# 2021 R&D Awards – Radiation Monitoring Devices, Inc.

*Multiplicity Counter for Thermal and Fast Neutrons (MC-TF)*

## Product/Service Categories

### Title

Multiplicity Counter for Thermal and Fast Neutrons (MC-TF)

### Award Category

Military/Defense/Nuclear Response Team Devices/Nuclear Safeguards

## R&D 100 Product/Service Details

### Name of Primary Submitting Organization

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### Product Name

Multiplicity Counter for Thermal and Fast Neutrons (MC-TF)

### Product Introduction Date

2019

## Price of Technology

$160,000-$200,000 (depending on configuration, as required by the customer)

## 60-Word Description of the Technology

The Multiplicity Counter for Thermal and Fast Neutrons (MC-TF) is a field-deployable device that first responders can use to quickly assess in real-time and with high confidence the threat level posed by a suspected nuclear weapon. The MC-TF is designed to detect time-correlated fast and thermal neutrons unique to special nuclear material (SNM); the core of a nuclear weapon.

## Type of Institution

Research and Development Company

## Submitter's Relation to the Entered Product/Service

Product Developer

## Product Photo

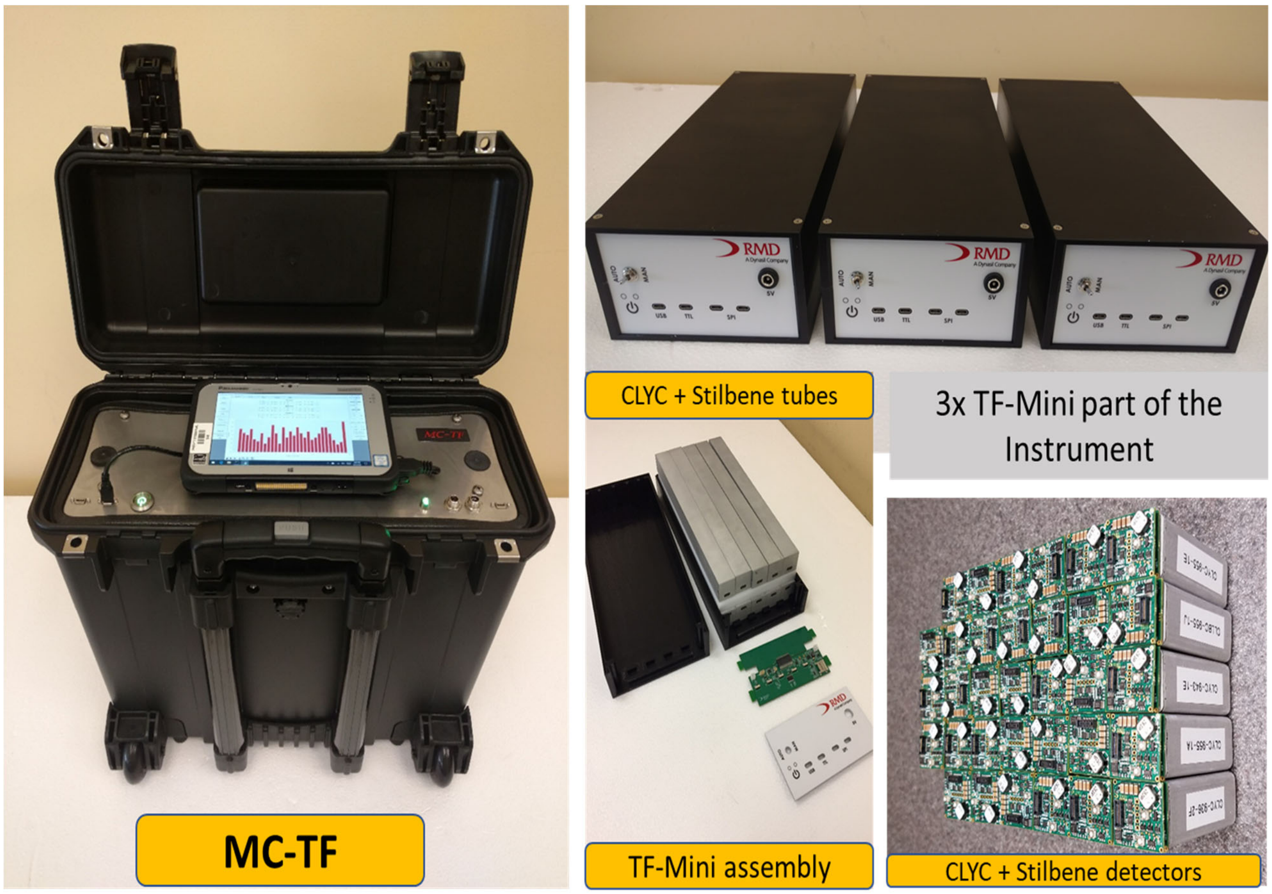


***Figure 1.*** The assembled MC-TF instrument (left) with its associated components (right)

# 1. Product/Technology Description

## 1.1. Describe the principal applications of this product

The principal application of the MC-TF (Figure 1) is for an emergency scenario where first responders must quickly and with high confidence identify the presence and extract detailed information of a suspected nuclear weapon in order to promptly initiate the appropriate response protocol.

## 1.2. How does the product or technology operate?

### 1.2.1. MC-TF Overview

An illustration of the basic system configuration and the intended application is shown in Figure 2. The fundamental objective of the device is to determine whether or not a source of radiation is special nuclear material (SNM). "SNM is defined by Title I of the Atomic Energy Act of 1954 as plutonium, uranium-233, or uranium enriched in the isotopes of uranium-233 or uranium-235…" [1]. If through a radiation detector with neutron detection capabilities, it

