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Real-time active cosmic neutron background reduction methods

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ABSTRACT

Neutron counting using large arrays of pressurized ^{3}He proportional counters from an aerial system or in a maritime environment suffers from the background counts from the primary cosmic neutrons and secondary neutrons caused by cosmic ray–induced mechanisms like spallation and charge-exchange reaction. This paper reports the work performed at the Remote Sensing Laboratory–Andrews (RSL-A) and results obtained when using two different methods to reduce the cosmic neutron background in real time. Both methods used shielding materials with a high concentration (up to 30% by weight) of neutron-absorbing materials, such as natural boron, to remove the low-energy neutron flux from the cosmic background as the first step of the background reduction process. Our first method was to design, prototype, and test an up-looking plastic scintillator (BC-400, manufactured by Saint Gobain Corporation) to tag the cosmic neutrons and then create a logic pulse of a fixed time duration (~120 μs) to block the data taken by the neutron counter (pressurized ^{3}He tubes running in a proportional counter mode). The second method examined the time correlation between the arrival of two successive neutron signals to the counting array and calculated the excess of variance (Feynman variance Y2F)[1] in the neutron count distribution from Poisson distribution. The dilution of this variance from cosmic background values ideally would signal the presence of man-made neutrons.[2] The first method has been technically successful in tagging the neutrons in the cosmic-ray flux and preventing them from being counted in the ^{3}He tube array by electronic veto—field measurement work shows the efficiency of the electronic veto counter to be about 87%. The second method has successfully derived an empirical relationship between the percentile non-cosmic component in a neutron flux and the Y2F of the measured neutron count distribution. By using shielding materials alone, approximately 55% of the neutron flux from man-made sources like ^{252}Cf or Am-Be was removed.

Keywords: Neutron counting, cosmic background, ship effect, spallation neutrons, Feynman variance Y2F, neutron shielding, electronic veto, time correlation

1. INTRODUCTION

The fluctuations in neutron background counting rates caused by spallation reaction in the presence of a large amount of metal structures or assemblies can negatively impact the sensitivity and operation of neutron detection systems. The natural background of neutrons that is observed in monitoring instruments arises almost entirely from cosmic ray–induced particles in the atmosphere and their interactions in the surrounding media. A significant source of variation in the observed neutron background is produced by the ship effect. The neutron spectrum and attenuation characteristics observed, as well as modeling results, indicate that it is the secondary neutrons that dominate the production of the observed neutron flux. Several factors affect the number of secondary cosmic particles reaching the surface of the earth; namely the local latitude, the ambient weather, solar activity, diurnal cycle, and barometric pressure. Ship effect is caused by production of neutrons from high atomic number elements such as lead or iron via the spallation mechanism. A 1 GeV proton can produce as many as 30 neutrons/proton from a thick mercury target. Large quantities of (~ ton) of heavy metal can produce from 40 to 60 neutrons per second by this mechanism.[3]

We purport to have effectively reduced the cosmic neutron backgrounds by several concurrent methods in real time. By incorporating highly concentrated neutron-absorbing materials into in light, hydrogenous neutron shielding materials we have removed lower-energy neutrons from the flux and moderated higher energy neutrons in the body of the shielding plates. After being moderated by the shielding material, the emerging neutrons pass through a plastic scintillator where they undergo charge-exchange processes, such as (n, p), (n, d), (n, t), (n, α) reactions, whereby light pulses are produced within the scintillators. These light pulses generate an electronic veto trigger to the neutron counting system, which prevents it from counting these on-coming cosmic neutrons; a 70% veto efficiency is achievable by this configuration. This electronic discrimination along with the physical shielding process reduces the cosmic flux by ~87%.

A software method that keeps tally of the neutron count distributions over very short windows of time and calculates the excess of variance from a random Poisson distribution (known as Feynman variance Y2F) was used to study the behavior of introducing a man-made source in near- and far-field measurements in the presence of cosmic neutron background. A portioning rule for discriminating between cosmic and non-cosmic neutrons was established using the correlation between neutron count rates and Y2F.

