Boron-Coated Straw Detectors: a Novel Approach for Helium-3 Neutron Detector Replacement

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

***Abstract*—US efforts to equip key points of entry with large area neutron detectors to intercept Special Nuclear Materials (SNM) have been undermined by a critical shortage of ^{3}He gas. Yearly demand for ^{3}He in US security applications alone is roughly 22,000 liters, exceeding current world supply. Neutron science, safeguards, defense, and other applications that depend on ^{3}He detectors have been severely limited as a result. Alternative neutron detection technologies with large sensitive areas, low gamma sensitivity, and low cost are needed to ensure the long term viability of US detection and interdiction capabilities. We propose a technology based on closely-packed arrays of long, 4 mm diameter, aluminum or copper tubes (straws), internally coated with a thin layer of ^{10}B-enriched boron carbide, as a ready replacement for ^{3}He in a variety of detection applications. The high abundance of boron on Earth and low ^{10}B enrichment cost give boron-coated straw (BCS) technology key advantages over ^{3}He detectors. We review three BCS detector configurations including: a large-area neutron-imaging panel, a long range monitor, and a detector module for portal monitors. The imaging panel has 1100 aluminum straws, each 1 m long and 4 mm in diameter. It offers a sensitive area of 1 m^2, 3D spatial resolution of 7×4×4 mm^3, and can sustain count rates up to 200,000 cps for each of its 22 readout channels without significant loss in resolution. The long-range monitor has 1100 copper straws of similar dimensions and has been subjected to rigorous environmental testing. Finally, the portal monitor design adopts the outer dimensions of currently deployed ^{3}He-based designs, but takes advantage of the small straw diameter to achieve more uniform distribution of neutron converter throughout the moderating material.**

I. Introduction

The US government is currently implementing its strategy to protect the country against radiological and nuclear threats. Widespread deployment of radiation portal monitors (RPM), at seaports and border crossings for fast and efficient screening of cargo traffic, is a critical component of this effort. RPM installations consist of gamma and neutron detector modules, housed together in a single panel. Typical installations employ four panels, two on either side of a drive-through lane. On each side, the two panels are stacked on top of one another, to form a radiation sensitive area that is about 4 m tall, as required for efficient screening of large cargo containers. Large installations may include up to 12 panels. It is estimated that 1100 RPM installations have already been deployed [1].

^{3}He tubes enclosed in moderator boxes are a standard RPM solution. In this design, a ^{3}He tube, 2 m long, pressurized to 3 atm, is enclosed in a high-density polyethylene (HDPE) box, as shown in Fig. 1. The box has outer dimensions of 30.5×12.7×215 cm^3 (W×D×H), and is assembled from separate pieces, with an internal opening that accommodates the tube. The amount of ^{3}He gas contained in a 4-panel RPM installation is about 44 liters [1], meaning that many thousand liters of the gas are needed for widespread deployment. Current installations already contain an estimated 44,000 liters of ^{3}He [1].

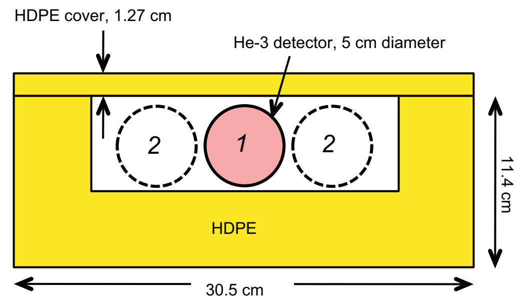

Fig. 1. Typical design and dimensions of a neutron detector for radiation portal monitors, with a single ^{3}He tube (dashed circles show possible tube locations in the two-tube design). The high-density polyethylene box has a height of 215 cm. The tube is pressurized to 3 atm.

The recent RPM demand has precipitated a critical shortage of ^{3}He, a rare gas with minute natural abundance on Earth, and demand by a host of other applications, such as neutron science instrumentation, nuclear safeguards, medical use, etc. The US demand in recent years has been close to 70,000 liters annually [2]. It is estimated that the annual demand for security applications alone is 22,000 liters [1]. The US produces ^{3}He from the radioactive decay of tritium stock, at a rate of 8,000 liters per year [2]. Tritium, a critical component of nuclear weapons, has not been in production since 1988, therefore the future production of ^{3}He is uncertain. Clearly, ^{3}He-free neutron detection technologies must be adopted, especially in homeland security applications, where large volume deployments are required.