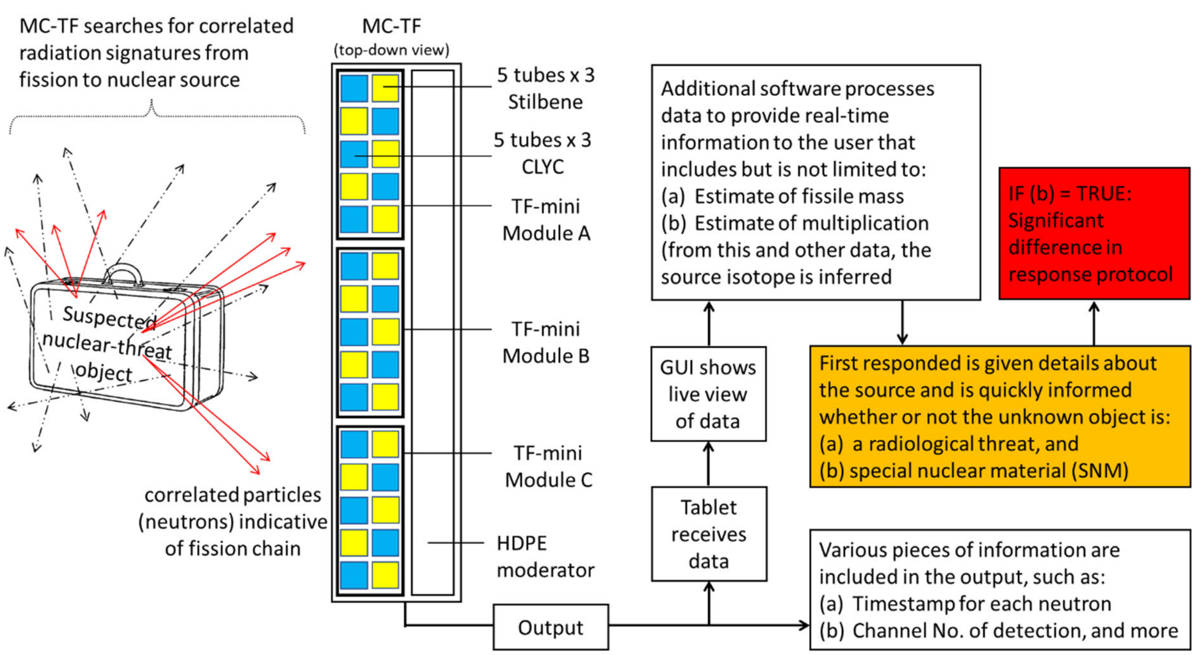


***Figure 2.*** *An overview of how the MC-TF system and software work together in real time.*

is determined that the object in question emits neutrons, then there is a chance that the object may contain SNM, but we can't know for sure [2-6]. The MC-TF is designed to resolve these type of uncertainties.

The object in question may contain a non-SNM source of neutrons, such as Cf252, Am-Li, or Am-Be. What's more, the response procedure and intensity will dramatically differ between the presence of an SNM versus a non-SNM source, where any SNM source is considered serious given that it is the primary ingredient of a nuclear weapon. To the best of our knowledge, there is currently no field-deployable instrument utilizing time-correlated signatures from both thermal and fast neutrons, which in addition is battery-operated, compact and equipped with a friendly user interface that a trained first responder can use to quickly identify and classify any SNM threat in real time. The MC-TF features SNM vs non-SNM discrimination, along with fissile-mass estimation, which gives the first responder valuable information so that they can initiate the appropriate response. The MC-TF leverages this capability through its use of compact processing and data acquisition electronics, along with multiple thermal (CLYC [7, 8]) and fast (stilbene [9, 10]) neutron detectors (in total 90 detection channels), allowing for faster and more detailed data collection than is currently possible with a state-of-the-art $He^3$-based (thermal neutron detection only) multiplicity counter [11, 12]. For a more detailed description of the MC-TF, please see Section 1.2.4.

### 1.2.2. MC-TF Methodology

The MC-TF records the time of a thermal neutron detection in any of the CLYC-scintillator channels, and a fast neutron detection in any of stilbene-scintillator channels. The channel number is recorded along with the timestamp. Through on-board electronics, pulse-shape discrimination (PSD) [13,14] is performed on-the-fly, thus removing from consideration any gamma-ray interaction in any of the scintillators so that the timestamp output only consists of neutron events. Data from neutron detection events (e.g., the timestamps and associated channel numbers) are collected every second, after which they are immediately sent over USB to a tablet. The tablet software (see Section 1.2.6) provides a live view of the event rates and analyzes the timestamps accumulated in the one-second data block. Specifically, the software is looking for correlated time signatures that are needed in order to retrieve the total number of neutrons produced (i.e., the multiplication) per fission-chain burst (see Section 1.2.3 for more information on fission and neutron multiplicity). The neutron emission distribution per fission chain burst is used to extract identifiable features of the unknown source, which can be used to determine if the source is SNM or not [3]. The time-intervals between each timestamp are used to interpret which events are uncorrelated and which are correlated, i.e., events detected by the MC-TF that happened to come from the same fission-chain [4,11].

Events with short time intervals between each other event, they have a high probability for having come from the same fission chain. Figure 3 illustrates the MC-TF timestamp detection process and compares it to the current state-of-the art $He^3$-based neutron multiplicity counter (the MC-15 [12]).

