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Fission Meter Information Barrier Attribute Measurement System - NA-243 FNI/UKC FY2017 Task 1-2 Report

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Fission Meter Information Barrier Attribute Measurement System

Task 1-2 Report

Document existing Fission Meter neutron IB system

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Introduction

An SNM attribute Information Barrier (IB) system was developed for a 2011 US/UK Exercise. The system was modified and extensively tested in a 2013-2014 US-UK Measurement Campaign. This work demonstrated rapid deployment of an IB system for potential treaty use. The system utilizes an Ortec Fission Meter neutron multiplicity counter and custom computer code. The system demonstrates a proof-of-principle automated Pu-240 mass determination with an information barrier. After a software start command is issued, the system automatically acquires and downloads data, performs an analysis, and displays the results. This system conveys the results of a Pu mass threshold measurements in a way the does not reveal sensitive information. In full IB mode, only the pass/fail result is displayed as a "Mass <= Threshold Amount" or "Mass >= Threshold Amount" as shown in Figure 4. This can easily be adapted to a red/green "lights" display similar to the Detective IB system for Pu isotopics as shown in Figure 6. In test mode, more detailed information is displayed. The code can also read in, analyze, and display results from previously acquired or simulated data.

Because the equipment is commercial-off-the-shelf (COTS), the system demonstrates a low-cost short-lead-time technology for treaty SNM attribute measurements. A deployed system will likely require integration of additional authentication and tamper-indicating technologies. This will be discussed for the project in this and future progress reports.

Development and Deployment History

The ORTEC Fission Meter is a portable neutron multiplicity detection system that was developed to identify special nuclear materials for nuclear counter-terrorism applications. It consists of 30 1" x 20" 7.5 atm He-3 proportional counter tubes. The Fission Meter has also been deployed for search, assay, and material protection, control, and accountability applications. In the field, the Fission Meter is typically controlled with a handheld PDA computer which allows stop/start/reset/download data controls via a 9-pin serial port. The display also provides some information to the user, but the intent is to provide the data to experts for later analysis.

The Information Barrier modifications to the control software started at LLNL in 2011 and continued through 2014. The goals for the IB software are three-fold:

1.) Simplify and further automate the acquire and download functions
2.) Add a fast, automated data analysis routine that can function on the PDA
3.) Demonstrate PDA display of a mass attribute result that avoids sensitive information

The PDA interface also has an IB Test mode that displays more detailed information, as well as a IB2-Read2A mode that allows analysis of previously stored data. This allows rapid software iteration and testing. The software was tested with materials at LLNL as well as many archived data files of various materials. The first deployment of the Fission Meter IB (FMIB) was in England in 2011 for a US/UK Exercise where it successfully measured an "unknown" test item.

The output information was selected to be a statement whether the mass was greater than or less than an agreed value, as well as a minimal diagnostic of the excess doubles parameter Y2F and count distribution, to give the user confidence that the instrument is working. These plots do not contain axis values or error bars to minimize information content. The Y2F and/or count distribution display could also be removed in future deployments of the FMIB if determined that they reveal too much information.

For the 2013 US-UK Measurement Campaign (MC-2013), the interface was adapted for use on a laptop computer. This facilitated archiving the data as well as preparing for integration of the list-mode board upgrade in 2014, which requires more computer processing power. Another rational for porting the software to a laptop computer is that this allows integration of Pu isotopics data and analysis from the Ortec Detective. The Detective is the second component of the COTS information barrier system developed by LLNL. This Ortec Detective component will be detailed in subsequent project reports. Figure 1 shows a photograph of the Fission Meter and Detective instruments used in developing the Information Barrier software for the U.S.-U.K. Measurement Campaigns.

In the 2013 campaign, the FMIB measured materials divided roughly equally in three drums. The drums were measured separately and together at various distances and acquisition times to establish detection limits and sensitivity. During 2013-2014, the software was modified to acquire data from the new Ortec list-mode board in preparation for 2014 US-UK Measurement Campaign (MC-2014). The list-mode board produces a stream of channel-by-channel timestamp data for each neutron event with 20ns time resolution. The list-mode data allows analysis with any current or future multiplicity sorting algorithm. List-mode data also allows sensing if one or more channels has a problem, as well as allowing removal of segments of time that contain an interfering effect such as unannounced material moves. Figure 2 shows a photograph of the List-Mode Fission Meter Board installed in the Fission Meter and used during the MC-2014 Measurement Campaign.

