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Statistical Data Filtration in Neutron Coincidence Counting

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by

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ABSTRACT

We assessed the effectiveness of statistical data filtration to minimize the contribution of matrix materials in 200-ℓ drums to the nondestructive assay of plutonium. These matrices were examined: polyethylene, concrete, aluminum, iron, cadmium, and lead. Statistical filtration of neutron coincidence data improved the low-end sensitivity of coincidence counters. Spurious data arising from electrical noise, matrix spallation, and geometric effects were smoothed in a predictable fashion by the statistical filter. The filter effectively lowers the minimum detectable mass limit that can be achieved for plutonium assay using passive neutron coincidence counting.

I. INTRODUCTION

For the passive-neutron assay of plutonium in waste drums, the detectability is limited by the neutron coincidence background that originates from cosmic-ray spallation. Menlove et al., have proposed a new technique to reduce the neutron coincidence background using statistical methods.[1]

The cosmic-ray events can be counted as prompt charged-particle reactions in the detector or as spallation source neutrons that spread in time over the slowing-down time of the detector body. The predelay (4.5 μs) eliminates the first category because they are short lived and the predelay vetoes them from the coincidence gate.[2] The spallation neutrons fall within the coincidence gate but often with high multiplicity. We used the data collection software to isolate high-multiplicity events and to eliminate them from the data averages. We are currently using statistical techniques to accomplish this. Our statistical filter for background reduction consists of a rejection threshold that can be defined by the user to be between 2.0 and 3.0 σ from the average of multiple, short data intervals. A typical counting time for a drum is ~1000 s, and we divide this into 33 intervals of 30 s each. If any interval is more than the user-defined *n*σ out of the average, we reject that interval from the average. This type of filter does not interfere with the data collection for drums with high or low plutonium content.

We used a neutron coincidence counter (NCC) to assess the effects of 200-ℓ-drum matrix materials on background neutron levels. This study examined the possibility of extending the low-end sensitivity limit of the barrel counter and how the barrel matrix material and software statistical filters affect this objective. The following primary issues were investigated:

(1) Required background corrections based upon matrix type and mass, and

(2) The effect of software-based statistical filtration on background counting rates, minimization of cosmic-ray coincidences, and smoothing of geometric matrix effects.

II. EQUIPMENT

The detection system used in this experiment was a passive barrel counter system (JOMAR/Canberra Model JCC-21), which allows a nearly 4-π counting geometry. The barrel counter is roughly cubic with six banks of ^{3}He tubes. The four vertical banks each contain ten 36-in.-active-length ^{3}He tubes. The upper and lower banks each contain ten 20-in.-active-length ^{3}He tubes. Each tube is contained in a 10.2-cm-thick slab of high-density polyethylene and centered at 4.16 cm from the interior face. The cadmium lining, normally present in these counters, has been removed. A photograph of the detector system is shown in Fig. 1. A complete report on the design and operation of the passive barrel counter is available elsewhere.[3]

The data were collected using the NCC software package[4] and a JOMAR/ Canberra JSR-11 shift register. The data were analyzed using the coincidence outlier statistical test feature of the NCC program. Complete information regarding the NCC program usage and algorithms is available in the NCC Users Manual.[4]

III. SAMPLE DESCRIPTION

Each of the materials examined in this study was placed in a 200-ℓ drum (19-kg carbon steel) and counted for approximately two thousand 30-s intervals. A suitable range of masses was chosen for each matrix based upon

