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A Comparison of Approaches to Determine Dead Time Parameters Using a Boron-Coated-Straw High-Level Neutron Coincidence Counter

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Abstract:

When characterizing a neutron coincidence counter for use in international safeguards, it is important to understand the dead time of the system. With current data acquisition in the form of shift register logic, there are several options to determine effective dead time model parameters. A customary approach consists of incrementally overwhelming the detection system with various sources to generate different count rates for analysis. An empirical fit to these data can then produce a dead time parameter. This method makes use of the expectation that the doubles to singles count rate ratio, after dead time correction, should remain fixed. In our measurements, we begin with a single ^{252}Cf source and successively combine it with 1, 2, 3, and 4 AmLi (α,n) sources. The time-correlated fission neutrons from the ^{252}Cf are detected by the neutron coincidence counter, and the random-in-time neutrons produced from the multiple AmLi sources provide excess counts to trigger on. Another recently reported approach [12] consists of utilizing the neutron-count number distribution, for a number of counting cycles, to permit a statistical analysis and subsequent determination of the dead time along with a robust estimate of the statistical uncertainty. Moments of several orders can be used; therefore, several estimates of the effective dead time parameter are obtained. In the results reported here, two and four AmLi sources are measured simultaneously within the well of the counter for a number of cycles. We have selected 24 cycles of 300 s each, with predetermined timing gates, where detected neutron multiplicities can range up to approximately 10 neutrons per cycle. These two methods were tested at Oak Ridge National Laboratory using a Boron Coated Straw High-Level Neutron Coincidence Counter, but the methods are also applicable to ^{3}He counters. In this paper, we compare the results of these approaches and discuss the relevance of both.

Keywords: Dead time correction; boron coated straws; high-level neutron coincidence counter; neutron coincidence counting; shift register

1. Introduction

Neutron coincidence counting is widely used in international safeguards applications for the nondestructive assay of nuclear material. Common thermal neutron coincidence and multiplicity counters take the form of an annular body filled with a moderator and populated with ^{3}He tubes, which surround a central well used for sample loading. When a sample undergoes fission, each event produces a simultaneous release of neutrons, the average number of which are characteristic of the sample's isotopics, which travel through the well of the detector and into the moderating body. These time-correlated neutrons are slowed in the moderator, spreading out this distribution over a longer period of time; this time is related to the neutron die-away time. The die-away time is characteristic of the geometry of the detector, and it cannot be altered. These thermalized neutrons are then captured in the ^{3}He tubes and can be detected, by software, in coincidence and higher order multiplicities using appropriate timing gates. The total number of neutron events measured is recorded as the singles count rate. The doubles count rate corresponds to two related neutrons detected within a specified time gate, and the triples count rate corresponds to three related neutrons within that gate. However, in addition to these fission neutrons, background and (α, n) neutrons can also be detected within these timing gates, generating artificial multiplicities mistaken as multiplicities related to fissions in the sample.

Each neutron interaction produces a pulse in the electronics connected to the ^{3}He tube, and the tube system is then dead for some amount of time. This means that any neutrons captured during this dead period are not counted and do not contribute to the total neutron pulse train. The dead period is related to the processing and recovery time of the electronics used and applies to each of the tube and electronic systems. Because the signals from each system are summed together in a total output, a total detector system dead time can be determined. For systems with several detector bank channel outputs, dead times for the individual channels can also be determined.

Neutron coincidence and multiplicity counting depend on the accurate measurement of these fission neutrons as a function of time to correctly determine the quantity of nuclear material within the measured sample [1, 2]. These distributions of neutrons are perturbed due to this dead time, thereby influencing assay values. Because detection systems cannot be 100% efficient, nor will every

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emitted neutron travel towards the moderated detector body, corrections are applied for neutron losses. In addition, another correction for the dead time related losses in the system is required. This value must be well-known to accurately adjust the measured neutron multiplicity rates for the true multiplicity rates.