During the July, 2014 measurement campaign, the material was removed from the three drums, and arbitrary configurations were possible. This allowed arranging the material from maximum mass and multiplication, to measuring a single item of 25g Pu-240. The FMIB successfully measured the material configurations in MC-2013 and MC-2014, as described in the Results section below.

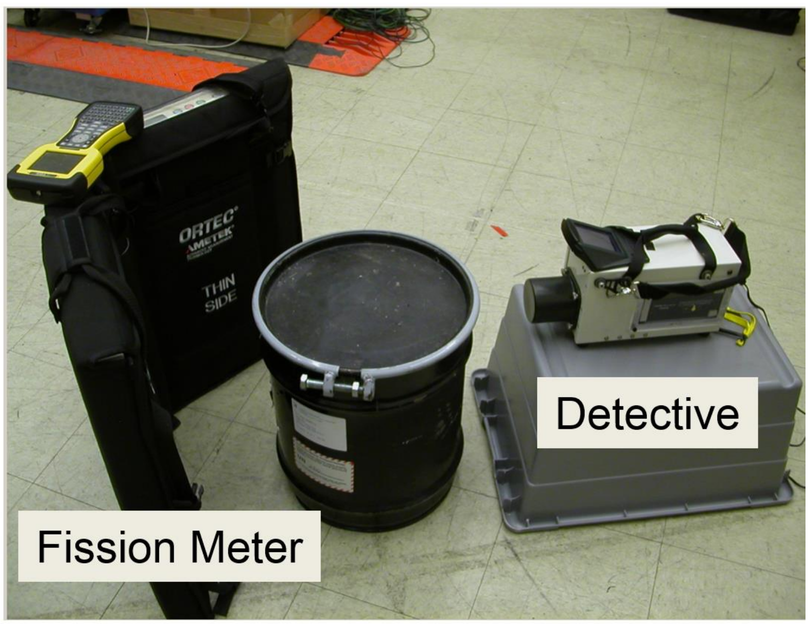

Figure 1 Photograph of the Fission Meter and Detective instruments used in development of the Information Barrier software interface.

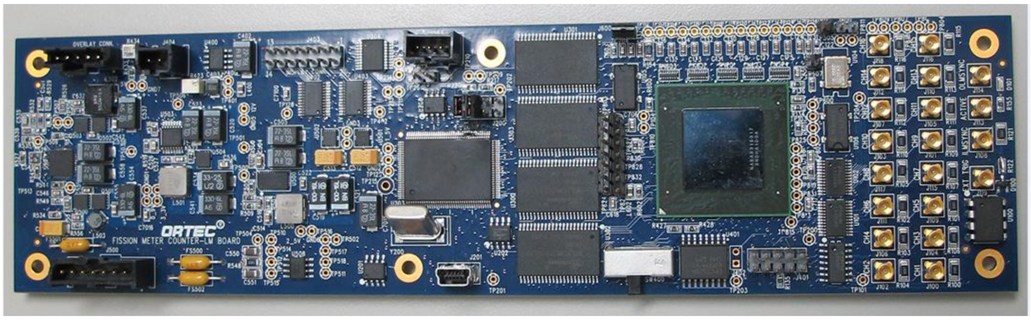

Figure 2 Photograph of the List-Mode Fission Meter Board installed into the Fission Meter for the MC-2014 Measurement Campaign

Operational Description

This section describes the basis and operation of the FMIB starting with the theoretical background and simplifications, followed by a description of the IB software graphical user interface (GUI).

Theory

The Fission Meter Information Barrier (FMIB) code is based on a simple implementation of the point model theory of neutron counting distributions that uses the first two moments of the distribution. The point model theory is based on a few sets of lumped parameters: intrinsic source strength of neutrons, S, multiplication M, alpha ratio A, detector efficiency for detecting neutrons, ε, and the neutron moderation time, λ^{-1}. We briefly describe these parameters. The source strength, S, is the intrinsic source rate of neutrons in the medium, either from spontaneous fission or an internal random source, and has units of neutrons per second (n/s). The multiplication, M, in the point model theory is defined by:

$$M = \frac{1}{1 - keff}, \;\; keff = p\nu$$

Where p is the probability that a neutron will induce a fission event in the medium and ν is the average number of neutrons created in that induced fission event. For a 1 MeV neutron induced fission on ^{239}Pu, ν ≈ 2.3. The alpha ratio, A, is the ratio of the random source of neutrons created through (α,n) reactions to neutrons created by spontaneous fission.

