LA-UR-19-32310
Approved for public release; distribution is unlimited.

Title: Experimental Evaluation of the Fast-Neutron Passive Collar (FNPC) Performance and Comparison with Scintillation Based Collars

Author(s): Menlove, Howard Olsen
Geist, William H.
Root, Margaret A.
Sarnoski, Sarah Elizabeth

Intended for: Report

Issued: 2019-12-09

Experimental Evaluation of the Fast-Neutron Passive Collar (FNPC) Performance and Comparison with Scintillation Based Collars

Howard Menlove, William Geist, Margaret Root, and Sarah Sarnoski

Los Alamos National Laboratory, Group NEN-1

Abstract

This report describes a new method for the verification of fresh low enrichment uranium (LEU) fuel assemblies that can reduce International Atomic Energy Agency (IAEA) inspection time in the field and be completely independent of operator declared burnable poison content. The passive measurement makes unattended mode operation practical, and thus provides the potential for reducing inspector time in the field for future applications. The new simplified passive neutron measurement uses the ^{238}U spontaneous fission in LEU fresh fuel rods to self-interrogate the ^{235}U mass in the neighboring rods. The measured response increases linearly with the increase in the linear density (LD) of ^{235}U. The relatively high efficiency of the passive neutron detector (24%) provides good statistical precision (~ 2%) for the singles, doubles, and triples counting rates in the thermal-neutron mode. The three observables makes possible multiplicity analysis so that both the ^{235}U LD and the effective burnable poison content can be determined independent of the operator declarations. This closes the potential diversion path of miss-declaration the burnable poison content.

This report presents the detector design, the as-built system, the detector parameter measurements, the calibration, and the assay uncertainty estimates. The calibration measurements were performed using the Los Alamos Laboratory mockup PWR fuel assembly. The measurements were made in both the fast-neutron mode (with Cd/Gd metal liners) and the thermal-neutron mode (no Cd/Gd liners). The calibration curves are more linear than for alternative neutron interrogation systems that use AmLi neutron sources because the ^{238}U spontaneous fission interrogation neutrons have a higher neutron energy spectrum with better penetrability into the interior of the fuel assembly, and the ^{234}U (α,n) neutrons increase with enrichment to add to the passive signals. The linear calibration curves provide the benefit that the statistical error in the measured rates does not increase in the calculation of the ^{235}U mass statistical error. Thus, a 1% error in the net counting rate translates to a 1% error on the 235U mass axis for the calibration curve. The measurement uncertainty is then combined with the calibration uncertainty to obtain the total uncertainty in the LD. The resulting error in mass determination is lower than for the current fresh fuel assembly measurement options that use AmLi neuron source interrogation. The result of the improved precision in the thermal mode is that the inspectorate could reduce the measurement time to less than 600 s and still meet the ITV accuracy goals.

Table of Contents

1. Background

This report represents a deliverable in the Safeguards Technology WBS # Project Title, 24.1.3.1, final report (laboratory-based performance testing of the FNPC).

A new, simplified method for the verification of the ^{235}U mass in fresh LEU fuel assemblies that is independent of burnable poison content has been developed. LWR fresh fuel assemblies are currently verified using the uranium neutron coincidence collar (UNCL) [1], which relies on an AmLi source to induce fission in the ^{235}U. The AmLi neutrons are slowed down in polyethylene, so the induced fission is primarily due to thermal-neutron reactions. Burnable poisons, which are added to nuclear fuel assemblies to extend the lifetime of the fuel, absorb neutrons that would otherwise have induced fission in the fuel, thereby reducing the neutron count rate and thus the measured ^{235}U mass. To remove this absorption bias factor, a correction is applied based on the operator's declared burnable poison content. However, the error associated with this correction is too large in many cases

The new passive neutron technique uses ^{238}U spontaneous fission in LWR fresh fuel rods to self-interrogate the ^{235}U mass in the neighboring rods. The ^{238}U spontaneous fission neutrons have a hard neutron energy spectrum, which means that the technique is less sensitive to burnable poisons than the AmLi based systems. This project has continued the work done over the past two years to study this new technique using the optimized ^{3}He based fast-neutron passive collar (FNPC). Fabrication of the FNPC has been completed and measurements have been performed using the LANL mockup PWR fuel assembly. Also, preliminary evaluations of advanced analysis techniques and unattended mode operation have been performed.