2. BACKGROUND

For passive detection of special nuclear materials from large stand-off distances, neutron signals are very important, particularly from an aerial platform or in a maritime environment because neutrons penetrate through common (high atomic number, Z_{eff}) construction materials such as lead, tin, and aluminum, and have high probability of reaching the detectors. Fast neutrons from a plutonium source can be detected at a long distance because the air scattering mean free path is long (>100 meters for 2 MeV neutrons).[4] The fundamental detection limit is always the neutron production by cosmic-ray interactions. Precise neutron counting becomes complicated because of varying and high cosmic neutron backgrounds (for example the average cosmic background neutron count rate is 120 neutrons/m^2/sec in the city of New York). The neutron background varies with geomagnetic latitude, atmospheric pressure, solar activity, and altitude of the observation location. In maritime environments neutron counting is made difficult because of the ship effect, the production of an excess of neutrons by secondary cosmic-induced interaction (spallation) of high Z materials (for example steel structures, containers, large engine blocks on board a ship). Minimization of ship effect for on-board neutron counting and measurement is a difficult challenge in maritime safeguard operations.

RSL-A has been working to resolve the neutron background issue for maritime measurements, and we have had some success. By making long-dwell background neutron measurements on board various categories of ships, we have been able to establish an enterprise-wide recognized Neutron Background Calculator tool set, which, when provided with a vertical neutron count rate profile of a particular class of ship, can decide with high degree of certainty if there is any anomalous neutron count in any particular deck; this shortens and simplifies search procedures for the first responder. The current project made an attempt to reduce (not just qualify) the cosmic neutron background on board a ship or in an aerial flight. The general approach used in this project to reduce cosmic neutron background was to (1) use effective shielding materials to remove neutron flux, (2) tag the remnant neutrons and use electronic veto for not counting them, and (3) use cumulative Feynman variance to indicate the presence of a man-made neuron source. Figure 1 describes the schematic of the experimental setup. All the elements above the ^{3}He tube array help perform operations (1) and (2), i.e., removal of cosmic background neutron flux; the items below the ^{3}He tube array perform real-time analysis of the neutron counts (Y2F calculations) from any neutron source present on the ground. The functional form of the Feynman variance Y2F(t) as a function of the time bin width of neutron correlation measurements is

$$Y2F(t) = \frac{A}{\alpha C_n}\left[1 - \frac{1- e^{-\alpha t}}{\alpha t}\right], \qquad (1)$$

where α^{-1} is die-away time (average time a neutron spends from the time of origination till it reaches the detector) in microseconds, t is the time bin windows in microseconds, C_n is the total neutron counts, and A is the normalizing constant.