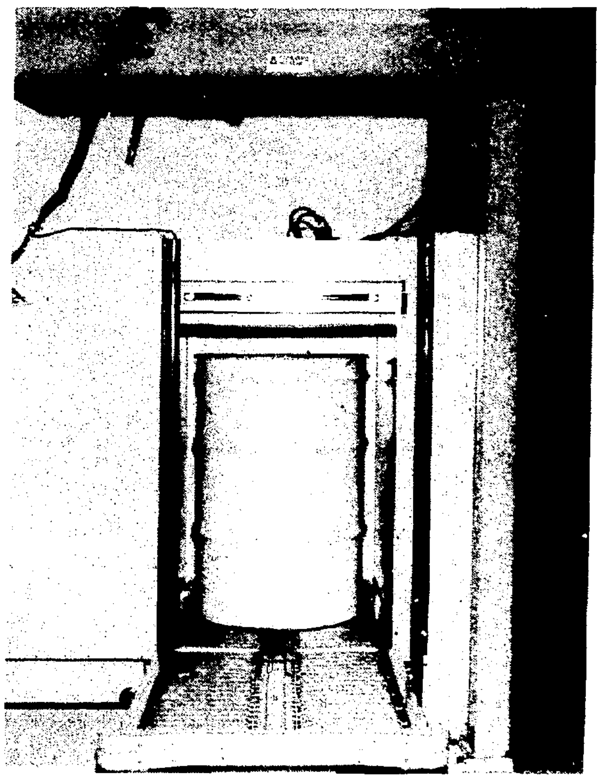

Fig. 1. Photograph of passive-neutron coincidence counter for 200-ℓ drums.

the material density and available quantities. Table I lists each of the matrix materials and the mass ranges that were used.

IV. DATA ANALYSIS

The data from each trial were examined using a predetermined range of values of the limit on the standard deviation of the coincidence counts defined by the user in the NCC statistical outlier test.[4] This range was typically 2.0 to 3.0 σ. An outlier in a group of runs is defined as a run whose coincidence count rate is greater than or equal to the user-specified number of standard deviations from the weighted average of the coincidence count rate of the set. Outliers are discarded from the data set.

The standard deviation of the reals counts is calculated in one of two fashions. If none of the reals values are equal to zero, then

$$\sigma(R_i) = \frac{W_{Ri}(C_{R+Ai} - C_{Ai})^{1/2}}{t_i} ,$$

where C_{R+Ai} = the real + accidental counts for the ith run,
C_{Ai} = the accidental counts for the ith run,
t_i = elapsed time during run i,
W_{Ri} = real count standard deviation weighting factor, and
R_i = $(C_{R+Ai} - C_{A2})/t_i$.

TABLE I. Mass Ranges for Study Matrices		
Matrix	Mass (kg)	Weight (lb)
Polyethylene[a]	26–118	57–259
Concrete[b]	53–259	116–570
Aluminum[c]	29–136	63–299
Iron[d]	19–340	42–747
Cadmium[e]	24–92	52–202
Lead[f]	22–87	48–192

[a]Mixture of beads and high-density scrap.
[b]In 39.6- by 19.1- by 14.4-cm blocks, 26.36 kg each (2.42 g/cm^3). Assumed elemental weight fractions: hydrogen (0.0056), oxygen (0.8791), sodium (0.0171), magnesium (0.0024), aluminum (0.0456), silicon (0.3158), sulfur (0.0012), potassium (0.0192), calcium (0.0826), iron (0.0122).
[c]Scrap plate stock.
[d]Scrap 3/4-in. pipe stock.
[e]Scrap sheet stock.
[f]In 20.5- by 10.3- by 5.0-cm bricks, 10.9 kg each.

In this study,

$$W_{Ri} = \left[1 + \frac{8\left(1 - \frac{1 - e^{-G/\tau}}{\frac{G}{\tau}}\right)(C_{R+Ai} - C_{Ai})}{e^{-P/\tau}\left(1 - e^{-G/\tau}\right) C_{Ti}} \right] ,$$

where G = gate length (128 μs),
τ = detector die-away time (80 μs),
P = predelay time (4.5 μs), and
C_{Ti} = totals count for the ith run.

This method of calculating the standard deviation, based upon the detector physics, allows the NCC program to assess individual data points. The weighted mean of the reals counts for a given data set is calculated as

$$\overline{R}_{set} = \frac{\sum_{i=1}^{n} \frac{R_i}{\sigma^2(R_i)}}{\sum_{i=1}^{n} \frac{1}{\sigma^2(R_i)}} ,$$

where n = the number of runs in the data set.

