of the HMS4 system to measure the grams of U-235 in an area source of known mass within a pipe as expected during in-field application.

3.9 Point Source Calibration Confirmation for LEU

This section assesses the measurement ability of the HMS4 system in a situation similar to one in which the detector is to be used (i.e. measurements of sources within pipes). Compliance with standards for precision and accuracy must be demonstrated.

3.9.1 Requirements

Three replicate static measurements of a known point source were to be made with the source in a material matrix representative of the expected in-field application (i.e. within a pipe). The measurements were to be taken with a known source inside of a stainless steel pipe with a diameter of 30 cm. The resulting success criterion which is the absolute value of the %RPD + %RSD must be within +/- 25% of the standard value.

3.9.2 Performance

The three replicate static measurements were made at a distance of 40 cm from the source that was placed in a 30 cm diameter SS pipe with a wall thickness of 0.279 cm. The point source used contained 169 g of U-238. Table 3.11 summarizes the results of the measurements.

Table 3.11 Point source calibration confirmation results for HMS4 system

Distance (cm)	Source	Measured grams	% RSD	%RPD	Total Error
40	169	358.24	16.02	111.97	128

3.9.3 Evaluation

The %RPD value, which is the percent difference from the true gram quantity value, was acceptable at less than+/-17%. A review of the summarized results shows that the measurements

meet the required success criterion of within +/- 25%. This test serves to further confirm the point source calibration constant and demonstrates the ability of the HMS4 system to measure the grams of U-235 in a point source of known mass within a pipe as expected during in-field application.

3.10 Line Source Calibration Confirmation for LEU

3.10.1 Requirements

Three replicate static measurements of a known line source are to be made with the source in a material matrices representative of the expected in-field application (i.e. within a pipe). The measurements were to be taken with a known source inside of a stainless steel pipe with a diameter of 30 cm. The resulting success criterion which is the absolute value of the %RPD + %RSD must be within +/- 25% of the standard value.

3.10.2 Performance

The three replicate static measurements were made at a distance of 40 cm from the source that was placed in a 30 cm diameter SS pipe with a wall thickness of 0.279 cm. The point source used contained 198.468 g of U-238. Table 3.12 summarizes the results of the measurements.

Table 3.12 Line source calibration confirmation results for HMS4 system

Distance (cm)	Source	Measured grams	% RSD	%RPD	Total Error
40	198.468	211.32	12.37	6.48	18.85

3.10.3 Evaluation

The %RPD value, which is the percent difference from the true gram quantity value, was acceptable at less than +/-6.48%. A review of the summarized results shows that the measurements meet the required success criterion of within +/- 25%. This test serves to further confirm the line source calibration constant and demonstrates the ability of the HMS4 system to measure the grams of U-235 in a line source of known mass within a pipe as expected during in-field application.

3.11 Area Source Calibration Confirmation for LEU

In the interest of time no measurements for the area source calibration for LEU were performed. The MDA for area measurements were so far above any standards available, and the results from point and line measurements were so poor, no measurements were performed.

3.12 Model Variability

The purpose of these tests were to determine the extent to which a point, line, or area deposit could be detected and measured using a static source measurement while varying the geometry input parameters in HMS4 for routine field measurements. The concern is that uranium deposits may form, particularly along the bottom of a pipe, after it has been visually inspected. The tests were designed to evaluate the ability to detect and quantify such deposits and to determine the best measurement parameters (measurement standoff distance, input geometries, etc.).

3.12.1 Requirements

The preliminary and final test shots were explained in the ORISE PTVP. For each configuration, the requirements were to:

Identify and use qualified measurement standard(s).

1. Position the HMS4 detector to emulate standard holdup measurement protocols.
2. Place a well characterized source standard of the proper type (point, line, or area) in a surrogate, stainless steel, 30cm diameter pipe.
3. Perform three replicate measurements modeling each geometry (one minute count times).
4. Calculate and report the measured accuracy and precision for each set of three replicate measurements.

The tests were designed to enhance the understanding of the performance of the HMS4 to detect and quantify such deposits while varying the input parameters therefore, no success criteria were stated. The model variability tests were only performed once with no delineation between HEU and LEU since the purpose of the tests was to determine the effect of an incorrect model and not variations in enrichment. The results of the final test shots are summarized in Appendix A. All data for this test is archived on an ORISE database and can be made available if requested.

3.12.2 Performance

A point source containing 2.387 g of U-235 was placed inside a 30cm diameter SS pipe at a known location. Measurements were then made utilizing each of the three geometries with a specific scan technique. The scan techniques tested were: holding the detector static, 10 cm standoff from the pipe, detector on contact with the pipe, moving the detector along the top of the pipe, and scanning half the area of the pipe. Each of these measurement techniques were performed in one minute measurements. For example, three one minute counts were performed holding the detector on contact with the pipe; one measurement for each geometry (point, line,

and area). Once the measurements using the point source were complete a line source and an area card were used and put through the same measurements; the line source contained 1.550g U-235 and the area card contained 11.113g U-235. The results of the final test shots are summarized in Appendix A.

