Blend Down Monitoring System Fissile Mass Flow Monitor Implementation at the Siberian Chemical Enterprise, Seversk, Russia

Taner Uckan, José March-Leuba, Ray Carlton Brittain, and Danny Powell
Oak Ridge National Laboratory, *P. O. Box 2008, Oak Ridge, TN 37831 USA*

Joe Glaser
U.S. Department of Energy, *19901 Germantown Rd, Germantown, MD 20874 USA*

Abstract

In this paper the implementation plans and preparations for installation of the Fissile Mass Flow Monitor (FMFM) equipment at the Siberian Chemical Enterprise (SChE), Seversk, Russia, will be presented. The FMFM, developed by Oak Ridge National Laboratory (ORNL), is part of the Blend Down Monitoring System (BDMS) for the U.S. Department of Energy (DOE) Highly Enriched Uranium (HEU) Transparency Implementation Program (TIP). The BDMS provides confidence to the United States that the Russian nuclear facilities supplying the lower assay (~4%) product low enriched uranium (P-LEU) to the United States from down-blended weapon-grade HEU are meeting the nonproliferation goals of the 1993 HEU Purchase Agreement signed between the Russian Federation and the United States.

The first BDMS has been operational at Ural Electrochemical Integrated Plant (UEIP), Novouralsk, since February 1999. The second BDMS became operational at Electro Chemical Plant (ECP), Zelenogorsk, in March 2003. These systems are successfully providing HEU transparency data to the United States. The third BDMS was successfully installed on the HEU down-blending tee in the SChE Enrichment Plant in October 2004.

The FMFM makes use of a set of thermalized californium-252 (^{252}Cf) spontaneous neutron sources for modulated fission activation of the uranium hexafluoride (UF_6) gas stream for measuring the ^{235}U fissile mass flow rate. To do this, the FMFM measures the transport time of the fission fragments created from the fission activation process under the modulated source to the downstream detectors by detecting the delayed gamma rays from the fission fragments retained in the flow. The FMFM provides unattended nonintrusive measurements of the ^{235}U mass flow of the UF_6 gas in the blending tee legs of HEU, the LEU blend stock, and the resulting P-LEU. The FMFM also confirms that $HEUF_6$ gas identified in the HEU leg flows through the blending tee into the P-LEU leg. This paper will discuss details of the SChE FMFM equipment characteristics as well as the technical installation requirements.

Introduction and FMFM Operational Description

The BDMS is a system for monitoring the down-blending of HEU to LEU. The BDMS measures the enrichment and flow rate of ^{235}U in the gaseous UF_6 flowing in the three lines (legs) of the blending facility as illustrated in Fig. 1. The HEU Transparency Agreement between the United States and the Russian Federation requires implementation of transparency measures in the Russian facilities that are supplying the lower assay P-LEU to the United States from down-blended weapon-grade HEU material. Moreover, this agreement provides for the monitoring of the down-blending of HEU at an assay of ~90% with blend stock LEU at an assay of ~1.5% to produce light water reactor-grade material (P-LEU) at an assay of ~4% to be used in U.S. nuclear power plants.

The BDMS has been developed to provide unattended and continuous monitoring of the HEU blending operations at these Russian facilities as part of the DOE HEU-TIP. The BDMS consists of the Enrichment Monitor (EM) developed by the Los Alamos National Laboratory [1] and the FMFM [2]. The FMFM provides measurements of ^{235}U mass flow of the UF_6 gas in the process legs of HEU, the LEU blend stock, and the resulting lower-assay P-LEU. The FMFM also traces fission products generated in the HEU flow through the blending tee into the resulting down-blended P-LEU flow, thus confirming down-blending of the HEU, as schematically illustrated in Fig. 1. The HEU material traceability gives the United States significant confidence that the HEU is indeed being blended into a lower-assay material, meeting the nonproliferation goal of the purchase agreement. The first BDMS has been operational at the UEIP, Novouralsk, since February 1999. The second BDMS has been operational at the ECP, Zelenogorsk, since March 2003. These systems are successfully providing HEU transparency data to the United States. The third BDMS was successfully installed on the HEU down-blending tee in the SChE Enrichment Plant (EP) in October 2004. In this paper, details of the FMFM implementation in the SChE EP are discussed.

