Boron-Coated Straw Detectors for Backpack Monitors

Jeffrey L. Lacy, *Member, IEEE*, Athanasios Athanasiades, *Member, IEEE*, Christopher S. Martin, *Member, IEEE*, Liang Sun, *Member, IEEE*, and Gerson J. Vazquez-Flores, *Member, IEEE*

***Abstract*—The limited inventory and minute natural abundance of ^{3}He gas on Earth necessitate the adoption of new technologies for the detection of neutrons, especially in homeland security applications, where large volume deployments are required. We investigate the neutron detection efficiency of a backpack radiation detector based on an unmoderated array of boron-coated straws (BCS). A neutron module was configured that would be light and small enough to fit inside a regular-sized backpack. The module consisted of 36 tubes, arranged in two rows, for a total number of BCS detectors equal to $36 \times 7 = 252$. The overall dimensions of the neutron module were 3.18 cm $\times$ 26.7 cm $\times$ 38.1 cm, and its weight was 1.62 kg (3.57 lbs). The module was fitted immediately inside the back side of the backpack. The detectors are thus very close to the torso of the operator, which, together with a plastic scintillator for gamma detection, act as moderators for high-energy neutrons. In order to maintain a low weight, no other moderating material was installed inside the backpack. The weight of the pack containing both neutron and gamma detector panels, along with foam packing, electronics, and battery, was 5.36 kg (11.8 lbs). The compact dimensions of the design afforded use of a computer style backpack of minimal dimension providing significant additional operational advantages. The testing results indicate that, through use of high-density straw cluster detectors, the proposed design meets both neutron and gamma response government requirements for backpack monitors.**

***Index Terms*—Backpack radiation detector, boron-coated straws, neutron/gamma source detection, radiation detectors.**

I. Introduction

HELIUM-3 (^{3}He) gas is the material of choice for neutron detection because of its high-capture cross section, effective discrimination between neutrons and gamma rays, and because detectors can be readily constructed with the large dimensions required. Over the past five years, the demand for ^{3}He-based detectors has increased greatly, while the supply continues to decrease. The primary reason for the increase in demand is the expanded use of ^{3}He in neutron detectors for national security, and neutron science applications.

The limited inventory and minute natural abundance of ^{3}He gas on Earth necessitate the adoption of new technologies for the detection of neutrons, especially in homeland security applications, where the large volume deployments that are being considered would exhaust the entire world supply. The boron-coated straw (BCS) detector technology offers a replacement for ^{3}He neutron detection solutions [1]–[3]. Previous developments focused on large detectors for portal monitors. This work demonstrates the flexibility of the technology by presenting a neutron detector having substantial advantages for backpack systems containing both neutron and gamma detectors. This flexibility derives from the ability of straws to be easily manufactured in small diameters, after the coating of a thin foil, and be packed in dense arrays.

We have developed and tested a BCS-based backpack radiation detector (BRD) in order to investigate the potential of this technology in portable detectors for security applications. Because straws can be readily fabricated with a small diameter (4 mm), they can be close-packed to form a compact panel, having high detection efficiency. The panel, when packaged inside a backpack, is in close proximity to thermal neutrons emerging from the operator's body. No additional moderator is thus needed, allowing for low weight and compact size. The proposed design takes advantage of these straw characteristics to effectively replace high-pressure, high-efficiency ^{3}He tubes currently used in backpack radiation monitors [4].

The large diameter of conventional boron-lined counters (BLCs) limits their ability to achieve high detection efficiency in compact forms. The sensitivity of a boron-lined detector array is approximately proportional to coated area. If a detector module with similar sensitivity to the proposed BCS panel is formed with 2.54-cm (1-in) tubes, then the module becomes too thick for a backpack. GE Reuter Stokes has recently employed such BLCs in portal monitors [5], but critical detector design details have not been published, including coating thickness and purity.

Centronic, Ltd., Houston, TX, USA, has developed a monolithic design with multiple "tubelets" machined from an aluminum core [6]. The core has a diameter up to 6.35 cm (2.5 in), accommodating up to 14 tubelets, each 1.27 cm (0.5 in) in diameter, and lined with ^{10}B (neither coating thickness nor purity are reported). This design has been tested in portal monitors [7]. If the Centronic tubelet design were to be employed in a backpack module, then several units would be required to achieve a similar coated area. These would have to be stacked in two layers

Manuscript received June 15, 2012; revised November 05, 2012 and December 31, 2012; accepted January 25, 2013. Date of publication March 19, 2013; date of current version April 10, 2013. This work has been supported by the U.S. Department of Homeland Security, Domestic Nuclear Detection Office (DNDO), under competitively awarded contract HSHQDC-11-C-00087. This support does not constitute an express or implied endorsement on the part of the Government. This work was additionally supported by the U.S. Defense Threat Reduction Agency (DTRA) , under contract DTRA-01-02-D-0067.

