

Fast Neutron - Gamma Pulse Shape Discrimination of Liquid Scintillation Signals for Time Correlated Measurements

William L. Bryan, *Member IEEE*, Charles L. Britton, *Member, IEEE*, John T. Mihalczo, John S. Neal, *Member, IEEE*, Sara A. Pozzi, and Raymond W. Tucker

Abstract—We describe a neutron/gamma pulse shape discrimination (PSD) system that overcomes count rate limitations of previous methods for distinguishing neutrons from gammas in liquid scintillation detectors. Previous methods of PSD usually involve pulse shaping time constants that allow throughput of tens of thousands counts per second. Time correlated measurements require many millions of counts per second to accurately characterize nuclear material samples. To rapidly inspect many test articles, a high-throughput system is desired. To add neutron - gamma distinction to the analysis provides a much desired enhancement to the characterizations. However, if the PSD addition significantly slows down the inspection throughput, this PSD feature defeats any analysis advantage. Our goal for the fast PSD system is to provide sorted timing pulses to a fast, multi-channel, time-correlation processor at rates approaching several million counts per second enabling high throughput, enhanced inspection of nuclear materials.

I. INTRODUCTION

The sensitivity of time-dependent coincidence signatures between two or more detectors to the attributes of fissile materials has been demonstrated using the Nuclear Materials Identification System (NMIS) [1]–[6]. Attributes of fissile materials are related to features extracted from the NMIS signatures. Pulse shape discrimination (PSD) of the neutron and gamma

Manuscript received October 20, 2003. This work was supported in part by the U.S. Department of Energy under contract DE-AC05-00OR22725.

William L. Bryan is with the Oak Ridge National Laboratory, Oak Ridge, TN 37831-6006 USA (telephone: 865-576-6844, e-mail: bryanwl@ornl.gov).

Charles L. Britton is with the Oak Ridge National Laboratory, Oak Ridge, TN 37830-6006 USA (telephone: 865-574-1878, email: brittoncl@ornl.gov).

John T. Mihalczo is with the Oak Ridge National Laboratory, Oak Ridge, TN 37831-6010 USA (telephone: 865-574-5577, e-mail: mihalczojt@ornl.gov).

John S. Neal is with the Oak Ridge National Laboratory, Oak Ridge, TN 37831-6010 USA (telephone: 865-576-8275, e-mail: nealjs1@ornl.gov).

Sara A. Pozzi is with the Oak Ridge National Laboratory, Oak Ridge, TN 37831-6010 USA (telephone: 865-574-5699, e-mail: pozzisa@ornl.gov).

Raymond W. Tucker is with the Oak Ridge National Laboratory, Oak Ridge, TN 37831-6010 USA (telephone: 865-576-0947, e-mail: tuckerrwjr@ornl.gov).

components of the signatures will allow extraction of new features that have been shown to be more sensitive to fissile material attributes than the features from the total signature [7], [8]. Recent work using the MCNP-PoliMi code [9] simulated detector-detector covariance functions for passive measurements on plutonium spheres and cylinders. The total signatures were divided into four components according to the detected particles: neutron-neutron, photon-photon, neutron-photon, and photon-neutron. These simulations demonstrated the ability to distinguish plutonium metal from oxide for spherical and cylindrical samples without knowing the shape or mass of the samples. In order to implement these simulations, one must use PSD techniques to separate neutron and gamma pulses.

Previous methods of PSD allowed throughput of tens of thousands counts per second. Time-correlated measurements require many millions of counts per second to accurately and quickly characterize fissile material samples. We have designed a neutron/gamma PSD system that overcomes count rate limitations of previous methods for distinguishing neutrons from gammas in liquid scintillation detectors and integrates with other commercially available nuclear instrument modules (NIM). Our goal for this fast PSD system is to provide sorted timing pulses to a fast, multi-channel, time-correlation processor at rates approaching several million counts per second.