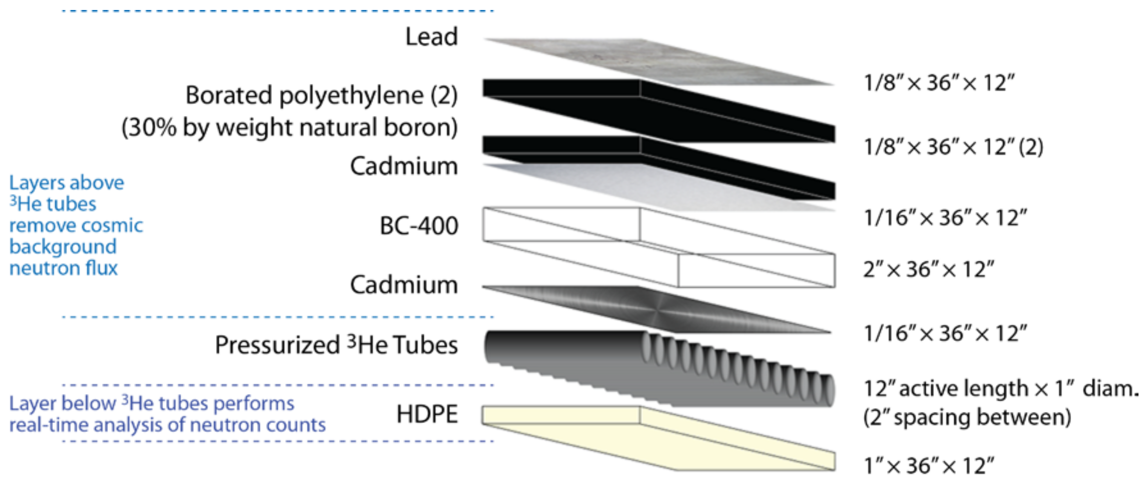

Figure 1. Schematic of the cosmic-ray shield experimental setup. From top to bottom are a lead sheet, two borated polyethylene sheets, a cadmium sheet, a BC-400 scintillator, a cadmium sheet, an array of 15 cylindrical pressurized ^{3}He (2.7 atmosphere) tubes spaced 2 inches apart, and a high-density polyethylene (HDPE) layer.

3. EXPERIMENTAL METHODS

Shielding Materials and Thickness

Choosing shielding materials requires considerable understanding of neutron interactions with materials like neutron converters (^{3}He, ^{6}Li, ^{10}B), moderators (^{1}H, CH_2, H_2O, D_2O), and absorbers (^{10}B, ^{113}Cd, ^{157}Gd). Neutron shielding is effectively accomplished by initially using good moderating materials followed by neutron absorber materials. Sometimes these absorbing materials (^{113}Cd or ^{157}Gd) are uniformly distributed in a matrix made out of the moderating material. Effective neutron moderators must be low cost and machineable, with high moderating power ($\Sigma_s\varsigma$), and defined as the product of the macroscopic scattering cross section (Σ_s) and the average logarithmic decrement of the kinetic energy of neutrons in each scattering process, ς. A good neutron moderator will also have to have a high moderating ratio, defined as ($\Sigma_s\varsigma/\Sigma_a$), where Σ_a is the absorption cross section. Referring to the table of moderating power and moderating ratio,[5] it is easy to understand why polyethylene with highly absorbing boron dopant followed by a thin cadmium sheet would make an effective cosmic neutron shielding block. The high-density (1.19 gm/cm^3) borated polyolefin (SWX-210 manufactured by Shieldwerx, a division of Bladewerx, LLC) that was used for this project had hydrogen and boron atomic densities per cm^3 of 6.07×10^{22} and 1.99×10^{22}, respectively; both had a macroscopic thermal neutron cross section of 14.5 cm^{-1} (represented as the inverse of the mean free path of thermal neutrons in the bulk medium).

Besides shielding, we used two more methods to address the cosmic neutron background problem: (1) electronic veto of tagged neutrons, and (2) studying time-resolved measurements of neutrons from a man-made source to find intervals between counts that are not random. Any deviation from the Poisson distribution of the neutron time correlation would prove the existence of a non-cosmic source. The two methods are described in detail below.

Method 1: Electronic Veto

A 2-inch-thick BC-400 paddle covered the entire active area of the ^{3}He tube array. A photomultiplier signal above a preset threshold indicated the presence of cosmic background. The ^{3}He tube array electronics were free running and counting neutrons. Whenever the plastic paddle detected a pulse above a preset threshold, it created a ~120 µs logic pulse to block the neutron counting by the ^{3}He array. These pulses blocked a large portion of the cosmic background—a signal-to-noise gain of a factor 2 was obtained. The veto pulse width was between 2 to 3 times greater than the die-away time for the detector. It is interesting to note that a commercially available fission meter has a die-away time of 40 µs.

Method 2: Y2F Calculation

The second method is a calculational procedure in which the Feynman variance (excess of variance over Poisson distribution of neutron counts), Y2F, is calculated continuously in the background for a series of measurements from 1 to 512 μs and repeated. For cosmic neutrons this value should be a constant and slightly positive. Any introduction of a neutron source would disturb this correlation, and the measure of the correlation function Y2F would be lower. Using a commercially available fission meter it has been shown that it is possible to partition the neutron counts into two groups, cosmic and non-cosmic, by establishing empirical rules relating neutron count rate and Y2F. This method does not exclude cosmic neutrons from being counted but shows what percentage of neutrons belongs to cosmic origin. This method involves understanding the characteristics of the neutron counter in great detail, whereas the first method is straightforward. We tested both methods to increase the counting sensitivity for man-made neutrons.

