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Benchmark Gamma Spectroscopy Measurements of UF_6 in an Aluminum Pipe with a NaI Detector

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ACRONYMS AND ABBREVIATIONS

BDMS	Blend-Down Monitoring System
DOE	U.S. Department of Energy
EM	enrichment monitor
FEMO	flow and enrichment monitor
F/W	feed and withdrawal
GCEP	gas centrifuge enrichment plant
HEU	highly enriched uranium
IAEA	International Atomic Energy Agency
kg-SWU	kilogram-separative work unit
LANL	Los Alamos National Laboratory
LEU	low-enriched uranium
LFUA	limited frequency unannounced access
MBA	material balance area
NA-241	DOE NNSA Office of Dismantlement and Transparency
NA-243	DOE NNSA Office of International Regimes and Agreements
NDA	nondestructive assay
NEF	National Enrichment Facility (also, LES NEF)
NNSA	National Nuclear Security Administration (DOE)
NPT	Nuclear Nonproliferation Treaty
NRC	U.S. Nuclear Regulatory Commission
NU	natural uranium
ORNL	Oak Ridge National Laboratory
R&D	research and development
SWU	separative work unit
t-SWU	metric tonne-separative work unit

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EXECUTIVE SUMMARY

The expected increased demand in fuel for nuclear power plants, combined with the fact that a significant portion of the current supply from the blend down of weapons-source material will soon be coming to an end, has led to the need for new sources of enriched uranium for nuclear fuel. As a result, a number of countries have announced plans, or are currently building, gaseous centrifuge enrichment plants (GCEPs) to supply this material.

GCEPs have the potential to produce uranium at enrichments above the level necessary for nuclear fuel purposes—enrichments that make the uranium potentially usable for nuclear weapons. As a result, there is a critical need to monitor these facilities to ensure that nuclear material is not inappropriately enriched or diverted for unintended use.

Significant advances have been made in instrument capability since the current International Atomic Energy Agency (IAEA) monitoring methods were developed. In numerous cases, advances have been made in other fields that have the potential, with modest development, to be applied in safeguards applications at enrichment facilities. A particular example of one of these advances is the flow and enrichment monitor (FEMO). (See Gunning, J. E. et al., "FEMO: A Flow and Enrichment Monitor for Verifying Compliance with International Safeguards Requirements at a Gas Centrifuge Enrichment Facility," *Proceedings of the 8th International Conference on Facility Operations – Safeguards Interface*. Portland, Oregon, March 30–April 4th, 2008.)

The FEMO is a conceptual instrument capable of continuously measuring, unattended, the enrichment and mass flow of ^{235}U in pipes at a GCEP, and consequently increase the probability that the potential production of HEU and/or diversion of fissile material will be detected. The FEMO requires no piping penetrations and can be installed on pipes containing the flow of uranium hexafluoride (UF_6) at a GCEP.

This FEMO consists of separate parts, a flow monitor (FM) and an enrichment monitor (EM). Development of the FM is primarily the responsibility of Oak Ridge National Laboratory, and development of the EM is primarily the responsibility of Los Alamos National Laboratory.

The FM will measure ^{235}U mass flow rate by combining information from measuring the UF_6 volumetric flow rate and the ^{235}U density. The UF_6 flow rate will be measured using characteristics of the process pumps used in product and tail UF_6 header process lines of many GCEPs, and the ^{235}U density will be measured using commercially available sodium iodide (NaI) gamma ray scintillation detectors. This report describes the calibration of the portion of the FM that measures the ^{235}U density. Research has been performed to define a methodology and collect data necessary to perform this calibration without the need for plant declarations.

The ^{235}U density detector is a commercially available system (GammaRad made by Amptek, www.amptek.com) that contains the NaI crystal, photomultiplier tube, signal conditioning electronics, and a multichannel analyzer (MCA).

Measurements were made with the detector system installed near four ^{235}U sources. Two of the sources were made of solid uranium, and the other two were in the form of UF_6 gas in aluminum piping. One of the UF_6 gas sources was located at ORNL and the other at LANL. The ORNL source consisted of two pipe sections (schedule 40 aluminum pipe of 4" and 8" outside diameter) with 5.36% ^{235}U enrichment, and the LANL source was a 4" schedule 40 aluminum pipe with 3.3% ^{235}U enrichment.

The configurations of the detector on these test sources, as well as on long straight pipe configurations expected to exist at GCEPs, were modeled using the computer code MCNP. The results of the MCNP calculations were used to define geometric correction factors between the test source and the GCEP application. Using these geometric correction factors, the experimental 186 keV counts in the test geometry were extrapolated to the expected GCEP geometry, and calibration curves were developed.

A unique method to analyze the measurement was also developed that separated the detector spectrum into the five detectable decay gamma rays emitted by ^{235}U in the 120 to 200 keV energy range. This analysis facilitated the assignment of a consistent value for the detector counts originating from ^{235}U decays at 186 keV. This value is also more accurate because it includes the counts from gamma energies other than 186 keV, which results in increased counting statistics for the same measurement time.

The 186 keV counts expected as a function of pressure and enrichment are presented in the body of this report. The main result of this research is a calibration factor for 4" and 8" schedule 40 aluminum pipes. For 4" pipes, the ^{235}U density is 0.62 ^{235}U g/m^3 per each measured 186 keV count. For 8" pipes, the ^{235}U density is 1.51 ^{235}U g/m^3 per each measured 186 keV count. Using the measured 186 keV counts and the constant volumetric flow rate of the pipes, this calibration factor provides the mass flow rate in terms of grams of ^{235}U per hour.

1.0 INTRODUCTION

This report is organized as outlined below.

1.0	A brief overview and introduction to the subject
2.0	Experimental arrangement used for performing the detector calibration, a detailed description of the ORNL gamma ray detector, and a description of the UF_6 sources used
3.0–4.0	Measurement results obtained from UF_6 sources at ORNL and LANL and the data analysis that uses the multi-peak methodology for resolving correctly the dominant 186 keV peak resulting from the ^{235}U decay
5.0	Monte Carlo modeling and the need to extend the model to long pipes that are extensively used for commercial GCEP cascade headers
6.0	How the FM could be used at a GCEP
7.0	Future plans and conclusions
Appendix	Input files for the MCNP computer code

1.2 BACKGROUND

Numerous countries are in the process of building new nuclear power plants, or have indicated imminent plans to build them. In the United States, all of the currently operating nuclear power plants began construction in the 1970s. However, in recent years the Nuclear Regulatory Commission has received approximately 30 applications for combined Construction and Operating Licenses (COLs) to build nuclear power plants.

Prior to the recent planned expansion of nuclear power, there have been adequate sources to supply the enriched uranium for nuclear power plants. These sources included diffusion plants in the U.S. and Russia, gaseous centrifuge facilities in Europe and Russia, and a significant contribution from the blending down of weapons-grade sources in Russia and the U.S. Approximately half of the fuel used in U.S. nuclear power plants currently originates from material previously produced for Russian nuclear weapons.

The expected increased demand for nuclear fuel, combined with the eventual depletion of the current supply of down-blended weapons-source material, has led to a scenario where new sources of enriched uranium for fuel will be needed. As a result, a number of countries have announced plans, or are currently building, gaseous centrifuge enrichment plants (GCEPs) to supply this material.

GCEPs have the potential to produce uranium at enrichments above the level necessary for nuclear fuel purposes—enrichments that make the uranium potentially usable for nuclear weapons. As a result, there is a critical need to monitor these facilities to ensure that nuclear material is not inappropriately enriched or diverted for unintended use.

Most countries in the world have signed the Nonproliferation Treaty (NPT) [India and Pakistan being notable exceptions], which contains an agreement that the country permits the International Atomic Energy Agency (IAEA) to inspect its nuclear facilities to confirm that safeguards commitments are being met. The current nuclear facility inspection methods were developed approximately 30 years ago and depend heavily on frequent on-site visits by IAEA inspectors. The methods, particularly for enrichment facilities, were not originally intended for facilities of the size (~< 3,000 t-SWU/year) currently being planned and/or built. If existing inspection methods are applied to new enrichment facilities, the results from the inspections are likely to be unwieldy, expensive, and inaccurate. Therefore, new instrumentation is urgently needed to increase the accuracy of the verification measurements as well as decrease the frequency needed for inspections.

Significant advances have been made in instrument capability since the current IAEA inspection methods were developed. In numerous cases, advances in instrumentation have been made in other fields that have the potential, with modest development, to be applied in safeguards applications at enrichment facilities. This report describes research performed for one of these instruments, which is designed to measure the ^{235}U flow in a GCEP.

1.3 FLOW MEASUREMENT CONCEPT

A particular example of the advances made in instrument capability is a flow and enrichment monitor (FEMO).[1] The FEMO is a conceptual instrument capable of continuously measuring, unattended, the enrichment and mass flow of ^{235}U in pipes at a GCEP, and consequently increase the probability that the potential production of HEU and/or diversion of significant quantity of fissile material will be detected. The FEMO requires no piping penetrations and can be installed on the outside of piping containing the flow of uranium hexafluoride (UF_6) at the facility. The planned location would be on all headers containing UF_6 entering and exiting the cascade halls.

The FEMO is being developed jointly by Oak Ridge National Laboratory (ORNL) and Los Alamos National Laboratory (LANL). The FEMO contains two parts: a flow monitor (FM) and an enrichment monitor (EM), integrated into a single device. Development, of the FM is primarily the responsibility of ORNL, and development of the EM is primarily the responsibility of LANL. The enrichment measuring instrument will not be addressed further in this report.

The proposed ORNL ^{235}U mass FM will measure ^{235}U mass flow rate by taking advantage of the type of process pumps used in many GCEPs. The main principle of this novel FM is based on the operational characteristics of process pumps (or compressors) that are often used in the product and tail UF_6 header process lines of a typical GCEP, as schematically shown in Fig. 1. It is well known in vacuum technology that the volumetric gas flow rate of these pumps is directly related to their power consumption and rotating frequency. Depending on the pump performance characteristics, this relationship might be complex and may depend on the properties of the gas in the flow. However, if the pump performance characteristics are known based on its power consumption and rotational frequency, a correlation can be developed to monitor the gas volumetric flow rate, dV/dt (also called pumping speed), expressed in m^3/h in nearly real time, with time constant of a few seconds.

To complete the proposed FM measurements, the second key parameter needed is the ^{235}U density (i.e., ^{235}U kg/m^3), ρ (^{235}U), in the UF_6 flow so that the ^{235}U mass flow rate (i.e., ^{235}U kg/h), Q, can be estimated by multiplying these two parameters as follows:

$$Q\left({}^{235}U \ \frac{kg}{hour} \right) = \rho\left({}^{235}U \ \frac{kg}{m^3} \right) \times \frac{dV}{dt}\left(\frac{m^3}{hour} \right) \tag{1}$$

Fig. 2 illustrates schematically the ^{235}U mass FM concept. The key components are indicated for the ^{235}U density measuring gamma ray detector and the instruments to detect the pump power consumption and the rotating frequency.

The ^{235}U density can be obtained by measuring the gamma ray scintillations because the count rate from the various characteristic gamma rays emitted by ^{235}U decay is related to the density of ^{235}U. In this work, the primary objective is to present details of the methodology used to obtain the calibration factors

[1] Gunning, J. E. et al., "FEMO: A Flow and Enrichment Monitor for Verifying Compliance with International Safeguards Requirements at a Gas Centrifuge Enrichment Facility," *Proceedings of the 8th International Conference on Facility Operations – Safeguards Interface*. Portland, Oregon, March 30–April 4th, 2008.

from the ^{235}U gamma ray measurements. The goal of this research effort is to develop two correlation databases, the volumetric pumping speed and the ^{235}U density. With these data, the proposed mass FM will be able to be calibrated independently of GCEP operator's declarations.

This R&D work could support IAEA advanced safeguards innovative technology initiatives to improve independent plant declarations. The safeguards instrument could be used to detect unauthorized enriched uranium production with possible components to include the ^{235}U mass flow monitor on the GCEP cascade header product piping for unattended continuous real-time independent monitoring. When the FM is ready to be implemented in a GCEP, the possible locations for installation will be on all headers transporting product and tails from the cascade halls for an effective safeguards application.

The primary purpose of this report is to present and document the calibration results of the ORNL ^{235}U density measuring detector system and describe how to extend the results to the FEMO/FM for the safeguards applications at GCEPs.

2.0 EXPERIMENTAL ARRANGEMENT

One of the key components of the ^{235}U mass flow monitor is a detector and associated equipment to measure the density of ^{235}U. This equipment provides the ^{235}U density, ρ (kg/m^3), shown in Equation 1. The density measuring detector consists of a commercially available 3” deep by 3” diameter sodium iodide (NaI) gamma ray scintillation crystal and associated electronics. As discussed later, the ^{235}U density measuring equipment is characterized using UF_6 sources with known gas pressure and enrichment to obtain the calibration factors that relate the detector counts to the ^{235}U density.

2.1 NAI DETECTOR SYSTEM FOR ^{235}U DENSITY MEASUREMENTS

The detector (see Fig. 3) is a commercially available system (GammaRad made by Amptek, www.amptek.com) that contains the NaI crystal, photomultiplier tube, signal conditioning electronics, and multichannel analyzer (MCA). The details of the detector components as well as the dimensions are shown in Fig. 4. This rugged, integrated, portable, gamma ray spectrometer system also includes the necessary power supply for the detector. Amptek also provides the GammaRad software (called ADMCA) to control the detector settings and data acquisition and collection on a computer. The computer communication is achieved with an Ethernet connection using cable of up to a 100-m long. The detector system is built to withstand mechanical shock and environmental vibrations. The details and other related operational and performance characteristics of this detector system are available at the Amptek website.

The detector’s NaI crystal is radially surrounded with a lead shield 0.2” thick and 5” long, as shown in Fig. 3, to reduce the background coming from outside the UF_6 pipe where the detector is installed. The face of the NaI crystal is recessed approximately 0.5” from the edge of the shield. The lead shield is painted (off-white), in accordance with ORNL policy, to prevent the spread of lead contamination during handling.

2.2 UF_6 TEST SOURCES AND DETECTOR ARRANGEMENTS

The detector characterization performed to obtain the ^{235}U density calibration was achieved using two independent UF_6 test sources: a pipe section with two different diameters (Figure 4a) connected to the UF_6 flow loop at ORNL (Fig. 5) and a contained UF_6 source at LANL. The characteristics of these sources are given in Table 1.

As shown in Fig. 5, and illustrated in Fig. 6 for details, the ORNL UF_6 source consists of a 12” long pipe section of 8” OD pipe mated on a 4” OD pipe section. Two identical detectors were placed on the 8” and 4” sections of the source and simultaneous measurements made on both the pipe sections. In Fig. 7, the ORNL UF_6 source is shown inside a hood that contains the UF_6 flow loop with associated pumping and valve control systems. The detectors were connected to a laptop (see Fig. 7) for detector control and data acquisition through an Ethernet switch (Linksys). In addition, an external 5-VDC (100mA) power supply was used to provide power to the detectors. As shown in Fig. 5 and Fig. 7, the detectors were wrapped in plastic to minimize the possibility of their becoming contaminated.

Fig. 8 and Fig. 9 show the details of the LANL UF_6 test source, the installed ORNL detector, the UF_6 source cylinders, the control valves, and the UF_6 pressure gauge. The UF_6 pipe temperature was also monitored using a sensor attached to the pipe as shown in the figure. The rest of the experimental arrangement was similar to the one used on the ORNL test source.

In addition to the UF_6 sources, measurements were also made using two solid sources, a foil and a uranium coating inside a fission chamber. The data from these sources were used in developing the spectral analysis method that provides an improved accuracy in differentiating the ^{235}U counts from the background counts.

3.0 MEASUREMENT RESULTS

Table 2 summarizes the experimental conditions, which include

1. Three different geometries with low-pressure UF_6 gas inside an aluminum pipe:
    a. An 8” pipe with 5.36% enriched UF_6,
    b. A 4” pipe with 5.36% enriched UF_6, and
    c. A 4” pipe with 3.3% enriched UF_6.
2. A solid HEU foil.
3. A solid fission chamber containing about 2 grams of HEU coated in an aluminum enclosure.

The measured spectra and corresponding room backgrounds for these measurements are shown in Table 11 through Table 25. The tables contain the spectra expressed in total number of measured counts per channel. The first line in the tables contains the measurement live time; counts per second are obtained by dividing the channel counts by the live time. The tables also contain the energy calibration constants to convert channel number to energy in keV.

Fig. 10 through Fig. 20 show the spectra for these measurements in the range 130 to 250 keV. These figures show the spectral decomposition described in the next section. The data for these figures have the room background removed, so they represent only the UF_6 contribution to the spectra. Once removed, the background only has the effect of increasing the statistical error of the measurements. Significantly long measurement times were chosen so that the measured spectra were well converged, even in the presence of the room background.

Note that the fission chamber of Case 15 in Table 2 was previously irradiated in a reactor, and it contains accumulated fission products. The 661 keV Cs-137 peak is readily apparent in the spectra, as seen in Fig. 21.

4.0 ANALYSIS OF MEASURED SPECTRA USING THE ^{235}U SPECTRAL FIT METHOD

The count rate from the detector measuring the characteristic gamma rays emitted by ^{235}U is proportional to the ^{235}U density inside the pipe.

Fig. 22 shows a typical spectrum from uranium hexafluoride (UF_6) in an aluminum pipe. For this particular example, the room background has been removed, and only the UF_6 component of the spectra is shown. The most prominent peak is at 186 keV, but there are others. The 186 keV count rates are used widely in safeguards applications to identify the presence of ^{235}U and to contribute to quantifying the density and/or enrichment. The common method is to measure the 186 keV count rate by defining a region of interest (ROI) within the measured spectrum and draw a straight line (or possibly other, more complex functions) from the left point of the ROI to the right point. Everything under the line is considered "background," and everything above it is considered "186 counts" and related to the ^{235}U density. Unfortunately, this commonly used method may yield inconsistent results because every user may pick a different ROI. In addition, not everything under the line is necessarily background; therefore, valuable information may be thrown out through employing this approach. Fig. 23 illustrates the problem when two different users select two different ROIs. Obviously inconsistent results would be obtained in that example.

An improved model for the ^{235}U spectra is needed to obtain consistent results that are independent of the user. Consistency is mandatory if count rates are calibrated based on either a priori computer calculations or calibration measurements.

The approach taken by our research is to fit the spectra to a model using the known ^{235}U spectral lines. This method provides the following benefits: (1) consistency, because the user is removed from any subjective decision; and (2) increased precision, because more gamma ray counts are used to define the count rate, which reduces the variance of the measurement.

Uranium-235 has a large number of spectral lines; however, only a few are of relevance to the final spectrum model. Table 3 shows the peak energies and relative yields for the most relevant spectral lines with energy greater than 130 keV. For energies lower than 130 keV, ^{235}U has spectral lines (most notably 109.18 keV with 1.5% yield) and a number of X-ray lines for U and Th between 80 and 100 keV (Thorium X-rays are produced as a consequence of the U alpha decay).

Modeling the X-ray region of the spectrum was judged to be beyond the scope of this work because the X-ray response varies and, most importantly, depends on the sample geometry. Uranium X-rays are emitted by fluorescence, where the exciting energy sources are the ^{235}U gamma rays. The probability of generating a gamma ray is proportional to the ^{235}U density, and the probability of fluorescence depends on the total U density; therefore, the X-ray intensity is proportional to the U density square, and the enrichment level plays a role. The actual X-ray intensity depends on the product of the total U density times the ^{235}U density. In addition, the geometry plays a role. A thin foil where the gamma rays have a large probability of escaping without interacting with the U electrons will have a smaller X-ray intensity than a sphere.

Furthermore, at lower energies, pipe attenuation plays a more important role. However, at energies between 130 and 200 keV, the change in attenuation from an aluminum pipe at different energies is small. Table 4 shows the effect of the pipe attenuation on the different ^{235}U spectral lines. The numbers on this table represent the relative amplitudes that would be measured by a detector placed outside the pipe for each energy peak. The 186 keV peak is used as a reference. We observe that for normal aluminum pipes (up to schedule 40), the relative attenuation of the spectral lines is essentially negligible. By this we mean that the attenuation at 143 keV is essentially the same as at 186 keV. Only for very thick pipes (schedule

80) is the attenuation significant enough to require model adjustments. This conclusion applies to aluminum pipes, which are commonly used in GCEPs. The attenuation for steel pipes would be significantly larger and the effect would need to be considered in the model.

Radiation detectors identify the energy of the incoming gamma ray by counting the photons generated by the gamma ray interaction with the electrons in a crystal (e.g., sodium iodide, or NaI). Typically, thousands of photons are generated and counted per each MeV of incoming gamma ray energy. However, not all the gamma rays deposit all their energy inside the crystal. One effect is known as Compton scattering, where the gamma ray interacts with a single electron and scatters outside of the crystal. Other gamma rays have multiple scatterings and deposit only part of their energy, while the majority of the gamma rays (for good detectors) deposit all of their energy inside the crystal on what is known as the "photopeak." The physics of Compton scattering are well known, and the maximum energy a gamma ray can deposit on a single electron interaction is known as the Compton edge energy, which is ~80 keV for a 186 keV gamma. Thus, Compton scattering affects only the low energy part of the spectrum (below ~80 keV). Multiple scatterings, however, can and do affect the spectrum up to the energy of the incoming gamma ray.

For the above reasons, our proposed model covers only energies down to ~130 keV, where the X-ray effects, aluminum pipe thickness, and Compton scattering can be neglected.

The proposed model includes two terms for each of the spectral lines, one term for the photo-peak, and a second term for the multiple scattering component. The photopeak is represented by a Gaussian distribution, G(E), centered at the peak energy and with a standard deviation (related to the full width half max, FWHM) that depends on energy and other measurement variables, such as room temperature. The function $G_p(E)$ for the spectral line at energy E_p is normalized to have an integral of 1.0, and it can be represented mathematically by the following equation.

$$G_p(E) = \frac{\Delta E}{\sigma_p \sqrt{2\pi}} e^{\left(-\frac{(E-E_p)^2}{2\sigma_p^2}\right)} \tag{2}$$

Note that the typical Gaussian distribution is normalized so that its integral is 1.0 and does not contain the ΔE term; however, this integral applies to probability density functions. In our case, the spectrum measurements, at each energy, have already been integrated over the energy bin, which is ΔE wide. Therefore, a factor of ΔE is required so the parameter A (see Eq. 4) is directly related to the 186 keV counts.

The multiple scattering component is observed in measurements as an increase of counts for energies lower than the peak energy. The amplitude of this contribution is geometry and detector dependent. For our model, we used a constant contribution for energies lower than the peak energy, which tapers down to zero using a cumulative Gaussian distribution with the same standard deviation as $G_p(E)$, the photo-peak function. The multiple scattering term, $MS_p(E)$, for the spectral line at energy E_p can be described mathematically as

$$MS_p(E) = 1 - C\left(\frac{E - E_p}{\sigma_p}\right) \tag{3}$$

The cumulative Gaussian distribution, C(e), does not have a simple closed mathematical form, but it can be approximated by the following function `FM2_pdfGaussCum()`:

```
// Returns the cumulative of a Gaussian normal distribution pdf value
// Normalized so the integral is 1.0
// Adapted from http://finance.bi.no/~bernt/gcc_prog/
float FM2_pdfGaussCum(float E, float meanE, float sdE) {
  static double b1 =  0.31938153;
  static double b2 = -0.356563782;
  static double b3 =  1.781477937;
  static double b4 = -1.821255978;
  static double b5 =  1.330274429;
  static double p  =  0.2316419;
  static double c2 =  0.3989423;
  double z, a, t, b, n;

  z = (E-meanE)/sdE;
  if (z >  6.0) { return 1.0; }; // this guards against overflow
  if (z < -6.0) { return 0.0; };

  a = fabs(z);
  t = 1.0/(1.0+a*p);
  b = c2*exp((-z)*(z/2.0));
  n = ((((b5*t+b4)*t+b3)*t+b2)*t+b1)*t;
  n = 1.0-b*n;
  if ( z < 0.0 ) n = 1.0 - n;
  return (float)n;
}
```

The final model for the spectrum, S(E), is a combination of: (1) a constant room background, B, (2) the photopeak, and (3) the multiple scattering contribution for each of the relevant ^{235}U spectral lines. Only one amplitude is used for all the spectral lines. The amplitude is normalized to the 186 keV peak, and the amplitudes of the other peaks are scaled according to their known relative yields, Y_p, (see Table 3).

$$S(E) = B + \sum_{p=1}^{N_{peaks}} \frac{Y_p}{Y_{186}} \left(A \times G_p(E) + C \times MS_p(E) \right) \tag{4}$$

The model is compared against the measured spectrum, and the parameters A, B, and C are adjusted to minimize the error between measurement and model. Note that the same amplitude values, A and C, apply to all spectral line peaks and are scaled by the known yield factors.

In addition to the parameters A, B, and C, the algorithm adjusts the following parameters:

1. The energy of the 186 and 143 keV peaks. Basically, calibration factors are found to convert MCA channel number to energy using these two peaks.
2. The σ (FWHM) of the 186 and 143 keV peak. The σ of the other three peaks is interpolated from these two values based on their energy because those peaks are not observable directly.

The parameters A, B, and C are linear and a linear least squares method can be used to obtain the optimal values if a simple matrix is inverted. The peak energy and width are non-linear and the optimal values are obtained through a parametric search by sequentially adjusting the non-linear parameters while adjusting the linear ones until a minimum is found.

The result of this process is illustrated graphically in Fig. 10 through Fig. 21. As observed, excellent agreement is obtained for all cases, which include low, medium and high UF_6 pressures for different aluminum pipe geometries as well as solid uranium samples with different geometries.

For the particular condition of Case 15, the irradiated fission chamber, a true background cannot be measured and removed from the signal, because the Cs is embedded in the uranium sample. The Cs contamination introduces mainly a 661 keV peak, but also a significant contribution in the 186 keV range due to Compton scattering (see Fig. 21). We observe that the algorithm automatically increases the room background term, B, to compensate for the presence of the Cs background, and the fit to the uranium peaks is excellent. The increase in the B term is clearly observable in Fig. 20 (the fission chamber case) when compared to Fig. 10 through Fig. 18 (the UF_6 cases). Fig. 19 (the HEU foil) also shows a small B background, indicating that the HEU foil has some decay product contamination that has built over the years. Note that this background is not included in the 186 keV counts estimate.

We conclude that the proposed uranium spectrum model is applicable to a wide range of conditions and can be used to calibrate the proposed flow monitor without requiring the use of plant declarations.

In the model, the amplitude term, A, represents the counts under the 186 keV Gaussian or bell-shape component of the spectrum. The model, however, includes the multiple scattering components of the detector signal in the parameter C. Even though the C counts, strictly speaking, are not part of the photopeak and should not be considered part of the 186 keV counts, we proposed to include the multiple scattering detector counts that fall inside the Gaussian bell shape. Since at the peak energy, the multiple scattering counts are equal to C/2, we add to the 186 counts in the model a Gaussian with the same σ and this amplitude. This results in the following formula for the 186 keV counts.

$$186\,keV\ counts = A + C \times \sigma_{186}\sqrt{\frac{\pi}{2}} \tag{5}$$

This definition of 186 keV counts is somewhat arbitrary, but consistent. By using this methodology, user judgments (e.g., ROI selection) are removed from the equation. Given a spectrum, this algorithm always reports the same number for 186 keV counts. By adding the multiple scattering contribution, the reported counts have the same order of magnitude obtained using an ROI approach.

Table 5 summarizes the measured 186 keV counts per second for all the different conditions.

A significant advantage of this algorithm is its ability to track changes in energy resolution caused by temperature changes. The energy resolution [σ in our model for $G_p(E)$] of NaI detectors is known to be dependent on both energy and temperature. When the temperature changes, σ also changes. An advantage of our model over the conventional ROI technique is that when σ and the effective peak energy change, the model detects this and adjusts the fit. Essentially, the model adjusts the ROIs adaptively to account for all the 186 keV counts. With the conventional ROI technique, as the temperature changes, some of the 186 keV counts leak outside the area and the measured counts change. For measurements that require high sensitivity, NaI detectors using the conventional ROI technique have been described as "very expensive temperature sensors," because the measurement can vary significantly with temperature.