The data point for the ith run is considered to be an outlier if

$$\frac{\left|R_i - \overline{R}_{set}\right|}{\sigma(R_i)} \geq n_\sigma ,$$

where n_σ = the user-specified number of standard deviations used in the filter.

The calculations shown above are performed on the entire data set in an iterative fashion until all remaining data in the set conform to the inequality shown above. The mean of the remaining data is returned to the user.

If any one of the runs in the initial data set has a real count equal to zero, then the unweighted average and standard deviation are used in the outlier test. The unweighted average of the reals is calculated as

$$\overline{R}_{set} = \frac{\sum_{i=1}^{n} R_i}{n} \ ,$$

where all terms have their previously listed definitions.

The unweighted sample standard deviation is calculated as

$$\sigma(R_i) = \left(\frac{S_1 - S_2}{n - 1}\right)^{1/2} \ ,$$

where

$$S_1 = \sum_{i=1}^{n} R_i^2 \ ,$$

$$S_2 = \frac{\left(\sum_{i=1}^{n} R_i\right)^2}{n} \ ,$$

and all other terms are as previously defined. The mean and standard deviation calculated in this case are then used in the earlier inequality to determine whether run i is an outlier.

It was arbitrarily decided that a loss of 10% or less of the raw background data to the statistical outlier test represented an acceptable fractional loss of data for normal operation of the barrel counter. An evaluation of the percentage of data lost as a function of the user-defined outlier limit for all matrices used in this study showed that a value of 2.5 σ generally resulted in a loss of close to 10% of the data in the background coincidence counts. For a sample containing significant amounts of plutonium, only ~2% of the runs were rejected.

Figure 2 shows the fraction of data discarded as a function of the user-defined standard deviation limit for the empty detector. Ten percent of the data were lost at a filter setting of 2.37 σ. Figure 3 shows the fraction of data discarded as a function of the user-defined standard deviation limit for a detector containing an empty 55-gal. barrel (19.1 kg of carbon steel). The 10%-data-loss criterion is met at a user-defined standard deviation limit of 2.4 σ. The small change in slope between Figs. 2 and 3 represents the effect of adding 19 kg of steel to the system. The extent of the slope change between the empty-detector and the empty-drum cases demonstrates that corrections for counts resulting from the empty drum are not required in typical low-end measurements. The empty drum was observed to add an average of 0.011 counts/s to the background (0.121 counts/s) using the 2.5-σ statistical filter.

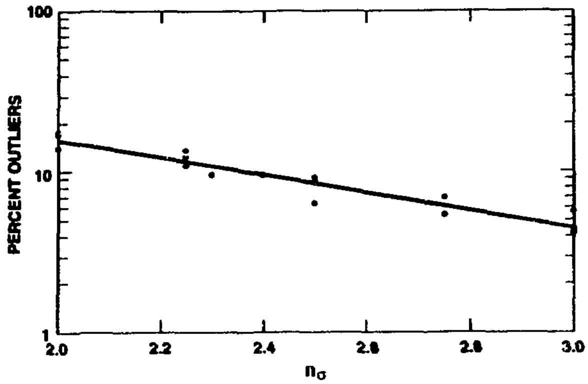

Fig. 2. Empty-detector-run-rejection variation vs statistical filter value.

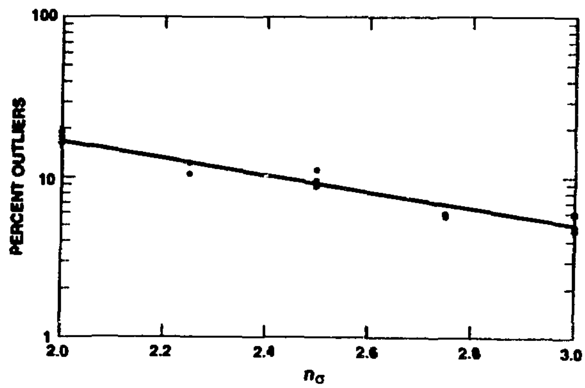

Fig. 3. Run-rejection percentage with an empty 200-ℓ drum placed in the counter.