Previous work has been done to determine the dead time of neutron coincidence counting systems and to characterize how this affects the incoming neutron pulse trains. The long-standing and widely used approach is extended to higher order multiplicities by Dytlewski [3] and is applied to safeguards systems, including High Level Neutron Coincidence Counter designs [4, 5], assuming a paralyzable (or updating) dead time model. The paralyzable model assumes that not only will a neutron captured during the dead period of the tube not be counted towards the total neutron pulse train, but that neutron event will extend the dead period. Although this model has been assumed for neutron coincidence counting, it has not been fully verified. The common experimental approach to measure the dead time uses multiple ^{252}Cf sources of increasing strength to determine two dead time parameters, which will be explained in detail later. Another approach utilizes random-in-time neutrons produced by AmLi (α, n) sources— in conjunction with a single ^{252}Cf spontaneous fission neutron source— to increase the uncorrelated single neutron events while maintaining the doubles neutron rate; this method was employed for this paper. Many others have built upon these methods by deriving alternative approaches to singles dead time corrections [6, 7] and investigating the effect of correlation in the neutron pulse train due to varying sources [8, 9], while also trying to simplify the theory and expressions for easy adaptation. However, the final expressions and implementation of the theory to experiment are complex, and as a result have not been adopted in favor of older simplifications.

Using the approach laid out by Menaa [10], based on the theory outlined by Foglio Para and Bettoni [11], random-in-time neutrons produced by AmLi sources are used to obtain a neutron-count distribution. Then, using the methodology outlined in [12], a statistical analysis is performed on this distribution over many cycles. With this analysis, the dead time parameters for second, third, and fourth order factorial moments can be determined, enabling an inter-comparison of values from a single data acquisition. These multiple samplings also allow for a robust estimate of the statistical uncertainty.

The importance of this method from a safeguards inspection perspective relates to the availability of sources for in-field measurements; AmLi sources are present for active interrogation in neutron coincidence or multiplicity counters. Meanwhile, it is not uncommon for a facility under inspection to not have ^{252}Cf at that location. Compared to the traditional method, the AmLi sources allow for shorter acquisition times with similar precision, and they do not have to be replaced as frequently due to the long half-life of Am isotopes. This work summarizes both the traditional approach and the new statistical approach and compares the two using data obtained using a boron-coated-straw (BCS) High-Level Neutron Coincidence Counter (HLNCC).

2. Experimental Setup

The BCS HLNCC was built by Proportional Technologies, Inc. (PTI) as a prototype ^{3}He alternative neutron coincidence counter. This prototype was designed to meet the specifications and performance objectives set for evaluation against other systems at an international workshop searching for a drop-in ^{3}He replacement [13]. Because of this, the BCS HLNCC was built as an aluminium-encased cylindrical high density polyethylene (HDPE) body measuring 34 cm in diameter and 68.2 cm in height (Figure 1a), preserving the dimensions of the ^{3}He-based HLNCC-II. The sample well is 17 cm in diameter and 41 cm in height and is sealed with top and bottom end plugs made of HDPE and aluminium. The main differences between the standard system and BCS system are a 6 kg increase in mass and the use of ^{10}B rather than ^{3}He for the neutron capture reaction.

The 18 ^{3}He tubes from the standard HLNCC-II were substituted for 804 ^{10}B straws, each measuring 4.4 mm in diameter, evenly dispersed throughout the HDPE body. The 96% enriched $^{10}B_4C$ coats a 2 μm thickness on the inside of aluminium or copper tubes, which are filled with a mixture of CO_2 (10%) and Ar (90%) at 1 atm [14-16]. The incident neutrons interact with the ^{10}B, releasing an alpha particle and ^{7}Li ion, which ionize the gas as they travel. Because this method of charge collection is similar to the method exploited in ^{3}He tubes, similar electronics and software can be used for both technologies. There are six detector banks, of 134 tubes each, connected and processed by six amplifiers. A conversion box consisting of inputs (Figure 1b), outputs (Figure 1c), and a field-programmable gate array (FPGA) module shapes the incoming pulses and amplifies them to produce the correct form for an output signal trigger to be used with shift register or list mode acquisition software (Figure 1d). An external power supply provides the +5 V needed for the detector.

