Instrumentation and Controls Division

FISSILE MASS FLOW MONITOR IMPLEMENTATION FOR TRANSPARENCY IN HEU BLENDDOWN AT THE URAL ELECTROCHEMICAL INTEGRATED PLANT (UEIP) IN NOVOURALSK

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Fissile Mass Flow Monitor Implementation for Transparency in HEU Blenddown at the Ural Electrochemical Integrated Plant (UEIP) in Novouralsk

Taner Uckan, José March-Leuba, Jim Sumner, Bob Vines, Edward Mastal[1], and Danny Powell
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Abstract
The Oak Ridge National Laboratory (ORNL) Fissile Mass Flow Monitor (FMFM) was deployed at the Ural Electrochemical Integrated Plant (UEIP) highly enriched uranium (BEU) blending facility in January and February 1999 at Novouralsk in Russia for the DOE HEU Transparency Program. The FMFM provides unattended monitoring of the fissile mass flow of the uranium hexafluoride (UF_6) gas in the process lines of HEU, the low enriched uranium (LEU) blend stock, and the product LEU (P-LEU) of the blending tee non-intrusively. To do this, uranium-235 (U-235) fissions are induced in the UF_6 by a thermalized and modulated califomium-252 (Cf-252) neutron source placed on each process line. A set of detectors, located downstream of source, measure delayed gamma rays emitted by the resulting fission fragments. The observed delay in the time correlated measurement between the source and the detector signal provides the velocity of UF_6 and its amplitude is related to the U-235 content in UF_6. An on-line computer controls the source modulator, processes the collected detector data, and displays the results. The UEIP Main and the Reserved process lines were implemented with minor modifications. The FMFM monitors the HEU blending operation by measuring UF_6 flows in the process blending lines, and the traceability of the HEU flow from the blend point to the P-LEU. The detail operational characteristics of the FMFM software (FM2) and the measurement methodology used are presented.

Introduction
The Fissile Mass Flow Monitor, which was installed to the UEIP process lines in January and February 1999, determines the fissile mass flow rate by relying on two independent measurements: (1) the time required for the fission fragment to travel along a given length of pipe, which is inversely proportional to the fissile material flow velocity, and (2) an amplitude measurement, which is proportional to the fissile concentration (e.g., grams of U-235 per length of pipe).

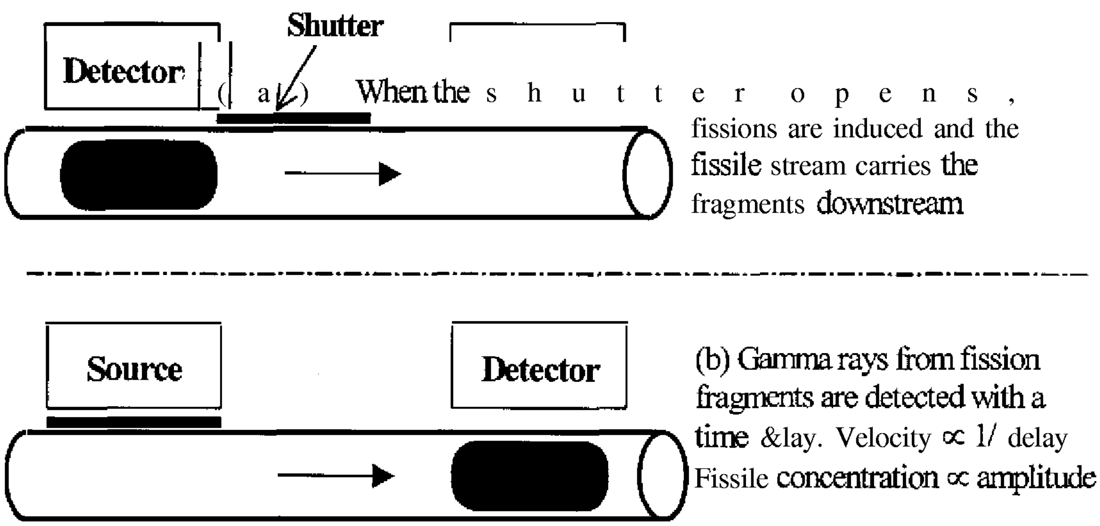

Figure 1. Fissile mass flow rate measurement concept

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This paper describes the methodology used to interpret the data measured by the FMFM, the models used to simulate the transport of fission fragments from the source location to the detectors, and the implementation of these algorithms in the FMFM software FM2. The basic FMFM measurement concept is illustrated in Figure 1 and can be described as follows: (1) Fast neutrons from a Cf-252 source are moderated by a polyethylene block. (2) A neutron-absorbing shutter modulates the source strength, superimposing a time-dependent signature is in the fissile stream. (3) The moderated neutrons induce fissions inside the process stream. (4) The resulting fission fragments are slowed down by the gas, and some are carried by the stream. (5) A downstream sensor detects delayed gamma rays emitted by the fission fragments. (6) A time-delay measurement is performed by detecting the signature caused by the shutter. (7) The tissile concentration is obtained from the measured detector response and a calculated calibration that is confirmed by measurements. (8) The fissile mass flow rate is determined by multiplying the average fissile velocity and the tissile concentration of step (7). This measurement methodology is insensitive to buildup on the pipe walls, and it can be applied to any flow stream capable of producing particles that emit delayed radiation that can be detected downstream.

In addition to measuring fissile mass flow, the FMFM traces the HEU through the blending tee by detecting in the P-LEU line detectors delayed gamma rays emitted by fission products generated in the HEU line. This traceability gives U.S. Monitors significant confidence that the HEU is indeed being blended into P-LEU.

Flow Monitor Algorithm

The FM2 software measures the time-dependent profile at the detector location following a shutter-induced pulse and compares it with all of the model-predicted profiles at different flow velocities. The time average flow velocity is the one that results in a minimum residual error, $\varepsilon(u)$,

$$\varepsilon(u) = \int_0^T \left[N_\gamma(t) - C\, N_{model}(t,u)\right]^2 dt,$$

where T is the time period of the shutter motion, and C is the amplitude parameter, which is proportional to the detector-response. The detector response, N_γ, is proportional to the number of fissions induced, N_{fis}, which is proportional to the concentration of U-235 in the pipe. Thus the amplitude parameter C is directly proportional to the tissile density, and the product of the amplitude multiplied by the flow velocity is proportional to the fissile mass flow rate, ω:

$$\omega\left(\frac{g}{s}\right) = u\left(\frac{m}{s}\right) \times C\left(\frac{g}{m}\right) \times N_{model}(t,u)$$

A calibration factor is required to scale the model profiles, $N_{model}(t,u)$, so that the units of the amplitude parameter C are mass of tissile material per unit length (e.g., grams per meter). The calibration factor is calculated using a Monte Carlo computer code that simulates the flow-meter geometry and the detector efficiency (including the energy discrimination). The calibration factor is also confirmed by off-line benchmark tests. The basic steps performed by FM2 to evaluate the fissile mass flow rate are as follows.

