1 DESIGN AND PERFORMANCE OF A ^3He -FREE COINCIDENCE COUNTER BASED ON
2 PARALLEL PLATE BORON-LINED PROPORTIONAL TECHNOLOGY
3

4 D. Henzlova^{a,#}, H.O. Menlove^a, and J.B. Marlow^a
5

6 ^aLos Alamos National Laboratory, Los Alamos, NM 87545, USA
7

8 **ABSTRACT**

9 Thermal neutron counters utilized and developed for deployment as non-destructive assay
10 (NDA) instruments in the field of nuclear safeguards traditionally rely on ^3He -based proportional
11 counting systems. ^3He -based proportional counters have provided core NDA detection
12 capabilities for several decades and have proven to be extremely reliable with range of features
13 highly desirable for nuclear facility deployment. Facing the current depletion of ^3He gas supply
14 and the continuing uncertainty of options for future resupply, a search for detection technologies
15 that could provide feasible short-term alternative to ^3He gas was initiated worldwide. As part of
16 this effort, Los Alamos National Laboratory (LANL) designed and built a ^3He -free full scale
17 thermal neutron coincidence counter based on boron-lined proportional technology. The boron-
18 lined technology was selected in a comprehensive inter-comparison exercise based on its
19 favorable performance against safeguards specific parameters. This paper provides an overview
20 of the design and initial performance evaluation of the prototype High Level Neutron counter –
21 Boron (HLNB). The initial results suggest that current HLNB design is capable to provide ~80%
22 performance of a selected reference ^3He -based coincidence counter (High Level Neutron
23 Coincidence Counter, HLNCC). Similar samples are expected to be measurable in both systems,
24 however, slightly longer measurement times may be anticipated for large samples in HLNB. The

Corresponding author: henzlova@lanl.gov

initial evaluation helped to identify potential for further performance improvements via additional tailoring of boron-layer thickness.

Keywords: boron-lined proportional counter, ^3He replacement, coincidence counting

1. INTRODUCTION

In order to prevent proliferation and clandestine use of special nuclear material (SNM) located in nuclear facilities worldwide safeguards instruments are deployed and used by the International Atomic Energy Inspectorate (IAEA) for material accountancy and verification purposes. The key technique for non-destructive assay (NDA) of SNM relies on detection of correlated neutrons, where pairs or higher order neutron coincidences are detected to provide a direct signature of nuclear fissions within the item. In order to accurately quantify the amount of SNM, high neutron detection efficiency is required to allow for simultaneous detection of multiple neutron events. To accommodate this requirement, nuclear safeguards instruments that employ correlated detection of thermal neutrons traditionally utilize ^3He gas-filled proportional counters embedded in high density polyethylene (HDPE). Counters based on ^3He proportional technology are in routine use in nuclear fuel cycle facilities including fuel fabrication plants, bulk plutonium handling facilities, and storage sites worldwide. During the past decade, the production of ^3He gas significantly declined primarily due to reduction of nuclear weapons stockpile and was

46 anticipated to no longer support the projected demand [1,2]. The decreased supply and
47 continuing uncertainty of options for future resupply prompted worldwide intense R&D to
48 develop and evaluate detection technologies that could provide feasible alternative to ^3He gas in
49 the near future [3]. Several alternative detection technologies have been developed over the past
50 few years and became commercially available. The techniques include scintillation materials
51 with ^6Li or ^{10}B compounds [4-7], liquid scintillators for fast neutron detection [8,9], and variety
52 of designs of boron-lined proportional counters [10-12]. The latter belong among the most
53 extensively considered ^3He -free technologies for near-term application in the field of nuclear
54 safeguards due to the high thermal neutron reaction cross section of ^{10}B (3836 barns at thermal
55 neutron energy, 72% of ^3He value), reliability and stability associated with the use of well-
56 established proportional detection technology and compatibility with the existing electronics
57 infrastructure.