II. Boron-Coated Straw (BCS) Detectors

We propose a neutron detection technology based on long tubes (straws), 4 mm in diameter, coated on the inside with a thin layer of ^{10}B-enriched boron carbide ($^{10}B_4C$). Thermal neutrons captured in ^{10}B are converted into secondary particles, through the ^{10}B(n,α) reaction. The reaction products,

This work was supported in part by the U.S. Department of Energy under grant no. ER84997 and by the Department of Homeland Security (DNDO).

All authors are with Proportional Technologies, Inc., Houston, TX 77054 USA (telephone: 713-747-7324, e-mail: jlacy@proportionaltech.com).

namely an alpha particle (α) and a lithium nucleus (^{7}Li) are emitted isotropically from the point of neutron capture in exactly opposite directions and, in the case of the dominant excited state, with kinetic energies of 1.47 MeV and 0.84 MeV, respectively.

Straw detectors can be easily and economically manufactured in large quantities, in a manner that guarantees a $^{10}B_4C$ lining that is pure, uniform and optimally thin. By making the boron carbide layer thin, typically 1 μm, one or the other of the two charged particles (whichever is directed inward) has a high probability to escape the wall and ionize the gas contained within the straw. The detection efficiency achieved is several times higher than that of standard boron-lined counters.

We have previously published on the BCS detection capabilities, fabrication, and development of prototypes for various applications [3], [4], [5], [6], [7], [8], [9].

III. BCS Module for Portal Monitors

The BCS detector can be manufactured in large volumes to replace ^{3}He-based detector modules in portal monitors, and support widespread deployment. A design based on BCS detectors is presented in Fig. 2, maintaining the outer dimensions of the HDPE box of Fig. 1 for a direct performance comparison. The detectors are distributed within an area of the moderator cross section, as indicated in the figure. The BCS detectors are 4 mm in diameter, 200 cm long, and are lined with 1 μm thick $^{10}B_4C$.

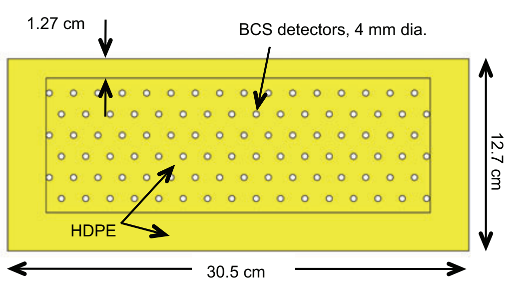

Fig. 2. RPM neutron module design based on BCS detectors. Straws are distributed within the central area of high-density polyethylene. The outer dimensions are those typically encountered in ^{3}He-based designs (see Fig. 1). Each straw detector is 2 m long.

A. Simulations

The detector design of Fig. 2 was modeled in Monte Carlo particle transport code MCNP5. The detector was oriented vertically, centered 1.5 m above a concrete ground, and inside a steel box, with an open side towards the neutron source. The source was placed 2 meters away from the moderator front surface, and emitted neutrons with energies specified by the built-in MCNP5 fission spectrum for ^{252}Cf. The source was surrounded with 0.5 cm thick lead, and 2.5 cm thick HDPE. Neutrons were allowed to thermalize and be reflected back out from the concrete ground, and from the steel box surrounding the detector.

Fig. 3 plots the computed count rate as a function of the straw density. The rate varies from about 2.3 cps/ng for 67 straws, to 4.5 cps/ng for 171 straws. The count rate keeps increasing for densities up to 800 straws, however, beyond 200 straws, the performance benefit is small, because the detector/moderator ratio is less than optimal. In the range beyond 800 straws, increasing the number of straws reduces the detection efficiency. The US government requirement for portal monitors tested under similar conditions is 2.5 cps/ng [10], as indicated in the figure.

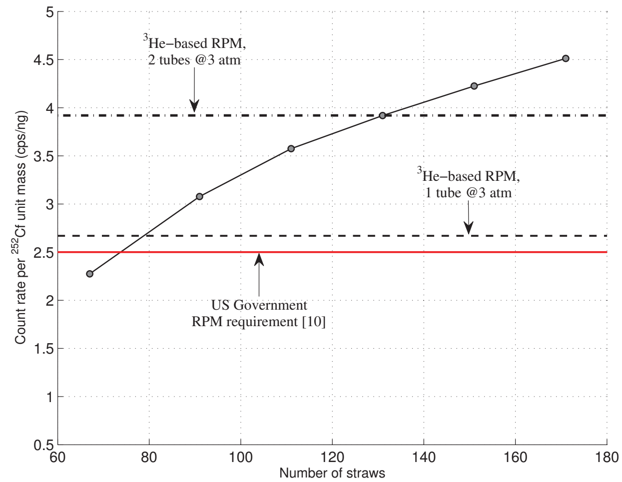

Fig. 3. Predicted count rate in BCS-based detector design of Fig. 2, as a function of the number of straws, for a moderated ^{252}Cf source at 2 m; and predicted rates for the ^{3}He-based design of Fig. 1, with 1 and 2 tubes.

