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Current Status of ^{3}He Alternative Technologies for Nuclear Safeguards

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and

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Current Status of ^{3}He Alternative Technologies for Nuclear Safeguards

ABSTRACT – International safeguards inspectorates (e.g., International Atomic Energy Agency {IAEA}, or Euratom) rely heavily on neutron assay techniques, and in particular, on coincidence counters for the verification of declared nuclear materials under safeguards and for monitoring purposes. While ^{3}He was readily available, the reliability, safety, ease of use, gamma-ray insensitivity, and high intrinsic thermal neutron detection efficiency of ^{3}He-based detectors obviated the need for alternative detector technologies. However, the recent decline of the ^{3}He gas supply has triggered international efforts to develop and field neutron detectors that make use of alternative materials. In response to this global effort, the U.S. Department of Energy's (DOE) National Nuclear Security Administration (NNSA) and Euratom launched a joint effort aimed at bringing together international experts, technology users and developers in the field of nuclear safeguards to discuss and evaluate the proposed ^{3}He alternative materials and technologies. The effort involved a series of two workshops focused on detailed overviews and viability assessments of various ^{3}He alternative technologies for use in nuclear safeguards applications. The key objective was to provide a platform for collaborative discussions and technical presentations organized in a compact, workshop-like format to stimulate interactions among the participants. The meetings culminated in a benchmark exercise providing a unique opportunity for the first inter-comparison of several available alternative technologies. This report provides an overview of the alternative technology efforts presented during the two workshops along with a summary of the benchmarking activities and results. The workshop recommendations and key consensus observations are discussed in the report, and used to outline a proposed path forward and future needs foreseeable in the area of ^{3}He-alternative technologies.

CONTENTS

1. List of Acronyms

ABUNCL……………....	Alternative Boron-based Uranium Neutron Coincidence Collar
AMSR……………….	Advanced Multiplicity Shift Register
ANN………………..	Ansaldo Nucleare
ANSI………………..	American National Standards Institute
ASAS………………..	Alternative Sample Assay System
BCS………………….	Boron Coated Straws
BWR………………...	Boiling Water Reactor
CANDU……………..	Canada Deuterium Uranium
cps…………………..	counts per second
DA…………………..	Destructive Analysis
DOE…………………	Department of Energy
ENMC……………….	Epithermal Neutron Coincidence Counter
FNMC……………….	Fast Neutron Multiplicity Counter
FOM…………………	Figure-of-Merit
FPGA………………..	Field Programmable Gate Array
GERS………………..	General Electric Reuter Stokes
HDPE………………..	High Density Polyethylene
HLNB………………..	High Level Neutron counter - Boron
HLNCC……………...	High Level Neutron Coincidence Counter
IAEA………………...	International Atomic Energy Agency
IEC………………..	International Electrotechnical Commission
INCC………………..	International Neutron Coincidence Counting software
INFN………………...	National Institute for Nuclear Physics
INVS………………...	Inventory Sample Verification System
ITV ………………….	International Target Values
JAEA………………..	Japan Atomic Energy Agency
JRC………………….	Joint Research Centre
JSR………………….	Canberra Multiplicity Shift Register
LANL……………….	Los Alamos National Laboratory
LED…………………	Light Emitting Diode
LEU…………………	Low Enriched Uranium
MCNP……………….	Monte Carlo N-Particle Code
MOX………………...	Mixed Oxide
NDA………………...	Non-Destructive Analysis
NNSA……………….	National Nuclear Security Administration
PDT…………………	Precision Data Technology
PERLA……………...	Performance Laboratory for Safeguards
PLiNS……………….	PNNL Lithium-based Neutron Scintillator
PMT…………………	Photomultiplier Tube
PNNL……………….	Pacific Northwest National Laboratory
PSD………………….	Pulse Shape Discrimination
PTI…………………..	Proportional Technologies, Inc.
PTR…………………..	Pulse Train Recorder
PVT………………….	Polyvinyl toluene
PWR…………………	Pressurized Water Reactor
RPM………………..	Radiation Portal Monitor
SiPM………………..	Silicon Photomultiplier
SNM………………...	Special Nuclear Material

UM………………….. University of Michigan
UNCL………………. Uranium Neutron Collar
WSP……………….... Wavelength Shifting Plastic

2. Introduction

Neutron detectors have been the major consumers of ^{3}He for the last few decades, particularly for neutron scattering science [Cooper 2004] and homeland security [Kouzes et al. 2008] applications, with safeguards being traditionally a relatively small consumer. Other applications include research detectors, commercial instruments, well logging detectors, dilution refrigerators, lung imaging, targets in nuclear research, and for basic research in condensed matter physics. The supply of ^{3}He has come under strict control since 2008, when it was realized that the supply was limited, largely due to mitigation of the gas consumption in homeland security applications. Nevertheless, this noble gas still plays a central role for nuclear safeguards applications.

The current world supply of ^{3}He comes entirely from the decay of tritium originating in the nuclear weapons programs in the U.S. and Russia [Kouzes 2009]. In the United States, ^{3}He is collected as a byproduct from the radioactive decay of tritium, where it is separated during the tritium processing conducted at the NNSA Savannah River Site in South Carolina. The U.S. DOE Isotope Program currently administers the policies for the allocation of the ^{3}He, which provides a limited supply for government use and a small allocation for public sale.

The U.S. inventory of ^{3}He (~260 kL in 2003) is slowly being depleted. For a worst-case hypothetical scenario for the U.S. ^{3}He supply that assumes a 4 kL/y public auction and 10 kL/y federal use, the supply would be depleted by about the year 2024. Under an optimistic scenario where there is no auction and only the actual U.S. government demand is provided, the supply lasts past the year 2040. There is thus a great uncertainty about how long the supply will actually last [Gillo 2014]. Any new supplies of ^{3}He, such as Canada Deuterium Uranium (CANDU) reactors or cryogenic separation from natural gas or CO_2 wells, is currently being left to private industry to develop.

As a result of this shortage, neutron detection alternatives have undergone active research and development around the world. Detection alternatives for homeland security and neutron scattering science have been under rapid development since 2008, and some of these alternatives have been considered for the needs of nuclear safeguards.

The important characteristics of any neutron detection system include: neutron detection efficiency, gamma-neutron separation, commercial availability, and robustness for deployment. It is very difficult to meet the performance capability of ^{3}He for neutron detection, and there are no existing replacements that combine all the capabilities of ^{3}He [GAO 2011]. However, a variety of ^{3}He alternative technologies are available to meet different thermal and fast neutron detection needs, including:

- BF_3 filled proportional counters
- Boron-lined proportional counters
- Glass fibers loaded with ^{6}Li
- Light guides with ZnS scintillator and ^{6}LiF
- Crystalline neutron detectors, such as CLYC ($Cs_2LiLaBr_6$:Ce)
- Scintillators doped with neutron capture materials
- Gamma-ray detectors surrounded by neutron capture material
- Semiconductor detectors with imbedded neutron capture materials
- Fission chambers
- Liquid scintillators for fast neutron detection
- Plastic scintillator for fast neutron detection
- High-pressure ^{4}He filled detectors for fast neutron detection
- Bubble detectors for fast neutron detection

The need for replacement of ^{3}He for homeland security applications, especially for radiation portal monitors, which have historically been a major user of ^{3}He, has led to several commercial alternative technology solutions, thus nearly eliminating the demand for ^{3}He gas in this area. The other large user of ^{3}He, the neutron scattering science community, has actively pursued research and development of alternatives, and several solutions are near fruition. These same solutions are also being applied to other areas of ^{3}He application.

Nevertheless, neutron measurements for safeguards applications have requirements that are unique to the quantitative assay of special nuclear materials (SNM) [Evans 2012]. Safeguards neutron detection systems include neutron coincidence and multiplicity counters, which measure correlated neutron distributions from spontaneous fission and/or induced fission events. High efficiency systems are thus required to allow for sufficient precision in the measured correlated count rates. In addition, several aspects essential for SNM assay need to be addressed in safeguards applications; including die-away time (i.e., neutron life-time in the detection system), in-plant stability (long term as well as environmental), overall system reliability and reproducibility of the assay results along with scalability for the production of commercial systems.

Due to the stringent safeguards requirements, a single technology is unlikely to solve the safeguards need; rather, some combination of technologies will be required. End users will include the IAEA, Euratom, Japan, and other governments. Safeguards instrumentation as a group uses less ^{3}He than several other applications (~1000 L/y). Existing instruments largely provide for current ^{3}He needs and demand for new instruments is predominantly driven by new, future facilities with the result that there is time, perhaps ten years or more, for development of alternatives. However, this does not mean that development work should not proceed now; it takes many years for new instruments to be developed, tested, commercialized and accepted by the community of users. This will be especially true of alternative technologies where such requirements as long-term stability have not yet been demonstrated.

To address this issue, DOE/NNSA and Euratom organized a series of two workshops on *He-3 Alternatives for International Safeguards*. The first of the workshops was held at Los Alamos National Laboratory (LANL) in June 2013 [Dolan et al. 2013] and was mainly focused on a review of international efforts to date on ^{3}He-alternative materials and technologies. The second and final workshop was organized at the European Commission’s Joint Research Center (JRC) at Ispra, Italy, in October 2014. The second workshop served as a direct follow-up to the 2013 workshop with the aim to provide a comprehensive technology summary, identify capability gaps and discuss implementation strategies to advance the prototype technologies to commercially deployable systems.

The purpose of the workshops was to gather world experts on technologies that can replace the use of ^{3}He for safeguards instrumentation. Participants in the two workshops included representatives from the IAEA, Japan Atomic Energy Agency (JAEA), European Commission’s JRC, U.S. universities, U.S. government, U.S. and European companies, and U.S. and European national laboratories. The final workshop included a benchmarking exercise held in the Performance Laboratory for Safeguards (PERLA) at JRC Ispra of various safeguards instruments with similar Technology Readiness Levels, particularly systems that are deployable in the near term, against reference ^{3}He-based systems. Participants performed testing with various gamma-ray and neutron sources, including SNM.

This report discusses the presented technologies, key results and recommendations from the series of workshops. Section 2 provides an overview of the various alternative technology development efforts for nuclear safeguards. These technologies are organized by proportional counter based approaches, scintillator based approaches, and solid-state approaches. Section 3 summarizes results from the benchmarking measurements at JRC Ispra. The technologies tested during the benchmarking exercise included boron-lined tubes (GE Reuter-Stokes), boron straw tubes (Proportional Technologies Inc.), parallel plate boron proportional counters (Precision Data Technology), LiF/ZnS on light guides (Symetrica), Stilbene scintillators (University of Michigan), and liquid scintillators (International Atomic Energy Agency). Sections 4 and 5 provide recommendations coming out of the presentations and discussions along with future work that should be performed in the area of ^{3}He-alternative technologies for safeguards applications and finally section 6 discusses the lead conclusions.

3. ^{3}He-alternative Technology Efforts

The workshops included presentations on, and measurements by, a number of alternative neutron detection technologies for safeguards. These included boron-based and lithium-based thermal neutron detectors (proportional counters as well as scintillators), solid state detectors, liquid scintillators and high-pressure helium fast neutron detectors. The following sections summarize the various technologies that were discussed at the two workshops that provide capabilities relevant for nuclear safeguards applications. For the purpose of this overview, the individual detectors will be grouped into broader categories based on their operating principle (i.e. proportional counter based, scintillator based, or semiconductor based).

As mentioned earlier, ^{3}He-alternative technologies have been under development for a range of ^{3}He-dependent applications providing a broad technology resource base for potential safeguards use. The first workshop provided a venue for a detailed overview of technologies developed or under development that offered capabilities relevant for challenging safeguards applications. By the time of the second workshop, several of the proposed alternative technologies had advanced from single module prototypes to full-scale prototype systems. The prototype systems were typically designed to replace specific reference ^{3}He-based counters in use within the safeguards community. For completeness and referencing purposes, the key features of the individual ^{3}He-based counters that were selected as reference systems will be summarized in the following section. For further reading regarding the individual ^{3}He-based counters references will be included in this section.

3.1. Reference ^{3}He-based Neutron Counting Systems

3.1.1. High Level Neutron Coincidence Counter (HLNCC-II)

The High Level Neutron Coincidence Counter (HLNCC-II), based on ^{3}He, was selected by the majority of technology developers, since it represents a working nuclear safeguards standard fielded in numerous nuclear facilities and is routinely used by the IAEA inspectorate. It was developed for passive neutron coincidence counting of high-mass plutonium samples and consists of a single ring of 18 cylindrical ^{3}He proportional detectors with 2.5 cm diameter. The detectors are filled at 4 atm pressure and embedded in a cylindrical high-density polyethylene (HDPE) body for neutron moderation. The external dimension of the counter corresponds to 34 cm at height of 68.2 cm (including the junction box with signal processing electronics). The sample cavity dimensions correspond to 17 cm diameter and 41 cm height to accommodate a range of sample sizes. The sample cavity is enclosed by top and bottom end plugs made of HDPE with aluminum core. There is a cadmium liner in the sample cavity to prevent thermal neutrons from reflecting back into the sample and inducing additional fission reactions.

The system is equipped with six A-111 amplifiers to process the detector signals. The thermal neutron detection efficiency (ε) 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 (τ) of the system corresponds to 43 μs, thus the Figure of Merit (FOM), defined as $\varepsilon/\sqrt{\tau}$, corresponds to 2.67. A photograph and schematic drawing of the system are shown in Figure 3.1. More details on the HLNCC-II specifications and performance can be found in [Menlove 1985].

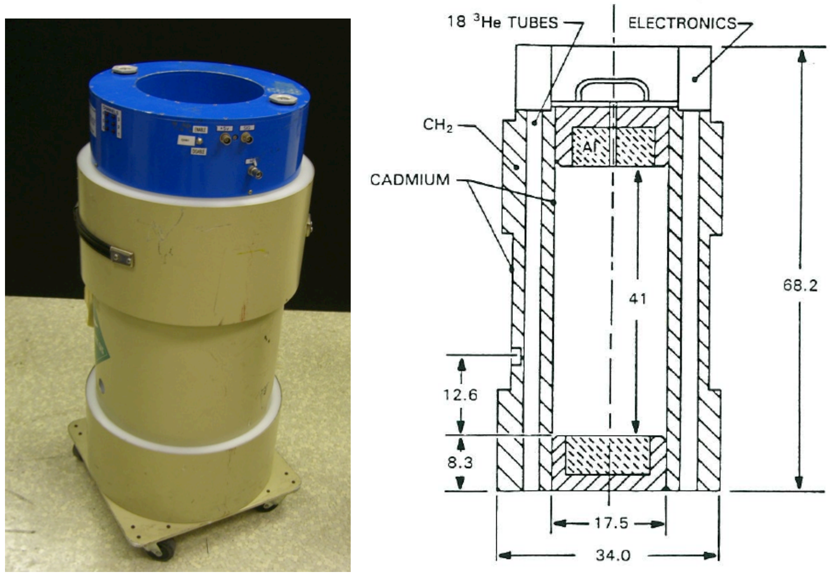


Figure 3.1. Photograph of HLNCC-II (left); schematic drawing in HLNCC-II (right). Dimensions are in centimeters.

3.1.2. Inventory Sample Verification System (INVS)

The Inventory Sample Verification System (INVS) was originally developed to quantify the Pu amount in a sample vial. The measurement target includes pellets, Pu solution and mixed oxide (MOX) powder in a sample vial that typically contains a few grams of Pu. The INVS is normally used for the inventory verification instead of destructive analysis (DA). While several days are needed to obtain Pu mass in the measured item using DA, the ^{3}He-based INVS system can determine Pu mass in the item quickly and obtains the result of inspection in a timely fashion (typically less than an hour). The ^{3}He-based INVS counter has two rings of 16 or 18 ^{3}He tubes filled at 6 atm, surrounding a small sample chamber (5.5 cm diameter, 15.7 cm height). The efficiency of the two designs corresponds to 31% and 42% with die-away time of 45 µs. The FOM, defined as $\varepsilon/\sqrt{\tau}$, thus corresponds to 4.6 and 6.3, respectively. A schematic cross section of the design with 16 ^{3}He tubes is shown in Figure 3.2. More details on the INVS specifications and performance can be found in [Miller 1991].

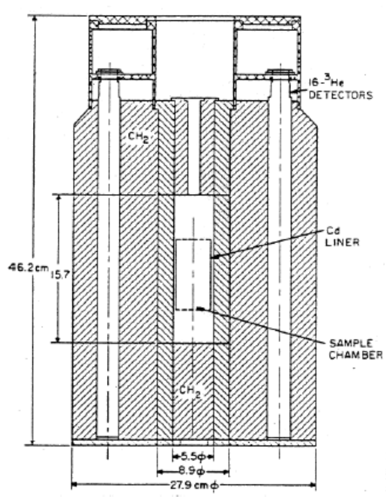


Figure 3.2. Schematic drawing of INVS counter.

3.1.3. Epithermal Neutron Multiplicity Counter (ENMC)

The Epithermal Neutron Multiplicity Counter (ENMC) is a high efficiency neutron multiplicity counter designed to measure thermal and epithermal neutrons from impure MOX and plutonium samples. The ENMC contains 121 tubes ^{3}He-filled at 10 atm pressure. The tubes are arranged in four rings surrounding a central well, which is 40 cm deep with 19 cm in diameter. The inner volume of the ENMC is covered by a cadmium (Cd) liner to prevent rescattering of thermal neutrons back into the counter volume, which would cause induced fissions in the sample. In addition, the Cd liner helps to keep the die-away time low. A 1 cm thick iron sleeve surrounds the central counting volume to reduce the intensity of γ-rays entering the detection volume. The ENMC has a uniform counting volume over 30 cm of sample height.

The ^{3}He tubes are attached to a junction box, which houses a high voltage distribution plane and 27 A-111 amplifier boards. Each amplifier processes signals from 3 to 7 tubes with the number of tubes per amplifier increasing toward the outer rings of the ENMC. This arrangement was implemented to minimize the system deadtime and to improve the uniformity of the ENMC response. The detection efficiency of this system corresponds to 65% 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 21.8 μs, thus the FOM, defined as $\varepsilon/\sqrt{\tau}$, corresponds to 13.9. A photograph and schematic drawing of the system are shown in Figure 3.3. More details on the ENMC specifications and performance can be found in [Menlove 2004].

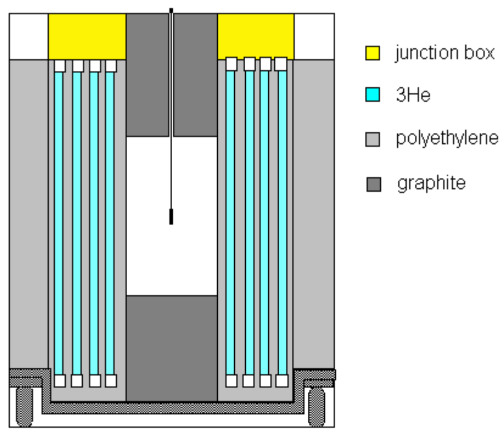


Figure 3.3. The ENMC counter with junction box and LED state of health display on top (left), cross section of ENMC counter with source on a source rod located in the middle of the sample cavity (right).

3.1.4. Uranium Neutron Collar (UNCL)

Neutron collars are used to verify the uranium content in light water reactor fuel assemblies and are used for routine inspection activities by both the IAEA as well as Euratom. Neutron collars include designs to accommodate boiling water reactor (BWR) as well as pressurized water reactor (PWR) assemblies and are composed of 4 detector banks made of HDPE containing a row of ^{3}He proportional counters. Neutron collars can operate in active (with an external AmLi neutron source) as well as passive modes. An AmLi neutron source is used to actively interrogate the fuel assembly to measure the ^{235}U content and the ^{238}U content is verified from a passive neutron coincidence measurement. Three detector banks are used for the active mode along with a dedicated HDPE source door for placement of the neutron source. For the passive mode, all four segments of the collar are used. In addition, neutron collars can operate in "fast" and "thermal" modes. In fast mode, a thin Cd liner is used inside the detector cavity to exclude thermal neutrons from the assembly. In this case, the measurement results are not very sensitive to the presence of neutron poison loaded pins.