58 In order for any detection technology to be viable for routine use in nuclear safeguards, its
59 performance characteristics essential for SNM assay need to be evaluated and compared with a
60 suitable ^3He -based reference. Over decades of their deployment at nuclear facilities, the ^3He -
61 based counters demonstrated extraordinary performance characteristics desirable for routine use.
62 High efficiency, excellent long term stability, high mean-time-between-failure and thus low
63 maintenance requirements are among the key technology features. Similar characteristics pose
64 ambitious performance requirements on any ^3He -free detection technology. To provide a
65 consistent performance evaluation platform, Los Alamos National Laboratory (LANL)
66 developed an integrated test program for evaluation of ^3He -free technologies for nuclear
67 safeguards use [13]. The test program was formulated based on safeguards specific requirements
68 derived from decades of experience with ^3He -based neutron counters. Several commercially

available boron-lined proportional technologies in form of single detector modules were experimentally evaluated within this test program. In addition to this evaluation, for any technology to be deployable and satisfy challenging requirements of nuclear facilities, attributes specific to design and implementation of a full scale counter need to be considered. Comparison of these attributes with an equivalent ^3He -based system is essential in order to assess possible application space of a given technology. Such comparison includes not only the full counter performance, but also additional design features such as size, robustness and compatibility with existing data acquisition infrastructure.

The evaluation of single detector modules against safeguards parameters at LANL provided input for selection of the most viable boron-lined technology in the context of nuclear safeguards. The technology was then used to design and build a full scale prototype ^3He -free neutron coincidence counter to be evaluated in side-by-side comparison with an existing ^3He -based counter. For the purpose of direct comparison, the design features of the boron-based coincidence counter were derived from an existing ^3He -based High Level Neutron Coincidence Counter (HLNCC-II) [14] that represents a working standard in broad use within the nuclear safeguards field as well as in routine inspections performed by the IAEA. The design specifications and comparison with HLNCC is presented in this paper. The full scale boron-based counter provides a direct insight into the scalability of the selected ^3He -free detection technology into a typical safeguards system. In addition to experimental performance evaluation, the newly built counter serves as a test-system to evaluate aspects relevant for user experience, facility deployment and compatibility with electronics infrastructure.

2. PHYSICS DESIGN OF BORON-BASED SAFEGUARDS COUNTER

The boron-lined technology selected for the design and build of a full scale neutron coincidence counter (High Level Neutron counter – Boron, HLNB) is manufactured by Precision Data Technology, Inc. (PDT) and represents a rectangular detector module consisting of boron-lined parallel plate detection chambers. Single detector module is comprised of six narrow boron-lined detection chambers interleaved with HDPE plates. Additional HPDE layer surrounds the detector case for optimum neutron moderation. The interleaved design as well as large surface area coated with ^{10}B allows achieving sufficient thermal neutron detection efficiency for correlated counting purposes. The PDT detector technology was selected for a full scale coincidence counter build based on its performance in a comprehensive experimental evaluation against safeguards specific requirements [13,6]. Photograph of the PDT detector module is shown in Figure 1 (left) with a schematic cross section illustrating the internal structure (right).

{space for Figure 1}

To provide a viable alternative the full scale neutron coincidence counter needs to be designed to provide similar performance as a ^3He -based equivalent system, while preserving the compact design and satisfying application requirements. The compact design is necessary for operator accessibility and sample insertion. In addition, weight of the counter should be kept low to allow its portability or simple transportation. To satisfy this requirement, the design parameters of the

newly designed full scale boron-based coincidence counter were derived from a typical ^3He -based neutron coincidence counter. A High-Level Neutron Coincidence Counter (HLNCC-II) was selected for this purpose, since it represents nuclear safeguards standard fielded in numerous nuclear facilities and routinely used by the IAEA inspectorate. In the context of nuclear safeguards, the performance of a neutron coincidence counter is typically characterized by a figure-of-merit, FOM, defined as [3,15]:

$$\text{FOM} = \varepsilon/\sqrt{\tau} \quad (1)$$

Here ε denotes the neutron detection efficiency and τ represents the neutron die-away time. The neutron die-away time is one of the key system parameters in nuclear safeguards as it refers to neutron lifetime in the detection system before it gets detected, or absorbed, or leaks out of the system. Thermal neutron coincidence counters typically exhibit die-away times of 10-100 μs [16]. As can be seen from Eq. (1) shorter die-away time values are desirable to maximize the FOM. The FOM definition in Eq. (1) was adopted, since it corresponds to an inverse of measurement precision of the coincident neutron signal (doubles). Hence it provides a convenient measure of the desired system performance.

The selected ^3He -based reference system, HLNCC-II, is shown in Figure 3 (left). It consists of a single ring of 18 cylindrical ^3He proportional detectors with 1" (2.5 cm) diameter. The detectors are filled at 4 atm pressure and embedded in a cylindrical HDPE body for neutron moderation. The external dimension of the counter corresponds to 13.4" (34.0 cm) at height of 29.2" (74.2 cm) (including the junction box with signal processing electronics). The sample cavity dimensions correspond to 6.7" (17.0 cm) diameter and 16.0" (41.0 cm) height to accommodate range of sample sizes. The thermal neutron detection efficiency of this system corresponds to

17.5 % for a bare ^{252}Cf neutron source located in the center of the sample cavity. The neutron die-away time of the system corresponds to 43 μs , thus the FOM corresponds to 2.67.

Based on the above specifications, the design criteria of the boron-based neutron coincidence counter, HLNb, were defined with the following key requirements:

- identical size sample cavity as the HLNCC-II
- comparable total height to allow good user access
- counting rate capability as good as, or better than, the HLNCC-II
- FOM close to that of the HLNCC-II

To satisfy the design requirements, the HLNb counter is composed of six 24.0" (61.0 cm) long PDT detector modules that tightly surround the sample cavity of 6.7" (17.0 cm) diameter. In order to achieve this compact geometry, two of the six detector modules have narrower footprint of 7.0" x 5.0" (17.8 x 12.7 cm), while the other four detector modules have footprint of 8.0" x 5.0" (20.3 x 12.7 cm). Top view of the detector arrangement inside the HLNb is shown in Figure 2 (left).

{space for Figure 2}

The height of the HLNb sample cavity corresponds to 16.1" (41.0 cm). The sample cavity is defined by a thin aluminum plate attached to the bottom support plate. The top and bottom of the counter is covered by end-plugs to minimize neutron leakage from the system and maximize the

detection efficiency. The end-plugs consist of an aluminum core surrounded by high density polyethylene. The top end-plug is removable for sample insertion. The bottom end-plug can also be removed and the bottom support plate has a 5.0" (12.7 cm) diameter opening to allow for measurements of large samples that extend beyond the 16.1" (41.0 cm) tall sample cavity. To additionally improve the detection efficiency, 0.5" (1.3 cm) thick HDPE slabs were added along the external sides of the counter to help scatter neutrons back into the counter volume. The external HLNb counter shell consists of thin stainless steel sheets that cover the detection part of the detector pods. The stainless steel sheets are attached to four corner posts that provide structural support. The counter is equipped with swivel casters and hand rails for transportability. A schematic drawing with the overall external dimensions is shown in Figure 2 (right).

To provide a direct replacement for ^3He -based safeguards counter, the boron-based counter must be compatible with the existing data acquisition infrastructure. Multiplicity shift register [17] is currently the most extensively used data acquisition technique by the IAEA inspectorate. Therefore, a primary function of the HLNb is to provide a single logical output (TTL) compatible with the multiplicity shift register electronics. In addition, the counter is equipped with a list mode data acquisition capability enabling thus event-by-event recording. This feature was implemented in order to allow for state-of-health monitoring and enable more advanced and flexible data analysis. The list mode data collection also adds to the tamper resistance of the system. List mode data acquisition is performed using Pulse Train Recorder (PTR-32) [18] that records time differences between two subsequent neutron detection events with 10 ns resolution.