The authors are with Proportional Technologies, Inc., Houston, TX 77054 USA (e-mail: jlacy@proportionaltech.com; aathanasiades@proportionaltech.com; cmartin@proportionaltech.com; lsun@proportionaltech.com; gvazquez@proportionaltech.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TNS.2013.2245915

in the pack making a 12.7-cm (5-in)-thick panel, again a rather bulky solution. The tubelet detectors are also heavy because the tube holes are bored in a solid Al bar.

BLC manufacturers insist on larger tube diameters because they apply the boron lining inside the final tube enclosure. With such processes typically involving evaporation, it is likely difficult to obtain a uniform layer, and the presence of a binder, used to fix boron particles onto the tube wall, compromises purity and thickness. The thickness of the coating is crucial to maximize efficiency, since the $^{10}\mathrm{B}(n,\alpha)$ reaction products cannot efficiently escape a coating that is more than a few micrometers thick. We are not aware of applications of the above BLC technologies in backpack monitors.

Other neutron technologies have been under development and proposed to replace ^{3}He tubes in backpacks, including ^{10}B or Gd-coated microchannel plates (MCPs) [8], [9], and lithium-loaded glass fibers [10]. These technologies may have deficiencies for the backpack application, and specific backpack designs and performance have not yet been published, to our knowledge. MCPs require additional components for gamma rejection, such as packaging the plates within NaI crystals in order to anticoincidence gamma events [9].

Lithium-6-based replacement technologies employ scintillating materials that are largely opaque and must be microscopically coupled to tiny ^{6}LiF crystals. The short range of the ^{6}Li fragments makes this challenging. The light must then be transmitted away from the opaque scintillator to photomultiplier tubes (PMTs), another substantial challenge. The introduction of scintillator, light guides, and PMTs increases weight and cost, both undesirable for backpack applications. In addition, such components are known to have significant aging issues. Neutron scintillators have considerable gamma sensitivity that can only be suppressed by use of complex digital signal pulse shape analysis. The digital processor may increase cost and power consumption and may compromise long-term reliability by introducing another complex component into a system.

In the following sections, we review the performance of the BCS-based BRD in terms of government-established requirements for neutron and gamma sensitivity at different orientation angles.

II. Methods

A. BRD Design

The design of the BRD is illustrated in Fig. 1. It contains both a neutron detection module and a gamma detection module. The neutron detection module consists of 36 0.5-in aluminum tubes, arranged in two rows, as shown in Fig. 2(a). Each tube is individually sealed and contains seven boron-coated straw detectors, as shown in Fig. 2(b). Each straw detector has an active length of 33 cm and a diameter of 4 mm. The total number of BCS detectors comprising the neutron detection module is thus $36 \times 7 = 252$. The overall dimensions of the neutron detection module are 38.1 cm $\times$ 26.7 cm $\times$ 3.18 cm $(\mathrm{H} \times \mathrm{W} \times \mathrm{D})$, and its weight is 1.62 kg (3.57 lbs).

In order to present an integrated solution, common in security applications, the proposed straw BRD incorporates a polyvinyl toluene (PVT) scintillator slab (Eljen Technology, Sweetwater, TX, USA), coupled to a PMT, for the detection of gamma rays. Because of its high hydrogen content, the PVT slab moderates high-energy neutrons and thus affects neutron sensitivity. It also substantially affects the overall size and weight of the device.

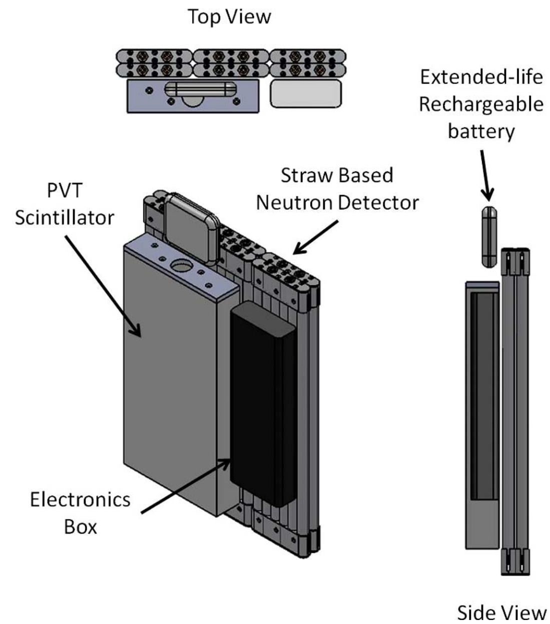

Fig. 1. Backpack radiation monitor design.