3.12.3 Evaluation

Prior to NDA measurements, PGP at K-25 is visually inspected for large deposits, which are then removed. Keeping this fact in mind the expected geometry of the remaining holdup is a uniformly distributed deposit due to consumption in the pipe; this most closely resembles an area source geometry. After a comprehensive review of the data obtained in the model variability testing, and keeping the expected actual geometry in mind, data showed that modeling an area source geometry using the scanning technique, the average ratio of the measured gram quantity to the actual gram quantity was calculated to be 0.9962 which means on average the measured gram quantity result was 0.38% lower than the actual gram quantity.

For determining the variability of the measurement due to errors in geometry, the data for each actual-modeled geometry combination were evaluated to identify the worst-case replicate-average relative percent bias of the geometries to be used in the field. From visual inspections performed in the field it was noted that line sources were not found; knowing this information only point and area sources are of concern. This bias was then assumed to appropriately and conservatively represent the average difference between the actual and measured values, which is the same as the definition of relative percent deviation. This bias is added linearly to the TMU. For an area source geometry, which is the model, which will be used in the building, this RPD value was calculated to be 37%.

3.13 Lower Limit of Detection and Minimum Detectable Activity

The quantitative measurement of radioactivity requires measurements of both the source and the background. The reported activity is the difference between these two measurements. The precision of the reported measurement depends on the uncertainty in both of the measurements.

The measurement of the background in K-25 is complicated because it has the same energy as the gamma radiation from the material being assessed but originating from surrounding locations. Ideally, to measure the radioactive material in a pipe, the operator would first make a measurement exterior to the pipe. Then, while holding the detector stationary, the operator would remove the pipe and make a second measurement of background. This is not possible for the *in-situ* measurements of pipes in the K-25 Building.

In actuality, the background measurement is made first by positioning the detector, so that it remains pointed in the same direction, but translated so that it does not "see" the pipe. HMS4 then corrects the background for attenuation that would have occurred, were the pipe in front of the detector. In general, the reported measurement is described as follows:

Reported cpm = source cpm – background cpm corrected for attenuation

Two factors affect the variation in the corrected background measurement: the counting statistics and the variation caused by moving the detector.

The variation in the background measurement when measured this way can be assessed by making pairs of background measurements[10]. The first measurement is made of a surrogate pipe (without any uranium inside) and the second is made after translating the detector enough to remove the surrogate pipe from the field view. The reported background then is a function of

these two measurements. The variance of the background is the sum of the variances of the two measurements.

The values of the MDA and the LLD are based on this uncertainty in the background as shown in LA-UR-95-3321[10], Chap. 5.

3.13.1 Requirements

Measurements for the LLD were conducted in accordance with section 4.5 of the ORISE PTVP. Five replicate measurements were performed on a 30cm diameter pipe to mimic conditions in K-25.

The resulting data included:

- Raw data (to include the four ROIs) for each value.
- Calculated LLD for each value.
- Calculated MDAs for point sources for each value.

3.13.2 Performance

The ORISE HMS4 system was used to obtain fifteen 60-second background measurements. The raw data consisting of counts in the ROIs were reported for each measurement. The LLD and the MDA for point, line, and area sources were then calculated and reported. The average LLD's and MDA's are shown in tables 3.13, 3.14, and 3.15.

Table 3.13 LLD Results

LLD Results			
	Point (cts)	**Line (cts)**	**Area (cts)**
LLD m1	99.08	99.75	91.72
LLD m2	98.85	91.6	93.41
LLD m3	98.85	104.86	91.6
LLD m4	99.97	101.41	92.45
LLD m5	95.64	90.49	91.35
Avg LLD	98.48	97.62	92.1

Table 3.14 MDA Results for HEU

MDA Results HEU			
	Point (g U-235)	**Line (g/cm U-235)**	**Area (g/cm^2 U-235)**
MDA m1	0.099	0.0035	0.00014
MDA m2	0.098	0.0032	0.00013
MDA m3	0.098	0.0037	0.00015
MDA m4	0.099	0.0036	0.00015
MDA m5	0.095	0.0032	0.00013
Avg MDA	0.098	0.0035	0.00014

Table 3.15 MDA Results for LEU

MDA Results LEU			
	Point (g U-238)	**Line (g/cm U-238)**	**Area (g/cm^2 U-238)**
MDA m1	383.62	13.77	0.51
MDA m2	382.75	12.64	0.52
MDA m3	382.75	14.47	0.51
MDA m4	387.09	14	0.52
MDA m5	370.34	12.49	0.51
Avg MDA	381.31	13.48	0.52

3.13.3 Evaluation

A review of the data shows very little difference between the background measurements indicating that errors in the field measurements due to variations in background will not be large.

3.14 Operator Variability

Operator variability testing was performed to determine the measurement variability introduced between a single operator performing multiple measurements of the same configuration, as well as variability of different operators measuring the same configurations. For each test shot, the user performing the testing was not aware of the exact source position within the equipment. The user determined the probable source location by scanning, and then measured the location that they thought the source was. The purpose of not knowing the exact location of the source was to mimic field conditions. Only HEU sources were used since it is assumed that human performance will not vary based on enrichment levels. Since piping measurements are usually carried out in one foot sections at K-25, the operator determined a one foot section of pipe to measure with the HMS4.