The signal processing electronics is housed in the junction box on top of each PDT detector module (Figure 2, left) and composes of three amplifier modules per detector pod. Each

amplifier module thus processes signals from a pair of boron-lined detection cells. The system has 18 amplifiers in total. The counter is equipped with an LED display for a direct state-of-health monitoring. Low voltage and high voltage signals are provided through standard BNC/SHV type connectors on the side of the HLNb top cover. The finished HLNb counter along with HLNCC-II is shown in Figure 3.

{space for Figure 3}

Overall the HLNb counter remains compact with similar height as HLNCC for convenient sample insertion. The footprint of HLNb is slightly larger than HLNCC due to the default depth of the individual PDT detector modules that corresponds to 5.0" (12.7 cm). The HLNb is mounted on heavy-duty swivel casters for transportability. Its weight corresponds to ~60 kg compared to ~40 kg of HLNCC, which still allows for system transportability using two side handrails. The individual detector modules are equipped with standard PDT electronics typically used in other safeguards systems, thus the provided signals are directly compatible with the existing electronics infrastructure. From the design point of view, the HLNb represents a direct alternative to HLNCC.

3. INITIAL PERFORMANCE EVALUATION OF HLNb AT LANL

Initial performance evaluation of the HLNb counter was performed at LANL using available ^{252}Cf neutron and ^{137}Cs gamma-ray sources as well as a range of small plutonium (Pu) samples. The experimental activities included evaluation of optimum high voltage (HV) setting, selection of HLNb operating parameters, determination of safeguards relevant parameters (die-away time, efficiency, figure-of-merit (FOM)) and performance evaluation with available low-mass Pu samples. The experimental results obtained with HLNb were reproduced and compared with parallel measurements in the HLNCC-II. The results of these measurements are summarized below.

3.1. Operating HV setting

To obtain operating HV setting for the newly built HLNb, the gains of the individual amplifier modules had to be matched to provide equivalent response. The matching of the individual signal processing amplifiers was performed using a 60 μCi ($\sim 2.5 \times 10^5$ n/s) ^{252}Cf source located in the center of the sample cavity. Following the gain matching procedure the operating HV was evaluated. For this purpose the total count rate dependence on HV setting (HV curve) was measured using neutron as well as gamma-ray sources as shown in Figure 4. As outlined in [13], operating HV selection must be performed in the presence of gamma-ray source of appropriate dose rate in order to account for gamma-ray discrimination threshold. Without such measurement, the extracted detection efficiency could be significantly overestimated.

Previous evaluations using high mass plutonium samples suggest the typical gamma-ray dose rate at the detector face of ~ 500 mR/hr [19]. Therefore a set of ^{137}Cs gamma-ray sources corresponding to a combined dose rate of ~ 450 mR/hr at the detector face was used to evaluate the correct operating HV setting. To quantify the importance of gamma-ray contribution, a

quantity known as GARRn (Gamma Absolute Rejection Ratio in the presence of neutrons) was utilized as defined in [20]. As described in [13], for a routine system operation in the presence of gamma-ray background, the gamma-ray contribution to the detected neutron signal should not exceed 0.3% (i.e. $GARRn \leq 1.003$). Based on this criterion, the operating HV setting was chosen to correspond to 880 V as indicated in Figure 4.

{space for Figure 4}

3.2. Selection of operating parameters

In order to operate the HLNb as a coincidence counter, several additional operating parameters must be determined. In the context of the passive neutron coincidence counting, the recorded neutron detection events are analyzed to extract total neutron count rate (singles, S) as well as pairs of correlated neutrons (doubles, D). The measured rate of doubles can be related to the plutonium content within an item via previously obtained calibration curve using well defined standards [16]. To extract the doubles rate from the stream of neutron detection events (also called pulse train) time-correlation techniques are employed that utilize multiplicities measured within fixed length gates applied on the pulse train [16,17]. The width of the gate is a fundamental property of the coincidence counter design and must be determined prior to routine operation. The optimum gate width is directly related to the concept of die-away time, since the optimum gate width needs to be long enough to capture the majority of the correlated events

from nuclear fission. In addition to gate width, another essential parameter utilized in neutron coincidence counting is pre-delay. The pre-delay is a short (1 - few μs) time interval that corresponds to the minimum time necessary for the detection system to return to quiescent conditions following a detection event to remove any dead-time and baseline shift effects.