A high-speed field-programmable gate array (FPGA) SBRIO-9602 manufactured by National Instruments, Inc. has been used to exploit the time correlations between neutrons from different sources.[6] For example, cosmic or background neutrons in a maritime environment are only mildly correlated, primarily because of the high rates of spallation neutrons created by cosmic interactions. Neutrons from the (α, n) channel are completely uncorrelated, and neutrons from fission, particularly when multiplications are taking place following spontaneous or induced fission, are very highly correlated. By following the detected neutron counting distributions with very narrow time gates ranging from 1 to 512 μs, one can partition between fission and cosmic neutrons within a very short time, on the order of 10 minutes. This approach provides a unique solution to discriminate against cosmic neutrons in a maritime search environment (in real time) and enables effective measurement of a neutron source on the ground from a large stand-off distance.

4. MODELING AND CALCULATIONS

The cosmic-ray shield (Figure 1) was constructed of two layers of 1-inch-thick borated high-density polyethylene (HDPE) with 30% natural boron by weight fabricated into a five-sided cover for two moderated neutron modules. A second thermal neutron absorber, cadmium, in the form of a 1/16-inch-thick sheet of ^{113}Cd composed of 12.2% of natural cadmium was placed between the neutron detector modules and the shield. The Monte Carlo N-Particle eXtended, MCNPX code,[7] version 2.5.0, was used to simulate neutron transport and to generate sensitivity shown in Figure 2. A ^{252}Cf source of 2 mCi strength was used to simulate the response function for the 16-element 72″ × 2″ cylindrical pressurized ^{3}He tube array (2.7 atmospheric pressure) (with ¼-inch moderating sleeves).

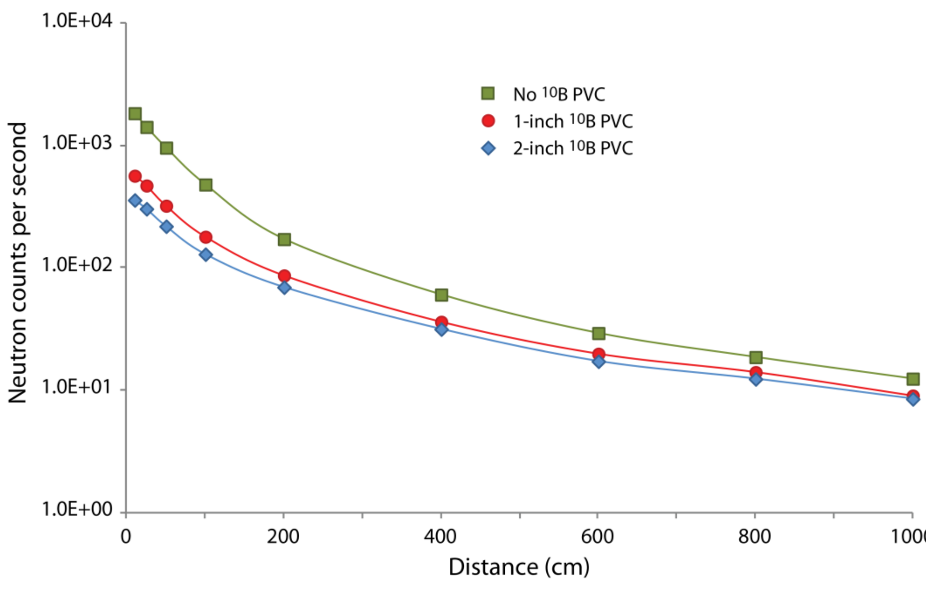

Figure 2. MCNPX-simulated neutron counts per second measured by a large array of 16 pressurized ^{3}He tubes (72″ × 2″ diameter). The neutron sensitivity (counts per second) as simulated by MCNPX is shown as a function of distance between the source and the detector for unshielded (green), and shielded with 1-inch (red), and 2-inch (blue) shielding materials, respectively.