Our proposed technique is self adaptive with temperature. This effect is illustrated in Fig. 24, which shows two measurements of UF_6 in an Al pipe, but at different temperatures, 26°C and 32°C (note that these are the internal temperatures of the NaI detector housing; the room temperature is ~4°C colder). The amplifier gain was maintained constant for both measurements. The counts per second have been normalized to show the relative effects of temperature; these two measurements are at two different UF_6 pressures and pipe geometries. We observe that, at the colder temperature, the peak MCA channel shifts to a higher value. The fitting algorithm adjusts automatically and obtains the Gaussian and multiple-scattering functions that best represent the data. After recalibration, each MCA channel number represents a particular energy in keV, and both measurements would show the 143 and 186 keV peaks at the same correct energies. However, the σ term (i.e., the FWHM) changes by about 1% from 7.90 keV at 29°C to 8.05 keV at 18°C. The σ change in terms of MCA channels is more pronounced, and any method that relies on fixed ROI channels would have some degree of error introduced when the temperature changes. Our proposed methodology captures these changes automatically and accounts for them.

We must note that for most applications, the MCA fine gain is adjusted to maintain the centroid of a reference peak at a constant MCA channel; therefore, for most applications, the spectra would not drift as shown in Fig. 24. However, the resulting fine gain changes affect the high voltage applied to the photomultiplier tube, which affects its resolution and has an impact on the resulting σ (FWHM). Our proposed methodology automatically adjusts for these changes in σ.

This methodology will be used to estimate the ^{235}U density for FEMO fissile-mass-flow measurements.

5.0 MONTE CARLO (MCNP) MODELING AND COMPARISON TO THE EXPERIMENTAL ARRANGEMENT

5.1 MCNP MODEL

The results from the UF6 source and detector arrangement installed at a specific GCEP need to be able to be easily predicted prior to installation. To this end, models of the source and detector arrangement used for the measurements at ORNL and LANL were created using the Monte Carlo computer code MCNP5. The results for the model were compared to the results obtained from experiments, and correction factors were obtained that could be applied to model GCEP configurations, thus allowing the measurement results made at a GCEP to be predicted. (The appendix to this report provides three of the input files for the MCNP computer code that modeled the configurations described here.)

A 3D depiction of the geometry model used in the MCNP model for the ORNL UF_6 flow loop is provided in Fig. 27. The smaller, more or less vertical cylinders represent the two NaI detectors, and the horizontal cylinders represent the 8” diameter and 4” diameter sections of the test section in the UF_6 flow loop. Pipes at a GCEP typically range from 4” to 8”, and thus these pipe sizes are appropriate representations for a GCEP configuration.

The detectors were modeled using representative densities for the NaI detectors and associated lead shielding that surrounds the detectors.

The pipes containing the UF_6 were modeled to reflect the appropriate thickness and diameter of aluminum pipe. The adjacent 4” and 8” pipes reflect an available previously configured component that was used in the experiment at ORNL.

The UF_6 source in the pipes was modeled to reflect counts from radiation emitted by ^{235}U at a density that corresponds to UF_6 at pressures of 27.0, 35.1, and 45.7 Torr, which reflected the pressures in the ORNL UF_6 flow loop during the experiment.

MCNP calculates the probability that a given event (decay gamma) has a specific interaction (is counted in the detector). Therefore, to obtain the total counts in a detector, the probability of the event needs to be multiplied by the number of events that the MCNP model uses to represent the source. The equations that relate the predicted counts rate in the detector to the ^{235}U source are below.

$C = A_{tot} * P_t$	MCNP count rate	(6)
$A_{tot} = n * M_f * N_A * \frac{\ln 2}{t_{1/2}}$	Total ^{235}U source activity in the UF_6	(7)
$\frac{M_f * 235}{M_f * 235 + (1 - M_f) * 238} \approx E$	^{235}U molar fraction, M_f	(8)
$n = \frac{PV}{RT}$	Number of moles, ideal gas law	(9)

Where:

C	calculated count rate in the detector
A_{tot}	activity of the 186 kev component of ^{235}U in the UF_6 source
P_t	probability of a single ^{235}U 186 kev decay event tallying as a 186 keV count in the simulated detector
n	number of moles of UF_6 in the source,
M_f	molar fraction of ^{235}U in the UF_6
N_A	Avogadro's number
$t_{1/2}$	half life of ^{235}U
E	enrichment of ^{235}U (by weight percent) of the U in the UF_6
P	pressure of the UF_6 gas
V	volume seen by the detector
R	ideal gas constant
T	temperature of the UF_6

Equation 8, an approximation of the enrichment appropriate for uranium containing primarily ^{235}U and ^{238}U, was solved iteratively for M_f using Microsoft Excel. If the uranium in the GCEP originates from reprocessed fuel, additional isotopes of uranium need to be included.

MCNP models were then made of 4" and 8" diameter pipes, but with lengths of 4 meters. GCEPs contain pipe lengths that are effectively "infinitely" long. Computer run time of the MCNP model increases rapidly as the source strength increases, and the 4 meter length effectively represented an infinitely long pipe in the MCNP model.

5.2 COMPARISON OF MCNP MODEL WITH EXPERIMENT

The predictions of the MCNP models and the experimental results are presented in Table 6.

MCNP5 models of the configurations at ORNL and LANL give predictions that exceed the measurements by approximately 40% for the 4" pipes, and approximately 20% for the 8" pipe at ORNL. The model was consistent in that it predicted similar overestimates for experiments on similar size pipes at both ORNL and LANL.

The over-prediction of the MCNP model is believed to be caused primarily by tallying all interactions that occur in the NaI crystal, whereas in the actual experiment, some of the incoming gamma rays undergo a single scatter (Compton scattering) or multiple scattering in the NaI crystal, but then exit the crystal. These events frequently create a scintillation, but at a lower intensity that shows up as an event at a lower energy that is outside the 186 keV region of interest.

As can be seen in Table 26, the model for the detector placed adjacent to 4" diameter section tallied considerably more counts than the model for an infinitely long 4" section. This is expected because many of the gammas from the adjacent 8" section model "leaked" into the detector adjacent to the 4" diameter section.

The model tallied fewer counts for the detector adjacent to the 8" diameter section than when the detector is adjacent to an infinitely long pipe. This is to be expected because the infinitely long 8" pipe source provides a larger source than the modeled sections of adjacent 4" and 8" pipes.

The ratio of the count rates predicted by the models of the "infinitely" long pipes and the test section models were calculated to determine a calibration factor to be applied to the experimental data for the corresponding configuration. The result is the predicted count rate from the detector subjected to corresponding conditions at a GCEP.

5.3 EVALUATION OF MCNP MODELS AND EXPERIMENTS

The primary result from the analyses in Sect. 4.0 is the ratio of the counts predicted by MCNP in the experimental setup to the counts predicted by MCNP for the geometry of a typical GCEP header. Using these ratios, the experimental results can be extrapolated to obtain a calibration that will be independent of facility declarations.

The "infinite pipe" correction factor is the ratio between the counts from the MCNP model for the measured geometry and the GCEP geometry. Table 6 shows these correction factors for the three geometries where UF_6 measurements were performed. As seen in Table 6, an MCNP model of an infinite 8" pipe will result in 113% of the counts that were calculated for the MCNP model of the 8" ORNL UF_6 loop. This is because the 8" section used in the ORNL loop has a limited length, and the modeled detector field of view would effectively see 13% more UF_6 in an infinite pipe.

For the case of the 4" ORNL UF_6 loop, the situation is changed, and the MCNP model of an infinite 4" pipe will see only 79% of the counts calculated for the MCNP model of the 4" ORNL UF_6 loop. The 4" detector in the ORNL loop model had part of the 8" pipe in its detector field of view; thus, it was tallying more counts that it would in a limited-length 4" pipe.

For the case of the 4" LANL UF_6 loop, the detector was located 8" from the left end of the 4" diameter pipe. MCNP models calculate that if UF_6 was located to the left of this end (to represent a long header pipe), the detector would receive 108% of the measured counts.

Table 7 through Table 9 summarize the analysis for all configurations that were measured. In these tables, the 186 keV counts per second are normalized to the appropriate pressure and enrichment. MCNP infinite pipe corrections are applied to account for the different experimental geometries. The results are shown in the right two columns. As observed in these tables, when properly normalized, all measurements at different pressures, enrichments and geometry show consistent results. These consistent results are summarized in Table 10. For a schedule 40 aluminum pipe of 4" OD (1 Torr, 1% enrichment, room temperature [25°C]), a count rate of 0.186 counts per second is expected. The counts scale linearly with pressure and enrichment. For example, at 4 Torr and 4.95% enrichment, a count rate of 3.68 cps is expected. For a schedule 40 aluminum pipe of 8" OD, the calibration factor is 0.453 cps at 1 Torr and 1% enrichment at 25°C. In an 8" pipe at 4 Torr and 4.95% enrichment, a count rate of 8.97 cps is expected. These results are shown graphically in Fig. 25.

Table 10 also shows the calibration factor in terms of grams of ^{235}U per m^3 in the pipe. This is just a units conversion from the previous factor, but these units are more useful for the flow monitor and are independent of temperature. The last two columns show the expected counts per second given a ^{235}U concentration in the pipe, or the ^{235}U concentration given a measured count rate.

As an example, if a count rate of 1.0 net 186 keV cps is measured in an 8" pipe, it can be inferred that the concentration of ^{235}U is 0.282 g/m^3. If the constant displacement pumps deliver 3,000 m^3/h, the total ^{235}U mass flow rate is the product of the two: 846 ^{235}U g/h. The UF_6 pressure, enrichment, and temperature play no role in the final calculation because their effects are incorporated in the ^{235}U concentration correlation. These results are shown graphically in Fig. 26.

The main result of this research is a calibration factor for 4" and 8" schedule 40 aluminum pipes. For 4" pipes, the ^{235}U density is 0.69 ^{235}U g/m^3 per each measured 186 keV count. For 8" pipes, the ^{235}U density is 0.282 ^{235}U g/m^3 per each measured 186 keV count. Using the measured 186 keV counts and the constant volumetric flow rate of the pipes, this calibration factor provides the mass flow rate in terms of grams of ^{235}U per hour.

6.0 APPLICATION FOR GCEP MASS FLOW MEASUREMENTS

Figure 28 illustrates schematically a FEMO/FM installed on a typical GCEP cascade product header showing the location of the ^{235}U density meter and the pump power monitor. The FM measurements entered in Equation 6 provide an immediate and continuous measure of the ^{235}U mass flow rate of the product.

A similar installation could also be made on the tails header (see Fig. 28). With the FM installed on all the GCEP outgoing headers, a ^{235}U material balance can be continuously monitored, in real time, and in unattended fashion. This objective is one of IAEA's main goals for implementing effective safeguards so that the likelihood of diversion of fissile material is minimized.

7.0 FUTURE RESEARCH PLANS AND CONCLUSION

This report addresses only the ^{235}U density meter calibration. In order to successfully complete the FM development that should occur prior to demonstration at a GCEP, the second key parameter (see Equation 6 and Fig. 2) that comes from the cascade pump needs to be evaluated to obtain the volumetric gas flow rate through the pump. This flow rate will be based on pump specifications and energy use and will be independent of plant declarations. To accomplish this next step, ORNL is creating an air flow testbed that uses pumps similar to, but smaller than, those used (see Fig. 29) in a typical GCEP. The results of the study will be presented in a separate report in the near future once the testbed is installed and the tests are completed.

In conclusion, the ^{235}U density correlations with gamma ray measurements can contribute to accurate monitoring of the ^{235}U mass flow in GCEPs.

The overall goal of this research is to generate reference data that may be used to calibrate instruments, which use existing technology to continuously monitor ^{235}U mass flow rate by detecting ^{235}U decay gammas and monitoring in real time the power consumption of a UF_6 pumps on GCEP headers.

This research effort supports IAEA safeguards initiatives by providing tools that can make measurements independent of GCEP operator's declarations.

Table 1. UF_6 test source characteristics

Site	Test Source Pipe Size (Aluminum, schedule 40)	UF_6 Enrichment (%)	UF_6 Pressure (Torr)	UF_6 Temperature
ORNL	4” and 8” (see Fig. 5)	5.35	26–45	64°F
LANL	4” (see Fig. 8)	3.3	1–60	84°F

Table 2. Summary of experimental conditions

Case #	Location	Enrich-ment	Press (Torr)	NDA Unit	Comments
1	LANL		< 1	0	Background for Cases 2–4
2	LANL	3.3%	59.2	0	UF_6
3	LANL	3.3%	38.8	0	UF_6
4	LANL	3.3%	19.0	0	UF_6
5	ORNL 8”		< 1	0	Background for Cases 6–8
6	ORNL 8”	5.35%	45.3	0	UF_6
7	ORNL 8”	5.35%	36.0	0	UF_6
8	ORNL 8”	5.35%	26.7	0	UF_6
9	ORNL 4”		< 1	1	Background for Cases 10–12
10	ORNL 4”	5.35%	45.3	1	UF_6
11	ORNL 4”	5.35%	36.0	1	UF_6
12	ORNL 4”	5.35%	26.7	1	UF_6
13	ORNL			1	Background for Cases 14–15
14	ORNL	99%	Solid	1	HEU Foil (< 1 g)
15	ORNL	99%	Solid	1	HEU fission chamber (~2 g) with Cs contamination

Table 3. Peak energy and relative yield of the five relevant ^{235}U spectral lines

Peak Energy (keV)	Yield (%)
143.76	10.96
163.33	5.08
185.72	57.20
202.11	1.08
205.31	5.01

Table 4. Effect of Al pipe thickness on relative yields of ^{235}U spectral lines

Peak Energy (keV)	Relative Yield as Function of Aluminum Pipe Dimension					
	Without Pipe	NPS 4”		NPS 8”		
		Schedule 40	Schedule 80	Schedule 20	Schedule 40	Schedule 80
143.76	19.16%	18.72%	18.53%	18.69%	18.56%	18.23%
163.33	8.88%	8.78%	8.74%	8.77%	8.74%	8.67%
185.72	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
202.11	1.89%	1.90%	1.91%	1.91%	1.91%	1.92%
205.31	8.76%	8.83%	8.86%	8.84%	8.86%	8.91%

Table 5. Measured 186 keV counts per second

Case #	Location	Enrich-ment	Press (Torr)	NDA Unit	186 keV counts per second
1	LANL		< 1	0	
2	LANL	3.3%	59.2	0	34.14 ± 0.01
3	LANL	3.3%	38.8	0	22.17 ± 0.00
4	LANL	3.3%	19.0	0	10.25 ± 0.00
5	ORNL 8”		< 1	0	
6	ORNL 8”	5.35%	45.3	0	100.63 ± 0.02
7	ORNL 8”	5.35%	36.0	0	80.00 ± 0.01
8	ORNL 8”	5.35%	26.7	0	56.88 ± 0.01
9	ORNL 4”		< 1	1	
10	ORNL 4”	5.35%	45.3	1	57.19 ± 0.01
11	ORNL 4”	5.35%	36.0	1	46.69 ± 0.01
12	ORNL 4”	5.35%	26.7	1	33.80 ± 0.00
13	ORNL			0	
14	ORNL	99%	NA	0	2455.63 ± 25.39
15	ORNL	99%	NA	0	1637.87 ± 10.00

Table 6. Infinite pipe correction factors calculated by MCNP

cps from geometry	Multiply times	To get cps in this geometry
8” ORNL UF_6 loop	1.13	8” infinite pipe
4” ORNL UF_6 loop	0.79	4” infinite pipe
4” LANL UF_6 loop	1.08	4” infinite pipe

Table 7. Calibration calculations for 8” ORNL UF_6 loop

Enrichment	5.35%			
Infinite Pipe MCNP Correction	1.13			
Temp (C)	19.00			
Density (@1 Torr)	0.01934	UF_6 kg/m3	0.699	U^{235} g/m3
P (Torr)	**cps**	**cps/Torr/E**	**Inf Pipe cps/Torr/E (@25°C)**	**Inf Pipe cps/ (U^{235}g/ m3)**
26.7	56.88	0.40	0.44	3.44
36.0	80.00	0.42	0.46	3.59
45.3	100.63	0.42	0.46	3.59
	Avg	0.410	0.453	3.540

Table 8. Calibration calculations for 4" ORNL UF6 loop

Enrichment	5.35%			
Infinite Pipe MCNP Correction	0.79			
Temp (C)	19.00			
Density (@1 Torr)	0.01934	UF6 kg/m3	0.699	U^{235} g/m3
P (Torr)	**cps**	**cps/Torr/E**	**Inf Pipe cps/Torr/E (@25°C)**	**Inf Pipe cps/ (U^{235}g/ m3)**
26.7	33.80	0.24	0.18	1.43
36.0	46.69	0.24	0.19	1.47
45.3	57.19	0.24	0.18	1.43
	Avg	0.238	0.184	1.440

Table 9. Calibration calculations for 4" LANL UF_6 loop

Enrichment	3.30%			
Infinite Pipe MCNP Correction	1.08			
Temp (C)	29.00			
Density (@1 Torr)	0.0187	UF_6 kg/m3	0.417	U^{235} g/m3
P (Torr)	**cps**	**cps/Torr/E**	**Inf Pipe cps/Torr/E (@25°C)**	**Inf Pipe cps/ (U^{235}g/ m3)**
19.00	10.25	0.16	0.18	1.40
38.82	22.17	0.17	0.19	1.48
59.17	34.14	0.17	0.19	1.49
	Avg	0.170	0.187	1.456

Table 10. Calibration results for schedule 40 Al pipe (effective infinite length)

Pipe OD (Schedule 40)	**186 keV cps per Torr at 1% enrichment at 25°C**	**186 keV cps per g/m^3 of ^{235}U in the pipe**	**g/m^3 of ^{235}U per 186 keV cps**
4"	0.186	1.448	0.690
8"	0.453	3.540	0.282

Table 11. Case 1: LANL background for cases 2–4

	Measurement Time (s) =		57354.4			E (keV) =	1.36	*ch	-12.93					
ch: 1-50	**51-100**	**101-150**	**151-200**	**201-50**	**251-300**	**301-350**	**351-400**	**401-450**	**451-500**	**501-550**	**551-600**	**601-650**	**651-700**	**701-750**
0	61599	29864	22893	15532	11939	9492	8285	7555	7456	4990	5234	3959	3629	3670
0	70691	29871	22431	15544	11866	9684	8529	7414	7385	4947	5181	3922	3754	3766
0	78688	29313	22358	15152	11900	9621	8189	7436	7453	4992	5326	3928	3562	3684
0	84981	28820	21714	15089	11921	9431	8225	7322	7279	4900	5264	3909	3550	3677
0	88201	28715	21398	14954	11861	9483	8231	7347	7298	4823	5266	3909	3606	3782
0	86718	28669	21188	14913	11791	9484	8284	7224	7167	4818	5179	3907	3707	3810
0	81758	28525	20570	14632	11978	9383	8159	7098	7259	4924	5356	3832	3544	3831
0	75888	28330	20362	14509	11807	9421	8369	7041	7255	4928	5250	3780	3598	3827
0	69911	28192	20206	14588	11874	9402	8224	7045	7097	4826	5379	3841	3691	3820
0	65525	27946	20137	14462	11905	9213	8211	6897	7071	4917	5249	3688	3697	3901
0	64048	28164	19870	14304	11975	9203	8256	6967	6959	4851	5323	3647	3745	3901
0	63894	27753	19667	14013	11719	9151	8277	6957	6997	4905	5371	3896	3711	3914
0	64794	27695	19394	14175	12058	9100	8337	6937	6805	4887	5436	3658	3830	3992
0	64612	27507	19436	14086	11813	9211	8145	6917	6773	4930	5453	3676	3746	3988
0	64695	27561	19433	13939	11813	9176	8189	6904	6693	4874	5436	3689	3713	3987
0	64211	27257	19187	13800	12079	9010	8140	6869	6469	4796	5511	3680	3748	4093
0	63273	26983	18958	13879	11708	9175	8161	6919	6689	4739	5356	3632	3802	4096
0	62918	26709	19010	13919	11751	9058	8331	6872	6549	4737	5366	3527	3807	4107
0	64136	26772	18720	13864	11540	9077	8347	6967	6267	4734	5506	3696	3806	4150
0	66737	26204	18986	13817	11681	9045	8337	6901	6138	4839	5252	3579	3706	4215
11866	70843	26304	18552	13636	11486	9057	8197	6903	6205	4806	5355	3651	3722	4234
13991	76905	25937	18312	13613	11603	9092	8298	7035	6176	4832	5475	3526	3814	4264
14952	83814	25819	18492	13707	11479	8957	8534	7080	6095	4799	5392	3448	3757	4216
15507	92490	25475	18198	13486	11479	8904	8424	7023	5920	4889	5308	3665	3825	4444
16518	100482	25598	18159	13354	11094	9041	8393	7004	5881	4688	5200	3565	3720	4462
17605	106153	25213	18091	13431	11100	8837	8433	7011	5773	4768	5220	3581	3779	4378
18758	109475	24946	17957	13394	11177	8882	8515	7089	5646	4839	5250	3658	3678	4375
19719	108946	24709	17832	13491	11216	8735	8665	6990	5679	4715	5159	3525	3730	4418
21004	103113	24664	18120	13321	10861	8905	8603	7072	5634	4757	5175	3601	3681	4410
21564	94340	24596	17958	13146	10889	8838	8510	7217	5490	4925	5127	3536	3764	4391
21786	84281	24238	17928	13415	10853	8655	8672	7270	5331	4829	4996	3475	3628	4472
21286	72138	24140	17732	12877	10601	8688	8700	7095	5492	4859	4945	3499	3836	4461
20130	62028	24166	17614	12982	10492	8736	8784	7210	5427	4948	4905	3553	3752	4542
19382	53272	23672	17672	12891	10279	8675	8542	7163	5347	4795	4895	3561	3835	4464
19396	46723	23551	17527	12965	10298	8612	8560	7338	5208	4895	4804	3530	3708	4502
19773	42292	23678	17581	12835	10172	8691	8570	7311	5354	4842	4776	3606	3749	4515
20515	39234	23728	17303	12543	10333	8592	8616	7284	5176	4912	4575	3610	3672	4407
21505	38266	23949	17108	12512	10217	8530	8459	7469	5249	4937	4544	3510	3682	4452
22362	37352	23748	17052	12626	10023	8599	8580	7357	5240	4967	4531	3581	3763	4538
23767	37177	24006	16965	12435	9906	8504	8463	7414	5141	4906	4497	3368	3679	4327
24810	36930	24191	16935	12428	9900	8443	8268	7354	5125	4911	4453	3505	3684	4267
25944	36719	24397	16598	12242	9841	8355	8319	7498	5198	4956	4301	3505	3558	4276
27549	36571	24335	16721	12135	9828	8448	8492	7368	5146	4938	4268	3455	3668	4276
29634	35525	24440	16318	12224	9725	8649	8262	7517	4962	5001	4341	3501	3703	4228
32065	34472	24357	16383	12117	9713	8371	8010	7386	5164	5132	4249	3502	3651	4139
35090	33762	24281	16348	12280	9796	8393	8021	7327	5052	5087	4307	3567	3608	4189
38130	32959	24388	16369	11977	9846	8478	8054	7430	5052	5049	4263	3599	3570	4083
41913	31541	23989	15950	12111	9742	8406	7915	7388	4937	5083	4046	3585	3707	3955
47376	30829	23480	15953	12094	9698	8414	7744	7450	5029	4998	4049	3559	3688	3817
53531	30413	23322	15778	12139	9616	8345	7689	7479	5017	5322	3943	3611	3657	3802

Table 12. Raw spectra counts. Case 2: LANL loop condition P60

	Measurement Time (s) =		16767.2		E (keV) =		1.36	*ch	-12.93					
ch: 1-50	**51-100**	**101-150**	**151-200**	**201-50**	**251-300**	**301-350**	**351-400**	**401-450**	**451-500**	**501-550**	**551-600**	**601-650**	**651-700**	**701-750**
0	21501	14761	36446	4658	3490	2690	2386	2221	2178	1475	1552	1149	1039	1114
0	23906	14406	33212	4512	3431	2827	2368	2246	2129	1511	1462	1208	1039	1084
0	26258	14339	29429	4523	3457	2769	2440	2089	2206	1431	1570	1137	1008	1082
0	28244	14302	26449	4494	3579	2789	2516	2199	2149	1473	1565	1152	1032	1040
0	29169	14597	22884	4455	3456	2737	2367	2138	2175	1416	1514	1093	1044	1118
0	29306	14486	20103	4415	3483	2733	2351	2060	2196	1377	1556	1154	1098	1072
0	28279	15246	17907	4318	3440	2799	2409	2092	2187	1477	1554	1070	1034	1051
0	27029	15741	15578	4265	3571	2708	2366	2072	2111	1474	1501	1184	1100	1087
0	26261	16689	14016	4285	3462	2785	2455	2028	2104	1478	1548	1119	1096	1074
0	26103	17469	12786	4363	3424	2661	2431	2057	2109	1444	1513	1073	1114	1103
0	26584	18414	11626	4251	3514	2761	2399	2080	2054	1402	1553	1098	1042	1121
0	27594	19328	10707	4192	3393	2693	2350	1979	2070	1482	1623	1069	1036	1112
0	28409	20427	10031	4186	3519	2697	2370	2028	2094	1469	1540	1111	1034	1164
0	28756	21255	9328	4161	3459	2673	2396	2073	1929	1442	1553	1062	1092	1144
0	28603	21867	8930	4128	3473	2646	2393	2077	1927	1444	1534	1057	1117	1145
0	28344	21503	8359	4165	3439	2762	2378	2053	1924	1401	1527	1063	1043	1092
0	27794	21170	7890	4111	3346	2716	2495	2085	1923	1363	1525	1049	1062	1189
0	27630	20428	7583	4125	3524	2632	2390	2090	1880	1477	1603	1076	1077	1171
0	28129	19337	7146	4165	3386	2577	2428	1954	1830	1386	1529	1114	1091	1173
0	29158	18722	6833	4148	3409	2732	2315	2043	1881	1352	1571	1069	1122	1238
4544	31009	17808	6637	3935	3359	2641	2375	2007	1822	1366	1543	1066	1063	1153
5550	32789	16779	6176	3982	3322	2591	2459	2074	1751	1394	1560	1030	1144	1202
5798	35459	16438	6225	3988	3469	2603	2401	2046	1802	1417	1518	1047	1098	1169
6059	38489	15746	5849	3931	3327	2600	2428	1998	1683	1419	1496	1076	1092	1241
6239	41300	15513	5692	4015	3356	2510	2471	1987	1673	1436	1550	1041	1128	1272
6351	43457	15627	5609	3937	3349	2668	2506	2072	1691	1417	1510	1033	1045	1271
6623	44883	15537	5492	3947	3296	2558	2536	1974	1680	1435	1499	1092	1046	1230
6960	43944	15389	5563	3973	3204	2600	2465	2084	1706	1378	1490	1030	1089	1195
7290	42488	15431	5531	3973	3135	2587	2374	2061	1606	1384	1441	1076	1085	1205
7551	38923	15599	5319	3920	3154	2521	2512	2024	1553	1384	1491	1030	1103	1252
7641	34815	15871	5274	3887	3127	2467	2497	2043	1616	1456	1470	1000	1055	1259
7473	30556	16026	5262	3969	3141	2468	2559	2078	1647	1429	1462	1031	1130	1284
7390	27080	16618	5242	3884	3118	2473	2607	2049	1604	1441	1378	1030	1061	1283
7195	24228	17246	5360	3870	3038	2575	2532	2065	1550	1402	1391	1053	1095	1338
7440	21969	17995	5361	3786	3075	2500	2531	2078	1565	1411	1439	1055	1057	1327
7836	20890	19485	5175	3817	3090	2549	2502	2180	1538	1463	1316	1032	1105	1358
7810	20207	21482	5222	3767	3024	2518	2537	2134	1473	1484	1345	1090	1081	1273
8575	19738	24133	5195	3653	3008	2449	2556	2135	1504	1439	1295	992	1061	1295
9147	19826	27136	5260	3701	2962	2504	2505	2105	1520	1495	1309	1014	1054	1287
9485	19889	30454	5151	3699	2923	2454	2531	2109	1555	1428	1308	1066	1120	1320
9834	19288	34387	5074	3633	2797	2514	2344	2248	1455	1430	1343	1000	1040	1261
10468	18970	38047	5050	3686	2923	2491	2517	2211	1443	1436	1302	1061	1104	1265
11425	18600	40969	4892	3664	2997	2415	2422	2156	1502	1478	1266	1054	1092	1370
12355	17946	43710	4919	3481	2865	2479	2361	2081	1450	1447	1278	1010	1030	1230
13397	17404	45575	5023	3588	2896	2482	2332	2099	1517	1518	1228	1067	1049	1217
14568	16678	46281	4857	3608	2850	2563	2400	2120	1474	1588	1235	1004	1053	1213
15667	15996	45747	4868	3584	2835	2437	2285	2109	1496	1469	1232	1011	1021	1215
16785	15648	44957	4736	3461	2879	2462	2288	2046	1433	1464	1147	1012	1057	1191
18253	15317	42279	4685	3579	2792	2443	2284	2182	1436	1556	1231	1039	1069	1124
19667	15073	40160	4630	3612	2810	2448	2266	2263	1452	1456	1212	1002	1100	1171

