U.S. DEPARTMENT OF
ENERGY

PNNL-21090

Introduction to Neutron Coincidence Counter Design Based on Boron-10

RT Kouzes
JH Ely
AT Lintereur
ER Siciliano

January 2012

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Pacific Northwest National Laboratory
Richland, Washington 99352

Executive Summary

The Department of Energy Office of Nonproliferation Policy (NA-241) is supporting the project "Coincidence Counting With Boron-Based Alternative Neutron Detection Technology" at Pacific Northwest National Laboratory (PNNL) for development of an alternative neutron coincidence counter.

The goal of this project is to design, build and demonstrate a boron-lined proportional tube based alternative system in the configuration of a coincidence counter.

This report, providing background information for this project, is the deliverable under Task 1 of the project.

Acronyms and Abbreviations

ANSI	American National Standards Institute
AWCC	Active well coincidence counter
BWR	boiling-water reactor
CCC	Channel Coincidence Counter
Ce	cerium
DOE	U.S. Department of Energy
DRCC	Dual-Range Coincidence Counter
ε	Detection efficiency
FOM	figure-of-merit
EC	end cap
HEU	Highly enriched uranium
HLNC	High-level neutron coincidence counter (also HLNCC)
IAEA	International Atomic Energy Agency
ISCC	Inventory sample coincidence counter
LANL	Los Alamos National Laboratory
MOX	Metal oxide (reactor fuel)
PANDA	Passive Nondestructive Assay of Nuclear Materials
PNCC	Passive Neutron Coincidence Col1ar
PNNL	Pacific Northwest National Laboratory
Pu	plutonium
PWR	pressurized-water reactor
SC	sample cavity
SNCC	Solution Neutron Coincidence Counter
τ	die-away time
U	uranium
UNCL	Uranium neutron coincidence collar
UWCC	Underwater coincidence counter

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1. Introduction

The Department of Energy Office of Nonproliferation Policy (NA-241) is supporting the project *Coincidence Counting With Boron-Based Alternative Neutron Detection Technology* at Pacific Northwest National Laboratory (PNNL) for development of an alternative neutron coincidence counter. This report provides background information for this project, and is the deliverable under Task 1 of the project, as described in Section 8.

Coincidence counting is used in applications where the mass of plutonium (Pu) or uranium (U) isotopes needs to be determined for safeguards applications. Such counters use multiple detectors arranged around a sample to provide high efficiency detection of neutrons emitted from the sample.

Neutrons can arise from spontaneous fission, induced fission, (α,n) reactions, and cosmic ray produced backgrounds. Correlated neutrons arise from fission events, which yield multiple neutrons simultaneously. The background events are random neutrons that originate principally from (α,n) reactions, or, for active systems, from the source used for interrogation.

The even-numbered isotopes of Pu (^{238}Pu, ^{240}Pu, and ^{242}Pu) spontaneously fission, producing neutrons at a rate of about 2500, 1020, and 1700 per gram-second, respectively [PANDA 1991]. When Pu undergoes spontaneous fission, two or more neutrons may be emitted almost simultaneously, with an average number of neutrons per fission between 2.16 and 2.26. For example, the probabilities P(n) for n neutrons to be emitted by the spontaneous fission of ^{240}Pu are given in Table 1.1 [Diveri 1956]. Uranium isotopes, and odd-numbered Pu isotopes, spontaneously fission at a much lower rate (0.0003 to 0.05 per gram-second) [PANDA 1991]. However, fissions can be induced in ^{239}Pu, ^{235}U, and ^{238}U by an external neutron source. The rates of singles and doubles (coincident) neutrons from spontaneous or induced fission are detected by a coincidence counter.

Table 1.1. Pu neutron multiplicity probability.

Number of Neutrons Emitted	Percent Probability of That Number Being Emitted
0	4.9
1	21.4
2	32.1
3	28.2
4	11.2
5	2.1
6	0.1

The equations for analysis of coincidence counter data can be found in [Bohnel 1985; Hage 1985; Lu 1992; PANDA 1991]. Thus, only a summary is provided here from Lu [1992]. For a coincidence counter, the sample information of interest for Pu is calculated from the number of singles (totals) and doubles (coincidences or reals). The singles rate (T) is the total number of detector triggers, and the reals rate (R) is the coincidences, related to the sample and detector parameters by:

$$T = \varepsilon\, M\, \nu_{1s}\, (1+\alpha)\, C\, m \qquad \text{Eq. 1.1}$$

$$R = \tfrac{1}{2}\, \varepsilon^2 M^2 f\, [\nu_{2s} + \{(M-1)\, \nu_{1s}\, \nu_{2i}\, (1+\alpha)\, C\, m /(\nu_{1i} - 1)\}] \qquad \text{Eq. 1.2}$$

T	totals count rate
R	reals coincidence count rate
ε	detection efficiency
ν_{1s}	first moment $<n_s>$ of the spontaneous fission neutron emission distribution function, about 2.14
ν_{2s}	second factorial moment of the spontaneous fission distribution function, about 3.735
ν_{1i}	first moment of the induced fission distribution function, about 2.876
ν_{2i}	second factorial moment of the induced fission distribution function, about 6.748
α	ratio of the neutrons from (α, n) reactions to those from spontaneous fission
m	effective mass of ^{240}Pu
C	rate of spontaneous fissions of ^{240}Pu, about 475 $g^{-1}s^{-1}$
f	fraction of neutrons counted within the coincidence gate
M	leakage multiplication factor

Coincidence counters provide a measure of two unknowns, T and R, so two sample parameters can be determined if the others are known. For pure samples, or samples with known impurities, α can be calculated and the equations can be solved for the mass and leakage multiplication. For impure samples whose leakage multiplication is known α and the mass can be determined.

The coincidence logic of the coincidence counter electronics system, usually in a "shift register," records time-correlated neutrons from spontaneous or induced fission ("reals"), and the random neutrons, combining them to get the net signal. The coincidence data is analyzed to give a "^{240}Pu effective" mass (or ^{235}U mass). The ^{240}Pu effective mass is a combination of the ^{238}Pu, ^{240}Pu, and ^{242}Pu masses in a sample given by:

$$m_{Pu240eff} = 2.52\, m_{Pu238} + 1.0\, m_{Pu240} + 1.68\, m_{Pu242} \qquad \text{Eq.1.3}$$

For Pu, this effective mass can be combined with an accurate gamma ray isotopic analysis to determine the individual Pu isotopic mass content.