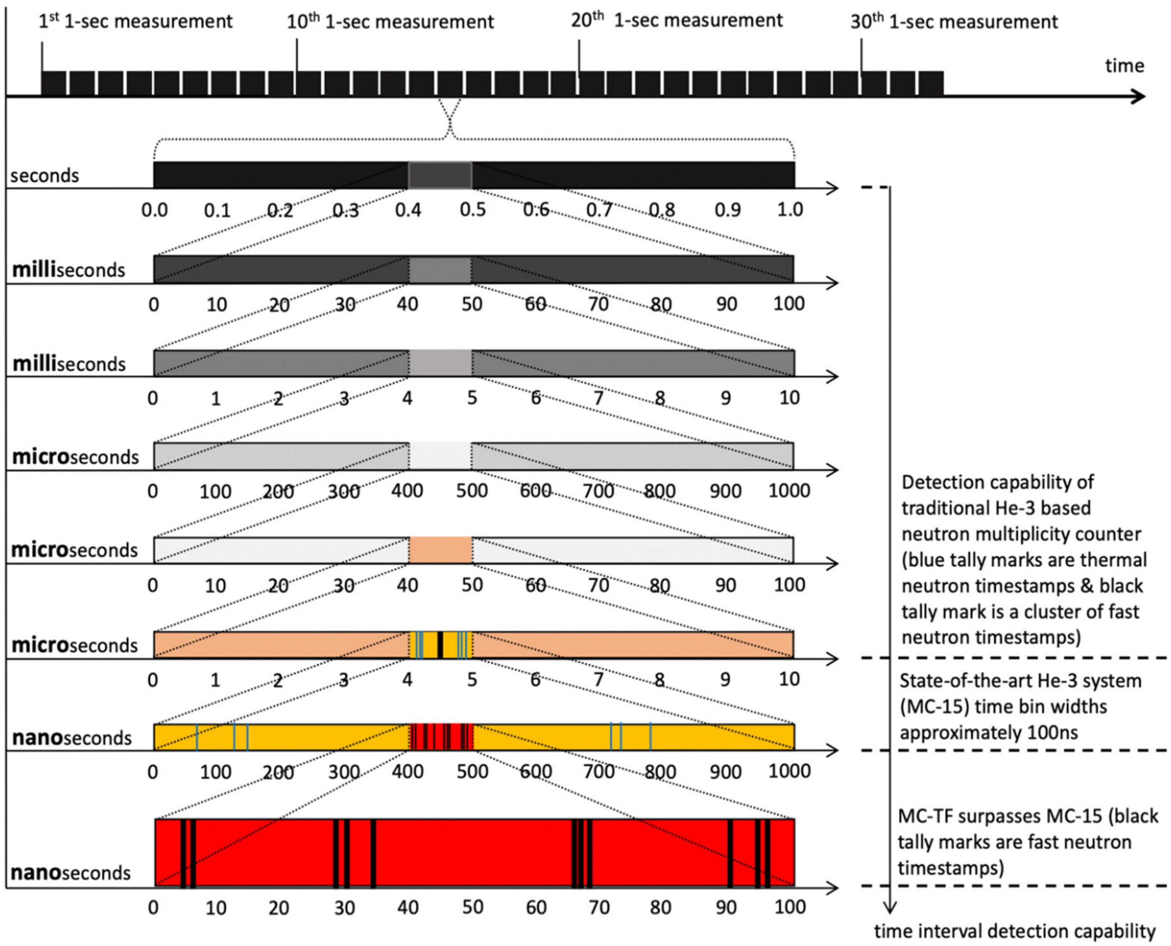


***Figure 3.*** *A graphical representation of the time-scale detection capability of the MC-TF for neutron events.*

The MC-15 can record data in blocks of 100 ns, where the MC-TF can directly digitize incoming pulses with 12 ns timing accuracy. At the top of Figure 3, we see a measurement in progress, where the timestamps for neutron-detection events are recorded in consecutive one-second measurement intervals. Progressing downward through Figure 3 is a graphical representation of the increasingly smaller timescales at which correlated events from thermal and fast neutron are expected to occur. A $He^3$-based system has an inherently slower response time to a fission chain event because it needs to wait for prompt-fast neutrons from the fission chain to thermalize (i.e., scatter multiple times to lose energy before they become detectable by the He-3 gas) [14-16]. On the other hand, the MC-TF can see both the correlated thermal neutron events, along with the correlated fast neutrons. As a byproduct, the MC-TF can observe the entire evolution of the fission chain. Figure 3 was created to both appreciate and

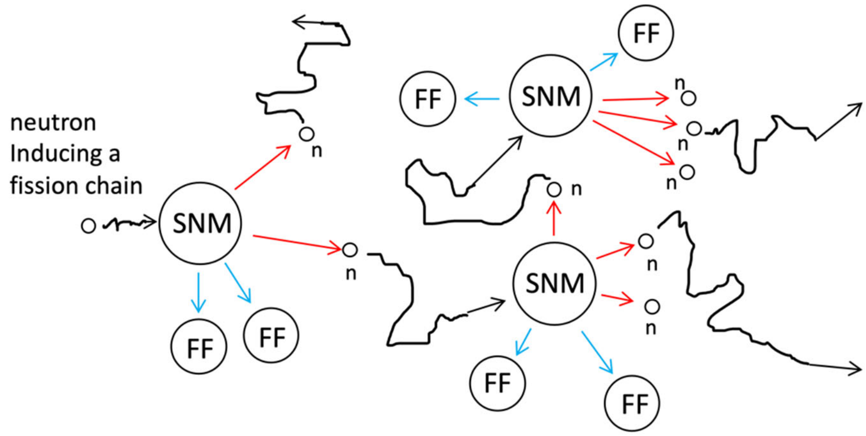


***Figure 4.*** *A simplified illustration of a fission chain occurring in SNM. The illustration shows a thermal neutron inducing fission in the first SNM atom, resulting in the emission of two fission fragments (FF) and two neutrons (n). One of these neutrons goes on to continue the chain reaction. Gamma emissions are not shown..*

emphasize the detection capability of the MC-TF.

A time-correlation analysis [4, 11, 12] on the neutron pulse train yields a histogram showing the quantity of detected neutrons that are also emitted from the same fission chain. This histogram is unique to each neutron source and therefore can be used to discriminate between SNM and non-SNM sources. The time-correlation analysis software designed by RMD Inc. collaborators is used to infer with high confidence a) the fissile mass content (the quantity of mass that is fissionable), and b) determine whether or not the source is SNM.

### 1.2.3. MC-TF Fundamentals (Fission and Neutron Multiplicity)

The defining quality of a special nuclear material (SNM) is the ability to sustain a fission chain. The neutrons that result from a fission chain come out closely-spaced in time. They are correlated in time in much the same way raindrops are correlated in time with thunderstorms. Neutrons from SNM come in bursts like intense downpours. In contrast, neutrons from benign sources come in a steady stream like raindrops in Seattle during the winter. A neutron multiplicity counter does not simply record *that* a neutron was counted, but also *when*. This pattern can tell us a great deal about SNM size and configuration through the multiplication *M*. [4,11,17-27]. A simplified and not-to-scale graphical representation of the fission chain process is illustrated in Figure 4.

In some cases, especially in sub-critical SNM like highly enriched U235 or weapons-grade Pu239, a single neutron can induce and sustain for a short period of time (10's of ns) a chain of fission reactions (on the order of 10's or less), producing a burst of many promptly emitted neutrons [4]. We define the total number of neutrons produced per fission chain as the total neutron multiplication, which also carries its own distribution given its convolution with