II. ELECTRONIC PULSE SHAPE DISCRIMINATION METHODS

Electronic PSD methods generally fall into one of three categories: (1) sensing differences in the decay times of pulses, (2) integrating pulse charge over different time intervals, and (3) digital capture and shape analysis of pulses [10], [11]. All of these methods depend on the ability to measure a difference in neutron and gamma pulse characteristics for the detector of our choice, the liquid scintillator BC501-A.

The rise time, or crossover, method [12] passes individual pulses through a shaping network, producing a bipolar pulse where the “zero-crossing” is a function of pulse shape and pulse decay time. The time difference between the pulse start and the zero-crossing is converted by a time-to-amplitude-converter (TAC) into a pulse amplitude. This method suffers from its dependence on

measuring a very small difference in pulse tail decay times for neutrons and gammas.

The charge integration method utilizes differing fluorescence properties in organic scintillators in response to neutrons and gammas. Several liquid scintillators produce light pulses that exhibit differences in pulse decay times for neutrons and gammas. While organic scintillators typically have both fast and slow components of scintillation, the majority of light is typically associated with the fast component. The fraction of light produced in the slow component often depends on the nature of the exciting particle, with the fraction depending primarily on the rate of energy loss, dE/dx . This light decay difference can be distinguished as a difference of integrated signal after the peak when normalized to the pulse peak value. Several methods have been devised to resolve this difference in pulse tail shape [13]-[16]. These methods produce either ratios of gamma and neutrons with scalers or two separate output signals for timing analysis. We are interested in the latter application where the separated neutron and gamma signals are later processed by the NMIS.

The digital capture and shape analysis method [11] acquires pulse waveforms using flash analog to digital converters (ADC) with sampling rates > 1 GigaSample per second. The captured waveforms are analyzed off-line to determine particle type, energy, and timing information. This technique cannot yet provide the necessary throughput for on-line, time-correlated measurements.

III. FAST PSD MODULE DESIGN

The fast PSD module described here has been designed to utilize the charge integration method. Commercial PSD modules generally measure differences between the integrated charge in the entire pulse and the integrated charge over the rising or falling portion of the pulse. The integrated charge over the entire pulse is a function of both the energy of the radiation and the type of radiation detected. The rising portion of the pulse is most representative of the energy of the radiation while the falling portion of the pulse is most representative of the type of radiation detected. This fast PSD module examines the ratio of charge in the pulse tail to the peak amplitude of the pulse (hereafter referred to as the charge ratio) [14]. The module normalizes pulses on energy and increases sensitivity to radiation type. In our case, the BC-501A scintillator may be described by the mean decay times of three components: 3.16, 32.3 and 270 ns [17]. It is assumed that these decay constants did not vary with particle type, but rather that the difference in neutron and gamma signals is due to varying proportions of the first two (3.16 and 32.3 ns) decay times.

As part of the design investigation process, liquid organic scintillators (BC-501A) were used to detect

neutrons and gamma rays from a Cf-252 source. The Cf-252 spectrum is a good surrogate for the neutron spectrum for both uranium and plutonium. Neutron and gamma pulses were differentiated using the time-of-flight technique, and pulses were digitized for subsequent analysis using a fast digital oscilloscope. Analysis of digitized pulses provided insight into optimum signal integration periods for pulse discrimination. A representative plot of discrimination charge ratios, with an integration period from 5-80 ns past the peak, is presented in Figure 1. These limited measurements were intended only to provide design insight.

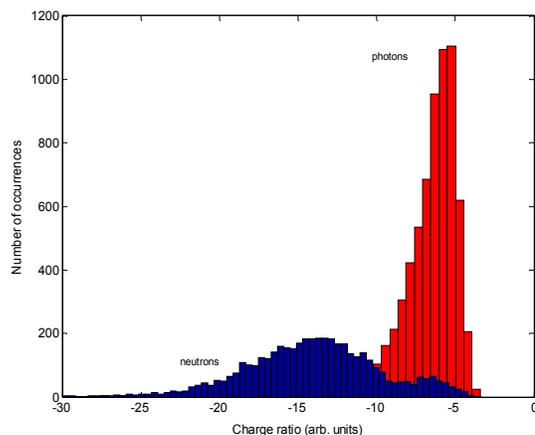


Figure 1. Charge ratio for gamma and neutron pulses from Cf-252 collected using the time-of-flight technique.