Coincidence counting is used for all types of Pu-based fuels (fresh and spent), as well as fuel processing, where Pu mass determination is the objective. Spent fuel is a particular challenge, as the large number of fission products masks the residual Pu mass. Active coincidence counting, where an external neutron source provides neutrons that induce fission, is used for U-based fuel.

The majority of neutron measurements made in the field by the International Atomic Energy Agency (IAEA) use coincidence counters and gross neutron detectors. The IAEA has prepared a report *Safeguards Techniques and Equipment* on the various instruments they use [IAEA 2011]. The table from that report listing IAEA coincidence counter types is reproduced in this report in Section 7. A second report from the IAEA, *International Target Values 2010 for Measurement Uncertainties in Safeguarding Nuclear Materials*, provides information about the precision of measurements made with various instruments, and provides one set of requirements for coincidence counters [IAEA 2010].

The shortage of ^{3}He has driven the need for identifying and implementing alternative neutron detection technologies for most applications; future safeguards instrumentation will have to be designed accordingly (Kouzes 2009). Previous projects at Pacific Northwest National Laboratory (PNNL) have shown that there are a number of commercially available alternatives to ^{3}He, and several of them are viable replacements for typical radiation portal monitor applications (Kouzes et al. 2010). For radiation portal monitor testing, the main considerations have been neutron detection efficiency and gamma-ray discrimination, with preference to safe, nonhazardous materials. From previous PNNL testing, at least two technologies were identified as promising replacement technologies: boron-lined proportional counters and light guides coated with ^{6}Li and ZnS. Through an integrated approach of MCNP modeling and physical measurements, PNNL has also gained expertise in the importance and optimization of the moderator surrounding the thermal neutron detector from the radiation portal monitor ^{3}He replacement testing. The experience gained from testing radiation portal monitors will be brought to the application of these technologies to coincidence counting for safeguards applications.

This project focuses on the previously identified boron-lined proportional tube alternate neutron detection technology for implementation into a coincidence-counting system for safeguards. The first year of effort is focused on the design of one selected coincidence-counting instrument using boron-lined tubes. The second year of effort will focus on the construction and testing of a prototype side-by-side with an existing ^{3}He based instrument of the same or similar design.

2. Alternative Technologies for Neutron Detection

Neutron detection is an active area of research and a number of novel technologies and devices that may serve as alternatives to ^{3}He are currently being investigated [Peurrung 2000; Milbrath 2008]. Detectors for safeguards applications require high efficiency and adequate separation of gamma ray and neutron signals [Kouzes 2010]. Liquid scintillator has been used for many years as a neutron detector, where differentiation of the gamma ray signal from the neutron signal is produced by the rise time separation of neutrons and gamma rays, but adequate separation is problematic, as it is for other bulk scintillators. There is a wide array of composite material-type neutron-sensitive scintillating materials available (see, for example, the list of materials in [Koroleva 2005]). There are multiple options for semiconductor-based neutron detectors but these devices tend to be small and thus are not applicable for safeguards-scale systems.

Of the available alternative neutron detection technologies, four have been identified as mature enough to be potentially applicable for use in safeguards systems in the near future: boron trifluoride (BF_3) filled proportional detectors, scintillating glass fiber detectors, scintillator coated light guide detectors, and boron-lined proportional detectors.

BF_3 filled proportional counters: As proportional counters, these are a direct physical replacement for ^{3}He tubes and are a mature technology that have equivalent gamma ray insensitivity as ^{3}He tubes, but have inherently lower neutron sensitivity [Bolewski 2008]. This is primarily because of the lower capture cross-sections and pressure limitations to maintain reasonable operating voltages. Boron trifluoride is also a hazardous gas and transportation of BF_3 is subject to strict U.S. Department of Transportation regulations, and may be prohibited in some locations. The isotopic abundance of ^{10}B in natural materials is about 18%, so the boron in detectors is isotopically enriched to over 90% ^{10}B to enhance the neutron capture probability [Bentley 1958]. Proportional counters filled with BF_3 are commercially available from LND (Oceanside, NY).

Lithium-6 loaded glass fibers: This technology, originally developed at Pacific Northwest National Laboratory (PNNL) [Bliss 1995] and commercialized by NucSafe (Oak Ridge, TN) [Seymour 2000], can be arranged to have comparable sensitivity to a ^{3}He tube assembly. In this technology, ^{6}Li-enriched lithium silicate glass fibers are doped with Ce(III). However, these glass fibers currently do not have the gamma-ray insensitivity required.

Light guides coated with scintillator and lithium-6: This technology, available from several vendors [e.g., Browne 2000], has good neutron sensitivity and neutron-gamma ray separation [Lintereur 2009]. The characteristics of this approach need further exploration to determine its applicability to safeguards applications.

Boron-lined proportional counters: These proportional counters are a direct physical replacement for ^{3}He tubes, do not contain hazardous materials, and have equivalent gamma insensitivity as ^{3}He tubes, but they inherently have lower neutron sensitivity than ^{3}He tubes. This is because the neutron absorber (^{10}B) is on the walls of the tube rather than occupying the entire volume [Lintereur 2010]. One approach to increasing surface area is to construct tubes with interior baffles [Digne 2007]. Another approach is to pack multiple smaller tubes ("straws") into an array [Athanasiades 2005]. General Electric (GE) Reuter-Stokes (Twinsburg, OH) has developed prototypes with multi-tube arrays of boron-lined tubes that show performance comparable to one ^{3}He tube.

Table 2.1 provides information on test results for various alternative neutron detection technologies, as measured at PNNL [Kouzes 2009; Kouzes 2010; Kouzes 2010a; Kouzes 2010b; Kouzes 2010c; Lintereur 2009; Lintereur 2010; Lintereur 2011; Woodring 2010; Woodring 2010a]. The table provides the gamma ray rejection (GRR) fractions, which is the ratio of gamma rays detected as neutrons to the number of incident photons, the gamma-ray absolute rejection ratio (GARRn), which is the ratio of the number of neutrons detected in presence of both a neutron and gamma ray source to the number detected when only the neutron source is present [Kouzes 2011], and the efficiency (ε) in terms of counts per second per ng of ^{252}Cf located at 2 m [Kouzes 2011].