The first generation of UNCL (UNCL-I) counters allowed for adjustment of the body size to accommodate different size PWR and BWR assemblies. The improved second generation (UNCL-II), developed to allow for shorter measurement times and implement improved electronics, has a fixed body size so two separate detector heads were designed for PWR and BWR assemblies, respectively. The summary of the individual configurations is provided in Table 3.1. Note that the die-away time is approximate and will be affected by the fuel assembly type and enrichment. The values provided are representative assuming the same fuel assembly as all the UNCL configurations and using 4-atm. ^{3}He tubes in similar thickness HDPE. Schematic cross section of the different configurations is shown in Figure 3.4. More details on the UNCL specifications and performance can be found in [Menlove 1990].

Table 3.1. Overview of the different UNCL configurations with the corresponding efficiency and die-away times.

Counter	Mode	Fuel type	Configuration	ε [%]	τ [µs]	FOM
UNCL-I	active	BWR	18 ^{3}He tubes, 3 banks	13.5*	~59	-
UNCL-I	active	PWR	18 ^{3}He tubes, 3 banks	10.3*	~59	-
UNCL-I	passive	BWR	24 ^{3}He tubes, 4 banks	~16	~59	-
UNCL-I	passive	PWR	24 ^{3}He tubes, 4 banks	~13.7	~59	1.6
UNCL-II	active	BWR	16 ^{3}He tubes, 3 banks	15.4*	~59	2.0
UNCL-II	active	PWR	20 ^{3}He tubes, 3 banks	12.6*	~59	-

* [Menlove 1990] using ^{252}Cf centered in sample chamber

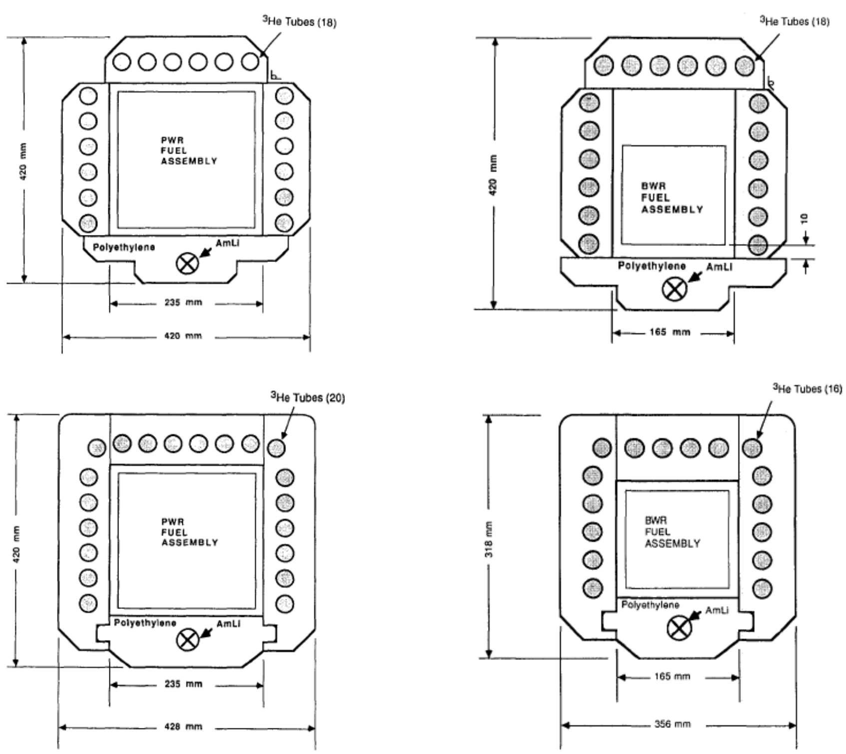


Figure 3.4. First generation (top) and second generation (bottom) configurations of the UNCL for the PWR (left) and BWR (right) assemblies.

3.2. Proportional Counter Based Technologies

The technologies presented in this section represent a concept similar to ^{3}He-gas filled proportional counters with the detection medium replaced by ^{10}B enriched deposit on the counter walls or BF_3 gas fill. Several technologies based on this concept were developed ranging from thin (few mm diameter) tubes (i.e., straws) through regular 1.3-2.5 cm diameter tubes similar to ^{3}He counters to systems utilizing parallel-plates. The concept is based on the same technology as standard ^{3}He filled counters and, as such, represents a mature approach, which makes these technologies very attractive alternatives. The key challenge for these technologies lies in the lower thermal neutron capture cross section of ^{10}B compared to ^{3}He (3836 b at thermal neutron energy, 72% of the ^{3}He value) that requires design features involving large boron surface area, while trying to maintain a compact footprint typical for ^{3}He-based technologies. The latter is required for the ease of access and sample insertion and to satisfy facility weight and size constraints [Evans 2012]. To achieve this design goal, the proposed boron-lined proportional counter based technologies often employ smaller diameter tubes and/or narrow plates. Nevertheless, some effect on the footprint may be expected as will be apparent from the following sections. Due to the similarity of this concept to ^{3}He-based detectors, the boron-based proportional counter technologies have largely reached a phase of full-scale prototype system implementation. The key features and performance of these full systems, along with description of the core technologies on which the systems are based, is provided in the following sections.

3.2.1. Alternative Boron-based Uranium Neutron Coincidence Collar (ABUNCL)

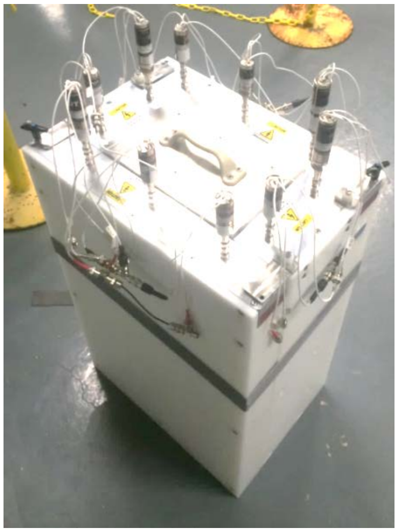
The General Electric Reuter-Stokes (GERS) passive neutron coincidence counting (GERS-NCC) system was adapted from the GERS ABUNCL [Kouzes 2012] neutron coincidence collar for use in the evaluation of traditional ^{10}B-lined proportional tubes in quantitative safeguards neutron assay systems. These tubes have a thin boron coating on the inside of cylinder and contain ~1 atm of argon gas (plus quench gas). The ABUNCL was developed and fabricated by GERS as a demonstration unit and possible alternative to the traditional ^{3}He-based uranium neutron coincidence collar (UNCL) [Menlove 1981] and has been evaluated at both Pacific Northwest National Laboratory (PNNL) and LANL. The observed measurement performance parameters (Table 3.2) for the ABUNCL were somewhat poorer in comparison to the ^{3}He-based neutron collar in use today by the IAEA but are sufficient to achieve the required performance specified by the International Target Values (ITVs) [Zhao 2010] with increased measurement times (~50% longer). The impact on measurement throughput needs to be considered.

Table 3.2. Observed measurement performance (with a ^{252}Cf fission source) for the ABUNCL and the standard ^{3}He-based neutron coincidence collar system

	^{3}He Proportional Tube Neutron Collar (JCC-71)		**^{10}B-Lined Proportional Tube Neutron Collar (ABUNCL)**	
	Passive	Active	Passive [Kouzes 2012b]	Active [Kouzes 2013]
Efficiency	11.3%	9.0%	11.6%	9.4%
Die-Away	52 μs	52 μs	75 μs	83 μs
Figure-of-Merit (FOM) ($\varepsilon/\sqrt{\tau}$)	1.57	1.25	1.34	1.03
Weight	38 kg		~100 kg	
Dimensions	42 × 42 × 52 cm (L × W × H)		36 × 51 × 80 cm (L × W × H)	

Note: The ^{3}He counter performances are with cadmium liners installed, while no liners are present in the ABUNCL.

To examine the potential performance of the GERS ^{10}B-lined proportional tube for use in other safeguards neutron coincidence counting systems, Cd liners and HDPE end plugs were fitted to the ABUNCL (Figure 3.5). Although, the configuration was not optimal (e.g., rectangular rather than cylindrical), the general arrangement was similar in most important respects to that of a typical neutron coincidence well counter such as the HLNCC-II.



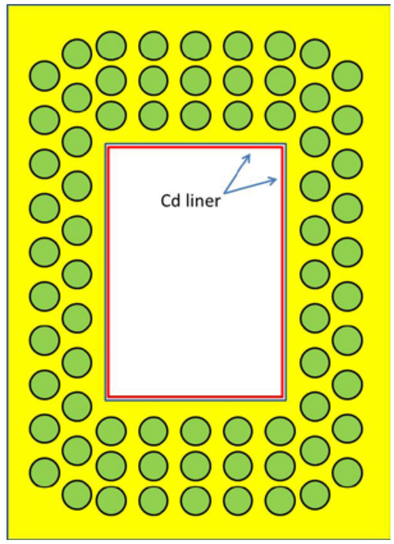


Figure 3.5. Photograph of the GERS NCC (ABUNCL) with end plugs fitted (left) and sketch of the tube arrangement (right).

A summary of the performance parameters for the ^{10}B-lined NCC is presented in Table 3.3 along with the corresponding values for the HLNCC-II. To achieve the same level of statistical precision using the ^{10}B-lined NCC as is possible with the ^{3}He-based HLNCC-II, it is necessary to count approximately three times longer, which impacts the sample throughput. The systematic error contributors (e.g., calibration error, sample uniformity) will, however, be approximately the same for the two systems. From this it can be concluded that the performance of the highly non-optimized ^{10}B-lined NCC system is sufficient to achieve the ITVs (Table 3.4), albeit in 1000 s assay time rather than 300 s. Monte Carlo simulations suggest that the measurement performance of the HLNCC-II could be met by a near optimized assay system incorporating 160 traditional (2.5 cm outside diameter [OD]) ^{10}B-lined proportional tubes [McElroy 2012].

Table 3.3. Observed measurement performance for the ABUNCL configured for well counting and a standard ^{3}He-based NCC (HLNCC-II)

	^{3}He Proportional Tube NCC (HLNCC-II)	**^{10}B-lined Proportional Tube NCC**
Detection	4 atm ^{3}He	^{10}B coating
Number Tubes	18	72
Active Length	50 cm	61 cm
Efficiency (ε)	17.5%	10.7%
Die-Away (τ)	43 μs	65 μs
FOM ($\varepsilon/\sqrt{\tau}$)	2.67	1.33
Sensitivity (Reals/g $^{240}Pu_{eff}$)	18.1	6.6
Weight	43 kg	120 kg
Sample Cavity	17.5 × 41 cm (OD × H)	16 × 22 × 38 cm (L × W × H)
Dimensions	34 × 76 cm (OD × H)	36 × 51 × 80 cm (L × W × H)

Note: The ABUNCL results are without a cadmium liner.

Table 3.4. HLNCC Random (r) and Systematic (s) Uncertainty ITVs [Zhao 2010]

Material	μ(r)	μ(s)	Combined
Plutonium Oxide	1	0.5	1.1
Mixed Oxide (>10% Pu)	2	0.5	2.1
Mixed Oxide (<10% Pu)	4	1.5	4.3
Mixed Oxide (clean scrap)	5	2.0	5.4

3.2.2. High Level Neutron Counter – Boron (HLNB)

The High Level Neutron Counter – Boron (HLNB) developed at LANL represents a full-scale neutron coincidence counter based on a parallel-plate boron-lined proportional technology manufactured by Precision Data Technology, Inc. (PDT). The counter contains six individual detector modules of a rectangular shape, each comprised of six narrow boron-lined detection chambers interleaved with HDPE plates. An argon mixture at less than 1 atm. is used as the fill gas. Additional HPDE layer backs the detector cases for optimum neutron moderation. The interleaved design along with large ^{10}B coated surface area allows achieving sufficient thermal neutron detection efficiency for correlated counting purposes [Henzlova 2012a]. 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 [Henzlova 2013]. Photograph of the PDT detector module is shown in Figure 3.6 (left) with a schematic cross section illustrating the internal structure (middle).

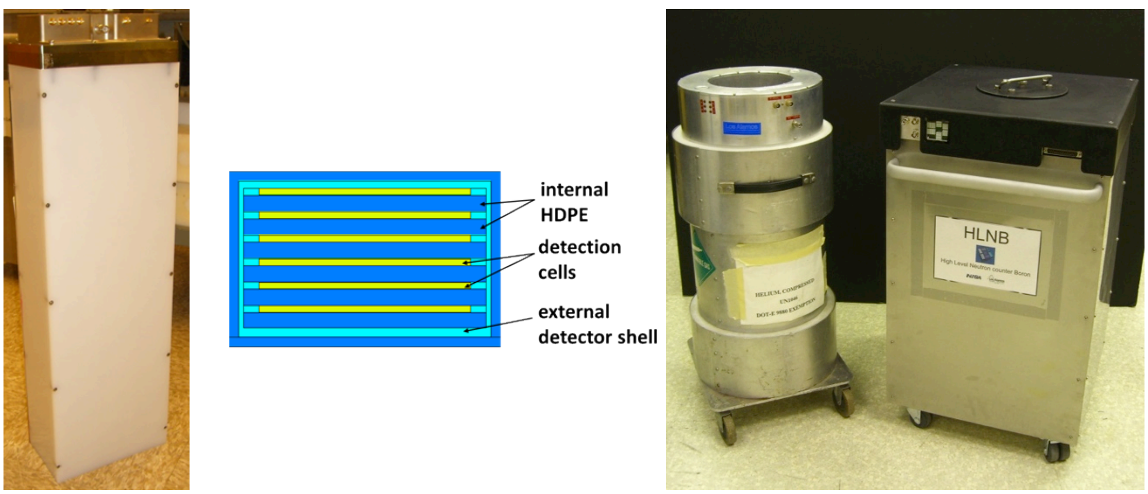


Figure 3.6. Single PDT detector module (left); schematic cross section of the PDT module (middle); photograph of the completed boron-based coincidence counter HLNB next to standard HLNCC-II (right).

The HLNB counter was designed as a direct replacement of ^{3}He-based HLNCC-II. The HLNB is composed of six 61 cm long PDT detector modules that tightly surround the sample cavity of 17 cm diameter. The height of the HLNB sample cavity corresponds to 41 cm. 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 top end-plug is removable for sample insertion. The bottom end-plug can also be removed and the bottom support plate has a 12.7 cm diameter opening to allow for measurements of large samples that extend beyond the 41 cm tall sample cavity. A photograph of the finished HLNB side-by-side with HLNCC-II is shown in Figure 3.6 (right).

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 Pu samples. The experimental activities included evaluation of optimum high voltage (HV) setting in the presence of ~450 mR/h gamma-ray background, 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 compared with parallel measurements in the HLNCC-II as shown in Table 3.5 and Figure 3.7.

Table 3.5. Efficiency and die-away time measured for HLNB counter at 880 V operating voltage. Measurements are compared to HLNCC-II.

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

From Table 3.5 it can be seen that HLNB detection efficiency exceeds that of HLNCC-II by ~1.3% (a ~7% increase), 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 the HLNB corresponds to 81% of the HLNCC-II performance. The higher HLNB detection efficiency is reflected in the higher values of doubles rates compared to HLNCC-II, shown in Figure 3.7, which is especially pronounced for the largest sample. The $^{240}Pu_{eff}$ is defined as mass of ^{240}Pu that would produce the same double coincidence response as that obtained from all the even isotopes contained in the measured sample **[**Reilly 1991]. The measurement precision (error bars in Figure 3.7. are smaller than the size of symbols) 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 full system has recently been upgraded to hermetically seal the individual parallel-plate counting cells to improve overall long-term stability performance. During the summer of 2015, the upgraded system is scheduled to undergo a field evaluation using a range of high-mass MOX samples at the JAEA's Plutonium Conversion Development Facility (PCDF).

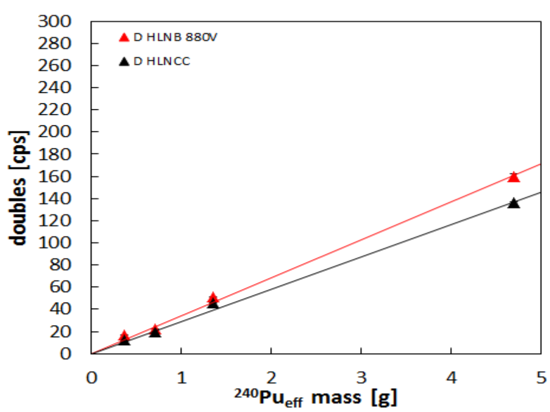


Figure 3.7. Doubles rates measured for a range of low mass PuO_2 samples in HLNB (red symbols) and HLNCC-II (black symbols).

3.2.3. Boron-Coated Straw Based Neutron Coincidence Counter

Computer models of a neutron coincidence counter based on a distributed array of boron-coated straw (BCS) detectors have previously shown that the BCS can successfully replace ^{3}He tubes in existing commercial counter designs, while maintaining overall dimensions [Lacy 2012]. A full-scale, fully operational prototype to replace the HLNCC-II was fabricated and tested at the ^{3}He Alternatives for International Safeguards Workshop that took place at the JRC in Ispra, Italy, in October 2014. The prototype, pictured in Figure 3.8, has overall and cavity dimensions identical to those of the HLNCC-II, and weighs 61 kg, only 6 kg heavier than its ^{3}He-based counterpart. It is populated with 804 BCS detectors, each 4.4 mm in diameter, and lined with 2-μm of vapor-deposited $^{10}B_4C$. The BCS detectors, pictured in Figure 3.9 (left) prior to assembly, are uniformly distributed in the moderator, as illustrated in Figure 3.9 (right). They are connected together in 6 groups of 134, each read out with a custom-designed amplifier, fully compatible with standard shift register electronics.

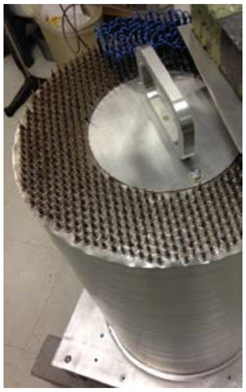


Figure 3.8. Prototype straw detector-based neutron coincidence counter.

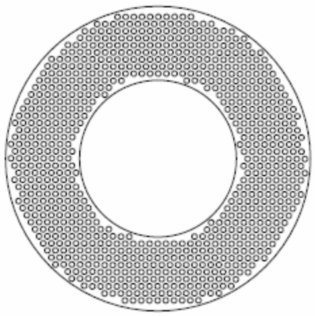


Figure 3.9. (left) Sealed boron-coated straw detectors; (right) cross sectional drawing of moderator showing 804 holes, to accommodate an equal number of BCS detectors.

Despite the large number of detector elements, fabrication is facilitated by a series of BCS production enhancements and automations, including a high-yield, continuous operation, reel-to-reel boron coating process. At the same time, new sealing methods were incorporated to assure reliable operation over many decades, comparable to other sealed proportional counters. Measurements of performance parameters collected at the second (JRC, Ispra) workshop, including detection efficiency, ε, and neutron die-away time, τ, are summarized in Table 3.6. Results demonstrate that the BCS-based counter achieves better performance than the standard ^{3}He-based HLNCC-II, which was also tested at the workshop. The FOM, defined as $\varepsilon/\sqrt{\tau}$, equals 2.66 %/√μs, an improvement over the ^{3}He-based counter, due to the significantly lower die-away time. The latter is attributed to the more uniform dispersion of neutron absorber throughout the moderator. In this initial benchmark comparison, a full-scale neutron coincidence counter, based on low-cost boron-coated straw detectors, shows performance similar to the standard ^{3}He-based system, in a compact geometry, fully compatible with existing electronics and procedures. Further evaluation of long term stability and reproducibility will provide additional input on the overall performance as a deployed system.

