FISSILE MASS FLOW MONITOR GAMMA RAY DETECTOR SYSTEM DESIGNED FOR LARGE-SIZE PROCESS PIPES

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Abstract
In this paper, a detailed design description and the performance characteristics are presented for the gamma ray detector system developed for the fissile mass flow monitor (FMFM) to be used on 8-in.-diam process pipes. The FMFM continuously measures the ^{235}U fissile mass flow rate of a UF_6 gas stream. It uses moderated and modulated ^{252}Cf neutron sources for fission activation of the UF_6 gas. Four pairs of bismuth germinate (BGO) scintillation detectors are placed around the process pipe (on the top, bottom, front, and back) downstream of the neutron sources so that a high detection efficiency can be achieved for measuring the delayed gammas (> 0.3 MeV) emitted from the fission fragments in the stream for the flow measurements. The BGO crystal was selected because it is a novel scintillation material (a rugged, nonhygroscopic, neutron-insensitive, high-density, and high-*Z* material) with high absorption (stopping) power and because it has high peak photoefficiency for high-energy gammas. Each 4-in.-diam, 2-in.-thick BGO scintillation crystal is coupled to a 3-in.-diam photomultiplier tube (PMT). Both are shielded with lead to reduce the background signal. Each detector pair is housed in a metal enclosure that also contains an electronics board for signal shaping and counting. The front-end electronics boards independently amplify and shape the detector signals before they are summed. The combined signal is then fed into two single-channel analyzers (SCAs), which separate the pulses into low- and high-energy bands and subsequently determine the count rate in each band. A local area network node for providing secure data transmission to the FMFM computer and a local temperature sensor are also parts of each detector electronics board. The temperature response of the detector signal resulting from the intrinsic temperature coefficient of each BGO-PMT assembly is used for real-time corrections of the system by monitoring the 186-keV spectrum line of ^{235}U obtained with the lower-energy SCA. The lower-energy SCA is also scanned during manual detector energy calibration to capture 186- or 96-keV spectral lines from the UF_6, depending upon its enrichment. The higher-energy SCA output provides for the measurement of the 0.3- to 2-MeV delayed gamma ray signal from the fission fragments in the UF_6 stream.

Introduction
The fissile mass flow monitor (FMFM) is designed to continuously measure the ^{235}U fissile mass flow rate of a UF_6 gas stream. The fissile mass flow rate measurement principle relies on detecting "delayed" gamma rays, which are emitted from fission fragments carried by the UF_6 flow. The fissions that produce the fragments are caused by active neutron interrogation. Neutron sources (^{252}Cf) are placed in annular sleeves filled with moderator material (high-density polyethylene) that surrounds the pipe, as illustrated schematically in Figure 1. A neutron-

* Managed by UT-Battelle for the U.S. Department of Energy under contract DE-AC05-00OR22725

absorbing shutter is used to time-modulate the induced fissions (see Figure 1) to create a time signature in the UF_6 gas flow. A gamma-ray-sensitive detector, located downstream of the sources (see Figure 1), measures delayed gamma rays (> 0.3 MeV) emitted by the resulting fission fragments. Then, the FMFM determines the fissile mass flow rate from two independent measurements: (1) the observed delay in the time-correlated measurement between the source modulator and the detector signal provides the velocity of the UF_6, and (2) the signal's amplitude is related to the ^{235}U concentration in the UF_6. The details of the FMFM models employed to predict the detector response are discussed in an earlier publication [1]. The earlier FMFM was designed for 4-in.-diam UF_6 process pipes. In this paper, a detailed design description and the performance characteristics are presented for the FMFM gamma ray detector system developed to be used on 8-in.-diam process pipes.

FMFM Detector System

In the case of low enriched UF_6 flow measurements, or for short process durations, the detector signal, N_s, from the delay gamma rays needs to be increased in order to achieve the measurements within a short period of time (less than the process duration) with statistically acceptable measurement results (measurement confidence level > 90%) since the measurement convergence time $\tau_c \sim N_b / N_s^2$, where N_b is the room background. This is only possible by increasing the delay gamma ray source that results from the fission activation of the UF_6 flowing in the process pipe. Using a higher neutron source strength of ^{252}Cf is not viable option because the facility dose rate requirement must be maintained. Therefore, the desired higher detector signal, N_s, is achieved by increasing the active volume of the fission process (i.e., using a larger-diameter process pipe) and thus having a higher volume of fission fragments flowing in the UF_6 gas stream. In order to take advantage of the large-diameter pipe, more detectors are needed than the number used in the 4-in.-diam pipe FMFM system. Increasing the number of detectors results in a higher detection efficiency, which results in a higher detection signal, N_s, because the value of N_s is related to the solid angle, Ω_d, of the detector as seen from the gamma ray source. (Here, Ω_d is defined by an integral over the detector area that faces the gamma ray source.)