A. Data Collection and Averaging

A new block of raw data is collected from the detector network in blocks of 60 seconds. These data consist of the detector counts per seconds measured as a function of time while the shutter is opening and closing. These new data are averaged with the old data using a running-average method. Two time constants are used for this running average. This results in a short- and a long-time-constant average block of data. Each of these average blocks is 60 seconds long but contains the average data over several hours. In the following steps, $M(t)$ represents the average block. The formula used to compute $M(t)$ is:

$$M(t) = \frac{M_0(t) \times (\tau - 1) + N(t)}{\tau}$$

where $N(t)$ represents each new 60-second block of data, $M_o(t)$ represents the old value of $M(t)$, and τ represents the time constant (expressed in minutes).

B. Flow Velocity Determination

To determine the mass flow, the model described in Section A is fitted to the average block, $M(t)$, using a weight function, $W(t)$. To tit this model, FM2 first obtains the uncorrelated background, ***bckgU***, correlated background, ***bckgC***, and a fissile concentration, C(u), that minimizes the residual error, $\varepsilon(u)$, for each trial velocity u,

$$\varepsilon(u) = \int_0^{T=20s} dt\ W(t)\ [M(r) - (bckgU + bckgC(t) + C(u)\ N_{model}(t,u))]^2$$

Then, FM2 calculates $\varepsilon(u)$ for each trial velocity, and it finally selects the velocity that results in minimum error. This fitting process is performed every minute (after sampling each new 60-second block of data) using the short- and long-time constant averages. This process results in the best-estimate gas velocity for the data. The weight function, $W(t)$, in the above equation is set to 1 at all times when the shutter is not moving. During shutter motion, $W(t)$ is set to 0.

C. Mass Flow Determination

The fissile concentration is estimated for the optimal velocity using the above equation. Note that in the above equation, $N_{model}(t,u)$ is defined in the FM2 profile database, which is scaled so that the fissile concentration, $C(u)$, units are in grams of U-235 per meter of pipe. Finally, the fissile mass flow, $\omega(t)$, is determined by multiplying the gas velocity times the fissile concentration,

$$w(t) = u \times C(u).$$

A fissile gas velocity, a fissile concentration, and a mass flow rate are determined every 60 seconds, when a new block of data becomes available. These are based on the short- and long-time constant running averages.

D. Statistical Test for Flow of Fissile Material

Once every 60 seconds, a statistical test is performed on the average data to determine a confidence level of the algorithm fit described in the above sections. For this purpose, a statistical F-test is performed between the residual error calculated in Section B for the optimal velocity, and the residual error obtained by setting $C(u)$ equal to zero (i.e., forcing a mass concentration to zero). The result of this F-test is a confidence level on nonzero flow of U-235 and represents the quality of the flow measurement. As with the velocity, concentration, and flow measurements, FM2 computes a flow confidence using the short- and the long-time constants.

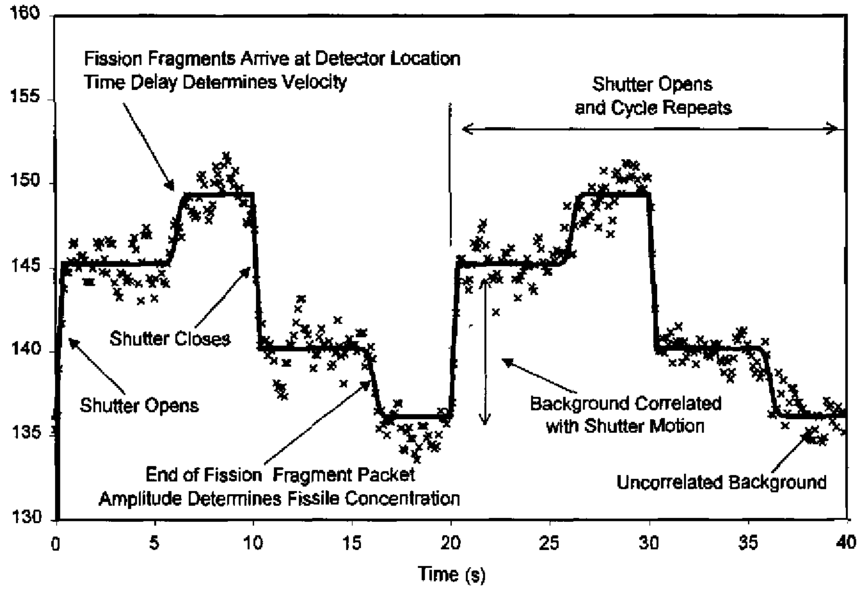

Figure 2. Illustration of the FMFM algorithm performance

Figure 2 shows an example application of the FM2 algorithm to data for a case of turbulent flow with a gas velocity of -0.5 m/s and a source-detector separation of -3-m. The crosses in this figure represent the average data [i.e., ***M*(*t*)**] and the solid line represents the optimal model selected by the FM2 algorithm as described in Section B. The uncorrelated and correlated backgrounds are evident in this figure. The fission-fragment-induced pulse is also evident at time 6 seconds, which is the expected time delay for a velocity of -0.5 m/s and a distance of -3-m. The amplitude of this pulse is proportional to the fissile concentration in the pipe.

Fissile Tracing Algorithm

The fission fragments that result from the Cf-252 induced fissions are relatively long-lived, thus their decay gamma rays can be detected at long distances from the source. This technique is used by FM'?. to monitor flow continuity through a possibly complex series of pipes and volumes such as pumps.

The time constant for the "tagging signal" must be optimized based on the source-detector time delay and the number of mixing volumes. For a typical configuration, FM2 cycles the HEU-leg shutter open and closed every 5 to 10 seconds for a 1 O-minute period and then is closed for the next 1 O-minute period. This results in a 20-minute cycle of buildup and decay of fission products that allows for continuity monitoring by comparing the difference in the P-LEU detector counts with and without induced fissions. This concept is illustrated in Figure 3.

Disabling the HEU-leg shutter periodically (every other 10 minutes) affects the correlated background level at the P-LEU leg, because the P-LEU detectors may be located close to the HEU shutter and are affected by its motion. For this reason, FMFM traceability only uses the data when all shutters are closed. The FM2 tracing algorithm averages the shutter-closed data over the complete 60-second block. The data are then averaged into a tracing data block with the appropriate time delay so that the data from minute 1 are averaged with the data from minutes 21, 41, and so on. The data for minute 2 are averaged with the data from minutes 22, 42, and so on. The tracing data block thus contains 20 data points, one per minute, and it is synchronized with the cycle time of the HEU-leg shutter.

