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 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, \( \frac{dE}{dx} \). 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 > 1GigaSample 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.](image)
computation are a) integration of the pulse trailing edge over a precise time after the peak, b) measurement of the peak amplitude, c) calculating the ratio of the integrated charge to the peak and d) distinguishing neutron ratios from gamma ratios with two window comparators. The final values of these components occur over a time continuum from some fraction of the pulse rise-time prior to the peak to some time after the pulse trailing edge has been integrated and a ratio has been determined. This time span for the peak determination, integration and ratio processing and the desire to use the result for time correlation between multiple detector pulses implies the need for precision timing circuits and precision analog delays since the timing measurement and the ratio calculation must be derived from the same pulse.

Figure 2 gives a block diagram of the fast PSD module design. The detector signal must be buffered and split into two signal processing paths, one for timing and one for charge ratio analysis. Since the charge ratio analysis is dependent on the self triggered timing signals, the analog signal to the peak stretcher and gated integrator must be precisely delayed to align the detector pulse rising and trailing edges with precision gating signals for peak measurement, trailing edge integration and sampling of the window comparators after the charge ratio computation has completed. This analog signal delay will vary depending on the method and time necessary to generate the required precision gates to control these measurements.

One output from the input buffer amp goes directly to a commercial constant fraction discriminator (CFD) to establish an exact time reference for a particular pulse. The output pulse width of this CFD is set to be relatively wide, ~250 ns, and the signal is used to gate the fast PSD’s two peak stretcher circuits. A second CFD is triggered from the output of the first CFD and its output pulse width is adjusted to the required integration gating time, 80 to 160 ns. The output from the second CFD is further delayed and retimed to gate the output of the window comparators after the charge ratio computation is complete.

The second output from the buffer amplifier is routed through an external adjustable analog delay module. The delayed detector pulse signal is fed to the first peak stretcher circuit and to the gated integrator circuit. The gated integrator circuit output is fed to a second peak stretcher circuit. Outputs from the two peak stretchers form the inputs to the ratio computer that is implemented with a direct denominator input, analog multiplier/divider integrated circuit. Output from the divider circuit is compared to three reference voltages by the three comparators and the comparator outputs are combined logically to form windows for gamma ratios and neutron ratios, plus an exclusion region where the ratios overlap with little discrimination. A fourth comparator monitors the peak value of the pulse to prevent analysis of pulses exceeding the dynamic range of the peak stretcher and integrator circuits. These logical windows are gated at the end of the divider’s settling time to provide a sorted timing signal for neutron or gamma inputs to the NMIS system for correlation analysis.

The fundamental function of this on-line, fast PSD module is to perform a fast calculation of the charge ratios from organic scintillator detector signals and our initial testing has concentrated on this fast analog calculation function. To date, testing of the PSD module included tuning peak stretchers, gated integrator and fast analog divider electronics. Tuning involved the adjustment of the timing and duration of gate signals for the gated peak stretchers and the gated integrator, adjusting the gated integrator integration time constant and gain and offset adjustments throughout to optimize analog dynamic range constraints. The output of the fast analog divider circuit was input to a multi-channel analyzer (MCA) to gauge the resulting charge ratio calculations. Cs-137 and Co-60 gamma sources and a mixed neutron and gamma source, Cf-252, were used to help in making these initial adjustments. The experimental setup consisted of a BC-501A scintillator (cylinder with 4.625-inch diameter and 4-inch height) coupled to an XP4512B phototube and the PSD module. The radiation sources were placed approximately 6 inches from the detector face with allowance for a 4×4×4-inch tungsten cube used as a gamma shield.

Adjustments were performed to first insure that gammas of any energy above a certain threshold were identified in the same charge ratio range. Measurements were performed using both a gamma-shielded and unshielded Cf-252 source with results plotted in Figure 3. After this shielded - unshielded gamma balance was achieved, integration times can be adjusted to optimize the n-g separation at the MCA for a range of energies. Next the thresholds for the window comparators must be adjusted to set the regions of interest that sort the output from the divider circuit into neutron and gamma output pulse streams. The over-range comparator is set to reject pulses the are too large. Finally, the delayed

![Figure 2. Block diagram of fast PSD module.](image-url)
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.

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VII. REFERENCES