Table 13. Raw spectra counts. Case 3: LANL loop condition P40

	Measurement Time (s) =		57735.1		E (keV) =			1.35	*ch	-13.18				
ch: 1-50	**51-100**	**101-150**	**151-200**	**201-50**	**251-300**	**301-350**	**351-400**	**401-450**	**451-500**	**501-550**	**551-600**	**601-650**	**651-700**	**701-750**
0	69624	43444	89789	15688	11916	9779	8531	7812	7460	4905	5139	4051	3563	3681
0	77259	43022	82170	15780	11942	9665	8297	7568	7338	4998	5208	3992	3681	3646
0	85398	42065	73769	15557	12127	9559	8399	7555	7432	4966	5107	3965	3647	3765
0	92352	42553	65966	15476	11902	9581	8396	7406	7301	4972	5146	3979	3599	3684
0	95233	42657	58338	15354	12039	9571	8367	7460	7217	4887	5331	3935	3651	3806
0	95861	43155	52213	15177	12008	9535	8409	7252	7206	5020	5245	3919	3670	3929
0	92401	43628	46911	15178	12200	9374	8460	7261	7144	4946	5321	3894	3602	3678
0	87404	45625	42391	14993	12007	9500	8437	7294	7243	4987	5391	3901	3587	3829
0	83485	46943	38785	14881	12293	9472	8351	7176	7262	5018	5478	4034	3703	3862
0	81872	49002	35466	14673	12176	9232	8355	7147	7204	5128	5373	3888	3586	3929
0	81174	51455	33089	14660	12033	9238	8185	7021	7050	5075	5312	3778	3729	3801
0	83045	53374	31116	14225	11906	9306	8237	7206	7027	4812	5388	3717	3633	3927
0	84823	55417	29335	14270	12065	9157	8331	7049	6806	4736	5463	3827	3660	3826
0	86478	56924	27691	14180	11957	9198	8310	7066	6951	4825	5445	3813	3793	3944
0	86107	57319	26882	14174	12127	9133	8276	6982	6811	4871	5332	3703	3746	3830
0	84617	57379	25496	14155	12033	9210	8221	7046	6606	4926	5481	3739	3852	4035
0	83213	56454	24503	14371	11905	9211	8116	7121	6750	4854	5385	3729	3750	3994
0	82738	55211	23325	14097	11930	9141	8262	7153	6514	4890	5366	3705	3775	4056
0	84105	53424	22501	14033	11854	8968	8323	6964	6345	4873	5468	3732	3880	4108
0	86327	51158	21877	13798	11875	9134	8278	7061	6304	4794	5449	3534	3825	4216
13958	92151	49054	21232	14182	11652	8952	8406	6875	6237	4872	5392	3626	3798	4249
17089	99657	47056	20628	13790	11597	9043	8503	6982	6116	4736	5361	3637	3847	4336
18260	107836	45110	20150	13789	11526	9017	8437	6932	6054	4824	5256	3634	3776	4208
18749	117359	44011	19758	13679	11559	8835	8684	7010	6124	4703	5345	3651	3692	4369
19385	125924	43945	19231	13753	11399	8832	8614	6990	5918	4836	5299	3538	3836	4352
20045	133343	43411	18973	13735	11447	8813	8511	6979	5869	4882	5132	3574	3766	4379
21124	136833	43511	18667	13747	11254	8857	8408	7094	5841	4656	5231	3585	3773	4448
22209	135210	42987	18716	13560	11027	8747	8430	7035	5743	5022	5090	3578	3710	4371
23763	130475	43368	18201	13439	10952	8679	8515	7210	5725	4883	5072	3570	3697	4498
24312	118850	43630	18311	13567	10866	8922	8584	7096	5568	4878	5110	3722	3671	4515
24711	107071	44173	18269	13121	10829	8820	8735	7318	5572	4817	4923	3537	3743	4510
24260	94422	44147	18403	13360	10905	8772	8667	7182	5369	4862	4892	3473	3747	4534
23535	81934	45583	18099	13152	10731	8712	8711	7021	5372	4960	5027	3563	3826	4486
23005	72276	46800	18152	13105	10834	8877	8793	7205	5390	4984	4949	3517	3627	4395
23157	66002	48889	17801	12976	10379	8716	8625	7295	5243	4869	4816	3456	3695	4395
23672	61098	52114	17998	12976	10216	8667	8653	7471	5203	4838	4773	3494	3651	4384
24987	59194	56931	17812	13002	10281	8758	8556	7298	5210	4901	4765	3553	3794	4542
26435	57701	62520	17517	12780	10238	8760	8586	7448	4972	5039	4610	3593	3766	4415
27734	57246	69197	17745	12673	10230	8730	8533	7351	5224	5034	4663	3471	3644	4508
29541	57153	76524	17646	12555	10277	8555	8443	7312	5229	4877	4553	3564	3659	4274
30941	56190	84544	17064	12632	10043	8511	8433	7418	5073	5015	4594	3467	3685	4348
32298	55252	92283	17428	12549	9959	8504	8423	7441	5204	5089	4397	3447	3768	4333
34873	54192	100549	16875	12339	9934	8535	8334	7330	5133	5092	4397	3569	3669	4365
37624	52668	105091	16911	12347	9746	8581	8329	7401	5049	5017	4424	3529	3804	4321
41034	51113	109874	16635	12372	9785	8403	8336	7437	5197	4970	4325	3639	3654	4243
44616	49678	111338	16418	12142	10023	8511	8194	7433	5120	5146	4377	3649	3620	4156
48156	47809	110931	16367	12283	9782	8453	8050	7589	5040	5205	4272	3505	3718	4159
51798	46214	108548	16272	12059	9587	8554	8048	7540	4995	5252	4064	3627	3655	3965
56965	44937	103757	16035	12214	9781	8350	7967	7399	5035	5295	4019	3584	3705	3912
62198	43737	96944	15854	12252	9700	8379	7757	7209	5097	5230	4010	3596	3605	3965

Table 14. Raw spectra counts. Case 4: LANL loop condition P20

	Measurement Time (s) =		15883.2			E (keV) =	1.36	*ch	-13.21					
ch: 1-50	**51-100**	**101-150**	**151-200**	**201-50**	**251-300**	**301-350**	**351-400**	**401-450**	**451-500**	**501-550**	**551-600**	**601-650**	**651-700**	**701-750**
0	18248	9972	14402	4246	3263	2681	2221	1991	2072	1357	1481	1131	1006	1033
0	20334	9841	13318	4278	3367	2665	2226	2063	2044	1364	1456	1149	1006	1068
0	22660	9747	12338	4107	3195	2666	2250	2061	2053	1418	1457	1094	1020	990
0	24185	9619	11296	4207	3299	2592	2270	2053	1988	1400	1465	1083	993	1097
0	25441	9878	10413	4264	3303	2592	2268	2015	2027	1318	1472	1039	1032	1050
0	24990	9771	9529	4110	3368	2673	2340	2022	2056	1417	1452	1094	1019	1018
0	23734	9780	9057	4098	3325	2615	2342	1992	1961	1396	1459	1071	939	1098
0	22209	10071	8302	4054	3351	2514	2282	1980	2034	1346	1542	1032	999	1011
0	20579	10215	7989	4055	3312	2503	2295	1978	1977	1368	1486	1020	1042	1053
0	19894	10554	7465	4002	3298	2675	2303	2021	1861	1416	1491	1005	988	1074
0	19715	10949	7150	3964	3355	2543	2246	1928	1899	1313	1453	1070	983	1052
0	20079	10990	6807	3918	3340	2465	2231	1887	1846	1385	1484	1081	987	1032
0	20333	11151	6553	3905	3306	2645	2310	1863	1874	1264	1492	1062	981	1175
0	20264	11473	6136	3926	3262	2595	2312	1915	1936	1311	1501	1007	1060	1128
0	20226	11335	6233	3905	3354	2505	2234	1899	1833	1343	1600	974	1047	1113
0	20045	11447	5979	3800	3292	2525	2299	1897	1856	1361	1492	1032	1027	1110
0	19808	11099	5852	3711	3263	2509	2272	1856	1829	1355	1500	963	1052	1142
0	19416	10959	5766	3823	3172	2548	2320	1873	1764	1362	1527	1016	1016	1128
0	20073	10650	5716	3858	3138	2528	2245	1925	1682	1318	1536	940	1028	1154
0	20631	10504	5536	3853	3188	2623	2375	1958	1744	1297	1492	1027	1123	1192
3461	21864	10072	5480	3767	3186	2531	2338	1927	1728	1377	1497	979	1059	1094
4155	23792	9838	5295	3794	3104	2558	2293	1865	1713	1347	1478	1049	1008	1173
4476	25939	9666	5315	3826	3162	2395	2288	1979	1620	1314	1499	924	997	1177
4769	28642	9558	5127	3727	3178	2390	2360	1888	1644	1348	1474	1005	1026	1238
4904	31012	9428	5187	3733	3184	2425	2349	1963	1649	1387	1434	1054	1037	1220
5090	32558	9241	5092	3780	3079	2568	2349	1934	1595	1351	1467	992	1023	1256
5291	33497	9222	5049	3712	3139	2438	2305	1970	1562	1306	1419	987	1068	1239
5768	33072	9175	5034	3682	3001	2469	2379	1855	1503	1344	1446	985	1026	1208
6097	31641	9179	5086	3801	3004	2438	2390	1958	1596	1334	1382	962	1011	1224
6299	28878	9402	4915	3717	2980	2443	2425	1945	1477	1408	1358	1022	1024	1264
6287	25617	9419	4969	3633	3066	2481	2377	2001	1576	1396	1401	1025	995	1197
6280	22239	9125	4973	3588	2896	2411	2424	1987	1451	1331	1357	978	1060	1210
6056	19523	9285	5009	3572	2947	2288	2417	1912	1519	1297	1374	976	1008	1275
5671	17012	9488	4898	3515	3002	2399	2364	1998	1471	1327	1347	976	1023	1277
5741	14913	9849	4973	3650	2854	2473	2458	1947	1440	1387	1288	975	1015	1192
6054	13877	10246	4935	3624	2773	2373	2454	2025	1479	1355	1329	1003	1018	1238
6136	13244	10948	4829	3506	2823	2385	2342	2006	1437	1361	1240	937	1029	1275
6668	13171	11864	4862	3514	2803	2427	2324	2012	1483	1348	1255	989	1049	1212
6929	12729	12731	4697	3457	2827	2335	2324	2053	1483	1345	1211	969	1028	1241
7129	12816	13703	4729	3408	2799	2360	2382	2022	1398	1368	1273	1007	999	1199
7592	12666	14733	4619	3397	2810	2324	2153	2008	1436	1426	1198	961	1022	1177
8091	12524	15758	4504	3388	2830	2405	2269	2074	1432	1398	1172	932	1036	1131
8629	12292	16644	4582	3412	2679	2264	2274	1990	1365	1436	1190	944	957	1157
9271	11993	17262	4714	3361	2765	2421	2269	2063	1405	1410	1157	988	1024	1194
10068	11631	17745	4461	3257	2636	2338	2212	2107	1343	1378	1159	1000	1009	1125
10829	11338	18130	4642	3415	2677	2422	2282	1987	1413	1436	1147	996	1032	1197
11631	10980	17709	4596	3360	2727	2303	2190	2054	1396	1411	1154	964	989	1116
12969	10449	17212	4503	3324	2709	2302	2225	2030	1451	1446	1079	949	992	1049
14135	10501	16408	4304	3284	2727	2296	2131	2076	1341	1485	1100	1013	1014	1059
16000	10209	15571	4335	3405	2754	2296	2109	2060	1384	1445	1110	1031	1004	955

Table 15. Case 5. ORNL 8” Unit 0 background for cases 6–8

	Measurement Time (s) =		164246.9			E (keV) =	1.32	*ch	-13.5					
ch: 1-50	**51-100**	**101-150**	**151-200**	**201-50**	**251-300**	**301-350**	**351-400**	**401-450**	**451-500**	**501-550**	**551-600**	**601-650**	**651-700**	**701-750**
0	56941	85563	119039	39489	34377	26154	22611	18992	16561	35187	5982	5177	3263	3422
0	59999	84940	117170	39410	34026	26007	22389	18959	16594	36232	5831	5098	3298	3512
0	64134	83944	114527	38935	33686	25933	22200	18819	16303	37156	5728	4939	3352	3409
0	68788	83207	111885	38342	33354	25729	22227	18948	16546	38171	5577	4924	3193	3435
0	72606	83348	107180	38160	32951	25685	22063	18647	16669	38751	5543	4792	3337	3442
0	76643	82903	100995	37824	32769	25511	22253	18544	16443	39956	5394	4811	3244	3402
0	80256	82096	95185	38141	32315	25476	21619	18393	16478	40552	5368	4791	3274	3448
0	83889	82118	89690	37810	32025	25663	21441	18454	16492	41043	5332	4599	3248	3373
0	87155	82211	84182	37571	31820	25459	21621	18116	16381	41483	5356	4512	3327	3371
0	91063	82720	78900	37270	31857	25325	21549	18091	16725	41599	5332	4492	3294	3333
0	96314	83261	73900	36332	31075	25250	21428	18048	16271	41908	5250	4334	3284	3312
0	103118	84208	69675	36580	31414	25548	21156	17937	16433	41668	5256	4373	3224	3350
0	110824	84850	66281	36500	31147	25204	21003	17818	16665	41763	5309	4294	3209	3398
0	118138	85917	63627	36187	31256	25500	20924	17483	16428	41432	5237	4340	3247	3309
0	124011	86816	61141	35914	30451	25198	20956	17642	16481	40567	5268	4143	3275	3382
0	129315	87880	58852	35615	30680	24945	20702	17329	16512	40500	5268	4231	3259	3332
0	131817	88994	57279	35879	30652	25236	20591	17326	16395	39690	5274	4123	3263	3333
0	133197	89493	55357	35590	30213	25104	20410	17342	16562	38579	5342	4116	3335	3362
0	134435	88845	54134	35309	30122	25056	20352	17227	16548	37533	5437	4020	3316	3289
0	135880	88944	53188	35489	30137	24905	20322	17068	16556	36037	5346	3950	3257	3352
19397	138962	88455	51873	35587	29983	24920	19987	17261	16799	34835	5425	4007	3257	3416
22783	141705	87281	50541	35153	29793	24867	19947	16857	16612	33501	5457	3808	3286	3316
24032	144584	86023	49866	35237	29882	24688	19802	16838	16846	31888	5332	3833	3339	3365
24426	146516	84681	49143	35027	29743	24506	19694	16659	16908	30794	5452	3795	3172	3317
25200	145668	83411	48446	35143	29584	24804	20032	16916	16947	28982	5506	3729	3349	3410
25836	144304	81639	47235	34947	29406	24474	19777	16870	16990	27395	5414	3717	3289	3509
25556	141431	80594	46763	35280	29174	24827	19720	16842	17300	26164	5439	3720	3298	3436
26374	137480	80217	45962	34839	29114	24691	19618	16771	17555	24392	5595	3651	3297	3513
26349	133999	80080	45524	35300	29407	24362	19568	16640	17691	22938	5462	3605	3366	3417
27403	128983	79336	45227	34995	29073	24491	19584	16482	18096	21592	5584	3568	3374	3517
27905	123829	79313	44854	34851	28949	24176	19381	16419	18325	19918	5623	3467	3415	3564
28154	118794	79097	44156	34969	28772	24129	19279	16416	18497	18744	5563	3516	3308	3528
28306	113896	79349	43848	34965	28508	24043	19493	16459	19040	17448	5493	3473	3296	3579
28757	108703	78752	43499	35031	28406	23921	19395	16283	19517	16206	5639	3479	3268	3543
29318	104180	79114	43568	35002	28151	23916	19629	16639	20112	14848	5541	3478	3387	3748
30166	100138	79269	43332	35236	27982	23663	19438	16525	20582	13759	5558	3381	3414	3727
31524	96866	79655	42856	35152	27900	23684	19600	16445	21288	12737	5672	3371	3401	3711
32643	94673	80448	42967	35159	27757	23787	19630	16454	21799	11879	5568	3397	3453	3677
34317	93938	80481	42726	35737	27526	23362	19466	16584	22467	11128	5502	3412	3358	3884
35559	93450	82889	42891	35424	27260	23412	19445	16415	23446	10353	5456	3385	3413	3784
36956	92719	84726	42450	35418	27128	23569	19452	16430	24332	9658	5583	3403	3415	3978
37992	93179	88171	42133	35494	27118	23321	19274	16520	25114	9037	5494	3436	3300	3937
39059	92728	91621	41332	35591	27100	23286	19383	16668	26179	8416	5371	3321	3367	3985
40177	92660	95958	41501	35222	26712	23242	19373	16378	27147	7965	5475	3438	3388	4150
41807	91831	100697	41362	35299	26440	23293	19275	16624	28057	7567	5425	3376	3362	4114
44260	90838	105974	40942	35376	26469	22940	19302	16426	29438	7066	5399	3291	3395	4142
46884	89716	109713	40783	35021	26459	22683	19302	16500	30677	6753	5332	3282	3435	4219
49132	88439	113895	40219	35006	26191	22766	19230	16541	31679	6574	5341	3286	3450	4336
52226	87820	117422	40306	34651	26312	22577	19231	16412	32661	6177	5144	3296	3436	4363
54631	86577	118682	39621	34517	26171	22574	19136	16336	34084	6170	5220	3281	3478	4482

Table 16. Raw spectra counts. Case 6: ORNL 8” loop condition P47, Unit 0

Measurement Time (s) =			9530.9			E (keV) =	1.32	*ch	-13.5					
ch: 1-50	**51-100**	**101-150**	**151-200**	**201-50**	**251-300**	**301-350**	**351-400**	**401-450**	**451-500**	**501-550**	**551-600**	**601-650**	**651-700**	**701-750**
0	10151	15852	69769	2326	1903	1462	1193	1080	890	1840	368	330	192	197
0	10307	15143	68983	2290	1928	1520	1262	1105	905	1927	389	339	173	182
0	10197	14972	66905	2244	1862	1472	1281	1027	904	2037	303	253	187	178
0	10363	14659	63110	2276	1884	1410	1176	1028	884	1983	323	311	193	182
0	11033	14396	58580	2176	1921	1457	1198	952	911	2123	318	285	200	210
0	11271	14311	53244	2218	1814	1361	1226	1013	906	2126	329	251	195	188
0	12012	14413	47944	2149	1856	1395	1226	1024	941	2246	305	272	168	197
0	12844	14495	41767	2157	1777	1428	1200	1030	936	2218	305	279	201	209
0	13848	14932	36251	2177	1791	1426	1224	1029	883	2180	284	255	184	202
0	14874	15368	31306	2082	1777	1437	1160	1025	894	2233	308	258	188	182
0	16756	16441	26622	2184	1774	1442	1189	1032	967	2229	296	239	215	214
0	18344	17824	22821	2100	1776	1405	1172	960	912	2175	332	245	182	207
0	20193	18952	19507	2078	1736	1414	1172	1024	902	2211	304	249	174	204
0	21506	20543	17181	2048	1737	1450	1141	1028	921	2116	327	228	201	181
0	22996	22071	14957	2059	1703	1387	1144	904	934	2200	298	230	178	202
0	23370	23890	12878	2015	1743	1437	1149	941	934	2116	327	258	195	204
0	23753	25121	11629	2064	1750	1427	1199	914	922	2018	313	250	175	185
0	23651	26289	10275	2050	1723	1314	1098	937	962	2024	305	254	191	186
0	23487	26700	9272	2071	1723	1347	1141	952	929	1920	303	236	199	171
0	23420	26518	8538	2054	1707	1411	1175	895	921	1909	327	264	183	175
2758	23896	25978	7725	2029	1713	1328	1124	987	896	1842	320	231	189	200
3316	24263	24852	7023	2042	1573	1361	1080	971	933	1714	313	243	176	194
3386	25408	23570	6329	2084	1659	1399	1076	937	926	1610	321	225	211	193
3677	26091	22134	5664	2028	1599	1398	1076	953	921	1570	323	227	184	213
3569	27517	21035	5214	1974	1683	1327	1098	900	1009	1474	307	221	198	196
3529	28508	19849	4675	1996	1601	1373	1134	941	933	1455	309	199	190	200
3530	29150	18824	4130	2048	1698	1304	1098	932	949	1391	339	208	183	216
3471	29217	18288	4038	2066	1618	1357	1082	871	927	1265	331	226	196	188
3509	29242	18109	3482	2032	1623	1437	1088	917	972	1166	336	201	177	193
3766	28963	18170	3353	2010	1587	1297	1136	938	991	1096	310	191	175	196
3687	27822	18226	3129	1983	1607	1353	1070	891	992	1017	304	207	168	196
3832	26642	18448	2999	2006	1572	1332	1112	893	1059	997	325	189	177	202
3959	24791	18747	2819	2085	1611	1348	1151	878	1001	952	294	227	200	213
3963	23121	19225	2793	2075	1649	1301	1094	969	1052	855	319	211	190	208
4159	21728	19359	2696	2041	1614	1363	1090	909	1080	810	337	212	185	235
4407	21041	19798	2691	2018	1560	1228	1023	894	1083	733	343	197	208	204
4884	19983	20445	2666	2081	1596	1322	1055	908	1131	702	323	221	184	229
5099	20065	21653	2661	2024	1513	1291	1137	897	1190	696	313	191	193	219
5323	20157	22891	2528	2021	1586	1295	1042	920	1264	573	346	186	183	219
5698	20341	25119	2531	1925	1517	1256	1041	883	1270	531	346	187	199	218
5908	20501	28151	2441	2047	1563	1266	1080	867	1321	507	338	181	206	235
6205	20750	31701	2551	2083	1483	1278	1110	917	1392	469	321	174	210	227
6458	20638	36177	2446	1989	1528	1286	1053	883	1401	457	304	211	205	264
7029	20114	41496	2508	1964	1431	1346	1106	937	1435	432	326	212	190	254
7495	19639	47109	2497	1980	1535	1256	1148	965	1528	431	315	197	219	238
8344	19155	52739	2462	2026	1491	1296	1077	917	1489	428	308	188	187	226
9207	18028	58316	2355	1964	1465	1264	1082	912	1670	367	311	233	186	248
9762	17365	62925	2401	1944	1430	1276	1116	937	1687	376	272	187	217	241
10106	16671	66693	2414	1883	1458	1282	1021	930	1769	338	314	188	191	256
10266	16062	69043	2303	1909	1446	1249	1075	936	1826	327	300	200	194	256

Table 17. Raw spectra counts. Case 7: ORNL 8 in. loop condition P37, Unit 0

	Measurement Time (s) =		53950.2			E (keV) =	1.32	*ch	-13.74					
ch: 1-50	**51-100**	**101-150**	**151-200**	**201-50**	**251-300**	**301-350**	**351-400**	**401-450**	**451-500**	**501-550**	**551-600**	**601-650**	**651-700**	**701-750**
0	49623	76322	321415	12987	11119	8380	7135	5986	5231	10540	2000	1710	1092	1080
0	50347	74708	320129	12931	10892	8249	7128	6032	5271	11154	1890	1663	1095	1141
0	50089	73075	311920	12861	10977	8309	7054	6018	5283	11206	1867	1655	1108	1178
0	51287	71450	296087	12811	10753	8341	7124	5977	5252	11629	1796	1613	1064	1155
0	52924	70792	275942	12717	10565	8374	6944	5912	5237	11952	1784	1633	1130	1107
0	55504	69807	252414	12527	10508	8139	6906	5888	5218	12113	1697	1566	1080	1116
0	58821	70257	226135	12428	10212	8293	7024	6029	5166	12509	1703	1502	1082	1087
0	62199	69983	200643	12219	10278	8085	6872	5868	5248	12511	1759	1549	1091	1138
0	66831	72304	174411	12263	10104	8163	6770	5847	5273	12842	1713	1495	1032	1080
0	72093	74805	150926	12055	10184	8248	6725	5807	5258	12847	1711	1466	1040	1049
0	78679	78668	129840	11961	9931	8074	6810	5710	5236	12810	1750	1493	1027	1098
0	86626	84158	111424	12072	9978	8196	6746	5751	5243	12750	1659	1451	1091	1153
0	96350	89964	96036	11977	10075	7998	6806	5735	5220	12730	1707	1440	1028	1069
0	103764	97622	83277	11855	9888	8101	6755	5635	5402	12740	1753	1411	1061	1036
0	110091	105169	72814	11793	9874	7956	6507	5606	5330	12710	1770	1346	1116	1074
0	113576	112336	64409	11761	10025	8076	6583	5574	5383	12364	1781	1306	1071	1061
0	115039	118874	57130	11689	9853	8090	6465	5462	5248	12138	1730	1391	982	1076
0	114716	122732	51686	11376	9689	8145	6562	5632	5254	11971	1714	1329	1084	1020
0	113291	126078	47529	11661	9747	8075	6512	5561	5221	11594	1747	1316	1081	1063
0	112572	125918	43160	11482	9704	7977	6410	5386	5339	11283	1693	1349	1092	1038
13797	114480	124129	38936	11472	9752	7940	6252	5392	5273	10942	1725	1235	1080	1036
16621	117260	119038	35451	11559	9583	7860	6254	5406	5321	10417	1746	1288	1071	1117
17471	121555	114439	32475	11672	9692	7935	6428	5287	5283	10010	1716	1289	1126	1112
17948	126966	107601	29679	11655	9608	7919	6353	5305	5313	9474	1722	1227	1064	1100
18186	130943	101581	27224	11494	9366	7788	6225	5334	5366	9025	1779	1241	1057	1117
17811	135670	95882	24421	11539	9615	7737	6300	5332	5427	8711	1757	1181	1077	1181
17634	138310	91784	22752	11538	9415	7795	6241	5275	5445	8297	1795	1238	1044	1093
17803	139571	88975	21101	11382	9528	7971	6326	5108	5467	7716	1790	1207	1091	1130
17750	139614	87251	19389	11671	9552	7784	6340	5292	5614	7312	1753	1156	1120	1138
17966	137096	86230	18322	11619	9312	7761	6375	5277	5531	6878	1772	1214	1095	1099
18457	133100	87725	17181	11270	9336	7798	6187	5378	5752	6370	1825	1167	1112	1174
18696	126480	88036	16490	11543	9172	7637	6293	5347	5719	6030	1829	1133	1042	1207
19405	119354	89312	16043	11337	9147	7626	6202	5257	5806	5515	1869	1161	1144	1135
19969	111341	90523	15532	11405	8941	7558	6147	5219	6084	5178	1810	1161	1111	1202
20677	104968	92583	15062	11682	9100	7610	6101	5153	6160	4799	1861	1179	1067	1225
22104	99777	94130	14808	11659	8990	7453	6148	5249	6369	4452	1802	1160	1132	1181
23144	96610	96648	14851	11583	9032	7558	6134	5175	6559	4162	1792	1140	1090	1229
25351	95805	101538	14591	11522	8826	7568	6109	5234	6591	3865	1847	1141	1131	1232
26583	96518	107847	14390	11627	8831	7473	6164	5262	6897	3591	1836	1107	1123	1235
27756	97223	116897	14274	11648	8666	7483	6250	5300	7164	3517	1847	1094	1110	1266
29038	98708	128488	14376	11474	8640	7324	6161	5289	7415	3122	1818	1119	1083	1281
30056	98791	145259	14427	11447	8778	7477	6226	5232	7638	2981	1760	1052	1083	1249
31593	98768	165089	14141	11530	8714	7385	6119	5203	7936	2753	1848	1141	1151	1277
33686	96966	186975	13973	11521	8506	7310	6073	5307	8226	2602	1799	1104	1150	1343
36747	94629	212261	13923	11514	8582	7266	6132	5197	8644	2402	1780	1101	1153	1329
39623	91548	238007	13861	11193	8496	7305	6082	5247	8924	2280	1769	1030	1146	1344
43664	88256	264055	13522	11335	8424	7207	6097	5151	9294	2244	1716	1104	1106	1417
46590	84872	286641	13566	11178	8398	7252	6035	5199	9757	2139	1665	1113	1124	1368
48792	81447	305066	13388	11186	8339	7127	6132	5158	9952	2096	1748	1057	1135	1402
49353	79244	315804	13247	11125	8364	7208	6128	5214	10200	1951	1730	1043	1129	1456