A list mode data acquisition system, Pulse Train Recorder-32 (PTR-32) [18], was used with the BCS HLNCC to bias, record, and analyze the neutron pulse train for each of the detector bank channels (Figure 1d). Because previous data taken with the PTR-32 have shown to be in agreement [19] with data taken with a JSR-15 shift register [20], the two were used interchangeably. PTR-32 can produce output files in a form similar to those output by

Figure 1a-1d. Left to right: The BCS HLNCC showing (a) the six detector bank outputs; (b) the BCS HLNCC-specific conversion box containing electronics to shape and amplify the output signals, resting on the external power supply used for the +5 V; (c) the output signal cables of the conversion box; and (d) PTR-32. See text for details.

the International Atomic Energy Agency (IAEA) Neutron Coincidence Counting (INCC) Program, including a neutron count distribution per every cycle recorded, in addition to neutron multiplicity analysis. PTR-32 can perform analysis using shift register logic when the user specifies predelay, gate width, and long delay time windows. As an added benefit, PTR-32 can perform this analysis for each individual detector channel connected to 1 of the 32 inputs on the board from a single measurement. The BCS HLNCC was biased to the standard setting of +850 V, and PTR-32 was set to analyze using the previously-determined optimal timing gates of 2 μs for the predelay, 48 μs for the gate width, and 4096 μs for the long delay for these measurements.

3. Traditional Dead Time Approach

As previously mentioned, the traditional and most commonly used approach for determining detector dead time was established decades ago, and extended to greater multiplicities by Dytlewski in 1990 [3], assuming a paralyzable dead time model. This methodology was then applied for use in neutron coincidence counters such as the ^{3}He-based HLNCC models [4, 5]. The combination of these works implement the following equations for the doubles (D) and singles (S) dead time correction factors (CF):

$$CF_D = e^{\delta_R \cdot S_m} = e^{(a+b \cdot S_m)\cdot S_m} \tag{1}$$

$$CF_S = e^{\delta_T \cdot S_m} = e^{\frac{1}{4}(a+b \cdot S_m)\cdot S_m} = CF_D{}^{1/4} \tag{2}$$

where δ_R is the dead time for the doubles, δ_T is the dead time for the singles, S_m is the measured singles rate, and *a* and *b* are the dead time parameters which are empirically determined for a specific detection system. Equation 1 represents the dead time correction factor for the doubles rate, and Equation 2 represents the dead time correction factor for the singles rate. The free parameters *a* and *b* are determined by a quadratic fit to doubles count rate data as a function of increasing singles rate. It is common for detectors of the same model to keep the ratio of a/b constant across all production, aiding in this analysis. The dead time-corrected rates can then be found by multiplying the measured rate for the respective multiplicity by the appropriate correction factor.

Data can be obtained using multiple ^{252}Cf sources of increasing strength, or with a single ^{252}Cf source in combination with random-in-time neutrons produced by AmLi sources to provide a range of count rates. The number and/or strength of the sources chosen should correlate with the full count range expected to be measured. Because the first method uses only ^{252}Cf point-like sources, there is no significant multiplication nor (α, n) contribution, and so the multiplicity ratios of triples to doubles (T/D), triples to singles (T/S), and doubles to singles (D/S) should all be constant and independent of the source strength once dead time corrected. This allows the dead time parameters to be determined and adjusted by minimizing the chi-squared value from each of these ratios.

For an uncorrelated neutron source, where the emitted neutrons have no time-dependent pattern (as a fissionable source would have), there is a very low probability that emitted neutrons will be counted in doubles or triples. Therefore, the (Reals + Accidentals) count rate should be approximately equal to the (Accidentals) count rate illustrated in the Rossi-Alpha distribution below (Figure 2). The second experimental approach to the traditional method uses a number of AmLi sources with a single ^{252}Cf source to incrementally overwhelm the detection system to generate different singles count rates for a similar analysis. This method benefits from the convenience and availability of using one ^{252}Cf source, while still having the ability to determine the dead time corrections for both the singles rate and the doubles rate. This is the method used in this section for analysis.

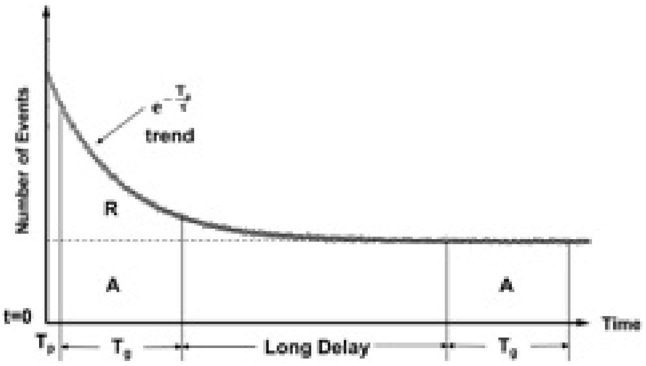

Figure 2: A Rossi-Alpha distribution illustrating the various gates used in shift register analysis and their chronological positions on the neutron pulse train.