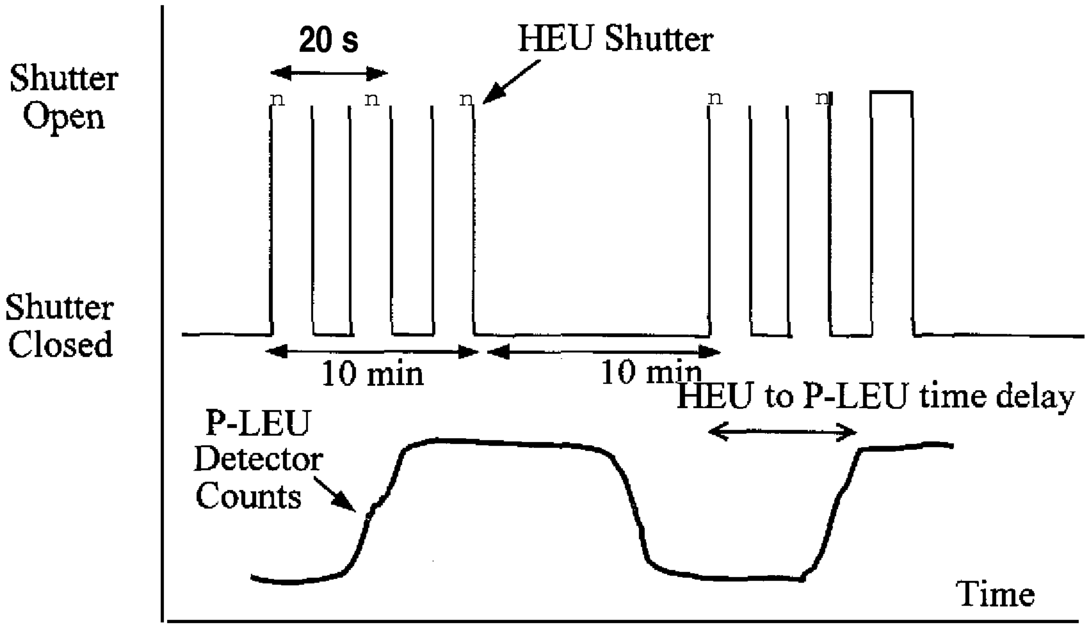

Figure 3. Illustration of shutter motion pattern to generate the low-frequency modulation required for HEU to P-LEU tracing

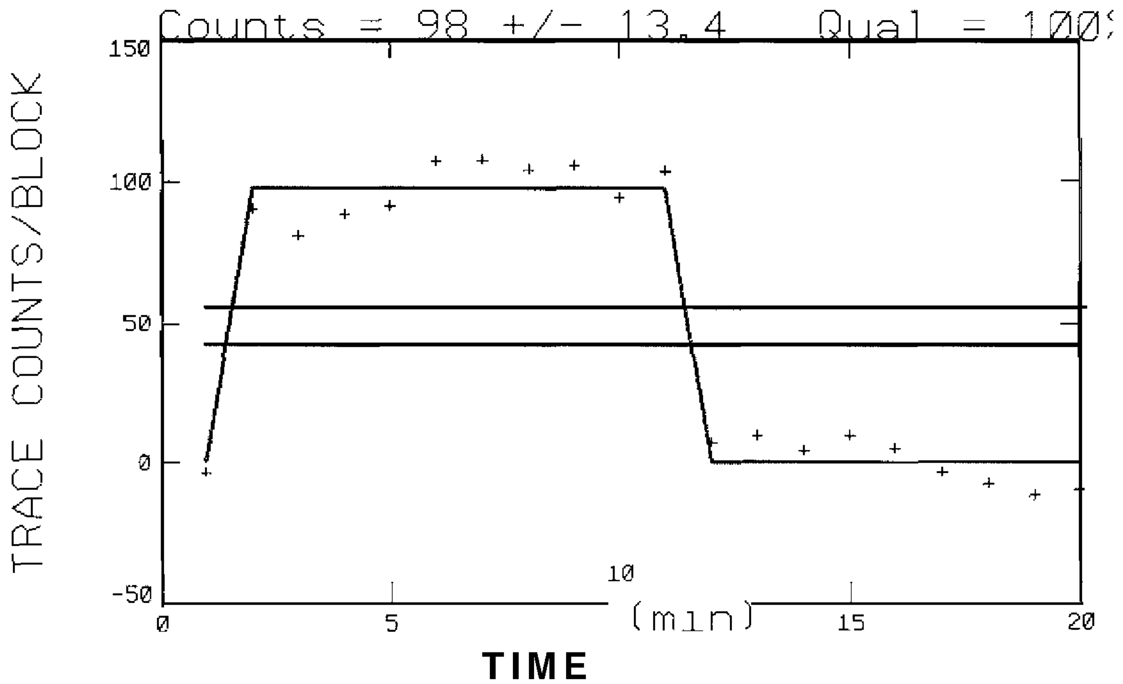

Figure 4. Sample tracing block showing high confidence of traceability

Figure 4 shows an example of a converged tracing block, which was measured using the procedure described above. Using the averaged tracing data block, two statistical tests are performed on the data. The first test compares the variance of the 20 data points with the theoretical variance if the measured dam were perfectly random, which would result in a variance equal to the inverse of the number of counts averaged. The results of these tests define a confidence level that the data has "structure." A second statistical test is performed to detect the lo-minute on, 10-minute off signature of the HEU-leg shutter in the data. For this test, a square wave with a variable time delay is fitted to the tracing block. The residual noise variance after removing the square wave fit is compared to the original variance using an F-test confidence level. The result of this last test defines the confidence level of the fitted tracing model.

After the above calculations are performed, FM2 reports two numbers:

1. The product of the two statistical confidence levels (the structure and the fit confidence levels).
2. The tracing counts per block, which correspond to the amplitude of the step in Figure 4, along with its calculated standard deviation.

Models and Correlations

To predict the detector response downstream of the source, it is necessary to model (a) the percentage of delayed gamma ray fission products that remain in the gas following an induced fission, (b) the flow of fissile material and fission products down the pipe, and (c) the decay of the fission products. Models and the resulting correlations are described in the following sections,

A. Fission Fragment Decay Model

The delayed emission data have been obtained by fitting a five-group model to measured data using the actual FMFM hardware. This mode1 includes 300-keV energy-discrimination filters that are accounted for in the overall detector efficiency. The parameters of the five-group model are summarized in Table 1, and a sample measurement is shown in Figure 5. The parameters in Table 1 correspond to a best tit to the decay gamma-ray data following a fission event, so that

$$n_\gamma(\tau) = \sum_1^5 \alpha_i e^{-\lambda_i \tau} ,$$

where $n_\gamma(\tau)$ represents the average number of photons per second following a fission event, λ_i is the group yield constant, which is related to the group precursor fraction, β_i, as $\alpha_i = \lambda_i \times \beta_i$.