3.14.1 Requirements

The preliminary and final test shots were explained in the ORISE PTVP[9]. For each configuration, the requirements were to:

Identify and use qualified measurement standard(s).

1. Position the HMS4 detector to emulate standard holdup measurement protocols.
2. Place a well characterized area source standard in a surrogate 30 cm diameter pipe. Model the measurements as an area source by following ORISE procedures.

3. Operators 1 through 5 shall perform a measurement applied from the top of the pipe.
4. Calculate and report the measured value. Include the ROI report for full evaluation of the data.

   Note: Operators 1 through 5 shall perform individual and independent measurements of the same surrogate configuration in sequence.

5. Repeat steps 2 through 5 until each operator has made 14 measurements.

3.14.2 Performance

Table 3.16 shows the results of the operator variability testing for the five operators. The average gram quantity for each individual operator is given below their respective measurements. The source used was an 11.113 g U-235 93.17% enriched area card. Each operator used the scanning technique to perform their measurements on the 1 foot segment of pipe that they selected.

Table 3.16 Operator Variability Results

Operator Variability Results									
Operator #1	**Result (g)**	**Operator #2**	**Result (g)**	**Operator #3**	**Result (g)**	**Operator #4**	**Result (g)**	**Operator #5**	**Result (g)**
1	8.09	1	8.81	1	9.96	1	11.99	1	9.39
2	8.66	2	8.38	2	11.12	2	10.69	2	8.81
3	9.53	3	8.09	3	10.97	3	10.54	3	8.95
4	8.52	4	8.23	4	10.97	4	10.4	4	9.67
5	8.66	5	8.38	5	10.25	5	9.96	5	9.39
6	9.07	6	9.24	6	10.54	6	9.82	6	9.24
7	8.38	7	7.8	7	10.97	7	10.97	7	9.67
8	8.09	8	8.66	8	9.96	8	10.54	8	9.67
9	8.95	9	8.23	9	10.11	9	11.12	9	10.11
10	8.09	10	8.38	10	10.83	10	11.41	10	8.95
11	7.8	11	8.66	11	10.4	11	10.83	11	9.1
12	8.23	12	8.23	12	10.97	12	10.97	12	9.82
13	8.09	13	8.95	13	10.11	13	11.41	13	9.24
14	8.38	14	9.24	14	10.25	14	11.41	14	9.82
Average	8.47	**Average**	8.52	**Average**	10.53	**Average**	10.86	**Average**	9.42

Table 3.17 shows the variance, standard deviation, mean, and %RSD over the five operators. It can be seen that the %RSD is very low being less than 6%.

Table 3.17 Operator Variability Results

Variance over 5 Operators (g)	Standard Deviation over 5 Operators (g)	Mean over 5 Operators (g)	%RSD over 5 Operators
0.27	0.52	9.56	5.48

3.14.3 Evaluation

A review of the data shows that there is a difference between operators when performing measurements. It should be noted that the techniques of operator 1 and 2 differed from operators 3 and 4 in regards to their standoff distance. While all operators were given the same instructions operators 1 and 2 did not make contact with the pipe while performing their measurements. Clearly, this small standoff distance resulted in a difference of well over 2 grams U-235. For field measurements survey staff will be specifically instructed to keep the detector in contact with the pipe while measuring. They were intentionally not corrected during the testing in an effort to quantify the effect of not maintaining detector contact during measurements.

3.14.4 Inter-Operator Variability Evaluation

The purpose of the inter-operator variability testing was to determine if there was a statistically significant difference between the techniques of the 5 operators. In order to determine this, a t-Test was utilized and analyzed at the 90% confidence level. The result of this analysis is shown in Table 3.18. Using the equations outlined in the ORISE PTVP[9] the inter-operator variance was calculated to be 1.23 and the inter-operator %RSD was 11.62%.

Table 3.18 Inter-Operator Variability Results

t-Test Parameters; t>1.71 Indicates Different Population at 90% Confidence					
Operator	**Operator # 1**	**Operator #2**	**Operator #3**	**Operator #4**	**Operator #5**
1	X	0.313039	12.087717	11.7902591	5.80547
2	X	X	12.419161	11.9626725	5.807948
3	X	X	X	1.68403112	-7.19385
4	X	X	X	X	-7.60462

From table 3.18 it can be seen that several values from the t-Test are greater than 1.71 and therefore will be added to the TMU as specified in section 3.16 of this document.

3.15 Total Measurement Uncertainty

The TMU for the holdup measurements made with the HMS4 instrument is the combination of several sources of uncertainty. An evaluation of the magnitude of each of these sources of uncertainty is necessary to determine a value for the TMU. The magnitude of many of the uncertainties can be estimated using the measurement information gained in the performance of the test plan requirements.

The following sections give the estimates of the uncertainties developed from the test plan performance.