The detector efficiency, ε, measures how many of the neutrons leaving the medium are counted, and in the point model includes the absorption probability of a neutron within the medium. Here we note that the FM consists of two hinged panels each with 15 He-3 tubes. This allows the measurements to be performed with two different FM geometries, folded, which takes maximum advantage of the polyethylene moderator built in to the FM and unfolded where the He-3 tubes have the greatest solid angle. In general, the unfolded geometry is most efficient for moderated sources. The detector efficiency for the FMIB code assumes that the device is in the "unfolded" configuration.

The neutron moderation time, λ^{-1} (from fast to thermal), describes the time difference between detection of correlated neutrons. In the point model, the moderation time includes any moderation in the medium itself as well as in the detector. For ^{3}He neutron detectors which are optimized for detecting thermal neutrons, the moderation time in the detector itself is typically several tens of microseconds (μs).

The neutron detector analysis determines how many neutrons were detected within each of several time intervals, typically ranging from 1 micro-s to 512 micro-s. This set of intervals is referred to as a cycle. During a measurement, this cycle is repeated many times to build up statistics. For good counting statistics, the number of cycles must be sufficiently large. If we denote C_n as the number of times n counts were detected in the gate width T over N cycles, then:

$$N = \sum_{n=0}^{\infty} C_n$$

We can define the average of the C_n as the average number of counts, $\bar{C}$, in the time interval, T:

$$\overline{C} = \frac{1}{N}\sum_{n=0}^{\infty} n\, C_n$$

We can further define the second correlated moment (cumulant) of C_n as:

$$Y_2 = \frac{1}{N}\sum_{n=0}^{\infty} \frac{n(n-1)}{2}\, C_n \; - \; \frac{\overline{C}^2}{2}$$

Finally, we define the second Feynman moment, Y_{2F}, of C_n as:

$$Y_{2F} = \frac{Y_2}{\overline{C}}$$

In the point model theory, assuming instantaneous fission events, one can relate these moments to the lumped parameters and gate width, T, through the following equations:

$$\overline{C} = R_1\, T$$

$$R_1 = \epsilon(1-p)M(1+A)S$$

$$Y_{2F} = R_{2F}\left(1 - \frac{1 - e^{-\lambda T}}{\lambda T}\right)$$

$$R_{2F} = \epsilon(1-p)M\left(\frac{D2S}{1+A} + (M-1)D2\right)$$

Here R_1 is the count rate, and R_{2F} quantifies the neutron doubles correlation rate in the data. For a random source of neutrons, R_{2F} is 0. If there is spontaneous fission and/or induced fission (neutron multiplication M > 1) in the medium, then $R_{2F} > 0$. Constants D2S and D2 relate to spontaneous and induced fission nuclear data of the medium and are typically on the order of 1 in magnitude. For a 1 MeV neutron induced fission on ^{239}Pu, D2 ≈ 1.23, and for spontaneous fission of ^{240}Pu, D2S ≈ 0.88. One can also compute higher correlated Feynman moments.

The FMIB code first fits the data $\overline{C}$ and Y_{2F} using the equations above to estimate R_1, R_{2F}, and λ^{-1}. For Y_{2F} the data is only fitted for large time gates, typically T ≥ 340 μs, since the simple point model formula for Y_{2F} above may not be a good fit for all values of T and we are ultimately interested in only the asymptotic value R_{2F} of Y_{2F}. The current implementation of the FMIB code assumes we are measuring a metal SNM so we can set the alpha ratio A = 0.

We have also developed an empirical model of the detection efficiency ϵ as a function of the neutron lifetime λ^{-1} and the distance d of the FM from the center of the SNM source. This empirical model for ϵ has been built using a database of measurements with the FM on various SNM sources, both bare and moderated, at various measurement distances d. When the neutrons emanating from the SNM are moderated they slow down and it takes longer for them to be detected in the detector. This moderation is reflected in an increased neutron lifetime λ^{-1}.

Using the above formulas for R_1 and R_{2F} along with the empirical efficiency ϵ model the FMIB code then estimates the multiplication M and the source strength S. The estimated source strength S is finally converted to an effective ^{240}Pu mass using a conversion factor of 1023 n/s/g.