The FMFM major assemblies and components are shown in Figures 2 and 3. The FMFM flow rate measurement principle relies on producing delayed gamma rays emitted from fission fragments carried by UF_6 gas flow. The fission events that produce the fragments are caused by active neutron interrogation. The FMFM uses thermalized isotopic ^{252}Cf-neutron sources for the fission activation of the UF_6 gas stream. The ^{252}Cf-neutron sources are placed in an annular sleeve filled with moderator material (made of high-density polyethylene) that surrounds the pipe, as illustrated in Fig. 2. The induced fissions are time-modulated using a neutron-absorbing shutter to create a time signature in the UF_6 gas flow. A gamma ray sensitive detector, located downstream of the sources, measures delayed gamma rays emitted by the resulting fission fragments. The FMFM then determines the fissile mass flow rate from two independent measurements: (1) the observed time delay, τ, in the time-correlated measurement between the source and the detector signal provides the velocity, $\sim 1/\tau$, 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 FMFM detector response are discussed in earlier publications [3, 4]. To satisfy the facility dose rate requirement the FMFM source moderator assembly is surrounded with lithiated polyethylene shielding, as shown in Fig. 3. The whole assembly is called the FMFM source modulator (SM).

The principle of the FMFM HEU traceability measurement is that the $HEUF_6$ flow through the blending tee can be traced by detecting in the P-LEU leg detector the delayed gamma rays emitted by fission products generated by the SM in the HEU leg (see Fig. 1). The fission fragments that are created from the ^{252}Cf-induced fissions are relatively long-lived [4]. Thus their delayed gamma rays can be detected at long distances from the source. This technique is used to monitor flow continuity from the FMFM source modulator on the HEU leg to the FMFM detector on the P-LEU leg. The FMFM tracing calculation is based on the difference in total count rate at the P-LEU detector with and without the HEU leg shutter in operation. The FMFM reports the HEU tracing results in terms of confidence level, which is a measure of the probability that the HEU flowed through the blending tee. The time constant for the low-frequency "tagging signal" must be optimized based on the source-detector time delay and the number of mixing volumes. For the SChE system the FMFM cycles the HEU leg shutter open and closed every 10 seconds for a 10-minute period and then is closed for the next 10-minute period, as illustrated in Fig. 4. The 20-minute cycle results in a buildup and decay of fission products that allows for continuity monitoring by comparing the difference in the P-LEU leg detector counts with and without induced fissions. Disabling the HEU-leg shutter periodically (every other 10 minutes) affects the shutter-correlated background level at the P-LEU leg detector. Therefore, for traceability, the FMFM only uses the data when all shutters are closed. An on-line FMFM computer, located in the cabinet assembly (see Fig. 2), controls all three leg SM shutters synchronously, processes acquired detector data, and reports results on the flow and trace measurements.

SChE BDMS FMFM Design strategy

The FMFMs implemented at the UEIP and the ECP were designed for nominal 10-cm-diam UF_6 process pipes. In the case of low enriched UF_6 flow measurements on the LEU (1.5% enriched) and the P-LEU leg (~4% enriched), 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%) because 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 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 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. The SChE FMFM for the LEU and P-LEU legs were designed for nominal 20-cm-diam process pipes. The facility modified the process pipes, which are part of a dedicated BDMS room, in order to accommodate the equipment, as discussed in detail in Ref. [5].

In this paper, detailed design characteristics of the FMFM SM and the detector assemblies together with the FMFM facility implementation specifications are presented.