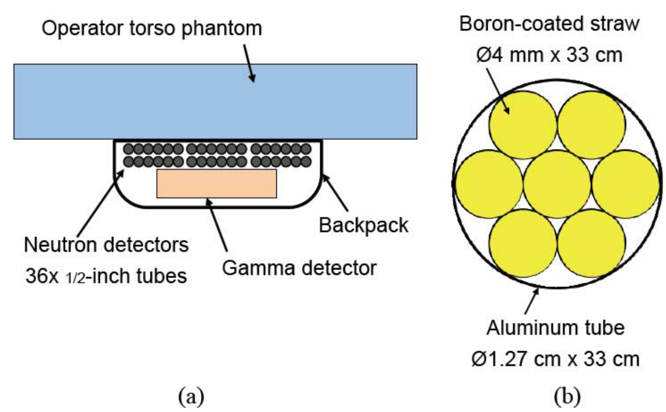

Fig. 2. (a) Neutron backpack detector contains six submodules, arranged in two rows; (b) seven straw detectors are sealed together inside a half-inch aluminum tube.

The gamma detection module was designed to be compact, lightweight and robust enough for field use. The PVT block outer dimensions are 30.5 cm$\times$15.2 cm$\times$3.81 cm $(\mathrm{H}\times\mathrm{W}\times\mathrm{D})$. The PMT is recessed inside the PVT block and supported in a manner that allows for robust operation in the field. The weight of the PVT block is 1.7 kg (3.8 lbs). Since the PVT acts as a moderator for high energy neutrons, it is configured to extend over a large fraction of the area immediately behind the neutron detectors, as shown in Fig. 1. The detectors are thus sandwiched between the PVT and the operator torso, with the latter providing additional neutron moderation.

B. Electronics and User Interface

High-speed, low-noise, compact electronics were designed to read out both neutron and gamma detectors of the BRD. The

Fig. 3. Custom-designed electronics board resting on its metal housing.

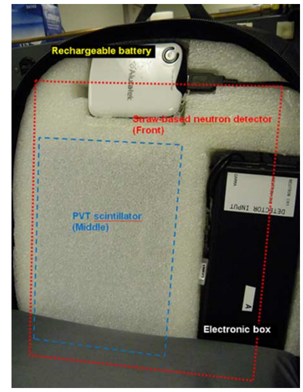

Fig. 4. Prototype backpack showing placement of various components.

main design specifications were to supply high voltage to bias the detectors (straws, PMT, and PVT), read out pulses generated in the boron-coated straw neutron detectors, and read out pulses generated in the PMT.

The architecture, implemented on a single board, pictured in Fig. 3, employed a high-speed 32-bit microprocessor for control, combined with environmental modules, and high-speed 12-bit ADCs for signal digitizing. Two channels were implemented to read out the straw detectors, allowing a panel to be divided into two segments, and another two channels to read out up to two PMTs. Straw signals from each half of the panel (126 straws) were daisy-chained together into each of the two neutron inputs. Neutron and PMT signals were processed through a low-noise charge-sensitive amplifier, shaping amplifier, and discriminator. Straw detector capacitance was less than 1500 pF/channel, presenting a negligible increase in amplifier noise compared with that obtained with only a few straws (after careful selection of the field-effect transistor).

A Transistor–Transistor–Logic (TTL) output was generated for every neutron and gamma event exceeding a selectable threshold, set to $\sim$ 70 keV for neutrons, and $\sim$ 30 keV for gammas. The amplitude of the analog neutron and gamma signal was captured using the microprocessor and high-speed ADC to generate pulse height spectra of neutron and gamma ray interactions in the BRD. Additional samples of analog signals were captured to facilitate rejection of microphonic events with distorted signal shape.

The power consumption of the electronics board was 1.8 W, 360 mA at 5 V. A rechargeable Li-ion battery provided 15 hours of continuous operation.

The BRD was connected to a Windows-based personal computer via USB cable, or wirelessly to a smartphone via Bluetooth. A graphical user interface (GUI) was designed to control settings, monitor environmental parameters, and display live data, including neutron and gamma count rates (over a preselected integration window), background rates, and pulse height spectra.

C. Integrated Backpack

A functional BRD was assembled with the neutron and gamma detection modules, and electronics, as pictured in Figs. 4 and 5. The entire backpack, including detector modules, electronics, and battery, is very compact, with overall dimensions 15.9 cm × 33.7 cm × 44.5 cm, and weighs 5.36 kg (11.8 lbs). The weight is 5.22 kg (11.5 lbs) without the battery.

Fig. 5. Backpack radiation detector on torso phantom.