Table 1. Delayed Gamma-Ray Data

Group #	α_i (γ/s per fission)	λ_i (s^{-1})
1	0.35	0.4
2	0.06	0.04
3	0.015	0.008
4	0.0015	0.0008
5	0.0002	0.00005

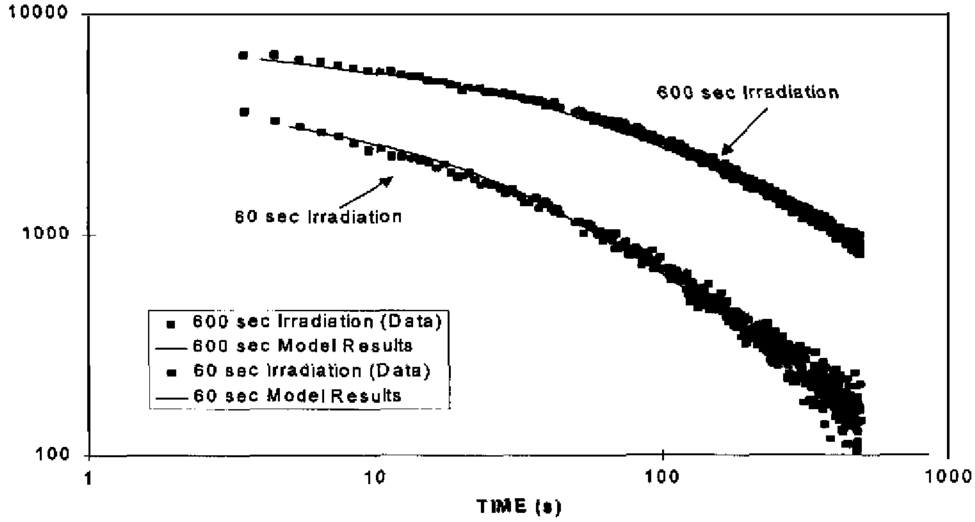

Figure 5. Comparison between ORNL irradiation measurements and decay model predictions

Figure 5 shows the results of applying our delayed gamma-ray emission model to measured data obtained by irradiating a U-235 fission chamber for 60 and 600 seconds and measuring the decay gamma rays with the actual flow-monitor hardware. As seen in Figure 5, the delayed gamma-ray emission model predicts the measured data accurately up to 500 seconds following the fission event. This decay model also benchmarks well against the impulse-response data published in the literature.

B. Fission Fragment Range in Low-Pressure UF_6 Gas

Fission fragment ranges can be very large in low-density materials. For this reason, a methodology was developed to estimate the ranges and distribution of fission fragments with the goal of determining the fraction of fission products that remain entrapped in the UF_6 gas.

The basic range data are derived from the measurements documented in the Nuclear ***Data Table?.*** These ranges are integrated path lengths of heavy charged particles traversing various media. Based on these dam, the fission fragment ranges in UF_6 were computed as functions of gas pressure and fission fragment energy. The distribution of fragment energies can be approximated by two Gaussian distributions (one for the light fragments and one for the heavy fragments'). The parameters of this distribution are as follows:

$$R_l = \frac{4174}{P}; \quad R_h = \frac{3154}{p}; \quad \sigma_l = \frac{183}{p}; \quad \sigma_h = \frac{236}{p},$$

where R_l and R_h are the average light and heavy fragments range expressed in millimeters, and σ_l and σ_h are their standard deviations, and the pressurep is expressed in Torr.

The above values represent the nominal ranges and their standard deviations, The range, however, represents the integrated path length, not the radial distance from the point of fission. To estimate the effect of nuclear scattering, the tabulated values were compared with measurements by Niday[5]. A comparison of the tabulated values with Niday's measurements indicates that the tabulated values

[3] ***Nuclear Data Tables,*** Vol. 7, No. 3-4, 1970
[4] Peasanton, ***Phys. Rev.*** 174, 1500, 1968
[5] "Radiochemical Studies of the Ranges in Metallic Uranium of the Fragments" from Thermal Neutron Fission, ***Phys. Rev.*** Vol. 121, No 5, 1961

(and the average ranges given in the Gaussian distributions) should be reduced by approximately 15%. Straggling, the statistical fluctuation in the ranges of charged particles traveling in a material, is accounted for by applying a 10% uncertainty to the ranges and to the standard deviations[6]

To determine the number of fission-fragment absorptions in the pipe wall, a Monte Carlo-type calculation with special tallies was performed. For this run, a homogeneous source of gamma rays was placed inside an empty pipe of diameter, D; then the gamma-ray currents were tallied at different radii as a function of the age of the photon. These ages were directly proportional to the range that the photon had traveled before reaching the inner wall of the pipe and allowed for the development of a correlation for the fraction of fission fragments that were absorbed by the pipe as function of fragment range (i.e., UF_6 pressure) and pipe inner diameter. The fraction, ε_s, of fragments that remained in the UF_6 flow and that contributed to delayed gammas at the detector location was computed from this correlation and the probability distribution function for fragment ranges. Based on these data, two correlations for the source effectiveness have been developed:

$$\varepsilon_s = \frac{1}{1 + e^{-0.025(pD-65)}} - 0.271 \; for \; (pD < 200 \; psi \; mm), \text{ and}$$

$$\varepsilon_s = 0.943 - e^{-0.006(pD-10.1)} \; for \; (pD > 20 \; psi \; mm),$$

where D is the pipe diameter in millimeters, and p is the gas pressure in pounds per square inch. The first correlation is more accurate but it can only be used for low pressures. The second correlation, while not as accurate, can be used at high pressures.

C. Fission Fragment Transport and Decay Model

The basic equation that describes the flow and decay of delayed gamma-ray fission fragments is the combined convection and decay equation:

$$\frac{dc_i(r,z,t)}{dt} + u(r)\frac{dc_i(r,z,t)}{dz} = \beta_i N_{fis} S(r,z,t) - \lambda_i c_i(r,z,t),$$

where $c_i(r, z, t)$ is the concentration of group-i fission fragments at time t and location (r, z), $u(r)$ is the gas velocity at radial position r, β_i is the fraction of group-i precursors generated per fission, λ_i is the decay constant, N_{fis} is the number of induced fissions, $S(r, z, t)$ is the normalized shutter efficiency, which combines the source field of view and the shutter motion as function of time.

The total concentration of delayed gamma-ray fission fragments is the sum over all delayed groups. The number of gamma rays per second counted at the detector, N,(t), is determined by

$$N_\gamma(t) = \frac{1}{\pi R^2}\int_0^R dr \left[2\pi r \int_{-\infty}^{\infty} dz \left[\varepsilon_d D(r,z) \sum_1^n \lambda_i c_i(r,z,t) \right] \right],$$

where $D(r, z)$ is the normalized detector field of view of all the detectors together, ε_d is the overall detector efficiency.

The above model for fission fragment transport and decay has been implemented in a computer code. This code solves the above equations numerically and computes the precursor concentration at a number of axial and radial nodes inside the fissile stream.