As shown in Figure 1, four pairs of bismuth germinate (BGO) scintillation detectors are placed around the process pipe (on the top, bottom, front, and back) downstream of the neutron sources so that higher detector detection efficiency can be achieved for measuring the delayed gammas. The BGO scintillation crystal was selected because it is a novel scintillation material with high absorption (stopping) power due to its high density ($\rho = 7.3$ g/cm^3) and because the high atomic number of bismuth ($Z = 83$) results in high peak photoefficiency for the high-energy (> 0.3 MeV) delay gamma rays. In addition, BGO has very low neutron activation characteristics. This is an important feature because the detectors are placed close to the source modulator that houses the ^{252}Cf-neutron sources (see Figure 1). Each 4-in.-diam, 2-in.-thick BGO scintillation crystal is coupled to a 3-in.-diam photomultiplier tube (PMT) housed in a container made of a nonmagnetic material, as shown in Figure 2 (St. Gobain Crystals and Detectors, Inc., Newbury, Ohio). The PMT dynodes are biased with a commercially available ORTEC Model 276 tube base that also contains signal-integrating preamplifier circuitry, which has very fast rise time (< 100 nanoseconds) with a decay time constant of 50 microseconds (ORTEC, Oak Ridge, Tenn.). The PMT operation requires high voltage, +1000-VDC; the detector preamplifier operates with ± 24-VDC.

Figure 3 is a diagram of one detector housing, or subassembly, for an 8-in.-diam process pipe. Each detector housing is designed to hold dual detectors (labeled "Detector A" and "Detector

B”). One housing is placed on the top, bottom, front, and back of the process pipe. This design is an extension of the one developed for the 4-in.-diam pipe FMFM, in which a single detector in each housing provides the optimum configuration for the pipe size. For the 8-in. pipe, high detector efficiency is achieved by increasing the number of detectors from total of four to eight in the FMFM assembly.

FMFM Detector Electronics
Each FMFM detector housing contains an electronics card for signal pulse shaping and counting [2] (see Figure 3). This front-end detector interface electronics card (DIEC) independently amplifies and shapes the detector signals coming out of the preamplifier before they are summed. The variable gain shaping amplifier (VGA) consists of CR^2-RC^5 two-pole low-pass filters [3] that generate a bipolar output signal with a zero-crossing time of about 2.5 microseconds. The signal is needed for the next-stage pulse-counting circuitry. The gain control of the shaping amplifier is accomplished by 64-bit variable attenuator with the attenuation range of 5:1. The attenuator is controlled by the FMFM computer via a sensor network communication (SNC) card. The SNC is included in the part of the DIEC design, as shown in Figure 4. The combined shaped signal from the dual detectors is then fed into two parallel FMFM computer-controlled single-channel analyzers (SCAs). The signal from the summing amplifier (see Figure 4) is separated into a low- and high-energy bands with these two SCAs, and subsequently, each SCA provides the count rate for the each energy band of interest. The SCAs generate digital transistor-transistor logic (TTL) pulses (+5-VDC amplitude and ~6 microseconds wide) for data counting by the FMFM computer, as shown in Figure 4. The detailed architectural design of the SCAs is given in Ref. [4]. A photograph of the custom made DIEC with surface-mounted components is shown in Figure 5. When the data acquisition cycle, which is a data collection block time of 60 seconds, is started, the counts are read from the SCAs every 100 milliseconds and are stored in the SNC over 55 seconds. In the last 5 seconds, the collected data packet is sent to the FMFM computer for data processing.