These scoping measurements revealed a range of charge ratios (-9 to -11 arbitrary units) in which gamma and neutron signals mixed in nearly equal proportions. In order to reduce neutron-gamma classification errors, the PSD module was designed to reject signals in a similar range of ratios through the use of window discriminators. A second neutron peak occurs at a charge ratio of approximately -6 arbitrary units. These pulses may actually be gamma pulses due to floor reflection effects, prompt gammas produced several nanoseconds or greater after fission, accidental coincidences, or gammas produced in the detector due to inelastic neutron collisions. We are investigating all of these potential sources and their effects on PSD. Numerous measurements were performed with multiple scintillator/photomultiplier tube/base combinations at various bias voltages to develop a sense of the variability in measurements.

This initial, fast PSD circuit design was developed to determine the viability of performing the charge ratio determination as a fast analog computation with minimal or no pulse shaping to slow the process down. This should provide the maximum throughput possible in keeping with the NMIS inspection goals. The basic components of this

strobe pulse that retimes the window comparators must be adjusted to sample the region of interest when the divider has settled to a stable value.

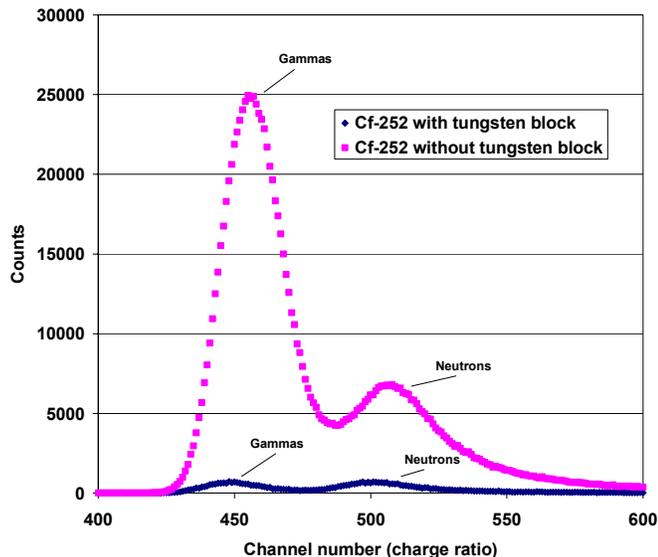


Figure 3. Distribution of PSD module calculated charge ratios for a Cf-252 source, with and without a tungsten gamma shield block.

V. SUMMARY

This is a report on work in progress. Initial test results show both the possibility of a fast PSD method of providing high throughput (2-3 Mcps), neutron/gamma sorted timing pulses to the NMIS correlation analysis system but also the limitations of pushing the limits on fast analog computation of the charge ratios. The measured MCA results of the analog ratio computation, shown in Figure 3, are in good agreement with results from previous PSD experiments using much slower zero-crossing or off-line computed methods [11], [13], [16]. But in performing these initial fast PSD design set-ups and measurements, limitations of the basic components of the analog computation were evident, in particular the dynamic range limits of the energies of pulses that could be reliably analyzed. The current fast PSD can manage pulses with a dynamic range of less than 15:1. Also limitations of the generation of precise and wide dynamic range timing signals to control the peak stretching, integration and window comparator strobing with off-the-shelf NIM components proved to be less than what was desired in terms of performance, ease of use and numbers of components. Consequently, a second generation fast PSD design is in progress to refine observed shortcomings in the peak stretcher and gated integrator dynamic ranges to double or triple the dynamic range of energies that may be analyzed. Internal timing signal generation is being integrated into the new fast PSD design as well as pile-up detection and rejection during the ratio computation.

VI ACKNOWLEDGMENT

The authors gratefully acknowledge the support of the Department of Energy, Office of Nonproliferation and International Security, International Safeguards (NA-241).