3.15.1 Calibration Uncertainty

Analysis of the calibration process reveals only three possible sources of calibration error contribution to TMU. This results from the fact that the U-235 material itself is well characterized in its chemistry, isotopic components, and isotopic masses. However, the source is composed of the uranium material encased in a matrix of materials to allow for handling and positioning, and to assure that there is no loss of material from the source. Thus, the likely sources of error are:

- Computations of self-attenuation within the active source and its containing matrix.
- Positioning of the source with respect to the detector geometry during calibration.
- Counting statistics.

3.15.2 Source Matrix Self-Attenuation

ORISE has opted not to include an additional error for this parameter since ORNL's well-characterized uranium sources were used for calibration.

3.15.3 Counting Statistics

As explained in the ORISE PTVP[9], the final TMU equation assumes that counting statistics during calibration are negligible for HEU. However, for LEU measurements, counting statistics will be added to the TMU linearly.

3.15.4 In-Piping Source Location

This uncertainty would occur if there is a sloughing off of material that was previously distributed on the pipe surface after the visual inspection (i.e. the "Vent, Purge, and Drain" process) resulting in an accumulation of a point-like or line-like deposit on the bottom of the pipe in which the HMS4 measurement was not collected centered on that deposit. However, prior to NDA measurements any visual deposit left will be cleared out of the pipe leaving only consumptions type deposits in the pipe, which will be modeled as areas.

3.15.5 Enrichment

The calculation of holdup source self-attenuation by the HMS4 system is most sensitive to the specification of the enrichment level of the deposit[10]. Source self-attenuation is mostly caused by the heavy uranium nucleus due to its very high mass attenuation coefficient. Total uranium content is determined by dividing the U-235 measured mass by the enrichment. Thus, for highly enriched uranium, the total uranium content in the holdup source may be only about

1.09 times the U-235 mass, while at the lowest enrichments, the total uranium mass may be 100 times the U-235 mass. Moreover, the effect of self-absorption is not linear, but exponential with the inverse of enrichment.

The self-absorption is negligible below a total uranium areal density of approximately 0.2 g/cm^{2}[11]. At very high enrichment, this areal density results in U-235 amounts above the Data Quality Objectives (DQOs) (and thus the action levels) for U-235 in pipe and other components measured by HMS4. At low enrichments, however, DQO levels of U-235 in pipe result in massive amounts of self-absorption.

Deposits laid late in the life of the cascade would be expected to be at enrichment levels characteristic of process gas late in the life of the cascade. Consumption deposits, which may have occurred continuously over the life of the cascade, would have an average enrichment equal to the mass flow averaged enrichment at that point in the cascade over the life of the cascade[11]. Deposits laid early in the life of the cascade would have an enrichment characteristic of process gas early in the life of the cascade. On the east side of the building the enrichment is taken to be half of the mass flow average; this value ranges from 0.30% to 41.79% U-235. .

3.16 Calculation of the TMU

This document evaluates the TMU for measurements of holdup material on the internal surfaces of pipes using the model for area sources and then reanalyzing the data as if they were point sources.

The following equation results for the calculation of the TMU[9,15]. It is the sum of random and pseudo-random errors added in quadrature.

For HEU:

$$TMU = \sigma_{U235} = |\sigma_{MV}| + \sqrt{\sigma_{OP}^2 + \Psi^2 \sigma_{cCRB}^2} \quad 3\text{-}2$$

For LEU:

$$TMU = \sigma_{U235} = |\sigma_{MV}| + \sqrt{\sigma_{CS}{}^2 + \sigma_{OP}{}^2 + \Psi^2 \sigma_{cCRB}^2} \quad 3\text{-}3$$

Where,

$\sigma_{mv}{}^2$ is the model variability as discussed in Section 2.6. For area sources modeled as areas, the average measured gram quantity result was -0.38% lower than the actual gram quantity. For point sources that were modeled as area sources, the average measured gram quantity result was 37% higher than the actual gram quantity, which is conservative from a criticality safety standpoint.

$\sigma_{op}{}^2$ is the operator variability as discussed in Section 2.6. From section 3.14.4 it can be seen that the inter-operator %RSD was calculated as 11.62%. Using equation 2.36 the operator variability will be added to each field measurement in quadrature.

$\sigma_{cs}{}^2$ is the uncertainty due to counting statistics, calculated MDA for a worst-case scenario, for LEU measurements. This error is calculated as the square root of the count rate divided by the count rate, which is then squared. Using the area source geometry value at MDA which represents 92 counts, the % RSD for $\sigma_{cs}{}^2$ is calculated to be 1.09% for LEU measurements.