[6] Experimental Nuclear *Physics,* E. Segre editor, 1953

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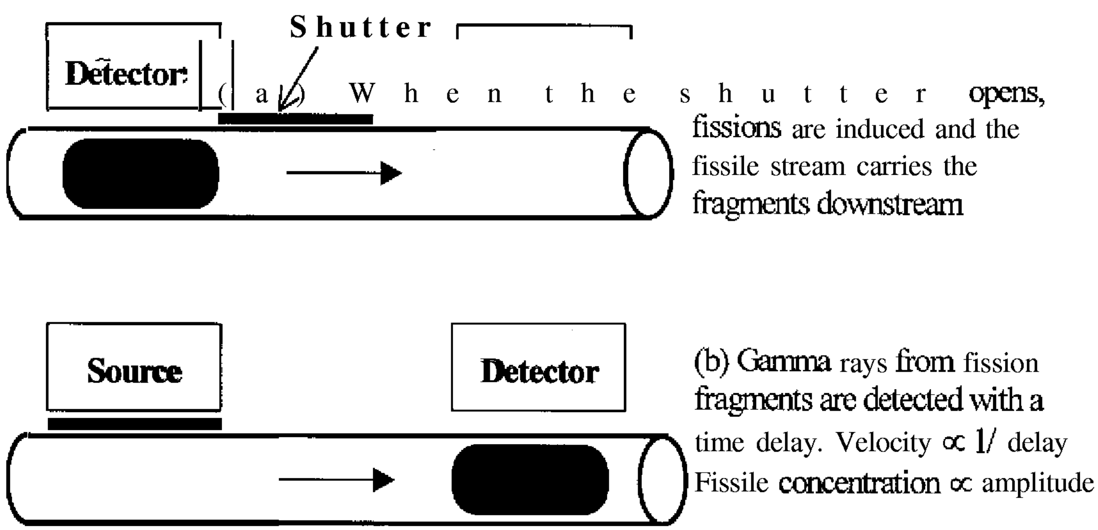

Figure 1. **Fissile** mass flow **rate measurement** concept

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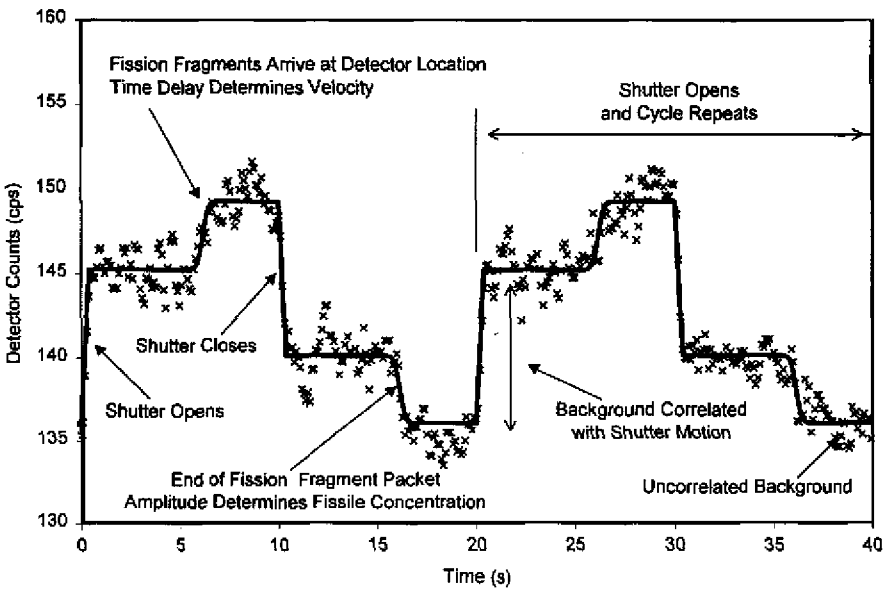

Figure 2. Illustration of the FMFM algorithm performance

Figure 2 shows an example application of the FM2 algorithm to data for a case of turbulent flow with a gas velocity of -0.5 m/s and a source-detector separation of -3-m. The crosses in this figure represent the average data [i.e., ***M(t)***] and the solid line represents the optimal model selected by the FM2 algorithm as described in Section B. The uncorrelated and correlated backgrounds are evident in this figure. The fission-fragment-induced pulse is also evident at time 6 seconds, which is the expected time delay for a velocity of -0.5 m/s and a distance of -3-m. The amplitude of this pulse is proportional to the fissile concentration in the pipe.

Fissile Tracing Algorithm

The fission fragments that result from the Cf-252 induced fissions are relatively long-lived; thus their decay gamma rays can be detected at long distances from the source. This technique is used by FM2 to monitor flow continuity through a possibly complex series of pipes and volumes such as pumps.

The time constant for the "tagging signal" must be optimized based on the source-detector time delay and the number of mixing volumes. For a typical configuration, FM2 cycles the HEU-leg shutter open and closed every 5 to 10 seconds for a IO-minute period and then is closed for the next IO-minute period. This results in a 20-minute cycle of buildup and decay of fission products that allows for continuity monitoring by comparing the difference in the P-LEU detector counts with and without induced fissions. This concept is illustrated in Figure 3.

Disabling the HEU-leg shutter periodically (every other 10 minutes) affects the correlated background level at the P-LEU leg, because the P-LEU detectors may be located close to the HEU shutter and are affected by its motion. For this reason, FMFM traceability only uses the data when all shutters are closed. The FM2 tracing algorithm averages the shutter-closed data over the complete 60-second block. The data are then averaged into a tracing data block with the appropriate time delay so that the data from minute 1 are averaged with the data from minutes 21, 41, and so on. The data for minute 2 are averaged with the data from minutes 22, 42, and so on. The tracing data block thus contains 20 data points, one per minute, and it is synchronized with the cycle time of the HEU-leg shutter.