Figure 4 shows the average percent data loss for various concrete matrix masses. Ten percent of the data were lost near a user-defined limit of 2.4 σ. A user-defined limit of 2.5 σ was observed to meet the 10%-data-loss criterion for most matrices and masses analyzed in this study. We observed a general trend in the percentage of data lost as a function of material atomic number (cosmic-ray stopping power); for high-Z (≥48) materials the percentage data lost at a 2.5-σ filtration was observed to be substantially larger than 10%. For matrices commonly encountered in waste barrels ($Z \leq 26$) the deviations are not

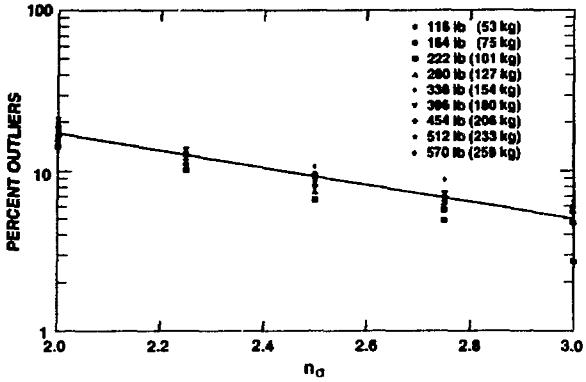

Fig. 4. Average run-rejection percentage for concrete matrices.

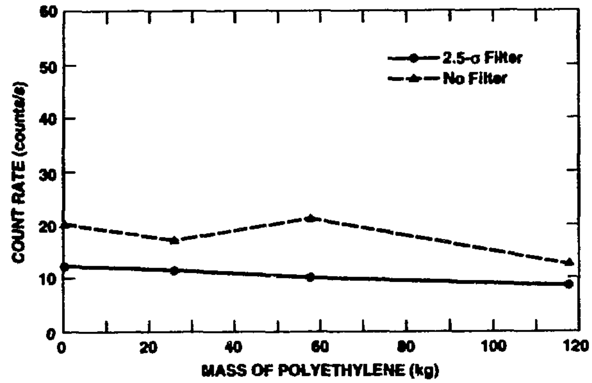

Fig. 5. Coincidence count rate as a function of polyethylene matrix mass for the filtered (2.5 σ) and unfiltered cases.

significant enough to warrant making matrix or mass-specific corrections to the outlier filter level.

V. RESULTS

The utility of a statistical filtering technique was borne out on all matrices analyzed in this study. The filtration removed the effects of spurious counts arising from cosmic-ray spallation and matrix geometry. The reals data from each matrix were consistently smoothed in a predictable fashion and the resulting data allowed ready comparison of the various matrices. The totals data were not significantly affected by the statistical filtration and these data have been omitted from the following discussion. Each of the six matrices will be considered separately.

A. Polyethylene

Figure 5 shows the effect of statistical filtration on polyethylene. The polyethylene was contained in a 200-ℓ steel drum. The effect of the drum has not been removed from the data. The negative slope of the curve demonstrates that hydrogenous materials absorb neutrons. The expected trend in the real count rate as matrix mass increases is clearly shown in the filtered data. This trend is also shown in the unfiltered data, although not as clearly. These data are typical of an overmoderated condition.

B. Concrete

Concrete in the form of 39.6- by 19.1- by 14.4-cm blocks (26.4 kg) was placed into a 200-ℓ drum and counted. Figure 6 shows the utility of filtration in smoothing the data from matrices that act as cosmic-ray spallation targets. The local peaks in the unfiltered data are caused by cosmic-ray showers that occurred during those trials. The statistical filter removed the anomalous data and resulted in a smooth, predictable trend with a slightly positive slope.