For comparison purposes, another simulation was set up for the ^{3}He-based design of Fig. 1. The ^{3}He tube was 187 cm long, 5.08 cm in diameter, and pressurized to 3 atm. The moderator box had a 1.27 cm thick front wall, a 5.08 cm thick back wall, and 2 cm thick side walls. The box height was 215 cm. Other aspects of the simulation were identical to the setup described above for the BCS-based design, including the concrete ground, steel box and source moderator. The resulting count rate was 2.67 cps/ng for the single tube design, and 3.92 cps/ng for 2 tubes, as indicated in Fig. 3. The same rates can be obtained in the BCS-based design with 80 straws, and 130 straws, respectively.

Reference [11] presents the simulated response of the SAIC RPM (model RPM82), as a function of the ^{3}He pressure, and reports an absolute efficiency at 3 atm of 0.12% for a single tube, and 0.18% for 2 tubes. The corresponding rates are 2.8 cps/ng and 4.1 cps/ng, respectively, and are in close agreement with the simulation presented here.

B. Prototype testing

A prototype portal monitor was built, and tested with a laboratory neutron source. The prototype consisted of a solid block of HDPE, with dimensions of 29.8×12.1×205 cm^3 (W×D×H), shown in Fig. 4. The block was formed by bonding together several long slabs of HDPE; long square grooves were machined into each slab, to accommodate the BCS detectors. A total of 171 grooves, with a pitch of about 10 mm, were machined. The BCS detectors were 4 mm in diameter and 200 cm long. Figure 4 shows a 200 cm long straw detector as it is being inserted into the moderator.

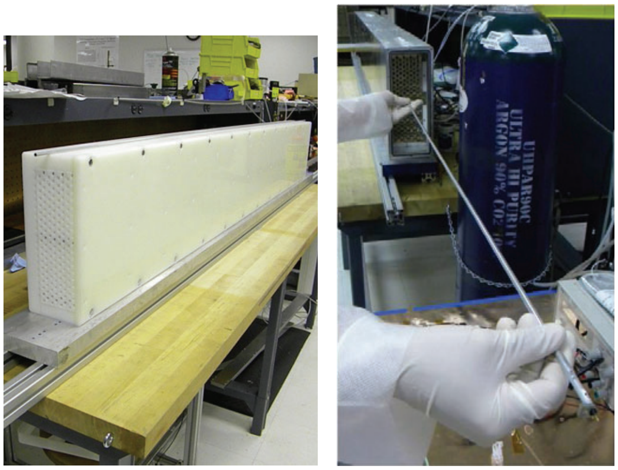

Fig. 4. Polyethylene moderator block (left), and 200 cm long straw detector (right) being inserted into one of the 171 holes machined into the polyethylene.

All BCS detectors were electrically connected together, and a single charge sensitive amplifier (Canberra model 2006) was used to read the whole array. Detector signals were initially shaped with an analog amplifier (Canberra model 2022, 1 μs shaping time), and then digitized (Amptek MCA-8000). The detectors were biased to 700 V through a 34 nF coupling capacitor.

A ^{252}Cf source, purchased from Frontier Technology (FT), was used in all measurements. The source size specified by FT was 1.40$\pm$0.042 μg on 2/21/2002. For the measurements presented here, the source size was 0.160 μg. The source was placed inside a pig that surrounded it with 0.5 cm thick lead, and 2.5 cm thick polyethylene. The measured rates were background subtracted and scaled down to correspond to 1 ng ^{252}Cf that emits 2300 n/s. During measurements conducted outdoors, the detector was supported vertically, 1.5 m above the concrete ground, and in front of a 2.54 cm thick steel plate, as shown in Fig. 5. The purpose of the steel plate was to simulate the effect of the steel housing commonly used in RPM installations. The source was supported on a tripod, 2 m away from the front face of the detector, and 1.5 m above the ground.

The results are plotted in Fig. 6 as a function of the number of straws present in the moderator. The count rate varied from 2.55 cps/ng for 67 straws, to 4.51 cps/ng for 171 straws. The background rate varied from 2.1 cps for 67 straws to 4.2 cps for 159 straws.