The technologies listed in the table include the ^{3}He and BF_3 proportional counters, five versions of boron-lined proportional counters, two versions of the lithium-ZnS coated light guides, and the lithium loaded glass fibers. Three of the configurations tested were multi-tube proportional counters (MTPC). All of these various technologies can meet the GRR requirement ($<10^{-7}$), and all but the lithium-loaded glass can meet the GARRn requirement ($0.9 <$ GARRn <1.1). The efficiency comparison is done to a full sized ^{3}He module, and results for scaling of different sizes is given in the “Details” column.

There is a broad range of performance seen, with boron-lined straw tubes giving the best efficiency, followed by the (lithium) coated plastic paddles, and one of the MTPC configurations. The efficiency depends strongly on the number and geometry of tubes and moderator design. These need to be varied in models in order to optimize the efficiency for any given tube design.

Table 2.1. Alternative Neutron Detection Technology Comparison.

Detector Type	GRR	GARRn	ε	Details
^{3}He	BT 10^{-8}	1.0	3.13	Single 3 atm tube
BF_3	BT 10^{-8}	Not measured	1.6	Single tube, 3 tubes = 3.0
Boron-lined PC	BT 10^{-8}	Not measured	0.16	Single tube, 3 tubes = 0.25
Boron-lined MTPC	BT 10^{-7}	1.01	3.01	Full volume
Boron-lined MTPC	BT 10^{-8}	1.01	0.98	Single tube
Boron-lined MTPC	BT 10^{-8}	1.06	0.12	12” tube, scaled to 3 full length tubes =~1.5
Straw tubes (B-lined)	BT 10^{-8}	1.0	4.0	Full volume
Coated Plastic Fiber	10^{-8}	1.03	2.0	~ Full volume
Coated Plastic Paddle	BT 10^{-7}	1.01	0.9	Small system, scaled by 4x =~3.5
Lithium Glass Fiber	10^{-7}	1.31	0.32	Middle setting (0.18*volume)

BT = Better Than

This project will utilize the boron-lined proportional counter technology for implementation of a prototype neutron coincidence counter. The current plan is to use tubes manufactured by GE Reuter-Stokes, similar to one as shown schematically in Figure 2.1. The tube length will be chosen, the tube diameter will be varied, and the detector geometry and moderator will be arranged to optimize the coincidence counter performance.

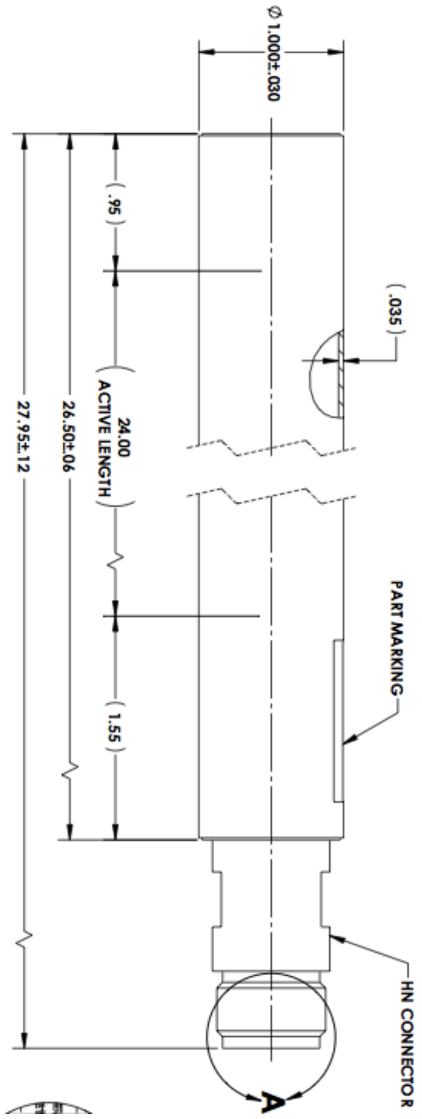

Figure 2.1. Schematic of a GE Reuter Stokes ^{10}B-lined proportional counter.

3. Coincidence Counters

Coincidence counters utilize an array of neutron detectors in a configuration that produces an optimal combination of high neutron detection efficiency and low neutron die-away time. The high efficiency allows coincident neutrons from fission events to be detected among a background of singles neutrons from various processes. Large detection efficiency is required because the efficiency for detecting coincidences varies as the square of the singles efficiency divided by the die-away time. A shift register is typically used to determine the coincidence count rate between the detectors due to fission in Pu or U. These coincident and singles count rates, along with assumptions about multiplication, provide a measurement of fissile mass.

For coincidence counting, the detection efficiency (ε) and the die-away time (τ), which is a measure of how long the neutron takes to slow down (thermalize) and be captured, are the two important parameters. These two key parameters are typically combined to provide a figure-of-merit (FOM), which is optimized for system performance, given by:[1]

$$\text{FOM} = \varepsilon^2/\tau \qquad \text{Eq. 3.1}$$

There are a large number of coincidence counter designs for various applications. The Bibliography of this report (Section 9) lists a number of journal articles on the topic of coincidence counting. The IAEA document *Safeguards Techniques and Equipment* [IAEA 2011] lists those designs used by the IAEA; the table from that report is reproduced in Section 7 of this report (Table 7.1). Most of the coincidence counters listed in the table will not be described here.

Information on the four coincidence counter systems of most interest to this study of alternative neutron detection technology for IAEA safeguards applications is provided below:

- Uranium neutron coincidence collar (UNCL)
- Underwater coincidence counter (UWCC)
- Active well coincidence counter (AWCC)
- High-level neutron coincidence counter (HLNC or HLNCC)

These four coincidence counter instruments are of particular interest because they are commonly used by the IAEA. The UNCL is used for verification of ^{235}U in low enriched U fuel assemblies. The UWCC is used for underwater verification of Pu in fresh MOX fuel assemblies. The AWCC is used for verification of ^{235}U in highly enriched U samples. The HLNC is used for verification of Pu in 20–2000 g canned samples.