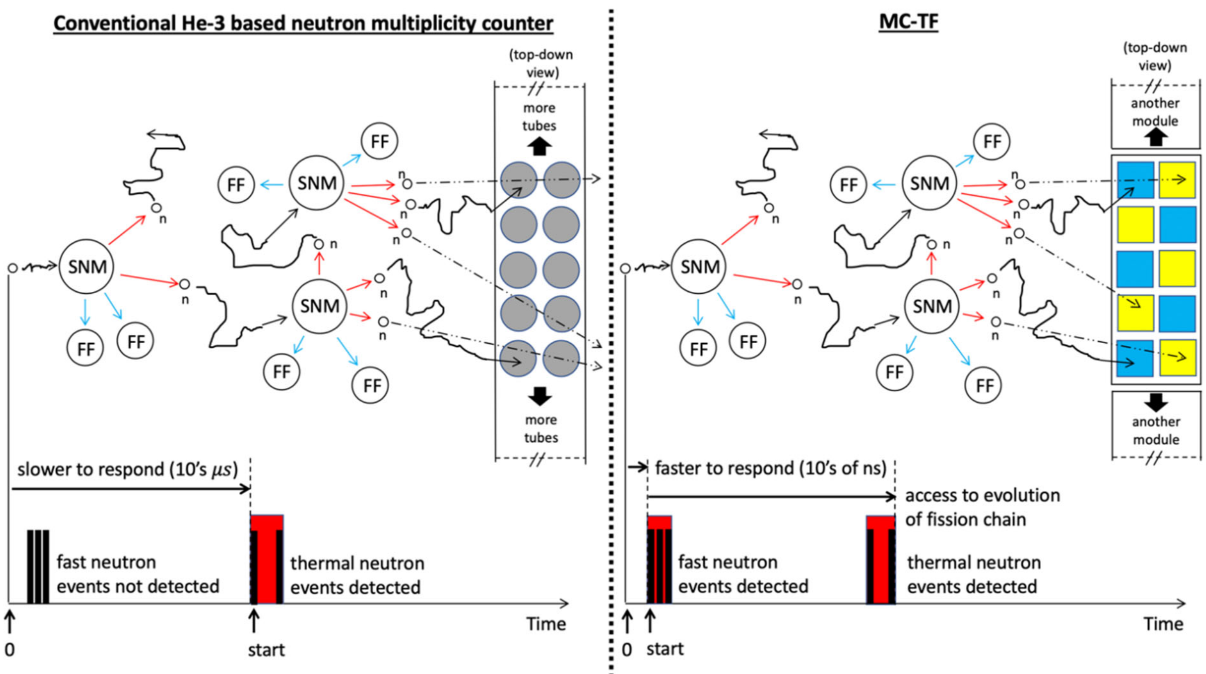


***Figure 5.*** *An illustration comparing a He-3- system and the MC-TF response to the same fission chain. Note that the processes described by this graphic are very simplified and do not account for the complexity associated with counting correlated particles in any multiplicity counter. The comparison, however, is valid.*

various neutron multiplicities from each atom that underwent fission in the chain. It is these neutrons from the total neutron multiplication distribution that the MC-TF and other current He-based systems, observe. And, it is this distribution from which a time-correlated analysis methodology can be employed to infer details about the source identity and mass [4,11]. Earlier, in Section 1.2.2., we discussed how a time-correlation analysis searches for neutron-detection timestamps that are very close in time to one another in order to identify a fission chain. This is possible because the fission chains in sub-critical SNM are separated well enough in time and each yield neutrons almost instantaneously. Some of these fast neutrons do not undergo moderation and can be detected by the stilbene scintillators of the MC-TF, whereas a He-3 based system would largely miss these events. On the other hand, some of the fast neutrons emitted from the fission chain burst are moderated and can be detected at a much later time (a few microseconds) after the start time of the fission chain. It is these thermal neutrons that a $He^3$ based system is sensitive to, and thus is slower to respond to fission chain events. Moreover, the MC-TF is capable of measuring these events as well due to CLYC. Consequently, the MC-TF is capable of observing the evolution of the fission chain process. Figure 5 attempts to graphically illustrate these processes for a $He^3$ system and the MC-TF.

### 1.2.4. MC-TF Design and Components

The MC-TF is a highly modular and portable system designed for the next generation of neutron multiplicity analysis. Figure 6 describes the overall system design. Currently the MC-

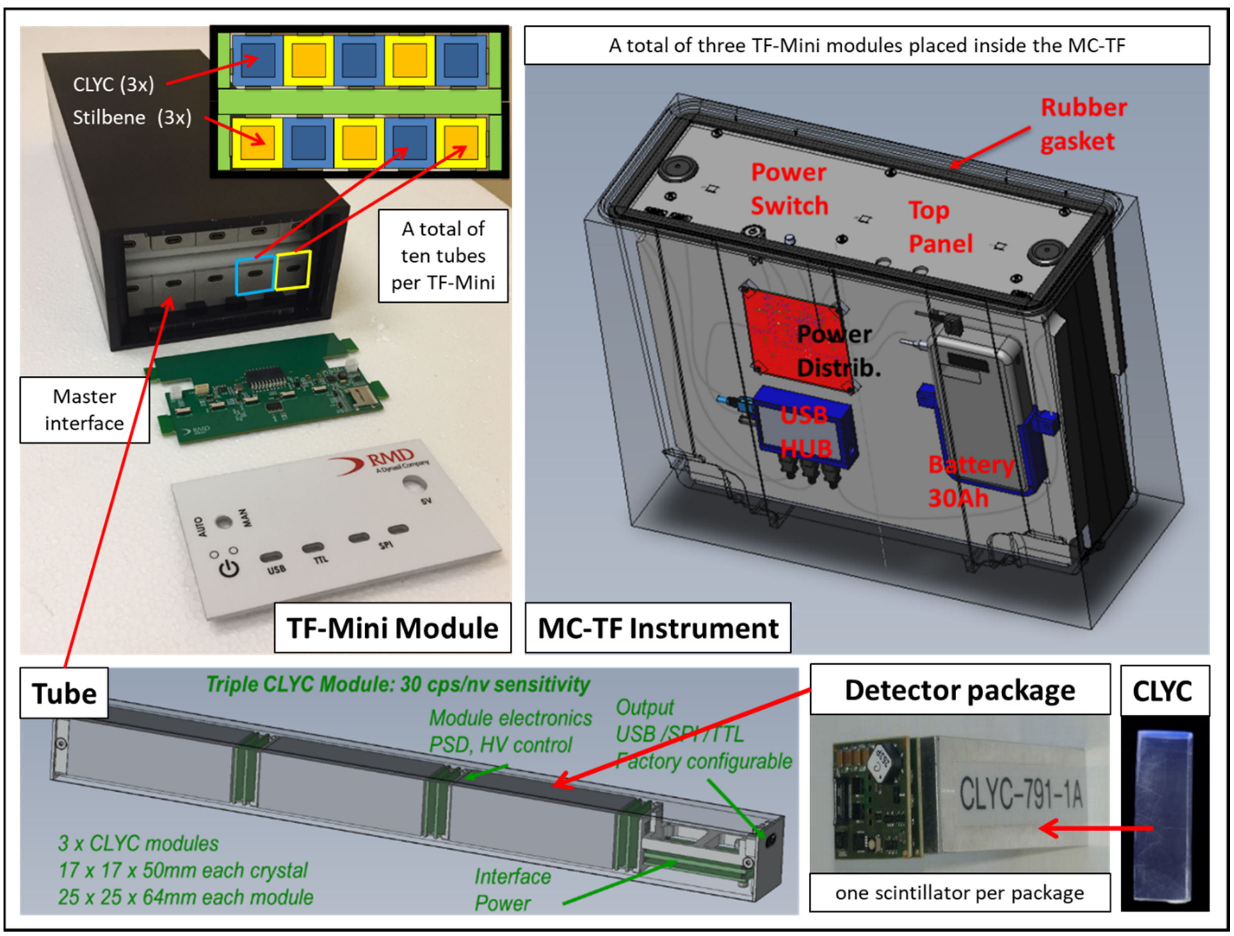


***Figure 6.*** *MC-TF design and associated components (tablet not shown). The example tube shown in this figure happens to only contain CLYC. The components for Stilbene are identical*

TF is comprised of 90 individual radiation detector channels evenly split between stilbene scintillators (intended for fast neutron detection), and the other half are CLYC scintillators (intended for thermal neutron detection) [14]. From a top-down perspective, the detectors are organized into three modules, referred to as "TF-Mini". Each TF-Mini consists of ten tubes containing three radiation detectors of the same scintillator material (where each detector is considered a single channel). Each detector is comprised of either a CLYC or stilbene scintillator. In other words, there are 5x3 CLYC-based radiation detectors and 5x3 stilbene-based radiation detectors in a single TF-Mini module. A single radiation detector is a combination of a scintillator crystal (CLYC or stilbene) coupled to a solid silicon photomultiplier (SiPM) array and associated electronics, making it a very compact design.