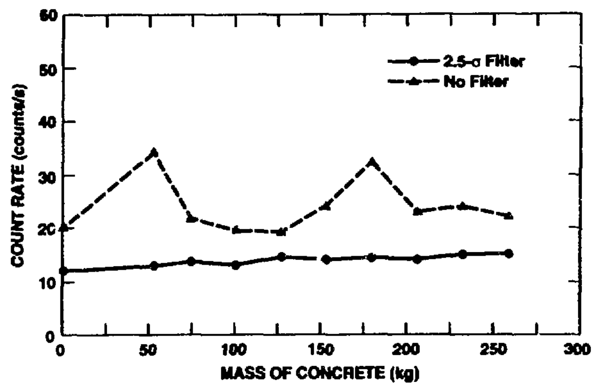

Fig. 6. Coincidence count rate as a function of concrete matrix mass for the filtered (2.5 σ) and unfiltered cases.

C. Aluminum

Figure 7 shows the aluminum case. The aluminum was contained in a 200-ℓ steel drum. The unfiltered data have a steeper slope than the filtered data. The steeper slope is probably caused by geometric effects associated with randomly loading the barrel with aluminum scrap of varying geometry. This effect is removed by the statistical filter and again the expected smoothing trend in the filtered data is observed.

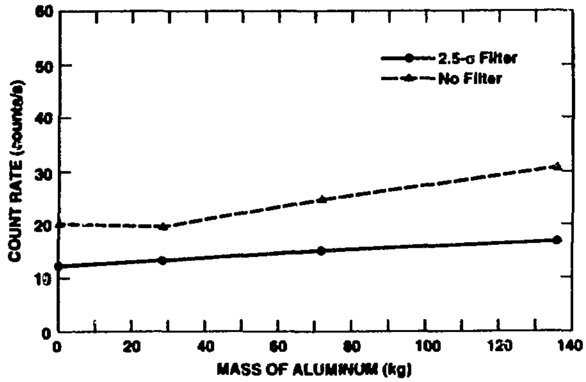

Fig. 7. Coincidence count rate as a function of aluminum matrix mass for the filtered (2.5 σ) and unfiltered cases.

D. Iron

Figure 8 shows the great utility of statistical filtration in iron. In the 237-kg case, there were no large cosmic-ray bursts and the count rates were sufficiently high that outliers that were lower than the 2.5-σ mean have been discarded from the data set. This effect has caused the unfiltered data to have a lower mean count rate than the filtered data. Again, the expected trend in the filtered data is observed and the inconsistencies in the unfiltered data have been smoothed.

E. Cadmium

Cadmium is not expected to be a common constituent of contaminated waste material, but many neutron detectors contain cadmium shielding. This material was chosen to demonstrate the continuation to high-Z materials of the trends observed in the more common matrix materials. The statistical filtration performs as expected in this high-Z regime. Figure 9 shows the anticipated relationship between the filtered and unfiltered data. This demonstrates a consistency in the behavior of the statistical filtration in high-Z materials with respect to low-Z materials.

F. Lead

Like the cadmium case, lead is not expected to be present in large quantities in typical barrel matrices. This case is presented to demonstrate the applicability of the statistical filtration routine to high-Z materials. The power of the statistical filtration in smoothing geometric and anomalous effects is clearly demonstrated in Fig. 10. The unfiltered data are sensitive to the geometry of the matrix. The stacked brick geometry yields a higher coincidence

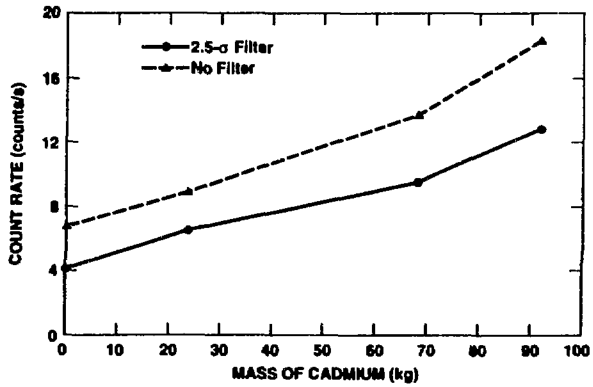

Fig. 9. Coincidence count rate as a function of cadmium matrix mass for the filtered (2.5 σ) and unfiltered cases.