Additional devices are described in the PANDA report [PANDA 1991] and the IAEA report [IAEA 2011] that will not be discussed further here, as they are more specialized, or more difficult to assemble or test, but are listed for completeness:

- Inventory sample coincidence counter (ISCC)

---

[1] This FOM is a simplification of the equation [Smith 1989]:

$$FoM = \frac{\varepsilon^2}{\tau s_E s_Z} \qquad \text{Eq. 3.2}$$

where s_E is efficiency as a function of energy and s_Z is efficiency as a function of vertical position.

- Passive Neutron Coincidence Collar (PNCC)
- Solution Neutron Coincidence Counter (SNCC)
- Dual-Range Coincidence Counter (DRCC)
- Channel Coincidence Counter (CCC)
- Bird Cage Counter (BCNC)
- Compact Neutron Coincidence Counter (CNCM)
- Drawer Counter (DRNC)
- Fuel Assembly/Capsule Assay System (FAAS)
- Fuel Pin/Pallet Assay System (FPAS)
- Glovebox Assay System (GBAS)
- Hold-up Blender Assay System (HBAS)
- Inventory Sample Counter (INVS)
- Large Neutron Multiplicity Counter (LNMC)
- Glovebox Counter (MAGB)
- Canister Counter (PCAS)
- Plutonium Neutron Coincidence Collar (PNCL)
- Plutonium Scrap Multiplicity Counter (PSMC)
- Passive Well Coincidence Counter (PWCC)
- Universal Fast Breeder Counter (UFBC)
- Waste Crate Assay System (WCAS)
- Waste Drum Assay System (WDAS)

3.1. Uranium Neutron Coincidence Collar (UNCL)

The UNCL is used for verification of ^{235}U in low enriched U fuel assemblies [Menlove 1981; Menlove 1990]. An example of a UNCL is shown in Figure 3.1 taken from ESARDA [2005].

Measurement of the fissile mass of uranium samples generally requires active techniques due to the low spontaneous fission yields of all the uranium isotopes. Using an external source of neutrons (such as americium-lithium [AmLi]) will induce fission in ^{235}U, resulting in multiple neutrons per fission (mean of 2.41 neutrons per fission induced by thermal neutrons in ^{235}U) that can be measured in coincidence. Coincidence counting with a shift register allows for discrimination between the external source neutrons and neutrons from uranium fission. Coincidence Collars use three or four slabs of detectors surrounding a sample, and are used for measuring fresh fuel assemblies. Measurement of Pu in mixed oxide (MOX) fuel with a Coincidence Collar can be done in passive mode (without external source). For uranium fuel measurements, active mode is used with three slab detectors, each containing four ^{3}He tubes, and a source on the fourth side. The mass of the uranium is determined from this process with an accuracy of 1-5% in measurement times of a few hundred seconds. Figure 3.1 shows an UNCL with one side removed and fuel rods being loaded between two of the three slab detectors. The fuel obstructs the third slab.

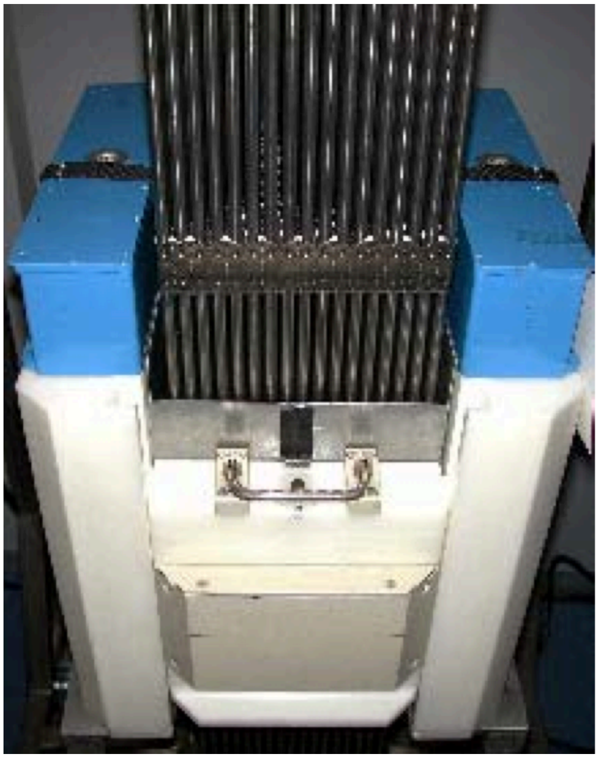

Figure 3.1. Uranium Neutron Coincidence Collar (UNCL) [ESARDA 2005].

3.2. Active Well Coincidence Counter (AWCC)

The AWCC, originally developed by Los Alamos National Laboratory (LANL), is typically used for verification of ^{235}U in highly enriched uranium (HEU) samples. The AWCC is used in active mode for measurements of uranium. One or more neutron sources (such as Am-Li) are inserted in the top and/or bottom of the detector well. Uncorrelated neutrons produced by the neutron source induce fission in ^{235}U samples placed in the measurement well. A shift register is typically used to determine the coincidence count rate due to the induced fission in ^{235}U. The mass of the uranium is determined from this process.

The AWCC is the most common device for measurement of HEU samples (pellets or powder) for nuclear safeguards [Ferrari 2010]. An example of a transportable AWCC is seen in Figure 3.2, taken from Zendel [2007]. Figure 3.3 shows a schematic of an AWCC, taken from El-Gammal (2006). A typical system operates in either fast mode or thermal mode, where the difference is the presence of a cadmium liner in fast mode. Thermal mode is used for low enrichment material and various enrichments where large amounts of hydrogenous material are present [Ferrari 2010]. Measurement times of 500-3000 s are used.

Figure 3.2. Active Well Coincidence Counter (AWCC) [Zendel 2007].