VII. REFERENCES

- [1] J.T. Mihalczco, J.A. Mullens, J.K. Mattingly, and T.E. Valentine, "Physical Description of Nuclear Materials Identification System (NMIS) Signatures", *Nuclear Instruments and Methods in Physics Research Section A*, 450, pp. 531-555, (2000).
- [2] S.A. Pozzi and F.J. Segovia, "²⁵²Cf-Source-Correlated Transmission Measurements and Genetic Programming for Nuclear Safeguards", *Nuclear Instruments and Methods A* 491/1-2 pp. 204-219 (2002).
- [3] J.K. Mattingly, J.T. Mihalczco, L.G. Chiang, and J.S. Neal, "Preliminary Analysis of Joint RFNC-VNIIEF/ORNL Measurements Performed In Year 2000", Y/LB-16,097, Y-12 National Security Complex, September 2001.
- [4] J.K. Mattingly, J. Neal, J.T. Mihalczco, "NMIS Passive Time-Dependent Coincidence Measurement for Plutonium Mass and Multiplication", *Proceedings of the Institute of Nuclear Materials Management 43rd Annual Meeting*, June 23-27, 2002, Orlando, Florida.
- [5] T.E. Valentine, L.G. Chiang, and J.T. Mihalczco, "Monte Carlo Evaluation of Passive NMIS for Assay of Plutonium in Shielded Containers", *Proceedings of the Institute of Nuclear Materials Management 41st annual meeting*, July 16-20, 2000, New Orleans, Louisiana.
- [6] L.G. Chiang, "NMIS Time Correlations for determining the Shape of Plutonium Using Second Order Statistics" *Proceedings of the Institute of Nuclear Materials Management 42nd Annual Meeting*, July 12-19, 2001, Indian Wells, California.
- [7] S.A. Pozzi, E. Padovani, J.K. Mattingly, and J.T. Mihalczco, "MCNP-POLIMI Evaluation of Time Dependent Coincidence Between Detectors for Fissile Metal vs. Oxide Determination," *Proceedings of the Institute of Nuclear Materials Management 43rd Annual Meeting*, June 23-27, 2002, Orlando, Florida.
- [8] S.A. Pozzi and J.T. Mihalczco, "Monte Carlo Evaluation of Passive Correlation Measurements on Containerized Plutonium Shells," *Institute of Nuclear Materials Management 44th annual meeting*, July 13-17, 2003, Phoenix, Arizona.
- [9] E. Padovani and S.A. Pozzi, "MCNP-PoliMi ver. 1.0. Users Manual", CESNEF-021125 Library of Nucl. Eng. Dept., Polytechnic of Milan, Italy, November 2002.
- [10] G.F. Knoll, *Radiation Detection and Measurement*, 3rd ed. New York: John Wiley & Sons, Inc., 2000, pp. 679-680.
- [11] S. Marrone et al., "Pulse Shape Analysis of Liquid Scintillators for Neutron Studies", *Nuclear Instruments and Methods A* 490 pp. 299-307 (2002).
- [12] M. L. Roush, M. A. Wilson, and W. F. Hornyak, "Pulse Shape Discrimination", *Nuclear Instruments and Methods* 31, pp. 112-124 (1964).
- [13] J. M. Adams and G. White, "A Versatile Pulse Shape Discriminator for Charged Particle Separation and Its Application to Fast Neutron Time of Flight Spectroscopy", *Nuclear Instruments and Methods* 156, pp. 459 - 476 (1968).
- [14] J. Cole, Idaho National Engineering Laboratory, personal communication, 2002.

- [15] Z. Bell, "Tests on a Digital Neutron - Gamma Pulse Shape Discriminator with NE-213", *Nuclear Instruments and Methods* A188, pp. 105 - 109 (1981).
- [16] M. Moszynski et al, "Study of n - γ discrimination with NE213 and BC501A liquid scintillators of different size", *Nuclear Instruments and Methods* A350 pp.226 -234 (1994).
- [17] F. T. Kuchnir and F. J. Lynch, "Time Dependence of Scintillations and Effect on Pulse Shape Discrimination", *Transactions on Nuclear Science* NS-15 No. 3 pp. 107 - 113 (1968).