In addition to the SiPM, the electronics inside a single detector include an analog processing unit with incorporated PSD functionality to discriminate gamma rays, a SiPM voltage-bias generator with temperature stabilization capabilities. Every 10 seconds, the voltage bias supplied to the SiPM is monitored and adjusted based on the temperature sensor readout. All scintillators were calibrated between -25°C to 55°C in order to provide a stable response in a broad temperature range.

### 1.2.5. MC-TF Electrical Systems

The electrical components associated with on-the-fly data processing, data transfer, and signal synchronization are shown in Figure 7. The electronic interface of each TF-Mini is shown in pink and is referred to as the "master" board. Recall, each TF-Mini consists of five CLYC (shown in blue) scintillators and five stilbene (shown in green) scintillators. Each tube interface consists of an SPI-2 bus. The SPI-1 bus is used for inter-module synchronization. The Windows PC tablet connected to the MC-TF assigns the prime master module during initialization, and this module is responsible for the full system synchronization. Synchronized data can then be transferred over a USB hub to the tablet. The tablet chosen for use with the MC-TF is from Panasonic FZ series of military grade toughbooks. It comes with a 7in display, a touch screen interface, and a long-life battery pack. The tablet has a 1.2GHz Intel Core i5-7Y57 processor, and comes with 8GB of RAM, and a 256GB SSD for storage. While the MC-TF is in operation, the tablet will make use of software described in Section 1.2.6.

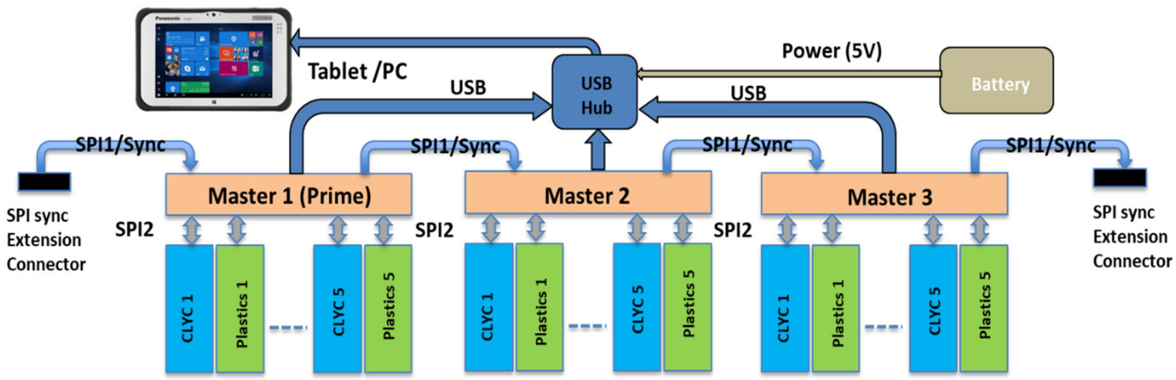


***Figure 7.*** *MC-TF system configuration, consisting of three TF-Mini modules, a USB hub, and a battery*

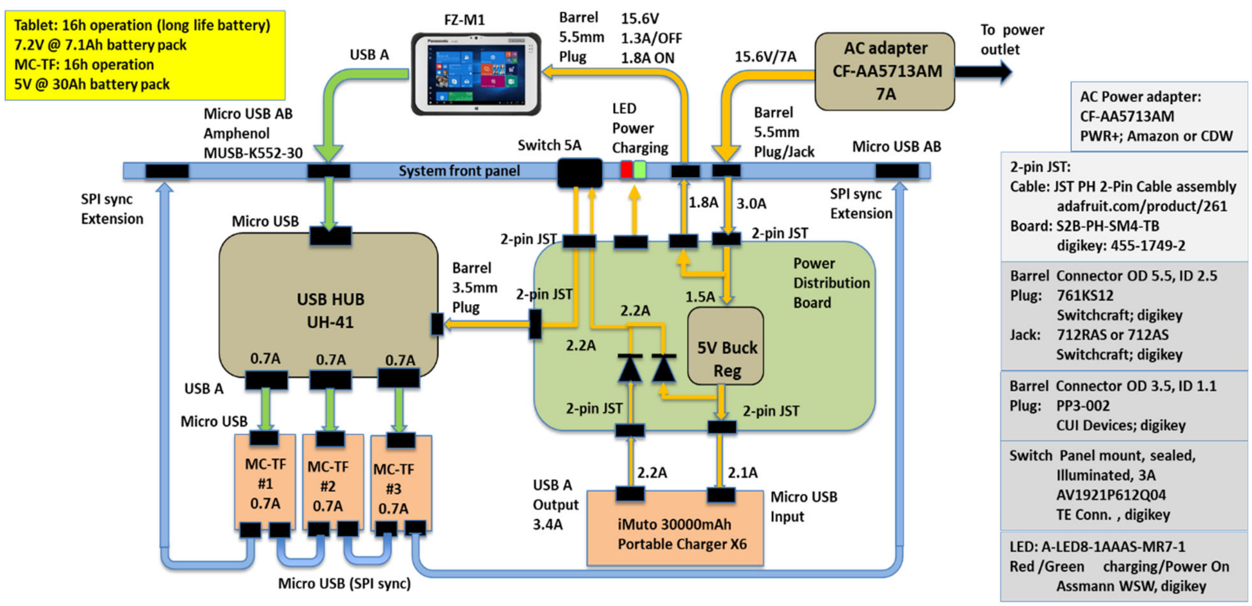


***Figure 8.*** *MC-TF system power distribution and wiring*

The electrical components associated with power distribution and wiring in the MC-TF is shown in Figure 8. The power consumption per tube and per TF-Mini (10 tubes) is approximately 50mA, and 500mA, respectively. The full power of the system is about 1.8A for the three TF-Mini modules and the USB hub. The 30Ah battery provides at least 16 consecutive hours of operation in the field. The tablet is equipped with long life battery providing also 16h run time. Low power operation provides for a long mission time.