The commercially available SNC card (Echelon Corp., Palo Alto, Calif.), which acts as an on-board computer, provides the local area network node for secure count data transmission to the FMFM computer (see Figure 4). In addition, the SNC card provides the computer gain control of the VGAs that is needed for the independent energy calibration of each of the detectors. In addition, each SNC has a unique programmed address that identifies the detector location on the detector assembly for consistent FMFM data acquisition and recording. The SCA lower and upper energy thresholds of the energy band are also controlled by the FMFM computer via the SNC card. The higher-energy SCA is used for obtaining the counts for the measurement of the 0.3- to 2-MeV delayed gamma-ray signal from the fission fragments in the UF_6 stream. The lower-energy SCA is set for the energy scan during the computer-controlled detector energy calibration to capture 186- or 96-keV spectral lines from the UF_6, depending upon its enrichment. When the FMFM computer is selected to perform the energy calibration, the lower-energy SCA is configured as a simple multichannel analyzer (MCA) by setting its energy window to a lower value (typically about 10 keV) and sweeping the window over its entire dynamic range (~500 keV). The operation of the DIEC requires ± 15 VDC; its SNC card needs + 8 VDC.

The signal response of the PMT and the BGO are very sensitive to local temperature variations. Local temperature measurements are provided by a sensor that is also a part of the DIEC (see

Figure 4). As discussed in detail in Ref. [4], the overall temperature response of the detector signal resulting from the intrinsic temperature coefficient of each BGO-PMT detector assembly is known and is utilized for real-time corrections of the detector response by monitoring the 186-keV spectrum line of ^{235}U obtained with the lower-energy SCA. The VGAs are adjusted accordingly to maintain the detector energy calibration. In addition, the aging of the PMT is corrected occasionally by using the built-in gain (5:1) adjustment of the VGAs; the technique is similar to that used for detector energy calibration.

The detailed engineering design drawing showing the cross-sectional view of the FMFM detector assembly is given in Figure 6. Both the BGO crystal and the PMT are shielded with the lead to reduce the room background signal, N_b, resulting from the inherent gamma ray emission from the ^{252}Cf and the radioactive capture gamma rays (~ 2.2-MeV) caused by the interaction of the source neutrons with the hydrogenous polyethylene. The shielding increases the signal-to-noise ratio (from the background radiation) and further improves the measurement convergence time, τ_c. Figure 7 shows the FMFM detector assembly and the detector signal power distribution box, where signals from all four detector subassemblies are summed and where the high- and low-voltage power supplies for the detectors are located.

Dual Detector Performance and Energy Calibration

The dual detector system has been tested, and it has been verified that even at high count rates (> 5 kcps), the total pulse count from each of the SCAs shows a count degradation of less than one percent from that of the same pulse sources counted separately. During calibration, the lower SCA window is set to a narrow width and is swept over the entire dynamic range of the SCA. The gain for each detector channel is determined with the other channel gain set to zero. After the calibration sweeps are done, both channel gains are set to their required levels. Figure 8 shows the energy calibration of the dual detectors when a 4% enriched uranium sample is placed under the detectors. The characteristic 186-keV spectral gamma ray peak of ^{235}U is clearly resolved and aligned for both detectors.

Conclusion

The FMFM detector design for 4-in.-diam process pipes has been successfully scaled up for 8-in.-diam process pipes. The dual-detector system design improves detection efficiency, thus enabling shorter measurement convergence times. The modified FMFM system will be-field implemented in late 2004.

References

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[2] G. P. Knoll, *Radiation Detection and Measurements 3rd Edition*, John Wiley and Sons, New York (2000).
[3] M. J. Paulus et al., *38th Annual INMM Meeting*, Phoenix, Arizona, July 20, 1997.
[4] M. J. Paulus et al., *Nuclear Science Symposium*, 1997.

[Figures and captions]