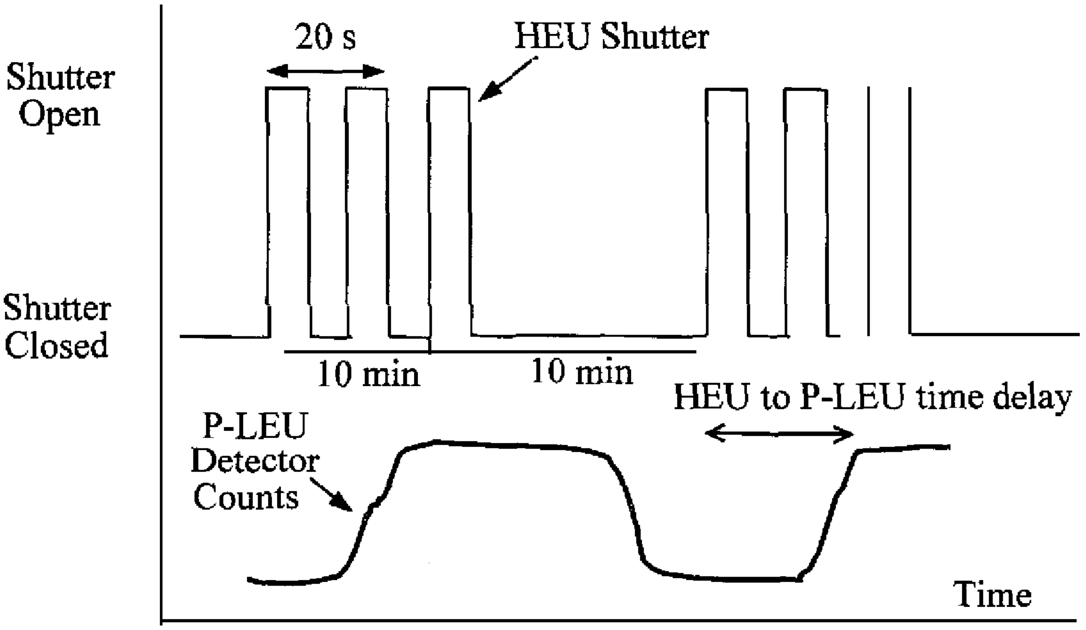

Figure 3. Illustration of shutter motion pattern to generate tbe low-frequency modulation required for HEU to P-LEU tracing

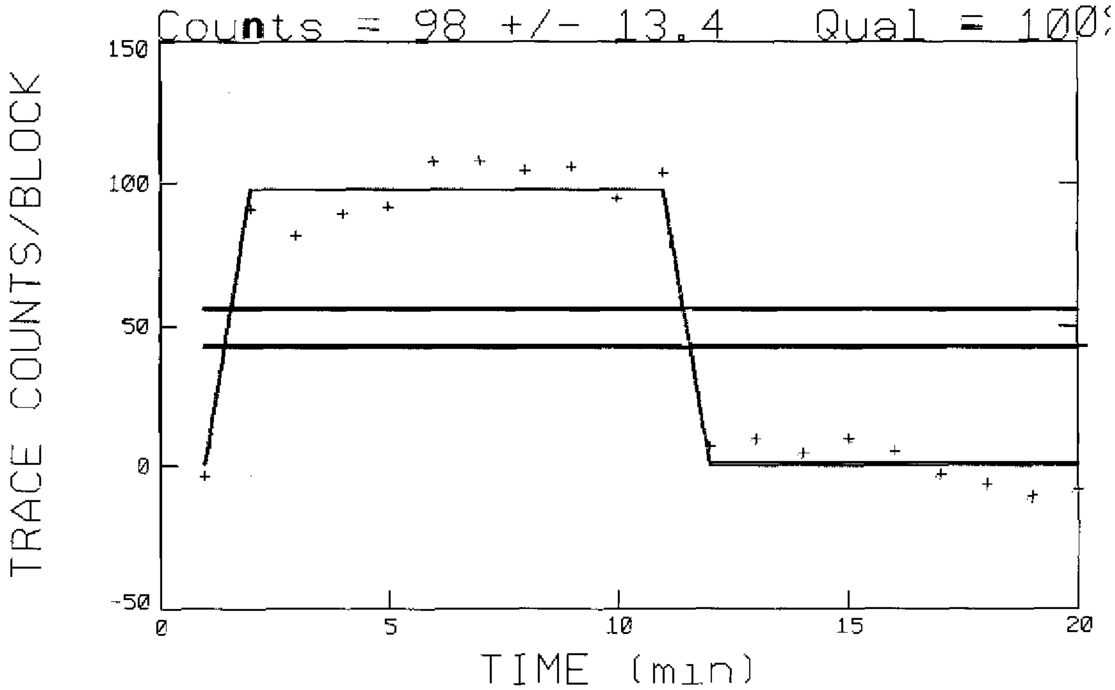

Figure 4. Sample tracing block showing high confidence of traceability

Figure 4 shows an example of a converged tracing block, which was measured using the procedure described above. Using the averaged tracing data block, two statistical tests are performed on the data. The first test compares the variance of the 20 data points with the theoretical variance if the measured data were perfectly random, which would result in a variance equal to the inverse of the number of counts averaged. The results of these tests define a confidence level that the data has "structure." A second statistical test is performed to detect the lo-minute on, IO-minute off signature of the HEU-leg shutter in the data. For this test, a square wave with a variable time delay is fitted to the tracing block. The residual noise variance after removing the square wave fit is compared to the original variance using an F-test confidence level. The result of this last test defines the confidence level of the fitted tracing model.

After the above calculations are performed, FM2 reports two numbers:

1. The product of the two statistical confidence levels (the structure and the fit confidence levels).
2. The tracing counts per block, which correspond to the amplitude of the step in Figure 4, along with its calculated standard deviation.

Models and Correlations

To predict the detector response downstream of the source, it is necessary to model (a) the percentage of delayed gamma ray fission products that remain in the gas following an induced fission, (b) the flow of fissile material and fission products down the pipe, and (c) the decay of the fission products. Models and the resulting correlations are described in the following sections.

A. Fission Fragment *Decay Model*

The delayed emission data have been obtained by fitting a five-group model to measured data using the actual FMFM hardware. This model includes 300-keV energy-discrimination filters that are accounted for in the overall detector efficiency. The parameters of the five-group model are summarized in Table 1, and a sample measurement is shown in Figure 5. The parameters in Table 1 correspond to a best fit to the decay gamma-ray data following a fission event, so that

$$n_\gamma(\tau) = \sum_{1}^{5} \alpha_i e^{-\lambda_i \tau} ,$$

where $n_\gamma(\tau)$ represents the average number of photons per second following a fission event, λ_i is the group yield constant, which is related to the group precursor fraction, β_i, as $\alpha_i = \lambda_i \times \beta_i$.

Table 1. Delayed Gamma-Ray Data

Group #	α_i (γ/s per fission)	hi (s^{-1})
1	*0.35*	*0.4*
2	*0.06*	*0.04*
3	*0.015*	*0.008*
4	*0.0015*	*0.0008*
5	*0.0002*	*0.00005*