Table 18. Raw spectra counts. Case 8: ORNL 8" loop condition P27, Unit 0

	Measurement Time (s) =		45497.3			E (keV) =	1.31	*ch	-13.93					
ch: 1-50	**51-100**	**101-150**	**151-200**	**201-50**	**251-300**	**301-350**	**351-400**	**401-450**	**451-500**	**501-550**	**551-600**	**601-650**	**651-700**	**701-750**
0	33011	53568	203243	10656	9189	6863	6047	4945	4368	7968	1726	1445	962	976
0	32959	51848	206337	10698	9093	6872	5803	4990	4314	8300	1655	1472	909	962
0	33122	50778	202953	10496	9079	6829	5775	5109	4325	8713	1624	1453	911	932
0	33956	50064	196458	10478	8896	6721	5856	5020	4358	8877	1561	1399	936	935
0	35234	49219	186156	10394	8836	6680	5835	5032	4407	9140	1599	1361	900	945
0	36857	48687	172255	10298	8701	6651	5614	4900	4414	9410	1557	1355	911	945
0	38720	48436	157480	10274	8695	6822	5798	5047	4359	9493	1487	1330	901	918
0	41462	48372	140558	10172	8623	6719	5652	4895	4436	9742	1521	1356	908	940
0	43605	49351	124336	10171	8510	6691	5770	4935	4343	9763	1489	1328	869	952
0	47564	50597	108687	9907	8368	6528	5708	4850	4334	10137	1463	1260	911	964
0	51728	52866	94104	9924	8434	6919	5530	4789	4254	10390	1454	1278	881	910
0	56976	55518	81134	9842	8270	6600	5557	4849	4323	10338	1416	1266	906	1006
0	62982	59550	70430	9802	8259	6611	5495	4746	4411	10446	1432	1253	943	940
0	68433	63383	60544	9563	8146	6649	5508	4612	4387	10477	1442	1285	897	960
0	72636	67732	53458	9676	8114	6613	5414	4691	4196	10441	1425	1219	893	904
0	75722	72941	47367	9445	7946	6670	5407	4730	4352	10300	1411	1152	855	875
0	76959	77336	42366	9376	8037	6520	5482	4692	4289	10109	1478	1169	868	893
0	76683	80769	38087	9506	7875	6518	5522	4672	4308	10206	1433	1155	883	938
0	75991	82531	34623	9502	7934	6587	5391	4637	4384	9901	1500	1130	933	886
0	75192	83678	31939	9525	7898	6568	5197	4597	4335	9809	1441	1163	888	931
9524	75528	83013	29175	9442	7952	6452	5188	4518	4419	9491	1419	1096	934	916
11365	77055	81181	26750	9323	7863	6384	5340	4522	4401	9298	1436	1110	928	908
12047	79141	77933	24769	9316	7978	6606	5178	4572	4303	8910	1478	1026	942	910
12413	82711	74090	22896	9343	7857	6533	5252	4500	4395	8646	1475	1080	867	916
12578	85081	70456	21043	9388	7781	6472	5171	4433	4333	8280	1440	1071	946	923
12508	87628	66559	19528	9416	7762	6419	5154	4377	4453	7897	1479	1066	884	908
11919	90680	63238	18224	9357	7887	6432	5243	4444	4333	7539	1517	1034	957	954
12328	91400	60953	16745	9523	7910	6374	5211	4519	4339	7148	1468	1007	857	898
12331	91609	59376	15423	9338	7711	6315	5136	4415	4491	6736	1474	1030	903	882
12597	91016	59115	14689	9174	7709	6243	5017	4492	4546	6333	1501	965	920	957
12770	88451	58738	14039	9392	7683	6252	5125	4445	4645	6101	1492	994	914	946
12997	84763	59099	13365	9360	7633	6273	5108	4296	4651	5601	1513	1007	909	948
13263	80410	59649	13117	9405	7567	6368	5051	4247	4703	5258	1496	962	940	947
13781	75469	60385	12795	9274	7385	6216	4995	4407	4762	4936	1520	968	898	917
14261	71657	61514	12554	9368	7456	6187	5077	4361	4805	4688	1535	991	880	949
14913	67681	62421	12107	9246	7476	6169	5130	4406	4998	4348	1489	970	928	979
15948	65531	63636	12100	9319	7342	6090	5165	4371	4962	4141	1572	908	879	979
16804	64248	65879	11888	9272	7323	6185	5141	4411	5138	3764	1493	971	936	992
18139	64648	68685	11630	9402	7302	6083	5011	4367	5312	3521	1539	910	989	1001
18837	65008	73774	11600	9313	7166	6135	4985	4403	5542	3253	1543	972	921	990
19686	66171	79874	11627	9595	7194	6019	5039	4381	5623	2965	1472	941	934	1056
20262	66588	88602	11607	9444	7150	5920	4959	4387	5749	2773	1552	945	946	1059
21056	66905	99877	11383	9404	7038	6153	5080	4378	5865	2622	1482	938	917	1018
22756	66550	112326	11275	9477	7008	6025	5098	4357	6103	2524	1478	913	921	1061
24110	64743	126429	11396	9401	6974	5996	5118	4412	6326	2273	1535	905	926	1068
26324	62582	142983	11144	9395	6822	5950	5175	4358	6788	2170	1530	944	947	1118
28499	60902	159544	11195	9401	6932	5985	5095	4289	6890	2062	1487	912	916	1076
30446	58723	174365	11134	9298	6998	6018	5072	4311	7061	1922	1477	961	953	1108
32097	57085	188749	10969	9358	6728	5910	5065	4247	7330	1937	1521	922	936	1105
32870	54796	197628	10842	9164	6786	5880	5195	4337	7584	1763	1470	916	911	1105

Table 19. Case 9: ORNL 4” Unit 1 background for cases 10–12

	Measurement Time (s) =		164229.8			E (keV) =	1.31	*ch	-13.59					
ch: 1-50	**51-100**	**101-150**	**151-200**	**201-50**	**251-300**	**301-350**	**351-400**	**401-450**	**451-500**	**501-550**	**551-600**	**601-650**	**651-700**	**701-750**
0	51745	86151	120061	36949	33513	23717	20440	16847	14137	27008	6083	5238	3258	3348
0	54187	85254	119977	37019	33343	23579	20109	16634	14258	27839	5781	5210	3283	3403
0	58119	83859	117774	36309	32982	23855	19959	16929	14294	28479	5653	5120	3232	3412
0	61854	82942	114996	36491	32762	23799	20079	16816	14392	29874	5482	5090	3237	3369
0	65600	82570	110493	36094	32162	23516	19691	16753	14090	30531	5493	4985	3204	3411
0	69851	82197	104659	35819	31756	23427	19966	16492	14087	31607	5294	5015	3241	3450
0	73423	81962	98229	35353	31301	23357	19519	16576	14347	32307	5379	5026	3298	3376
0	76116	81355	91802	35079	31201	23266	19565	16384	14199	33118	5199	4843	3272	3322
0	79394	81540	85778	34985	30681	23120	19355	16169	14341	33481	5150	4866	3264	3354
0	82864	81065	79505	34587	30287	23213	19469	16329	14164	34571	5273	4715	3283	3404
0	88096	81354	74423	34473	29890	23035	19087	16226	14144	34934	5077	4646	3176	3291
0	94286	82448	69868	34371	29643	23268	19211	16044	14388	35281	5068	4476	3305	3290
0	102501	82947	65522	34067	29254	23216	19016	15789	14041	35426	5159	4605	3142	3374
0	110087	83868	62417	34095	28902	22930	18777	15603	14258	35313	5149	4559	3262	3312
0	117197	85203	59745	33633	29164	22971	18744	15483	14277	35654	5096	4288	3162	3357
0	122835	86873	58034	34012	28696	23002	18510	15381	14022	35480	5155	4378	3252	3344
0	125598	88190	55462	33658	28621	22795	18394	15311	14230	35225	5151	4202	3222	3302
0	127277	88796	54034	33765	28250	22818	18296	15115	14208	34898	5181	4204	3144	3232
0	127796	89074	53081	33496	27807	22890	18070	15261	14221	34406	5157	4166	3269	3253
0	128471	89189	51563	32960	28217	22502	18227	15026	14220	33678	5339	4036	3203	3250
18520	130600	88354	50416	33042	28167	22605	18130	14881	14228	32974	5104	3901	3229	3363
22066	134355	88235	49564	33073	27820	22619	17872	14932	14212	31873	5189	3907	3210	3329
23187	138059	86480	48542	32830	27654	22432	17777	14779	13973	30737	5293	3950	3167	3283
24099	140470	84554	47325	32719	27503	22342	17650	14941	14048	29847	5253	3809	3253	3326
24510	140978	82917	46757	32883	27557	22731	17541	14547	14282	28567	5217	3827	3250	3234
24799	140080	81973	45672	32761	27486	22408	17545	14474	14368	27491	5248	3831	3225	3319
24889	136477	80572	44983	32694	27496	22062	17371	14467	14387	26257	5238	3667	3265	3211
25086	132743	79950	44029	32724	26974	22293	17444	14460	14311	25067	5471	3666	3227	3323
25478	129399	79234	43556	32646	26940	22162	17372	14360	14489	23564	5364	3631	3271	3333
26040	125771	79076	43006	32861	26813	22060	17489	14449	14881	22403	5302	3621	3248	3311
26155	121720	78830	42679	32420	26640	22129	17562	14311	14762	20970	5449	3531	3356	3451
26768	118042	78627	42351	32646	26427	22106	17168	14218	14980	19878	5360	3564	3254	3410
26653	112648	79102	41714	32661	26337	21798	17200	14485	15333	18507	5453	3601	3292	3404
26891	106444	78390	41572	33126	26267	21682	16993	14220	15692	17148	5369	3552	3338	3570
27781	102501	78923	40867	33253	25979	21655	17055	14191	15849	16263	5431	3472	3190	3509
28204	98234	78744	40988	33315	25757	21741	17241	14315	16084	14806	5368	3407	3284	3508
29635	94740	78218	40974	33288	25735	21386	17159	14205	16235	13928	5474	3414	3238	3495
30779	92924	78741	40573	33519	25460	21416	17026	14163	17053	12866	5479	3396	3344	3590
32347	91557	78668	40049	33875	25190	21415	17288	14109	17277	12100	5450	3378	3344	3645
33200	91808	80136	40367	33816	25135	21057	17119	14112	17735	11442	5443	3403	3302	3691
34281	91638	81114	40117	34254	25015	21097	17090	14023	18592	10249	5575	3310	3372	3605
35591	91565	82988	39747	34130	24797	21332	17163	14256	18916	9647	5580	3383	3291	3767
36037	92430	86196	39315	33796	24902	20928	16904	14258	19457	9095	5379	3266	3323	3730
37034	92095	90275	39678	33958	24517	20992	17060	14235	20333	8507	5486	3253	3430	3725
38518	92121	94795	39163	33979	24190	20807	17101	14146	21437	7969	5430	3336	3342	3851
40158	91071	99999	38860	34300	24108	20691	17022	14093	22210	7519	5337	3252	3340	3824
42109	90473	104986	38526	34070	24271	20599	17081	14313	23004	6967	5481	3286	3401	4020
44650	88994	110594	38072	33931	24207	20430	17062	14271	23830	6857	5249	3202	3363	4062
46576	88039	114776	37525	33806	23938	20533	16862	14283	24697	6534	5341	3162	3413	4045
48992	86884	117459	37393	34025	24168	20278	16869	14110	25852	6209	5282	3294	3326	4196

Table 20. Raw spectra counts. Case 10: ORNL 4” loop condition P47, Unit 1

	Measurement Time (s) =		9529.8			E (keV) =	1.31	*ch	-13.59					
ch: 1-50	**51-100**	**101-150**	**151-200**	**201-50**	**251-300**	**301-350**	**351-400**	**401-450**	**451-500**	**501-550**	**551-600**	**601-650**	**651-700**	**701-750**
0	7546	12573	46064	2117	1917	1308	1115	932	781	1431	338	295	197	199
0	7625	12031	46620	2187	1913	1348	1086	953	771	1456	355	305	203	194
0	7504	11972	45812	2200	1830	1329	1157	965	787	1508	328	296	212	190
0	7648	11798	44254	2039	1852	1377	1037	922	828	1606	326	287	190	183
0	7993	11733	40774	2107	1791	1320	1104	913	762	1552	291	332	190	187
0	8313	11499	37278	2078	1758	1271	1084	965	818	1660	275	300	185	192
0	8977	11424	33719	2020	1790	1339	1026	935	745	1739	334	300	191	217
0	9198	11318	29234	2048	1729	1308	1095	926	782	1730	304	259	183	196
0	10073	11682	25502	2048	1822	1296	1085	904	773	1787	307	257	185	180
0	10908	11856	21971	2015	1736	1290	1092	905	771	1819	301	273	189	179
0	11802	12135	18607	2001	1709	1305	1049	896	813	1796	281	253	183	189
0	13195	12583	15783	1927	1699	1368	1147	863	793	1795	310	270	174	199
0	14766	13548	13627	2004	1648	1318	1079	860	748	1914	318	215	181	188
0	16130	14271	11759	1920	1625	1279	1064	900	746	1880	315	259	203	192
0	17422	15467	10601	1947	1613	1348	1038	867	793	1939	300	250	178	197
0	18367	16591	9281	1930	1609	1274	1037	838	794	1878	292	232	192	203
0	18320	17921	8401	1923	1597	1281	1009	854	770	1855	309	238	178	188
0	18219	18824	7677	1800	1629	1344	971	856	825	1763	318	242	186	193
0	18144	19321	7005	1928	1584	1280	1007	855	832	1766	277	240	183	183
0	17886	19524	6426	1858	1616	1226	1021	864	770	1718	309	248	183	177
2159	18075	19339	5986	1974	1630	1255	955	892	746	1745	297	238	178	182
2618	18679	18563	5431	1952	1634	1255	1043	849	741	1657	319	222	217	208
2806	19353	17953	5090	1909	1615	1293	1037	847	811	1682	304	209	191	189
2919	20133	16838	4553	1938	1544	1279	1040	801	808	1529	294	223	157	183
2864	20796	15703	4300	1869	1552	1246	979	847	822	1462	301	210	177	212
2881	21507	14488	3791	1847	1562	1311	1039	825	842	1444	297	197	190	199
2811	21635	13920	3690	1822	1527	1200	918	842	867	1389	323	208	167	190
2925	21904	13248	3283	1852	1522	1232	983	796	827	1299	304	217	179	184
2843	21836	12971	3075	1835	1542	1295	1038	798	793	1232	282	184	189	181
2889	21509	12877	2964	1840	1606	1247	968	834	803	1208	324	230	179	153
2934	20852	12829	2788	1865	1437	1279	967	800	864	1084	317	219	182	217
2950	19870	13108	2696	1883	1499	1281	925	782	845	1027	300	208	204	175
2978	18429	13459	2635	1904	1444	1244	1005	812	775	990	323	217	176	223
3127	17013	13609	2512	1920	1495	1172	949	777	840	895	322	190	195	184
3261	16103	13725	2397	1913	1450	1225	961	750	895	849	333	177	226	209
3414	15076	13783	2493	1886	1418	1159	995	800	925	825	316	186	181	197
3591	14465	13769	2389	1887	1431	1172	974	789	923	732	361	193	190	196
3877	14179	13903	2383	1941	1463	1181	958	785	895	722	346	205	193	217
4152	14394	14392	2365	1912	1469	1164	953	804	913	628	332	217	182	192
4434	14569	15290	2426	1942	1429	1134	983	807	916	592	323	181	188	205
4528	14884	16299	2368	1941	1430	1206	953	815	1094	594	319	191	173	196
4682	15134	18083	2276	1896	1425	1164	945	766	986	514	305	178	185	229
4943	15204	19963	2290	1817	1287	1152	987	813	1059	492	311	185	211	195
5266	15118	22951	2294	1900	1388	1141	979	773	1130	480	304	192	224	245
5567	14753	26566	2245	1981	1376	1128	925	768	1163	432	312	209	224	212
6099	14263	30292	2286	1951	1377	1187	879	769	1121	430	319	196	207	232
6690	14127	34484	2234	1956	1376	1145	959	813	1220	452	314	180	187	234
7276	13367	38684	2296	1907	1315	1167	930	809	1291	401	298	186	187	238
7440	13025	41735	2162	1875	1311	1150	961	828	1300	372	336	194	194	233
7431	12675	44266	2177	1938	1325	1111	1004	839	1398	333	305	211	207	239

Table 21. Raw spectra counts. Case 11: ORNL 4 in. loop condition P37, Unit 1

		Measurement Time (s) =	53944.5			E (keV) =	1.31	*ch	-13.81					
ch: 1-50	**51-100**	**101-150**	**151-200**	**201-50**	**251-300**	**301-350**	**351-400**	**401-450**	**451-500**	**501-550**	**551-600**	**601-650**	**651-700**	**701-750**
0	36231	61476	213669	12112	10777	7356	6270	5327	4504	7584	2025	1684	1063	1086
0	36240	60719	216740	11861	10611	7352	6243	5262	4366	7797	1976	1724	1121	1069
0	36547	59515	214952	11839	10435	7421	6298	5156	4371	8179	1941	1709	1032	1148
0	37859	58599	207879	11674	10370	7213	6127	5162	4390	8341	1821	1638	1085	1091
0	39089	57931	195613	11538	10122	7300	6175	5230	4472	8455	1813	1653	1057	1080
0	41182	57525	180789	11366	10202	7361	6199	5214	4545	8906	1687	1658	1065	1110
0	43652	56524	164038	11445	10038	7365	6122	5076	4464	9170	1742	1593	1050	1133
0	45765	56797	144960	11347	9989	7343	5957	5200	4431	9316	1712	1612	1005	1140
0	48695	56826	126776	11156	9905	7404	6161	5202	4342	9558	1761	1605	1082	1105
0	52464	57242	109469	11166	9714	7350	5914	5162	4413	9869	1670	1594	1053	1066
0	56954	58482	93720	10950	9545	7289	5847	4961	4391	9862	1718	1485	1069	1079
0	63635	61378	80312	11019	9498	7111	5947	5066	4479	10171	1682	1514	1061	1177
0	70894	64454	68990	10958	9398	7059	6027	4991	4425	10143	1660	1521	1049	1112
0	77939	69030	59837	10952	9350	7335	5916	5060	4465	10112	1703	1503	1060	1043
0	84424	73632	52601	11053	9148	7158	5905	4970	4491	10197	1667	1437	1058	1134
0	88383	79159	47096	10810	9207	7173	5818	4931	4466	10153	1650	1398	1039	1068
0	89838	84480	42799	10737	9065	7087	5915	4845	4457	10249	1750	1398	1070	1118
0	89708	89179	39147	10794	9260	7123	5776	4809	4492	10197	1747	1386	1042	1060
0	88678	92641	36162	10705	8961	7198	5647	4813	4412	10197	1667	1429	1008	1079
0	87587	93401	33448	10640	8688	7103	5552	4630	4454	9886	1747	1357	1031	1085
10886	88303	93124	31164	10644	9017	7094	5596	4766	4358	9776	1657	1380	1050	1055
13320	90068	90877	28893	10409	8863	7148	5706	4738	4406	9551	1754	1266	1097	1013
14083	94209	87190	26700	10525	8850	7066	5583	4652	4280	9208	1715	1297	1053	1093
14481	98047	81964	24489	10524	8704	6982	5664	4593	4397	9030	1659	1314	1094	1063
14628	100724	77363	22821	10475	8725	6894	5505	4672	4459	8697	1739	1263	1081	1118
14428	102826	72095	20998	10564	8798	6960	5489	4550	4405	8382	1744	1195	1071	1074
14185	104209	68559	19612	10608	8676	6985	5420	4648	4324	8051	1676	1215	1074	1069
14016	105073	65798	18193	10623	8763	7037	5481	4479	4623	7745	1736	1220	1077	1093
14185	104834	63804	17098	10627	8528	6996	5333	4404	4464	7393	1736	1225	1092	1096
14493	103337	63205	16396	10557	8465	6935	5343	4524	4453	6985	1736	1220	1051	1086
14690	100271	63315	15251	10395	8532	6898	5451	4574	4528	6555	1799	1151	1045	1075
15053	95612	64238	14740	10446	8483	6905	5299	4530	4410	6135	1735	1219	1060	1078
15112	90560	64983	14508	10446	8324	6817	5372	4500	4605	5894	1757	1142	1076	1085
15726	84020	65424	13913	10502	8452	6838	5285	4523	4603	5423	1854	1150	1099	1117
15930	78499	66000	13503	10606	8157	6726	5368	4361	4770	5162	1790	1197	1002	1108
17111	74355	66297	13723	10684	8101	6835	5383	4330	4729	4825	1768	1086	1094	1130
18177	70834	66971	13410	10694	8253	6747	5378	4430	4903	4472	1791	1133	1094	1164
19320	69730	67584	13262	10638	8023	6568	5386	4431	4920	4139	1871	1073	1103	1104
20604	70078	68944	13236	10803	7946	6638	5371	4505	5136	3857	1811	1086	1154	1174
21609	70933	71824	13159	10728	7987	6702	5304	4486	5266	3582	1794	1085	1077	1139
22539	72290	76135	13197	10535	7761	6549	5285	4542	5374	3419	1791	1116	1090	1201
23147	73174	82722	12848	10785	7806	6457	5387	4433	5459	3077	1751	1121	1039	1260
23807	74027	92417	12873	10856	7812	6545	5393	4366	5611	2979	1803	1088	1143	1196
25019	73734	105450	12813	10830	7573	6629	5364	4459	5911	2806	1862	1103	1112	1208
26977	72377	120137	12877	10766	7604	6469	5373	4401	6178	2597	1813	1083	1109	1237
29239	70755	137317	12679	10833	7617	6450	5366	4478	6223	2569	1736	1040	1093	1228
31731	68843	156042	12520	10882	7484	6458	5344	4377	6522	2389	1770	1134	1066	1260
33821	66548	174890	12385	10730	7518	6475	5331	4497	6621	2220	1767	1079	1108	1285
35641	64059	191140	12339	10845	7433	6311	5265	4399	7077	2151	1763	1048	1084	1304
36135	62517	203827	12140	10683	7353	6351	5410	4387	7169	2024	1748	1065	1082	1295

Table 22. Raw spectra counts. Case 12: ORNL 4” loop condition P27, Unit 1

	Measurement Time (s) =		45492.7			E (keV) =	1.30	*ch	-13.57					
ch: 1-50	**51-100**	**101-150**	**151-200**	**201-50**	**251-300**	**301-350**	**351-400**	**401-450**	**451-500**	**501-550**	**551-600**	**601-650**	**651-700**	**701-750**
0	24809	44036	135016	10060	8881	6070	5210	4456	3616	5724	1883	1471	922	943
0	24406	43003	139484	9802	8870	6275	5128	4399	3756	5824	1772	1421	918	911
0	24845	42810	141733	9718	8846	6244	5088	4475	3629	6095	1764	1434	896	941
0	25679	41770	139434	9672	8704	6037	5131	4399	3707	6267	1601	1486	908	985
0	26392	41235	134225	9701	8538	6075	5196	4422	3712	6510	1580	1486	886	978
0	27832	40721	125995	9570	8425	6028	5126	4334	3761	6714	1534	1440	920	983
0	29082	40380	116036	9516	8300	6004	5151	4438	3692	6928	1499	1374	903	946
0	31129	39840	104514	9361	8397	6058	5121	4306	3666	7202	1543	1350	850	918
0	33201	40096	93534	9362	8263	6129	4961	4348	3761	7336	1470	1402	878	923
0	34840	40050	81268	9302	8282	6033	4920	4404	3705	7518	1438	1391	879	965
0	38392	40767	70614	9087	8085	5936	5052	4322	3669	7878	1407	1372	928	933
0	42456	42604	60962	9205	7928	6092	4958	4187	3680	7871	1438	1298	903	946
0	47285	44081	52403	9044	7898	6095	4885	4167	3675	8161	1392	1303	873	932
0	51899	46315	45498	9037	7669	5963	4939	4239	3767	8298	1400	1319	890	936
0	56160	48850	40108	9057	7652	5940	4789	4140	3743	8383	1432	1215	866	936
0	60009	52344	35801	8909	7588	5937	4878	4093	3696	8386	1392	1308	833	946
0	61857	55862	32182	8991	7651	6054	4793	4014	3675	8470	1322	1247	826	934
0	61598	58773	29821	8848	7530	6023	4713	3961	3669	8294	1393	1243	841	944
0	60606	61269	27346	8809	7491	5874	4700	4012	3766	8427	1334	1183	874	946
0	59506	62959	25561	8864	7529	5910	4698	4045	3754	8500	1378	1168	862	968
7827	59577	63463	23841	8740	7336	5947	4812	4002	3624	8454	1363	1167	865	936
9376	60096	63260	22175	8692	7298	5816	4683	3898	3621	8365	1381	1125	926	925
9848	61877	60961	20624	8828	7289	5827	4582	3908	3691	8139	1428	1115	882	902
10320	64519	57949	19410	8760	7249	5800	4674	3952	3667	7957	1383	1133	877	904
10416	66259	54994	18304	8727	7385	5826	4623	3909	3735	7912	1418	1062	834	875
10111	68058	51953	16835	8519	7274	5826	4639	3805	3659	7561	1420	1055	856	931
9917	69168	49084	15918	8712	7121	5809	4552	3870	3682	7482	1396	1062	855	881
9976	70243	46722	15015	8671	6946	5875	4548	3879	3714	7084	1403	1064	881	851
10146	70427	45243	14170	8678	7313	5847	4404	3801	3719	6890	1435	1037	907	888
10427	69783	44127	13366	8680	7057	5750	4511	3724	3741	6503	1432	1031	904	880
10546	68082	44041	12743	8483	7048	5793	4476	3753	3635	6148	1417	1004	939	898
10692	65396	44139	12096	8708	7017	5559	4496	3696	3778	5961	1470	976	874	944
10767	62563	45063	11827	8759	7050	5676	4418	3771	3730	5623	1466	990	903	927
11058	58665	44947	11721	8626	6871	5577	4476	3731	3866	5355	1477	981	927	870
11356	54725	45590	11460	8629	6722	5610	4328	3740	3757	4942	1523	989	923	877
11817	51618	45540	11167	8786	6790	5578	4444	3781	3802	4711	1530	951	889	927
12586	49376	46242	11131	8736	6867	5605	4422	3613	3905	4423	1531	970	864	904
13361	48131	46319	10991	8893	6676	5417	4449	3708	4045	4048	1481	928	908	945
14317	48066	46924	10888	8787	6700	5389	4393	3779	4051	3858	1392	977	887	974
14995	48776	47631	10669	8782	6658	5499	4418	3661	4102	3559	1545	902	896	951
15471	50311	49959	10763	8865	6492	5471	4549	3719	4112	3455	1532	943	877	909
15940	50208	53731	10713	8899	6363	5412	4408	3687	4414	3193	1464	937	911	963
16499	51643	57958	10752	8957	6449	5332	4368	3609	4417	2957	1444	937	951	986
17188	51513	63914	10484	8973	6409	5326	4412	3699	4526	2756	1509	912	877	984
18279	50915	72984	10565	9005	6292	5408	4442	3720	4690	2565	1501	965	885	1037
19663	49415	83399	10314	9097	6400	5380	4405	3667	4732	2431	1490	908	899	1013
21159	48519	94068	10494	9033	6235	5275	4339	3672	4869	2264	1418	938	947	945
22864	47260	105905	10359	8937	6354	5319	4527	3664	5116	2178	1507	907	926	994
23749	46115	116803	10273	8995	6251	5184	4373	3672	5351	2069	1540	891	911	984
24290	45254	127330	10009	9012	6246	5266	4387	3758	5365	1942	1428	909	943	1066