For the MCNP calculation a bare neutron source using small quantities of ^{252}Cf was used. An SCX special tally was used to count the neutrons in each proportional counter. The count rates in each tube were tallied and the sum total count rates in all tubes are shown as a function of the distance between the source and the detector array (in cm) in Figure 2.

5. ELECTRONIC VETO

In low-rate multiplicity measurement conditions (as those present in maritime searches for special nuclear materials), even though mildly time-correlated, the cosmic-coincidence neutron backgrounds are the biggest challenge. Essentially all neutron coincidence background counts in a ^{3}He thermal neutron detector originate from the cosmic-ray spallation events. To reduce the neutron-coincidence background, the incident cosmic rays must be reduced both by shielding and by electronic means. Material shielding cannot reduce the coincidence background rate. By using a 5 cm thick plastic scintillator slab as the veto trigger, a reduction of 72% of coincidence background has been reported.[8] A similar technique has been employed in this project. The conceptual design of the experiment is shown in Figure 3, in which an array of 15 pressurized ^{3}He tubes is covered on one side (cosmic-ray incidence side) by a 2-inch-thick rectangular slab of BC-400 plastic, measuring 36″ (length) × 12″ (width) with an extended light guide used to collect light pulses using a photomultiplier tube (RCA 8575). An Ortec Model 265 tube base was placed on one end. A coincidence unit was used as the gate. This National Instruments module unit accepts as inputs the logic signal output from the ^{3}He detector; the veto pulses are accepted through an anticoincidence gate. The output of this unit is then sent to the FPGA for time-correlation counting of the ^{3}He signals. When the anticoincidence gate input is positive, the coincidence unit gives a zero (null) output; in the absence of an anticoincidence pulse, the ^{3}He signal passes through the unit to the FPGA with minimal signal distortion.

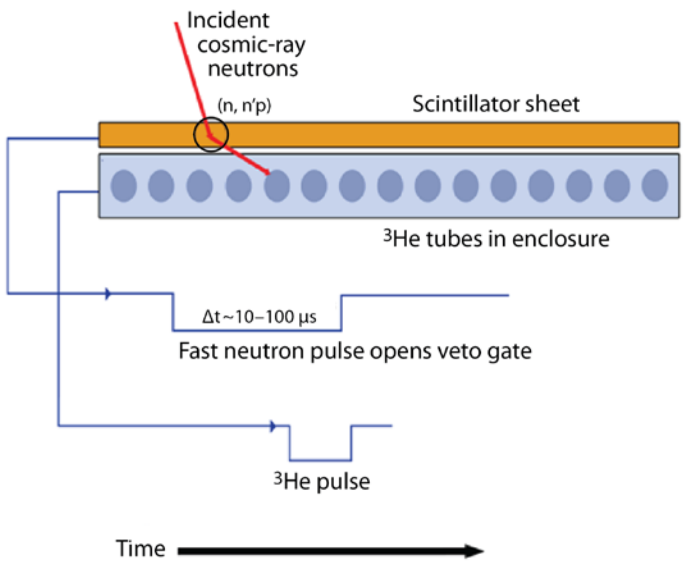

Figure 3. The incident cosmic neutrons undergo (n, n), (n, n´p) and charge-exchange reactions within BC-400 (predominantly made of H (5.23 × 10^{22}/cm^{3}) and C (4.74 × 10^{22}/cm^{3}) atoms) and create light pulses. Neutron pulses are discriminated against gamma-ray and other charged particle pulses and tagged by creating a transistor-to-transistor logic pulse that signals to open a 120 µs veto gate that is sent to the anticoincidence unit to block the neutrons from being counted by the ^{3}He counter electronics.