GUI Code

The display screen and graphical user interface of the IB code provides results of the Pu-240 mass measurement and demonstrates protection of sensitive mass information. Typically, a threshold mass is established for the pass/fail assessment. For example, the threshold may be 500g. For weapons-grade plutonium, this is about 25g of Pu-240. The Fission Meter and other neutron multiplicity counters measure this Pu-240 “source” mass only. Measurement of Pu isotopics using a gamma-ray detector is necessary to measure the isotopics, which in combination with a Pu-240 mass measurement can provide the total plutonium mass. Figure 6 shows the Detective IB code output of Green/Red “lights” that can be used in Fission Meter IB.

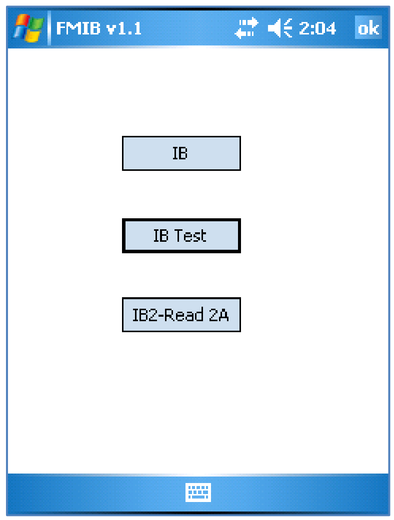

Figure 3 Main control screen of the FMIB system as seen on a TDS Ranger PDA

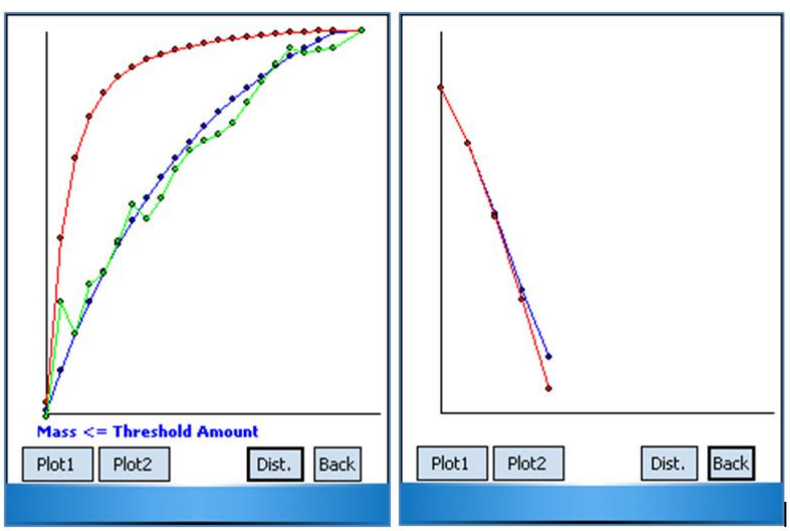

Figure 4 Results screen showing Y2F and mass result (left) and count distribution (right) for a Cf-252 source. Note the plots do not contain axis values or error bars which may reveal sensitive information for a treaty item.

Figure 5 Plots of the GUI adapted for use on a laptop computer

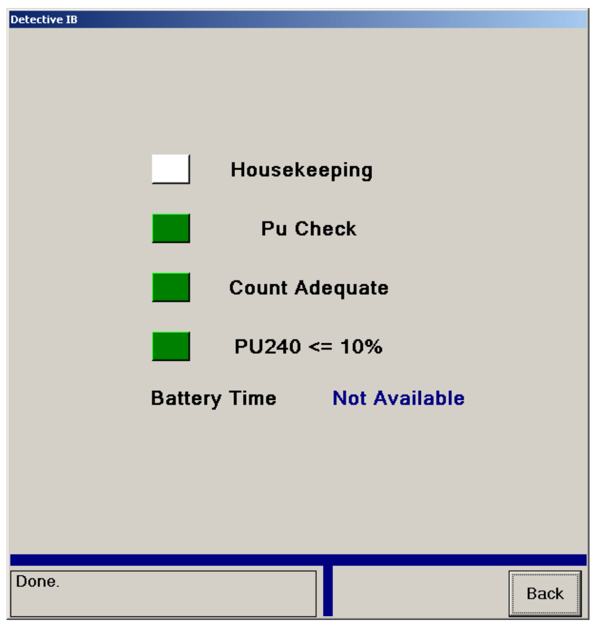

Figure 6 Example Green/Red Light GUI feedback from Detective IB. This could also be used for Fission Meter IB.