### 1.2.6. MC-TF Software for Data Acquisition and Plotting

A simple approach to data acquisition and analysis was taken. The user begins by loading the "MC Parser" application, which was written in Java. The MC Parser software connects to the MC-TF through a USB connection to start and stop a measurement. A screenshot of MC Parser is shown in the figure below. If the MC-TF is already connected by USB to the tablet, the software will automatically detect the device. Each of the three columns shown on the home page of the software are dedicated terminal outputs for the three modules. When the user presses "start" the acquisition begins. One-second-long chunks of data are recorded by each module of the MC-TF and these data drunks are synced together in time and transferred over USB to the software. The software prints out pertinent information in the terminal output about every new data chunk that comes in, such as the number of counts collected. When the user is ready to end the measurement all they have to do is press the "Stop" button and close the program. Closing the program after a measurement has been completed saves the data to an excel file that can be viewed using a second piece of software, also written in Java, called "MP Viewer." The homepage of MP Viewer is also shown below. In short, MP Viewer has three main tabs that the user can select from: "Tube Stats, Weighting Stats, and Counts in time." The "Open" button is used to load the data saved by the MP Parser. When the data is loaded, the "Tube Stats" tab will show the counts obtained per tube (15 thermal neutron tubes and 15 fast neutron tubes). The "Weighting Stats" tab will show the weighting-time distribution that shows a histogram of time intervals between neutron detection events. Lastly, the "Counts in time" tab shows the number of thermal, fast, and total neutron counts as a function of time (i.e., for the entire length of the measurement). The following section (1.2.7) shows the output of MP Viewer after a Cf252 measurement.

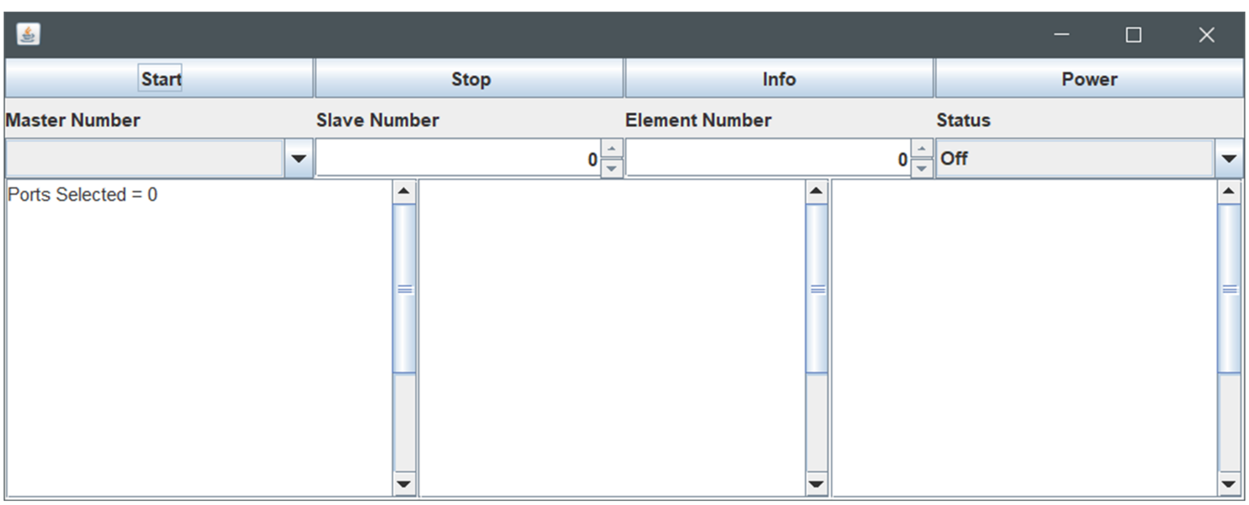


*Figure 9. MP Parser software: controls measurement/data acquisition*


*Figure 10. MP Viewer software: plots measurement results*

### 1.2.7. MC-TF Sample Measurements

Two example measurement (Figures 11a & 11b) were taken to showcase the valuable data that can be collected and viewed in real time. First, a Cf-252 source was placed 40cm away from the front face of the MC-TF and the MP Parser was set to run for 10 minutes. The second measurement was a repetition of the first with the addition of a 3" thick HDPE brick placed between the MC-TF and source to further thermalize the fast neutrons emanating from the source. Figures 12a and 12b show the counts per tube for the bare and moderated measurements, respectively. Note how the moderation reduces the fast neutron counts and simultaneously increases the thermal neutron counts. Figures 13a and 13b show the weighting-time distributions for the bare and moderated measurements, respectively. Note how without any moderation, prompt-fission fast neutrons are observed at the right-base of the fast neutron distribution (green). Figures 14a and 14b represent the same conclusion as Figures 11a and 11b as a function of time.


*Figure 11a. Bare Cf-252 measured for 10 minutes at 40 cm away*


*Figure 11b. Moderated Cf-252 measured for 10 minutes at 40 cm away*


*Figure 12a. Bare-measurement "Tube Stats" tab showing thermal (orange) and fast (green) neutron counts per tube*

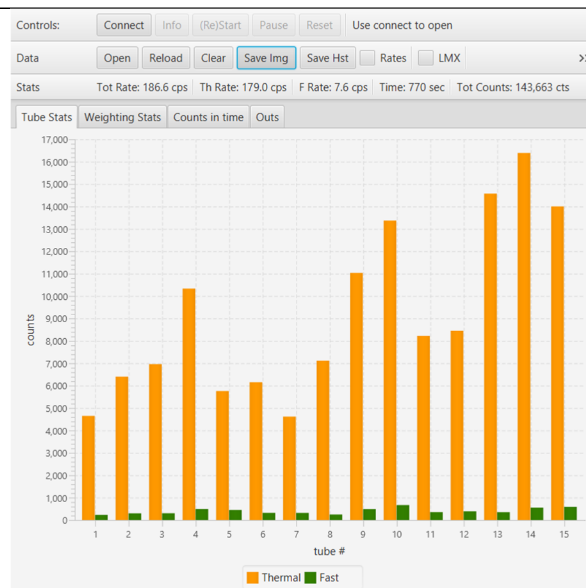


*Figure 12b. Moderated-measurement "Tube Stats" tab showing thermal (orange) and fast (green) neutron counts per tube*

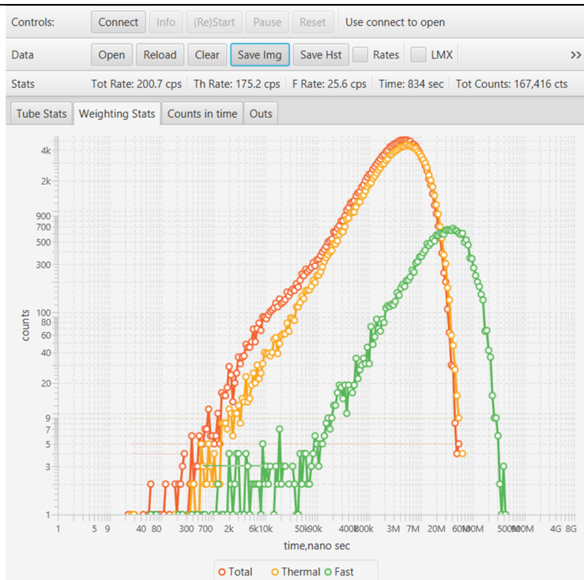


*Figure 13a. Bare-measurement weighting-time distribution, note the promptly-detected fast neutrons from fission at the base of the green distribution on the right.*