6. MEASUREMENTS AND RESULTS

Shielding

A series of shielding measurements were conducted using an Am-Be source (RAM-95048, 47.6 mCi) and a series of ^{252}Cf (ranging in strength from 1.8 μCi to 96.4 μCi) neutron sources to determine the effectiveness of the shielding block, which consisted of two highly borated polyethylene sheets, each 1 inch thick; the second layer away from the source had a sheet of 1/16-inch-thick Cd glued onto it to capture the moderated neutrons. The neutron counting equipment used to perform the tests were from RSL-A. The equipment included a neutron drop sensor, an infield backpack, RSL mobile neutron pods, and a 6-foot ^{3}He tube array. Figure 4 shows the source detector and shielding block orientation and configurations for the shielding measurement campaign.

Figure 4. (a) The shielding side of the 6′ × 2″ ^{3}He tube array, (b) the detector side of the 6′ × 2″ tube array, (c and d) two mobile neutron pods facing the source. The detectors, shielding elements, and the source were always centered about 1 meter above ground.

Long-dwell static data were collected to obtain stable and statistically valid neutron count rates from the ^{3}He tube detector arrays first without shielding in the presence of a neutron source and then by bringing in the shielding layers one at a time. First, a single 1-inch layer of the borated polyethylene, then two layers of 1-inch polyethylene panels, and finally 2-inch polyethylene plus a 1/16-inch sheet (away from the source side) were used. Effective shielding power was calculated (in percentile form) as

$$P_s = 100 * \frac{N_u - N_s}{N_u}, \quad (2)$$

where P_s is the shielding power, and N_u and N_s are neutron count rates measured by the ^{3}He tubes in unshielded and shielded configurations, respectively. Table 1 shows the shielding power (P_s) for various deployable RSL-A neutron counters, which vary greatly in terms of their size (solid angle coverage) relative to neutron count rates.

Table 1. Shielding measurements count rate data (counts per second (cps)) for various neutron counters

Equipment Type (Generic Name)	**Active Counting Element**	**Unshielded Neutron Count Rate**	**Shielded Neutron Count Rate**	**Shielding Power (P_s)**
Drop Sensor	Single ^3He (2.7 atm) tubes (12″ × 1″ diameter) with moderator	59.3 ±0.45	30.8 ±0.32 Bkg 0.17 (cps)	48%
Infield Backpack	Five ^3He tubes (12″ × 1″) with moderator	214.3 ±4.9	54.1 ±2.3 Bkg 0.7 cps	75%
Mobile Neutron Pods	16 ^3He tubes (36″ × 2″) with ¼″ polyethylene sleeves	216.8 ±14.7	102.7 ±11.1 Bkg 5.1 cps	53%
6-foot ^3He Tubes for Aerial Measurements	16 ^3He tubes (72″ × 2″) with ¼″ moderator sleeves	174 ±22.7	137.4 ±20.7 Bkg 135.6 cps	21% (all counts above background removed)

Parameterization of Non-Cosmic Neutron Content in Terms of Measured Y2F

One of the goals of this project was to parameterize the known percentile component of man-made neutrons in a mixed neutron flux as a function of the cumulative value of Y2F as measured by the free-running ^3He proportional counter system. A large amount of data were collected to provide a varied range of neutron counting rates so that a stable, statistically valid algebraic relation could be established between the Y2F and corresponding man-made neutron component. Figure 5 shows the plot of stable Y2F values versus the fractional composition of the man-made neutrons.