For HLNb operation, the initial value of pre-delay was taken over from the parameters of HLNCC-II counter and set to 4.5 μs . Further optimization of this value by a dedicated measurement is possible. It can be anticipated that due to faster timing characteristics of the PDT detector modules [10], the optimum pre-delay should be shorter than 4.5 μs . Thus, the current selection of the pre-delay value will be conservative, however, should not affect the results presented in the following sections.

The operating gate width for HLNb was evaluated by measuring doubles rates corresponding to several different gate width settings and extracting corresponding relative standard deviation (RSD). The RSD plot as a function of gate width was then constructed to find the optimum gate width corresponding to the minimum RSD. Since the RSD plot exhibits a rather shallow minimum, the final gate width setting was further constrained using known parameters of HLNCC-II (die-away time of 43 μs and corresponding gate width of 64 μs). The HLNb operating gate width was selected to correspond to the same fraction of the system die-away time as in case of the HLNCC-II counter and corresponds to 112 μs .

3.3. Die-away time and detection efficiency

Using the HV, pre-delay and gate width settings determined in the previous sections, the die-away and efficiency measurements were performed. Both measurements were performed using ^{252}Cf neutron source located on a source rod in the center of the HLNb sample cavity. The results are summarized in Table 1.

{space for Table 1}

From Table 1 it can be seen that current HLNb design exceeds the detection efficiency of HLNCC-II by ~7%, however, the die-away time of HLNb is about a factor of 1.7 longer than in case of the HLNCC-II. As a consequence, the safeguards FOM of HLNb corresponds to 81% of the HLNCC-II performance. From the summary in Table 1, it can be concluded that the significantly longer die-away time of HLNb considerably penalizes its overall performance. Longer die-away time in coincidence system adversely affects the measurement precision of correlated rates (doubles), since it allows for larger portion of accidental correlated events to be counted within the longer gate window. This effect is typically more pronounced for samples with large neutron output and thus it can be anticipated that slightly longer measurements times will be needed with large samples in HLNb. However, for small plutonium sample measurements, the penalty diminishes as demonstrated in the following section. HLNb performance evaluation with large plutonium samples will be performed in a separate field test of the unit and will be reported separately.

Parallel Monte Carlo N-Particle Code (MCNP) simulations of the HLNB counter were performed to evaluate the influence of boron-layer thickness on the system die-away time and efficiency. The calculations indicated strong sensitivity of the die-away time to the boron-layer thickness, while the effect on the overall system efficiency remained fairly moderate. The MCNP results are summarized in Table 2. The results indicate a possibility to further improve HLNB performance via additional optimization of the boron-layer thickness. Alternative techniques for coating the boron lined plates could provide room for better boron-layer optimization and improved overall HLNB performance.

{space for Table 2}

3.4. Evaluation with plutonium samples

A range of low mass PuO_2 samples available at LANL was measured in the HLNB and HLNCC-II in parallel to compare their performance with realistic samples. Pu samples were positioned in the center of the sample cavity of each counter and measured for 1-2 hr. The characteristics of the Pu samples are summarized in Table 3.