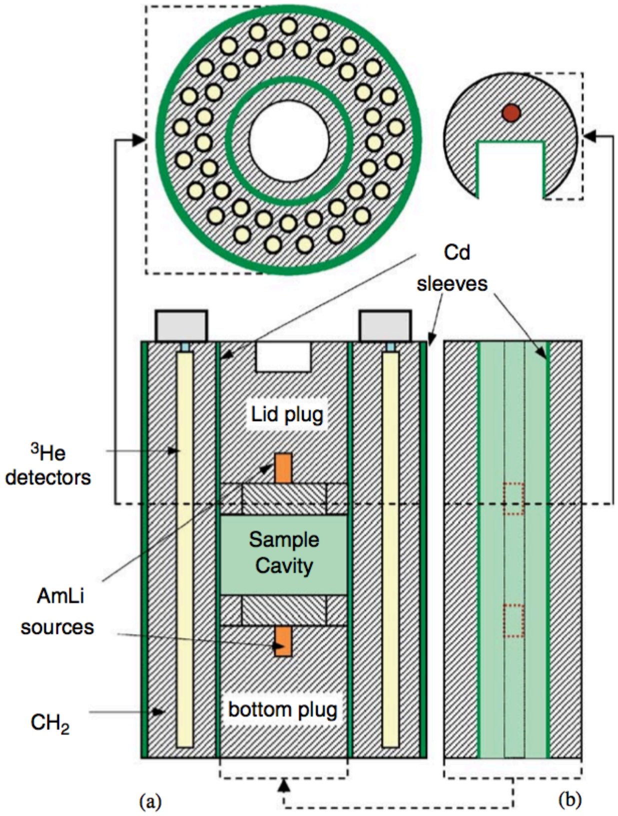

Figure 3.3. AWCC schematic (a) and Material Testing Reactor insert (b) [El-Gammal 2006]

3.3. Underwater Coincidence Counter (UWCC)

The UWCC is used for underwater verification for international safeguards of Pu in fresh MOX fuel assemblies. The UWCC can be applied to either boiling-water reactor (BWR) or pressurized-water reactor (PWR) fuel assemblies to determine plutonium loading per unit length to a accuracy of less than 1% in a measurement time of 120-180 s [Eccleston 1998; Eccleston 1999]. The example of a UWCC seen in Figure 3.4 consists of two detector slabs, each containing four ^{3}He tubes, to be placed around fresh MOX fuel in a water pool. Standard shift register electronics and analysis software are used to determine ^{240}Pu$_{\text{eff}}$ per unit length of a fuel bundle. Corrections for large nonlinear coincidence and multiplicity responses that are produced by the underwater measurements need to be included in the analysis.

Figure 3.4. Underwater Coincidence Counter (UWCC) [Antech Model 2106].

3.4. High-Level Neutron Coincidence Counter (HLNCC)

The HLNCC, developed originally at LANL and seen in Figure 3.5 (from [Zendel 2007]), is used for verification of Pu in 20–2000 g canned samples. Figure 3.6 shows a schematic of the HLNCC [Krick 1979]. The HLNCC is termed high-level because it is designed to handle the high count-rates from several kg of Pu. The performance of the HLNCC was upgraded with higher efficiency, improved ruggedness and transportability, and fast electronics to the HLNC-II [Whan 1987], shown schematically in Figure 3.7. A shift register is typically used to determine the coincidence count rate and ^{240}Pu$_{\text{eff}}$.

Counting times for the HLNC-II are on the order of hundreds of seconds to obtain measurements with several percent accuracy, depending strongly on the material being measured. Doyle [2008, page 44] states that a HLNC-II "can measure large samples of PuO_2 to a precision of 0.5-2% in a 300s count." Guardini [2002, page 23] indicates random uncertainties of ~0.5% and systematic uncertainties of 1-3% for 1000 s measurements of 0.1-1 kg quantities of Pu metal and PuO_2.

Figure 3.5. High Level Neutron Coincidence Counter (HLNC) [Zendel 2007]

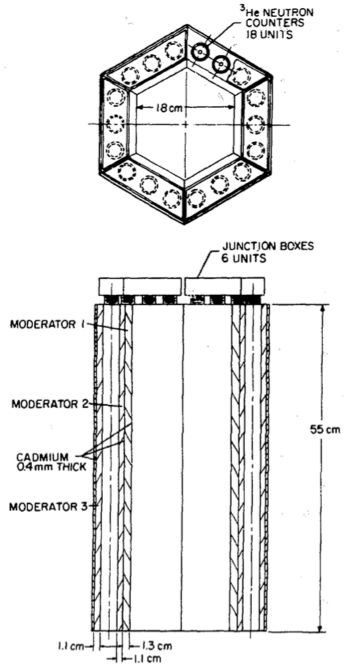

Figure 3.6. Schematic of HLNCC [Krick 1979].

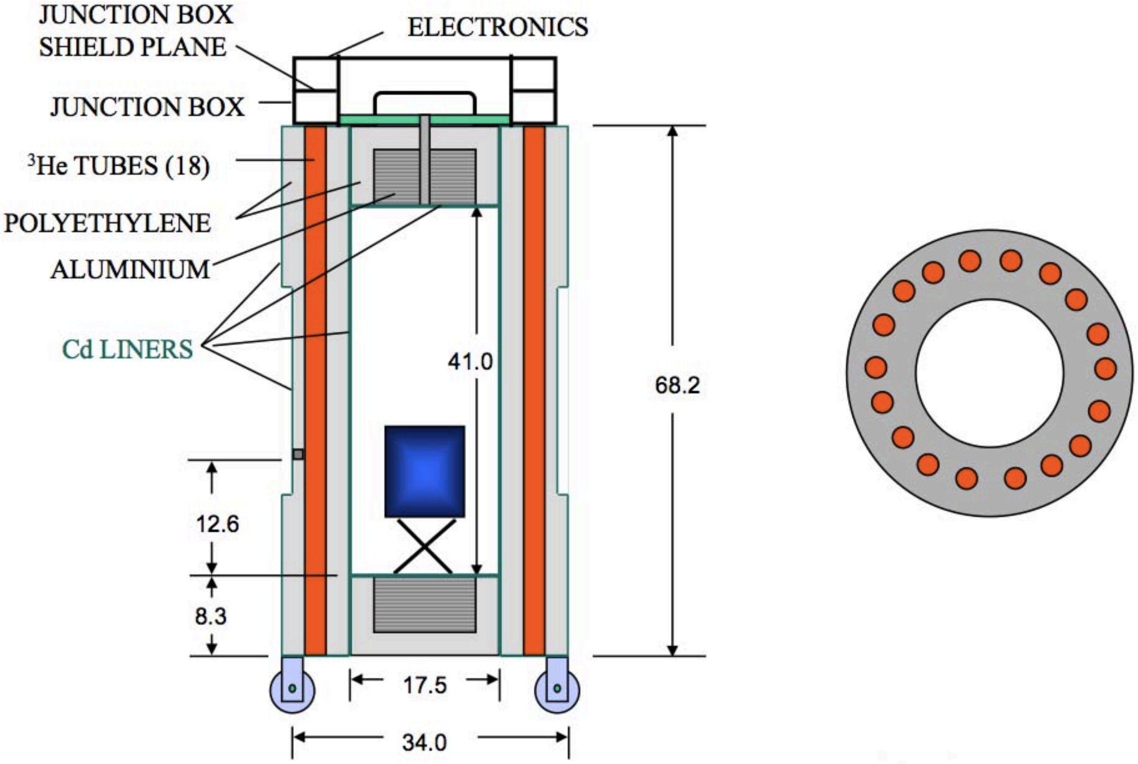

Figure 3.7. Schematic of HLNCC-II [IAEA 2009].