A newly-acquired NIST-traceable ^{252}Cf source, with a known neutron emission rate around 94,000 cps and 1.10% relative standard error, was placed in the center of the BCS HLNCC. Two different metal cans were used to hold the ^{252}Cf and the AmLi sources: the ^{252}Cf was placed just below the middle plane of the BCS for optimal efficiency, and a second, slightly taller, metal can was placed over this and served as a stand for the AmLi sources. The ^{252}Cf source and the metal cans remained stationary throughout the entire experiment to ensure that no associated systematic errors were introduced. Using the experimental setup described here, a 120 minute acquisition, using only the ^{252}Cf source, was obtained to ensure good counting statistics on the doubles count rate. The total detector signal was collected along with the six individual channel neutron pulse trains, as a result of using the PTR-32. In this work, we only analyze the total detector signal, but the same procedure would apply when analyzing each of the channels. The next measurement taken was of ^{252}Cf along with two AmLi sources. These two AmLi sources had measured strengths around 7,300 cps with a count rate uncertainty of 0.11% with the selected timing gates. Because of the greater singles count rate, the acquisition time for this data collection was reduced to 30 minutes. A third AmLi, with a measured strength around 10,200 cps and a count rate uncertainty of 0.11%, was then added. Data were taken again for 30 minutes. A fourth, and final, AmLi source, with similar strength to the third, was then added. For this run, the acquisition time was increased to 45 minutes to give a greater certainty of the count rate, as this is crucial for producing an accurate fit.

These files were then analyzed in PTR-32 with the standard 2 μs predelay, 48 μs gate width, and 4096 μs long delay in order to find the singles and doubles count rates for each of these runs. This method is the same as the analysis performed using a shift register. Figure 3 shows a plot of the ratio of doubles to singles count rates as a function of singles count rate with the dotted empirical fit reflecting the ratio of the dead time-corrected rates using Equations 1 and 2 above.

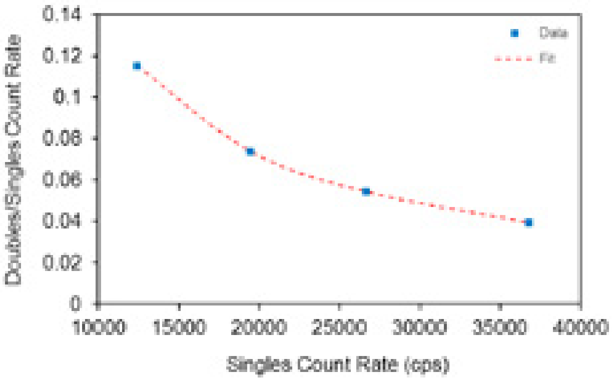

Figure 3: A plot of the measured Doubles to Singles count rate ratio as a function of the measured singles count rate. An empirical fit used to determine the dead time parameters is shown as the dotted red curve. The error bars are smaller than the markers.

The method described above is not robust under our experimental conditions, as it relies on the user to manipulate the terms by hand to produce the best fit. This method is also sensitive to the number of data points acquired, thereby increasing the total experimental time and number of sources needed for a more accurate result. Because of this, there can be several values which minimize the sum of squared errors of the deviation between the dead time corrected doubles to singles ratio to the uncorrected ratio with respect to a and b. For a set of standard counters, the ratio of b/a has typically been determined previously using a large number of ^{252}Cf sources; but for this new BCS HLNCC, there is no predetermined ratio. Instead, assuming that $b = \frac{a^2}{4}$ as outlined in the literature [6,7], the fitting parameters were found to be $a = 6.53 \cdot 10^{-8}$ and $b = 1.066 \cdot 10^{-15}$, resulting in an average dead time of (0.0653 ± 0.0054) μs. The uncertainty in this value was determined through chi squared analysis of minimizing the sum of squared error and is relatively large due to the reasons discussed previously. Next, b was constrained to 0 and a was found to be $6.199 \cdot 10^{-8}$ producing a dead time of (0.0620 ± 0.0077) μs. The dead time values found are within error using the different empirical approaches, due to the insensitivity of the equations to b over a wide range of values.