{space for Table 3}

The measured doubles rates as a function of ^{240}Pu effective mass ($m_{240\text{Pu}} = 2.52 \cdot m_{238\text{Pu}} + m_{240\text{Pu}} + 1.68 \cdot m_{242\text{Pu}}$ [16]) for both counters are shown in Figure 5. The higher HLNb detection efficiency is reflected in the higher values of doubles rates compared to HLNCC-II, which is especially pronounced for the largest sample. The measurement precision is comparable for the smallest samples, however, for the largest sample the HLNCC-II precision is slightly better due to its shorter die-away time and thus shorter coincidence gate width. The error bars shown in the figure are smaller than the size of the symbols for both counters.

{space for Figure 5}

4. CONCLUSIONS

The design and initial performance evaluation of a prototype thermal neutron coincidence counter developed using boron-lined proportional technology was presented. The High Level Neutron counter – Boron (HLNB) represents a first system based on modern boron-based technology that was built to a full size safeguards counter to fully evaluate its performance, provide direct user experience with sample loading, data acquisition and analysis as well as compare its physical dimensions to an equivalent ^3He -based system. The design parameters of the HLNb were derived from an existing ^3He -based HLNCC counter and the finished system satisfied the core requirements aimed to maintain similar dimensions and sample cavity as

HLNCC as well as compatibility with the existing electronics infrastructure. The HLNb has slightly larger footprint and weight than HLNCC due to the larger size of individual PDT pods, however, still allows for transportability using swivel casters and a pair of handrails.

Initial performance evaluation of the HLNb coincidence counter using ^{252}Cf neutron sources demonstrated the significant potential of the technology. The thermal neutron detection efficiency of HLNb was shown to be ~7% higher than that of ^3He -based HLNCC. This advantage was, however, countered by a factor of 1.7 longer die-away time in case of HLNb. The FOM of the HLNb thus corresponds to 81% of an equivalent ^3He -based system performance. Evaluation using realistic small Pu samples illustrated that the overall performance of the two systems was essentially the same for the range of samples tested. However, for high rate counting (i.e. large mass samples), the HLNCC precision is expected to be slightly superior due to its shorter die-away time. Overall it is expected that current HLNb design will be capable to perform NDA of the same family of samples as HLNCC, however with slightly longer measurement times for large samples. The initial performance evaluation also revealed areas for potential future improvement with the main focus on optimization and better control of boron-layer deposition. Further optimization of boron-layer thickness is expected to reduce the die-away time of HLNb without significantly compromising the neutron detection efficiency.

Further field evaluation of HLNb side-by-side with HLNCC using broader range of Pu samples including large (hundreds of grams-kilograms) samples not available at LANL is being pursued in order to fully assess the target HLNb design criteria. Field trial will also provide essential input on deployment related questions, including shipment and transportation, as well as

performance under non-laboratory conditions (different environmental conditions, potential external sources of noise etc.). Based on the performance characteristics of HLNb presented in this paper (efficiency, die-away time, FOM) it can be anticipated that the system will be capable to perform measurements over a full sample range corresponding to its design basis as a replacement to HLNCC (i.e. broad range of Pu bearing materials up to and including several kg samples). Nevertheless, its longer die-away time will be reflected in the measurement precision and longer measurement times (of the order of 1.5 times longer) might be needed.

5. ACKNOWLEDGEMENTS

This work was funded by the U.S. Department of Energy, National Nuclear Security Administration, through the Office of Nuclear Nonproliferation and International Security's Next Generation Safeguards Initiative (NGSI).

REFERENCES

[1] R. T. Kouzes, "*The ^3He Supply Problem*", Pacific Northwest National Laboratory Report, PNNL-18388 (2009)

366 [2] D. A. Shea, D. Morgan, “*The Helium-3 Shortage: Supply, Demand, and Options for*
367 *Congress*”, Congressional Research Service Report for Congress R41419 (2010).