Table 3.6. Performance parameters measured at the JRC Workshop for different replacement technologies.

	BCS-based HLNCC	HLNCC-II
Efficiency (ε) [%]	13.6	16.5
Die-away time (τ) [μs]	26.0	43.3
FOM (ε/√τ)	2.66	2.51

3.2.4. BF_3 Based Neutron Correlation Counter (BBNCC)

Gas proportional counters based on boron trifluoride gas (BF_3) enriched in the ^{10}B component have been used over the last fifty years as thermal neutron detectors. Applications are wide ranging from reactor instrumentation to survey meters. The advantages of BF_3 gas proportional counters include the high thermal neutron capture cross section for ^{10}B, the high Q value for the (n,α) reaction in ^{10}B (and consequently good γ/n discrimination possibilities), as well as the uniformity of detection efficiency in extended detectors. Finally, the relatively low price of BF_3 gas, even when enriched in ^{10}B to 99%, is an important factor. Disadvantages include the loss of pulse linearity at higher gas pressures, larger high voltage needed, and perhaps most importantly the toxicity of BF_3 gas.

Due to the advantages mentioned above JRC decided to investigate the feasibility of a HLNCC type instrument based on BF_3 gas proportional counters. The premise was to design and build a prototype well-type neutron counter with sample cavity of the same size as the HLNCC-II, neutron detection efficiency sufficiently high to allow neutron multiplicity counting, and finally developing a design that would address the problem of toxicity of the BF_3 gas. The prototype detector was named the Boron Based Neutron Correlation Counter (BBNCC).

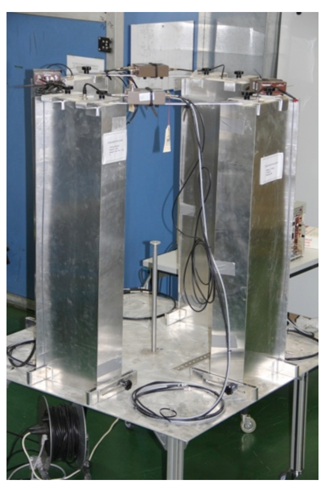


Figure 3.10. JRC test bed for gas proportional counters with variable HDPE thickness, 2.54 cm and 5.05 cm ^3He and BF_3 detectors of various pressures and ^{10}B-lined detectors.

The design process included experimental comparison of single detectors embedded in HDPE in the JRC test bed, comparison of measured and MCNP calculated neutron efficiency and die-away parameters of test bed detector configurations, and MCNP calculations for optimization of the well-type cylindrical detector configuration. A photograph of detector configuration during the test bed measurements is shown in Figure 3.10. One encouraging observation from the test bed measurements was that when adjusting the thickness of the HDPE moderator to the detector type, the detection efficiency ratio of 0.42 was observed between 2.54 cm diameter detectors of types: 0.95 bar $^{10}BF_3$ and 4 bar ^{3}He. The ratio is far better than suggested only by the pressure ratios and the cross section ratios. The result indicates that the gas volume is better utilized for the "thinner" ^{10}B gas compared the "denser" ^{3}He gas for thermal neutrons.

A variety of detector configurations using both 2.54 cm and 5.08 cm diameter BF_3 detectors were considered in the well counter design. The detector pressure was kept at 0.95 bar to alleviate the toxicity issue, although a pressure above one bar would still be acceptable for the signal processing.

Changing to boron based gas detectors has an adverse effect on the die-away time. Generally speaking when using HDPE moderated low pressure BF_3 gas in 5.08 cm diameter tubes rather than high pressure ^{3}He gas in 2.54 cm diameter tubes, the value of the die-away time will increase both because of the lower absorption per gas volume and because of the larger detector volume. This means that a BF_3 based system will always have a larger die-away time than a ^{3}He based system. Both experiments and MCNP calculations confirmed that when using 5.08 cm diameter BF_3 detectors, the benefits in efficiency, however, outweigh the disadvantage in the increased die-away time. Design parameters such as inner ring radius, outer ring radius, external radius, top/bottom plug design were optimized using the standard FOM ($\varepsilon/\sqrt{\tau}$) in the MCNP calculations as illustrated in Figure 3.11.

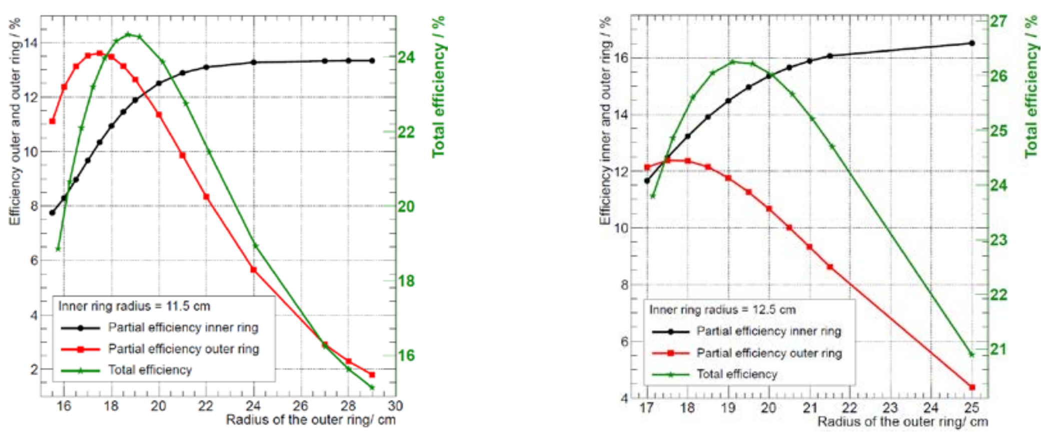


Figure 3.11. Example of data from the MCNP optimization of inner and outer ring radii for 12 BF_3 tubes in each ring; (left) inner ring radius of 11.5 cm; (right) inner ring radius of 12.5 cm (*caption of left figure needs to be modified to 'Efficiency inner and outer ring'*)**.**

The final concept configuration of the BBNCC counter based on the MCNP calculations is shown in Figure 3.12. The active length of the detector tubes is 50% more than in the HLNCC-II. The greater length combined with the top and bottom plug makes the axial efficiency profile slightly better than the HLNCC-II. The number of detectors is 24 compared to 18 in the HLNCC-II. The MCNP calculations showed for a neutron source from a bulk Pu sample in a stainless steel containment the following values for the detection efficiency and die-away time: 28.67% and 73.70 μs, respectively.

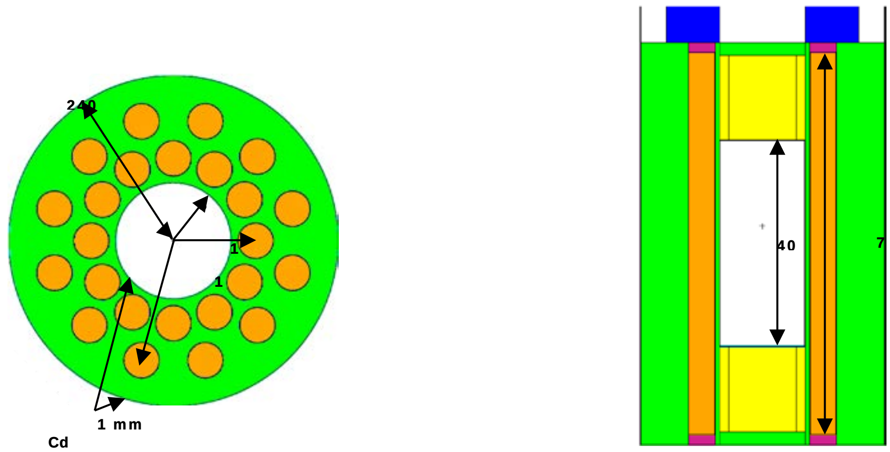


Figure 3.12. Final configuration of the BBNCC well counter based on MCNP calculations.

Design drawings of a prototype counter are based on the dimensions shown in Figure 3.12. The BBNCC detector is both wider and taller than the standard HLNCC-II. A sealed junction box is included, as well as a base plate with four wheels. The total height of the instrument is 115.0 cm. The issue of toxicity has been addressed by making the channels for the detector tubes airtight and interconnected with the junction box, thus constituting a secondary containment for the detector gas. The concept includes implementing a reservoir inside the junction box for a chemical reactant such as sodium carbonate (Na_2CO_3) to neutralize the boron trifluoride gas in case of leakage. The prototype BBNCC is currently under construction.

3.3. Scintillator Based Technologies

Scintillator based technologies for safeguards have undergone significant development over the past several years to optimize their design and performance to accommodate challenging safeguards requirements. A range of scintillator-based technologies is currently under development for potential safeguards applications including ZnS scintillators with ^{6}Li or ^{10}B containing compounds, liquid scintillators for fast neutron detection and ^{6}Li loaded glass beads. The key challenges for these technologies include effective neutron/gamma-ray discrimination in relatively high gamma-ray backgrounds typical for safeguards applications as well as assuring long-term environmental stability to allow for reliable and reproducible assay results. In addition, one of the crucial considerations of routine nuclear safeguards use is compatibility of an alternative technology with the existing data acquisition and analysis infrastructure, largely motivated by the need to provide a consistent and user-friendly environment for the instrument operators. This requirement brings along additional effort needed to effectively reduce the measured information (typically full waveform recorded for neutron/gamma-ray identification), while maintaining good neutron/gamma-ray discrimination and low deadtime, to provide digital signal compatible with standard shift register electronics for thermal neutron counting systems. Fast neutron counting systems, on the other hand, do not require thermalization process and as such operate in significantly shorter time domains. List mode based data acquisition and dedicated analysis software tools are being developed for these technologies. Despite these challenges, several scintillator-based technologies have recently been developed to the stage of full-scale prototype neutron counting systems. The key features and performance of these full systems along with description of the core technologies the systems are based on is provided in the following sections.

3.3.1. Alternative Sample Assay System (ASAS)

The Alternative Sample Assay System (ASAS) represents a full-scale coincidence counter developed at JAEA as an alternative to an existing ^{3}He-based INVS counter and is comprised of $ZnS/^{10}B_2O_3$ ceramic scintillators. The design of the ASAS counter is related to the INVS. The small amount of Pu in MOX powder or a Pu nitrate solution in a vial can be measured. The current basic design of ASAS is shown in Figure 3.13 (left) and includes 24 $ZnS/^{10}B_2O_3$ ceramic scintillator neutron detection modules. Individual neutron detection modules are composed mainly of three components: an aluminum regular square tube, a scintillator with a rectangular $ZnS/^{10}B_2O_3$ ceramic sheet and two photomultiplier tubes (PMT). The sheet is fit on the diagonal inside the square tube as shown in Figure 3.13 (top right), while the two PMTs are installed at both ends of the tube. The detection modules are oriented so that the $ZnS/^{10}B_2O_3$ ceramic scintillator sheets face the sample chamber to detect neutrons effectively. Nuclear reaction products from reaction of neutrons that enter the scintillator from outside the tube with the ^{10}B atoms in the scintillator induce the emission of scintillation light from the surface of the scintillator. The light photons are divided into two directions, toward both ends of the tube, and are detected individually by the two PMTs as two pulse signals. The light signals detected with the PMTs are amplified with pre-amplifiers and discriminated. The neutron signal is finally detected according to the coincidence of the two light signals from the two PMTs, to eliminate the electrical noise signal.

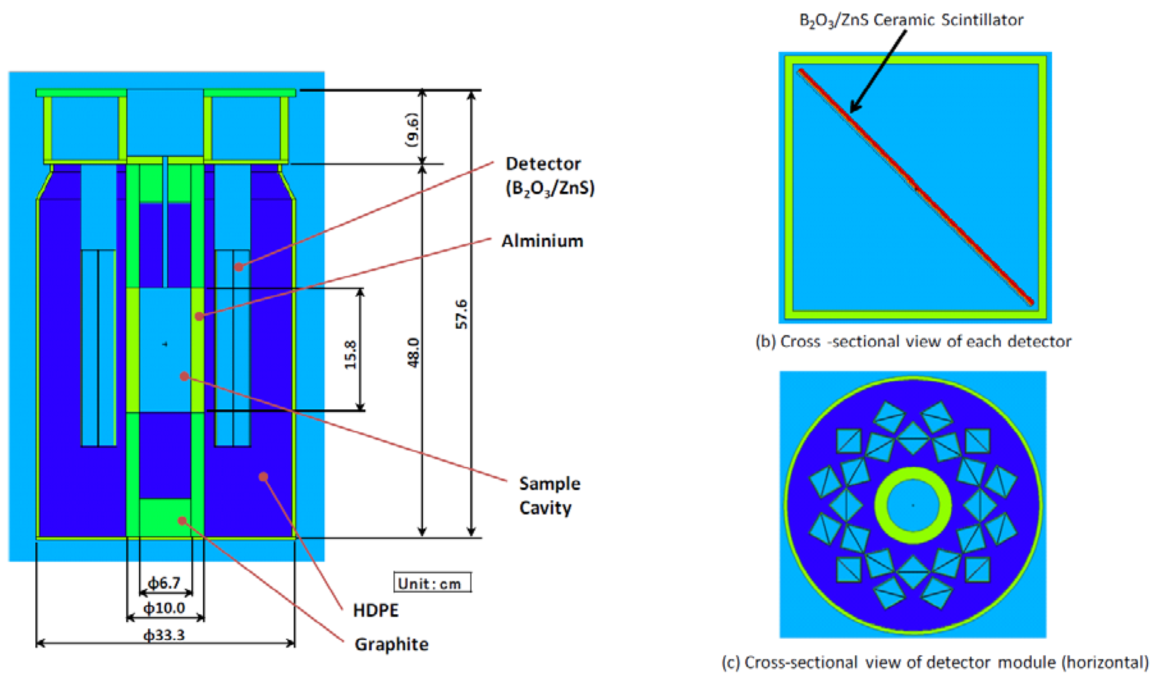


Figure 3.13. (left) vertical (x-z plane) cross-sectional view of ASAS detector; (right - b) cross-sectional view of each detector module tube equipped $ZnS/^{10}B_2O_3$ ceramic scintillator sheet (x-y plane); (right - c) horizontal cross-sectional view of ASAS detector (x-y plane)

The ASAS will be composed of detector modules using the $ZnS/^{10}B_2O_3$ solid scintillator, standard shift register (JSR-15) and data acquisition computer as an ASAS system. In the current investigation, it is expected that the counting efficiency for a ^{240}Pu point source located in the center of the sample chamber will be about 32.1%. In order to optimize and reduce the die-away time, which is one of the important parameters for the measurement uncertainty, the arrangement of detectors and number of detectors might be changed in the final configuration.

In order to prove progress for the technology and performance after the fabrication of the new detector, there are plans to conduct calibration and demonstration activities of the ASAS detector. The calibration activity will consist of the evaluation of detector parameters including basic performance check (i.e. flat response profile for vertical and radial axis) and calibration using MOX powder to determine Pu mass in a sample vial. After that, demonstration activities will include the performance comparison between ASAS and INVS.

3.3.2. LiF/ZnS Based HLNCC

This ^{3}He-free neutron blade coincidence counter, shown in Figure 3.14, measures the ^{240}Pu effective mass in a sample by detecting coincidence neutrons from spontaneous fission of plutonium. The counter was designed as an alternative to ^{3}He-based HLNCC-II and consists of four detector slab modules surrounding a sample cavity chamber of square cross-section. There are eight ^{6}LiF/ZnS-based blades distributed in each moderating slab, for a total of 32 blades in the counter. Each slab module is enveloped in a cadmium sleeve to maintain a low die-away time and minimize thermal neutron albedo to the sample chamber. The counter has been used to assay plutonium metal, plutonium oxide, and mixed oxide in a laboratory environment with a subset of only 8 of the 32 possible blades. The digital (TTL) output pulses from all blades are combined into a logical OR using an aggregator unit, which also houses LED indicators for state-of-health of each blade. Coincidence counting requires a separate shift register or list mode acquisition hardware and analysis software. The digital output signal is compatible with existing shift register/list mode data acquisition hardware.

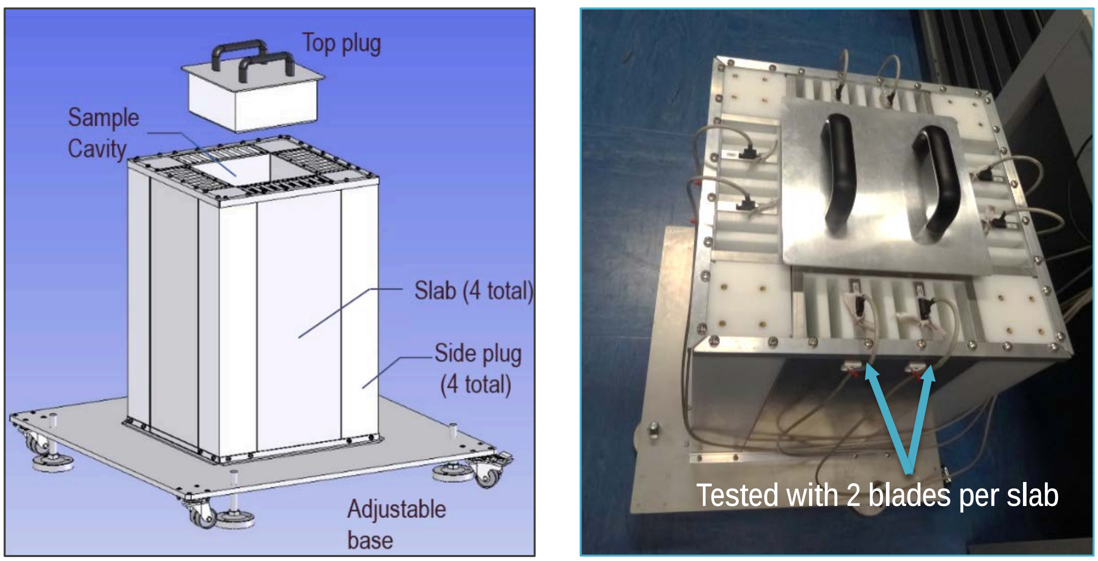


Figure 3.14. LiF/ZnS-based Blade Neutron Coincidence Counter (left) and as tested with eight blades (right).

Each compact detector element, or blade (see Figure 3.15) weighing 395 g and 6 cm x 50 cm in active area, consists of a thin bulk polyvinyltoluene (PVT) wavelength shifting guide coated with LiF/ZnS(Ag) neutron screens on both sides, and surrounded by light-tight packaging. Solid-state readout silicon photomultipliers (SiPM) and compact pulse processing electronics are mounted at the top of the detector active area, resulting in a slim-profile, low-power (<100 nW), robust neutron detector. A proprietary firmware-based pulse-shape discrimination (PSD) algorithm is used to maximize neutron eficiency whilst maintaining suitable gamma-ray rejection. The blades each have a gamma-ray rejection factor of $5x10^{-8}$ for ^{137}Cs (using a 100 μSv/h flood illumination normal to the largest area of the blade), and an average neutron sensitivity at 2.5 cm of 8.5 cps/ng for ^{252}Cf moderated with 5 cm of HDPE, where cps is counts per second.

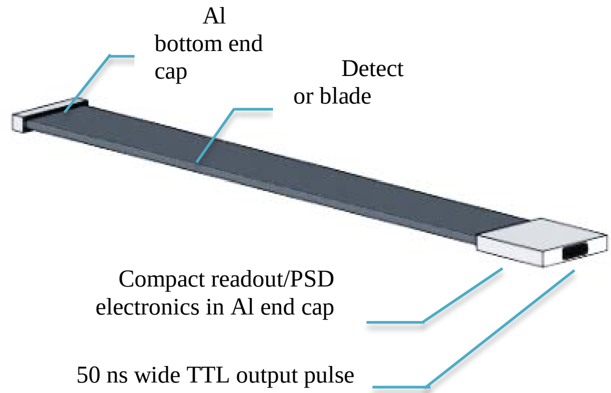


Figure 3.15. Compact LiF/ZnS neutron detector blade

Each slab module is designed to consist of eight LiF/ZnS detector blades (with readout electronics) embedded in a HDPE slab. A cadmium sleeve and a thin aluminum cover surround the moderator slab for safe handling. Each blade is easily removable from the moderating slab and is surrounded by HDPE shims to boost the neutron detection efficiency. The digital neutron signal (pulse train) from each blade is combined into an aggregate pulse train for analysis. The counter consists of four slab modules, each 21 cm x 60 cm x 9.4 cm, arranged with HDPE side plugs for a well counter configuration. The measured intrinsic efficiency of an individual eight-blade slab for a ^{252}Cf source is 18.5%, and the readout efficiency is approximately 85%. The measured absolute efficiency at 8 cm from the slab face is 5.17%±0.17%.