D. Radiological Testing

According to ANSI N42.53 (draft) standard for backpack monitors [11], for a moving ^{252}Cf source of 20 000 n/s activity, at speed of 1.2 m/s at 1.5-m distance, the required positive detection is 96% with false alarm probability (FAP) of 1/h. In order to facilitate testing, we have correlated the ANSI requirement to a static sensitivity of 0.29 cps/ng for a fixed ^{252}Cf source at 1.5 m, assuming a background rate of 0.3 cps, measured in Houston, TX, USA. The derivation of the static requirement is presented in the Appendix. It should be pointed out that the derived static requirement is a function of the (square root of the) background rate and will be higher if assuming operation at a different location with a higher natural neutron flux.

In neutron sensitivity testing, the BRD was attached onto a torso phantom, as shown in Fig. 5. The phantom was fabricated in-house, using polymethyl methacrylate (PMMA) slabs, and according to the specifications of the ANSI standard [11]. Fig. 6 shows a drawing of the phantom with dimensions.

An unmoderated 110 ng ^{252}Cf source was supported on a stand, 1.5 m away from the center of the prototype backpack, and 1.3 m above the concrete ground. The source emitted 253 000 neutrons/s. The BRD was also centered 1.3 m above the ground. Measurements were repeated at 45° angle increments, as illustrated in Fig. 7. At angle 0°, the torso phantom was facing the source.

Gamma response testing was conducted with four different gamma sources, as required by the ANSI N42.53 standard,

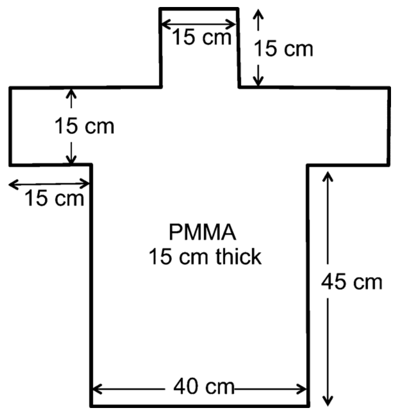

Fig. 6. Torso phantom shape and dimensions specified in the draft backpack standard N42.53.

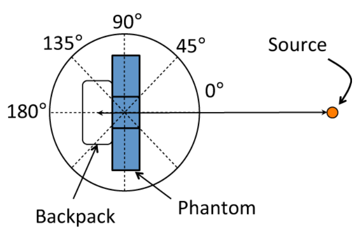

Fig. 7. Experimental setup, indicating rotational orientation of backpack with relation to the source.

TABLE I
GAMMA REQUIRED RATES AND SOURCE ACTIVITIES

	Required rate, at 1 m		Source activity	
	(cps/kBq)	(cps/μCi)	(kBq)	(μCi)
^{241}Am	0.068	2.5	407	11
^{137}Cs	0.16	6.0	207	5.6
^{57}Co	0.18	6.8	370	10
^{60}Co	0.38	14	37	1.0

specifically ^{241}Am, ^{137}Cs, ^{57}Co, and ^{60}Co. According to the standard, the required positive detection is 96% with a FAP of 1 per hour, assuming the source moves at a speed of 1.2 m/s, and the fluence on the detector is 4.0 gammas/(s*cm^2). The derived static requirements for a stationary source at 1 m are listed in Table I. These assume a background rate of 302 cps, measured in Houston, TX, USA.

The BRD was set up as described above for the neutron tests, except the distance between source and detector was now 1 m. The actual gamma source activities are listed in Table I. Results presented below were obtained directly from the GUI, with the backpack connected via USB cable to a laptop computer.

III. RESULTS

A. Neutron Response

The neutron background rate was 0.296 cps ±0.022 cps based on six different collections over several months of testing.

Results of ^{252}Cf neutron sensitivity are listed in Table II. There is some variation of the response, as the backpack rotates from 0° to 180°, due to the large size of the phantom, which reflects many neutrons away from the detectors. The minimum is observed at 45° and 90°, while the maximum is at 180°. The calculated ANSI standard requirement is 0.29 cps/ng and will be easily satisfied at angles higher than ~ 120°, i.e., when the operator turns such that the backpack is facing towards the source. Fig. 8 shows the results graphically, comparing the response at each angle to the ANSI requirement of 0.29 cps/ng.