FMFM Source Modulator Assembly and Supplemental Shielding

The FMFM SM assembly is located upstream from the FMFM detector assembly (Fig. 2). The purpose of the SM is to imprint a time-dependent signature on the fissile stream by modulating the ^{252}Cf source neutrons. The ^{252}Cf sources provide the neutrons required for activation of the UF_6 process gas stream. The sources are held in high-density polyethylene source plugs. The source plugs are inserted into the moderator subassembly, which is made of high-density polyethylene for moderating the fast neutrons from the four ^{252}Cf sources. The moderator holds four source plugs oriented perpendicularly to the process pipe and spaced at 90-degree intervals (see Fig. 3). The modulation of the neutron flux intensity is accomplished by using a cylindrical aluminum shutter with a lithium/epoxy (neutron absorber) lining. A voided section in the lithium/epoxy lining creates a window region. The shutter mounts to the linear positioner subassembly. The linear positioner subassembly moves the shutter to modulate the neutron flux intensity. The movement of the shutter assembly results in a modulation of the neutron flux intensity in the UF_6 process gas stream. The positioner contains an integral stepping motor that is in turn controlled by a controller mounted in the SM assembly, powered by the FMFM cabinet assembly, and controlled by FMFM software. The SM assembly is shielded to reduce the surface radiation levels for the SM assembly, as shown in Fig. 3. A layer of lead shielding segments encloses the moderator. A layer of lithium-impregnated polyethylene segments surrounds the lead shielding. The shielding was designed in segments for reducing the weight and size of shielding components for easier handling during installation and maintenance operations. Sheets of high-density polyethylene shielding are installed at each end of the SM assembly frame. Both high-density polyethylene and lead supplemental shielding components are provided for installation on the process pipe to augment SM assembly shielding as needed to meet facility radiation standards.

FMFM Detector Assembly

More detectors are needed for the large-diameter process pipe than the number used in the 10-cm-diam pipe FMFM system (see Fig. 2). Increasing the number of detectors results in a higher detection efficiency, or higher detector solid angle, Ω_d, which results in a higher detection signal because the value of N_s is related to 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.) In reference [6], a detailed design description and the performance characteristics are presented for the FMFM gamma ray detector system developed to be used on 20-cm-diam process pipes. As shown in Fig. 2, four pairs of bismuth germinate (BGO) scintillation detectors are placed around the process pipe (on the top, bottom, front, and back). The BGO is a novel scintillation material (rugged, non-hygroscopic, neutron-insensitive, high-density and high *Z*-material) with high absorption power and has high photo peak efficiency for high-energy delay gammas (> 0.3 MeV). Each 10-cm-diam, 5-cm-thick BGO scintillation crystal is coupled to an 8-cm-diam photomultiplier tube. Both the BGO crystal and the PMT are shielded with the lead to reduce the room background signal 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. Each detector pair is housed in a metal enclosure that also contains an electronics board for signal shaping and counting.

FMFM Implementation Specifications

The block diagram of the BDMS equipment installation layout on the HEU blending system at SChE is shown in Fig. 5. The blending system process pipes that directly support the FMFM equipment where the BDMS is installed are about 1 m off the floor in order to have easy access to the equipment for maintenance. The major FMFM assembly dimensions and approximate weights are given in Table 1. The facility radiation dose rate requirement, which is 2 mrem/h at 1 m from the surface of the equipment that houses the radioactive sources, is met by the design of the FMFM source modulator assemblies and has been verified with measurements for certification.

FMFM ^{252}Cf Neutron Sources

The FMFM source modulator on the each leg of the blending system uses a total of four neutron sources. Each has 3 micrograms of ^{252}Cf (half-life ~2.65 years), the equivalent of 1.65 millicuries. These sources provide a total of about 2.6×10^7 neutrons per second for fission activation of the UF_6 gas flow under the source modulator. As shown in Fig. 2, the sources are installed to the source modulator using a source plug, which is made of polyethylene, and the four source plugs are evenly distributed around the SM. The radial location of the sources was determined from the Monte Carlo modeling studies for maximizing the thermal neutron flux under the SM [2]. The sources need to be replaced about every two years to maintain the FMFM performance.

UF_6 Gas Pressure and FMFM Flow Regime Operations

The recommended UF_6 gas pressure range for the FMFM equipment operation is between 50 and 60 Torr (regulated) at the locations of the FMFM equipment. The FMFM can operate with either laminar or turbulent UF_6 gas flow. At SChE, the FMFM is designed to measure the laminar flow of the HEU leg and the turbulent flow of the LEU and P-LEU legs. Table 2 specifies the range of gas velocities that the FMFM can measure.