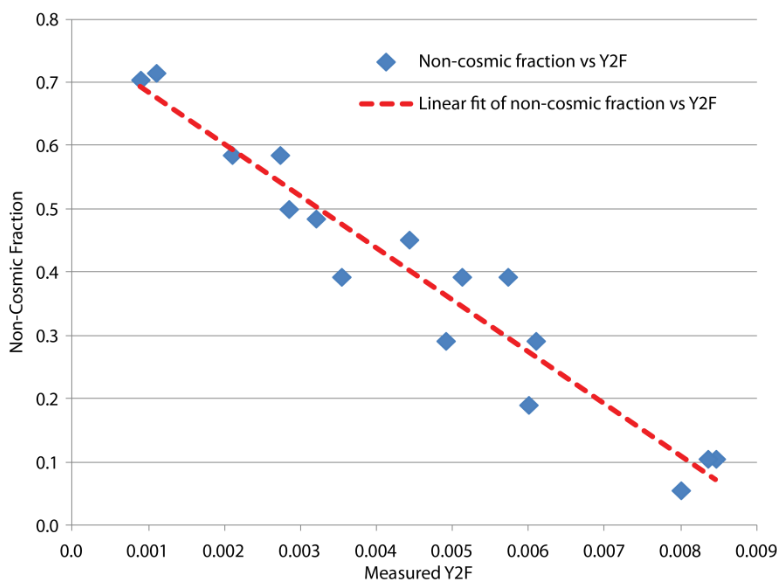

Figure 5. Non-cosmic fraction of the total neutron counts are plotted for measured Y2F values for various count rates. The red line shows a weighted mean slope (linear fit of the data points) of negative magnitude, meaning the increasing non-cosmic counts results in a decrease in Y2F.

BC-400 Electronic Veto

The electronic veto system shown in Figure 3 was set up using the BC-400 plastic paddle shown in Figure 6. The gamma-ray and neutron pulses generated by the plastic paddle are shown in Figure 7. The pulse height difference in them can be seen; on the basis of pulse height separation, we can tag the neutrons inside the BC-400 and start the anticoincidence window. If the threshold is set at 2.1 VDC, a cosmic reduction of 68% is expected,[8] which would translate into an improvement of detector sensitivity by a factor of 1.8.

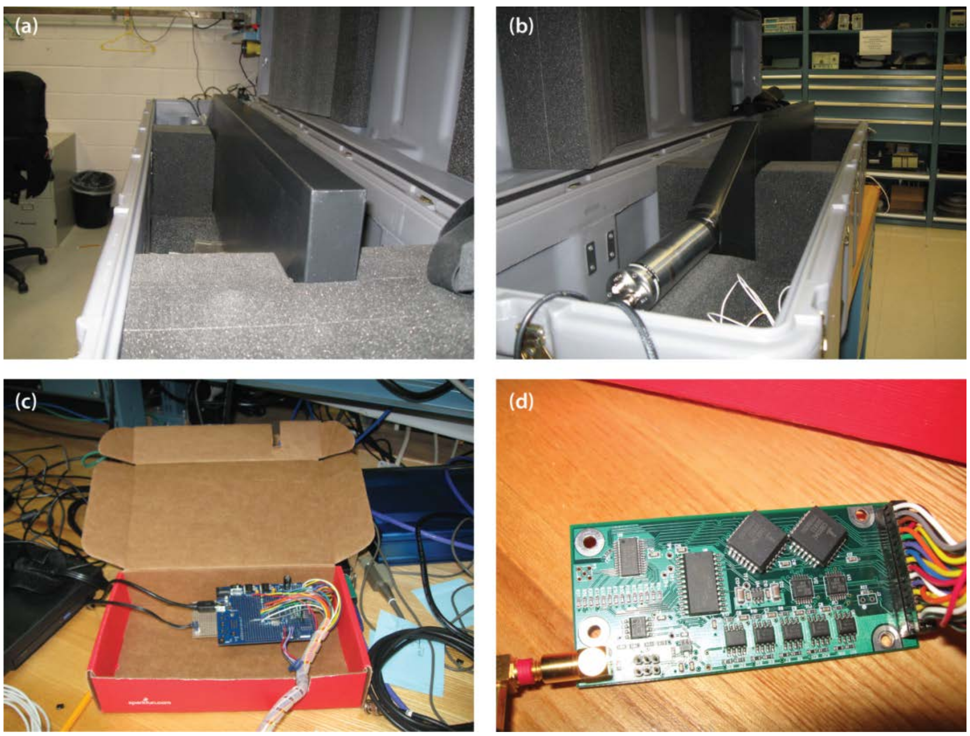

Figure 6. (a and b) A 2-inch-thick BC-400 (12″ × 36″ length without the light guide) with photomultiplier tube at one end was used along with the (c) high-voltage pre-amplifier and (d) amplifier board to tag the cosmic neutrons and separate them by stopping them from being counted by the ^{3}He proportional counter array.