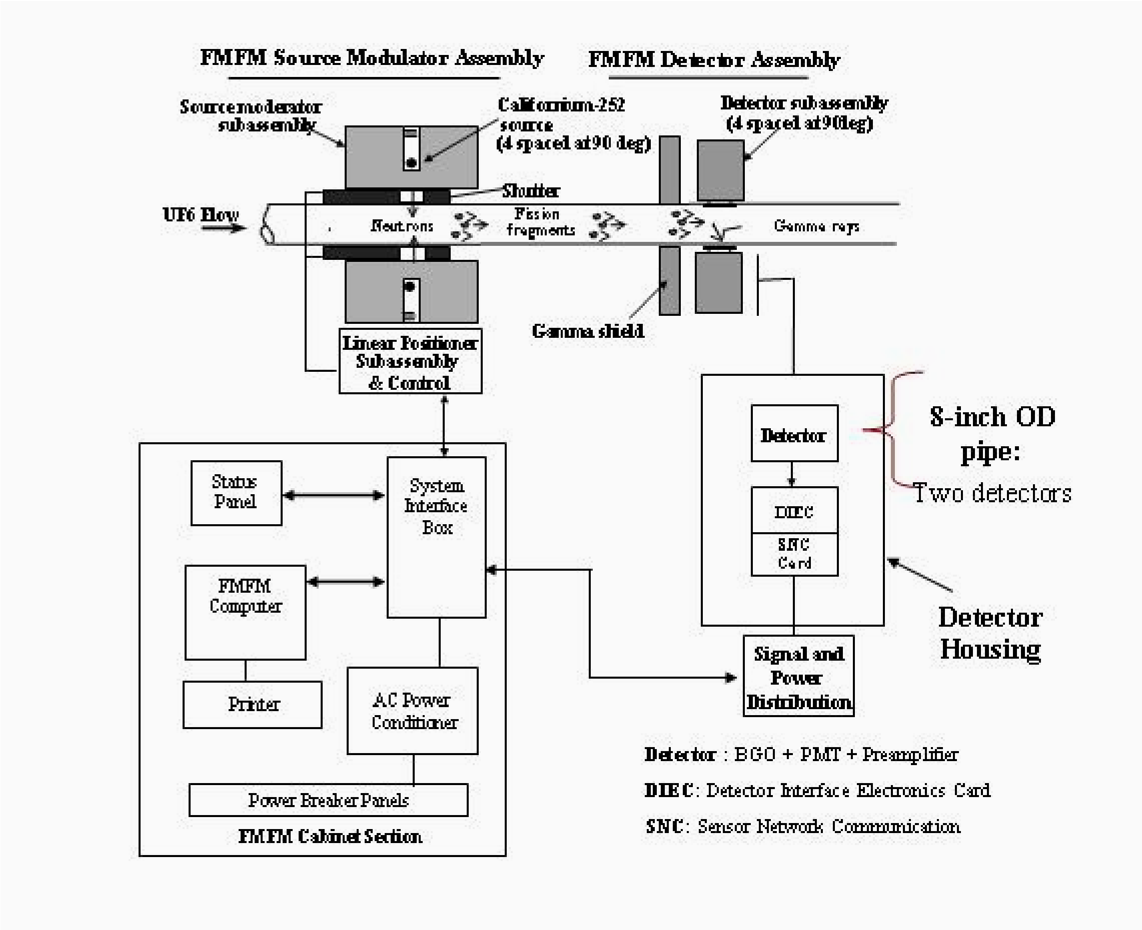

Figure 1. Fissile mass flow monitor operational principle and major components.

Figure 2. Fissile mass flow monitor gamma ray detector, composed of commercially available bismuth germinate scintillation detector and a preamplifier.