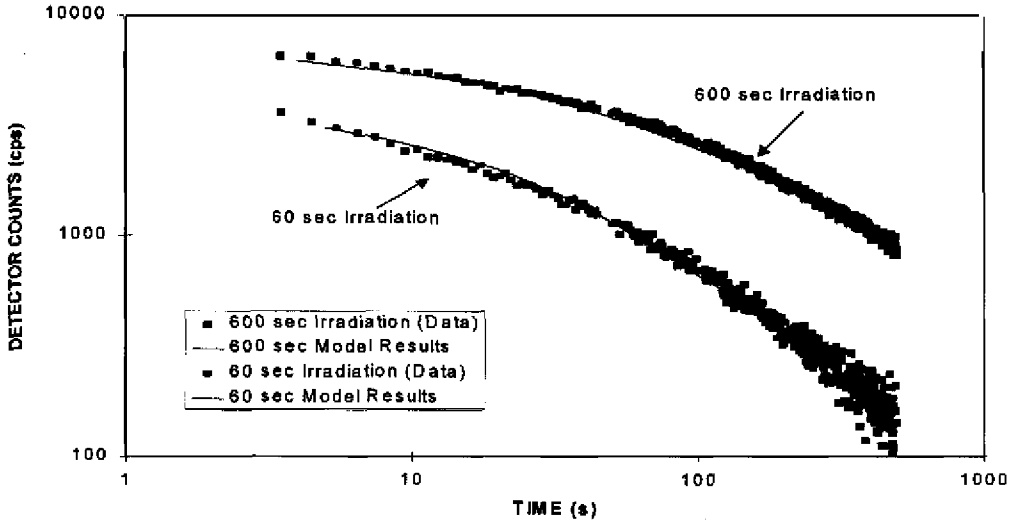

Figure 5. Comparison between ORNL irradiation measurements and decay model predictions

Figure 5 shows the results of applying our delayed gamma-ray emission model to measured data obtained by irradiating a U-235 fission chamber for 60 and 600 seconds and measuring the decay gamma rays **with** the actual flow-monitor hardware. As seen in Figure 5, the delayed gamma-ray emission model predicts the measured data accurately **up** to 500 seconds following the fission event. This decay model also benchmarks well against the impulse-response data published in the literature.

B. Fission Fragment Range in Low-Pressure UF_6 Gas

Fission fragment ranges can be very large in low-density materials. For this reason, a methodology was developed to estimate the ranges and distribution of fission fragments with the goal of determining the fraction of fission products that remain entrapped in **the** UF_6 gas.

The basic range data are derived from the measurements documented **in** the Nuclear *Data Tables*[3]. These ranges are integrated path lengths of heavy charged particles traversing various media. Based on these data, the fission fragment ranges in UF_6 were computed as functions of gas pressure and fission fragment energy. The distribution of fragment energies can be approximated by two Gaussian distributions (one for the light fragments and one for the heavy fragments[4]). The parameters of this distribution are as follows:

$$R_l = \frac{4174}{P}; \quad R_h = \frac{3154}{P}; \quad \sigma_l = \frac{183}{P}; \quad \sigma_h = \frac{236}{P},$$

where R_l and R_h are the average light and heavy fragments range expressed in millimeters, and σ_l and σ_h are their standard deviations, and the pressure p is expressed in Torr.

The above values represent the nominal ranges and their standard deviations. The range, however, represents the integrated path length, not the radial distance from the point of fission. To estimate the effect of nuclear scattering, the tabulated values were compared with measurements by Niday[5]. A comparison of the tabulated values with Niday's measurements indicates that the tabulated values

[3] Nuclear Data Tables, Vol. 7, No. 3–4, 1970
[4] Peasanton, *Phys. Rev.* 174, 1500, 1968
[5] "Radiochemical Studies of the Ranges in Metallic Uranium of the Fragments" from Thermal Neutron Fission, *Phys. Rev.* Vol. 121, No 5, 1961

(and the average ranges given in the Gaussian distributions) should be reduced by approximately 15%. Straggling, the statistical fluctuation in the ranges of charged particles traveling in a material, is accounted for by applying a 10% uncertainty to the ranges and to the standard deviations[6]

To determine the number of fission-fragment absorptions in the pipe wall, a Monte Carlo-type calculation with special tallies was performed. For this run, a homogeneous source of gamma rays was placed inside an empty pipe of diameter, D; then the gamma-ray currents were tallied at different radii as a function of the age of the photon. These ages were directly proportional to the range that the photon had traveled before reaching the inner wall of the pipe and allowed for the development of a correlation for the fraction of fission fragments that were absorbed by the pipe as function of fragment range (i.e., UF_6 pressure) and pipe inner diameter. The fraction, ε_s, of fragments that remained in the UF_6 flow and that contributed to delayed gammas at the detector location was computed from this correlation and the probability distribution function for fragment ranges. Based on these data, two correlations for the source effectiveness have been developed:

$$\varepsilon_s = \frac{1}{1+e^{-0.025(pD-65)}} - 0.271 \; \textit{for } (pD < 200 \textit{ psi mm}), \text{ and}$$

$$\varepsilon_s = 0.943 - e^{-0.006(pD-10.1)} \; \textit{for } (pD > 20 \textit{ psi mm}),$$

where D is the pipe diameter in millimeters, and p is the gas pressure in pounds per square inch. The first correlation is more accurate but it can only be used for low pressures. The second correlation, while not as accurate, can be used at high pressures.

C. Fission Fragment Transport and Decay Model

The basic equation that describes the flow and decay of delayed gamma-ray fission fragments is the combined convection and decay equation:

$$\frac{dc_i(r,z,t)}{dt} + u(r)\frac{dc_i(r,z,t)}{dz} = \beta_i N_{fis} S(r,z,t) - \lambda_i c_i(r,z,t),$$

where $c_i(r, z, t)$ is the concentration of group-i fission fragments at time t and location (r, z), $u(r)$ is the gas velocity at radial position r, β_i is the fraction of group-i precursors generated per fission, λ_i is the decay constant, N_{fis} is the number of induced fissions, $S(r, z, t)$ is the normalized shutter efficiency, which combines the source field of view and the shutter motion as function of time.

The total concentration of delayed gamma-ray fission fragments is the sum over all delayed groups. The number of gamma rays per second counted at the detector, $N_\gamma(t)$, is determined by

$$N_\gamma(t) = \frac{1}{\pi R^2}\int_0^R dr \left[2\pi r \int_{-\infty}^{\infty} dz \left[\varepsilon_d D(r,z) \sum_1^n \lambda_i c_i(r,z,t)\right]\right],$$

where $D(r, z)$ is the normalized detector field of view of all the detectors together, ε_d is the overall detector efficiency.

The above model for fission fragment transport and decay has been implemented in a computer code. This code solves the above equations numerically and computes the precursor concentration at a number of axial and radial nodes inside the fissile stream.

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[6] *Experimental* Nuclear Physics, E. Segre editor, 1953

The computer code solves the time and space equations converted to discrete form and determines the detector response for a particular flow regime, velocity, and shutter pattern. Figure 6 and Figure 7 show the calculated response profiles for turbulent and laminar flow, respectively. Once calculated, these profiles are stored in the FM2 profile database and are used to determine the mass flow rate from the detector count measurements.