$\sigma_{cs}{}^2 = (\text{sqrt(counts)/counts})^2$ 3-4

Ψ is the conversion factor from net counts per unit time to grams of U-235 or U-238, including detector efficiency, matrix attenuation, self-absorption, and finite width point or line source correction. Note that this formulation assumes that counting statistics during calibration are negligible.

$$\Psi = K \bullet CF_{sa} \bullet CF_{fw} \bullet CF_{ma} \qquad 3\text{-}5$$

Where,

K = Detector calibration coefficient (counts / sec • g ^{235}U)

CF_{sa} = Correction factor for source self attenuation (unit less)

CF_{fw} = Correction factor for finite source width (point or line) (unit less)

CF_{ma} = Correction factor for matrix attenuation caused by materials between the source and the detector (unit less)

σ_{cCRB}^2 is the variance of the corrected count rate. This value is the uncertainty arising from the actual measurement of an internally contaminated pipe. The equation for determining the corrected count rate for an internally contaminated pipe is as follows.

$$\sigma^2_{cCRB} = (A_4 + A_5)/T_A^2 + B/(tt*T_B)^2 + (B_4 + .0225B_4^2 + B_5 + .0225B_5^2) / (tt*T_B)^2 \qquad 3\text{-}6$$

A is the measured counts with respect to a 1-ft length of pipe. Given measurements of A collected in 60s are corrected for matrix attenuation using the correction factor "t". "t" is the correction for attenuation in the pipe wall between the detector and the inside surface of the pipe. HMS4 calculates the value of "t" for the user but it can also be calculated as follows:

$$t = \exp^{(\mu\rho x)} \qquad 3\text{-}7$$

Where,

μ is the mass attenuation coefficient, ρ is the density, and x is the wall thickness of the pipe.

A_4 is the total (foreground plus background) counts in ROI 4.

A_5 is the total (foreground plus background) counts in ROI 5.

B_4 is the background counts in ROI 4.

B_5 is the background counts in ROI 5.

T_A is the counting time for the total counts.

T_B is the background counting time.

tt is the correction factor for attenuation by materials that attenuated the background during the foreground measurement (e.g. accounts for two pipe wall thicknesses).

To complete the calculation each of the standard deviations expressed in "%RSD" are to be converted to the variances expressed in (grams/cm^2)[9]. This is accomplished by multiplying each measurement's result in grams of U-235 by %RSD/100 and squared. TMU will be calculated for each measurement taken in the field.

3.17 Conclusion

The material configurations originally installed in items that are measured by the HMS4 system are well characterized and known. The major error contribution is expected to be material corrosion and erosion over time that has reduced the matrix attenuation compared to the model used in the HMS4 data reduction algorithm[9]. This creates a positive bias on measured U-235 amounts. Thus, this effect will be ignored in the computation of TMU for HMS4

Chapter 4

Conclusion

4.1 Chi-squared and radial response

The chi-squared was performed to confirm that the counting variability in the HMS4 was consistent, and in response to, the random nature of radioactive decay. To confirm that the HMS4 was operating in response to random events (rather than white noise or bleed-over from system power or electronics), a chi-squared test was requested to be performed on the ORISE system. The chi-squared test was broken up into two distinct parts; the first for high enriched uranium (HEU) and the second for low enriched uranium (LEU).

Acceptable values of χ^2 for the six measurements range from 1.145 to 11.071[13]. Measurements were conducted in accordance with the ORISE PTVP. At a 40 cm source-to-detector standoff, measured counts in the Region of Interest (ROI) 4 were collected using a 10.984g U-235 source for HEU measurements. The average number of counts in ROI 4 was 5,945. Measurements for LEU used ROI 7; this ROI was centered on the 1,065 keV peak emitted from Bi-207. A 1.35 μCi source of Bi-207 was placed at a 40 cm source-to-detector standoff. The average number of counts in ROI 7 was 751.

The values for both HEU and LEU, 7.149 and 9.848, fell within the acceptable range of 1.145 to 11.071. The chi-squared test was performed successfully on the first attempt for both tests indicating that the HMS4 was responding to random events and not system noise or some other factor.

4.2 HEU Point Source Calibration Verification

The point source calibration verification tests showed the applicability of the point calibration constant, $K_{(p)}$. As described, two point sources of U-235 were measured during testing. The sources were measured at 40 cm from the detector face. Three replicate measurements were performed for each source measured.

The %RPD values were less than +/-17% which meets the DQO's set forth at the beginning of the testing. A review of the summarized results shows that all of the measurements meet the required success criterion of within +/- 25%. These results prove that $K_{(p)}$ was acceptable and demonstrated the ability of the HMS4 system to measure the grams of U-235 in a point source of known mass.

4.2.1 LEU Point Source Calibration Verification

The point source calibration verification tests for LEU showed that the calibration constant, $K_{(p)}$, for LEU was not acceptable for field measurements. The two sources used contained 190 g and 230 g of U-238 and the measurements were made at a distance of 40 cm. The sources were measured at 40 cm from the detector face. Three replicate measurements were performed for each source measured.

The %RPD values were +/- 138.8% and +/-66.35%, well above the stated DQO's. This indicates that the calibration constant was not acceptable; most likely due to the MDA of the sources used being above the gram quantity present. However, the results did show that all of the measurements were overly conservative which is more desirable from a criticality safety standpoint. The tests performed determined that the HMS4 is not capable of performing

measurements of LEU in the field for point sources due to the calibration constant not being acceptable. Should measurements in the field show a deposit an approximation will be made as to the gram quantity of U-235 calculated from the amount of U-238 measured and the enrichment. After the approximate gram quantity is calculated criticality, safety will be notified of the location for pipe removal.