368 [3] M. M. Pickrell, A. Laviates, V. Gavron, D. Henzlova, H. Menlove, M. J. Joyce, R. T.
369 Kouzes, “*The IAEA Workshop on Requirements and Potential Technologies for Replacement of*
370 *^3He Detectors in IAEA Safeguards Applications*”, Journal of Nuclear Materials Management,
371 Volume XLI, No. 2 (Winter 2013)

372 [13] H. Nakamura, A. Ohzu, N. Kobayashi, Y. Mukai, K. Sakasai, T. Nakamura, K. Soyama,
373 M. Kureta, T. Kurita, M. Seya, “*Development and Demonstration of a Pu NDA System using*
374 *$\text{ZnS}/^{10}\text{B}_2\text{O}_3$ Ceramic Scintillator Detectors*”, proceedings of 55th INMM Annual Meeting (2014).
375

376 [5] S. Stave, M. Bliss, R. Kouzes, A. Lintereur, S. Robinson, E. Siciliano, and L. Wood,
377 “*LiF/ZnS Neutron Multiplicity Counter*”, to be published in Nuclear Instruments and Methods A,
378 [doi:10.1016/j.nima.2015.01.039](https://doi.org/10.1016/j.nima.2015.01.039) (2015).

379 [6] M. Dallimore, C. Giles, D. Ramsden and G. S. Dermody, “*The Development of a Scalable*
380 *He-3 Free Neutron Detection Technology and its Potential Use in Nuclear Security and Physical*
381 *Protection Applications*”, proceedings of 52nd INMM Annual Meeting (2011).
382

383 [7] K. D. Ianakiev, M. P. Hehlen, M. T. Swinhoe, A. Favalli, M. Illiev, T. C. Lin, M. T. Barker,
384 B. L. Bennett, “*Neutron Detector Based on Particles of ^6Li Glass Scintillator Dispersed in*
385 *Organic Lightguide Matrix*”, to be published in Nuclear Instruments and Methods A
386 [doi:10.1016/j.nima.2014.10.073](https://doi.org/10.1016/j.nima.2014.10.073) (2015).

- [8] A. D. Lavietes, R. Plenteda, N. Mascarenhas, L. M. Cronholm, M. Aspinall, M. Joyce, A. Tomanin, and P. Peerani. “*Liquid scintillator-based neutron detector development*” In Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), 2012 IEEE, 230-244.
- [9] J.L. Dolan, M. Flaska, A. Poitrasson-Riviere, A. Enqvist, P. Peerani, D.L. Chichester, S.A. Pozzi, “*Plutonium measurements with a fast-neutron multiplicity counter for nuclear safeguards applications,*” Nuclear Instruments and Methods in Physics Research Section A 763, pp. 565-574 (2014).
- [10] D. Henzlova, L. G. Evans, H. O. Menlove, M. T. Swinhoe, J. B. Marlow, “*Experimental Evaluation of a Boron-lined Parallel Plate Proportional Counter for Use in Nuclear Safeguards Coincidence Counting*”, Nuclear Instruments and Methods in Physics Research A 697 pp. 114-121 (2013).
- [11] J. L. Lacy, A. Athanasiades, L. Sun, C. S. Martin, T. D. Lyons, M. A. Foss, H. B. Haygood, “*Boron-coated straws as a replacement for ^3He -based neutron detectors*”, Nuclear Instruments and Methods in Physics Research A 652 pp. 359-363 (2011).
- [12] R. T. Kouzes, J. H. Ely, A. T. Lintereur, E. R. Siciliano, “Boron-10 ABUNCL Active Testing”, Pacific Northwest National Laboratory report PNNL-22567 (2013).
- [13] D. Henzlova, L.G. Evans, H.O. Menlove, M.T. Swinhoe, V. Henzl, C. Rael, I. Martinez and J.B. Marlow, “*Results of the Evaluation and Comparison of Alternative Neutron Detectors for Potential ^3He Replacement for Nuclear Safeguards Applications*”, Los Alamos National Laboratory Report LA-UR 12-00837

410 [14] H. O. Menlove, J. E. Swansen, “A *high-performance neutron time correlation counter*”,
411 Nuclear Technology 71, 497, 1985