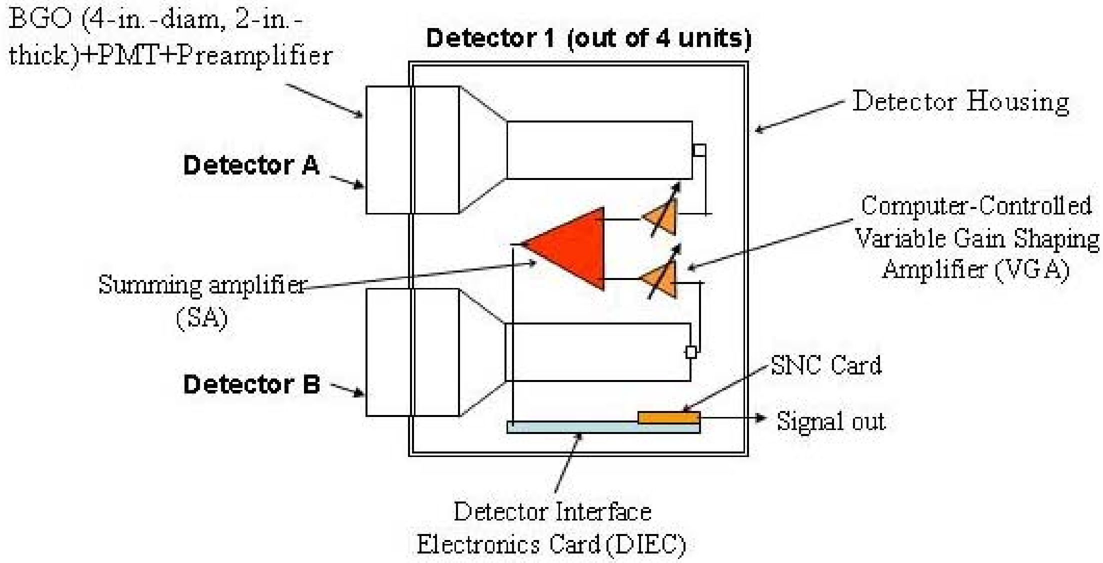

Figure 3. Housing for the dual bismuth germinate (BGO) detectors. The VGA and SA, shown separately, are part of the detector interface electronics card.

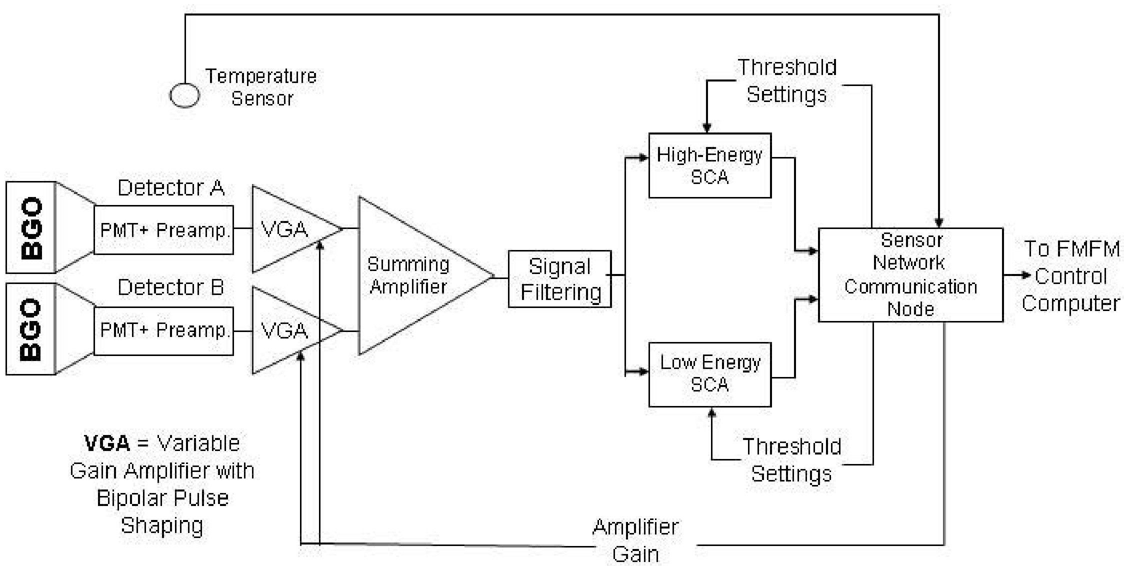

Figure 4. Schematic block diagram of the fissile mass flow monitor detector interface electronics card.

Figure 5. The custom-made detector interface electronics card with the sensor network communication card that mounts on it.