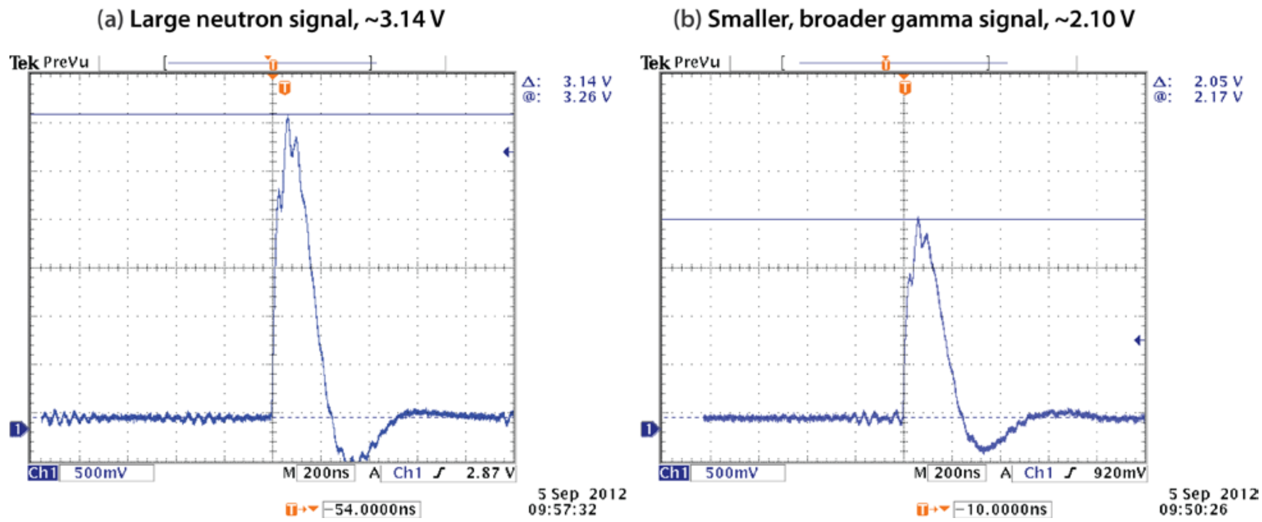

Figure 7. (a) The neutron pulses at 3.14 VDC amplitude are distinctly higher than the (b) gamma-ray pulses at 2.10 VDC and are, therefore, separable. Pulse shape discrimination was not applied because that would have caused unacceptable dead time.

7. CONCLUSION

A set of neutron moderating and absorbing materials in the form of rectangular slabs and sheets have been arranged to form a shielding package that successfully removes neutron flux from a source at a rate above 55%. A 2-inch-thick and 36-inch-long (length without the light guide) rectangular plastic scintillator BC-400 (acting as an active electronic veto) was configured successfully to tag incident cosmic neutrons and inhibit them from being counted by an array of ^{3}He tubes. This veto system removes another 70% of the remaining cosmic neutrons, effectively eliminating 87% of the incident cosmic background neutron flux. The efficiency of this veto counter has not been experimentally bench-marked. A factor of 2.8 improvement in detection sensitivity is accomplished with 70% veto efficiency (in conjunction with the shielding mechanism).

A real-time algorithm has been developed that determines the percentile man-made neutron component in a neutron flux from the real-time measured values of the excess of variance (Feynman variance, Y2F), providing software partitioning of neutrons. Because the two methods can run in parallel without interference, simultaneous application of these combined methods is most beneficial in maritime search operations where one is trying to find small correlated neutron signals.

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