Additional testing was conducted at PNNL [12], with the 171-straw prototype installed inside a steel housing, part of the standard RPM installation used for all commercial systems. In addition to the metal housing weighing over 1500 lbs all nearby surrounding equipment was included as well. The detector center was positioned 1.33 m above ground in this setup. A gamma detection panel was installed inside the housing, immediately to the left of the neutron module. The source was supported on a tripod, 2 m from the face of the

Fig. 5. The prototype detector during testing outdoors. The detector is supported in front of a 1-inch thick steel plate, with its center 1.5 m above ground. A ^{252}Cf source is supported on a tripod 2 m in front of the detector face.

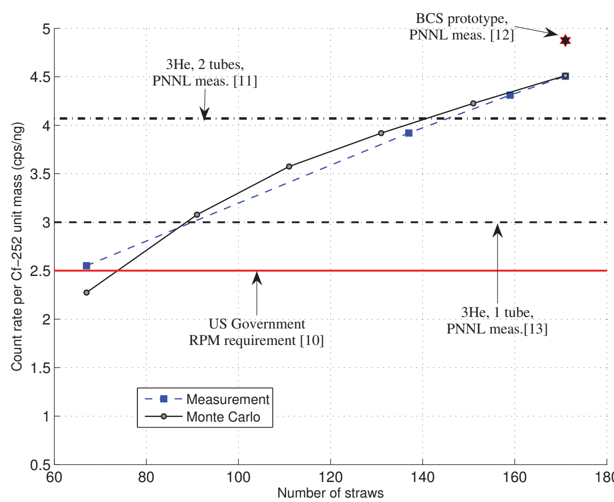

Fig. 6. Measured and predicted (Monte Carlo) count rates in the prototype monitor, as a function of the number of straw detectors, for a moderated ^{252}Cf source at 2 m; PNNL measurements of the BCS prototype and of ^{3}He-based RPMs are indicated.

detector, centered at the same height. The measured rate was 4.93 cps/ng, as indicated in Fig. 6. This value is higher than our measurement of 4.51 cps/ng, because of reflections from the steel housing and other nearby materials.

PNNL has measured the response of ^{3}He-based RPMs currently deployed and reports a rate of 3.0 cps/ng for the single-tube design [13], and 4.07 cps/ng for the 2-tube design [11]. The tubes were pressurized to 3 atm. These values are indicated in Fig. 6, as well.

C. Discussion

Measurements collected with the BCS-based portal module show that the proposed design can exceed the government RPM requirement of 2.5 cps/ng [10], for a number of straw detectors equal to 70 or higher. Ninety straw detectors can match the performance of a ^{3}He-based design with a single tube pressurized to 3 atm, and 140 straws can match the performance of the 2-tube ^{3}He design. Significant improvement in performance can be obtained with a higher number of straw detectors, as shown in Fig. 6.

It is instructive to consider what will be required to deploy straw systems as a drop-in replacement for existing portal monitors. Because of the total absence of new sources of ^{3}He on earth, it is vitally important going forward to replace the ^{3}He detectors in existing portals with detectors employing an inexpensive, inexhaustible and readily available alternative. Based on results presented here, 90×2 meters of 4 mm straw detector material can match the performance of 11.4 liters of ^{3}He, contained in a 1.87 m long tube, pressurized to 3 atm. The requirement for total replacement of 70,000 liters of ^{3}He in the US portals is thus $70{,}000 \times 15.8 = 1110$ km of straw. The amount of ^{10}B required can be obtained as follows. Each meter of 4 mm straw has an inner surface area of 125 cm^2 and the total amount of $^{10}B_4C$ required for a 1-μm-thick coating is $0.0001 \times 125 \times 2.38 = 0.0297$ g. The total required for replacement is $0.0297 \times 1110 \times 10^3 =$ 33 kg. Ceradyne Inc. (Costa Mesa, CA) currently produces 10,000 kg of enriched boron annually, and have the capability to produce similar quantities of enriched boron carbide. Hence entire replacement of the portal monitor ^{3}He can be achieved while only diverting 0.33% of the current production. Clearly availability of enriched boron carbide is not and never will be an issue that would impede replacement.

IV. Neutron Imaging

The proposed detection technology can offer significant advantages over conventional ^{3}He tubes in neutron imaging applications, including higher counting rate capability, parallax-free position decoding, lower cost, safer operation and a wide array of geometry configurations.