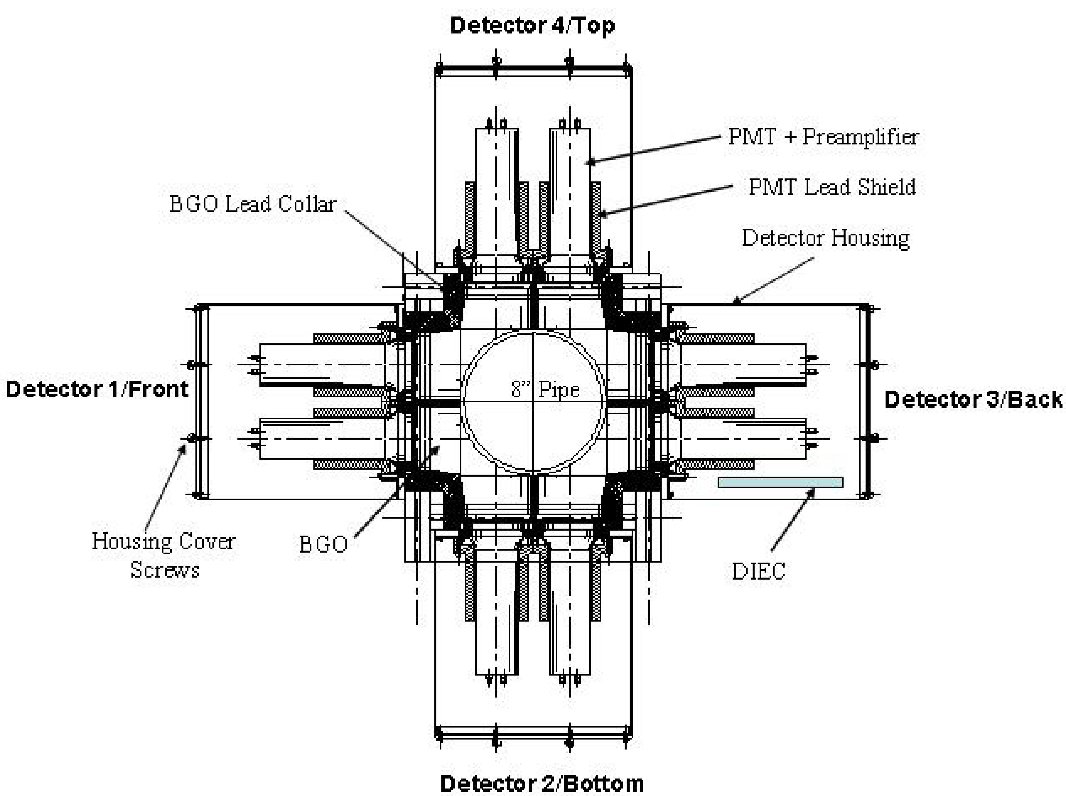

Figure 6. Detailed engineering design drawing showing a cross section of the FMFM detector assembly around a process pipe.

Figure 7. (left) Additional lead gamma shielding near the sources on the FMFM detector assembly to reduce the background signal; (right) the detector signal and power distribution (DSPD) box.

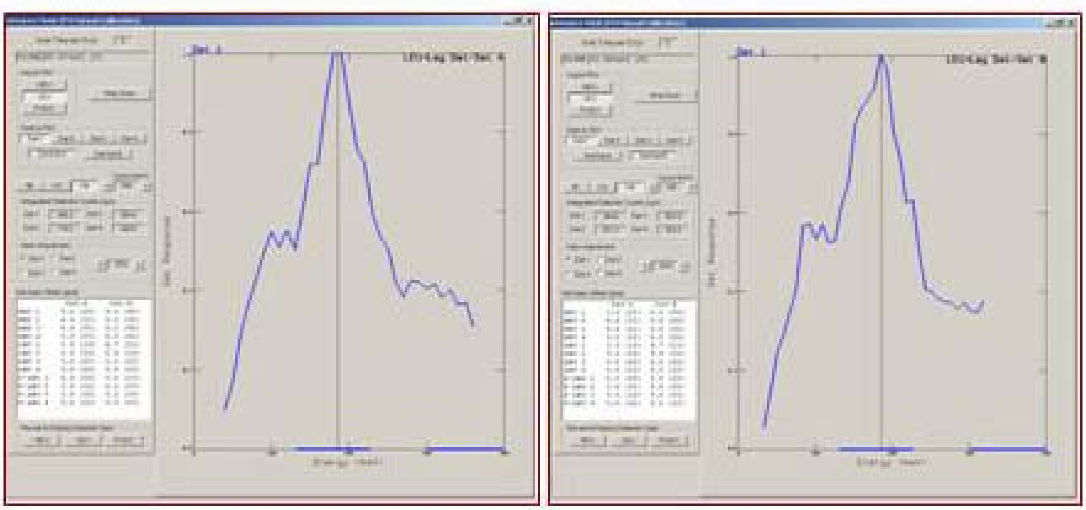

Figure 8. Energy calibration plots for a pair of detectors in a single subassembly. These pulse-height spectra show the characteristic 186-keV line from ^{235}U. The calibration source was a 4% enriched uranium sample placed under the detectors.