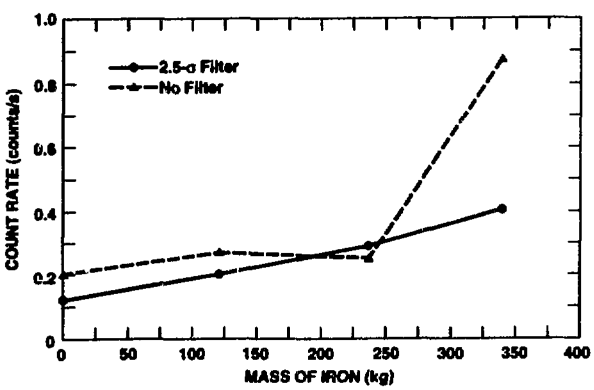

Fig. 8. Coincidence count rate as a function of iron matrix mass for the filtered (2.5 σ) and unfiltered cases.

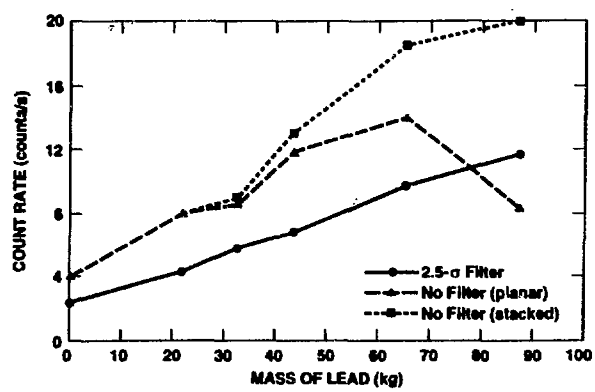

Fig. 10. Coincidence count rate as a function of lead matrix mass for the filtered (2.5 σ) and unfiltered cases.

count rate than the unstacked planar geometry. The difference is substantial in the 192-kg case. The geometries have different coincidence count rates because (1) the stacked geometry enhances the probability of (*n*,2*n*) reactions in the lead bulk and (2) the planar geometry places the matrix in a comparatively low-sensitivity region of the detector system. The filtered data return nearly the same value in either case, effectively homogenizing the barrel contents.

G. Overall Comparison

Figure 11 shows the compilation of the 2.5-σ filtered data presented in Figs. 5–10. The coincidence count rate attributed to the empty drum (0.011 counts/s) has been subtracted from each data point to facilitate comparison of the various materials. The y-axis intercept is the coincidence count rate for an empty detector observed during these measurements. The steady increase in slope of the curves as the matrix stopping power (Z) increases is clearly depicted.

Figure 12 shows an analogous compilation of the singles count rate over the same range of materials and masses shown in Fig. 11. The singles count rate attributed to the empty drum (0.126 counts/s) has been subtracted from each data point to facilitate comparison of the various materials. The y-axis intercept is the background count rate for singles measured with an empty detector during these measurements. The increasing slope with stopping power observed in the coincidence data is also evident in the singles data. The count rate sensitivity to a Z value (>26) observed in Fig. 11 is reduced in the singles case.

The negative slope for the polyethylene matrices observed in Figs. 11 and 12 indicates an overmoderated detection system. The polyethylene acts as a neutron

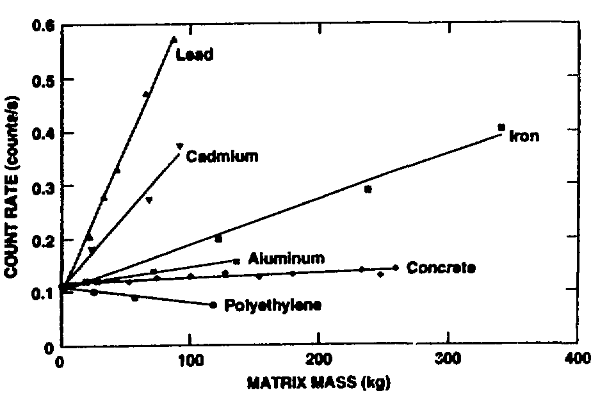

Fig. 11. Filtered (2.5 σ) coincidence count rates for each matrix.