FMFM Measurement Performance Parameters

Table 3 shows the system performance specifications for the range of variables over which the FMFM is designed to operate, along with their measurement uncertainty.

Recommended FMFM Equipment Installation Configuration

This section describes the recommended installation configuration for all major FMFM components in the SChE facility. Figures 6 and 7 show the recommended installation configuration for the FMFM assemblies for the HEU, LEU, and P-LEU legs. The SM-to-detector separation distances, L, optimized for these process legs, are obtained from simulation modeling [3] studies to achieve the design performance (i.e., given shutter period and detector background, the time delay, τ, was optimized for the expected velocity, L/τ, range of measurements). The FMFM assemblies include the supplemental polyethylene neutron shielding, as shown in Figs. 6 and 7. Figure 8 shows the recommended schematic of the complete FMFM system equipment installation configuration for the blending system. In order to improve the measurement convergence time, τ_c, the proposed configuration lowers the crosstalk (background signal N_b) from sources such as minimum back shine from the SM to detectors between the HEU, P-LEU, and LEU process legs. In addition, as shown in Fig. 8, supplemental gamma shielding may be installed to further lower the FMFM detector background signal from the sources in the SM on the HEU, P-LEU, and LEU legs.

BDMS Implementation Status at SChE

In May 2004, a Russian delegation participated in a week long training held at ORNL on the operation and installation of the BDMS equipment. In June 2004, after more than a month of complete BDMS system operational testing at ORNL, the equipment was packed in 37 crates and was shipped to SChE. The joint U.S. and SChE inventory of the crates was performed in September 2004, and the required 30-day security inspection by the Russian Federal Agency for Atomic Energy (RosAtom) was also completed. The recommended installation schedule was prepared by DOE and was provided to RosAtom.

BDMS implementation was accomplished at SChE in two steps. In October 2004, the BDMS hardware was succefully installed at the SChE; and in February 2005, the system was calibrated and was accepted for operation by RosAtom to be used by the DOE HEU-TIP. The main BDMS implementation activities during the February 2005 were to (1) perform background measurements on the evacuated piping, (2) complete calibration of the system, (3) work with the Russian Certification Commission selected by RosAtom to verify that the system met its criteria and that the system was placed into transparency operation, and (4) confirm operation of the installed system. All four objectives were successfully accomplished and the Russian Commission approved the SChE BDMS for transparency operation. The following details of the SChE implementation and results are discussed in Ref. 5: (1) the characteristic features of BDMS configuration at SChE EP blending facility; (2) process technology of the pipelines preparation for BDMS installation; (3) personnel training; (4) installation of the system together with the sources of ionizing radiation; and (5) setup, testing, and certification process of BDMS.

References

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[2] J. K. Mattingly, J. March-Leuba, T. E. Valentine, J. T. Mihalczo, and T. Uckan, “Physics Design of Fissile Mass Flow Monitoring System,” *38th Annual Meeting of the Institute of Nuclear Materials Management (INMM)*, Phoenix, Arizona, July 20, 1997.
[3] J. March-Leuba, J. K. Mattingly, et al., “Methodology for interpretation of Fissile Mass Flow Measurements,” *38th Annual Meeting of the INMM*, Phoenix, Arizona, July 20, 1997.
[4] T. Uckan, R. Oberer, J. March-Leuba, et al., “Measurement Methodology of the Fissile Mass Flow Monitor for the HEU Transparency Implementation Instrumentation in Russia,” *42nd Annual Meeting of the INMM*, Indian Wells, California, July 20, 2001.
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Acknowledgment

The authors wish to thank Kim N. Castleberry, Richard W. Jones, Carl W. Martin, Ken S. Weaver, and Wes R. Wysor (Engineering Science and Technology Division) for their relentless help for making the BDMS FMFM a reality.