Table 23. Case 13: ORNL room background for Cases 14–15

Measurement Time (s) =			3232.2			E (keV) =	1.32	*ch	-13.5					
ch: 1-50	**51-100**	**101-150**	**151-200**	**201-50**	**251-300**	**301-350**	**351-400**	**401-450**	**451-500**	**501-550**	**551-600**	**601-650**	**651-700**	**701-750**
0	461	798	570	380	362	249	229	217	200	170	133	105	106	103
0	466	781	588	458	325	284	224	237	209	145	125	125	101	91
0	449	779	599	433	340	252	219	232	198	151	151	122	95	121
0	503	776	558	404	325	249	243	225	196	142	119	106	116	103
0	571	793	576	450	318	247	202	233	192	127	133	135	114	119
0	590	765	551	364	323	283	206	256	216	130	132	111	104	113
0	634	732	532	394	321	265	238	261	190	148	128	110	107	96
0	619	792	479	396	312	263	240	268	197	125	149	146	106	121
0	680	812	525	401	305	253	256	231	205	138	122	124	115	133
0	687	781	545	402	319	249	223	237	198	119	114	132	122	120
0	731	750	544	364	310	224	251	225	228	153	117	104	90	119
0	807	729	529	389	317	274	216	216	204	164	145	126	87	102
0	815	774	542	388	307	250	225	230	211	149	119	101	110	108
0	937	748	515	419	303	249	203	209	213	152	141	116	88	97
0	1005	728	495	369	332	277	215	234	205	118	116	97	99	111
0	1006	718	462	369	305	248	271	215	211	130	144	111	91	122
0	1039	728	480	358	327	265	194	207	208	120	105	134	124	127
0	1091	705	513	369	337	259	209	216	171	158	158	112	108	109
0	965	742	507	419	307	252	217	198	218	146	125	108	116	111
0	1013	678	480	345	343	218	224	179	248	156	127	106	101	129
224	967	692	493	365	292	240	237	206	224	141	121	127	99	110
255	964	722	437	347	299	249	240	238	199	155	116	95	96	92
253	916	730	469	369	310	229	220	190	209	142	120	104	111	86
237	930	694	463	373	360	252	201	172	202	124	117	117	109	102
262	873	701	495	390	356	228	208	187	207	136	111	90	97	108
255	930	731	498	345	300	228	229	173	213	135	117	109	115	100
250	948	704	440	345	303	261	242	185	181	140	121	115	104	108
275	857	680	490	360	337	280	245	197	232	125	128	112	105	121
273	938	654	478	399	336	262	222	186	210	126	130	115	87	109
293	867	692	475	351	324	241	204	176	210	144	124	107	94	107
273	818	644	501	352	329	249	238	181	193	128	116	125	115	115
289	893	640	505	301	325	243	218	187	190	116	127	121	110	114
262	795	644	491	361	313	236	232	200	177	127	136	110	108	106
253	820	660	509	377	325	224	235	183	207	138	121	91	94	92
299	771	608	461	321	301	261	214	166	186	134	117	98	101	112
293	862	600	473	348	298	222	243	196	186	137	110	105	93	109
293	805	628	515	363	275	223	237	217	198	118	133	113	112	103
323	826	642	468	354	287	247	221	169	181	118	141	117	113	111
318	850	613	456	330	281	245	219	192	181	135	131	90	114	116
328	796	596	490	354	333	221	223	186	169	125	127	104	100	97
380	827	602	506	338	280	232	233	192	169	135	140	119	113	110
351	802	614	499	317	242	239	247	182	160	139	132	110	121	110
337	798	598	473	328	288	232	261	196	171	136	129	97	120	108
354	788	614	475	328	309	284	249	192	175	141	112	99	112	101
378	842	626	473	344	262	233	266	204	144	117	140	105	100	105
384	860	549	472	336	269	275	241	189	180	130	127	97	97	102
355	807	558	456	327	274	246	231	188	142	129	130	90	106	98
396	790	552	446	295	293	199	270	192	169	135	109	112	96	114
414	792	573	392	316	241	232	257	187	162	114	142	102	117	110
441	837	583	458	300	263	256	216	200	164	126	115	88	102	111

Table 24. Case 14: ORNL HEU foil Unit 1

	Measurement Time (s) =		4614.4			E (keV) =	1.31	*ch	-14.44					
ch: 1-50	**51-100**	**101-150**	**151-200**	**201-50**	**251-300**	**301-350**	**351-400**	**401-450**	**451-500**	**501-550**	**551-600**	**601-650**	**651-700**	**701-750**
0	87559	116938	786548	7564	3559	2031	478	404	327	238	195	205	166	167
0	81472	102098	808820	7410	3576	1998	464	436	305	255	202	188	177	163
0	75659	90165	811075	7289	3189	2017	502	373	292	236	200	194	169	158
0	73186	81118	786857	7129	3112	2035	432	405	334	196	205	184	151	191
0	72189	73790	745613	6962	3117	2062	442	396	334	231	207	187	188	168
0	73713	68542	685715	6824	2986	1901	419	370	296	218	191	198	148	168
0	76296	65356	616862	6746	2845	1980	415	365	323	199	190	188	157	174
0	79510	64152	540659	6671	2733	2084	426	380	313	200	203	175	173	176
0	84769	65036	468896	6531	2794	1922	458	395	343	205	195	169	166	155
0	92036	67259	396329	6429	2767	1933	437	369	321	203	193	192	162	158
0	101874	73032	332949	6508	2697	2007	402	341	325	203	200	188	165	151
0	114509	82912	277273	6446	2634	1886	431	347	356	204	188	172	147	154
0	130302	94885	232498	6293	2668	1920	405	323	343	218	178	178	136	187
0	146300	110983	194361	6354	2621	1908	430	361	339	212	196	176	153	160
0	162332	131237	166172	6252	2512	1933	394	376	291	239	185	190	164	155
0	173843	153079	141903	6298	2705	1842	430	342	359	205	177	152	172	166
0	181974	174565	123818	6447	2511	1783	386	333	346	215	194	190	154	180
0	189463	194215	109551	6484	2702	1695	417	315	334	229	207	178	155	191
0	198683	209028	96909	6426	2592	1680	430	310	396	205	191	173	169	150
0	211566	216960	86361	6535	2647	1606	360	319	351	205	202	201	158	143
26052	230657	217915	77129	6522	2727	1572	379	310	333	213	187	163	150	169
32756	256407	212811	68508	6842	2613	1428	410	309	343	212	212	197	153	165
37300	284649	199353	60558	7031	2522	1333	422	302	356	202	184	150	169	166
40059	310099	182068	52262	7156	2519	1320	394	278	320	203	196	183	147	168
39870	330541	164760	45178	7413	2598	1163	394	302	341	229	186	192	166	152
35915	347540	147828	38816	7467	2637	1142	374	313	352	212	196	159	155	176
31094	365133	134173	32427	7603	2567	972	408	276	327	195	173	147	174	132
27254	386547	123354	27419	7788	2582	969	417	321	315	211	174	171	160	156
25389	412499	118374	22838	7886	2480	823	354	303	323	210	194	187	154	141
24811	443296	116086	19104	7923	2523	822	396	277	367	212	174	157	174	148
24462	471175	117040	16375	7933	2517	768	414	285	286	219	183	177	153	161
24593	493565	120461	13825	7729	2396	739	355	297	365	186	207	149	156	167
24884	501162	123988	12181	7766	2493	669	375	294	311	215	201	176	168	177
25509	493896	128292	10941	7546	2457	678	373	281	280	213	158	170	167	154
27104	470231	132314	10029	7273	2385	580	397	271	295	210	213	151	147	130
29053	432460	133667	9610	7157	2337	581	389	314	302	202	201	160	151	178
31374	386192	135884	9017	6820	2330	566	370	274	329	212	181	167	170	200
33818	340119	138912	8732	6653	2187	563	381	283	269	224	190	164	124	146
36637	299578	144208	8391	6316	2315	516	354	289	309	200	171	149	146	162
39495	267881	155985	8268	6173	2233	444	383	294	271	182	195	151	160	161
40942	246986	174054	8217	5793	2273	495	361	310	292	192	200	146	146	158
42989	235002	202639	8276	5559	2133	470	390	283	265	204	177	168	139	196
45491	229936	244592	8407	5405	2104	504	456	312	268	205	157	149	159	163
50503	224632	296193	8131	4921	2025	487	389	307	264	209	195	165	119	160
57989	218608	361909	8073	4744	2159	444	407	292	238	188	200	163	158	132
68174	207667	437401	8055	4527	2134	488	383	311	264	192	184	158	198	141
79025	193181	519330	7900	4366	2012	456	386	289	250	190	185	171	157	184
87949	174226	601023	7799	4152	2068	488	393	313	235	178	192	155	154	171
92572	154012	677414	7692	3945	2036	480	388	351	241	198	177	174	170	141
92489	134247	740973	7693	3765	2112	474	394	311	238	203	195	166	163	164

Table 25. Case 15: ORNL HEU fission chamber (with Co contamination) Unit 1

	Measurement Time (s) =		5274.3			E (keV) =	1.31	*ch	-13.47					
ch: 1-50	**51-100**	**101-150**	**151-200**	**201-50**	**251-300**	**301-350**	**351-400**	**401-450**	**451-500**	**501-550**	**551-600**	**601-650**	**651-700**	**701-750**
0	79803	138749	625793	20394	14592	12544	11314	5225	4150	48573	3331	690	416	232
0	83977	134728	636357	19818	14665	12472	11248	5221	4185	51329	2948	698	473	228
0	88439	130009	630542	19713	14882	12605	11211	5179	4127	54701	2709	687	446	247
0	92115	127576	610958	19418	14455	12606	10903	5078	4110	57568	2417	686	447	204
0	96239	125948	572441	19444	14799	12658	10716	5040	4141	60997	2050	698	442	231
0	100864	125535	526527	19391	14266	12541	10626	5003	4089	63349	1895	728	413	235
0	105751	125177	472342	19127	14298	12360	10373	5032	4128	66241	1715	641	426	209
0	112960	125620	415952	18921	14437	12344	10455	5004	4010	67960	1490	667	423	248
0	120951	128365	360268	18676	14294	12556	10292	5045	3972	70478	1403	672	436	215
0	134039	131488	308335	18666	14247	12415	9968	5095	4180	72856	1366	630	414	213
0	149131	137358	261187	18280	14112	12366	9748	4846	4221	74598	1277	684	426	217
0	167896	144471	221110	18516	14125	12380	9675	4884	4125	75936	1201	635	364	234
0	188300	154823	187970	18499	14144	12297	9483	4820	4105	76900	1241	647	390	222
0	209313	168119	160643	18285	13846	12325	9140	4807	4092	77524	1036	648	360	211
0	227955	183965	139729	18251	13915	12367	8919	4692	4123	78035	1073	593	402	211
0	240537	200405	122257	17842	14020	11998	8802	4660	4181	77809	1039	587	355	187
0	247702	216200	108789	17946	13910	12306	8457	4640	4222	77469	985	634	369	218
0	248438	230845	97507	17827	13817	12094	8341	4596	4193	76122	969	597	340	195
0	251631	241108	88638	17754	13741	11819	8043	4738	4239	74645	943	554	372	201
0	254492	247208	80561	17776	13846	12160	8068	4715	4376	73091	1011	580	322	225
24422	263459	244534	73529	17842	13883	12085	7824	4505	4498	71353	948	560	369	191
29698	277623	237696	67119	17553	13738	12103	7687	4568	4686	68870	951	586	294	190
32970	292256	226449	60488	17765	13898	11943	7540	4504	4677	66050	884	560	273	216
35886	306218	211887	54986	17459	13612	12001	7321	4475	4889	64117	919	554	295	189
37550	313322	196433	49544	17527	13572	11909	7240	4347	5142	60498	892	533	312	204
37938	314073	181923	44320	17322	13524	12032	7142	4444	5467	57213	912	577	296	210
37804	308981	169264	39976	17375	13722	12186	7016	4376	5752	54204	903	585	313	226
38481	301415	161624	36118	17080	13447	11996	6840	4286	6087	50959	823	539	316	190
40628	295173	156289	32878	17343	13501	12006	6782	4424	6790	47619	888	539	298	219
41765	284310	154717	30065	17085	13297	11908	6577	4287	7231	43966	881	552	279	189
42233	274467	155161	28023	17306	13181	11950	6420	4429	7938	40516	886	512	292	191
41702	259685	158128	26760	16754	13298	11904	6393	4286	8491	37103	850	587	273	221
41005	244765	160471	25208	16768	13024	12012	6349	4363	9470	33924	889	521	256	210
41146	226142	162868	24526	16564	13222	11849	6351	4433	10556	30748	808	487	251	210
42024	209982	164841	23357	16410	13002	11929	6192	4217	11552	27629	896	519	263	230
43386	196451	166968	22985	16276	13096	12066	6093	4083	12728	25142	822	525	268	216
46029	185594	168566	22739	16148	13046	11687	6049	4283	14169	22510	849	472	279	228
48540	181211	170361	22188	16211	13015	12085	5948	4257	15785	19810	800	509	248	228
50820	181003	174594	22109	15992	12802	11980	5827	4229	17370	17622	788	523	230	192
53246	182778	182879	21888	15886	12915	11866	5884	4245	19156	15476	834	528	236	185
54494	186769	196282	21728	15710	13024	11881	5779	4179	21085	13997	775	496	261	189
54845	188781	217978	21661	15613	12943	11675	5696	4146	23113	12265	781	473	237	206
55438	188755	248050	21465	15435	12989	11574	5616	4179	25714	10684	732	497	251	205
56263	188591	285996	21438	15331	12622	11587	5689	4173	27495	9325	754	465	233	200
57426	183693	333750	21026	15248	12747	11867	5549	4172	30482	7905	736	502	216	223
60037	177290	387996	20790	15278	12682	11557	5501	4154	33274	6895	777	489	246	216
63219	168635	445783	20442	15071	12962	11671	5628	4191	36282	5898	714	500	261	212
67503	159842	503317	20848	15022	12626	11630	5425	4152	39117	5182	778	446	226	198
71585	151690	555776	20415	14873	12559	11641	5500	4212	42086	4446	674	434	233	186
75795	143462	598516	20231	14758	12739	11460	5360	4149	45297	3961	680	444	229	199

Table 26. MCNP simulation results

ORNL 5.35% enrichment

8" Pipe								
UF_6 Partial Pressure [Torr]	Experiment		MCNP Flowloop Model		MCNP Infinite Length Model		Calibration Factors (inifinite/flowloop)	
	Count Rate [cps]	cps/torr [cps/Torr]	Count Rate [cps]	cps/torr [cps/Torr]	Count Rate [cps]	cps/Torr [cps/Torr]	Count Rate Basis [-]	cps/Torr Basis [-]
26.7	56.88	2.13	71.56	2.68	80.77	3.02	1.13	1.13
36.0	80.00	2.22	96.18	2.67	108.52	3.02	1.13	1.13
45.3	100.63	2.22	120.94	2.67	136.43	3.01	1.13	1.13
						Averages	1.13	1.13

ORNL 5.35% enrichment

4" Pipe								
UF_6 Partial Pressure [Torr]	Experiment		MCNP Flowloop Model		MCNP Infinite Length Model		Calibration Factors (inifinite/flowloop)	
	Count Rate [cps]	cps/torr [cps/Torr]	Count Rate [cps]	cps/torr [cps/Torr]	Count Rate [cps]	cps/Torr [cps/Torr]	Count Rate Basis [-]	cps/Torr Basis [-]
26.7	33.80	1.26	46.96	1.76	36.92	1.38	0.79	0.79
36.0	46.69	1.30	63.13	1.75	49.71	1.38	0.79	0.79
45.3	57.19	1.26	79.41	1.75	62.56	1.38	0.79	0.79
						Averages	0.79	0.79

LANL (3.3% enrichment)

4" Pipe								
UF_6 Partial Pressure [Torr]	Experiment		MCNP Flowloop Model		MCNP Infinite Length Model		Calibration Factors (inifinite/flowloop)	
	Count Rate [cps]	cps/torr [cps/Torr]	Count Rate [cps]	cps/torr [cps/Torr]	Count Rate [cps]	cps/Torr [cps/Torr]	Count Rate Basis [-]	cps/Torr Basis [-]
19	10.25	0.54	14.95	0.79	16.18	0.85	1.08	1.08
38.82	22.17	0.57	30.54	0.79	33.05	0.85	1.08	1.08
59.17	34.14	0.58	46.56	0.79	50.38	0.85	1.08	1.08
						Averages	1.08	1.08

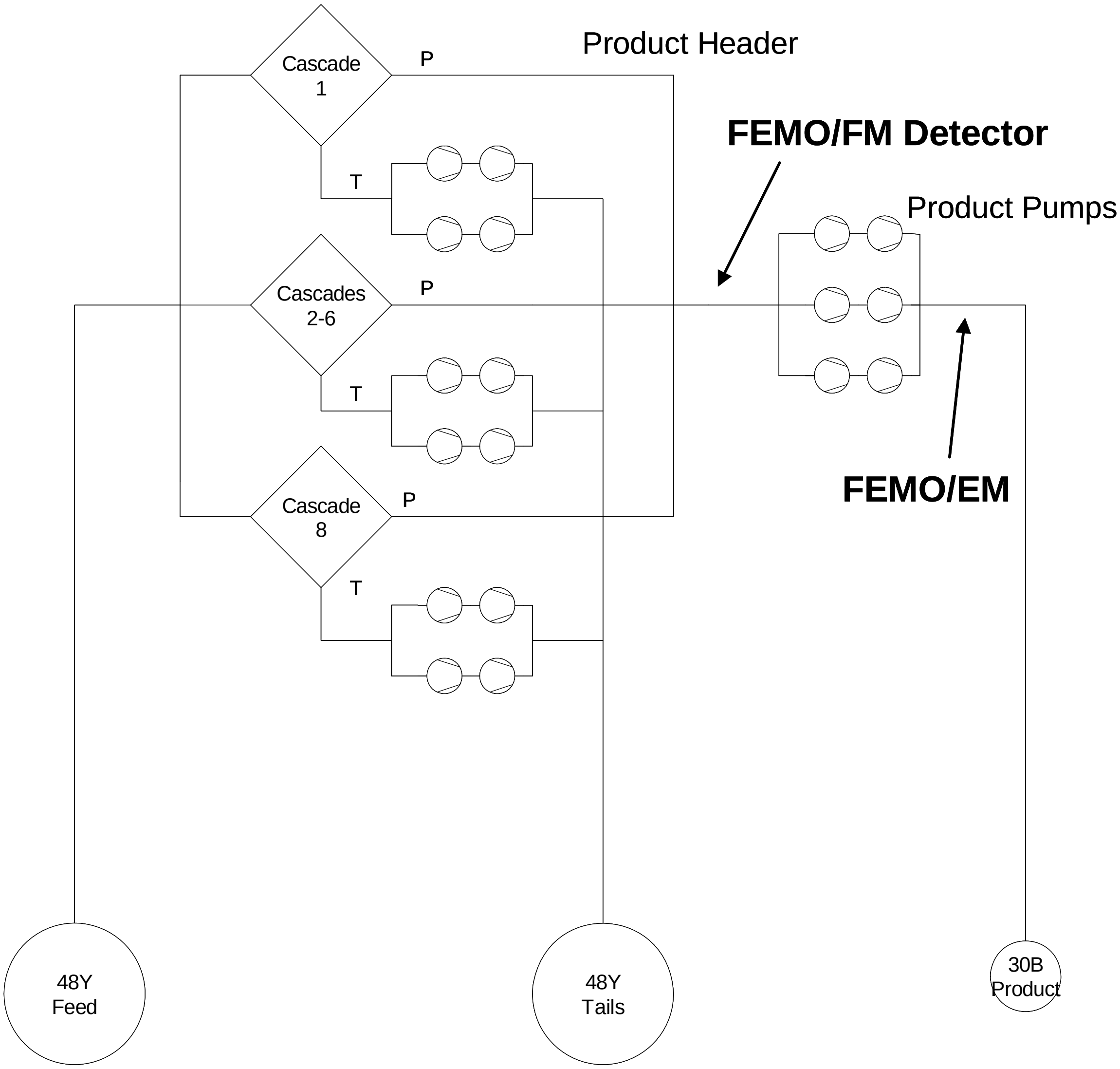

Fig. 1. Typical GCEP plant arrangement showing the locations of the FEMO/FM and the FEMO/EM.

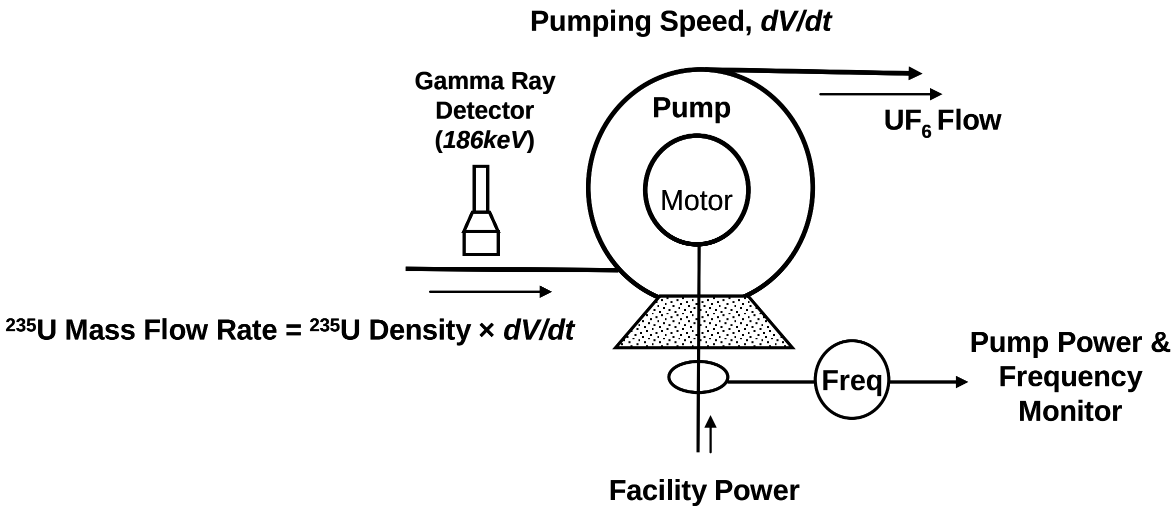

Fig. 2. Location of the flow monitor (FM) components and how to measure ^{235}U mass flow rate.

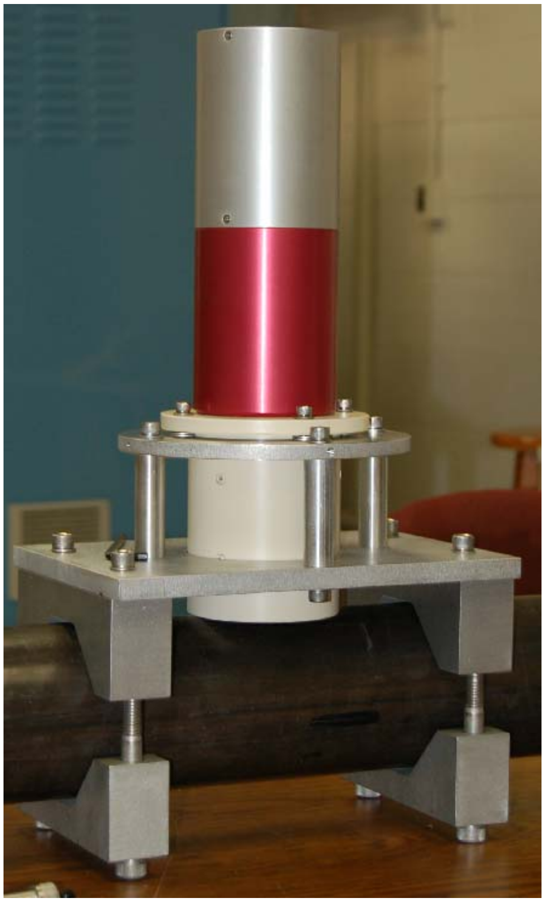

Fig. 3. FM scintillation detector and bracket mounted on pipe section.

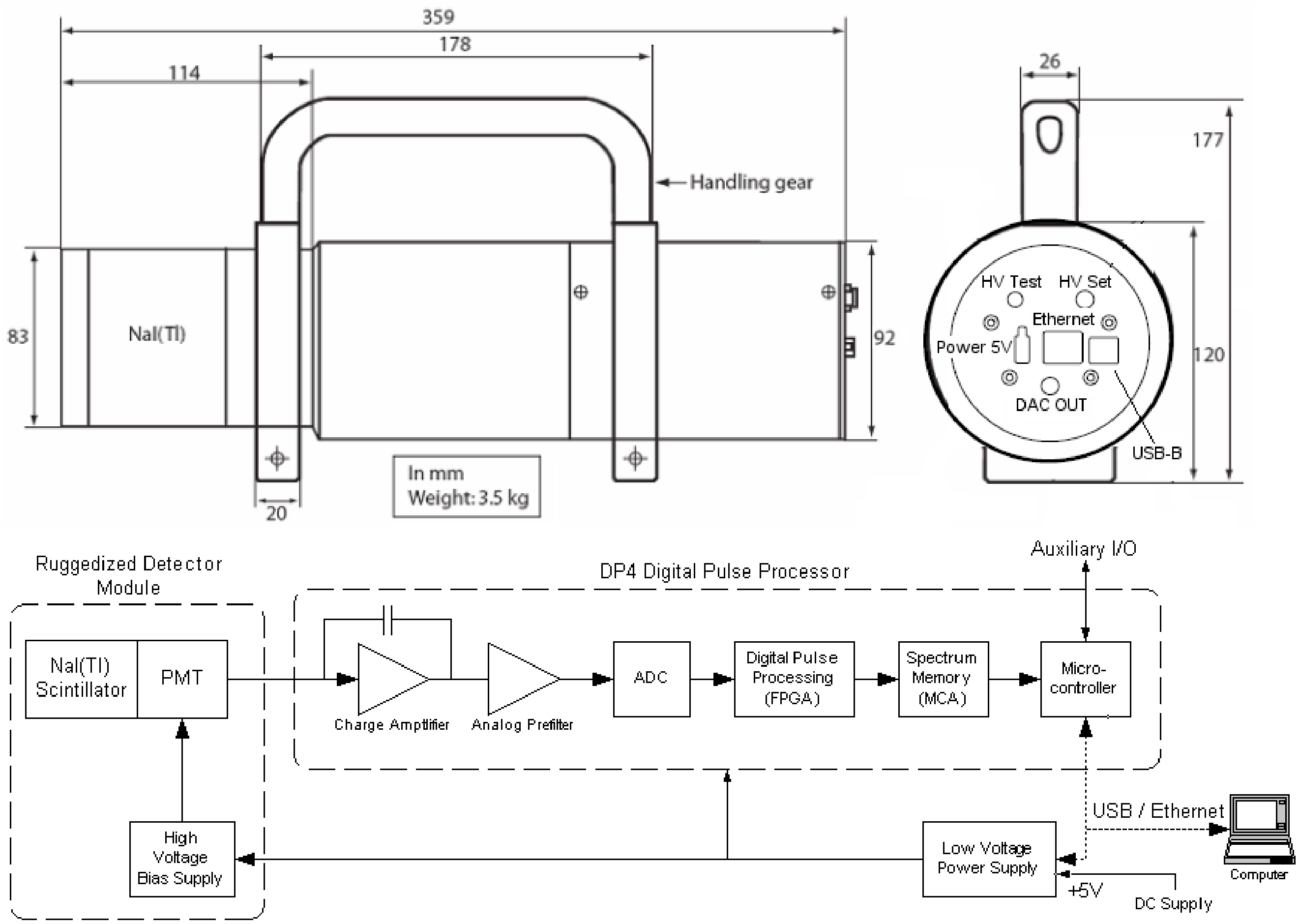

Fig. 4. FM scintillation detector outline and schematic of associated electronics.