Historical Results and Conclusions from 2013 and 2014 Measurement Campaigns

Measurements obtained with the Ortec Fission Meter in the UK and other sites have demonstrated the capabilities of portable commercial instruments to quickly measure mass of small quantities of Pu. The COTS system has the added advantage of rapid deployment and multi-lateral familiarity.

MC-2013 Results

The neutron multiplicity data obtained during MC-2013 data allowed demonstration of a rapid and compact system for verification of SNM mass. Note that in this information-barrier system, the goal was to demonstrate the use of a COTS system and custom software to produce a pass/fail result with minimal information displayed and minimal user interaction. The Information Barrier code was used throughout the measurements and demonstrated one potential custom implementation of protecting data from the Fission Meter. However, the current implementation does not address certification or authentication of the hardware or software, or protection of the data that is behind the display.

The internal Fission Meter counting board sorts the neutron data into time and multiplicity bins that are downloaded at the end of the measurement. The counting board was originally developed at LLNL and is called the 5-Mode board because there are five selectable counting modes available. Historically, only one of these modes has been used for neutron characterization. This is the so-called 2A mode which has a sorting structure as shown in Figure 7. The MC-2013 software would download this data, convert it to a readable format file called -2A.log, then analyze and display the results as described in the Theory section above. The raw data is in volatile memory and is lost when the Fission Meter is powered off. The -2A.log data file is currently stored on the computer. It could be deleted after data analysis.

The measurements were also conducted to test the empirical model of efficiency as a function of distance and neutron lifetime. Using this model on MC-2013 data, a mass bias high of 30% was found. The source of this discrepancy has not yet been identified. The model was developed using many measurements of varying distance and moderator with the same model of instrument in similar facilities. The discrepancy may be resolved by re-examination of the previous data. However, this bias appeared equally for one- and two-drum data at all distances. Therefore, a simple scaling adjustment of the model produced an accurate average mass with only a 10% standard deviation across all distances, 106g±10g (compare to actual value of 105g). This is shown in Figure 8.

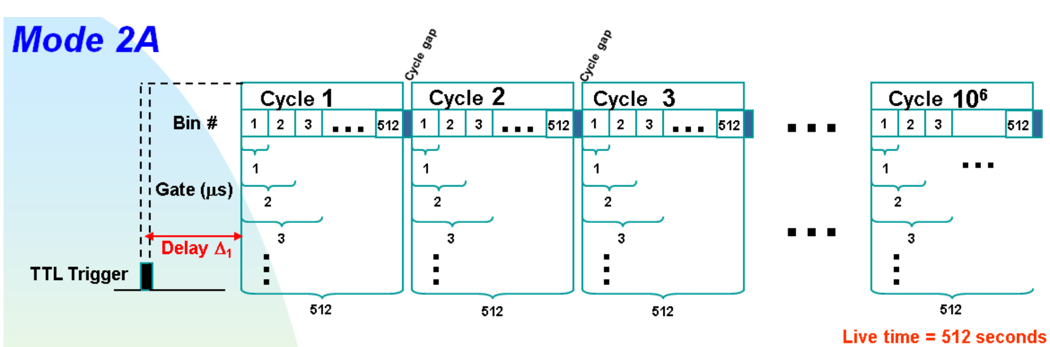

Figure 7 Fission Meter 2A counting mode. Every 512 micro-s time window contains neutron multiplicity information for the first 1 micro-s, 2-micro-s, 3 micro-s, etc. to 512 micro-s.

The MC-2013 data was acquired in a well-controlled environment with no moderating materials present. The non-list mode Fission Meter used at MC-2013 worked well in this environment. In more realistic monitoring environments, several factors can complicate the quality and analysis of data. These include unknown amounts of moderator, unannounced movement of other materials in the area or neighboring rooms, and long-term use of equipment. In these cases, there is a significant benefit to the use of list-mode data. This was the goal for the follow-on MC-2014 measurements. List mode data can be resorted to optimize for differing amounts of moderator, replayed to look for changes in count rate due to unknown material moves, and examined tube-by-tube to look for hardware changes or failures. A primary goal of the MC-2014 campaign was to demonstrate the use of list-mode acquisition, and the MC-2014 data set from July 2014 was successfully acquired using a list-mode Fission Meter.