Table 1. FMFM assembly dimensions and weights

Major assembly	Number of assemblies	Dimensions, L × W × H (cm)	Weight (kg)
Control cabinet (consists of combined EM and FMFM sections)	1	183 × 153 × 92	367
FMFM source and modulator assembly (10.8-cm OD Pipe)	1	150 × 100 × 120	740
FMFM source and modulator assembly (21.9-cm OD pipe)	2	150 × 110 × 130	950
FMFM detector and gamma-ray shielding assembly (10.8-cm OD pipe)	1	58 × 91 × 91	210
FMFM detector and gamma-ray shielding assembly (21.9-cm OD pipe)	2	58 ×105 × 105	420

Table 2. FMFM UF_6 gas velocity ranges during operation

Leg	Flow regime	Velocity range (m/s)
HEU	Laminar, 10.8-cm OD pipe	0.02–0.2
LEU	Turbulent, 21.9-cm OD pipe	0.4–1.5
P-LEU	Turbulent, , 21.9-cm OD pipe	0.4–1.5

Table 3. FMFM flow measurement range and associated uncertainty

Leg	Flow parameter	Measurement range	Uncertainty (%)
HEU	gas velocity (m/s)	0.06–0.12	± 5
LEU	gas velocity (m/s)	0.4–1.0	± 5
P-LEU	gas velocity (m/s)	0.4–1.0	± 5
HEU	^{235}U fissile mass flow (g/s)	0.27–0.54	± 25
LEU	^{235}U fissile mass flow (g/s)	0.12–0.3	± 25
P-LEU	^{235}U fissile mass flow (g/s)	0.4–0.9	± 25

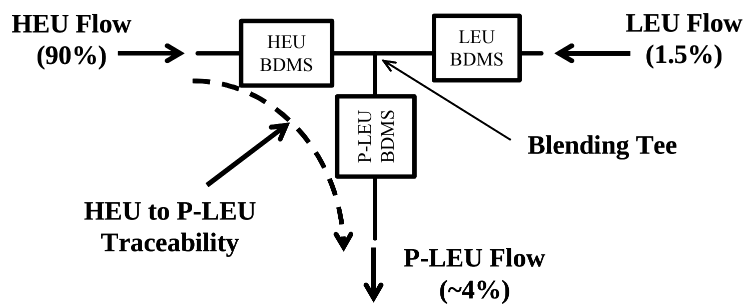

Fig. 1. The Blend Down Monitoring System (BDMS) installed on a HEU blending tee.