A note to the reader: in the first work characterizing the BCS HLNCC [17], it was stated that the dead time parameters were $a = 0.55 \cdot 10^{-6}$ and $b = 0$ using ^{252}Cf sources. For the sources measured at PTI, these values were selected as the best fit for the D/S ratio allowing a constant value, independent of the source strength, once dead time corrected. However, only three sources of a limited count rate range were used, therefore influencing the accuracy of the fit. Also, these values applied to a measurement using only a single detector bank rather than the total six banks combined for the total detector output. As expected, when the whole system was measured for this paper, the total detector dead time decreased.

4. Neutron Count Distribution Dead Time Approach

Menaa et al [10] outlined and experimentally justified an alternative method to the traditional approach. It was proposed that dead time could also be experimentally estimated using random-in-time neutrons produced by a source such as AmLi, to generate an uncorrelated neutron count distribution. The equations presented in [11], under the assumption of a paralyzable not-free (the system starts counting the initial neutron pulse while it may be dead) detector, represent the mean value of the count distribution and the variance of that distribution. They are then used by Menaa et al. to derive expressions for the dead time, δ, in terms of the gate width, T_g, and the statistics of the neutron count distribution:

$$\varphi = 1 - \sqrt{1 - \left[\frac{\langle i \rangle - \sigma_i^2}{\langle i \rangle^2} \right]} ; \varphi = \frac{\delta}{T_g} \tag{3}$$

with i representing the mean value of the neutron count distribution as

$$\langle i \rangle = \frac{\sum_i i \cdot A_i}{\sum_i A_i} \tag{4}$$

and σ_i^2 representing the variance of the distribution as

$$\sigma_i^2 = \frac{\sum_i [i - \langle i \rangle]^2 \cdot A_i}{\sum_i A_i} . \tag{5}$$

Through simple measurement of an AmLi source, all necessary variables can be obtained in a short period of time.

Croft et al. [12] reviewed this method in detail, and built upon this work to extend the same methodology to higher order moments of the neutron count distribution. The expressions derived for the third and fourth reduced factorial moments,

$$\varphi = \frac{1}{2} \left[1 - \sqrt[3]{\frac{\langle i(i-1)(i-2) \rangle}{\langle i \rangle^3}} \right] \tag{6}$$

and

$$\varphi = \frac{1}{3} \left[1 - \sqrt[4]{\frac{\langle i(i-1)(i-2)(i-3) \rangle}{\langle i \rangle^4}} \right] \tag{7}$$

respectively, can all be determined from a single measurement. It was proven that the dead times determined from each of these expressions were consistent within counting precision. All three values are reported below.

Because the bias,

$$Bias = 100 \left[\frac{\langle i \rangle_{R+A}}{\langle i \rangle_A} - 1 \right], \%, \tag{8}$$

should be approximately zero for an uncorrelated neutron source, the neutron count distributions should be roughly equal between the (Reals + Accidentals), or (R + A), and the (Accidentals), or (A), gates (as illustrated in Figure 2). To test this theory, the (R+A) and (A) neutron count distributions were analyzed separately to produce individual dead time values, checked for bias, and then combined into a single 48 cycle data set for an additional dead time determination.

Twenty-four cycles of 300 s data acquisition runs were taken to randomly sample the neutron count distribution, produced by the AmLi sources previously listed, a large number of times. The AmLi sources were centered vertically and radially within the well to load an approximately even count rate on each of the six detector banks. Two separate acquisition runs were taken, one using two AmLi sources for a combined measured singles count rate of approximately 14,000 cps with a standard error of 0.02%, and the other using all four AmLi sources for a combined measured singles count rate of 33,500 cps with a standard error of 0.016%. The optimal detector parameters were set at 2 μs for the predelay, 48 μs for the gate width, and 4096 μs for the long delay. The total neutron pulse train recorded in PTR-32 was exported to INCC format to produce the count distributions. As is customary with shift register electronics and INCC software, the neutron distributions in each of the cycles are reported as a function of multiplicity for both the (R+A) and (A) gates. These count distributions were analyzed using the second, third, and fourth order moment expressions to determine the dead time and the bias. The results are reported below in Tables I-III.