The physical specifications of the neutron blade coincidence counter are compared to the HLNCC-II, the in Table 3.7. The MCNP modeled efficiency for a fully populated neutron blade coincidence counter (25.4%) is predicted to exceed that of the HLNCC (17.5%), and yet have a lower die-away time of 31 μs, resulting in a safeguards FOM, defined as $\varepsilon/\sqrt{\tau}$, of 4.56 compared to the 2.67 of the HLNCC-II.

Table 3.7. Comparison of HLNCC-II with LiF/ZnS Blade Counter

Specifications	HLNCC-II	LiF/ZnS Blade Counter
External Dimensions	73.7 x 34cm (HxDia)	70 x 26x26 cm (HxLxW)
Weight	55 kg	~130 kg (fully equipped)
Sample Cavity Size	40.6 x 17cm (HxDia)	40.6x 17x17cm (HxLxW)
Detectors	18 He-3 tubes at 4 atm	32 LiF/ZnS blades
Detector active length	50.8x2.54 cm (HxDia)	50x 6 cm (HxW)
Efficiency	17.5%	8.5% (25.4% for full system)
Die-away	43 μs	52 μs (31 μs for full system)
FOM	2.67	4.56

3.3.3. LiF/ZnS Based UNCL

Testing at PNNL evaluated whether a lithium-based coincidence counter, with its short die-away-time, could be used to make measurements on Gd-loaded low enriched uranium (LEU) fuel. The coincidence counter used for this evaluation is based upon the PNNL developed Lithium-based Neutron Scintillator (PLiNS) detector [Ely 2013].

One current safeguards challenge is in the assay of fresh uranium fuel doped with 3-12% Gd as a burnable poison to control the fuel burn-up rate [e.g., Soba 2014]. Currently, the IAEA uses active well coincidence counters based on ^{3}He [Pickrell 2013], but for fuel assemblies with high Gd content, systematic errors can be high and measurement times very long (hours), in contrast to about ten minutes for non-Gd loaded fuel. Coincidence counters with short die-away times may be a solution to this Gd problem. A new design of the UNCL based on high-pressure ^{3}He tubes was developed to overcome this problem [Evans 2013]. In this counter, a Cd liner was used to reduce the sensitivity to slow neutrons, shortening the die-away-time, but also significantly reducing the detection efficiency. The result was a detector that could meet the requirements of enabling nuclear safeguards inspectors to perform a measurement on fresh fuel containing Gd within a target assay time of 15 minutes and with a precision of 2% relative uncertainty in the doubles neutron-counting rate. This is sufficient to achieve the required performance specified by the International Target Values (ITVs) [Zhao 2010] with increased measurement times.

From PNNL testing of four alternative neutron detection technologies for national security applications, two were identified as most promising replacement technologies for safeguards use: light guides coated with ^{6}LiF and ZnS [Lintereur 2009] and boron-lined proportional counters [Lintereur 2010]. A previous PNNL modeling search for alternatives [Lintereur 2012] addressed development of multiplicity detectors and showed that minimally moderated configurations based upon neutron scintillation via thin sheets of a ^{6}LiF-ZnS blend in a hydrogenous binder (abbreviated LiF/ZnS) have much shorter die-away times than conventional, fully-moderated ^{3}He-based multiplicity counters. Construction of the PLiNS prototype detector has verified this characteristic [Ely 2013], and thus indicates that a passive lithium-based neutron detector should be applicable to the problem of Gd-loaded fuel.

The work on this coincidence counter began with the validated PLiNS model from the previous study [Ely 2013] and then explored a number of possible active configurations for coincidence counting to determine if such a configuration can obtain reasonable efficiencies and short enough die-away times to measure fresh fuel with a range of Gd loading. After determining an active configuration model that gave the best performance, named PLNS3A-R1 (Figure 3.16), it was used to simulate what might be possible by comparing models for LEU fuel against Gd-loaded LEU fuel. Modeling to evaluate optimization of the parameters of these assemblies was performed using MCNPX [Pelowitz 2011].

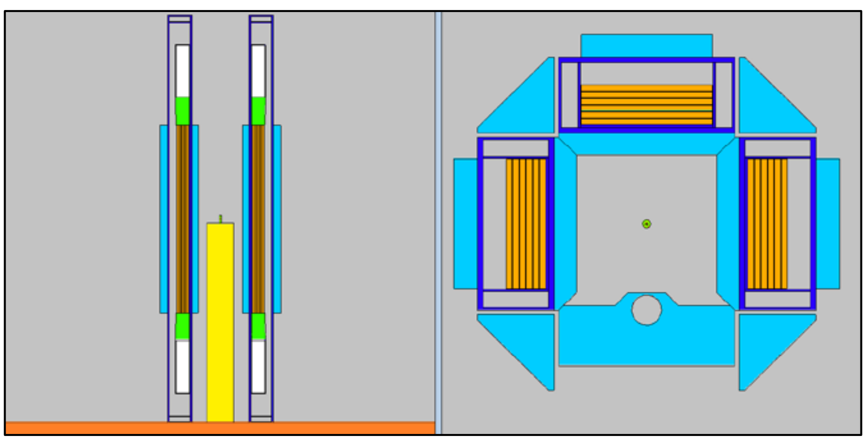


Figure 3.16. PLNS3A-R1 with reversed detector panels, +1.0 cm to front, and +1.5 cm to lining and backing.

Table 3.8 lists the characteristics of the active UNCL, the redesigned active UNCL for Gd-loaded fuel measurements [Evans 2013], the active PLiNS-3, and the optimized active PLNS3A-R1. The FOM in Table 3.8 is defined as efficiency divided by the square root of the die-away time ($\varepsilon/\sqrt{\tau}$). The lithium-based PLNS3A-R1, showed promise for assaying Gd loaded fuel, with better performance (in simulation) than the ^{3}He-based UNCL modified to measure Gd-loaded fuel. This detector should be able to obtain 1% precision in 10 minutes, which cannot be obtained with the other detectors evaluated.

Future research will be required to measure the performance of the PLNS3A-R1, or a similar configuration, and the performance of the UNCL-II with identical fuel configurations. Future research may also be used to further refine the PLNS3A-R1 design to optimize the safeguards FOM. The next step would be to assemble the prototype of this detector and test its performance against the predictions provided in this study.

Table 3.8. Comparison of various coincidence counter performances.

Detector	Configuration	Die-away Time (μs)	ε (%)	FOM	Approximate Assay Precision in 10 minutes
^{3}He UNCL II	Standard	53	12.3	1.7	6%
^{3}He UNCL (Gd)	Cd liner	28	15.7	3.0	3%
^{6}LiF/ZnS	PLiNS-3	21	16.7	3.6	2%
^{6}LiF/ZnS	PLNS3A-R1	18	18.7	4.3	1%

3.3.4. LiF/ZnS Based ENMC

One of the most challenging applications for ^{3}He-alternatives in nuclear safeguards is in neutron multiplicity counters. The highest performing neutron multiplicity counter is the ^{3}He-based ENMC. It is the goal of this ^{3}He-alternative detector development project to match the performance of the ENMC without the use of ^{3}He. A previous project at PNNL investigated replacing the ^{3}He in a multiplicity counter with LiF/ZnS neutron-scintillator sheets and wavelength-shifting plastic for light pipes [Ely 2013]. Experiments were performed with panels constructed of LiF/ZnS sheets layered with wavelength shifting plastic (WSP) light pipes. A PMT was then attached to both ends of the panels. Data from this demonstrator system were collected using analog electronics for the timing measurement and waveform digitizers for the neutron detection efficiency measurement. These measurements were used to validate MCNP modeling results and gave confidence in the ability to scale up the system to a larger, more efficient system.

One challenge in using LiF/ZnS as opposed to ^{3}He is gamma-ray sensitivity. ^{3}He is extremely insensitive to gamma-rays, whereas gamma-rays can interact with the ZnS or in the WSP to generate light that is then detected by the PMTs. However, there is a difference in the shape of the light pulse that is generated. Neutron-induced events tend to have pulses with sharp rise times but tails that can continue for several microseconds. Gamma-ray-induced events tend to be less bright and have pulses with sharp rise times and short tails. The current effort has used fast, dead-time free waveform digitizers to capture and record every pulse from the detector. Then, an offline analysis program performs PSD by integrating the charge in windows with various optimized lengths. The ratio of those charge windows allows selection of neutron versus gamma-ray induced events.

A further reduction in gamma-ray sensitivity has been achieved by requiring coincidence between the PMTs at each end of the panel. However, the offline storage and computing requirements associated with continuously digitizing the signals are relatively large and the off-line analysis considerably slower than the current neutron multiplicity counters. In order to match their short reporting time, real-time PSD is required. The current digitizer contains a fast field programmable gate array (FPGA) that allows it to perform simple operations on the waveform. The current research is focused on using multiple charge windows and comparing the various ratios. By saving to disk only the time of the pulse and several integrated charge windows, the data storage requirements are minimized, and the processing of the resulting data file is much more rapid.

At very high rates, the simple two-window charge integration PSD technique is expected to fail. Multiple neutrons and/or gamma-rays can pile-up, confusing the algorithm. More advanced PSD techniques are also under study with the goal of implementing them on the FPGA as well. A template matching routine has shown promise and a simplified version of it may be able to be implemented on the FPGA. Alternatively, pile-up problems can be mitigated by using smaller, optically isolated components but at the cost of more channels of data read-out. All options are being explored in an attempt to optimize performance and cost.

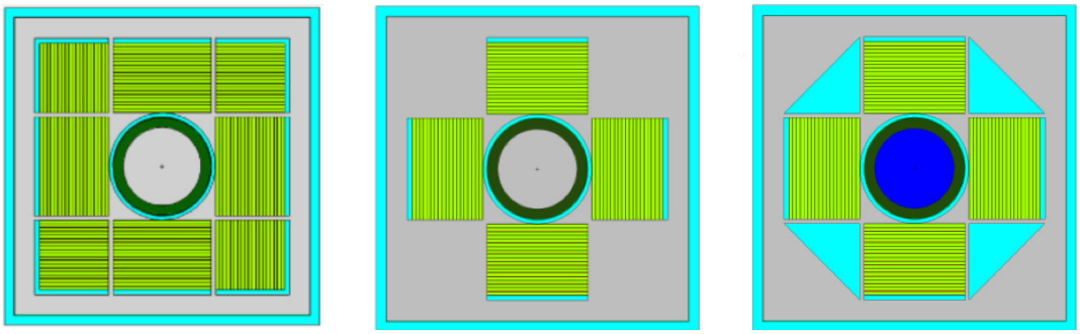


Figure 3.17. Design with eight (neutron capture) panels - LINMC-8 (Left), four panels - LiNMC-4 (Center), and mixed design with four active panels and four passive (HDPE) panels – LiNMC-4+ (Right).

The full-scale designs that are being pursued consist of different combinations of the well-understood panels from the demonstrator system. Three potential designs are shown in Figure 3.17, the full eight-section detector (LiNMC-8), a four-sector detector (LiNMC-4) and a four-sector detector with HDPE corners (LiNMC-4+). Two key properties of a thermal neutron multiplicity counter are the absolute neutron detection efficiency (ε) and the die-away time (τ) reflected in a safeguards FOM, defined here as $\varepsilon/\sqrt{\tau}$, which is to be maximized. The detector design with eight active sections (left frame of Figure 3.17) has a FOM that is approximately 1.5 times that of the best ^{3}He-based neutron multiplicity counter, the ENMC (see Table 3.9). However, a mixed design (right frame of Figure 3.17) replaces the four corner blocks with HDPE. The overall efficiency of the LiNMC-4+ system decreases relative to the LiNMC-8, and the die-away time is increased. The current MCNP model results indicate that the mixed design should perform with a similar FOM to the ENMC, but with half the data acquisition channels of the eight-panel system. This mixed system would also have the ability to be upgraded in the future to improve the FOM.

Table 3.9. Summary of modeled performance for promising designs compared with the ENMC.

System	ENMC	LiNMC-8	LiNMC-4	LiNMC-4+
ε [%]	66	59	41	51
τ [μs]	23	10	10	15
FOM	13.7	18.7	13.0	13.2

3.3.5. Liquid Scintillator Neutron Coincidence Collar (LS-NCC)

The IAEA is developing a liquid scintillator-based neutron coincidence counter in collaboration with the European Commission's JRC in Ispra, Italy, and Hybrid Instruments, Ltd. (UK). The development represents an alternative to ^{3}He-based UNCL. Liquid organic scintillators are often used for fast-neutron detection due to their fast time response with the ability to use PSD to distinguish between neutron and gamma-ray interactions. The fast-neutron detection capabilities are particularly beneficial for coincidence counting safeguards applications. Detection of neutrons from fission events does not require a thermalization process, thus all neutrons coming from the same event are detected with almost zero delay. This feature makes it possible to reduce the detector coincidence gate by three orders of magnitude, compared to standard thermal neutron detectors, resulting in significantly lower statistical measurement error.

Figure 3.18 shows the current prototype LS-NCC schematic and components. It consists of twelve liquid scintillator cells, each of cubic geometry of 10 cm x 10 cm x10 cm, arranged on the three sides of the collar. The front side is designed to accommodate an AmLi interrogation source. HDPE was placed between the cells and inside the measurement cavity to increase the moderation of the AmLi neutrons that induce thermal fissions in the fuel element being measured, and to enhance the interrogation uniformity.

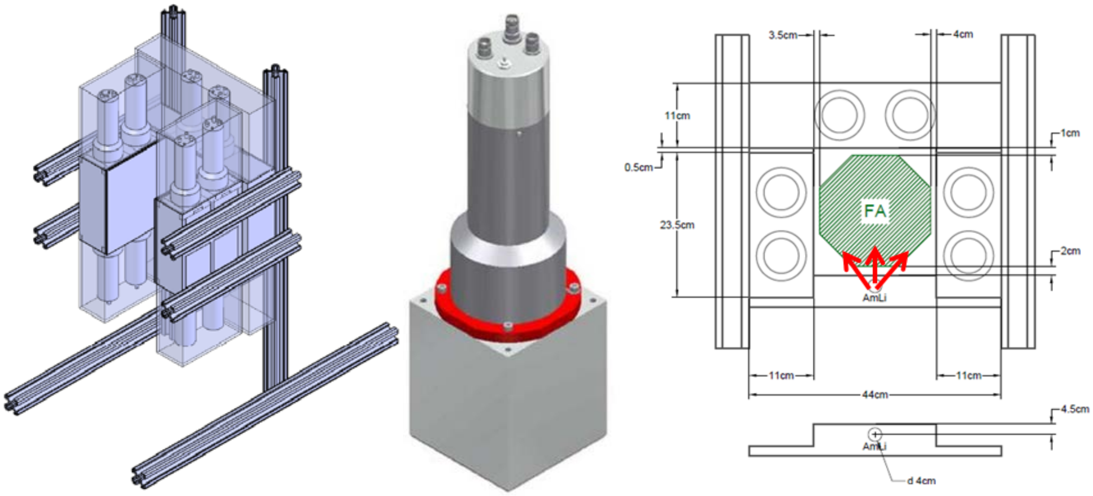


Figure 3.18. Design of the LS-NCC (left); EJ309-Single liquid scintillator detector cell (center); Ground view of fuel assembly measurement (right).

There exists the possibility that an incident neutron can scatter and deposit sufficient energy in two adjacent cells to be detected as two different events in coincidence. To reduce this probability of artificial coincidence to a negligible value, the detectors were separated by introducing a 1 cm layer of HDPE to reduce the neutron energy below detection threshold after the first scatter. An anti-crosstalk logic was also implemented at the signal acquisition stage that rejects second events in the adjacent cells (Figure 3.19). A 4 mm thick layer of lead is placed in the inner cavity to minimize the gamma-ray background (misclassified neutrons), and a (removable) 1 mm thick layer of cadmium, which is only used when the system is operated in a fast mode configuration. Figure 3.20 shows the actual prototype during the detector test with use of PWR fuel assembly performed in 2013.

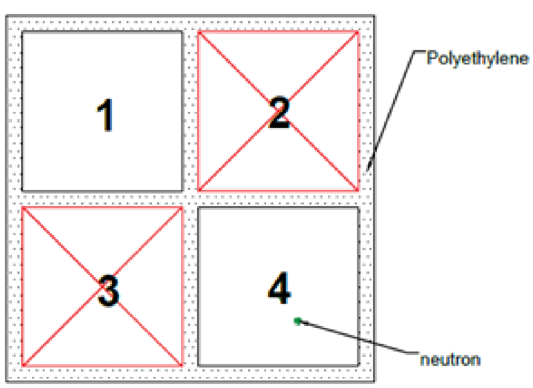


Figure 3.19. Concept of an Anti-Crosstalk Filter shown on vertical cross section of a collar side.

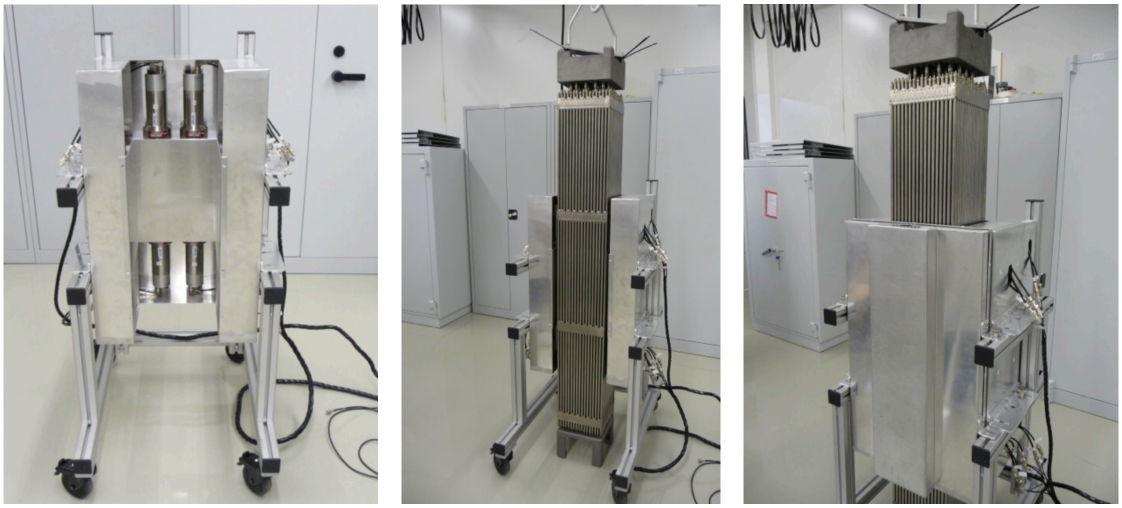


Figure 3.20. Liquid scintillator collar prototype (left); prototype with the fuel assembly (center); fuel measurement (right).

Figure 3.21 shows the PSD units rack (16 channels = 4 x 4 channel units). The PSD units were developed through collaboration with Hybrid Instruments, Ltd. (UK). The very fast pulses that arise from each liquid scintillator's PMT are processed in real-time, discriminated, and converted into TTL output signals (one for gamma-rays and one for neutrons). The processing is done independently for all 12 channels of the collar.

Figure 3.21. Instruments with 4 x 4-Channel Mixed-Field Analyzer by Hybrid Instruments, Ltd.