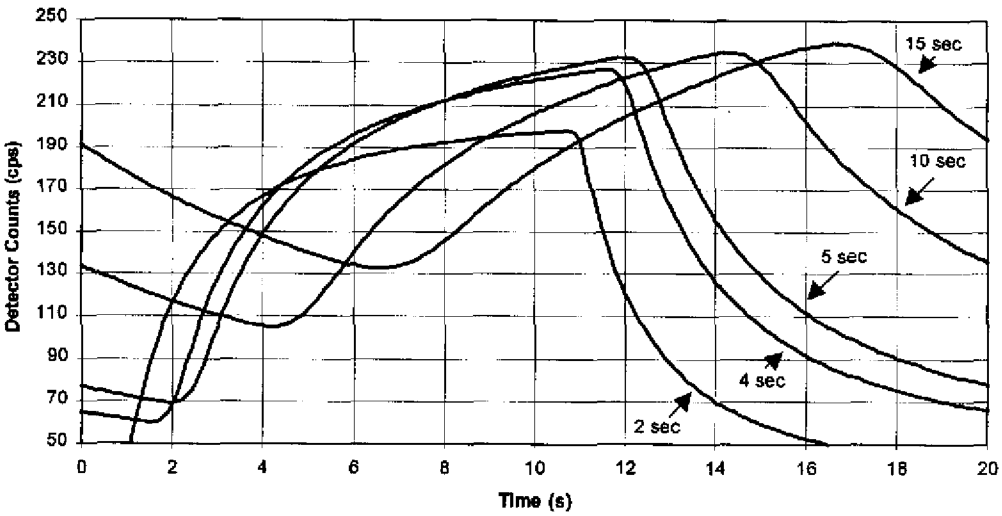

Figure 6. Calculated profile database for laminar flow and l-m source-detector separation

These profiles are calculated as functions of the time delay between the source and the detector center lines. For laminar flow, the time delay is defined as the distance divided by the average velocity. For both figures, the assumed detector efficiency is 22%, which includes an energy discrimination filter for gamma rays with less than 300-keV.

For the laminar flow case (Figure 6), the calculations assume a source-detector distance of l-m and a fissile concentration of 7 g/m of the four-inch ID pipe (equivalent to -1 psia pressure and 90% enrichment). For the turbulent flow case (Figure 7), the calculations assume a source-detector distance of

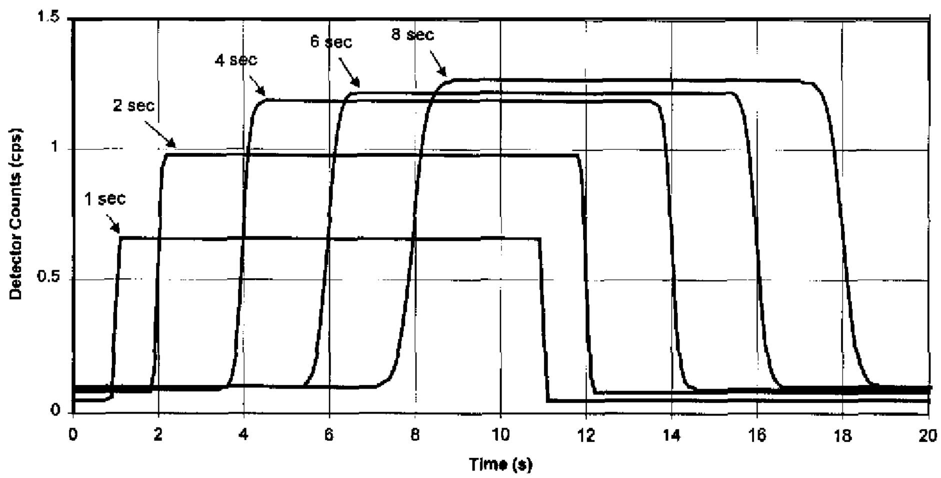

Figure 7. Calculated profile database for turbulent flow and 3-m source-detector separation

3-m and a fissile concentration of 0.1 g/m of 4-inch pipe (equivalent to -1 psia pressure and 1.5% enrichment). Both cases assume that equilibrium conditions have been reached in the pipe and that the shutter efficiency is 95%. For these calculations, the shutter is opened and closed in 20-second cycles (10 seconds open and 10 seconds closed).

D. Correlated Background Model

Motion of the shutter inside the source modulator results in a change of background counts at the detector location. This background change is due to a change in the number of capture gamma rays emitted by the moderator and by a change in the number of capture gamma rays emitted in the pipe. This background change is correlated with the shutter motion and therefore is not reduced by increasing the measurement time. The correlated background magnitude is very substantial; it can be as high as 25% of the total background if the detector is located close to the source modulator. Thus, the correlated background must be taken into account in the model. Because of the possibly large amplitude of the correlated background, shutter synchronization is mandatory to allow for its removal during the data analysis process.

An example of a measured correlated background (with no gas flow) is shown in Figure 8. This figure corresponds to a detector assembly located 1-m downstream of a source modulator.

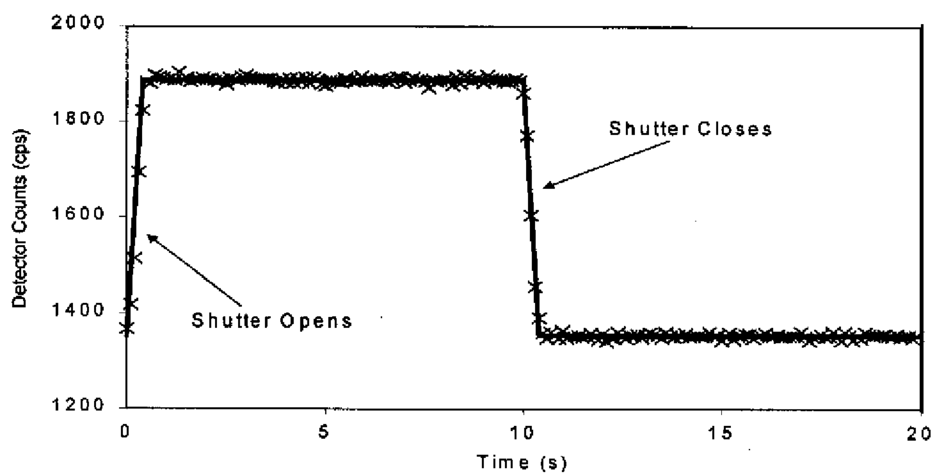

Figure 8. Correlated background (no UF_6 flow)

As shown in Figure 8, the FMFM correlated background model is a constant background between the times of 0 and 10 seconds, and a constant background of different magnitude between the times of 10 and 20 seconds. The two constant-background sections are connected by a linear interpolation at times 0 and 10, which represent the shutter motion. The duration of shutter motion is a field-selectable parameter that can be adjusted if different shutter speeds are used. For the nominal shutter speed, the shutter motion time is 450 ms, and the shutter settling time following this motion is typically 150 ms.

Conclusion

The FMFM was successfully implemented on the UEIP Main and the Reserve process lines at UEIP. The independent measurements of the FMFM measures the UF_6 mass flow rate continuously in the process blending lines, and monitors the traceability of the HEU flow from the blend point to the P-LEU. These measurements give U.S. Monitors significant confidence that the HEU material is indeed being blended into a lower assay P-LEU material.