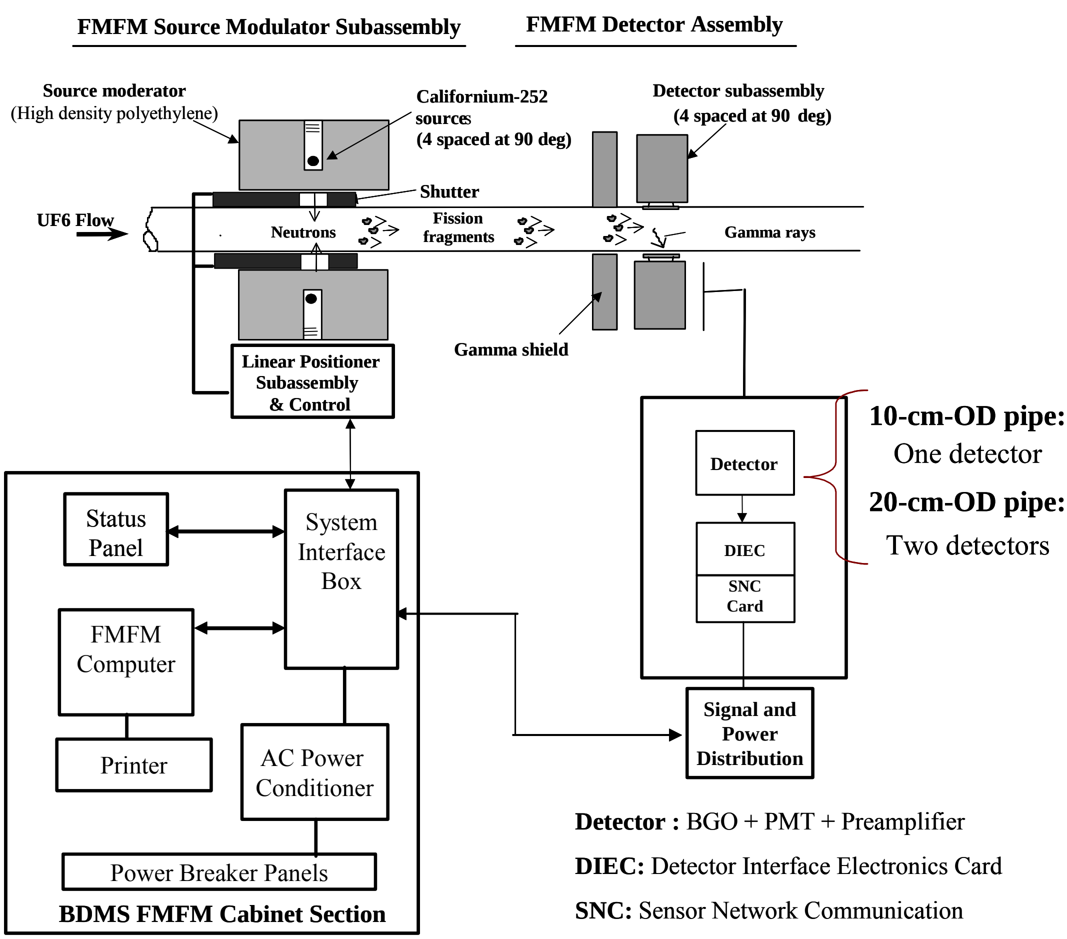

Fig. 2. The BDMS Fissile Mass Flow Monitor (FMFM) operational principle and the major assemblies and components.

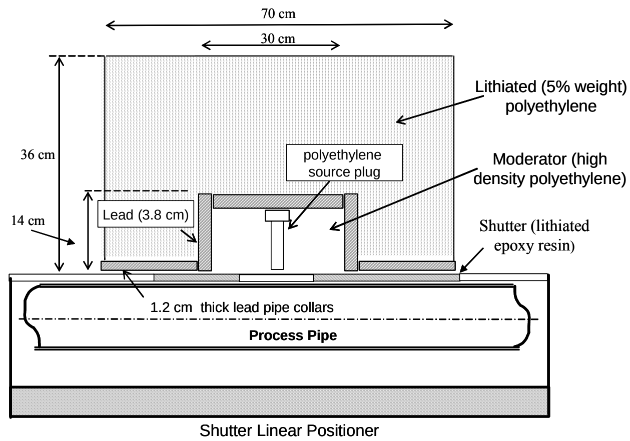

Fig. 3. Details of the FMFM source modulator (SM) assembly and components.

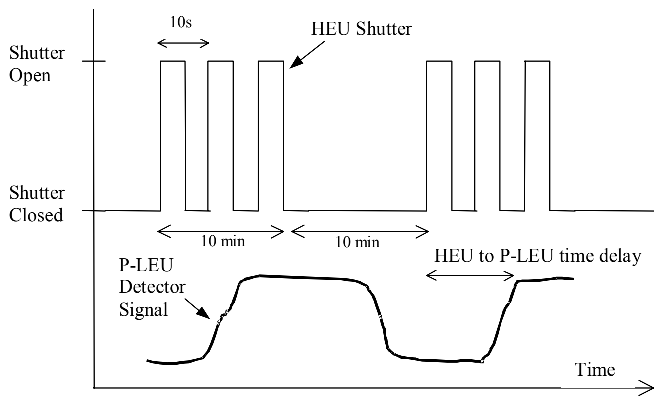

Fig. 4. Illustration of the FMFM HEU leg shutter motion pattern to generate the low-frequency modulation required for tracing the HEU flow to the P-LEU leg.