TABLE II
NEUTRON RESPONSE MEASUREMENTS WITH PROTOTYPE BRD

	Neutron sensitivity, unmoderated ^{252}Cf (cps/ng)				
Source distance	**0°**	**45°**	**90°**	**135°**	**180°**
1.5 m	0.30	0.24	0.25	0.41	0.47

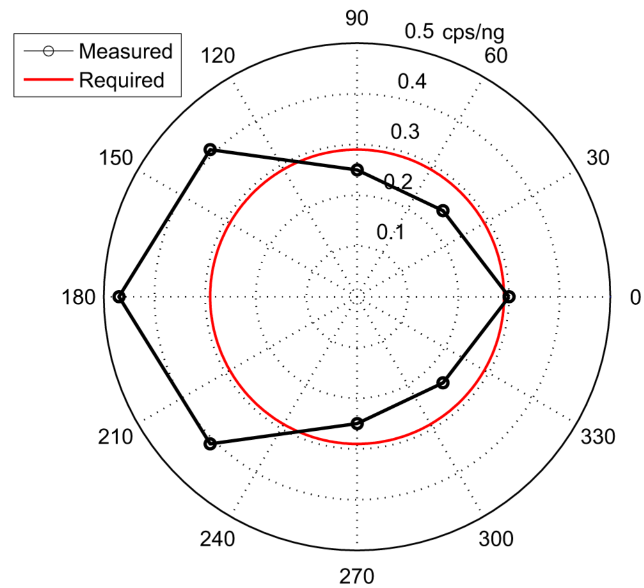

Fig. 8. Angular neutron response measured in the prototype BRD. The circle at 0.29 cps/ng corresponds to the calculated ANSI requirement.

The BRD readout software is capable of displaying neutron pulse height spectra from either neutron channel. A typical ^{252}Cf spectrum from the GUI is shown in Fig. 9. Only pulses surviving the discriminator are included. The low amplitude peak is channel pedestals (noise). This noise peak is collected automatically by the electronics because the neutron panel is read in two segments with separate amplifiers on the front and back layers of tubes. The discriminator however is sensitive to the sum of the two layers and triggers the digitization of both amplifier outputs. Both spectra are collected, and each shows a pedestal peak when, in fact, the other layer of tubes produced the signal triggering the discriminator. High-amplitude events are piled up under the peak on the right end of the spectrum.

B. Gamma Response

The gamma background rate was 300 cps ±12.5 cps based on nine different collections over several months of testing.

The net gamma response to four different sources is plotted in Fig. 10. The plots also show the gamma response required for different sources at 1 m in order to satisfy the moving source detection requirement specified in ANSI N42.53. The results of

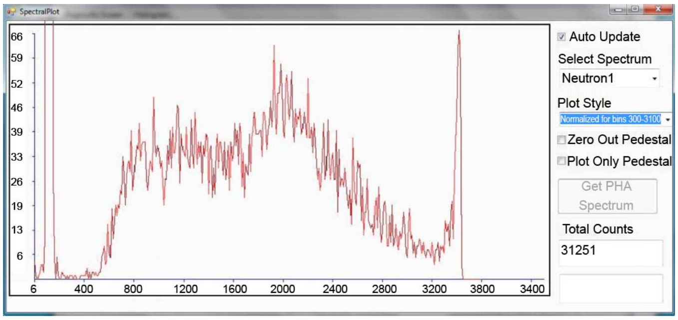

Fig. 9. ^{252}Cf pulse height spectrum captured with built-in electronics and displayed in GUI.

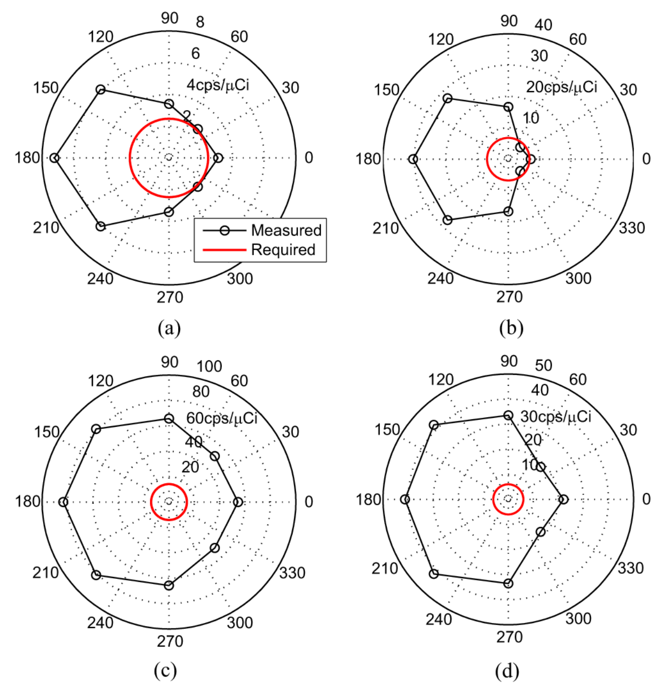

Fig. 10. Angular gamma response measured in the prototype BRD, with four different gamma emitters, as indicated. The circles correspond to the calculated ANSI requirement for each source: (a) ^{241}Am; (b) ^{57}Co; (c) ^{60}Co; and (d) ^{137}Cs.

gamma sensitivity meet requirements at all angles, except at 45° with the two low-energy sources ^{241}Am and ^{57}Co.