Number of Sources	δ(R+A) (μs)	±	δ(A) (μs)	±	δ(Combined) (μs)	±	Bias (%)	±
2	0.0669	0.0050	0.0657	0.0054	0.0663	0.0036	0.0008	0.0197
4	0.0641	0.0015	0.0652	0.0018	0.0646	0.0012	0.0060	0.0069
Average	0.0655	0.0052	0.0654	0.0057	0.0654	0.0038	0.0034	0.0209

Table I: Total detector dead time values calculated using the second order factorial moment

As expected, there is less uncertainty in the dead time calculated for the measurement using four AmLi sources rather than just two sources, due to better counting statistics. However, as is typical for in-field measurements, two AmLi sources may be more readily available and still provide accurate evaluations of the detector dead time. The bias is consistent with 0, the individually calculated dead time values are consistent within counting precision across sources, and therefore, the average dead time values between (R+A), (A), and combined gates are also in agreement.

Number of Sources	δ(R+A) (µs)	±	δ(A) (µs)	±	δ(Combined) (µs)	±
2	0.0639	0.0069	0.0723	0.0063	0.0681	0.0047
4	0.0632	0.0019	0.0635	0.0018	0.0634	0.0013
Average	0.0635	0.0071	0.0679	0.0065	0.0657	0.0049

Table II: Total detector dead time values calculated using the third order factorial moment

Number of Sources	δ(R+A) (µs)	±	δ(A) (µs)	±	δ(Combined) (µs)	±
2	0.0603	0.0111	0.0711	0.0086	0.0657	0.0072
4	0.0598	0.0029	0.0609	0.0026	0.0604	0.0020
Average	0.0600	0.0115	0.0660	0.0090	0.0630	0.0075

Table III: Total detector dead time values calculated using the fourth order factorial moment

As the ordered factorial moments increase, the uncertainty in the dead time parameter increases due to the lower precision of higher neutron multiplicity rates. Because an uncorrelated source is used, higher order multiplicities are not likely to be detected with this count rate. Despite this, all three expressions result in values that are in agreement within counting precision. This result verifies, using another detector model than was used by Croft et al. [12], that this approach is robust and appropriate for estimating the dead time of a system.

5. Conclusion

The comparison of dead times determined from both the traditional and statistical methods are shown below in Table IV. The traditional approach values are reported for two different empirical fits: where $b = \frac{a^2}{4}$ and when b was constrained to zero. The second order (R+A) and (A) combined gate average dead time value, obtained from both the two source and four source measurements, are reported for this comparison. The values are in agreement within uncertainties. It is evident that the uncertainty in the neutron count distribution analysis approach is much less than the uncertainty associated with the traditional approach. This is due to the insensitivity of the equations to *b* over a wide range of values and the number of experimental data points used to find the empirical fit.

Method	δ (µs)	±
Traditional- b=a^2/4	0.0653	0.0054
Traditional- b=0	0.0620	0.0077
Statistical- 2 sources	0.0663	0.0036
Statistical- 4 sources	0.0646	0.0012
Statistical- Average	0.0654	0.0038

Table IV: Comparison of total detector dead time values using the traditional method and the statistical approach

Both methods have been previously used with ^{3}He-based neutron multiplicity counters, and are shown here to apply to BCS as well. The neutron count distribution approach allows for a quick, robust, and convenient way to determine the dead time of a system. The availability of AmLi sources in facilities also serves as another benefit to the traditional approach. Multiple dead time values can be calculated with a single data acquisition run using the higher order factorial moment expressions, allowing for a cross-verification.

In this work, it has been shown that both approaches return similar dead time values. We have discussed the underlying theories of both methods, while acknowledging many other works over the last few decades. This list is certainly not exhaustive, and it illustrates the revived drive to accurately, precisely, and easily represent detector dead times based on true physical models. This comparison was performed to show the capabilities of both approaches, while justifying the newly proposed analysis with another detector system. The statistical approach provides an experimentally determined approximation to the neutron multiplicity counter's dead time which may be more simple to grasp and implement, returning values with greater confidence due to the robust uncertainty calculations. Future work may include extending this analysis to each of the detector channels, in addition to quantifying the impact these dead time determinations have on the uncertainty in the final calculated mass values of an assay.

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