The PSD algorithm implemented in the system is based on a comparison of the peak amplitude of the pulse to the second amplitude in the decay face of the pulse after a 16 ns delay (Figure 3.22). The 16 ns delay was arrived at by looking for the greatest separation between filtered gamma ray and neutron pulses. The system can obtain an operational gamma ray rejection factor of ~$5x10^{-4}$. Pulses that have long decay times are classified as "neutrons" and the others are classified as "gamma-rays." The TTL outputs of the PSD units are collected and sent to the data acquisition system whose key component is a National Instruments Industrial Controller. The controller includes a FPGA-based data acquisition card and data acquisition analysis software developed with LabVIEW. This data acquisition system and related software analysis implementation was designed and developed within the Project Engineering Team (PET) at the IAEA. The system is also compatible with other list mode acquisition devices such as the PTR32 (Institute of Isotopes, Hungary).

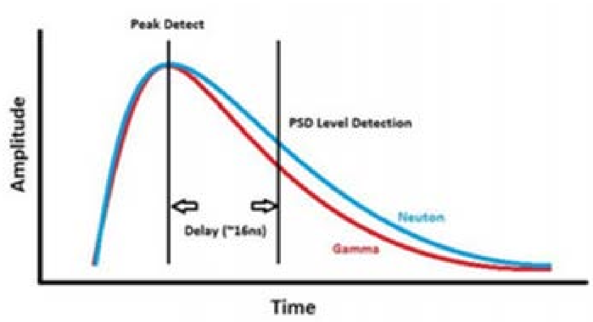


Figure 3.22. Neutron and gamma PMT pulse shape comparison.

3.3.6. Fast Neutron Multiplicity Counter

The University of Michigan-designed Fast Neutron Multiplicity Counter (UM-FNMC) represents a development to replace ^{3}He-based multiplicity counters such as ENMC. UM-FNMC consists of sixteen 7.62 cm ø by 7.62 cm EJ-309 liquid scintillators (Eljen Technology, Sweetwater, TX), digital electronics, and algorithms for PSD and timing. Figure 3.23 shows a photograph of the UM-FNMC: a fissile sample is placed at the center of an array consisting of two rings of eight detectors. The primary measurable is the number of coincident neutrons (doubles) measured by two of the detectors in the array within a coincidence gate of 50-100 ns.

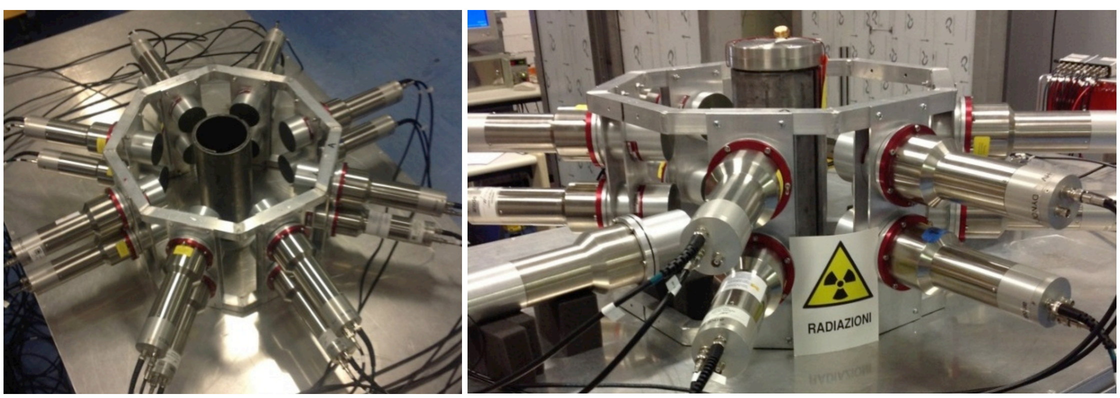


Figure 3.23. The sixteen-detector FNMC setup at the JRC facility in Ispra.

The prototype UM-FNMC was successfully tested with a set of plutonium samples at the JRC facility in Ispra, Italy, in 2013. Results are shown in Figure 3.24, where the number of measured neutron doubles per second is plotted as a function of the effective mass of ^{240}Pu (defined as mass of ^{240}Pu that would produce the same double coincidence response as that obtained from all the even isotopes contained in the measured sample [Reilly 1991]). Results show a linear trend for the range of masses considered here, enabling the measurement of the mass of an unknown sample.

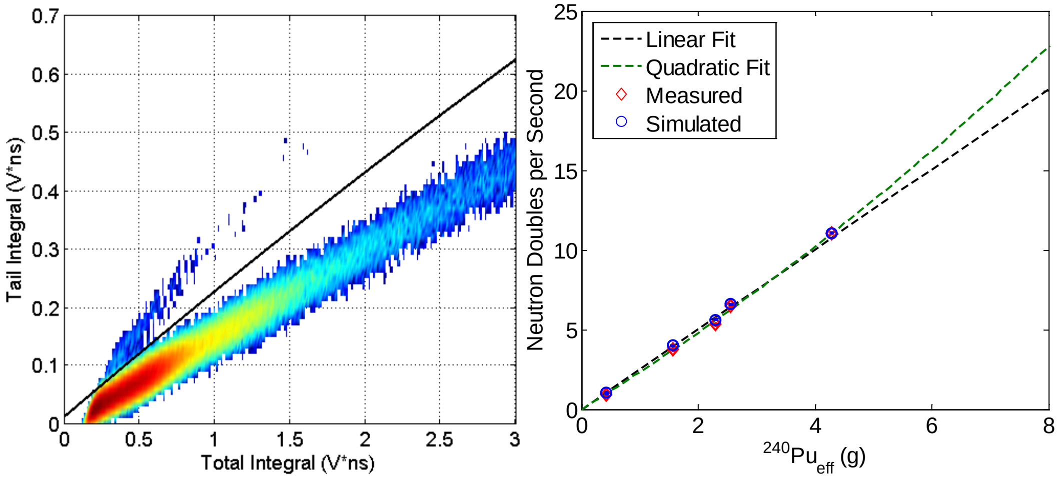


Figure 3.24. (left) PSD showing neutrons (top) and gamma-rays (bottom) measured with a liquid organic scintillator in the UM-FNMC measuring a Pu metal sample; (right) number of measured neutron doubles as a function of ^{240}Pu effective mass.

Future work includes a study of stilbene scintillators to replace the liquid scintillator used in this first prototype. It can be expected that the use of stilbene would alleviate the difficulties associated with the use of liquid in the field, as well as improve the PSD capabilities of the system. Crosstalk due to scattering between detectors needs to be incorporated into the analysis.

3.3.7. Neutron Detector Based on Particles of ^{6}Li Glass Scintillator

A new detector concept for ^{3}He replacement based on GS20 ^{6}Li scintillator glass particles uniformly distributed in mineral oil that serves as both light transport and neutron moderation medium has recently been developed at LANL. The technology provides good neutron/gamma-ray separation by selection of a scintillator particle size that limits the energy deposited by gamma-rays to below the peak of the ^{6}Li reaction products [Ianakiev 2014a]. A prototype detector with an active volume of 7.6 cm diameter by 25.4 cm length containing ~2.7 vol% of GS20 glass scintillator was developed and is shown in Figure 3.25. The selected volume density corresponds to the ^{6}Li atom density used for modeling of the ^{6}Li-metal foil neutron counter [Ianakiev 2011] considered as replacement of ^{3}He based HLNCC-II counter. The detector features $4.5 \cdot 10^{23}$ atoms of ^{6}Li neutron absorber and $8 \cdot 10^{25}$ atoms of H moderator for the 1140 cm^{3} active detection volume.

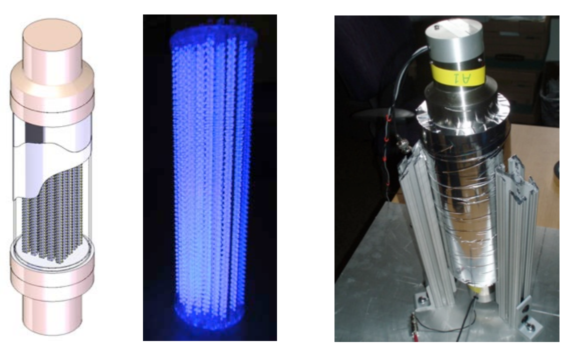


Figure 3.25. Left to right: Conceptual design, assembly of ^{6}Li scintillator glass particles, and 7.6 cm dia. by 25.4 cm long prototype.

The prototype detector was characterized using neutron and gamma-ray emitting sources (^{252}Cf, ^{137}Cs), bare and shielded (using 5 cm lead shielding) PuO_2 sample as well as a neutron generator. The initial evaluation demonstrated separate neutron and gamma-ray pulse height distributions (Figure 3.26 (left)) resulting in a plateau in the HV characteristic (Figure 3.26 (center)). KM200 fast shaper- discriminator for ^{3}He and ^{10}B proportional counters [Ianakiev 2014b] was used for the plateau and neutron generator measurements. The time response of the detector to a neutron generator burst was used to extract a die-away time (shown in Figure 3.26 (right)) that corresponded to <15 μs and was found to be in a good agreement with MCNP modeling presented in [Ianakiev 2011]. In addition, the neutron generator measurements established counting rate capabilities of the prototype detector above 10^6 cps. Finally an order of magnitude lower dead-time than a standard 2.54 cm diameter ^{3}He proportional counter (0.15 μs versus ~2 μs) was demonstrated [Ianakiev 2014b, Henzlova 2012c] allowing for an expanded dynamic range of measured materials.

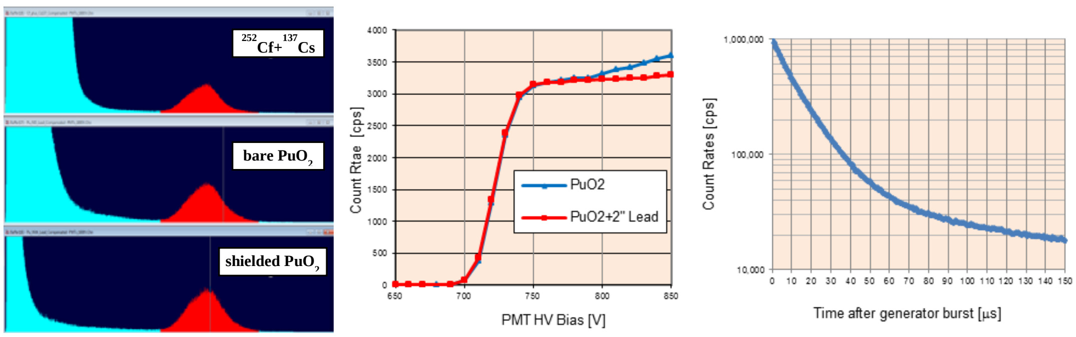


Figure 3.26. (left) Pulse height spectrum indicating separate neutron and gamma-ray distributions; (center) HV characteristic with 40 V wide plateau observed for the bare PuO_2 source; (right) time response of the detector to a neutron generator burst.

The combination of separate neutron/gamma-ray pulse height distributions, high ^{6}Li atom density, very low dead-time, and fast system recovery times following an intense neutron burst enable the development of large area neutron detectors with the possible potential to outperform ^{3}He proportional counters for demanding applications such as nuclear safeguards and Differential Die-Away measurements [Henzl 2014] for emergency response and treaty verification.

3.3.8. Rugged-by-Design™ - Natural Helium Filled Scintillation Detectors

The Arktis (Zürich, Switzerland) Rugged-by-Design™ neutron detector, shown in Figure 3.27, is sensitive to fast, and optionally thermal, neutrons. This provides potential for wide range of applications in nuclear safeguards, including dry cask fingerprinting, multiplicity counting, active interrogation and spent fuel monitoring, as discussed in more detail below.

Figure 3.27. Arktis Rugged-by-Design™ neutron detectors.

The Rugged-by-Design™ neutron detector is filled with natural helium and uses SiPM based signal readouts, making it immune to shock, vibration, and scalable in length. It is available in two standard lengths, or custom built to customer specifications. The detector is sensitive to both fast (>100 keV) and thermal neutrons. The detector output is a standard TTL output for each neutron detected, making it compatible with other detection systems. Alternately, a USB output is provided. Several detectors can be easily combined, allowing scalable systems.

The detectors consist only of steel, gas, and solid-state circuitry with no fragile components, aimed to withstand a 2 m drop. The detector design avoids typical fragile components such as crystals, photo multiplier tubes and anode wires potentially prone to vibration/microphonics. The basic signal processing is performed directly in the gas volume, minimizing the need for signal feed throughs. The design is very compact and fully integrated in the detector, providing demonstrated stable performance over a temperature range of -30°C to 45°C (according to the vendor’s claims). The detector specifications are given in Table 3.10.

Table 3.10. Specifications and performance parameters of

	Model S-670	Model S-1270
Physical Specifications (incl. electronics)	87.5 cm total, 60 cm sensitive length 5.2 cm diameter 6.6 kg	147.5 cm total, 120 cm sensitive length 5.2 cm diameter 10 kg
Neutron Detection Performance	Fast neutron sensitivity: 0.040 cps/ng ^{252}Cf at 2 m Intrinsic thermal neutron sensitivity: 5% over an area of 240 cm^2	Fast neutron sensitivity: 0.080 cps/ng ^{252}Cf at 2 m Intrinsic thermal neutron sensitivity: 5% over an area of 480 cm^2
Gamma-Ray Rejection	Gamma-ray rejection: 10^{-7} <10% change in neutron count rate in up to 200 µSv/h gamma-ray background	Gamma-ray rejection: 10^{-7} <10% change in neutron count rate in up to 200 µSv/h gamma-ray background

Fast neutrons are detected directly as they scatter elastically off of the pressurized helium fill gas, which then produces scintillation light that in turn is detected by SiPM light sensors. On-board electronics perform digital PSD to reject gamma-ray induced events and provide a TTL pulse for each detected fast neutron. The detectors provide fast recovery times and good timing resolution.

A ^{6}Li-based coating on the inside of the pressure tube can optionally be provided to capture thermal neutrons, thus emitting highly energetic charged particles (an alpha particle and a triton) in the process. The energy of the charged particles is converted into light and collected the same way as the light from a fast neutron interaction.

Examples of potential applications include:

- Dry cask fingerprinting: Mounted in a collimator vertically above a dry cask, these detectors can be used to verify which slots of a dry cask are occupied by spent fuel in cases where continuity of knowledge was lost [Chung 2014].
- Coincidence counting: Well-counters based on fast neutron detectors allow coincidence counting using short coincidence windows (of the order of tens of nanoseconds), thereby nearly eliminating accidental coincidences [Murer 2011].
- Active Interrogation: Since these detectors can operate at significantly higher gamma ray fields than liquid scintillators, they are well suited for active interrogation applications such as differential die away measurements [Lewis 2014; Lewis 2014b].
- Reactor and spent fuel monitoring: Customers are investigating the use of Arktis' fast neutron detectors for reactor and fuel monitoring in novel applications [Chung 2014].

3.3.9. Gd-lined Plastic Scintillator Technology

The Gd-lined plastic scintillator detector was developed in collaboration between INFN and Ansaldo Nucleare (ANN) within the European Project SCINTILLA [SCINTILLA]. The device is a Radiation Portal Monitor (RPM) and represents a prototype ^{3}He-free neutron detection technology designed for a specific application in the nuclear safety field.

RPM systems are usually made of 2 pillars of twin detectors placed as a gate to scan vehicles or cargo containers as illustrated in Figure 3.28. Most of them have two distinct detection systems, one for neutrons and the other one for gamma radiation. The neutron sensitivity is necessary to detect plutonium, which is the only natural neutron emitter, while gamma ray detection is necessary to identify SNM and radioactive sources such as naturally occurring radioactive materials, medical radioisotopes and orphan sources. Important requirements are good gamma-ray detection efficiency over a wide energy range (50 keV - 2.2 MeV), good neutron/gamma discrimination to detect masked neutron sources and good sensitivity to both fast and moderated neutron sources.

Figure 3.28: The INFN/ANN RPM prototype during the blind benchmark in the ITRAP+10 JRC facility. The trolley, used for testing, is transiting in between the 2 pillars.

The Gd-lined plastic scintillator RPM provides these functionalities using a single technology for both neutron and gamma-ray detection. The system consists of two twin detectors, the RPM pillars, connected to a single readout electronic box. A proprietary algorithm is used to reconstruct single neutron events, calculate the rate as a function of time and issue an alarm signal if the neutron rate exceeds the natural background. Gamma-ray signals are detected and counted as a function of the reconstructed energy: event rates are estimated in different energy windows giving information on the energy of the radioactive source. The analysis algorithm is embedded in the System Control Software (SCS) of the RPM, which runs on a computer connected to the electronics box. This allows for configuring and operating the RPM, and provides a graphical user interface for the users. The SCS also correlates in real time the detected neutron and gamma rates to transits of vehicles, generating specific output data required by standards of the category.

The Gd-lined plastic scintillator RPM was tested, in parallel with other similar systems, during a blind benchmark at the JRC (Ispra) ITRAP+10 facility as shown in Figure 3.28. The selected test procedures were developed in order to verify the compliance of the RPM performances to international standards (IEC and ANSI) and determine the system detection limits. Test procedures require the detection in real time of radioactive sources transiting in between the RPM pillars. The results showed that the Gd-lined plastic scintillator RPM is capable of detecting gamma-ray sources as well as moderated and non-moderated neutron sources, alarming in 100% of the transits while keeping the False Alarm Rate within the limits established by standards [ANSI N42.35]. The standard requires 1000 transits with no alarms to test the false alarm rate, while the system had more than 3000 transits and only 1 false gamma-ray alarm and no neutron alarms.

It was also demonstrated that the system performance is comparable to, and sometimes exceeds, commercially available systems. The only limitation encountered during tests was related to the system capability of detecting a neutron source masked with a strong gamma-ray source (^{137}Cs 7.67 GBq in this case, giving a 100 µSv/h dose at the RPM surface). The limitation was proven to be due to saturation of the commercial data acquisition system used for the detector readout. In fact, the repetition of the same test with different readout configurations demonstrated that, even in these extreme conditions, the detector remains sensitive to neutrons.

In summary, the Gd-lined plastic scintillator technology was developed for a specific nuclear safety application obtaining very positive results and performance that complies with international standards. The flexible design of the detector allows it to adapt to different applications, while the plastic scintillator robustness, moderate cost and commercial availability of the components make it relevant for applications requiring large active surfaces or large detection volumes. The capability of performing real time measurements, neutron event counting with a fast response and high neutron detection efficiency are aspects that could make this technology an interesting candidate for replacing ^{3}He detectors in the field of nuclear safeguards.

3.4. Semiconductor Detectors

Optimization of semiconductor neutron detectors specifically for nuclear safeguards applications represents a relatively recent development. The technology typically involves a semiconducting wafer doped or lined with materials containing ^{6}Li or ^{10}B. Similarly to scintillator-based technologies, one of the key challenges for this technology will involve efforts to optimize efficiency performance in the presence of gamma-ray backgrounds typical for safeguards applications. In addition, the small size of the individual detectors (typically less than ~100 cm^{2}) will require multiple detector configurations to achieve system dimensions typical for a nuclear safeguards environment. This brings additional challenges involving the setting of signal processing electronics to match the response of individual components and assure the overall long-term and environmental stability of the complete system. The semiconductor technologies currently under development for nuclear safeguards typically involve small subsystems of several individual detectors in the form of planar or cylindrical arrangements to represent a full-scale single detector module. The present report is focused on technologies discussed and presented within the scope of the ^{3}He alternatives workshop series, however, several other developments involving semiconductor technologies are currently being pursued, the details of which can be found in the following references [Fronk 2015, Mandal 2014].