Gamma response uniformity testing with the PVT scintillator was done by placing a ^{137}Cs source at 18 different locations, as shown in Fig. 11, covering the entire sensitive area (30.5 cm × 15.2 cm). The gain variation over the 18 points as expressed by normalized Compton edge position is ±11%, as show in Fig. 12, indicating that the scintillator and light collection system are capable of producing reasonably good spectroscopic information despite the highly compact planar form. Such information is not employed at present but is planned for the next generation as a means of norm/threat discrimination. A second PMT may be added to enhance uniformity even further and firmware will be upgraded to allow analysis of spectra in real time (not currently implemented).

Gamma spectra collected with various sources at 1 m distance, using laboratory electronics, are shown in Fig. 13. The energy resolution of the ^{137}Cs Compton edge was measured at 29.8% (energy resolution was defined as the full-width-at-half-

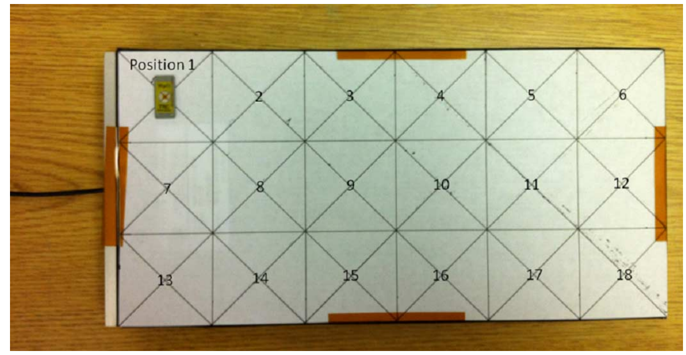

Fig. 11. PVT scintillator panel with map showing successive placement of ^{137}Cs source during uniformity testing.

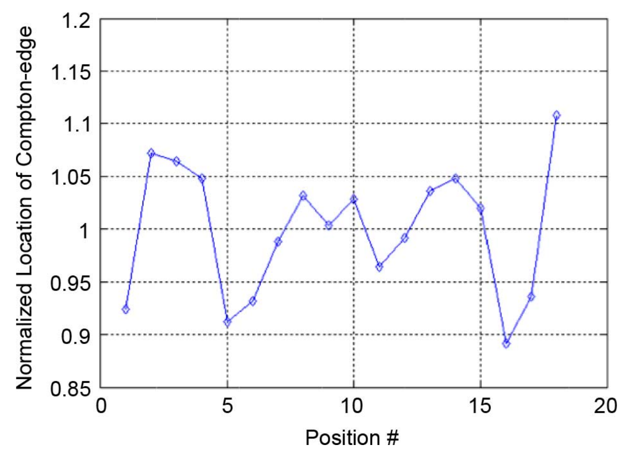

Fig. 12. Uniformity measurements at 18 different irradiation locations on the face of the PVT block.

maximum of a Gaussian peak that is the least-squares fit of the edge, expressed as a percent fraction over the centroid of the peak). In contrast, this Compton edge resolution improved to only 27.7% when the scintillator was irradiated at only position 10 in Fig. 11. These measurements indicate that the gamma detector has adequate energy resolution to support the planned future implementation of norm/threat discrimination.

Fig. 14 shows a typical ^{137}Cs pulse height spectrum collected with built-in electronics and displayed in the GUI.

C. *Predicted Response of BRD to Moving Source*

Based on the measured response shown in Figs. 8 and 10, further calculations (see Appendix) predict that the minimum detectable activity (MDA) for a moving neutron source is 12 400 n/s (20 000 n/s required), when the BRD is facing the source. The predicted MDA for a moving gamma source is 65.3 kBq for ^{60}Co (254 kBq required), 161 kBq for ^{137}Cs (592 kBq required), 496 kBq for ^{57}Co (522 kBq required), and 1150 kBq for ^{241}Am (1420 kBq required). The BRD is facing the source in all cases.