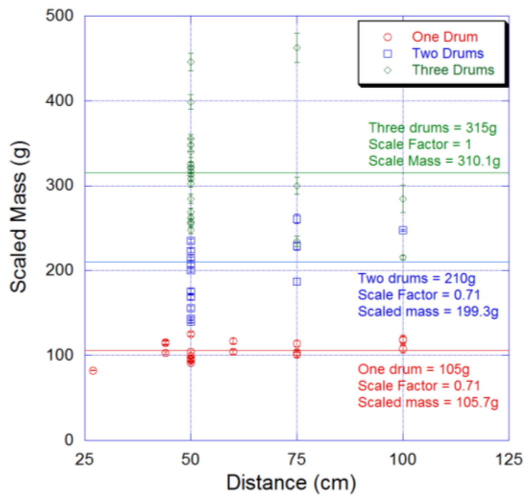

Figure 8 Plot masses for one, two, and three drum measurements vs. distance.

MC-2014 Results

The neutron multiplicity data obtained during MC-2014 measurement campaign allowed the demonstration of the list-mode capability for the Fission Meter on a wide range of plutonium masses. The successful measurement campaign demonstrated the value of this capability to Arms Control verification. During acquisition, the list-mode data was streamed via USB port to a data file on the computer. The list-mode data was then converted to the -2A.log format using the NeutronFileConverter code. This -2A.log file was then analyzed by the FMIB code as during MC-2013.

Converting the list-mode to the -2A.log format could be automated by integrating the list-mode to -2A.log file converter into the FMIB code. During MC-2013, the analysis of the 5-Mode -2A.log file was done using the FMIB within seconds of completing the data download.

The FMIB code analyzes the data using a simplified version of the LLNL code BigFit called MiniBigFit. In BigFit, the data is compared to a matrix of computed count distributions with accompanying mass, multiplication, detector efficiency, and alpha ratio values, to find the best match using a chi^2 minimization. The results are displayed as a rank-sorted list of mass, multiplication, efficiency, and alpha ratio.

In MiniBigFit, the detector efficiency parameter is replaced with fixed values based on an operator-defined distance. As discussed below and in previous reports, the MiniBigFit results showed a slight bias of high mass. The same data was later analyzed with the full BigFit to better understand this bias. The BigFit analysis suggests a slight adjustment to the built-in efficiency model may correct for the bias high mass. For example, the typical efficiency is about 0.6%. A discrepancy of 0.1% would account for most of the bias. That is, a true efficiency of 0.6% + 0.1%=0.7%.

The results of the BigFit analysis also provided information on the alpha ratio of the samples. Such a determination typically requires very high efficiency and quality 3^{rd} Moments (triples). However, after a comparison of multiple runs (with low triples statistics), and using consistent parameter ranges in BigFit across these measurements, the rank-sorted solutions had an alpha ratio between 0 and 0.1 and consistent with 0. This additional analysis reasonably excludes the possibility of these Pu items having a non-zero alpha ratio. Measurement of the Pu blocks in a higher-efficiency detector, such as a well counter, would enable a more definitive result.

The current MiniBigFit automated analysis has a fixed value of 0 for alpha ratio. If alpha is determined to be an important arms control variable, a more advanced MiniBigFit would be required, potentially analyzing multiple measurements to converge on a consistent value.

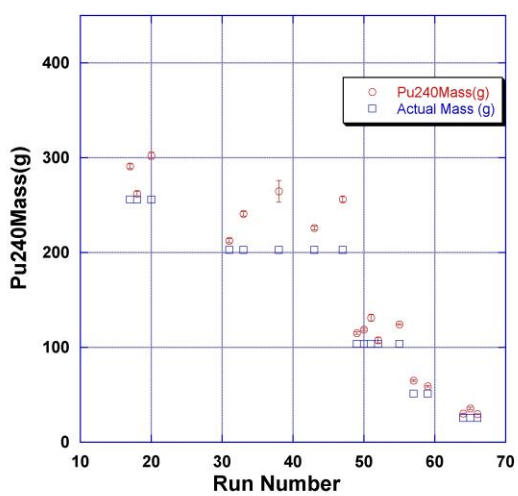

Figure 9 Plot of calculated Pu-240 mass for each FM Unfolded measurement using list-mode converted to the random 2A file (red circles). Also shown is the actual mass (blue squares)