4. Modeling Approach

Task 2 of this project calls for modeling a ^{10}B-based proportional counter implementation of a coincidence counter and will be performed using MCNPX [MCNP 2009].

Simulation is used to vary designs, configurations, and parameters to optimize the neutron detection capability, built on previous experience [Lintereur 2010]. Modeling the complete detection process is complicated with boron-lined tubes, since the process involves two steps: the capture of the neutron in the ^{10}B, and then the detection of the reaction products (either the alpha or lithium ion). Tracking of the lithium ion is a relatively new addition to MCNPX (version Beta 2.7b or newer) [MCNP 2009], and PNNL was the first to use this capability applied to modeling boron-lined tubes [Lintereur 2010]. The tracking of the reaction products is important, as it allows a more complete simulation and allows for optimization of parameters such as the boron lining thickness. The experience and expertise gained in previous boron-lined tube modeling is being applied to this project.

To achieve the performance capability of ^{3}He, alternatives typically utilize multiple units of the detection media. For the boron-lined tubes, the challenge is to maximize the amount of boron, which amounts to maximizing the surface area. There are various approaches to this, including multiple tube configurations and possibly multiple anode configurations similar to wire chambers.

The modeling for this project is being done in two phases. The first phase is to experimentally validate some simple model configurations. The metrics that will be used to validate the model predictions are the efficiency and the die-away time [Henzlova 2010].

The efficiency measurements will be made first with a single tube, and then with a simple multiple tube configuration. The measurements will be performed with bare and moderated sources, several different detector moderator configurations, and with the source positioned at various distances from the detectors.

The die-away time will be measured using the relationship [PANDA 1991; Chapter 16]:

$$\frac{R_1}{R_2} = \frac{1-e^{-\frac{G_1}{\tau}}}{1-e^{-\frac{G_2}{\tau}}} \qquad \text{Eq. 4.1}$$

where $R_1$is the coincident rate with a gate width of $G_1$and R_2 is the coincident rate with a gate width of G_2. If G_2 is set equal to $2G_1$ then :

$$\tau = \frac{-G_1}{ln\,(\frac{R_2}{R_1}-1)} \qquad \text{Eq. 4.2}$$

MCNPX models of the experimental configurations will be developed and the simulated efficiency and die-away times will be compared to those measured. The goal will be to obtain agreement between model and experiment of 10%.

Upon successful validation of the simple design, an iterative design process will be performed with simulations to determine the optimal ^{10}B-lined tube configuration for a coincidence counter. The optimization process will maximize neutron detection efficiency and minimize the neutron die-away time to achieve the highest possible FOM. The detector and moderator geometry will be designed to attain optimal performance in a reasonable system footprint that can be built cost effectively.

Task 3 of this project will be to construct a prototype coincidence counter based upon these modeling results. This task is not funded in the current effort.

A modeling study has been performed at PNNL on some multiplicity counter implementations of ^{3}He alternative neutron detectors [Ely 2011]. The baseline design used in that study was an epithermal neutron multiplicity counter (ENMC-125 [Stewart 2000]) with 121 ^{3}He tubes of 2.54 cm (1”) outer diameter and ten-atmosphere pressure arranged in four circular rings. A top view of the ENMC baseline is seen in Figure 4.1 with the 121 tube locations. The detector body was high-density polyethylene with Cd liners around the sample chamber and the last ring of detectors (to absorb neutrons rather than let them increase the die-away time).

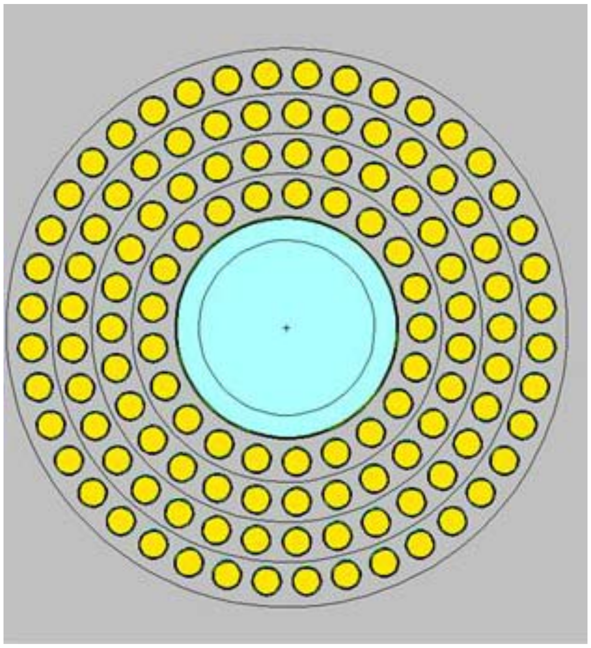

Figure 4.1. Top of ENMC baseline design showing the 121 tube locations in the moderator.

Figure 4.2 shows an ε vs. τ plot for several counter configurations. The solid lines in the figure are contours of constant FOM = ε^2/τ for several values of FOM (indicated with C=), as shown on each line. The response of the baseline ENMC is the red dot, which has 121 ^{3}He tubes at 10 atm. The response of the same ENMC model with a configuration using 121 BF_3 filled tubes at one atm. is shown as the open circle. The response of the same ENMC model with a configuration using 121 boron-lined tubes is shown as the plus sign. The dashed curves show the FOM contours in epsilon-tau space for two example coincidence counter systems (AWCC and HLNC-II) where their FOMs (15.7 and 7.1 respectively) were evaluated from the data given in references [Krick 1979; Menlove 1979]. It can be seen that the 121 boron lined tube configuration of the ENMC can meet the performance of the HLNC-II.