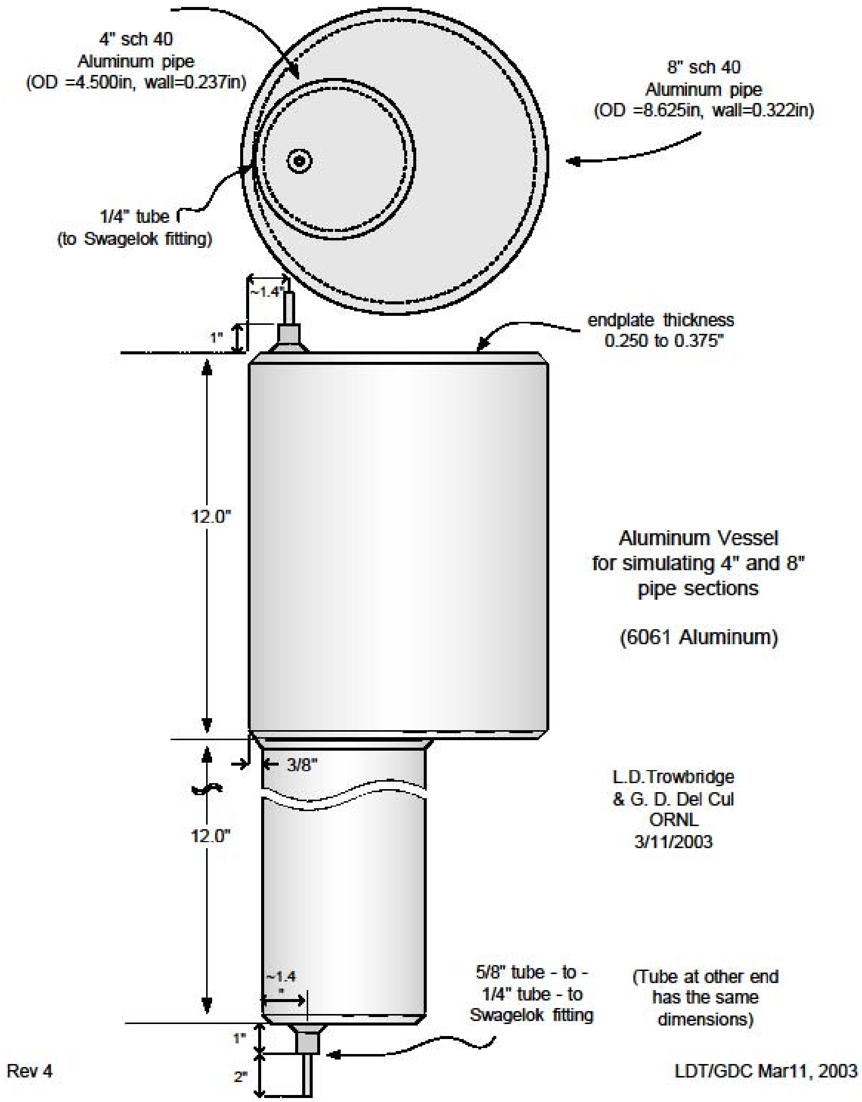

Fig. 4a. Piping configuration containing UF_6.

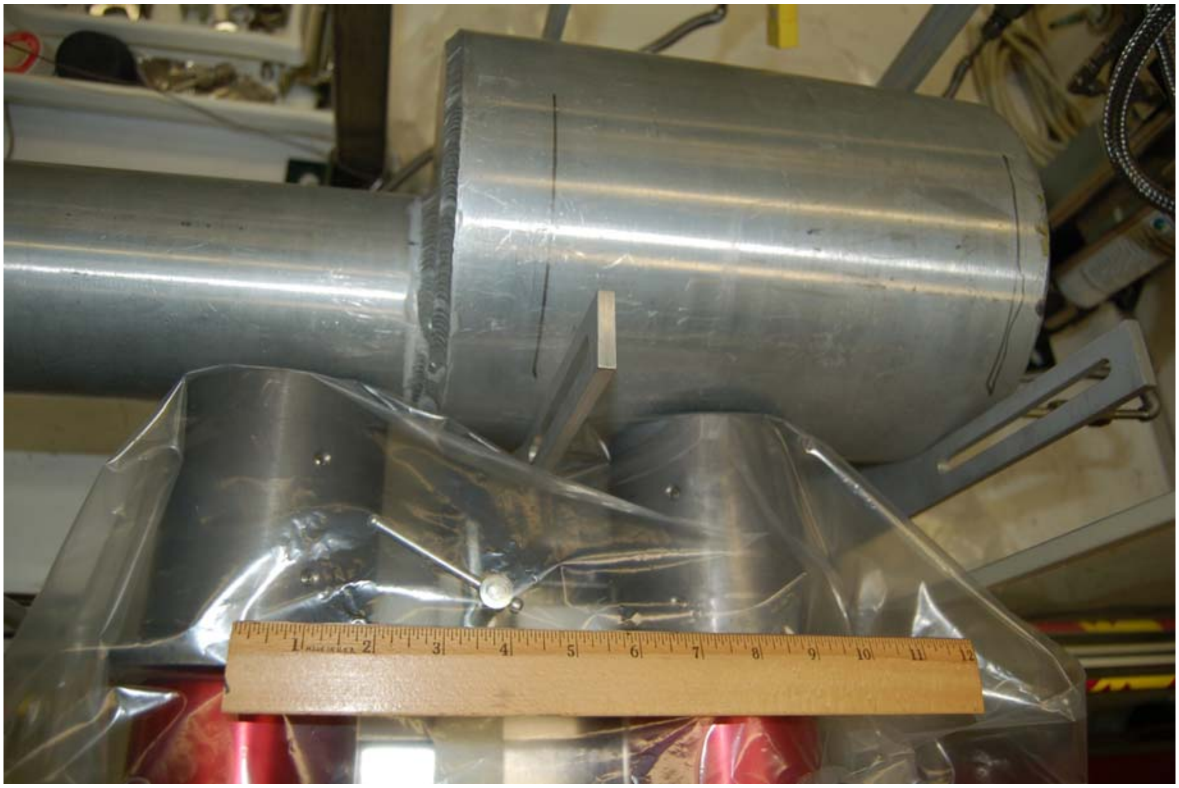

Fig. 5. Picture of FM scintillation detectors during measurements on ORNL UF_6 flow loop.

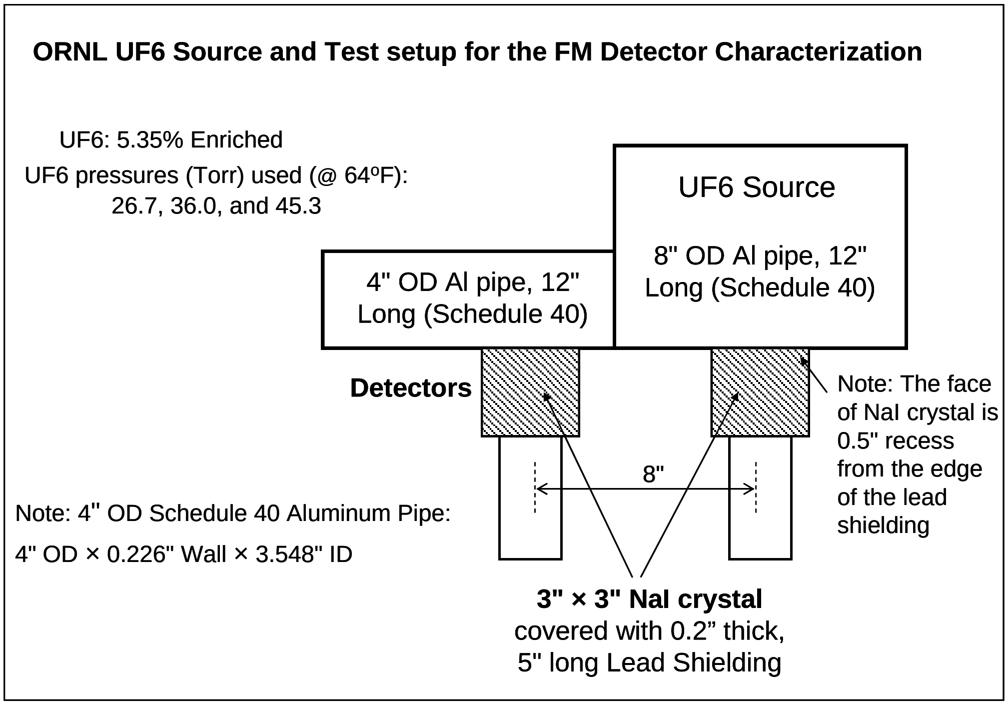

Fig. 6. Schematic arrangement of FM scintillation detectors during measurements on ORNL UF_6 flow loop.

Fig. 7. ORNL UF_6 flow loop with FM scintillation detectors and associated electronics.

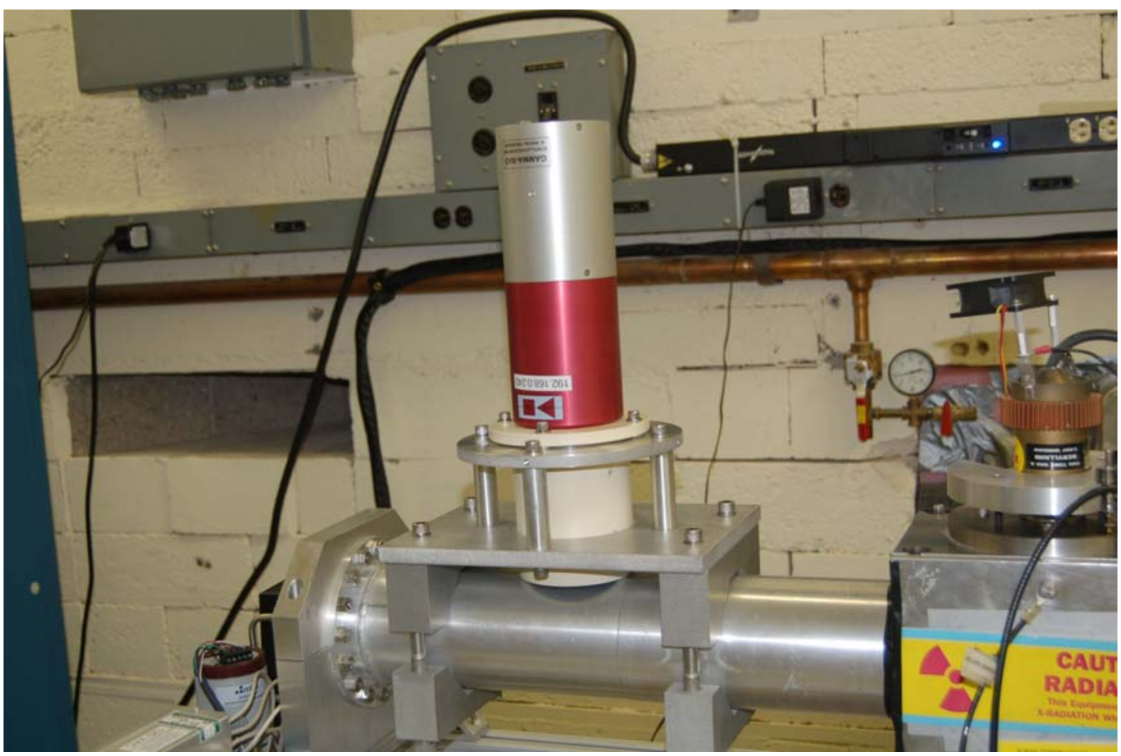

Fig. 8. FM scintillation detector mounted on LANL UF_6 source.

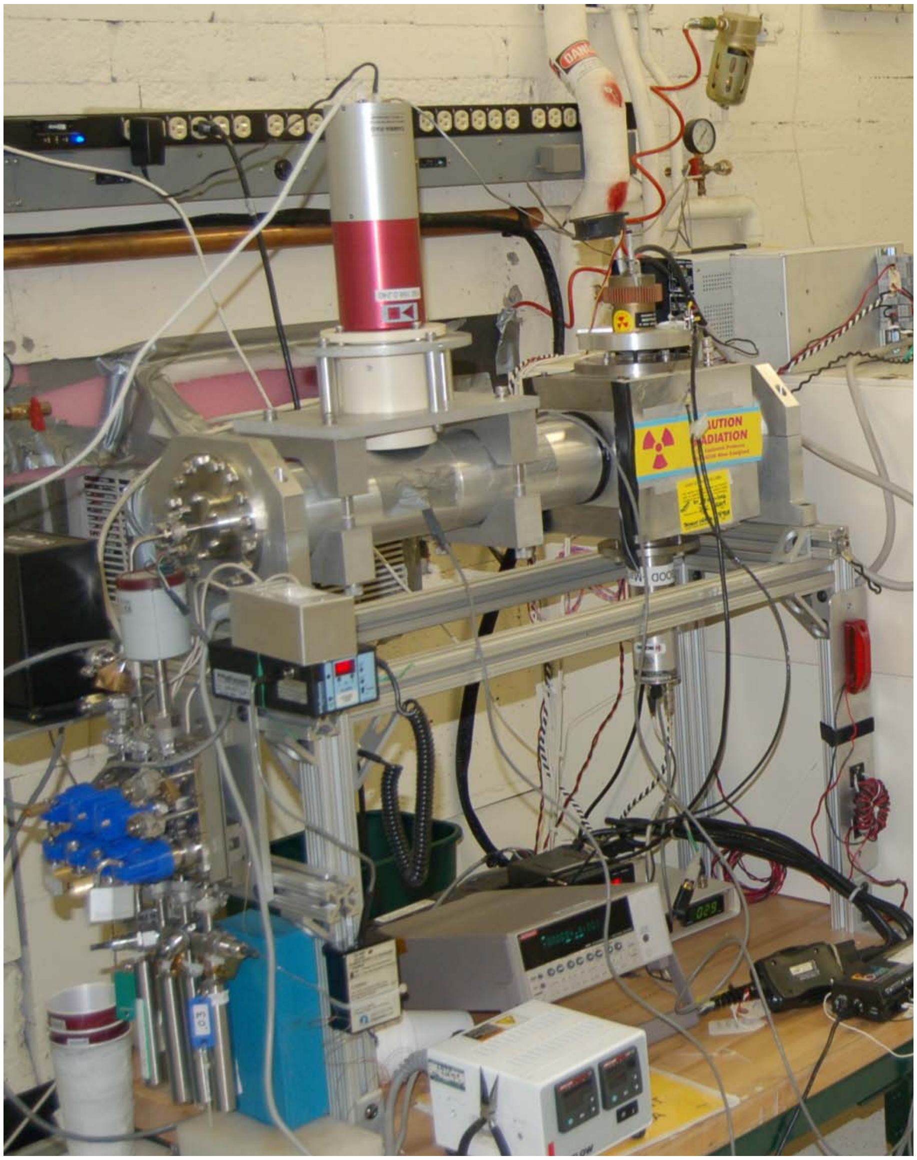

Fig. 9. LANL UF_6 source with FM scintillation detector installed.

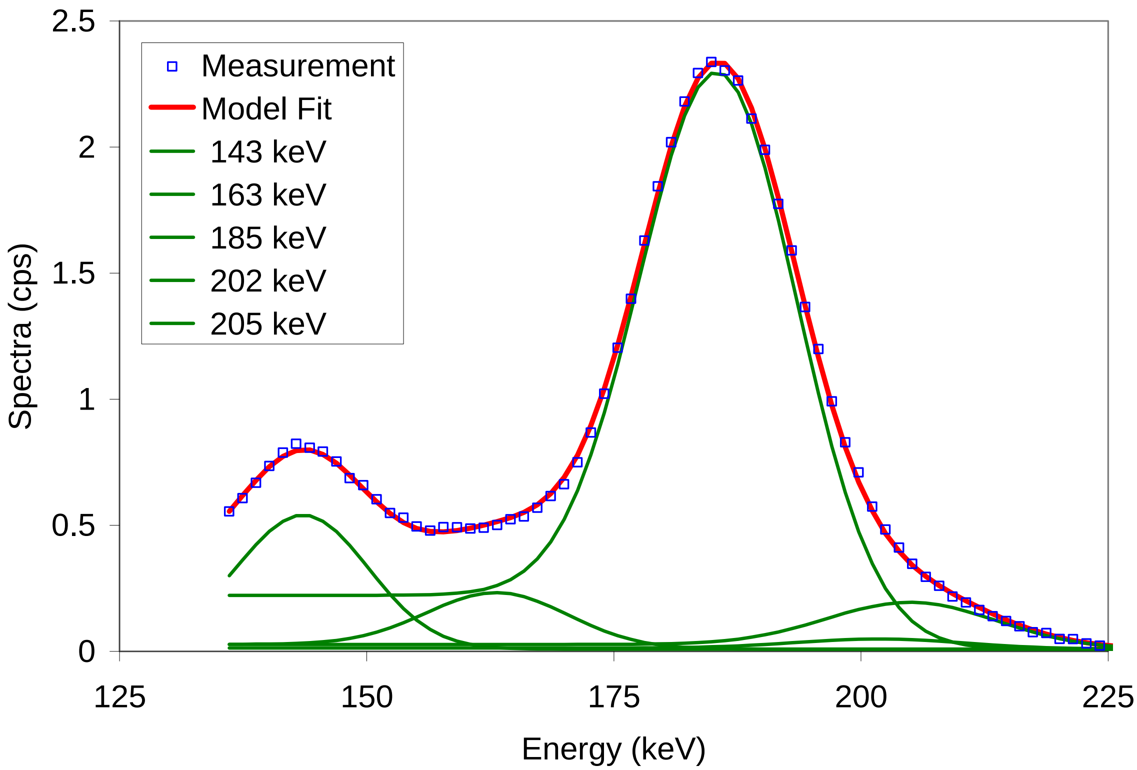

Fig. 10. Spectral data and fit components for Case 2: LANL loop condition P60.

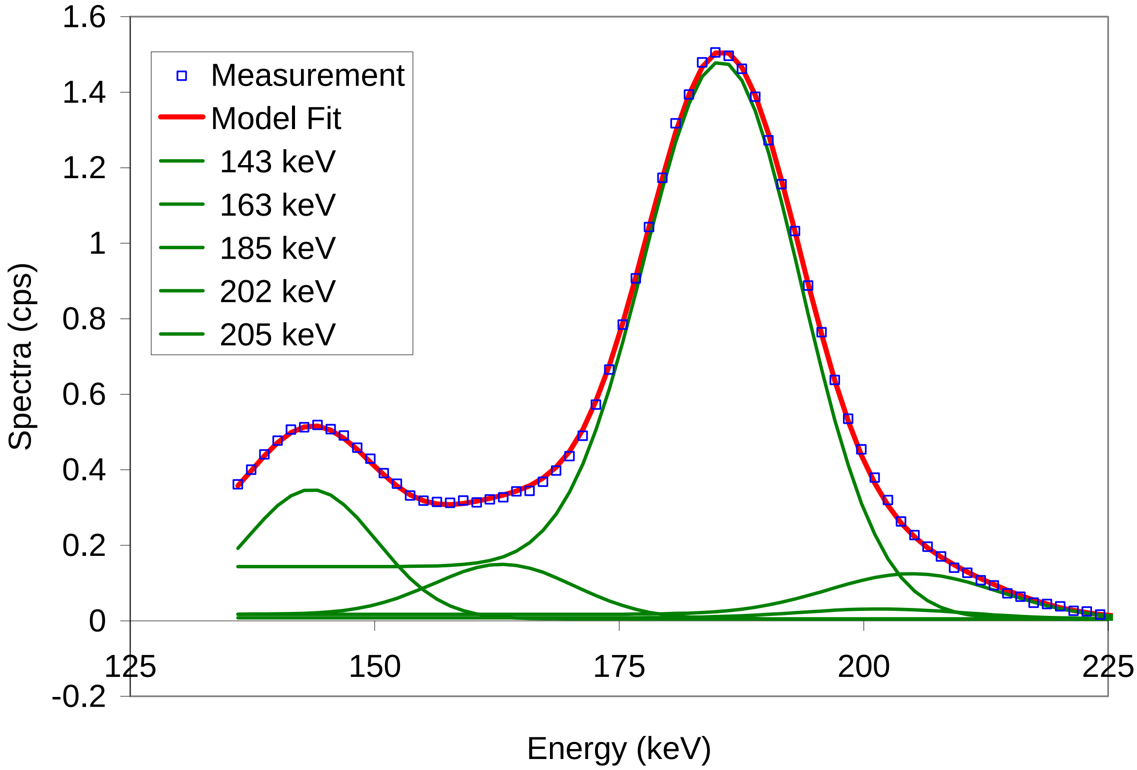

Fig. 11. Spectral data and fit components for Case 3: LANL loop condition P40.

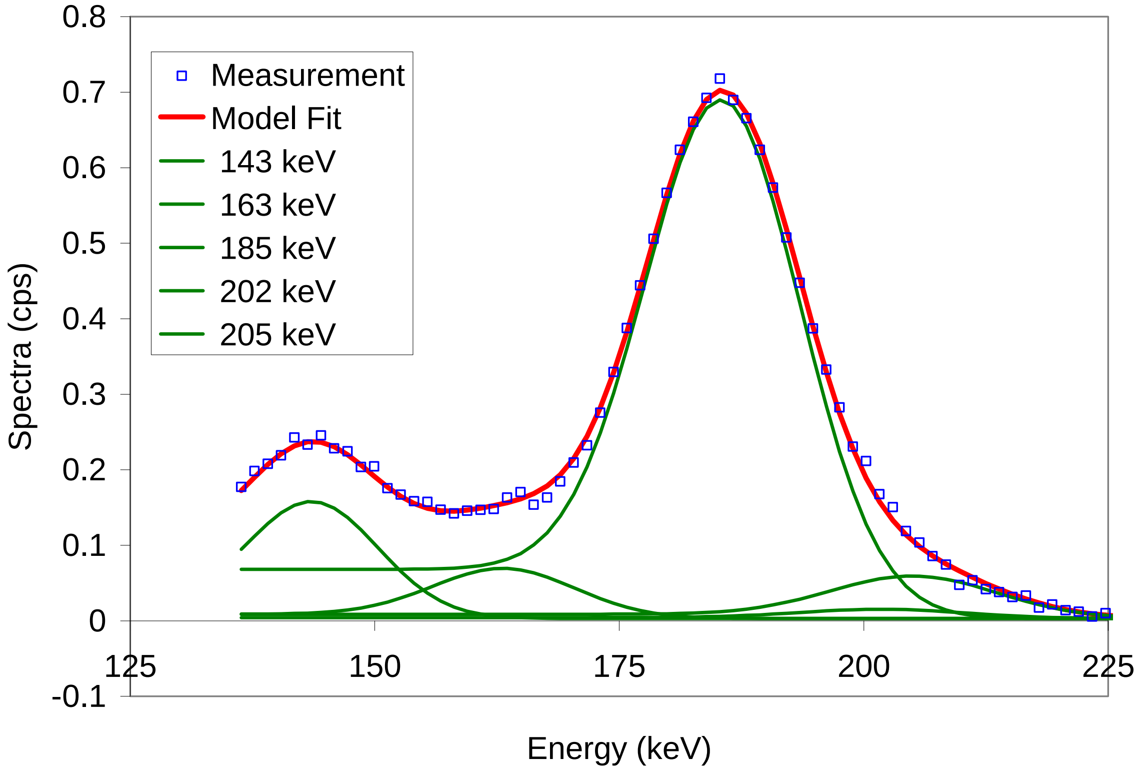

Fig. 12. Spectral data and fit components for Case 4: LANL loop condition P20.

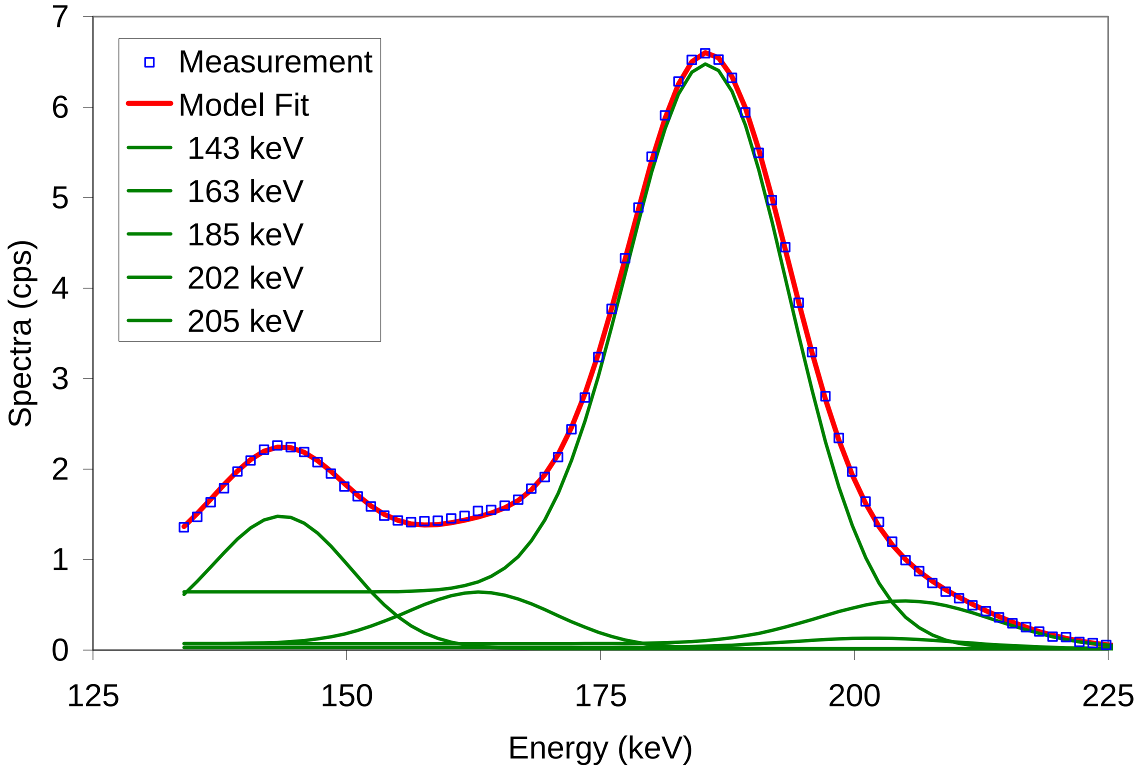

Fig. 13. Spectral data and fit components for Case 6: ORNL 8” loop condition P47, Unit 0.

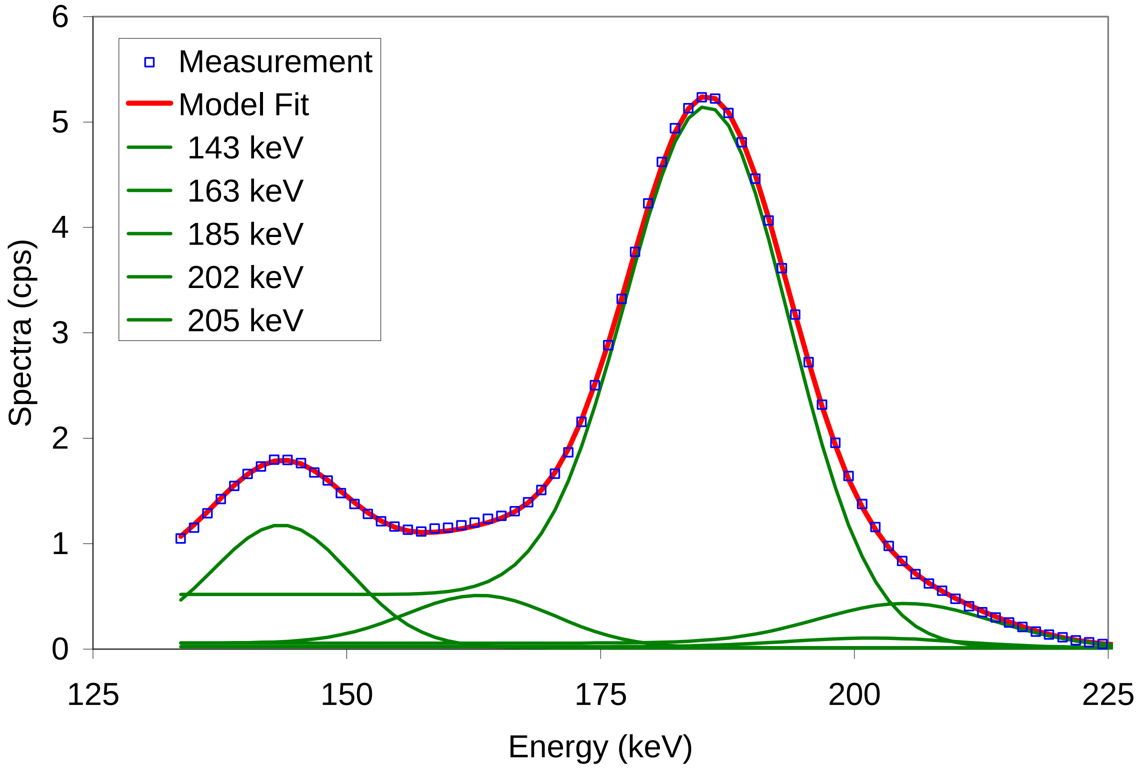

Fig. 14. Spectral data and fit components for Case 7: ORNL 8" loop condition P37, Unit 0.