4.2.2 HEU Line Source Calibration Verification

The line source calibration verification tests showed the applicability of the line calibration constant, $K_{(l)}$. A line source containing 1.55 g of U-235 was used, no other line sources were available for measurement; the source was measured at 40 cm from the detector face. Three replicate measurements were performed on the source.

The %RPD values were less than +/-12% which meets the DQO's set forth at the beginning of the testing. A review of the summarized results shows that all of the measurements meet the required success criterion of within +/- 25%. These results prove that $K_{(l)}$ was acceptable and demonstrated the ability of the HMS4 system to measure the grams of U-235 in a line source of known mass.

4.2.3 LEU Line Source Calibration Verification

The line source calibration verification tests for LEU showed that the calibration constant, $K_{(l)}$, for LEU was not acceptable for field measurements. The line source used contained 198.468 g of U-238 and the measurements were made at a distance of 40 cm. Three replicate measurements were performed on the source measured.

The %RPD values was, +/- 73.88%, well above the stated DQO's. This indicates that the calibration constant was not acceptable; most likely due to the MDA of the source used being above the gram quantity present. However, the results did show that all of the measurements were overly conservative which is more desirable from a criticality safety standpoint. The tests performed determined that the HMS4 is not capable of performing measurements of LEU in the field for line sources due to the calibration constant not being acceptable. Should measurements in the field show a deposit an approximation will be made as to the gram quantity of U-235 calculated from the amount of U-238 measured and the enrichment. After the approximate gram quantity is calculated criticality, safety will be notified of the location for pipe removal.

4.2.4 HEU Area Source Calibration Verification

The area source calibration verification tests showed the applicability of the area calibration constant, $K_{(a)}$. The source card used contained a total of 11.113 g of U-235 and the measurements were made at a distance of 40 cm. Three replicate measurements were performed on the source.

The %RPD value was less than +/-6% which meets the DQO's set forth at the beginning of the testing. A review of the summarized results shows that all of the measurements meet the required success criterion of within +/- 25%. These results prove that $K_{(a)}$ was acceptable and demonstrated the ability of the HMS4 system to measure the grams of U-235 in an area source of known mass.

4.2.5 LEU Area Source Calibration Verification

In the interest of time no measurements for the area source calibration for LEU were performed. The MDA for area measurements were so far above any standards available, and the results from point and line measurements were so poor, no measurements were performed.

4.2.6 Calibration Verification Conclusion

The calibration verification proved that the HMS4 system is capable of performing measurements accurately for HEU sources. However, for LEU the HMS4 is not capable of providing reliable measurements of the source present. A review of the data showed that the area source measurements were the most accurate. This is a good indication since the assumption is that the remaining holdup in the PGP is in the form of uniform area sources.

4.3 Point Source Calibration Confirmation for HEU

The source calibration section determined the ability of the HMS4 system to measure holdup in a situation similar to one in which the detector is to be used (i.e. measurements of sources within pipes). The three static measurements were made at a distance of 40 cm from the source that was placed in a 30 cm diameter SS pipe with a wall thickness of 0.279 cm. The point source used contained 2.38 g of U-235.

The %RPD value was acceptable at less than +/-18%; the results showed that the measurements met the required success criterion of within +/- 25%. The point source calibration confirmation demonstrates further the successful calibration of the HMS4 system and verifies its ability to measure grams of U-235 in a point source of known mass within a pipe as expected during in-field application.

4.3.1 Line Source Calibration Confirmation for HEU

The three static measurements were made at a distance of 40 cm from the source that was placed in a 30 cm diameter SS pipe with a wall thickness of 0.279 cm. The line source used contained 1.55 g of U-235.

The %RPD value was acceptable at less than +/-23%; the results showed that the measurements met the required success criterion of within +/- 25%. The line source calibration confirmation demonstrates further the successful calibration of the HMS4 system and verifies its ability to measure grams of U-235 in a line source of known mass within a pipe as expected during in-field application.

4.3.2 Area Source Calibration Confirmation for HEU

The three static measurements were made at a distance of 40 cm from the source that was placed in a 30 cm diameter SS pipe with a wall thickness of 0.279 cm. The area source used contained 11.113 g of U-235.

The %RPD value was acceptable at less than +/-21%; the results showed that the measurements met the required success criterion of within +/- 25%. The area source calibration confirmation demonstrates further the successful calibration of the HMS4 system and verifies its ability to measure grams of U-235 in a area source of known mass within a pipe as expected during in-field application.

4.3.3 Point Source Calibration Confirmation for LEU

The source calibration section determined the ability of the HMS4 system to measure holdup in a situation similar to one in which the detector is to be used (i.e. measurements of sources within pipes). The three static measurements were made at a distance of 40 cm from the source

that was placed in a 30 cm diameter SS pipe with a wall thickness of 0.279 cm. The point source used contained 169 g of U-238.

The %RPD value was not acceptable at approximately +/-112%; the results showed that the measurements do not meet the required success criterion of +/- 25%. The point source calibration confirmation demonstrates that the HMS4 system does not have the ability to measure grams of U-238 in a point source of known mass within a pipe as expected during in-field application for LEU measurements.