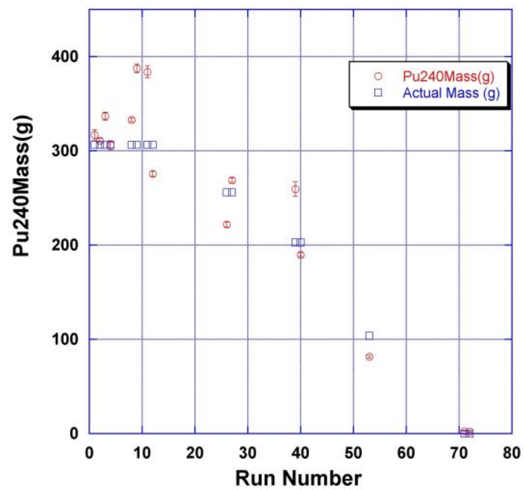

Figure 10 Plot of calculated Pu-240 mass for each FM Folded measurement using list-mode converted to the random 2A file (red circles). Also shown is the actual mass (blue squares)

Certification and Authentication Potential of the Fission Meter

The approach taken with the current Fission Meter IB system was demonstration of the speed, accuracy, and simplicity of a COTS-based system. Authentication and certification of elements of the system behind the information display were to be developed later. This section describes some potential methods to increase confidence in the measurement in a treaty environment.

We propose a graded approach to IB system component vulnerability mitigation and authentication. The justification being the general complexity of authenticating commercial hardware and software, and the expectation that this IB system is one component of several implemented for a treaty verification CONOPS. A reasonable graded approach to authentication of the Fission Meter may be authentication of one subcomponent, e.g. the low-cost list-mode data-acquisition board.

Being a commercial-off-the-shelf item, the Fission Meter offers potential for a rapid deployment and site acceptance path. The theoretical background for use of neutron multiplicity to measure SNM mass is well known and would require minimal review. The hardware can be characterized as two separable components: the detector system of He-3 proportional counter tubes and preamplifiers, and the data-acquisition system electronics board. Between these systems, the data-acquisition board is the most complex to authenticate. The board is also the least expensive, and therefore could be authenticated by using the random selection method. In this authentication method, two boards are chosen at random from an inventory of several boards. One board is placed in the instrument, and the other is taken by the visiting partner for testing at home. If the second unit is authenticated at home, this increases confidence that the board in use is reliable. Figure 2 shows a photograph of the List-Mode Board.

The most significant technical issues involve authentication of the primary electronics boards in the COTS equipment. Because these are COTS equipment, they cannot be extensively modified and still be considered COTS. In addition, these electronics were not designed with authentication and certification in mind. As suggested above, one approach is to consider these low-cost subcomponents as a candidate for random selection by the host. Compared to the cost of the Fission Meter, the cost of the list-mode board is minimal, and several boards could be made available for selection and installation prior to a treaty measurement.

The COTS Fission Meter and software have a wider range of functionality than required by and IB mass measurement system. For example, the electronics board can be set to sort data in any of five counting modes. These modes include alternate multiplicity sorting methods, as well as a time-interval distribution mode, and a triggered time spectrum mode for pulsed sources. The software has multiple functionality for varied user needs such as mobile and static search. In future IB developments with the Fission Meter, significant simplification of both the hardware and software is possible. Board simplification would reduce the cost of the electronics board in the long run, which reduces the cost of the random selection method, though it would require an initial investment in board redesign. A new version of the data-acquisition software with minimal functionality would be a cost-effective investment in simplifying certification of authentication of the software.

Another approach is to enclose the Fission Meter, a low-cost computational block, and a low-cost display in a tamper-indicating enclosure. The simplicity of the computational block and display reduce the burden of certification and authentication of the PDA or laptop, and the tamper-indicating enclosure increases confidence that the instrument has not been tampered.

The low-cost computational block and low-cost display are intended to be custom designed and approved by treaty parties, and are intended to be an interface between the Fission Meter and the user. This is intended to eliminate extra, unnecessary functionality, and is a basis to reduce the certification and authentication requirements. The information on the display is also subject to agreement and may include some neutron data or only a Pass/Fail message.

The prioritization of which systems or sub-systems are behind the IB and subject to authentication will be based on level of vulnerability, mitigation complexity, and cost. In this approach, the strategy is to consider the system as one element of a multi-element treaty verification platform, and to specify requirements to design confidence into all or an acceptable subset of subcomponents. The Fission Meter is fundamentally like other neutron detectors. Authentication and certification requirements for the Fission Meter should be similar to previous neutron detectors. The key difference is in the neutron pulse processing board and software analysis of this data. Certification and authentication will be focused on these elements.