A prototype imager with a 1 m^2 sensitive area, shown in Fig. 7, has been developed at Proportional Technologies, Inc., and tested at ORNLs High Flux Isotope Reactor (HFIR). The imager incorporates 22 detector modules, each consisting of a 5×10 close-packed array of aluminum straws. Straws were 4 mm in diameter, and 100 cm long, and lined with a thin coating of B_4C (non-enriched). The applied potential was 1150 V and the gas mixture was Ar/CO_2 (continuous flow). Experiments were conducted in a pulsed neutron beam delivering neutrons in the wavelength range from 1 Å to 20 Å. A ^{3}He-based monitor was used to characterize the beam current, and its rate was used to determine the detection efficiency of the BCS panel, as a function of the neutron wavelength. The efficiency measured in the non-enriched modules was 8.7% at 1.8 Å.

Other experiments showed that the BCS panel can offer spatial resolution on the order of 7×4×4 mm^3 [3], and that resolution does not degrade for count rates up to 200,000 cps per 50-straw module.

Fig. 7. Prototype neutron imaging 1 m^2 detector (left), and testing at the HFIR neutron science facility (Oak Ridge, TN).

V. Long-range Detection

The BCS detector has been additionally proposed for long-range detection and localization of hidden neutron and gamma sources, in homeland security applications [7]. Straw detectors are stacked to form a large area (1 m^2 or higher), moderator-free panel that is lightweight and safe to transport. Each module consisted of a 5×10 close-packed array of copper straws, each 4 mm in diameter, 100 cm long, and lined with a nominal 1 μm thick coating of enriched $^{10}B_4C$.

Large 0.5 m^2 devices have been tested according to ANSI 42.35-2006 and have been extensively employed in demanding field applications demonstrating the robustness of the straw system. Fig. 8 shows a temperature cycling test, over the range from -40°C to +60°C. The gain variation is small, a result of the change in gas pressure.

The count rate due to the natural neutron background was recorded over the course of a transport from Oak Ridge, TN to Houston, TX. The road trip was over a time period of about 13.5 hours. The recorded rate is plotted in Fig. 9, along with the natural neutron flux profile. The latter was based on calculations that accounted for the geographical elevation and rigidity cutoff [14], which in turn depend on geographical location (latitude & longitude).

VI. Conclusion

It is imperative to address the imminent shortage of neutron detectors for homeland security and neutron science applications. The limited inventory of ^{3}He gas, and uncertain future

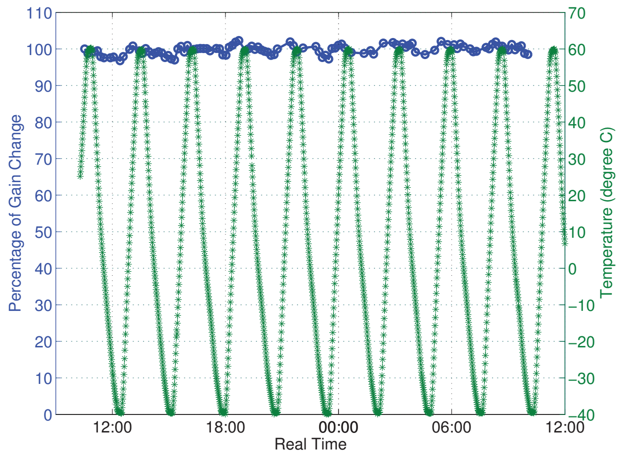

Fig. 8. Temperature cycling of straw detectors.

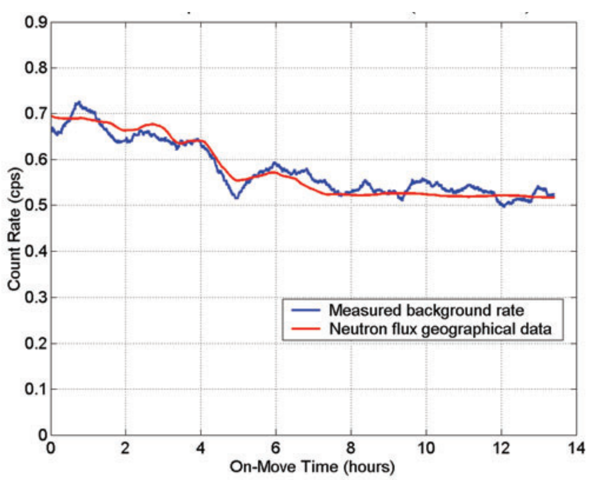

Fig. 9. Background count rate measured in the long-range detector during a road trip from Oak Ridge, TN to Houston, TX. The red line is an estimate of the cosmic neutron flux at each corresponding geographical location, based on equations published in [14].

production, dictate the need for alternative neutron detection technologies. The proposed boron-coated straw detectors can readily satisfy the portal monitoring requirements for high sensitivity, large sensitive area, low cost and good gamma-ray discrimination, and it can support the high-rates required in neutron imaging instruments.