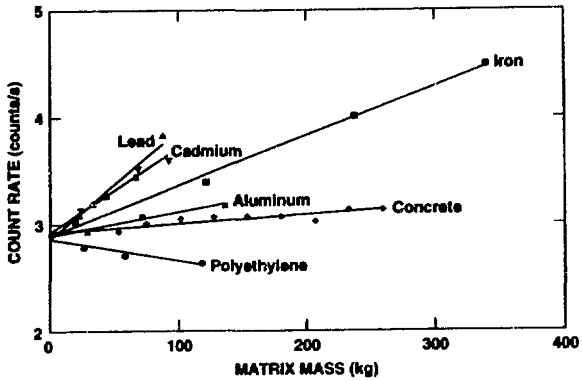

Fig. 12. Singles count rates for each matrix.

shield located in the center of the detector's sample cavity. This effect is expected for hydrogenous matrices, but may not be significant for typical loadings (<0.02 g H/cm^3 or 36 kg of H_2O).

VI. CONCLUSION

It is clear from Figs. 5–10 that the use of statistical filtering on assay data for matrices containing minute quantities of special nuclear materials will extend the lower limit detectability of a nondestructive assay system. Further, the potential effects of matrix geometry and stochastic phenomena are smoothed by statistical filtration. The spurious large-count runs resulting from cosmic-ray spallation within the matrix are reliably eliminated from the data.

Figure 11 shows a predictable variation of the coincidence count rate vs mass data with increasing matrix stopping power (Z). This trend is borne out in the singles count rates shown in Fig. 12. Theses figures indicate that a mass-dependent background correction could be applied to extend the lower limit detectability of plutonium in metallic matrices. From Figs. 11 and 12, nonmetallic matrices with a mass of less than 125 kg typically require no mass-dependent background correction to optimize the system sensitivity. Clearly, high-Z materials require background correction at masses above ~50 kg, although the need for matrix-specific corrections is diluted by the high background in the singles counting case.

From the coincidence count rate reductions observed in Figs. 5–10, the use of this statistical filtration technique effectively reduces the plutonium minimum detectable mass limit and reduces the matrix effect on background. For singles counting, the filtration technique has insignificant benefit for matrix smoothing; however, the filter still removes spurious data from electrical noise and background transients from external sources.

The statistical filtration technique that was demonstrated in this report for the reduction of neutron coincidence backgrounds induced by cosmic rays can be used in any experimental measurement of steady-state emission, such as radioactive decay. Noise events such as high-voltage leakage, microphonics, electromagnetic interference, and short-term background spikes can be effectively eliminated from the data set using this statistical filter technique.

REFERENCES

1. H. O. Menlove, J. Baca, W. Harker, K. E. Kroncke, M. C. Miller, S. Takahashi, H. Kobayashi, S. Seki, K. Matsuyama, and S. Kobayashi, "WDAS Operation Manual Including the Add-A-Source Function," Los Alamos National Laboratory report LA-12292-M (April 1992).

2. D. Reilly, N. Ensslin, H. Smith, Jr., and S. Kreiner, Eds., *Passive Nondestructive Assay of Nuclear Materials* (U. S. Nuclear Regulatory Commission, Washington, DC, 1991), NUREG/CR-5550; Los Alamos National Laboratory document LA-UR-90-732.

3. D. W. Miller and N. Ensslin, "Drum Counter Design and Operation Manual," Los Alamos National Laboratory report LA-11892-M (July 1990).

4. M. S. Krick and W. C. Harker, "NCC Users Manual," Los Alamos National Laboratory report (in preparation).