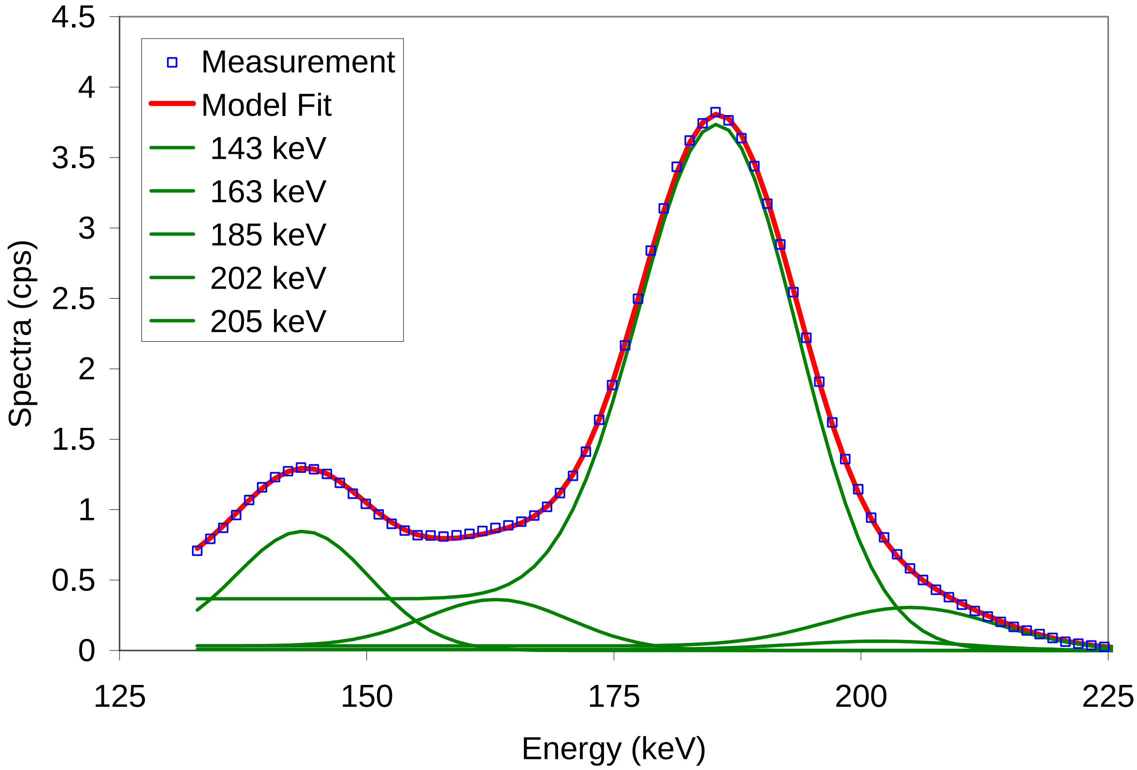

Fig. 15. Spectral data and fit components for Case 8: ORNL 8" loop condition P27, Unit 0.

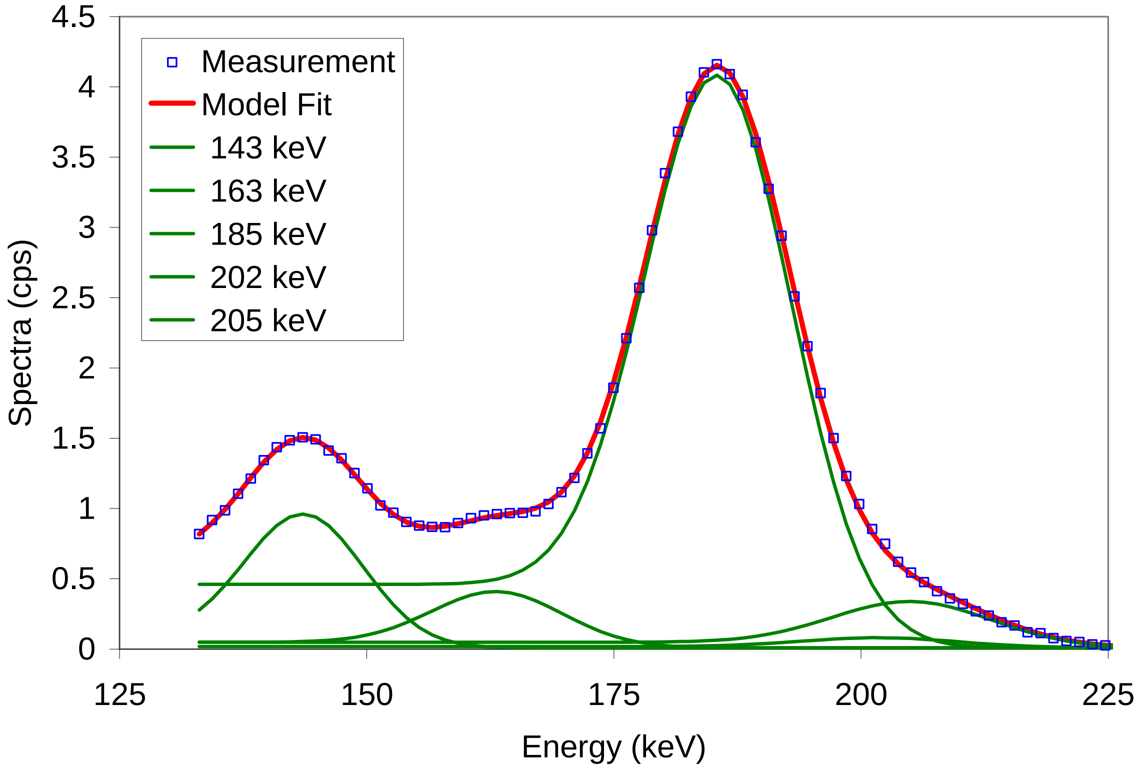

Fig. 16. Spectral data and fit components for Case 10: ORNL 4" loop condition P47, Unit 0.

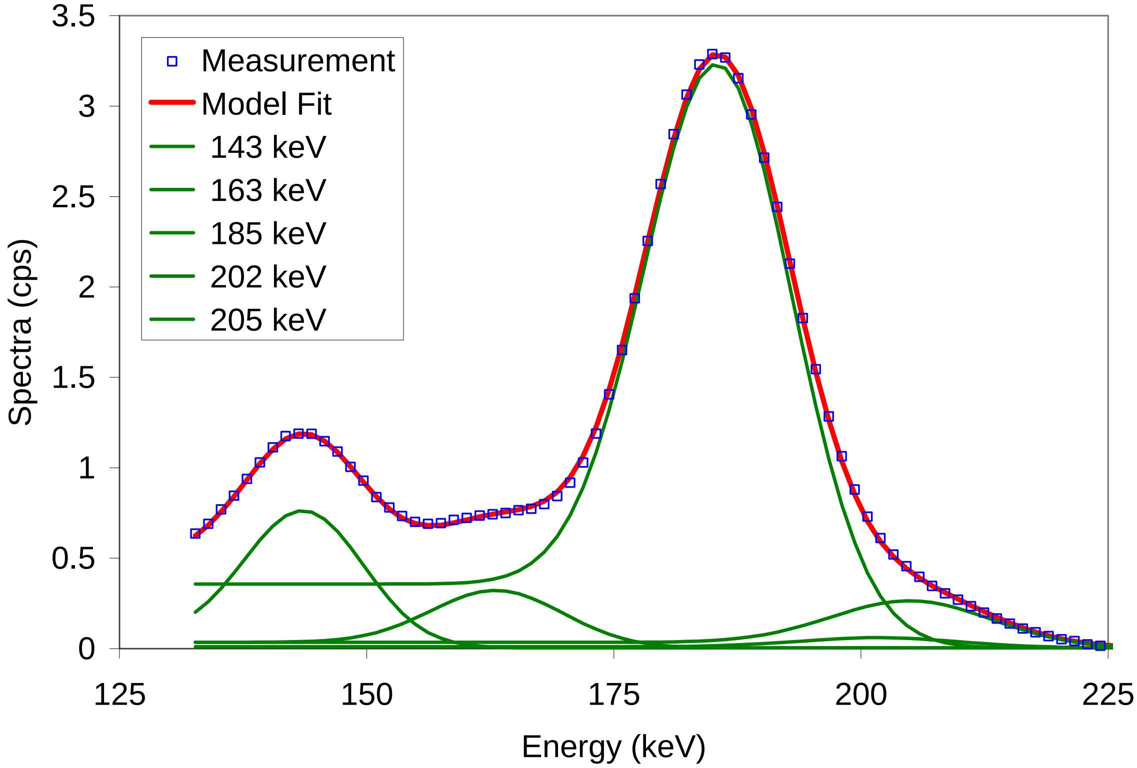

Fig. 17. Spectral data and fit components for Case 11: ORNL 4" loop condition P37, Unit 0.

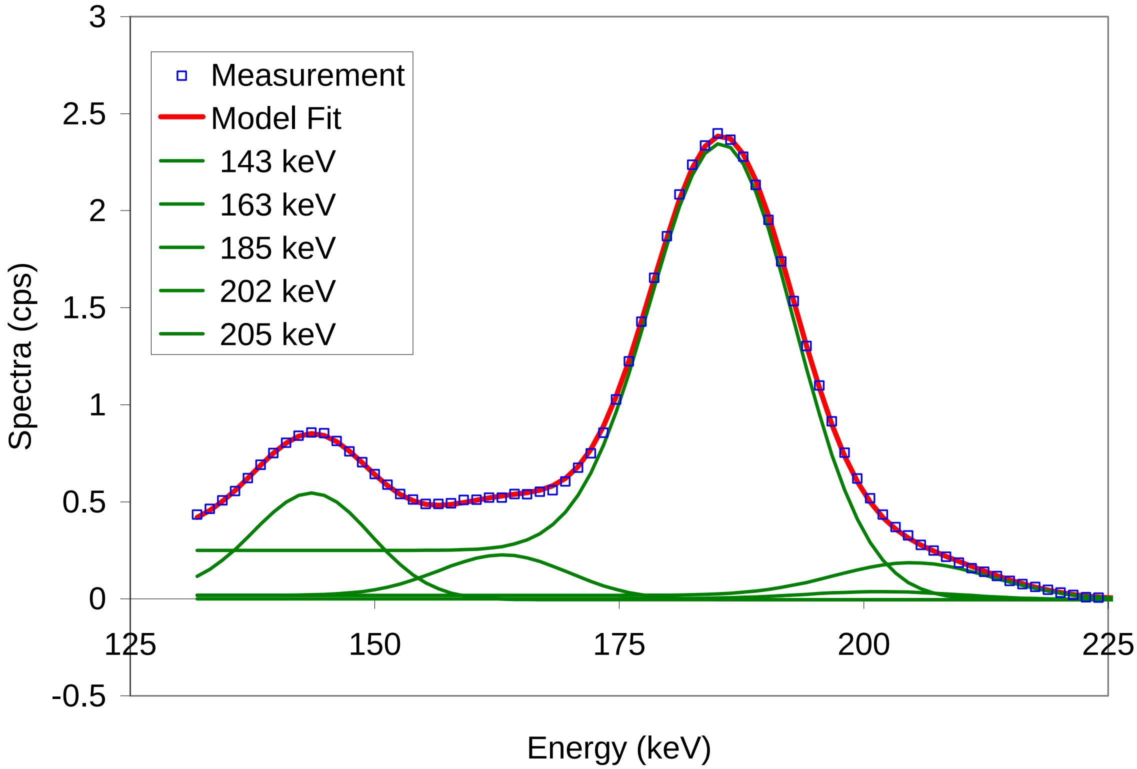

Fig. 18. Spectral data and fit components for Case 12: ORNL 4” loop condition P27, Unit 0.

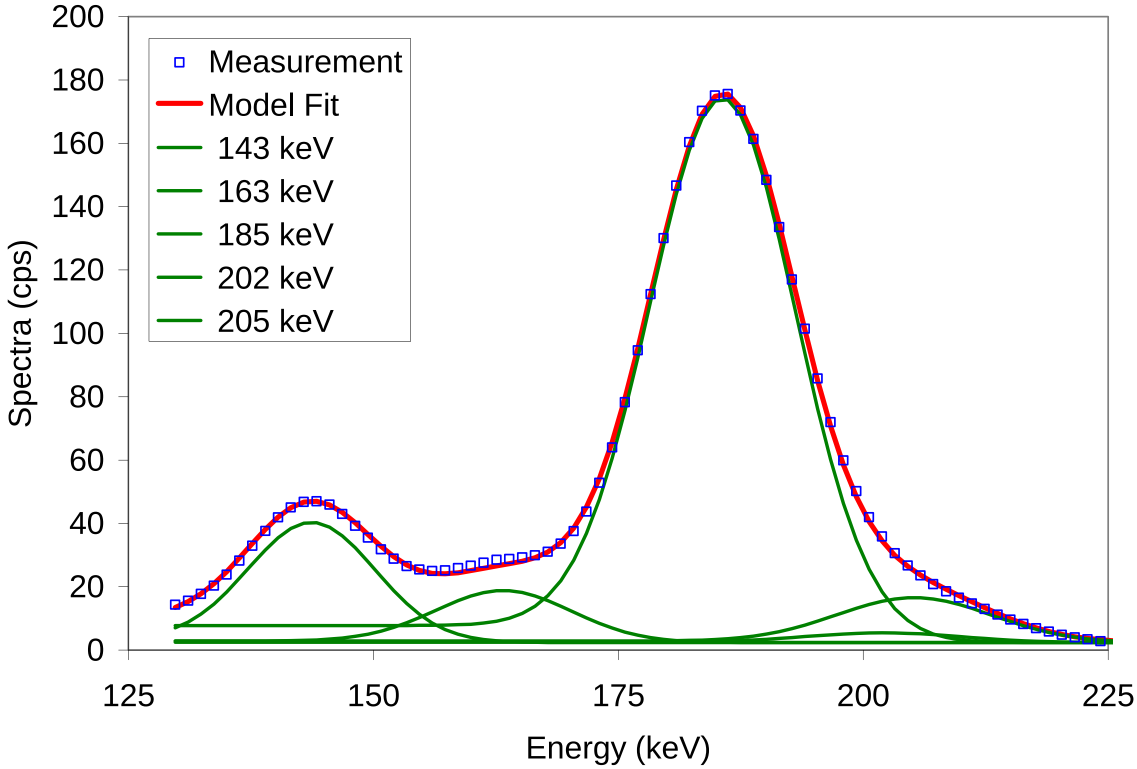

Fig. 19. Spectral data and fit components for Case 14: ORNL HEU foil, Unit 1.

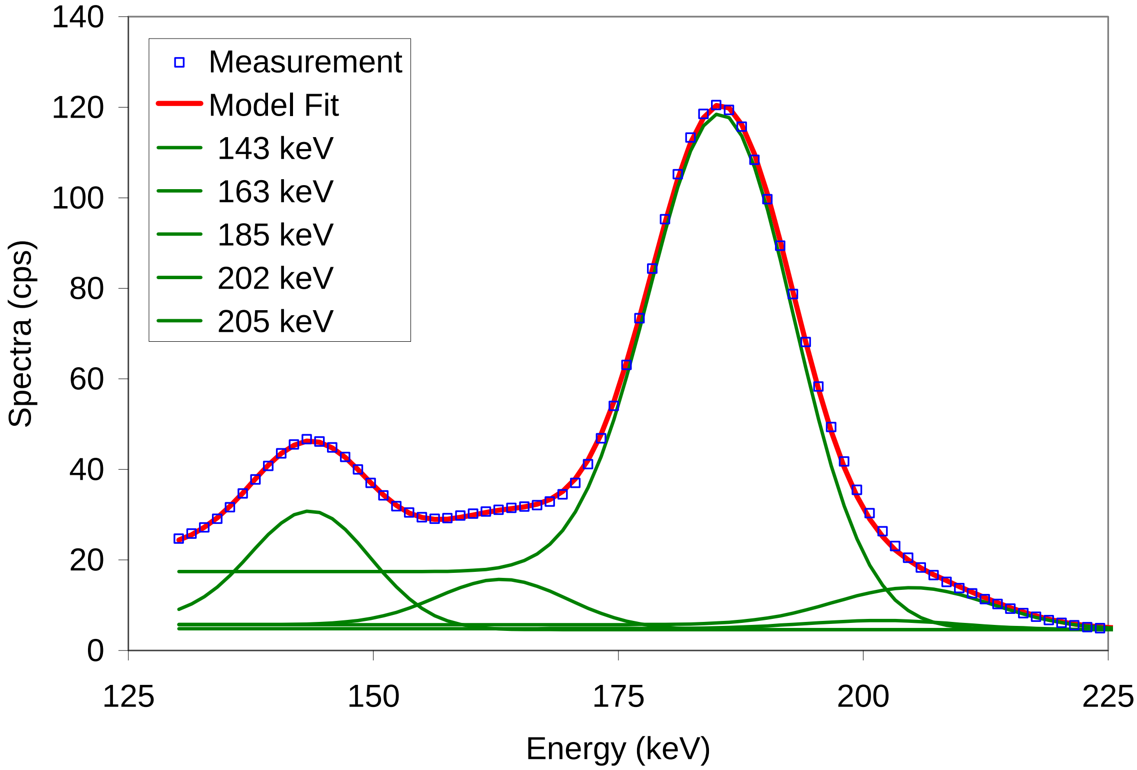

Fig. 20. Spectral data and fit components for Case 15: HEU fission chamber, Unit 1.

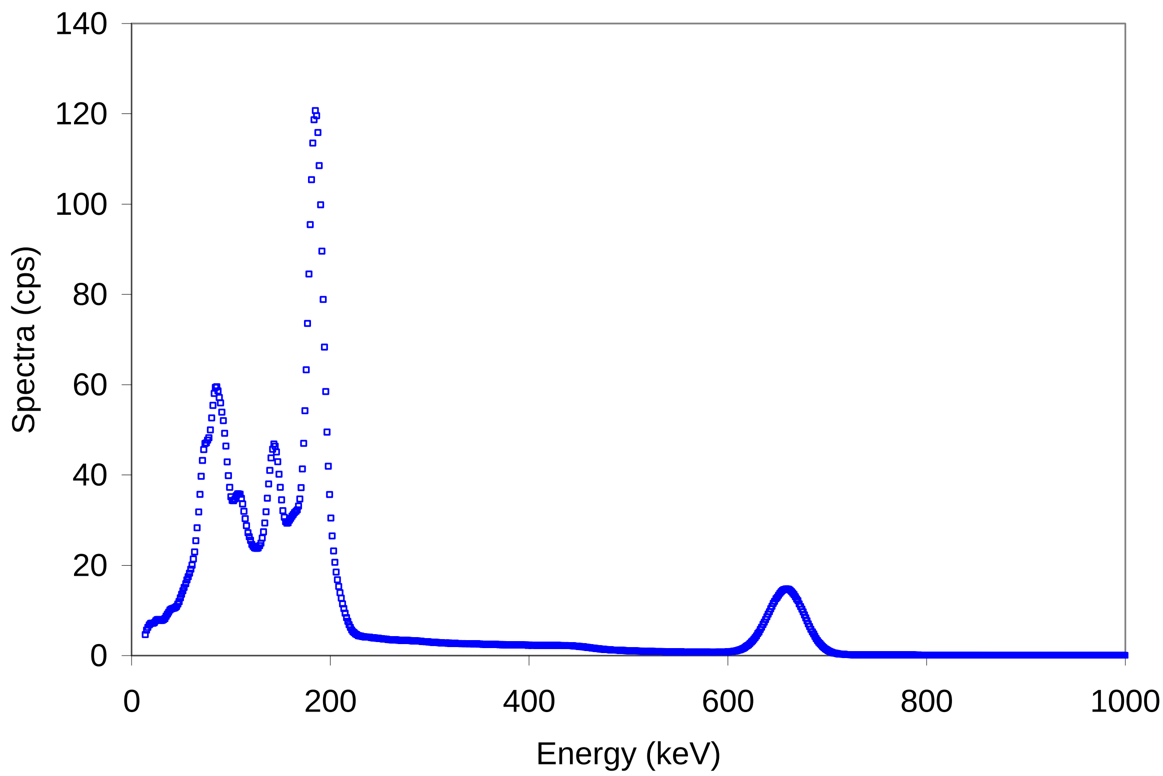

Fig. 21. Spectrum for Case 15, HEU fission chamber, showing the 661 keV Cs contamination.

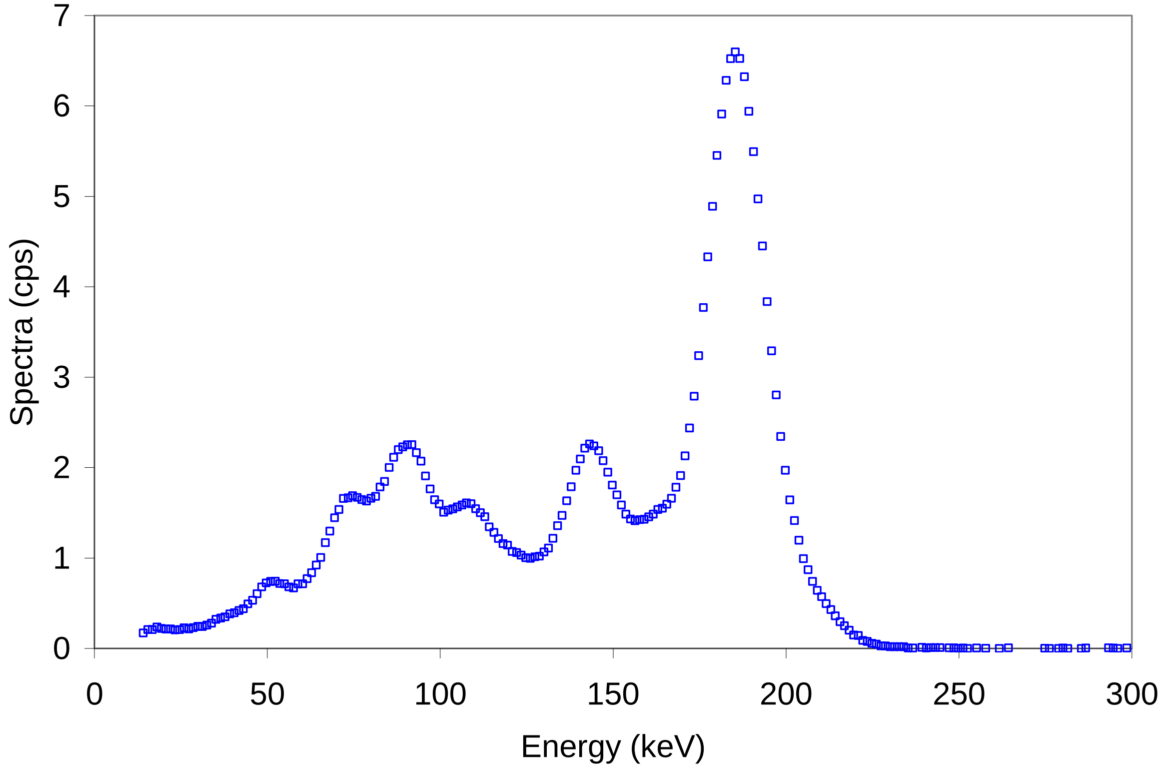

Fig. 22. ^{235}U spectrum for Case 6: 47 Tor of partial UF_6 pressure in an Al 8 in. pipe.

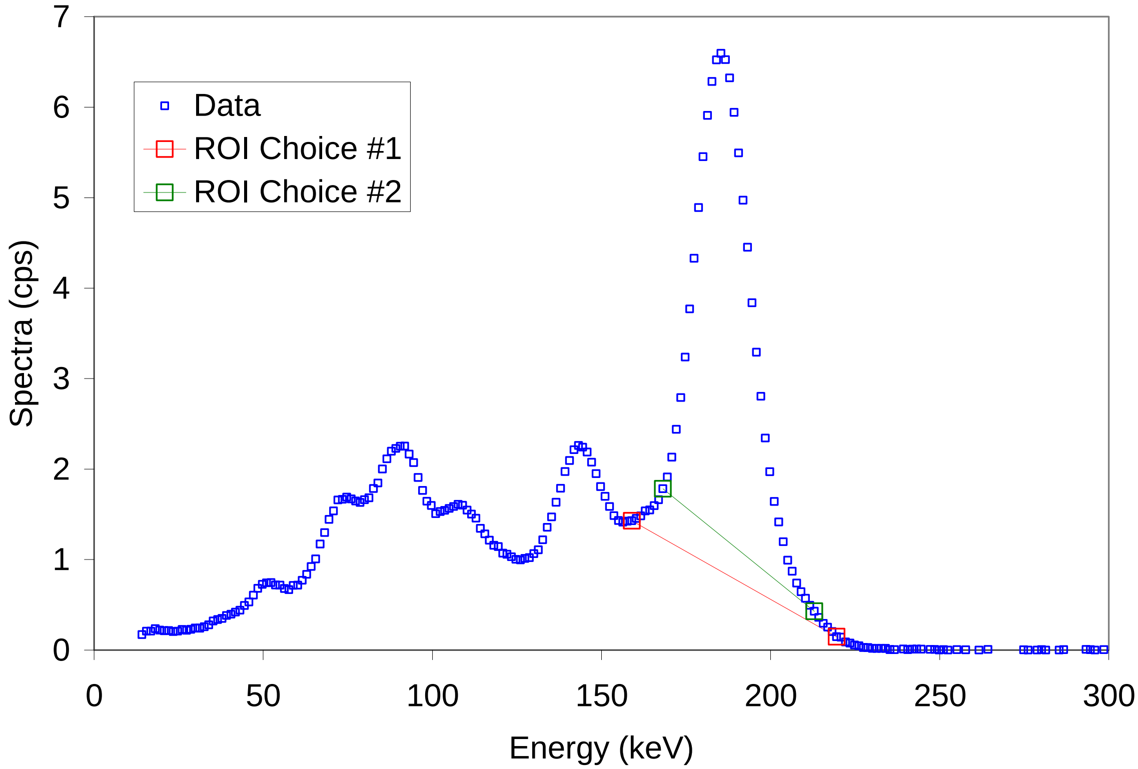

Fig. 23. ^{235}U spectrum showing two possible ROI choices that result in different 186 cps.

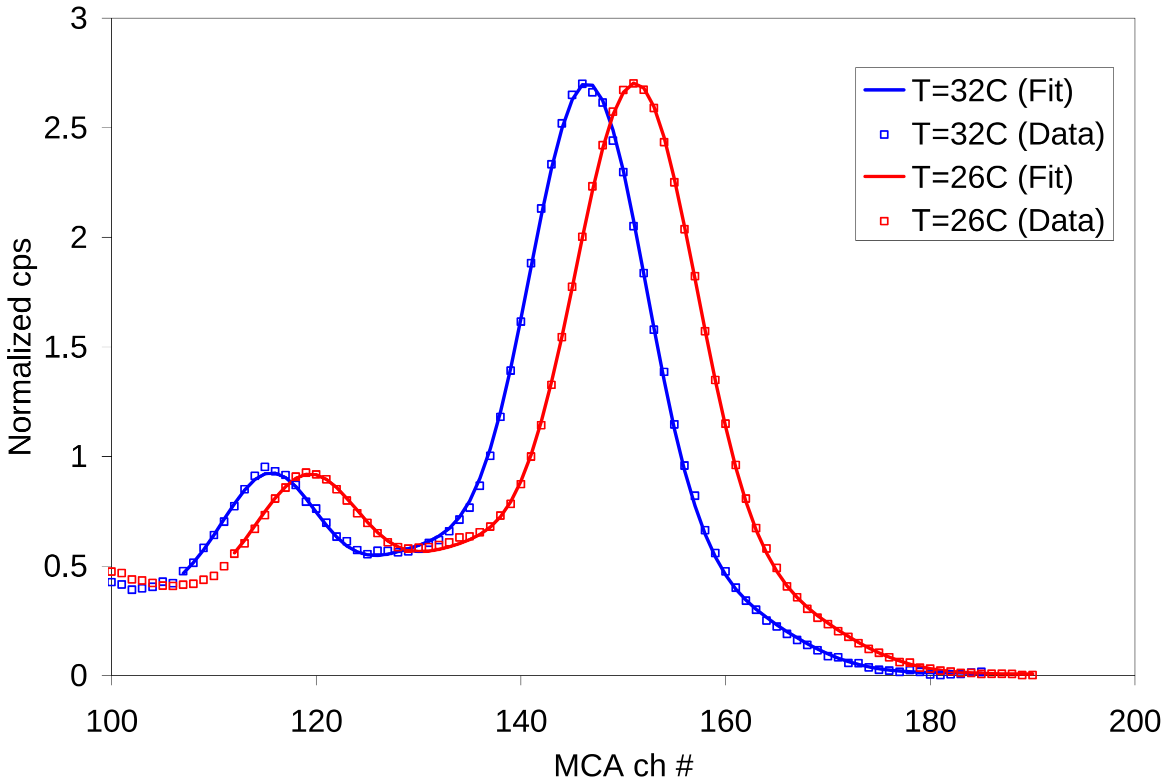

Fig. 24. Normalized UF_6 spectrum at two different temperatures. The MCA channel number for the peak changes.