3.4.1. Silicon Pads with ^{6}Li Converters

For the detection of thermal or low energy neutrons as an alternative to ^{3}He proportional counters, semiconductor-based detectors can be used in combination with a neutron reactive film, usually called a neutron converter, which converts neutrons into charged particles [Manfredotti 2005, Nikolic 2006]. The main characteristics of a converter suitable for use in combination with a solid-state detector are large neutron absorption cross section, small gamma-ray emission, and presence of decay channels into energetic charged particles. The two nuclear species commonly considered suitable for neutron converters are ^{6}Li (natural abundance ≈7%, thermal neutron cross section ≈940 b) and ^{10}B (natural abundance ≈20%, thermal neutron cross section ≈3840 b).

The detectors under development at the National Institute for Nuclear Physics (INFN) utilize ^{6}Li because, after capturing a neutron, it has a unique decay channel accompanied by no gamma-rays, with a higher available kinetic energy and with lighter particles produced, therefore easier to detect than in the case of

^{10}B. It is used in the form of LiF, enriched to 95% in ^{6}Li, which is a stable and inexpensive salt that can be deposited uniformly in very thin layers onto rather large substrates up to several hundreds of cm^2. Based on these assumptions it can be shown that low-cost solid state neutron detectors with good neutron/gamma-ray discrimination can be built. The individual detectors exhibit a rather low intrinsic efficiency, however, a new implementation has shown considerable improvements [Finocchiaro 2015].

The light charged particles produced in the neutron capture reaction lose some of their energy passing through the converter material. The amount of energy loss depends on the converter material itself, the particle type and its energy; therefore the choice of converter film thickness that can be practically used is limited. Moreover, the reaction products entering the detector must have sufficient energy in order to produce signals large enough for charged particle discrimination from the gamma-ray background. The dependence of the spectrum shape on the converter thickness has been observed in several papers [McGregor 2003, Baker 2002, Philips 2007, Uher 2007, Voytchev 2003, Barbagallo 2013] where it is evident that a thinner film ensures a better separation between the reaction products and the background, although the detection efficiency becomes smaller.

Figure 3.29 schematically illustrates the conversion mechanism of a neutron inside the ^{6}LiF layer. The case shown makes use of a double-sided silicon pad detector, 3 cm x 3 cm, 300 μm thick, with a neutron converter on each face. The ^{6}LiF deposition on the substrates was done in house, and the choice of having the converter independent of the detector allows for an efficient modularity, operation, partial replacements and re-configurability. In Figure 3.30 we show a picture of a nine-tile detector prototype, which was sandwiched between the two converters and then placed inside a neutron moderator made from polyethylene blocks, in order to be tested with an AmBe neutron source. Testing was performed under several different configurations, in order to investigate the detector response. Figure 3.31 shows superposition of three typical spectra that were obtained with one detector tile under the following respective conditions: no neutron source, converters installed (area 1); with neutron source but no converter (area 2); with neutron source, converters installed (area 3). It is immediately apparent that the spectrum without the neutron source is entirely below about 0.3 MeV due to background gamma (and cosmic) rays.

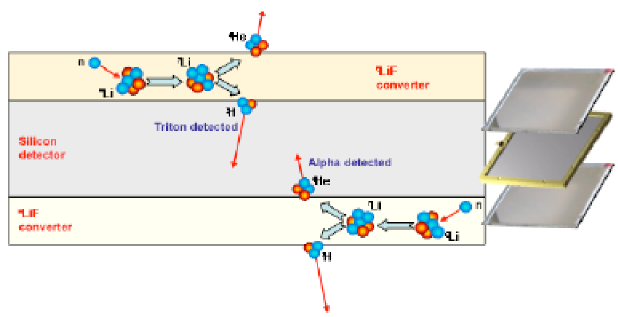


Figure 3.29. Sketch of a thermal neutron detector consisting of a double-sided silicon detector coupled with two ^{6}LiF neutron converters. Since the neutron energy is very low, the reaction products are emitted in opposite directions in the laboratory frame, and only one is detected.

When exposing the detector without neutron converters to the AmBe source, the only contribution to the spectrum comes from gamma-rays. In this case it can be seen that such a contribution is below ≈ 0.5 - 0.6 MeV. Conversely, when installing the two converters and exposing the full sandwich to the neutron source, a very different spectrum shape can be seen corresponding to the detection of alpha and triton particles and representing a signature of a neutron detection. The intrinsic efficiency of each 1.8 μm thick ^{6}LiF converter is about 1%, therefore with two converters it becomes 2%. Thicker layers have already been tested, showing that the neutron absorption efficiency can easily reach up to 10%-20%. In such a case, even though the spectrum shape broadens towards lower energies, the separation of tritons from gamma-rays is still well defined to clearly identify neutrons.

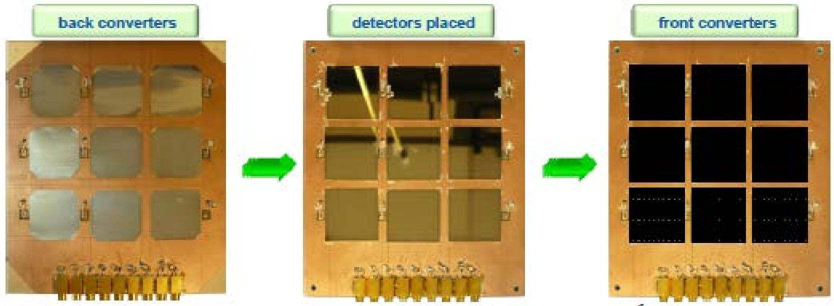


Figure 3.30. Nine silicon detector pads tiled and sandwiched between two ^{6}LiF neutron converters.

It can be anticipated that the use of ^{6}LiF, in suitable arrangement onto several substrates, could represent a viable replacement of ^{3}He in various applications including, for instance, homeland security or nuclear safeguards. Two possible applications are currently being pursued by INFN. The first one involves a set of neutron sensitive panels placed around nuclear material in a 4π solid angle coverage for coincidence neutron counting applications [Reilly 1991, Ensslin 1998]. The second application under consideration is the extension of the Detector Mesh for Nuclear Repositories (DMNR) system [Finocchiaro 2011] developed for the online monitoring of radioactive waste repositories. In the new configuration such a system would also be equipped with a large number of small neutron detectors, capable of ensuring the continuity of knowledge on spent fuel rods sealed inside their casks. This technology is aimed at preventing the diversion of fuel elements for illegal or, worse, weapons use in line with IAEA safeguards [IAEA 2007]. A patent has also been filed for a design using ^{6}LiF converters with scintillators [Finocchiaro 2013].

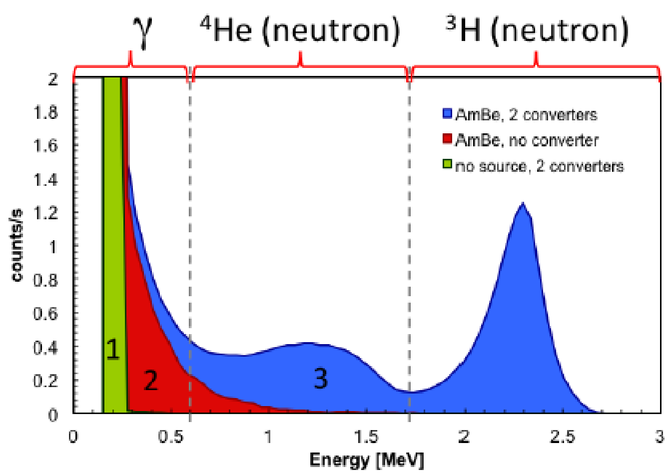


Figure 3.31. Three typical spectra obtained with the detector under the respective conditions: no neutron source, converters installed (area 1); with neutron source but no converter (area 2); with neutron source, converters installed (area 3).

4. Overview of Selected Technology Benchmarking

Within the second workshop, held at JRC Ispra, JRC hosted a comparison benchmark exercise that took place in the PERLA laboratory on the two days before the workshop start (October 13th-14th, 2014). The scope of the benchmark exercise was to inter-compare the performances of several prototype neutron counters based on alternative technologies and to compare them to standard ^{3}He-based devices typically used by the IAEA and Euratom for safeguards inspections. Six prototypes were tested and compared to three reference ^{3}He instruments corresponding to three different usage cases, as described in Table 4.1. Four of the prototypes involved full-scale coincidence counters and two represented single modules. During the benchmark exercise, each developer operated their own instrument, whereas JRC staff operated the reference instruments.

Table 4.1. Prototype ^{3}He alternative technologies tested in the benchmark exercise.

Usage cases	Reference ^{3}He instrument	Alternative prototypes	Developer
Passive coincidence counting in Pu-bearing cans	HLNCC	GERS-NCC BCS-based HLNCC Well counter with ^{6}Li/ZnS blades	GERS PTI Symetrica
Active coincidence counting for fresh fuel elements	UNCL	LS-NCC	IAEA
Neutron monitors	UNCL slab	Parallel-plate boron-lined slab counter Stilbene scintillator	LANL Univ. of Michigan

4.1. Testing Comparison Procedures

The purpose of the benchmark exercise was to demonstrate the performance of alternatives to ^{3}He systems against safeguards relevant parameters, and perform benchmarking of these systems against available reference ^{3}He-based systems. The key component of this activity involved side-by-side comparative measurements of a range of available SNM samples in the ^{3}He-based systems and their proposed alternatives. The actual procedures were slightly different for the three usage cases as detailed in the following sections. It should be pointed out that environmental and long-term stability measurements, that represent one of the key safeguards relevant parameters, were not performed during the benchmark exercise due to the limited time available. Future performance assessments of each of the systems should include the overall stability, reliability and reproducibility to address all aspects essential for safeguards performance.

4.1.1. HLNCC-type counters

The main benchmarking parameters for the high-level neutron coincidence counter (HLNCC) comparison were:

1. *HV characteristic and gamma-ray sensitivity*: The HV characteristic was measured in the presence of a ^{252}Cf and ^{137}Cs gamma-ray source (with dose rates of operational interest – see Table 4.3.) to establish the optimum HV setting for benchmarking measurements and efficiency evaluation.
2. *Efficiency*: Using an available well-characterized ^{252}Cf source and the optimized HV setting determined in step 1, the neutron detection efficiency was measured and compared with the reference ^{3}He-based system.
3. *Figure-of-Merit*: The die-away was measured and then the FOM was computed as FOM = $\varepsilon/\sqrt{\tau}$ and compared to the reference ^{3}He-based system.

4. *Gamma-ray sensitivity*: Measuring a strong gamma-ray source in the absence and presence of a reference ^{252}Cf source assessed the influence of gamma-rays.
5. *Statistical uncertainty*: Side-by-side measurements were performed using the available SNM samples in the alternative and reference ^{3}He-based systems, and the statistical uncertainty was compared.

4.1.2. UNCL-type counters

The main benchmarking parameters for the uranium neutron coincidence collar (UNCL) were:

1. *Efficiency*: Using an available well-characterized ^{252}Cf source, the neutron detection efficiency was measured and compared with the reference ^{3}He-based system.
2. *GARR*: The gamma-ray rejection was estimated by adding a strong gamma-ray source (3.7 MBq ^{137}Cs) to the reference ^{252}Cf source.
3. *Statistical uncertainty*: Side-by-side measurements were performed mimicking passive and active fuel measurements in the alternative and reference ^{3}He-based systems, and the statistical uncertainty was compared.

Due to the unavailability of a real fuel element, the operating conditions were simulated by placing a ^{252}Cf source in the cavity providing a fission rate comparable to that expected in the presence of a fuel element. Three types of measurements have been simulated:

- Passive measurement (with a weak ^{252}Cf source in the cavity reproducing the spontaneous fission rate from ^{238}U).
- Active measurement in thermal mode with an AmLi source in the lateral slab and a strong ^{252}Cf source in the cavity reproducing the induced fission rate in ^{235}U in thermal mode (ratio AmLi/^{252}Cf = 10:1).
- Active measurement in fast mode with an AmLi source in the lateral slab and a weak ^{252}Cf source in the cavity reproducing the induced fission rate in ^{235}U in fast mode (ratio AmLi/^{252}Cf = 100:1).

4.1.3. Monitor Detectors

By their nature, slab monitors are scalable, so the efficiency has to be compared either as intrinsic efficiency (neutrons detected per neutron hitting the surface of the detector) or the absolute efficiencies should be normalized per unit surface or solid angle covered. In the case of the systems demonstrated during the benchmark exercise, the main purpose was not necessarily to provide a direct comparison of efficiency with ^{3}He-based detectors. For the technologies presented during the benchmark, the key focus was on the neutron/gamma-ray discrimination and improved count rate capability for stilbene scintillators of UM and boron-lined parallel-plate slab of LANL, respectively.

4.2. Benchmarking Results

The following sections summarize the main results obtained during the benchmark exercise. Figures 4.1 – 4.2 show the alternative technology systems that were benchmarked against the reference ^{3}He systems. Figure 4.1 (left) is the GERS ^{10}B-based ABUNCL modified to a well counter configuration (GERS-NCC) that uses 2.54 cm diameter boron-lined proportional counters. Figure 4.1 (center) shows the PTI BCS-based well counter using thin diameter boron-lined proportional counters. Figure 4.1 (right) shows the Symetrica ^{6}Li/ZnS-based well counter. Figure 4.2 is the IAEA developed LS-NCC fast neutron detector.

Figure 4.1. (left) GERS-NCC, modified ABUNCL well counter; (center) BCS-based HLNCC well counter developed by PTI; (right) well counter with ^{6}Li/ZnS blades developed by Symetrica.

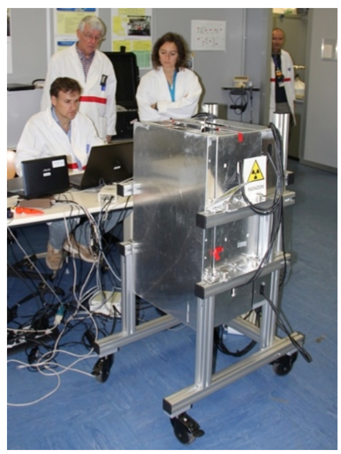


Figure 4.2. LS-NCC fast neutron detector developed by IAEA.

4.2.1. HLNCC-type counters

The major detection characteristics for the three ^{3}He-alternative coincidence well counters compared to the ^{3}He-based HLNCC reference are reported in Table 4.2 as measured for optimum HV selected as described in Section 4.1.1. Note that the GERS-NCC used vendor specified HV of 800V, which was confirmed to be optimum for the tested gamma-ray source as shown in Figure 4.3 (bottom). The optimum HV for BCS-based HLNCC corresponded to 850V. Figures 4.3 (top-bottom) report the HV plateaus for the three proportional-counter-based systems.

Table 4.2. Detection characteristics of HLNCC-type prototypes (^{3}He-based system in first column).

Safeguards parameters	^{3}He-based HLNCC	GERS-NCC	^{6}Li/ZnS based HLNCC*	BCS-based HLNCC
Efficiency [%]	16.50	10.20	8.90	13.56
Die-away time [μs]	43.30	65.40	55.90	26.00
FOM (ε/√τ)	2.51	1.26	1.19	2.66

*results for ^{6}Li/ZnS based HLNCC represent values for partial system (8 contrary to 24 blades)

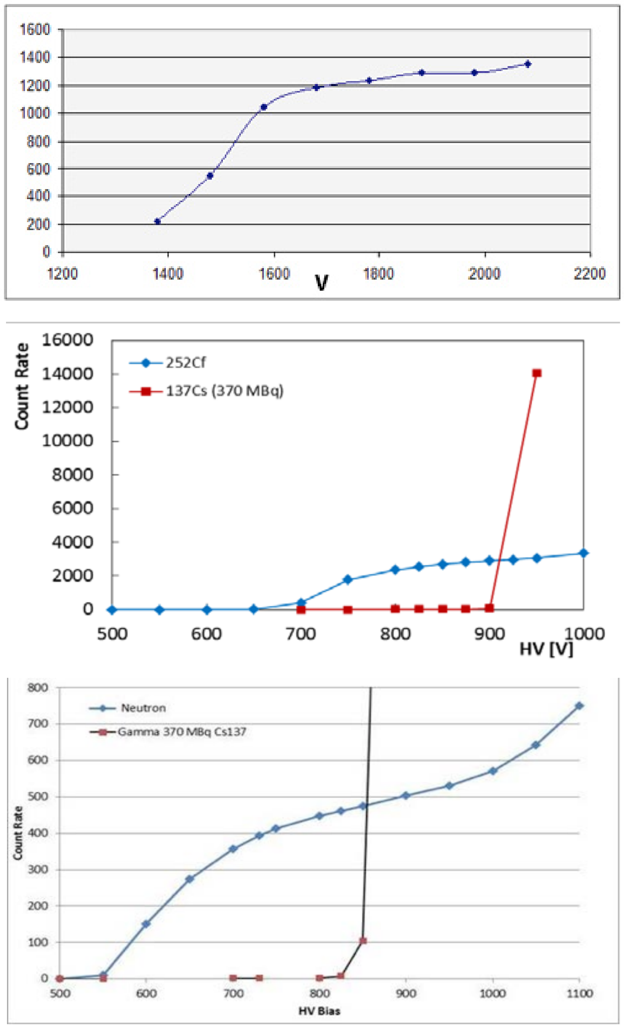


Figure 4.3. HV characteristics for (top) ^{3}He-based HLNCC; (middle) BCS-based HLNCC; (bottom) GERS-NCC.

Table 4.3 provides the performance with respect to gamma-ray sensitivity. Table 4.4 summarizes the statistical uncertainty for measurements of available MOX samples. Measurement with ENEA02 sample was not performed in BCS and ^{6}Li/ZnS based HLNCC counters due to time limitations. Finally, Tables 4.5 and 4.6 report the Pu mass accuracy evaluation for a set of plutonium samples for the two systems (GERS-NCC and BCS-based HLNCC) that had a preliminary calibration (the ^{3}He-based HLNCC did not have a calibration). The effect of deadtime is negligible due to low rates.

Table 4.3. Gamma sensitivity results of HLNCC prototypes as configured in the benchmark.

Source type	Source strength	^{3}He-based HLNCC		GERS-NCC		^{6}Li/ZnS based HLNCC		BCS-based HLNCC*	
		Singles [s^{-1}]	Doubles [s^{-1}]	Singles [s^{-1}]	Doubles [s^{-1}]	Singles [s^{-1}]	Doubles [s^{-1}]	Singles [s^{-1}]	Doubles [s^{-1}]
^{137}Cs	3.7 MBq	40.3	0.008	11.4	0.013	0.7	0.000	4.9	0.003
^{137}Cs+^{252}Cf		1196.6	218.003	1888.6	178.779	1688.5	116.680	NA	NA
^{252}Cf	~7000 n/s (~20,000 n/s for ^{6}Li/ZnS system)	1194.1	215.991	1893.9	183.927	1674.5	115.520	NA	NA

*note: further source combinations were not measured in BCS-based HLNCC, since no elevated counts within background were observed with ^{137}Cs only

Table 4.4. Statistical uncertainty on Pu sample measurements of HLNCC prototypes as configured in the benchmark.

	^{3}He-based HLNCC	GERS-NCC	^{6}Li/ZnS based HLNCC	BCS-based HLNCC
ENEA01 (168 g Pu)				
Measurement time [s]	600	600	600	600
Doubles [s^{-1}]	1088.95	315.81	165.33	770.76
σ	8.71	3.74	4.39	4.19
Relative precision [%]	0.80	1.18	2.66	0.54
ENEA02 (191 g Pu)				
Measurement time [s]	600	600	NA	NA
Doubles [s^{-1}]	1242.54	357.43		
σ	9.94	4.99		
Relative precision [%]	0.80	1.40		

Table 4.5. Mass accuracy for Pu sample measurements with the GERS-NCC.