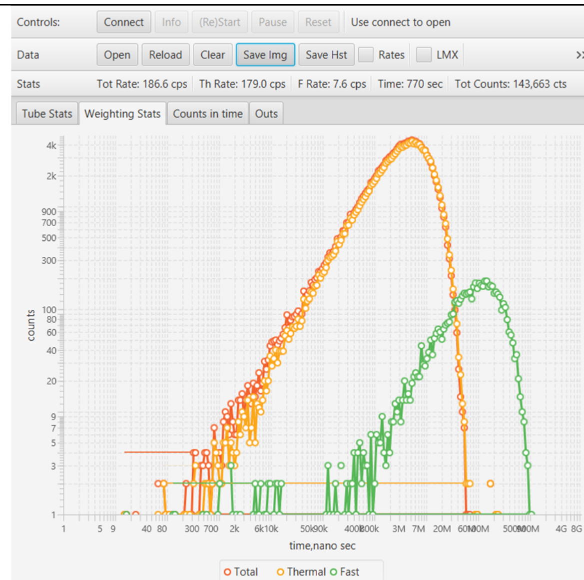


*Figure 13a. Moderated weighting-time distribution, note the higher thermal neutron counts and absence of prompt-fast neutron detections.*

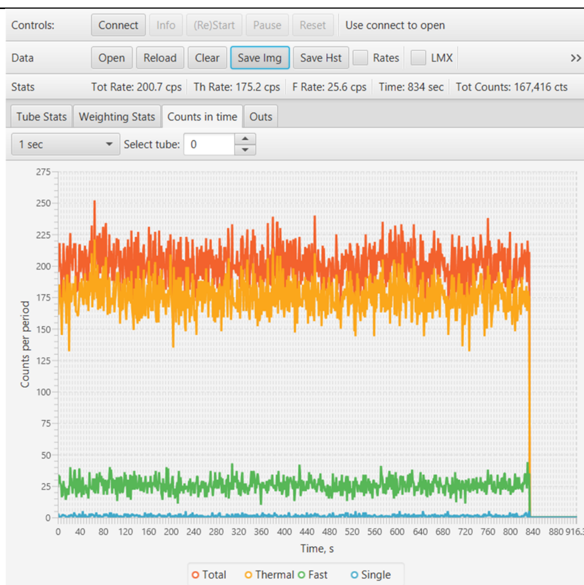


*Figure 14a. Counts as a function of time for the bare measurement*

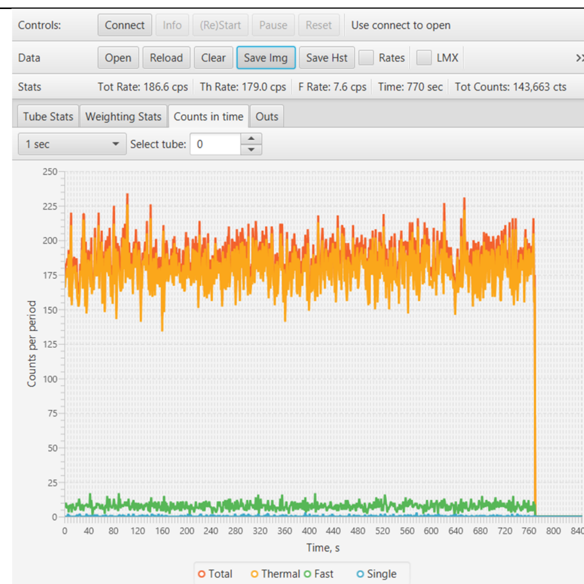


*Figure 14b. Counts as a function of time for the moderated measurement*

### 1.2.8. MC-TF Software for Detailed Source Characterization

An additional piece of software (Figure 15) that the user will have access to is called OSANTC (On-line Statistical Analysis of Neutron Time Correlation). OSANTC was written by our collaborators at LLNL. This software is self-calibrating, quantifies uncertainties, and reduces measurement times by as much as a factor of 100. OSANTC operates online and in real-time and the best answer the data supports is available on an ongoing basis. OSANTC eliminates the need for multiplicity data to be transmitted to an expert—located remotely—for a batch analysis after the fact thus saving valuable time. OSANTC is capable of directly estimating the MC-TF's detection efficiency from the list-mode time-tagged neutron data. Additional neutron detector equipment to estimate the multiplicity counter's detection efficiency is unnecessary and the need for the remote expert to attempt to estimate the detection efficiency is obsolete. The provided confidence intervals give first responders and decision makers an ability to assess the reliability of a result. In short, this software will perform a time-correlation analysis on the neutron data obtained, and it will return an estimation of the SNM mass and multiplication. As will be discussed in Section 2.1, there are limitations to the currently available neutron multiplicity detection systems that first responders could use in a nuclear-threat scenario. The MC-TF, paired with OSANTC, address these limitations.