IV. CONCLUSION

We have successfully developed a backpack radiation detector, based on boron-coated straw detector technology, with significant advantages for homeland security applications. BCS detectors provide a replacement solution for ^{3}He tubes, with distinct advantages over other technologies, including low weight, ability to configure as desired (in this case, close to the

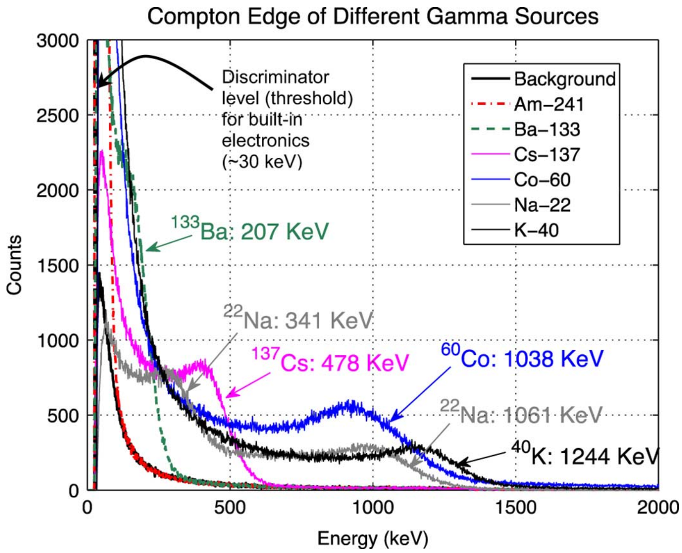

Fig. 13. Pulse height spectra collected in the BRD (with external electronics) from different gamma sources, as indicated. Scintillator was uniformly irradiated from a distance of 1 m for all sources. The vertical dashed line indicates the discriminator level of the built-in electronics.

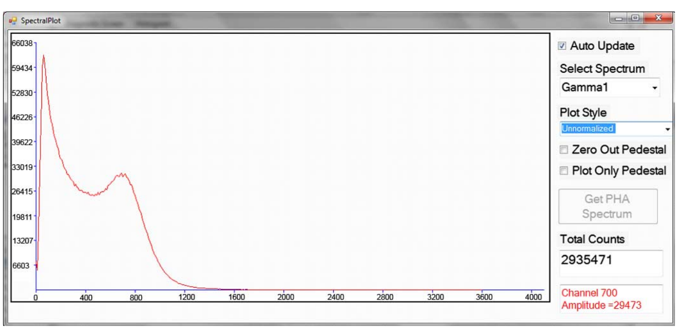

Fig. 14. ^{137}Cs pulse height spectrum captured with built-in electronics and displayed in the PC GUI. Data is transferred to the PC via USB connection to the backpack electronics box.

operator's torso for neutron moderation), and safe and robust operation over long times.

Wire detectors, like the BCS, are intrinsically reliable, due to their simple operation, based on gas avalanche signal formation. Previous BCS-based detector developments have had an excellent record in US government reliability testing, carried out in 2010, 2011, and 2012 by the U.S. Department of Homeland Security, Domestic Nuclear Detection Office (DNDO). In the DNDO contract NDRP program, five portal monitor detectors were delivered and underwent extensive government and government/contractor testing [2]. BCS-based units were subjected to extreme environmental testing, conducted at an independent laboratory, followed by government testing spanning several months in duration. Throughout all testing campaigns, not a single failure occurred, and all ANSI standard based DNDO requirements were passed.

Testing of the BRD has shown promising results, both in neutron sensitivity and gamma sensitivity. Requirements in moving source detection, as specified in the ANSI N42.35 standard, are easily met when the BRD is facing the source. Plans for the next generation of straw-based backpack include upgrade of firmware to support gamma spectroscopic norm/threat discrimination, inclusion of a second PMT in the gamma scintillator, and packaging of larger numbers of 4-mm straws in each sealed tube cutting cost of the system.

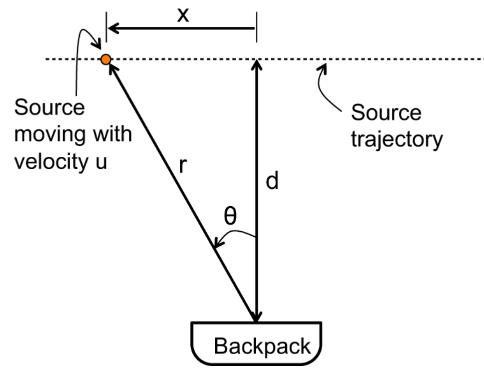

Fig. 15. Moving source geometry, and variables used in (2).

Appendix

Neutron and gamma response requirements specified in ANSI N42.53 [11] are expressed in terms of the minimum activity that will trigger the alarm when the source moves past the detector at a specified speed and distance. In order to simplify testing, we derive a relationship between the minimum detectable rate (MDR) specified in the standard, and the corresponding absolute efficiency for a *stationary* source at a fixed distance from the detector.