Item ID	Measurement time [s]	Doubles RSD [%]	Pu mass [g]	σ (tot) [g]	Declared Pu mass [g]	(Meas-decl)/decl [%]	Measured Multiplication*
WG-PuO_2	900	2.84	5.85	0.07	5.82	0.5	1.004
RG-PuO_2	600	2.11	5.33	0.06	5.53	-3.6	1.017
WG-Pu metal	330	3.89	9.70	0.39	9.39	3.3	1.000
WG-Pu metal	6630	0.88	9.56	0.13	9.39	1.8	1.000
MOX	600	1.18	161.68	2.49	163.84	-1.3	1.000
MOX	600	1.57	163.19	3.03	164.09	-0.6	1.000
RG-Pu metal	600	1.46	8.87	0.16	9.34	-5.0	1.000
RG-Pu metal	600	1.96	8.97	0.20	9.34	-4.0	1.000
MOX	600	1.40	182.99	3.13	186.11	-1.7	1.000

*note: Multiplication was set equal to 1 for samples where measured M was <1

Table 4.6. Mass accuracy for Pu sample measurements with the BCS-based HLNCC.

Item ID	Measurement time [#repetitions x s]	Doubles RSD [%]	Pu mass [g]	σ (tot) [g]	Declared Pu mass [g]	(Meas-decl)/decl [%]	Measured Multiplication*
WG-PuO_2	1865 x 30	0.23	5.98	0.11	5.83	2.7	1.010
RG-PuO_2	20 x 30	1.16	5.40	0.11	5.53	-2.3	1.016
RG-PuO_2	120 x 30	0.33	5.41	0.11	5.53	-2.1	1.016
WG-Pu metal	40 x 30	1.26	9.45	0.22	9.39	0.6	1.000
MOX	20 x 30	0.54	161.6	3.35	163.85	-1.4	1.000

*note: Multiplication was set equal to 1 for samples where measured M was <1
RG-Pu metal items and the larger MOX sample were not measured with the BCS-based HLNCC due to time constraints.

The results of the HLNCC benchmark comparison can be summarized as follows:

- The BCS-based HLNCC by PTI exhibited a slightly lower efficiency than the ^{3}He-based HLNCC, but a shorter die-away. As a combination of the two, it had a slightly better FOM, with the effect confirmed by the lower statistical uncertainty in the ENEA01 MOX sample measurement. In addition, it had better gamma-ray rejection (*the results for these measurements are missing in the Table 4.3*).
- The partial ^{6}Li/ZnS based HLNCC by Symetrica (8 out of 32 blades present) exhibited half of the efficiency of the HLNCC and a longer die-away time, but the prototype contained only one quarter of the expected blades. Monte Carlo extrapolations have estimated that a full system

would have an efficiency of 25%, a die-away time of 31 μs and a FOM of 4.5 (60% better than the HLNCC). The gamma-ray sensitivity for the 3.7 MBq ^{137}Cs source was comparable with the HLNCC.

- The GERS-NCC system showed less performance than the HLNCC both in terms of efficiency as well as die-away time. But, this demonstrator unit was created as a direct modification of a collar prototype and as such it was not optimized in terms of geometry for comparison to a ^{3}He-based HLNCC. The benchmark exercise provided a useful performance overview and proof of feasibility of the technology. Additional optimization should be performed. The gamma-ray sensitivity for the ^{137}Cs source was comparable to the HLNCC.

4.2.2. UNCL-type counters

The results for the UNCL comparison are reported in Table 4.7. From the data it can be concluded that the LS-NCC has the potential to provide better performance than an UNCL, especially for measurements in fast mode (used mostly for Gd-loaded fuel elements).

Table 4.7. Comparison of results for a ^{3}He-based UNCL and the LS-NCC.

Safeguards parameters	^{3}He-based UNCL*	LS-NCC*
Efficiency - singles (S) [%]	10.01	9.54
Efficiency - doubles (D) [%]	3.23	3.43
GARR S/(S+γ) at 3.7 MBq	< 1.0e-8	8.4e-4
D - passive mode (^{252}Cf only)	61.55±0.87%	67.30±0.50%
D – active thermal mode (AmLi** + ^{252}Cf 10:1)	64.78±2.05%	68.98±0.49%
D – active thermal mode (AmLi** + ^{252}Cf 100:1)	4.07±9.77%	4.77±1.87%

* Results are not corrected for dead-time
**AmLi source strength ~50,000 n/s

4.2.3. Monitor Detectors

For the University of Michigan, the goal of the benchmark exercise was to demonstrate the capabilities of novel plastic scintillators (in particular stilbene) as dual-particle detectors with satisfactory gamma-ray/neutron separation using PSD. Figure 4.4 shows the gamma-ray sensitivity results. The neutron detection in presence of a strong gamma-ray source was unaffected up to a dose rate of 30 μSv/h.

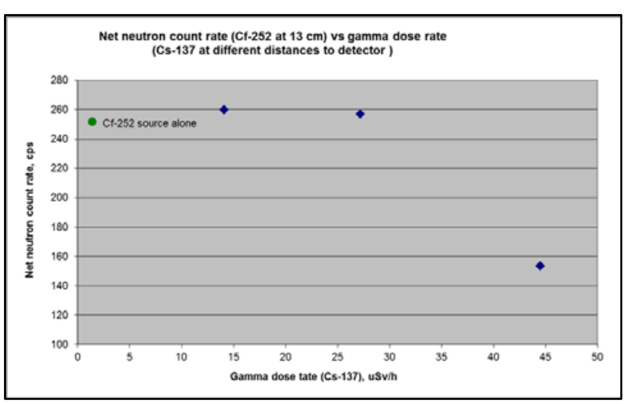


Figure 4.4. Gamma-ray sensitivity of stilbene detectors

For the parallel plate slab, the main purpose was to demonstrate the high count-rate performance of a novel PDT-developed fast amplifier compared to the standard PDT-10A amplifier. The comparison was performed using list-mode data acquisition. Unfortunately, the response of the parallel-plate module was affected by noise on one of the amplifiers that degraded the performance of the detector during the benchmark exercise. Results of an earlier comparison are summarized in Figure 4.5 that shows the detail of time-interval distributions spanning over the initial 10 μs for the boron-lined parallel-plate counter as well as the standard 2.54 cm diameter ^{3}He tube. A gap at the beginning of each distribution corresponds to the time window affected by dead-time from the previous pulse. It can be seen that the boron-lined parallel-plate detector with fast amplifier exhibits significantly faster recovery after time 0 than the other detector/amplifier configurations. It is worth noting that shaping time characteristics of this prototype PDT fast amplifier are similar to the standard AMPTEK amplifier (~200 ns). Nevertheless, the boron-lined counter exhibits faster initial recovery than the standard ^{3}He-based tube, demonstrating the influence of detector signal shape on the overall system timing.

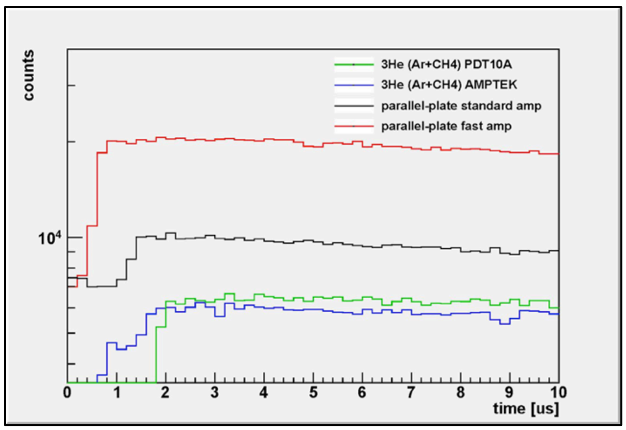


Figure 4.5. Performance at high count-rates (time interval plot) for the boron-lined parallel-plate slab with fast amplifier compared to standard 2.54 cm diameter ^{3}He tube using different typical amplifiers.

5. Key Recommendations and Consensus Observations

The workshop held at JRC Ispra was concluded with a round table to which all participants contributed. The discussion was structured as four consecutive topics, and for each topic an expert was invited to present a short statement that was supposed to trigger a discussion involving the entire audience. The four discussion topics were:

- Technical challenges
- Standardized best practices for testing instruments
- Use cases and technology gaps
- Implementation and path forward

The following sections summarize the discussion around these four topics.

5.1. Technical Challenges

(Facilitator S. Croft, ORNL)

In the introductory statement the facilitator noted three major technical challenge areas for research:

1. The need to further develop the fundamental theory of coincidence and multiplicity counting,
2. Improve simulation tools for alternative technologies.
3. Availability of experimental facilities and round robin exercises.

There probably will not be a one size fits all solution, rather, the safeguards applications should seek to match technologies to specific uses. This might increase the number of technologies that end users may have to implement for safeguards.

In some cases, a change from the classical way of working could be needed; the traditional way of measuring coincidences through shift register logic could be replaced by other way of processing raw data, in particular for fast neutron detectors. In this view, list mode data collection and analysis can open up a wider spectrum of possibilities for data processing. The use of fast neutron detectors (organic scintillators) would get a remarkable boost from developments in the data acquisition electronics: for instance, the capability to perform PSD analysis in real time and/or wave form digitalization. The use of neutron spectroscopy could bring some advantages, but this needs to be first investigated and assessed.

The lifetime of the new technologies must be demonstrated. Proportional counters using ^{3}He have a long history of use over decades. The implementation of new technologies leaves open the question of whether they will maintain performance over many years, or will degrade in time. The lifetime performance needs to be known, or monitored, before new technologies can be used reliably.

Current Monte Carlo simulation tools work very well for ^{3}He counters, but require improvements to properly model the physics of the novel technologies. Modeling of boron or lithium based detectors require a complete charged particle transport, whereas organic scintillators need modeling of a complex process including light emission/transport/collection and computation of pulse shape/height distributions. Improvements in this area will require developing models at a single module level to thoroughly understand the underlying phenomena.

The need was identified to bring appropriate competencies from different disciplines to the field of non-destructive analysis (NDA). Finally, the issues related to cost of development of ^{3}He-alternative technologies were discussed in light of the relatively small market presented by the safeguards community. The IAEA typically requires only a few instruments to satisfy routine inspection requirements.

5.2. Standardized Best Practices for Testing

(Facilitator R.T. Kouzes, PNNL)

The first fundamental question is: There are no current standards for safeguards and do we need them? The safeguards "market" is relatively small and restricted. Thus, there may be no justification for the effort to develop safeguards standards.

As a consequence, the next question follows: Can best practices replace standards and how? The answer is probably yes, but this would in any case require an intensive review of testing campaigns and the publication of agreed consensus testing methods and protocols.

Benchmarking of technology is an alternative to specific standards, where the best of class is determined. The organization of benchmarks can be challenging, mostly from a logistic point of view. Benchmarks can be performed both as inter-comparisons (among different technologies) and versus real material. These benchmarks need to be targeted to end-user goals. Use-cases are valuable in defining scenarios for benchmarking.

The expected performance of instruments should be driven by the end-user needs. For instance the International Target Values (ITV) of the IAEA are useful for some applications, but are not fully comprehensive and are, in any case, determined by experience in past performances.

In addition, there is no certification of instruments currently in place due to the high cost of maintaining the ISO certification process. Viable systems are typically authorized for use by IAEA after thorough evaluation and comparison with relevant reference systems.

5.3. Use Cases and Technology Gaps

(Facilitator R.D. McElroy, ORNL)

A challenge statement: Since ^{3}He supply will be available in the short term and due to the highly attractive attributes of ^{3}He-based system performance, some new technologies might find use only in specific safeguards applications. Developers should aim to identify and target where their technology fits and where it can provide a viable solution for replacement or for improving the current situation. For instance, attended/unattended applications might be tackled from different perspectives.

Use cases where current equipment is not fully satisfactory and where research and development should be focused can include:

- Fresh fuel with poisons
- Fresh fuel with heterogeneity
- Partial defect in spent fuel
- Encapsulation/final repository safeguards

5.4. Implementation and Path Forward

(Facilitator T.H. Lee, IAEA)

The facilitator presented the IAEA perspective on ^{3}He shortage and listed recommendations considered most relevant for implementation:

- Optimize the use of ^{3}He (e.g., use of modular detector assemblies - maintain a reserve of standard ^{3}He tubes to repopulate different fielded assay instruments; consider hybrid ^{10}B+^{3}He proportional counters with lower ^{3}He pressure [developed and demonstrated in an ABUNCL variant by GERS, but not yet fielded])

- Replace ^{3}He by ^{10}B or other alternatives for less challenging applications and where efficiency is not an issue (e.g., gross counting)

- Continue to rely on ^{3}He for demanding applications (e.g., multiplicity counting)
- For active interrogation applications, use fast neutron systems (e.g., organic or noble gas scintillators)
- Additional information could be obtained from gamma-ray plus neutron detectors (multi-particle coincidences)

According to IAEA, other properties of replacement technologies that are needed include:

- High fidelity Monte Carlo modeling of the ^{3}He-alternative system must be possible
- Compatibility with existing electronics is strongly desired
- Ability for a simple physical swap is desired

Finally, the requirements for future systems should take into account the ability to be deployed in the field (weight, cost, stability, etc.), the user friendliness of the system, and the authorization process through evaluation versus existing systems.

The IAEA recommendations are essential for future safeguards technology developments, however, needs of new facilities under current or future development need to be factored in to obtain a comprehensive overview on the future of the nuclear safeguards landscape.

6. Topics Needing Further Development

As outlined in the previous section, the workshops identified several focus areas that will require further development to assure a fully deployable infrastructure for the ^{3}He-alternative technologies. The key areas include gaps in current performance evaluation best practices and available technology, modifications to the data acquisition and analysis framework and declaration of item-based scenarios to help assess the detector/system performance. Each of these topics will be addressed in more detail in the following sections.

6.1. Use Case Scenarios

The concept of Use Cases has been introduced to aid in the evaluation of potential detection technologies relative to the needs of an international safeguards program. Neutron coincidence and multiplicity assay represent the primary methods for quantification of Pu in MOX, and account for the lion’s share of the ^{3}He consumed in safeguards measurements. Potential ^{3}He-alternative neutron detection technologies must be evaluated in the context of the safeguards measurement to be performed and must consider a broad range of factors beyond detection efficiency. It is beneficial to consider the operation of the fully-scaled assay systems (not just the neutron detector module) as they would be used in a typical production facility. By consideration of the existing installed base and projected future facility needs, it is possible to gage the impact of a given detector technology and its value as a replacement to the current ^{3}He biased safeguards infrastructure.

The “Use Case Scenario” examines the capability of the candidate neutron detection technology to meet the safeguards objective for the system in which it will be used, on the materials for which it will be used, operated in the manner in which it will be used, and in the environment in which it will be installed.

6.1.1. Neutron Detection vs. Assay Performance Goals

Safeguards measurement objectives are normally discussed in terms of precision and accuracy within a prescribed measurement time. The performance of the assay system is generally discussed in terms of the properties of the collection neutron detectors within the system taken as a whole and described by a detection efficiency (ε), die-away time (τ) and FOM ($\frac{\varepsilon}{\sqrt{\tau}}$). These metrics are valuable in the evaluation of a detection technology but are not sufficient to determine the ability of the system to achieve the safeguards objectives for the measurement. In neutron coincidence or multiplicity assay a number of additional factors impact the measurement performance such as sample mass, plutonium isotopics, physical and chemical form of the special nuclear materials and the sample matrix.

Examples of the application specific factors that need to be considered in the evaluation of a candidate detection technology include:

- Dynamic Range vs. Pu Mass Range: Pu and MOX samples occur in many forms such as clean product grade materials to dirty, high-burn scrap. The measurement system must accommodate the sample sizes, sample mass range, neutron emission rates, and decay heats. It is not uncommon for a given assay system to accommodate neutron emission rates spanning 5 orders of magnitude. Detectors, electronics, and analysis software must be designed to accommodate the extreme count rate ranges while meeting the target performance goals.
- Form Factor vs. Facility Constraints:
    - Footprint Limitations: Floor space is limited within active nuclear facilities and comes at a high price. As a facility is designed, constructed, and commissioned, modifications to accommodate NDA measurement systems becomes progressively more difficult such that the NDA system must physically fit within the existing or allocated footprint and is subject to floor loading constraints. Physically larger, heavier systems are generally less desirable than smaller ones.
    - Practicality: Routine system operations cannot be onerous to the facility. That is, operations such as loading and unloading samples must be achievable within the normal operating constraints of the facility (e.g., attended systems are generally loaded manually without the need for steps, ladders or overly extending the operator).
    - Seismic Qualification: The assay system will be installed within an active nuclear facility and must meet the structural requirements of the facility. Larger, heavier systems introduce more risk in a seismic event. The assay system must be physically robust and allow for proper anchoring when required.
    - Maintenance Access: Regardless of the projected reliability of a new technology, systems must be accessible for maintenance purposes. Additionally, the NDA system cannot permanently block access to process areas needing periodic maintenance. The systems must in general be easily moveable or removable.
- Environmental Response vs. Facility Constraints: Safeguards measurements are often carried out under industrial rather than laboratory conditions. Environmental factors such as temperature, humidity, dust and vibration are generally poorly controlled yet the measurement system must provide reliable results across the full range of these conditions. The relevant environmental factors must be identified and the system performance characterized against these conditions.
- Gamma-Ray Sensitivity vs. Sample Exposure Rates: Gamma-ray exposure rates from plutonium and MOX materials can be very high; contact exposure rates in excess of 2 mSv/h are routine and in excess of 10 mSv/h are not uncommon. Detector technologies must be able to accommodate the maximum expected exposure for that application whether through inherent insensitivity to

gamma-rays, distance, or shielding. Of course, it must be remembered that increases to assay system size and weight required for gamma-ray tolerance must be considered in parallel with form factor and seismic constraints.

- Gamma-Ray and Neutron Sensitivity vs. Background Exposure Rates: Gamma-ray and neutron backgrounds within an operating nuclear facility will be elevated relative to normal background levels. The sensitivity of the assay system to external sources of neutron and gamma-ray backgrounds must be considered. External shielding necessary for the proper operation of the system is considered to be an integral part of the assay system and impacts the footprint and seismic evaluations.

To illustrate the value of this approach a single "Use Case Scenario" was selected here as an example. In this case, a simple neutron coincidence counting application performed in attended mode. The example was chosen because the assay system ultimately fielded for the application was an HLNCC-II of the same model used as the reference counter in the JRC workshop benchmark exercise.

6.1.2. Plutonium Inventory Monitoring

The Pu inventory monitoring systems provide quantitative mass assay of Pu-oxide and MOX containers of product and clean scrap materials. These are generally modest performance neutron coincidence systems with detection efficiencies of less than 25% and die-away times of less than 50 μs (typically $2 < FOM < 3.5$) constructed for use in either attended or unattended monitoring and are used to verify the declared mass of plutonium within an item. Because of the large number of these systems (more than 100 in current use) this class and the relative importance of the measurements, these counters represent an important category of safeguards systems that must be supported into the future. These counters individually require only a relatively modest volume of ^{3}He (20 to 100 liters) however collectively they represent a total safeguards investment of several thousand liters. Three different types of coincidence counters that are considered plutonium inventory monitors are shown in Figure 6.1.

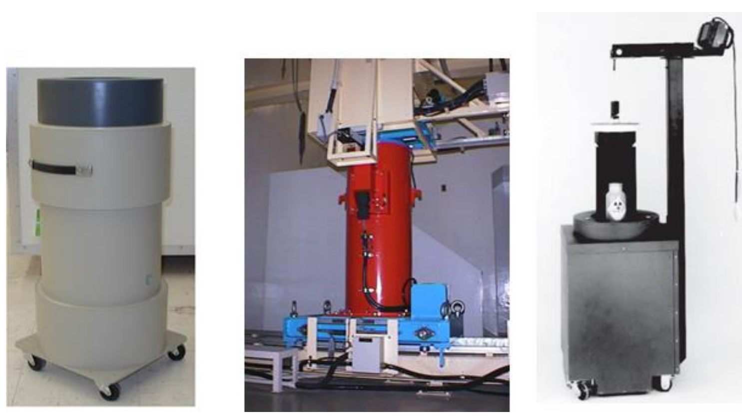


Figure 6.1. Examples of Plutonium Inventory Monitoring Systems. From left to right the HLNCC-II [Menlove 1979], PCAS [Menlove 1995], and Flat Square [Menlove 1989] Counters.