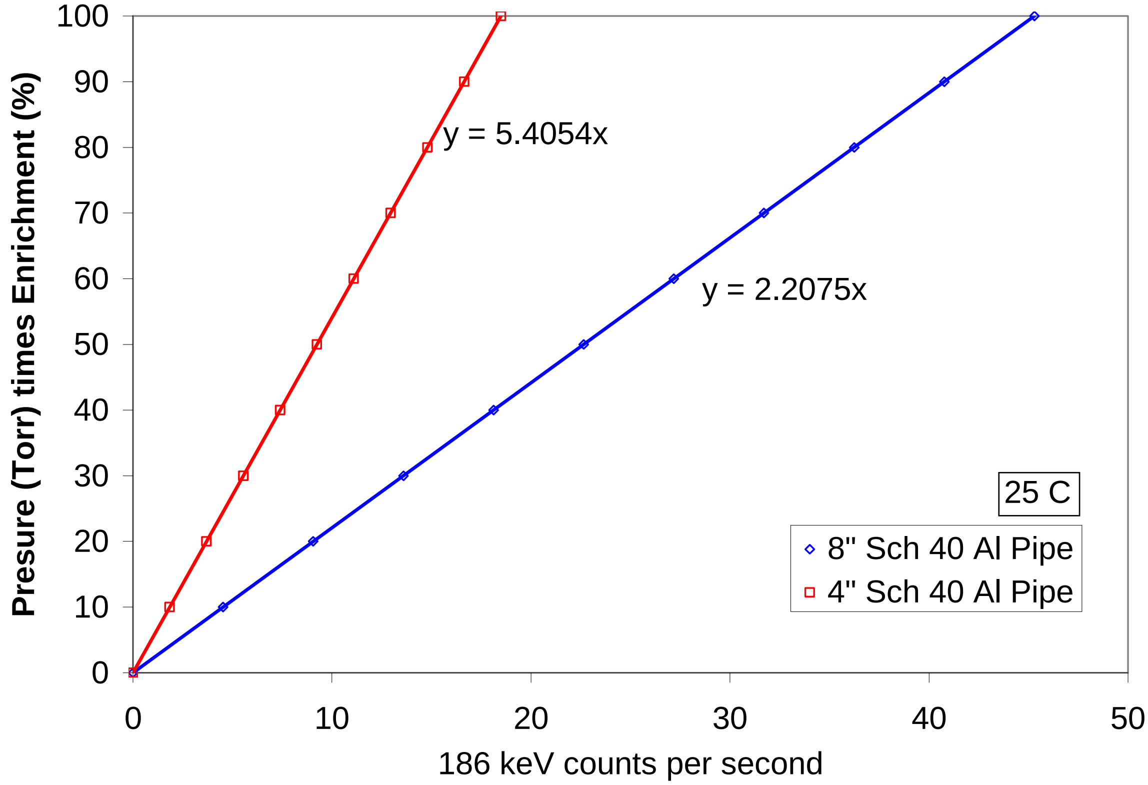

Fig. 25. Calibration factor. 186 keV cps for given pressure and enrichment at 25°C.

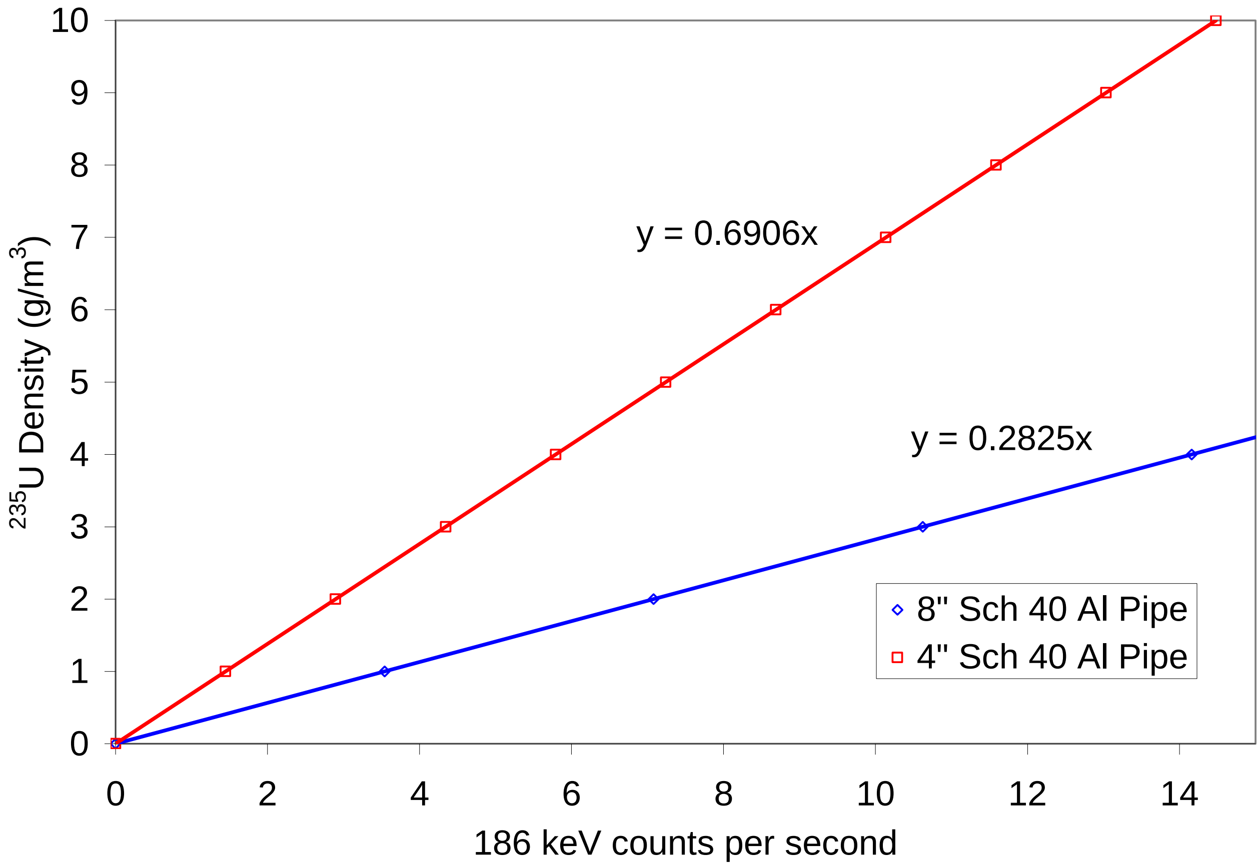

Fig. 26. Calibration factor. U-235 density for given 186 keV cps.

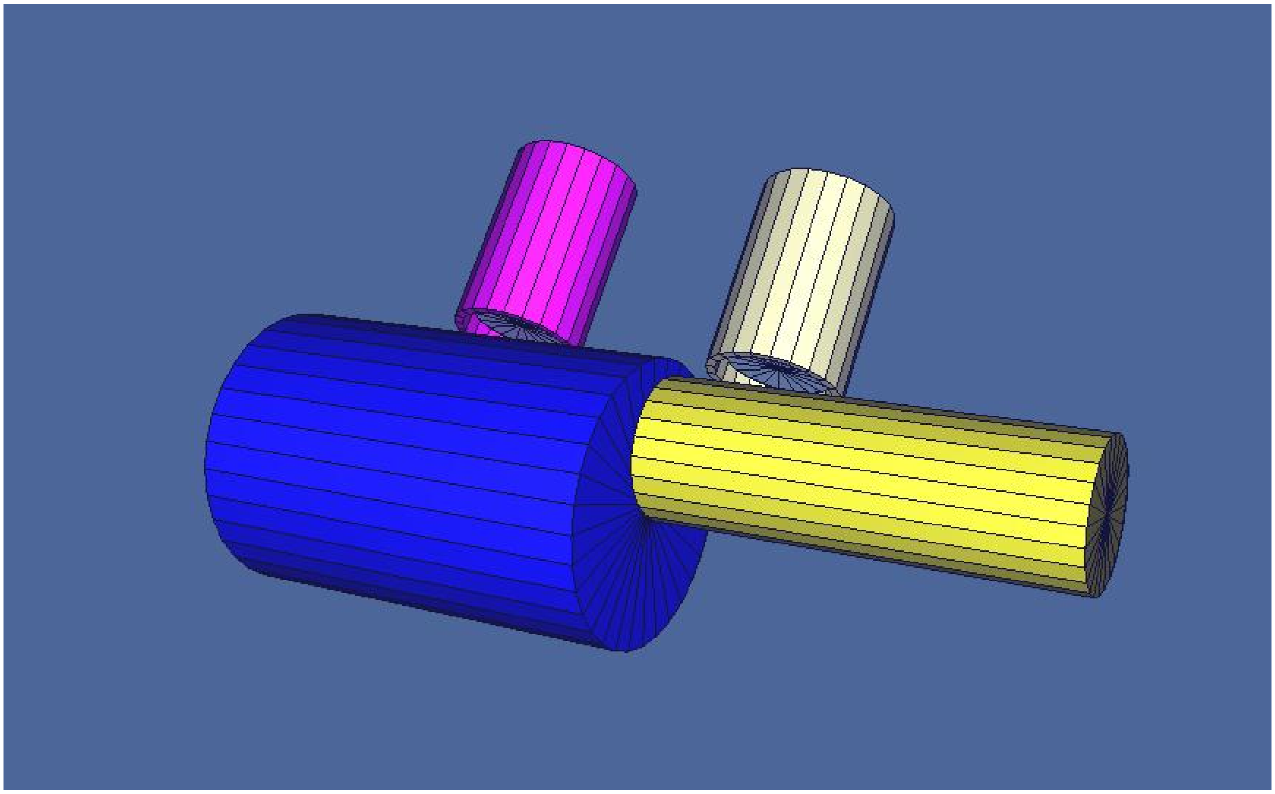

Fig. 27. MCNP geometry model of FM scintillation detectors on ORNL UF_6 flow loop.

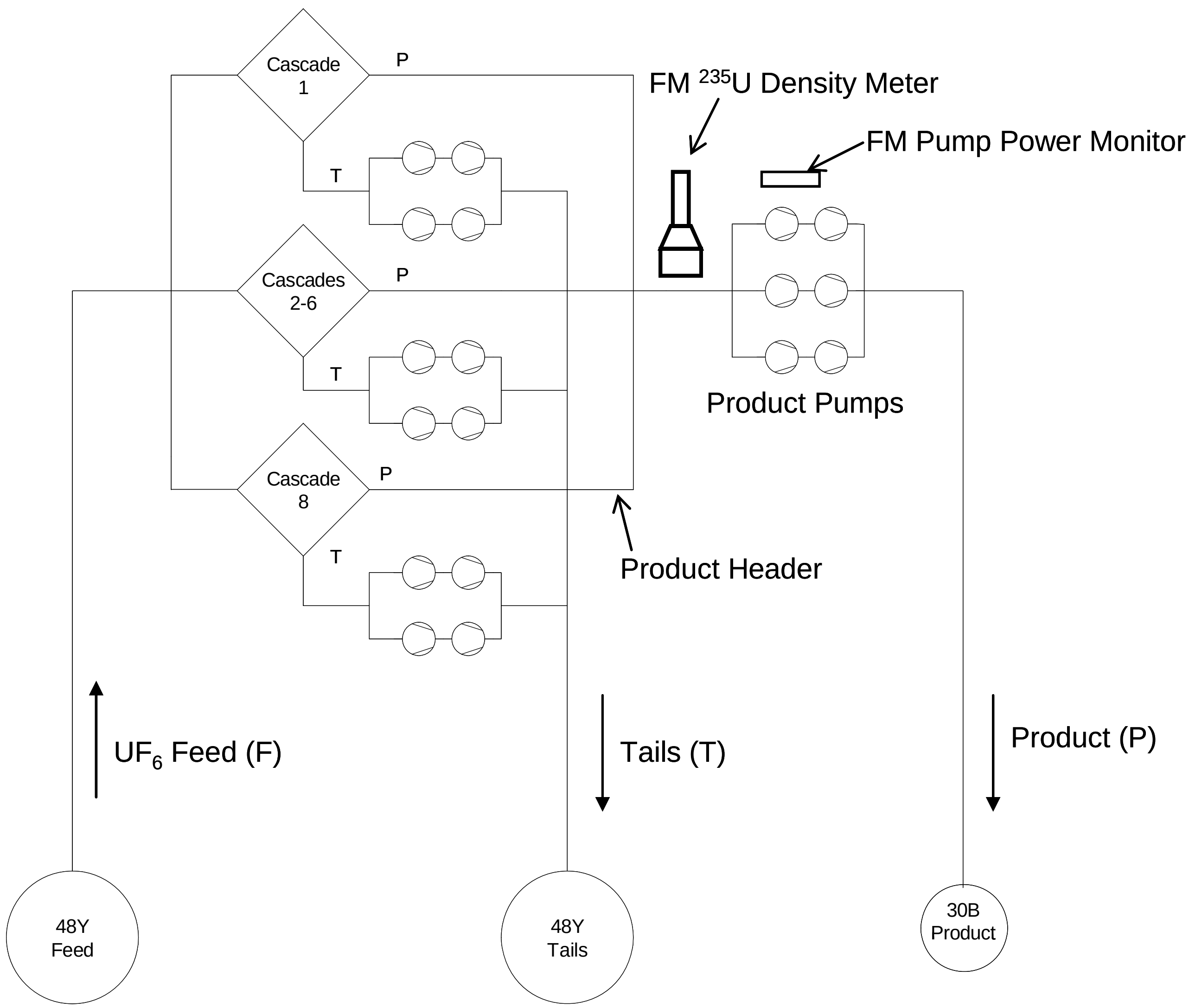

Fig. 28. Schematic arrangement showing location of FM components on a typical GCEP.

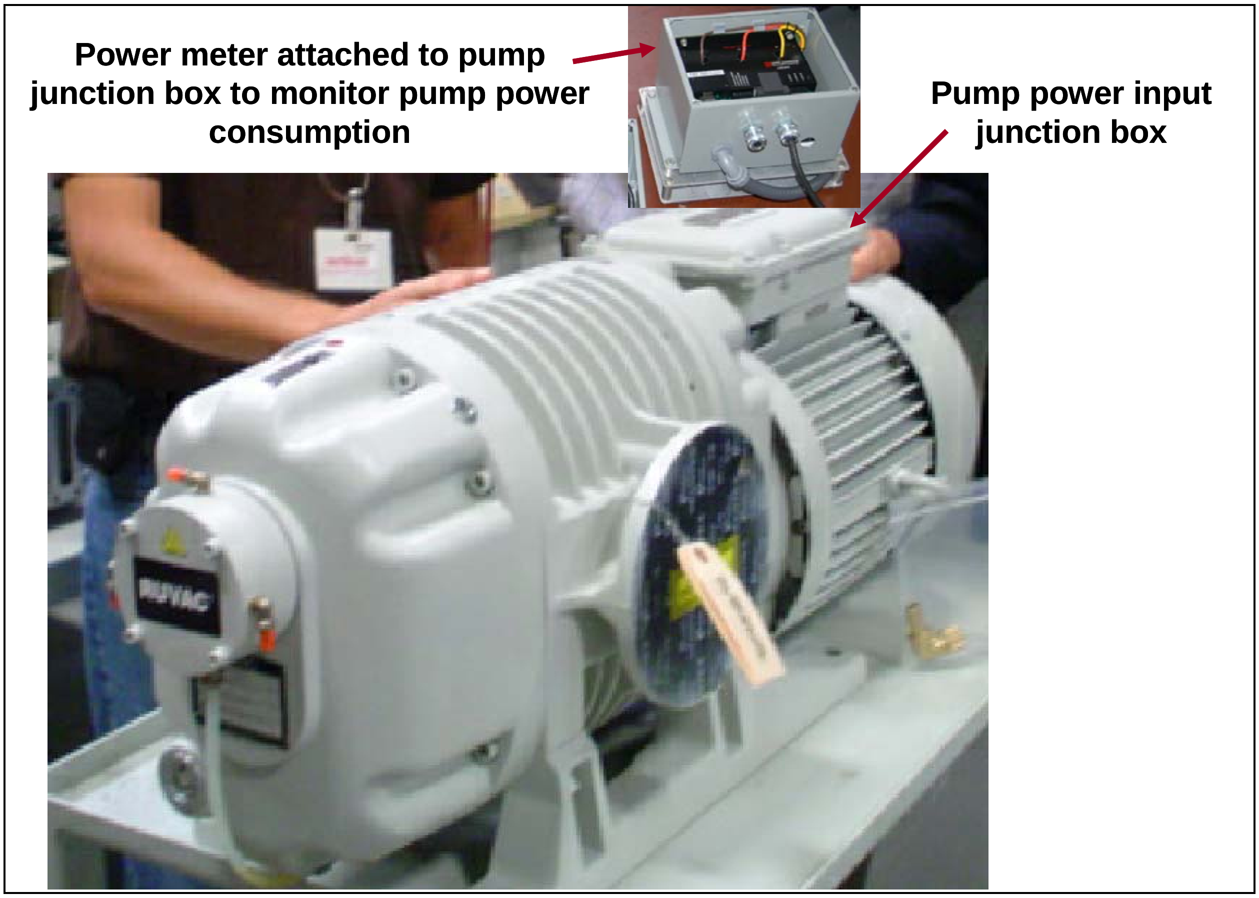

Fig. 29. Location of FM pump power monitor on pump.

APPENDIX: MCNP INPUT FILES

This appendix provides three of the input files for the MCNP computer code that modeled the configurations described in the report.

Input File for ORNL 4" pipe at 47 Torr

```
MCNP FEMO model
c     ---------------------------Cell Cards----------------------------
c
10    1 -0.000866555  -99 -10           imp:p=1  $UF6 Gas
11    2 -2.70        10 -11 -99         imp:p=1  $Aluminum Pipe
20    3 -4.404       -20 80 -81         imp:p=1  $Scintillator Crystal
c 21    5 -0.001293    -21 20 80 -81      imp:p=1  $Air Gap
22    4 -11.34       -22 21 79 -82      imp:p=1  $Lead Housing
23    0              -21 81 -82         imp:p=0  $vacuum behind crystal
98     5 -0.001293 (-99 #10 #11 #20 #22 #23):
            (-21 20 80 -81 ) imp:p=1 $air air everywhere
99     0          99  imp:p=0 $Outside Universe
c     -----------------------------------------------------------------
c     Specs: 4 inch Sch 40 Aluminum pipe with
c     .237 inch thickness (4.500 inch O.D.)
c     3 inch x 3 inch Sodium Iodide crystals
c     .25 inch thick lead shields, 3.340 inch I.D., 3.84 inch O.D.
c     0.17 inch air gap between shields and crystals
c     0.5 inch gap between pipe and crystals

c
c     ----------------------------Surface Cards--------------------------
c
79    pz   6                        $Bottom of lead shield
80    pz   7.27                     $bottom of all detectors
81    pz   14.89                    $top of crystals, air/vac. boundary
82    pz   20.4                      $top of lead shields
10    cy   5.11302                   $UF6 Gas
11    cy   5.71500                    $Aluminum Tube
20    c/z  0 0 3.81          $Scintillator Crystal
21    c/z  0 0 4.2418        $Air Gap
22    c/z  0 0 4.8768        $Lead Housing
99    rcc  0 -200 0 0 400 0 35       $Universe Boundary

c
c     ---------------------------Data Cards------------------------------
c
mode p
print
nps 1E8
c
c      ---------------------Tally on Scintillation counters----------------
c
c      ------------Energy Deposition per gamma emitted w/ GEB
```

```
f8:p   20
ft8 geb  0.00219292 0.0331461 1.39417 $Gaussian Energy Broadening
c      Bins
e8     0.00 0.001 755i 0.757 100 $Bin
sd8    1 $sets cell area to unity
c      ------------Energy Deposition per gamma emitted
f18:p   20
c      Bins
e18     0.00 0.001 755i 0.757 100 $Bin
sd18    1 $sets cell area to unity
c      -----------------------Flux thru pipe
f1:p   10 11
sd1    1   1
c      -----------------------Flux into detectors by energy
f4:p   20
e4 0.0 199i 2.0
sd4    1
c     ------------------------------Materials----------------------------
c     --------UF6
m1    9000. -0.323990047
      92238. -0.639856851
      92235. -0.036153102
c     --------Aluminum Pipe
m2    13000. -1.00
c     --------Na-I Crystal
m3    11000. 1.0
      53000. 1.0
c     --------Lead Housing
m4    82000. -1.00
c     --------Air
m5    7014. -0.78
      8016. -0.22
c     --------------------------------The Source-------------------------
sdef   cel=10 par=2 erg 0.185715 rad=d3 ext=d4  pos=0 0 0 axs=0 1 0
c
c      *UF6 source in cell 10 with energy defined by d2 and sampling cylinder of
height d4
C      *extending in the y-axis direction with a radius defined by d3
c
si3 0 5.11302      $Sampling cyl. inner, outer radii
sp3 -21 1        $Cylindrical Source Distribution
si4 -200 200     $H/2, half of sampling cyl. height
sp4 0 1
```

Input File for ORNL 8" pipe at 47 Torr

```
MCNP FEMO model
c     ---------------------------Cell Cards----------------------------
c
10    1 -0.000866555  -99 -10           imp:p=1  $UF6 Gas
11    2 -2.70        10 -11 -99         imp:p=1  $Aluminum Pipe
20    3 -4.404       -20 80 -81         imp:p=1  $Scintillator Crystal
c 21    5 -0.001293    -21 20 80 -81      imp:p=1  $Air Gap
22    4 -11.34       -22 21 79 -82      imp:p=1  $Lead Housing
23    0              -21 81 -82         imp:p=0  $vacuum behind crystal
98     5 -0.001293 (-99 #10 #11 #20 #22 #23):
           (-21 20 80 -81 ) imp:p=1 $air air everywhere
99     0         99  imp:p=0 $Outside Universe
c     -----------------------------------------------------------------
c     Specs: 8 inch Sch 40 Aluminum pipe with
c     .322 inch thickness (8.625 inch O.D.)
c     3 inch x 3 inch Sodium Iodide crystals
c     .25 inch thick lead shields, 3.340 inch I.D., 3.84 inch O.D.
c     0.17 inch air gap between shields and crystals
c     0.5 inch gap between pipe and crystals

c
c     ----------------------------Surface Cards--------------------------
c
79    pz   11                          $Bottom of lead shield
80    pz   12.27                       $bottom of all detectors
81    pz   19.89                      $top of crystals, air/vac. boundary
82    pz   25.4                        $top of lead shields
10    cy   10.13587                      $UF6 Gas
11    cy   10.95375                      $Aluminum Tube
20    c/z  0 0 3.81           $Scintillator Crystal
21    c/z  0 0 4.2418         $Air Gap
22    c/z  0 0 4.8768         $Lead Housing
99    rcc  0 -200 0 0 400 0 35       $Universe Boundary

c
c     ---------------------------Data Cards------------------------------
c
mode p
print
nps 1E8
c
c      ---------------------Tally on Scintillation counters----------------
c
c      ------------Energy Deposition per gamma emitted w/ GEB
f8:p   20
ft8 geb  0.00219292 0.0331461 1.39417 $Gaussian Energy Broadening
c      Bins
e8     0.00 0.001 755i 0.757 100 $Bin
sd8    1 $sets cell area to unity
c      ------------Energy Deposition per gamma emitted
f18:p   20
c      Bins
```

```
e18      0.00 0.001 755i 0.757 100 $Bin
sd18     1 $sets cell area to unity
c       -----------------------Flux thru pipe
f1:p    10 11
sd1     1   1
c       -----------------------Flux into detectors by energy
f4:p    20
e4 0.0 199i 2.0
sd4     1
c      ------------------------------Materials----------------------------
c      --------UF6
m1     9000. -0.323990047
       92238. -0.639856851
       92235. -0.036153102
c      --------Aluminum Pipe
m2     13000. -1.00
c      --------Na-I Crystal
m3     11000. 1.0
       53000. 1.0
c      --------Lead Housing
m4     82000. -1.00
c      --------Air
m5     7014. -0.78
       8016. -0.22
c      --------------------------------The Source-------------------------
sdef    cel=10 par=2 erg 0.185715 rad=d3 ext=d4  pos=0 0 0 axs=0 1 0
c
c       *UF6 source in cell 10 with energy defined by d2 and sampling cylinder of
height d4
C       *extending in the y-axis direction with a radius defined by d3
c
si3 0 10.13       $Sampling cyl. inner, outer radii
sp3 -21 1         $Cylindrical Source Distribution
si4 -200 200      $H/2, half of sampling cyl. height
sp4 0 1
```

Input File for LANL 4" pipe at 31 Torr

```
MCNP FEMO model
c     ---------------------------Cell Cards----------------------------
c
10    1 -0.000573442  -99 -10 30 -31           imp:p=1  $UF6 Gas
11    2 -2.70        10 -11 -99 30 -31         imp:p=1  $Aluminum Pipe
20    3 -4.404       -20 80 -81         imp:p=1  $Scintillator Crystal
c 21    5 -0.001293    -21 20 80 -81      imp:p=1  $Air Gap
22    4 -11.34       -22 21 79 -82      imp:p=1  $Lead Housing
23    0              -21 81 -82         imp:p=0  $vacuum behind crystal
98     5 -0.001293 (-99 #10 #11 #20 #22 #23):
            (-21 20 80 -81 ) imp:p=1 $air air everywhere
99     0         99  imp:p=0 $Outside Universe
c     -----------------------------------------------------------------
c     Specs: 4 inch Sch 40 Aluminum pipe with
c     .237 inch thickness (4.500 inch O.D.) 1m length
c     3 inch x 3 inch Sodium Iodide crystal, 12" from edge of pipe
c     .25 inch thick lead shields, 3.340 inch I.D., 3.84 inch O.D.
c     0.17 inch air gap between shields and crystals
c     0.5 inch gap between pipe and crystals

c
c     ----------------------------Surface Cards--------------------------
c
79    pz   6                        $Bottom of lead shield
80    pz   7.27                     $bottom of all detectors
81    pz   14.89                    $top of crystals, air/vac. boundary
82    pz   20.4                      $top of lead shields
10    cy   5.11302                   $UF6 Gas
11    cy   5.71500                    $Aluminum Tube
20    c/z  0 0 3.81          $Scintillator Crystal
21    c/z  0 0 4.2418        $Air Gap
22    c/z  0 0 4.8768        $Lead Housing
30    py   -20.32            $Start of pipe
31    py   79.68             $End of pipe
99    rcc  0 -200 0 0 400 0 35      $Universe Boundary

c
c     ---------------------------Data Cards-----------------------------
c
mode p
print
nps 1E8
c
c      ---------------------Tally on Scintillation counters----------------
c
c      ------------Energy Deposition per gamma emitted w/ GEB
f8:p   20
ft8 geb  0.00219292 0.0331461 1.39417 $Gaussian Energy Broadening
c      Bins
e8     0.00 0.001 755i 0.757 100 $Bin
sd8    1 $sets cell area to unity
c      ------------Energy Deposition per gamma emitted
f18:p   20
```

```
c       Bins
e18      0.00 0.001 755i 0.757 100 $Bin
sd18     1 $sets cell area to unity
c       -----------------------Flux thru pipe
f1:p    10 11
sd1     1   1
c       -----------------------Flux into detectors by energy
f4:p    20
e4 0.0 199i 2.0
sd4     1
c      ------------------------------Materials----------------------------
c      --------UF6
m1     9000. -0.323990047
       92238. -0.639856851
       92235. -0.036153102
c      --------Aluminum Pipe
m2     13000. -1.00
c      --------Na-I Crystal
m3     11000. 1.0
       53000. 1.0
c      --------Lead Housing
m4     82000. -1.00
c      --------Air
m5     7014. -0.78
       8016. -0.22
c      --------------------------------The Source-------------------------
sdef    cel=10 par=2 erg 0.185715 rad=d3 ext=d4  pos=0 0 0 axs=0 1 0
c
c       *UF6 source in cell 10 with energy defined by d2 and sampling cylinder of
height d4
C       *extending in the y-axis direction with a radius defined by d3
c
si3 0 5.11302      $Sampling cyl. inner, outer radii
sp3 -21 1        $Cylindrical Source Distribution
si4 -20.32 79.68     $H/2, half of sampling cyl. height
sp4 0 1
```