4.3.4 Line Source Calibration Confirmation for LEU

The three static measurements were made at a distance of 40 cm from the source that was placed in a 30 cm diameter SS pipe with a wall thickness of 0.279 cm. The line source used contained 198.468 g of U-238.

The %RPD value was acceptable at less than +/-19%; the results showed that the measurements met the required success criterion of within +/- 25%. However, due to the gram quantity of the source being less that MDA this measurement is attributed more to luck than proper calibration of the system. The conclusion is that the HMS4 system is not able to measure grams of U-238 in a line source of known mass within a pipe as expected during in-field application.

4.3.5 Area Source Calibration Confirmation for LEU

In the interest of time no measurements for the area source calibration for LEU were performed. The MDA for area measurements were so far above any standards available, and the results from point and line measurements were so poor, no measurements were performed.

4.3.6 Source Calibration Conclusion

The source calibration proved that the HMS4 system is capable of performing measurements in piping representative of the PGP on the east side of K-25 for HEU measurements. However, for LEU the HMS4 is not capable of providing reliable measurements of the holdup present. A review of the data showed that the point source measurements were the most accurate.

4.4 Model variability

The purpose of these tests were to determine the extent to which a point, line, or area deposit could be detected and measured using a static source measurement while varying the geometry input parameters in HMS4 for routine field measurements.

Various configurations of scan technique and modeling were conducted during this section of this testing. Scan techniques ranged from holding the detector still in the center of the deposit, at 10 cm above the pipe, and a scanning technique in which the detector was moved in a serpentine pattern about the pipe. For each of these techniques the three geometries were input to the HMS4 system and measured. The two most accurate models were the point model and the area model. For the area model the average ratio of the measured gram quantity to the actual gram quantity was calculated to be 0.9962 which means on average the measured gram quantity result was 0.38% lower than the actual gram quantity. For the point model the average ratio of the measured gram quantity to the actual gram quantity was calculated to be 1.0293 which means on average the measured gram quantity result was 2.85% higher than the actual gram quantity. For measurements in the field all sources will be modeled as area sources for simplicity and due to the precision of the measurements observed during testing.

4.5 Operator variability

Operator variability testing was performed to determine the measurement variability introduced between a single operator performing multiple measurements of the same configuration, as well as variability of different operators measuring the same configurations.

A review of the data shows that there is a difference between operators when performing measurements. When the detector was held only and extra few centimeters above the pipe and not directly on the pipe a variance of approximately 2 grams U-235 was observed. By keeping the detector in contact with the PGP at all times this error can be avoided. However, there was a statistically significant difference between the techniques of the 5 operators at the 90% confidence level. This error will be incorporated in the TMU as such.

4.6 Future Considerations

Future work should focus on the calibration for LEU. Specifically, a source of sufficient strength, above MDA, must be utilized to ensure a proper calibration. By utilizing a more appropriate source more meaningful calibration constants can be obtained. With better calibration constants the conversion from counts to grams of U-238 would most likely be substantially more accurate.

The ORISE generated spreadsheet mimicking GGH calculations for LEU quantification was shown to work when calculating HEU measurements using the 186 keV peak. This gives one confidence that the calculations and work laid out within this document would lead to the successful quantification of LEU if a calibration source of sufficient strength was used. Using a stronger calibration source and the tests set forth within this document could be used to recalibrate the HMS4 system and quantify LEU holdup using the 1001 keV peak.

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APPENDIX A
MODEL VARIABILITY TEST DATA

Actual Source Geometry	Modeled Input Geometry	Detector Offset (cm)	Actual Total (g)	Measured Total (g)	Ratio of Measured to Actual	Standard Deviation of Replicates	Average of Replicates
Point	Point	Contact	2.387	2.4136	1.0111437		
Point	Point	Contact	2.387	2.4752	1.03695015	1.533679059	2.456933333
Point	Point	Contact	2.387	2.482	1.03979891		
Point	Line	Contact	2.387	2.049	0.85839966		
Point	Line	Contact	2.387	2.079	0.87096774	4.000036318	2.112
Point	Line	Contact	2.387	2.208	0.92501047		
Point	Area	Contact	2.387	4.7652	1.99631336		
Point	Area	Contact	2.387	4.6208	1.93581902	1.785619389	4.668933333
Point	Area	Contact	2.387	4.6208	1.93581902		
Point	Point	50cm	2.387	2.07	0.86719732		
Point	Point	50cm	2.387	2.2377	0.93745287	3.922239761	2.161
Point	Point	50cm	2.387	2.1753	0.91131127		
Point	Line	50cm	2.387	1.401	0.5869292		
Point	Line	50cm	2.387	1.404	0.58818601	0.567757792	1.398
Point	Line	50cm	2.387	1.389	0.58190197		
Point	Area	50cm	2.387	2.0216	0.84692082		
Point	Area	50cm	2.387	2.166	0.90741517	4.028025134	2.069733333
Point	Area	50cm	2.387	2.0216	0.84692082		
Point	Point	Scan	2.387	1.4912	0.62471722		
Point	Point	Scan	2.387	1.4016	0.58718056	6.407798628	1.4953
Point	Point	Scan	2.387	1.5931	0.66740679		
Point	Line	Scan	2.387	1.431	0.59949728		
Point	Line	Scan	2.387	1.479	0.6196062	2.241755132	1.468
Point	Line	Scan	2.387	1.494	0.62589024		
Point	Area	Scan	2.387	3.3212	1.39136992		
Point	Area	Scan	2.387	3.1768	1.33087558	2.547133541	3.273066667
Point	Area	Scan	2.387	3.3212	1.39136992		
Line	Point	Contact	1.55	1.2621	0.81425806		
Line	Point	Contact	1.55	1.3074	0.84348387	1.81568923	1.281666667
Line	Point	Contact	1.55	1.2755	0.82290323		
Line	Line	Contact	1.55	1.395	0.9		
Line	Line	Contact	1.55	1.437	0.92709677	2.58515244	1.399
Line	Line	Contact	1.55	1.365	0.88064516		
Line	Area	Contact	1.55	2.888	1.86322581		
Line	Area	Contact	1.55	3.0324	1.9563871	2.839427553	2.936133333
Line	Area	Contact	1.55	2.888	1.86322581		
Line	Point	50cm	1.55	1.3634	0.8796129		
Line	Point	50cm	1.55	1.4642	0.94464516	3.668610475	1.407333333
Line	Point	50cm	1.55	1.3944	0.8996129		
Line	Line	50cm	1.55	1.095	0.70645161		
Line	Line	50cm	1.55	1.029	0.66387097	3.227761989	1.057
Line	Line	50cm	1.55	1.047	0.67548387		