As a typical Use Case for a plutonium inventory monitor the following real world example is considered: *Measurement of product grade MOX containers for material balance within a storage vault.*

The materials and performance goals in this example are typical of a MOX fuel manufacturing facility. Definition of the required assay system properties must consider a large number of factors. These factors are summarized as follows:

I. Sample Description:

- Material Forms: Pellets, Product Powders, Clean Scrap

- Scrap: similar to product materials but may contain small impurities
- Chemical form of each material type is well characterized and known
- Pu Isotopic abundances for each sample are available and well known

- Mass Range: 50 - 1200 g Pu in MOX
- $^{240}Pu_{eff}/g \sim 0.36$; $^{241}Am \sim 2\%$
- Container Sizes: 10-13 x <25 cm (OD x H)

II. Measurement Description:
Verification of operator plutonium mass declarations by neutron coincidence assay combined with declared isotopics data for each container. The agreed upon assay performance requirements for the measurement were typical of those encountered in MOX production facilities:

- Goal Measurement Performance:
  - $\sigma_{systematic}$: <0.5%;
  - $\sigma_{random:}$ < 1% product, 2% scrap
- Measurement time: 1800 seconds

III. Complicating Factors:

- System storage location: Outside vault
  - Required Portable System (2 man carry, fit through standard door)
- Assay location: Inside vault
  - Elevated neutron/gamma-ray backgrounds, nearly isotropic in distribution

IV. Environmental Conditions:

- Nominally Environmentally Controlled: ΔT+/-5 °C, Humidity <90%

In selecting the appropriate neutron assay system for this application, the first step is to examine the various assay error contributions relative to the target performance goals. The well characterized materials allow the use of known alpha, neutron coincidence counting analysis where two unknowns in the neutron assay are assumed, the $^{240}Pu_{effective}$ mass and the sample multiplication (i.e., multiplicity analysis is not required). It is <u>assumed</u> that the uncertainties due to the chemical form of the plutonium are negligible, as are the error contributions from the declared isotopic values. The dominant sources of error under such conditions are:

- Spatial uniformity of the neutron counter response: The neutron detection performance of the counter should not vary significantly (relative to the target performance values) across the container volume. The error contribution due to variations in material fill height and radial extent should not have a significant impact on the measurement result.

- Measurement precision: The measurement precision for an assay system is determined by the material characteristics, neutron detection efficiency and die-away time, background conditions, and the assay time allotted. The measurement precision is generally the largest contributor to the total measurement error.

- Linearity of the neutron detection performance as a function of neutron energy: An ideal counter will have a flat efficiency profile as a function of neutron energy. However, in this example, the neutron energy variation from item to item is small such that a linear energy response profile is not a key requirement. It is sufficient to require that the assay cavity be lined with cadmium to eliminate re-entrant thermalized neutrons from inducing fission within the sample.

- Calibration errors: Calibration error is generally limited by the quantity and quality of the available calibration standards. These standards must be representative of the items to be verified.

In general the calibration error will be small relative to the measurement precision and spatial uniformity effects.

In consideration of the systematic errors, for this example the only significant error term under the control of the system designer is the spatial uniformity of the neutron counter response. For a traditional ^{3}He proportional tube based system spatial uniformity is improved by increasing the assay cavity size within the limits of practicality and cost. The appropriate cavity size is determined either by examining measurement performance data of similar systems or by use of Monte Carlo modeling tools. However, as a general rule of thumb, for ^{3}He-based systems the assay cavity height should be at least equal to the height + diameter of the container and the inner diameter of the cavity should be 1.5 to 2 times the diameter of the container.

The random uncertainty contribution is addressed by selection of an assay system with a sufficiently high FOM. In a normal background environment an assay system with a FOM of ~1 would be sufficient to meet this performance requirement for this example. However, the elevated neutron background levels encountered in the measurement area drives up the required FOM. Modeling suggested that a FOM of greater than 2 was required. Systems providing neutron detection efficiency of 15% or more with a characteristic die-away time of 50 μs or less would meet this requirement.

The mass range, chemical form and isotopic abundances, allow us to estimate the maximum neutron emission and gamma-ray exposure rates. The detectors, acquisition electronics, and analysis computer must be able to accommodate the maximum expected exposure rates. The neutron emission rates and exposure rates are estimated from the sample mass range and chemical form:

- Expected neutron emission rate: < 1.5×10^{6} n/s
  The hypothetical 15% efficient neutron assay system would need to tolerate neutron count rates of 2.3×10^{5} cps in order to accommodate the expected plutonium mass range.
- Gamma-ray exposure rates: < 5 mSv/h
  The neutron assay system must be able to tolerate a significant gamma-ray exposure without misclassifying gamma-rays as neutrons. The typical ^{3}He-based coincidence counter can be operated at exposures between 5 mSv/h and 10 mSv/h so the expected exposure rates would not have been a limiting factor.

The final requirement that the system be man-carried into and out of the assay area for use limits the physical size and weight of the system. The requirement limited the total system mass to less than 50 kg and did not allow significant external shielding. (The measured neutron background count rate with the selected system was 1000 cps).

Rather than build a custom assay system to meet these needs, a COTS system, the HLNCC-II was selected for use in this application. The HLNCC-II provides 18% neutron detection efficiency, a 50 μs die-away time, meeting the measurement precision goals, and the assay cavity 40 cm x 19 cm (H x ID) accommodates the expected range of container sizes. The system had been demonstrated to handle both the neutron-counting rates from the sample and the elevated background conditions. Testing of the HLNCC-II at the MOX facility demonstrated performances consistent with the measurement objectives (Table 6.1).

Table 6.1. Average Biases and Standard Deviation by sample types.

Sample Type	Alpha Weight	Average Bias	Standard Deviation
Pellets	1.0	1.1%	0.8%
Scrap Powder	1.1	1.3%	2.1%
Feed Powder	1.0	0.0%	0.9%
Product Powder	1.0	0.6%	0.8%
Recycled Powder	1.0	-0.6%	0.5%
Scrap Powder	1.0	-2.7%	1.2%
All samples		**0.2%**	**1.6%**

The use case scenario allowed identification of an appropriate assay technology that would meet the target performance values for the specific measurement application. Examination of new detection technologies across a range of potential use cases facilitates assessment of the impact of the candidate technology against the needs for replacement neutron technologies in an international safeguards program taken as a whole. The use case approach allows the determination of whether the candidate technology has broad application or if it is suitable only for niche applications.

6.2. Performance Evaluation Gaps

The discussions during the workshops highlighted the need for well-defined evaluation best practices in order to assure reproducibility, reliability and relevance of the performance evaluations of novel safeguards instruments. The key areas of interest can be divided into two categories including: (1) initial evaluations of prototype technologies in a single module configuration, and (2) evaluations of advanced concepts developed to full-scale system configurations. While the latter can significantly benefit from the definition of use cases as outlined in the previous section, the former presents a significant challenge due to variables including geometry, number of detection units, amount of moderating material (for thermal neutron detectors), etc. Appropriate definitions of detection efficiency and die-away time, two key parameters, then becomes of essential importance. In addition, quantification of performance based on safeguards FOM represents another aspect that needs additional attention and appropriate definition.

As addressed during the LANL workshop on ^{3}He alternatives and described in detail in [Dolan 2013], the concept of FOM, defined as $\varepsilon/\sqrt{\tau}$ (used in this report) or alternatively ε^2/τ [Evans 2012], represents well defined metrics for a subgroup of ^{3}He-alternative technologies over a limited range of measurement scenarios. Specifically, such a definition of FOM was derived for thermal neutron coincidence counting applications under the assumption of a high contribution of accidental coincidences and may not be valid for fast neutron counting systems, where no thermalization process is required. The coincidence gate requires only tens of ns in fast neutron counting applications, essentially removing the contribution of accidentals to the measurement gate. Similarly, for small Pu-bearing items (less than ~tens of grams) such an approximation is no longer valid due to the reduced contribution of accidental coincidences. Thus strictly speaking, the currently established FOM is only valid for large mass samples (i.e., high count rates) in thermal neutron counters. Therefore, a cautious use of the FOM was recommended during the workshops. The FOM can largely be substituted by a definition of use case scenarios that would allow for application specific evaluation of system performance for the given anticipated use. Such a concept would help to significantly simplify and clarify performance evaluation activities on a full-system level. Initial suggestions on use case scenarios were discussed in the previous section.

Nevertheless, a well-defined metric will still be required for evaluation of single module prototypes that represent a necessary initial step in the evaluation of merit of any newly developed ^{3}He-alternative technology. For single module prototypes, the performance metric will likely involve assessment against a full set of key safeguards relevant attributes including neutron detection efficiency, gamma-ray discrimination, long term and environmental stability and dead-time. Die-away time will be of importance for assessment of thermal neutron counters. It is of particular importance to establish best practices for these evaluations. Among the key considerations are:

- definition of an appropriate and relevant ^{3}He reference to be used as a comparison benchmark
- efficiency and die-away time evaluation for realistic system configuration
- well defined and reproducible measurement configuration
- selection of neutron and gamma-ray sources representative of realistic measurement scenarios

To define an appropriate ^{3}He reference, considerations including similar physical dimensions or detector versus source arrangements (solid angle effects) as well as ^{3}He tube arrangements and parameters (gas pressure, diameter) are of high importance. For situations, where a ^{3}He-based reference is not readily available, Monte Carlo simulations of ^{3}He systems could be considered, provided the model has been appropriately benchmarked. A similar approach was adopted in [Henzlova 2012a]. The ^{3}He-alternative module should be evaluated in a configuration including the optimum amount of moderating material (for thermal neutron counters) or realistic (usable in practical applications) lead shielding for scintillator-based technologies. Finally it is essential to establish a measurement configuration that assures reproducibility of the measured results and minimizes neutron scattering into the system under evaluation.

To appropriately evaluate the detection efficiency it is essential to account for the measurement scenarios anticipated under real world conditions. In particular, the use of gamma-ray sources with dose rates of operational interest is needed along with neutron sources to establish key operating parameters such as electronics thresholds/gains and HV settings as well as optimize neutron/gamma-ray discrimination algorithms. The gamma-ray emission rates vary with the type of sample and some of these aspects can be included based on use case scenarios. Nevertheless, typical safeguards applications require gamma-ray backgrounds significantly higher than many other applications (typically up to ~10 mSv/h at the detector face) and corresponding dose rates should be used in practice. Evaluations involving technology prototypes will often be performed by commercial developers with limited access to radiation sources. Therefore, the initial evaluation will largely rely on measurements using commercially available sources such as ^{252}Cf or gamma-ray emitters such as ^{137}Cs or ^{60}Co. Such evaluations, if performed under the conditions mentioned above, provide good initial representation of the technology performance to assess merits for further development. The next stages of technology evaluation should include more realistic samples to allow for complete technology assessment under realistic conditions. Therefore, collaborations with national laboratories equipped with special nuclear materials should be included to allow for extended technology evaluation.

6.3. Data Acquisition Needs

Traditional nuclear safeguards rely on use of multiplicity shift registers (MSR) such as the AMSR [Stewart 1999] or JSR-15 [Menaa 2007]. These units are equipped with electronics capable to perform correlated counting. The data from MSR are typically analyzed using International Neutron Coincidence Counting (INCC) software [Krick 2010] that performs data quality checks, background and dead-time corrections and calculates item specific parameters (Pu mass, multiplication and/or contribution of random neutrons from (α,n) reactions). The combination of MSR/INCC represents a standard toolkit utilized and authorized by the IAEA inspectorate. The MSR is designed to accept digital signals corresponding to neutron detection times (pulse train). It is of high importance to the IAEA to maintain the existing infrastructure, as any modifications would naturally require re-training of the instrument operators and facility personnel. Designs of technologies considered for nuclear safeguards use are therefore encouraged to provide similar output for plug-in replacement features.

Development of ^{3}He-alternative technologies goes hand-in-hand with new, possibly non-standard requirements on the associated data acquisition and analysis tools. The majority of the technologies presented in this document were designed to provide MSR compatible digital signal for a seamless transition. Nevertheless, some technologies, in particular technologies that rely on neutron/gamma-ray discrimination algorithms, will require a certain amount of pre-processing or storing of the full pulse shapes for post-analysis. In addition, fast neutron detectors provide neutron detections on much shorter timescales than traditional thermal neutron detectors with essentially instantaneous detection of correlated signal, and as such, will require different analysis software than standard INCC/JSR15. Finally, the benchmark exercise at JRC, Ispra, highlighted the increased interested in list mode data acquisition as multiple alternative systems were equipped with list mode data acquisition units.

The scintillator technologies typically require advanced neutron/gamma-ray discrimination algorithms to allow for efficient neutron and gamma-ray identification. The recent developments in these algorithms allow performing this analysis in real-time, and output single digital stream corresponding to pre-identified neutron signals. Nevertheless, these algorithms require additional processing time that could considerably slow down the data acquisition, and result in increased overall system dead-time. Additional work will be required to optimize these algorithms for feasibility for high count-rate/high gamma-ray background applications involving for example large mass items (hundreds of grams to kilograms of Pu).

In addition to MSR based acquisition, the IAEA has recently authorized use of list mode capable data acquisition devices, specifically the Pulse Train Recorder (PTR-32) unit developed in Hungary [PTR-32]. The advantage in the use of list mode data acquisition consists of increased flexibility of data analysis due to the availability of a full record of the detected pulse train. Key features include state of health monitoring, utilization of alternative analysis algorithms, advanced data analysis, etc. The first item benefits from records of individual subcomponents (e.g., signal processing amplifiers) of a given detection system. Availability of this information provides for a direct monitoring of the state of health of individual channels, simplifies troubleshooting and identification of potential failures, as well as providing tamper resistance due to multiple channels being monitored simultaneously. Advanced analysis of list mode data for safeguards is a relatively new subject that is currently being extensively explored. Approaches involving algorithms typically used in the field of sub-criticality experiments that rely on Feynman variance approach [Croft 2012] are under investigation [Henzlova 2012b]. Advanced analysis methods that utilize detailed Rossi-alpha information as well as novel dead-time algorithms are also under development [Hauck 2013]. These developments could improve the current coincidence/multiplicity counting applications and improve the quality and accuracy of the assay results. The full benefit of these implementations is yet to be demonstrated. In addition, techniques involving fast counting systems exhibit very different timing characteristics than thermal neutron counting systems. As such, they will require different algorithms to extract the correlated information not supported by tradition MSR electronics. Dedicated software developments in this area have already been pursued as presented during the workshops.

The key efforts to proceed with list mode implementation include demonstration of high count rate capabilities, development of efficient data reduction algorithms, and analysis software. Traditional MSR electronics are typically capable of handling count rates of several (up to ~5) MHz. List mode technologies are typically rated to similar count rates, however, a dedicated evaluation of these technologies, including benchmarking against traditional MSR electronics, is needed to fully characterize their capabilities. Data reduction is of fundamental importance for field applications to assure a seamless transition from the point of view of the operator to minimize data storage requirements and re-training efforts. Approaches are currently under development to aid in this transition. Finally, existing software in use by safeguards practitioners will need to be refined to allow for list mode data acquisition and analysis. Similarly, as in the previous case, this effort is currently being pursued at various safeguards institutions including extension of the standard INCC software [Longo 2014]. The use of list mode is becoming increasingly popular and, with improved computing capabilities and promising additional features, could provide an attractive alternative for traditional safeguards applications.

6.4. Technology Gaps

No existing ^{3}He-alternative technology fully matches the capability of ^{3}He for the detection of neutrons and the rejection of gamma-ray interference. In the near term (next five to ten years), there is a good probability that enough ^{3}He will remain available to satisfy the needs of international safeguards. However, within 20 years, ^{3}He supplies will be diminished to the point that the needs of international safeguards will not be able to be satisfied at a reasonable cost.

Thus, the first technology gap that needs to be considered is how to bring the performance and reliability of the current prototype alternative neutron detection technologies to the level that they can be deployed for safeguards use. Several of the alternatives demonstrated to date are promising, but they are not mature. Planning and funding is needed to complete the development of alternatives so that they will be available for routine use within a decade.

A second technology gap is the lack of understanding of the long-term aging of these ^{3}He-alternative technologies. The current ^{3}He-based systems are robust, remaining stable over a lifetime of tens of years. Such a performance basis does not exist for ^{3}He-alternative technologies, except perhaps BF_3-based systems that are generally not acceptable to the safeguards end-user. There is sufficient experience to doubt that the current ^{3}He-alternative-based prototypes will remain stable over many years, and work remains to improve this performance and demonstrate the required stability and precision of systems based on alternatives.

A third technology gap is the need for new electronics and data acquisition capabilities (discussed elsewhere in this report) to match the unique characteristics of the various alternative technologies.

A fourth technology gap is how to make the ^{3}He-alternative-based systems transparent to the safeguards end-user. Current ^{3}He-based systems with standardized shift registers and analysis software are familiar to the safeguards instrument operator. ^{3}He-alternative technologies have different performance characteristics requiring different electronics and analysis methods. These details should be hidden from the end user.

Related to this latter gap is the reality that the ^{3}He-alternative technology used will likely be application specific, with different technologies being optimal for differing safeguards needs. This expands the training and experience that end-users will require in order to perform safeguards measurements unless the technology can be hidden behind a common, familiar user interface.

7. Conclusions and Future Outlook

The series of workshop on ^{3}He-alternative technologies organized jointly by the U.S. NNSA/DOE and Euratom provided unique opportunity for in-depth and intense review and discussions of a range of technologies currently under development for use in nuclear safeguards applications. Direct interaction among international experts, technology users and developers allowed for an efficient and comprehensive information exchange. The workshops highlighted significant progress in the area of ^{3}He-alternative technologies, culminating with a benchmark exercise of several full-scale coincidence counting systems. Hand-in-hand with these advancements, the implementation and deployment questions are becoming increasingly the focus of future considerations in order to assure a smooth transition into the facility environment. The key contribution of the workshops was in formulation of several crucial recommendations and in addressing of outstanding pending issues as discussed earlier in this document.

Overall the workshops presented an important paradigm shift from traditional FOM-based performance evaluations towards a more application-oriented approach as was already discussed in [Dolan 2013]. This modification was driven in part by appreciation of deficiencies of the traditional FOM definition, but above all, by consensus observation that a single ^{3}He-alternative technology will be unlikely to span all the performance aspects of ^{3}He-based counters. Thus, a more individualized approach was recommended, encompassed in use-case scenarios, where a more target use-oriented evaluation is envisioned. Such an approach will not only aid in a declaration of performance evaluation criteria, but also allow for the dedicated development of the individual technologies with emphasis on a specific application space, where the intrinsic features of a given ^{3}He-alternative technology could potentially bring substantial benefits over traditional ^{3}He-based counters.

Another important outcome involved realization of the need for flexibility and openness towards certain modifications of existing data acquisition hardware and software infrastructure. These include the need for efficient and real-time neutron/gamma-ray discrimination algorithms for scintillator-based technologies, growing use of list mode data acquisition, as well as analysis software developments to accommodate fast neutron counting systems and/or list mode data formats. To minimize the impact and re-training requirements on the instrument operators, these modifications should be designed to be largely hidden from the end user. Initial steps to develop and implement these approaches have already been launched.

In addition, a clear need for additional Monte Carlo modeling development was identified to appropriately describe the novel ^{3}He-alternative technologies. This is of particular importance for the IAEA, who expressed a direct interest in high fidelity Monte Carlo models in order to authorize the use of proposed ^{3}He-alternative technologies. In the area of experimental measurements, a need was identified for common guidelines on evaluation best practices to aid in technology evaluation across the entire spectrum of technology developers, including national laboratories as well as commercial vendors. This could be partially encompassed in the proposed use-case scenario definition.

Finally, the key outstanding issue in performance evaluation involves assessment of the environmental and long-term stability and reliability of the ^{3}He-alternative technologies. This remains to be one of the leading concerns and future recommendations to assure full viability of any alternative technology.

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