412 [15] L. G. Evans, D. Henzlova, H. O. Menlove, M. T. Swinhoe, S. Croft, J. B. Marlow, R.D.
413 McElroy, “*Nuclear Safeguards ³He Replacement Requirements*”, Journal of Nuclear Materials
414 Management (JNMM), Spring 2012, Volume XL, Number 3

415 [16] D. Reilly, N. Ensslin, and H. Smith, Jr., “*Passive Nondestructive Assay of Nuclear*
416 *Materials*”, Los Alamos National Laboratory Technical Report LA-UR-90-732 (1991)

417 [17] N. Ensslin, W. C. Harker, M. S. Krick, D. G. Langner, M. M. Pickrell, J. E. Stewart,
418 “*Application Guide to Neutron Multiplicity Counting*”, Los Alamos National Laboratory Manual
419 LA-13422-M (1998)

420 [18] http://www.iki.kfki.hu/radsec/groups/ptr_en.shtml

421 [19] H. O. Menlove, R. J. Dickinson, I. Douglas, C. Orr, F. J. G. Rogers, G. Wells, R. Schenkel,
422 G. Smith, A. Fattah, A. Ramalho, “*Field Test and Calibration of Neutron Coincidence Counters*
423 *for High-Mass Plutonium Samples*”, Los Alamos National Laboratory Report LA-10815-MS
424 (1987)

425 [20] R.T. Kouzes, J.R. Ely, A.T. Lintereur, D.L. Stephens, “*Neutron Detector Gamma*
426 *Insensitivity Criteria*” Pacific Northwest National Laboratory Report, PNNL 18903 (2009)

427

428

429

List of Figures:

Figure 1. Single PDT detector module (left), schematic cross section of the PDT module (right).

Figure 2: Top view of the PDT detectors inside the HLNb counter (left). Schematic drawing of the HLNb (right).

Figure 3: Photograph of the completed boron-based coincidence counter HLNb (right) next to the standard HLNCC-II (left).

Figure 4: HV curves for ^{252}Cf neutron source (full triangles) and set of ^{137}Cs gamma-ray sources (open triangles) with optimum HV setting highlighted by a red dashed line.

Figure 5: Doubles rates measured for a range of low mass PuO_2 samples in HLNb (red symbols) and HLNCC-II (black symbols).

List of Tables:

Table 1: Efficiency and die-away time measured for HLNb counter at 880 V operating voltage.

Measurements are compared to HLNCC-II.

Table 2: MCNP study of the influence of boron-layer thickness on the HLNb response.

Table 3: Overview of PuO₂ samples measured in HLNb and HLNCC-II (declaration date: 08/16/2008).

476 Table 1:

counter	HV [V]	ε [%]	τ [μ s]	FOM
HLNB	880	18.8	75	2.17
HLNCC-II	1680	17.5	43	2.67

477

478

479

480

481

482

483

484

485

486

487

488

489

490

491

492

493

494

495

496

497 Table 2:

	counting efficiency ^{252}Cf [%]	die-away [μs]
MCNPX - (thicker ^{10}B)	18.1	54.4
MCNPX - (thinner ^{10}B)	18.7	99.0

498

499

500

501

502

503

504

505

506

507

508

509

510

511

512

513

514

515

516

517 Table 3:

Sample ID	mass [g]	²³⁸ Pu	²³⁹ Pu	²⁴⁰ Pu	²⁴¹ Pu	²⁴² Pu	²⁴¹ Am	²⁴⁰ Pu _{eff} mass [g]
CBNM Pu93	5.82	0.0098	93.5614	6.3124	0.0768	0.0396	0.2455	0.37
FZC158	0.69	0.0128	0.9622	94.2590	0.1681	4.5979	0.5223	0.71
CBNM Pu70	5.56	0.7381	76.1791	18.9758	1.9475	2.1595	4.8304	1.35
STD11	59.75	0.0233	92.6925	6.6165	0.0852	0.5825	0.3286	4.70

518

Figure

Figure

Figure
[Click here to download high resolution image](#)

Figure

Figure