REFERENCES

[1] R. T. Kouzes, "The ^{3}He supply problem," Pacific Northwest National Laboratory, Richland, WA, Tech. Rep. PNNL-18388, 2009.

[2] W. F. Brinkman, http://www.congressional.energy.gov/documents/Final_Testimony(8).pdf, April 22 2010, Congressional Testimony.

[3] A. Athanasiades, N. N. Shehad, C. S. Martin, L. Sun, and J. L. Lacy, "Straw detector for high rate, high resolution neutron imaging," in *IEEE Nuclear Science Symposium Conference Record*, vol. 2, Oct. 23-29 2005, pp. 623–627.

[4] J. L. Lacy, A. Athanasiades, N. N. Shehad, C. S. Martin, and L. Sun, "Performance of 1 meter straw detector for high rate neutron imaging," in *IEEE Nuclear Science Symposium Conference Record*, vol. 1, Oct. 29-Nov. 1 2006, pp. 20–26.

[5] J. L. Lacy, A. Athanasiades, C. S. Martin, L. Sun, and T. D. Lyons, "Fabrication and materials for a long range neutron-gamma monitor using straw detectors," in *IEEE Nuclear Science Symposium Conference Record*, 19-25 Oct. 2008, pp. 686–691.

[6] A. Athanasiades, N. N. Shehad, L. Sun, T. D. Lyons, C. S. Martin, L. Bu, and J. L. Lacy, "High sensitivity portable neutron detector for fissile materials detection," in *IEEE Nuclear Science Symposium Conference Record*, vol. 2, Oct. 23-29 2005, pp. 1009–1013.

[7] J. L. Lacy, A. Athanasiades, C. S. Martin, L. Sun, J. W. Anderson, and T. D. Lyons, "Long range neutron-gamma point source detection and imaging using unique rotating detector," in *IEEE Nuclear Science Symposium Conference Record*, vol. 1, Oct. 26 - Nov. 3 2007, pp. 185–191.

[8] J. L. Lacy, L. Sun, C. S. Martin, A. Athanasiades, and T. D. Lyons, "One meter square high rate neutron imaging panel based on boron straws," in *IEEE Nuclear Science Symposium Conference Record*, Oct. 24 - Nov. 1 2009, pp. 1117–1121.

[9] J. L. Lacy, A. Athanasiades, L. Sun, C. S. Martin, and G. J. Vazquez-Flores, "Boron coated straw detectors as a replacement for ^{3}He," in *IEEE Nuclear Science Symposium Conference Record*, Oct. 24 - Nov. 1 2009, pp. 119–125.

[10] D. C. Stromswold, J. H. Ely, R. T. Kouzes, and J. Schweppe, "Specifications for radiation portal monitor systems," Pacific Northwest National Laboratory, Richland, WA, Tech. Rep. PIET-43741-TM-017, 2003, revision 6.7.

[11] R. T. Kouzes, J. H. Ely, A. T. Lintereur, E. R. Siciliano, D. C. Stromswold, and M. L. Woodring, "^{3}He neutron detector pressure effect and comparison to models," Pacific Northwest National Laboratory, Richland, WA, Tech. Rep. PNNL-19110, 2010.

[12] R. T. Kouzes, J. H. Ely, and D. C. Stromswold, "Boron-lined straw-tube neutron detector test," Pacific Northwest National Laboratory, Richland, WA, Tech. Rep. PNNL-19600, 2010.

[13] R. T. Kouzes and J. H. Ely, "Status summary of ^{3}He and neutron detection alternatives for homeland security," Pacific Northwest National Laboratory, Richland, WA, Tech. Rep. PNNL-19360, 2010.

[14] M. S. Gordon, P. Goldhagen, K. P. Rodbell, T. H. Zabel, H. H. K. Tang, J. K. Clem, and P. Bailey, "Measurement of the flux and energy spectrum of cosmic-ray induced neutrons on the ground," *IEEE Trans. Nuc. Sci.*, vol. 51, no. 6, pp. 3427–34, 2004.