The MDR can be expressed as

$$\mathrm{MDR} = \frac{(z_{1-\alpha}+z_{\beta})\sqrt{R_b \cdot t_i}}{2\varepsilon d^3 \int_{t=0}^{t_i/2} \frac{1}{(d^2+(ut)^2)^{3/2}} dt} \tag{1}$$

where

- R_b the background rate;
- d the shortest distance between source path and detector;
- u the source transiting speed (1.2 m/s);
- t_i the integration time, set to $t_i = 2d/u$;
- ε the absolute detection efficiency, for a stationary source at distance d;
- $z_{1-\alpha}$ the (1–α)-quantile of the standard normal distribution, where α is the false alarm probability (FAP);
- z_{β} is the β-quantile of the standard normal distribution, where β is the probability of detection.

The numerator of (1) represents the net count that needs to be achieved for the alarm to go off, and depends on the desired FAP (parameter $z_{1-\alpha}$), and the desired probability of detection (z_{β}). The denominator of (1) represents the absolute efficiency of the detector, for a source located at a distance $x = ut$, as depicted in Fig. 15. Following a similar analysis in [12] for portal monitors, this efficiency is given by

$$e(x) = \varepsilon \left(\frac{d}{r}\right)^2 \cos(\theta) \tag{2}$$

where ε is the absolute efficiency at $x = 0$, and r and θ are the distance and angle drawn in Fig. 15. The term $(d/r)^2$ is a distance scaling factor, and $\cos(\theta)$ is a factor that accounts for the loss of effective detector area as the source moves away. This latter term is required because the detector width is comparable to distance d, and thus the detector cannot be viewed as a point in space. Now, the following formulas apply:

$$r = \sqrt{d^2 + x^2} \tag{3}$$

$$\cos(\theta) = \frac{d}{r}. \tag{4}$$

Substituting (3) and (4) into (2), we get

$$e(x) = \varepsilon \left(\frac{d}{\sqrt{d^2 + x^2}} \right)^3. \tag{5}$$

As a final step, we substitute $x = ut$, then integrate over the integration time t_i, to get the denominator of (1) (the integral is, in fact, evaluated over $t_i/2$, then multiplied by 2, since the detector response is identical over the two halves of the track). Equation (1) can then be solved for ε given the required MDR.

REFERENCES

[1] J. L. Lacy *et al.*, "Boron-coated straws as a replacement for ^{3}He-based neutron detectors," *Nucl. InstrumKer. Methods A*, vol. 652, pp. 359–363, 2011.

[2] J. L. Lacy *et al.*, "Straw-based portal monitor ^{3}He replacement detector with expanded capabilities," in *Proc. IEEE Nucl. Sci. Symp. Med. Imag. Conf.*, Oct. 23–29, 2011, pp. 4865–4868.

[3] J. L. Lacy *et al.*, "Initial performance of sealed straw modules for large area neutron science detectors," in *Proc. IEEE Nucl. Sci. Symp. Med. Imag. Conf.*, Oct. 23–29, 2011, pp. 431–435.

[4] PackEye, Radiation Detection Backpack (Model FHT 1377) . Thermo Fisher Scientific, Inc, Erlangen, Germany.

[5] A. T. Lintereur *et al.*, "Boron-lined neutron detector measurements," Pacific Northwest Nat. Lab. (PNNL), Richland, WA, USA, PNNL Rep. 18938, 2010.

[6] K. Tsorbatzoglou and R. D. McKeag, "Novel and efficient ^{10}B lined tubelet detector as a replacement for ^{3}He neutron proportional counters," *Nucl. Instrum. Methods A*, vol. 652, no. 1, pp. 381–383, 2011.

[7] M. L. Woodring, J. H. Ely, R. T. Kouzes, and D. C. Stromswold, "Boron-lined multitube neutron proportional counter test," Pacific Northwest Nat. Lab. (PNNL), Richland, WA, USA, PNNL Rep. 19726, 2010.

[8] R. C. Runkle, A. Bernstein, and P. E. Vanier, "Securing special nuclear material: Recent advances in neutron detection and their role in nonproliferation," *J. Appl. Phys.*, vol. 108, pp. 111–101, 2010.

[9] W. B. Feller *et al.*, "Microchannel plate special nuclear materials sensor," *Nucl. Instrum. Methods A*, vol. 652, pp. 25–28, 2011.

[10] R. T. Kouzes *et al.*, "Neutron detection alternatives to ^{3}He for national security applications," *Nucl. Instrum. Methods A*, vol. 623, pp. 1035–1045, 2010.

[11] *Performance Criteria for Backpack Based Radiation Detection Systems Used for Homeland Security (Draft)* , American National Standards Institute (ANSI) N42.53 Draft, 2013.

[12] R. C. Runkle, T. M. Mercier, K. K. Anderson, and D. K. Carlson, "Point source detection and characterization for vehicle radiation portal monitors," *IEEE Trans. Nucl. Sci.*, vol. 52, no. 6, pp. 3020–3025, 2005.