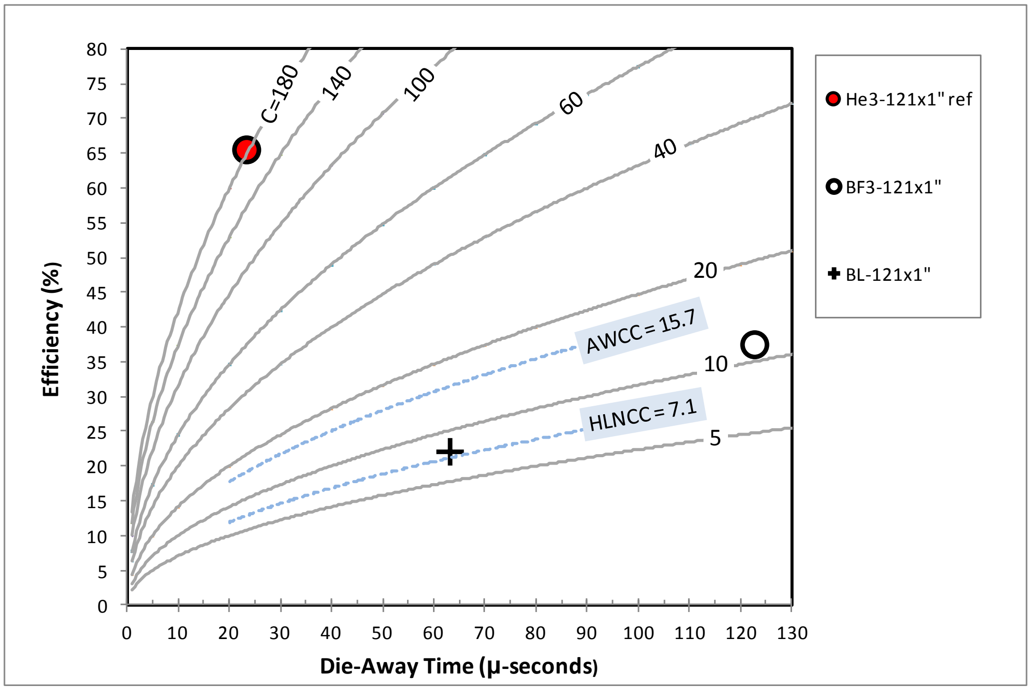

Figure 4.2. Efficiency vs. die-away time comparison of BF_3 and boron-lined tubes in baseline 2.54 cm diameter configuration, with contours for constant FOM.

Table 4.1 provides the characteristics for the HLNCC series and the AWCC. The ENMC is included for comparison purposes. Note the values for efficiency, die-away-time and FOM. The impact of the moderator configuration and the tube pressure is clearly illustrated by comparing the performance characteristics of the HLNCC, HLNC-II and HLNC10.

Table 4.1. Characteristics of various coincidence counters.

Detector	**Total # Tubes, Configuration, & Moderator/EC Changes**	**Active Height (in)**	**Total No. Moles**	**Total-Count Efficiency (ε), in %**	**Die-Away Time (τ), in µsec**	**Efficiency per Mole**	**FOM =ε^2/τ, in units of $(\%)^2$/µsec**
UNCL	18 (Active) – 24 (Passive) in 3(A) –4(P) Rectang. Slabs.	13”	0.44(A) 0.59(P)	13.5 (A)- 11.5 (P)	~51**	30.7 (A) 19.6 (P)	3.6 (A) 2.6 (P)
UWCC	8, in 2 Rectang. Slabs, 7.5-atm.	11”	0.31	5	38	16.1	0.7a
HLNCC	18, in 1 Hex Ring Body: O.D. & middle lined w/ 0.4mm Cd HDPE End Caps	20”	0.68	12	33	17.71	4.4
HLNC-II	18, in 1 Ring, Body: Cd liner Cavity: 41-cm H., w/ Al End Caps	20”	0.68	17.5	43	25.83	7.1
HLNCC10	Same as HLNCC-II, but w/ 10-atm.	20”	1.69	20	37	11.81	10.8
AWCC	42, in 2 Rings, Cavity: 21-23 cm H, w/ Al-HDPE Caps	20”	1.58	33	51	20.87	21.4
ENMC	121, 10-atm in 4 Rings	28”	15.94	65	22	4.08	192

** Evaluated from reported optimal gate width = 1.257 times tau.

Assumption/Abbreviations for Table data, unless otherwise stated:

1) All tubes have 2.54 cm o.d. and filled with 4-atm. ^{3}He (assumed 22.5°C/68°F). Four active heights used were 50.80 cm (20”), 71.12c m (28”), 33 cm (13”), and 27.7 cm (11”) GE-RS model #’s, RS-PR-0820-118, RS-0828-105, RS-P4-2813-107, and RS-P4-0811-105, respectively.
2) All rings are circular,
3) All detector bodies composed of high density polyethylene
4) All sample cavities (SC) and end caps (EC) lined with Cd to absorb/filter low-energy neutrons returning into the sample and causing additional multiplication

5. Selected Coincidence Counter System

The performance characteristics of the HLNC-II coincidence counter is chosen as the baseline for comparison and the goal for the ^{10}B-lined technology to attain, that goal being an efficiency of 17.5%, a die-away time of 43 μsec, and a resulting FOM of 7.1. Although the HLNC-II single-ring configuration will be the starting point, the final configuration will need to be enlarged or otherwise altered to attain comparable performance.

The coincidence counter to be built using ^{10}B-lined proportional counters may not be able to achieve the full performance in efficiency and die-away-time of the existing ^{3}He-based HLNC-II system at a reasonable cost. Modeling has shown that some configurations of boron-lined tubes in large numbers can meet the efficiency and die-away time of the HLNC-II, but the cost would probably be prohibitive using currently available commercial tubes. A compromise may be necessary in order to keep the cost down, with the result that longer measurement times would be needed to reach the detection requirements of the IAEA. Discussions will be held with the IAEA on what those requirements might be. The goal will be to meet the HLNC-II performance, with a fallback goal of meeting the FOM of the HLNCC.