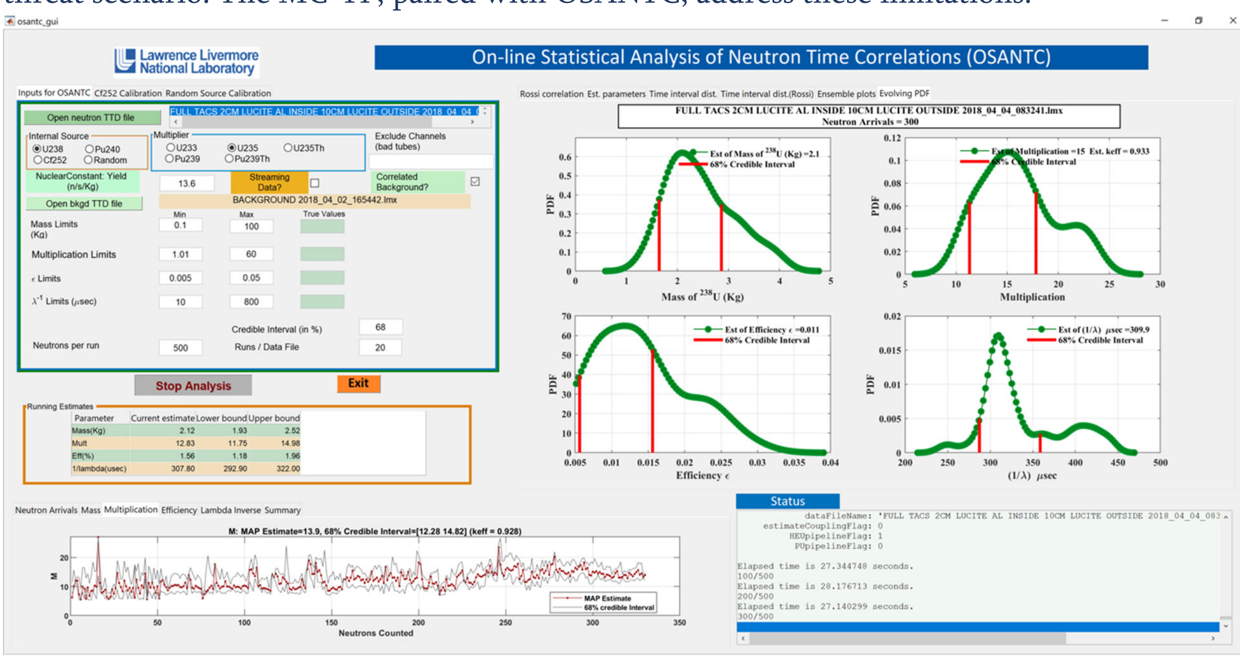


*Figure 15. LLNL OSANTC GUI. The green curves (four plots, upper right) show the probabilities (y-axis) for each parameter to have a particular value (x-axis): $^{238}$U mass, multiplication M, detection efficiency ε, and neutron diffusion time $\lambda^{-1}$. Each parameter's current estimate—with 68% confidence interval (red)—is the peak of the corresponding distribution. The strip chart in the lower left corner shows the evolution of the estimate for multiplication M as neutrons are counted.*

# 2. Product/Technology Comparison

## 2.1. Describe how the product/technology improves upon competitive products or technologies

As mentioned in Section 1.2.1, to the best of our knowledge, there is currently no field-deployable instrument utilizing time-correlated signatures from both thermal and fast neutrons, which in addition is battery-operated, compact and equipped with easy to use software that a trained first responder can use to quickly identify and classify any SNM threat. Furthermore the instrument can distinguish between SNM and non-SNM threats (SNM being the primary ingredient of a nuclear weapon) by collecting data from both thermal and fast neutrons. The MC-TF leverages this capability through the use of 45 dedicated fast-neutron detectors (stilbene) and 45 dedicated slow-neutron detectors (CLYC). Utilizing CLYC in the MC-TF increases the thermal neutron efficiency compared to $He^3$ based systems due to the higher specific efficiency of CLYC and practically eliminates the microphonic effect associated with $He^3$ tubes. The MC-TF's sensitivity to both neutron-energy ranges (i.e., fast and thermal) enables the device to observe the entire fission-chain burst from a suspected SNM source (see Figure 5). Specifically, the MC-TF is more sensitive to the emitted neutron multiplicity, angular, and energy distribution from SNM [4]. This data, which can be extracted from the timestamps of neutron detection events, can be used to reveal a wealth of source characteristics that current state-of-the-art $He^3$-based neutron-multiplicity counters do not possess. Furthermore, the MC-TF operates on a timescale that is an order of magnitude faster than $He^3$-based multiplicity counters, thus increasing the measurement accuracy for identical acquisition times (see Figure 3). It is worth mentioning that the modular construction of the MC-TF allows the device to be scaled up or down in size to accommodate the form factor required by the users and their mission.

Currently, in an emergency-response scenario where a nuclear-threat object is suspected, there are limitations in the neutron-multiplicity detection instruments that are available to first responders. Some of these limitations are listed below:

- An expert (usually located remotely) must estimate the multiplicity counter's detection efficiency, which is a difficult process that involves assumptions that often don't hold up, thus requiring additional detection equipment to estimate efficiency
- Confidence intervals are not provided leaving decision makers to guess the precision of estimates of SNM mass and multiplication

- Multiplicity detector data must be sent to remotely-located experts to perform an off-line analysis. This delays getting design information of the bomb to decision makers and answers to urgent criticality safety questions to the first responders

### 2.2. Describe the limitations of your product/technology

Some reasonable assumptions are made in order to simplify the mass and multiplication estimations of a fissile source. We assume that the source behaves like a point source, in other words, that the neutron detection efficiency is uniform throughout the volume of the unknown object. In addition, we assume that the source is essentially homogenous, i.e., the composition of the material does not depend on the location within the volume. As a result, the MC-TF can identify with higher certainties a source comprised of a single SNM isotope, and less effective for a mixture of different SNM isotopes. In the case of mixed sources, however, the MC-TF should still be able to determine whether or not SNM is present and generate a SNM type of alarm. Another limiting factor is the battery life of the MC-TF. Although it provides more than sufficient time to run multiple measurements, the battery is still limited to approximately 16 hours. If longer mission time is required, the user should secure an additional portable power source.

## 3. Summary

The Multiplicity Counter for Thermal and Fast neutrons (MC-TF) is an exciting new technology that offers unprecedented access to fission-chain evolution data. The MC-TF leverages 90 state-of-the-art scintillators. Half are meant for fast neutron detection and the other half are for thermal neutron detection. Should a first responder ever need to immediately determine whether or not an unknown source of radiation is in fact special nuclear material (SNM), the MC-TF can quickly and with high confidence make a determination, which greatly aids the response protocol process. The MC-TF breaks the barrier for neutron multiplicity counter response time and event-time interval analysis when compared to the state-of-the-art $He^3$-based system.

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## 6. Affirmation

By submitting this entry to R&D 100 you affirm that all information submitted as a part of, or supplemental to, this entry is a fair and accurate representation of this product. You affirm that you have read the instructions and entry notes and agree to the rules specified in those sections.

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## Appendix A: Articles Published

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## Appendix B: Patents

1. CSLILN Halide Scintillator,
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2. Cesium and Lithium-Containing Quaternary Compound Scintillators,
   9069085 US, 06/30/15, Shah, et al.
3. CSLILN Halide Scintillator,
   8969824 US, 3/03/2015, Shah, et al.
4. Cesium and Lithium-Containing Quaternary Compound Scintillators,
   8415637 US, 4/19/2013, Shah, et al.
5. CSLILN Halide Scintillator,
   8440980 US, 5/14/2013, Shah, et al.
6. Cesium and Lithium-Containing Quaternary Compound Scintillators,
   8586935 US, 11/19/2013, Shah, et al.
7. Cesium and Sodium-Containing Scintillator Compositions,
   8575553 US, 11/5/2013, Shah, et al.
8. Mixed Cesium Sodium and Lithium Halide Scintillator compositions,
   8362439 US, 1/29/2013, Shah, et al.
9. Cesium and Sodium-Containing Scintillator Compositions,
   8242452 US, 8/14/12, Shah, et al.
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