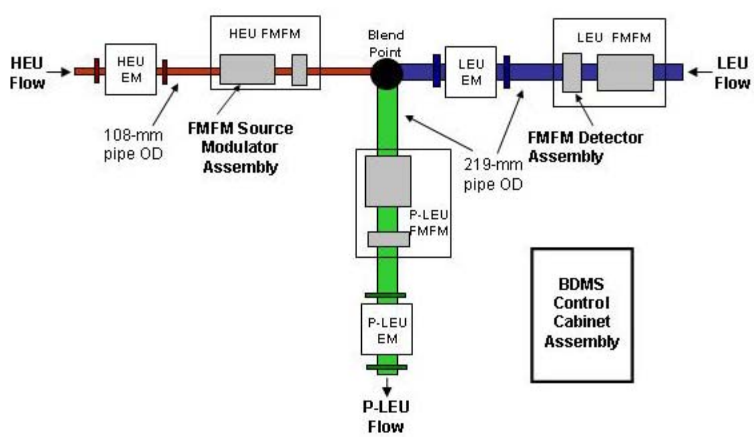

Fig. 5. Block diagram of the BDMS installation on the HEU blending system at SChE.

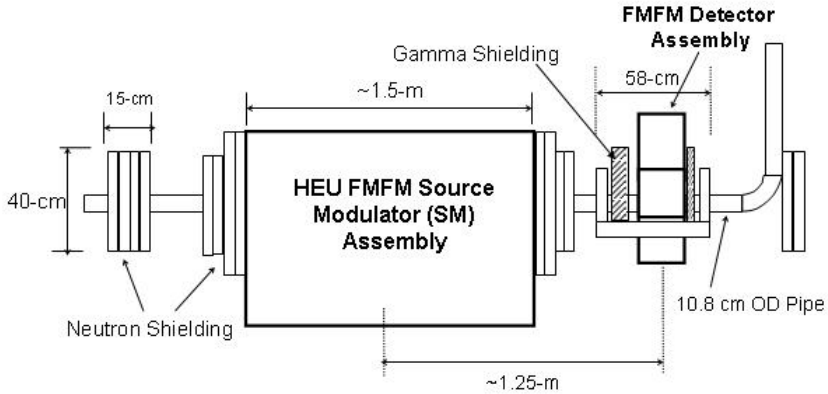

Fig. 6. Recommended FMFM installation configuration for HEU leg.

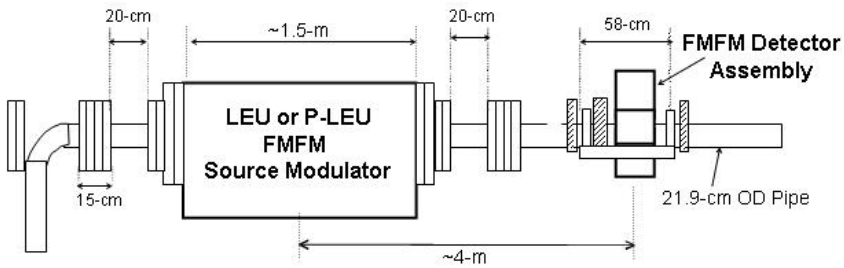

Fig. 7. Recommended FMFM installation configuration for the LEU and P-LEU legs.

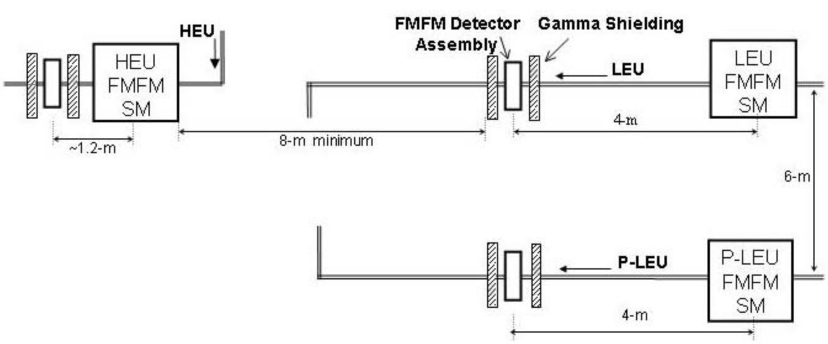

Fig. 8. Recommended FMFM installation configuration for all three legs designed to reduce the cross talk between the sources in the source modulators and the detectors. Pipes are about 1-m off the floor.