The project will attempt to achieve as much of the performance of the HLNC-II as possible, with trade offs in cost and size.

6. Conclusions

This report provides an overview of neutron coincidence counters for applications in safeguards as the deliverable for Task 1 of the project *Coincidence Counting With Boron-Based Alternative Neutron Detection Technology*.

In selecting the coincidence counter to model, design and build, the practicality of the selection needs to be considered. The UNCL is an active system used for nuclear fuel, which would be difficult to test and introduces the complication of active sources. The AWCC is simple in design, but like the UNCL, introduces the complication of active sources. The UWCC is used for MOX nuclear fuel underwater, and thus would be difficult to test. The HLNC-II is the system design selected for development of a prototype for this project since it is one of the common systems used by the IAEA, is compact, simple in design, test sources are readily available, and an active interrogation source is not needed.

The performance characteristics of the HLNC-II coincidence counter are chosen as the baseline for comparison and goal for the ^{10}B-lined technology to attain. Although the HLNC-II single-ring configuration will be the starting point, the final configuration will most likely need to be enlarged or otherwise altered to attain comparable performance. The project will attempt to achieve as much of the performance of the HLNC-II as possible, with trade offs in cost and size.

The next task in this project is to perform modeling and simulations to first validate the modeling against testing of a simple boron-based system, and then to optimize a coincidence counter design using this alternative technology.

7. Appendix: IAEA Coincidence Counters

This table is taken from the IAEA *Safeguards Techniques and Equipment* [IAEA 2011].

Table 7.1. Table III. Coincident Neutron Detector Systems For Non-Irradiated Fissile Fuel [IAEA 2011]

Code	Equipment name	Primary applications
Passive Neutron Coincidence Counters		
BCNC	Bird Cage Counter	Verification of Pu mass in special storage configurations
DRNC	Drawer Counter	Verification of Pu mass in facility specific containers
FAAS	Fuel Assembly/Capsule Assay System	Verification of Pu mass in MOX fuel assemblies
FPAS	Fuel Pin/Pallet Assay System	Verification of Pu mass in MOX fuel pins in facility specific storage trays
GBAS	Glovebox Assay System	Semiquantitative determination of Pu hold-up in gloveboxes
HBAS	Hold-up Blender Assay System	Semiquantitative determination of Pu hold-up in facility blenders
HLNC	High Level Neutron Coincidence Counter	Verification of Pu in 20–2000 g canned samples (pellets, powders, scrap)
INVS	Inventory Sample Counter	Verification of Pu in 0.1–300 g samples. Modified version can be attached to gloveboxes
LNMC	Large Neutron Multiplicity Counter	Verification of Pu in contaminated/impure items
MAGB	Glovebox Counter	Verification of Pu mass in facility gloveboxes
PCAS	Canister Counter	Verification of Pu mass in MOX canisters
PNCL	Plutonium Neutron Coincidence Collar	Verification of Pu mass in MOX fuel assemblies
PSMC	Plutonium Scrap Multiplicity Counter	Verification of Pu in 1–300 g canned samples of scrap
PWCC	Passive Well Coincidence Counter	Verification of Pu mass in CANDU MOX fuel bundles
UFBC	Universal Fast Breeder Counter	Verification of Pu (up to 16 kg) in FBR fuel
UWCC	Underwater Coincidence Counter	Underwater verification of Pu in fresh MOX fuel assemblies
Active Neutron Coincidence Counters		
AWCC	Active Well Coincidence Counter	Verification of ^{235}U in high enriched U samples
UNCL	Uranium Neutron Coincidence Collar	Verification of ^{235}U in low enriched U fuel assemblies; a variety of collar configurations are available.
WCAS	Waste Crate Assay System	Verification of waste materials
WDAS	Waste Drum Assay System	Interrogation of low level waste drums for Pu mass

8. Appendix: Proposed Project Tasks

Coincidence Counting With Boron-Based Alternative Neutron Detection Technology

Task 1. *Review of coincidence counting applications*. We will evaluate the four existing coincidence counting implementations in order to define the range of required efficiencies, die-away times, and gamma ray rejection capabilities. In concert with the Office of Nuclear Safeguards and Security, we will select one configuration for prototype development. Duration: 2 months at start of year 1. Deliverable: Report on requirements for coincidence counting.

Task 2. *Design the boron-lined alternative neutron detector coincidence counting geometry, and perform modeling of the design*. Modeling is the most effective way to determine the range of capabilities. Models will be developed and simulations will be performed over a range or parameter space including the moderator locations, neutron detection medium thickness and position, and signal collection and readout, resulting in a conceptual design. Experiments will be conducted to validate the model using existing alternative detectors. All these efforts will significantly leverage our previous work in this area. Duration: 10 months in year 1. Deliverables: Reports on coincidence counting parameter studies and experimental validation.

Task 3. *Prototype construction and experimental verification*. Based on the selected instrument and initial modeling results, a prototype coincidence counter will be engineered, fabricated and assembled using boron-lined tubes from a selected vendor with whom we have worked. Experimental measurements will be compared to the specific relevant model results. Duration: 12 months beginning halfway through year 1. Deliverables: Reports on prototype performance compared to modeling results. [Not currently funded in year 1]

Task 4. *Coincidence counter measurements*. The prototype coincidence counter will be used to perform measurements on various samples of material typical of those of interest to safeguards applications. Tests will be performed to compare with the equivalent ^{3}He based instrument (at Los Alamos National Laboratory). Duration: 12 months in year 2. Deliverables: Reports on prototype performance. [Not funded in year 1. Will require collaboration with LANL]

Task 5. *Second prototype construction and experimental verification*. Based on the success of the testing of the first prototype instrument, a third year is proposed to implement a second of the coincidence counter instruments using boron-lined tubes. The second prototype coincidence counter will be assembled, modeled, and tested against the equivalent ^{3}He based instrument. Duration: 12 months in year 3. Deliverables: Reports on second prototype performance. [Not funded in year 1]

Task 6. *Reporting of results*. A detailed report will be provided on the findings of this project, including recommendations for future research that should be performed. A conference presentation and journal article will be produced. Duration: 2 months at the end of year 2, and if year 3 is funded, at the end of year 3. Deliverable: Final report on findings from this coincidence counting research. [Not funded in year 1]

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