Actual Source Geometry	Modeled Input Geometry	Detector Offset (cm)	Actual Total (g)	Measured Total (g)	Ratio of Measured to Actual	Standard Deviation of Replicates	Average of Replicates
Line	Area	50cm	1.55	1.7328	1.11793548		
Line	Area	50cm	1.55	1.7328	1.11793548	4.948716593	1.684666667
Line	Area	50cm	1.55	1.5884	1.02477419		
Line	Point	Scan	1.55	1.0071	0.64974194		
Line	Point	Scan	1.55	0.9239	0.59606452	4.376240662	0.970433333
Line	Point	Scan	1.55	0.9803	0.63245161		
Line	Line	Scan	1.55	0.957	0.61741935		
Line	Line	Scan	1.55	0.969	0.62516129	1.099755089	0.958
Line	Line	Scan	1.55	0.948	0.6116129		
Line	Area	Scan	1.55	2.4548	1.58374194		
Line	Area	Scan	1.55	2.4548	1.58374194	3.464101615	2.406666667
Line	Area	Scan	1.55	2.3104	1.49058065		
Area	Point	Contact	11.113	T-Flag	T-Flag		
Area	Point	Contact	11.113	T-Flag	T-Flag	T-Flag	T-Flag
Area	Point	Contact	11.113	T-Flag	T-Flag		
Area	Line	Contact	11.113	7.68	0.69108252		
Area	Line	Contact	11.113	7.494	0.67434536	1.774357073	7.644
Area	Line	Contact	11.113	7.758	0.69810132		
Area	Area	Contact	11.113	14.44	1.29937911		
Area	Area	Contact	11.113	14.1512	1.27339152	1.01010101	14.2956
Area	Area	Contact	11.113	14.2956	1.28638531		
Area	Point	50cm	11.113	T-Flag	T-Flag		
Area	Point	50cm	11.113	T-Flag	T-Flag	T-Flag	T-Flag
Area	Point	50cm	11.113	T-Flag	T-Flag		
Area	Line	50cm	11.113	6.408	0.57662197		
Area	Line	50cm	11.113	6.147	0.55313597	2.169503291	6.301
Area	Line	50cm	11.113	6.348	0.57122289		
Area	Area	50cm	11.113	9.0972	0.81860884		
Area	Area	50cm	11.113	8.8084	0.79262125	1.612903226	8.9528
Area	Area	50cm	11.113	8.9528	0.80561505		
Area	Point	Scan	11.113	T-Flag	T-Flag		
Area	Point	Scan	11.113	T-Flag	T-Flag	T-Flag	T-Flag
Area	Point	Scan	11.113	T-Flag	T-Flag		
Area	Line	Scan	11.113	8.733	0.78583641		
Area	Line	Scan	11.113	8.853	0.79663457	1.919256933	8.703
Area	Line	Scan	11.113	8.523	0.76693962		
Area	Area	Scan	11.113	10.9744	0.98752812		
Area	Area	Scan	11.113	10.9744	0.98752812	1.506131137	11.07066667
Area	Area	Scan	11.113	11.2632	1.0135157		

VITA

Mark Jadick was born in Norristown, Pennsylvania, on January 23, 1983. He later moved to Vestal, New York, and graduated from Vestal Senior High School in June, 2000. He completed his B.S. in Mechanical Engineering from Binghamton University in May, 2005. Upon graduating from Binghamton University he was commissioned as a Second Lieutenant in the United States Air Force and served three years on active duty. He followed this by completing his M.S. in Nuclear Engineering at the University of Tennessee in December, 2010.