In 2018, the ^{3}He tube based detector was compared with a ^{10}B sealed-cell based detector for the same set of PWR fuel assemblies in the Rodeo-II program [2]. The results were that the optimized ^{3}He detector had higher efficiency and less weight than the ^{10}B based system where both systems had about the same cost. Thus, the 2019 work continued exclusively with the ^{3}He based detector; although, either system had the potential for future applications. However, the high efficiency of the FPNC (~24%) is critical for precise measurements of the triples rate that is necessary in the multiplicity advanced analysis technique which can solve for the burnable poison content.

2. Concept

The concept for the new technique is that the combined spontaneous fission and the induced fission reactions in the fuel emits a boosted effective average number of neutrons ($\bar{\nu}$) that is a combination of $\bar{\nu}$ (spontaneous fission) = 2.07 and $\bar{\nu}$ (induced fission) = 2.44. This higher effective multiplicity provides an increase in the net coincident signal from the ^{235}U compared with the spontaneous fission reactions from the ^{238}U. Also, as the ^{235}U enrichment increases in the fuel pellets, the ^{234}U (α,n) neutron emission rate increases the observed neutron emission rate. The hard energy spectrum, the uniform neutron source distribution, and the increase in the neutrons with enrichment result in a more linear calibration functions for the measured single, doubles, and triples rates than with the standard UNCL. The high efficiency of the new detector and the low singles counting rates provides triples rates with useable statistical precision in measurement times of about 600s. The availability of the singles, doubles, and triples makes multiplicity counting and advanced analysis possible to determine both the ^{235}U and the burnable poison loadings. The "advanced analysis" concept for active neutron interrogation has been documented in a prior paper by Root [3].

3. Passive Neutron Collar Design and Hardware Status

The optimization of the FNPC detector slabs was completed in 2018 and the final MCNP based design is shown in Fig. 1 [4]. There are 28 ^{3}He tubes with 6 bar pressure. The detector size and weight are approximately the same as the current UNCL that is in use by the IAEA. One of the detector slabs for the passive collar is shown in Fig. 2 where the new junction box design by PDT is compact allowing an additional 10 cm of active length to the 3He tubes while keeping the total height the same as for the current UNCL. The V notch in the front and back slabs shown in Fig. 1 are to accommodate the size of the hexagonal VVER-1000 fuel assemblies. There is a HDPE filler piece that is used for PWR assemblies.

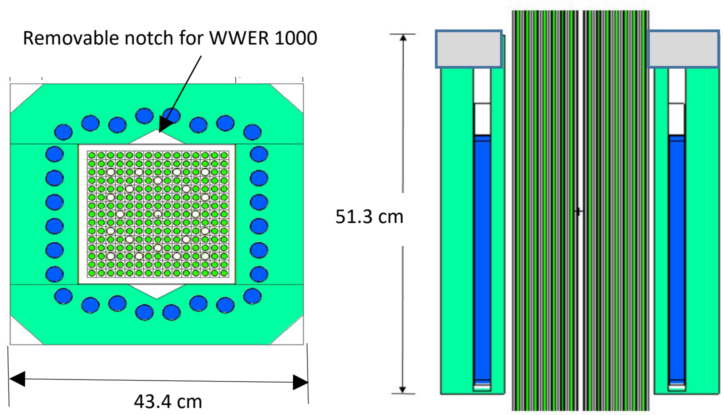

Fig. 1. The MCNP design for the optimized FNPC based on 3He tubes

One of the detector slabs with the ^{3}He tubes and the PDT junction box is shown in Fig. 2 where the Reuter-Stokes ^{3}He tubes are described in Table 1. The ^{3}He tubes screw directly into the new junction box (JB) without opening the lid, so that the tubes are easily removable. The JB is only 3.5 cm deep and contains one PDT amplifier to service the 6 or 8 tubes. The thin JB design allowed for the additional 10 cm of active length for the tubes compared with prior UNCL designs (i.e. 17" vs. 13") [1]. All HV connections are hermetically sealed to be moisture resistant.

Table 1. Detector tube specifications for the FNPC

Tube Model	RS-P4-0817-104
Admixture	ArCH^4
Number	28
Gas pressure	6 bar
Cathode	Al
Operating Bias	1260 V

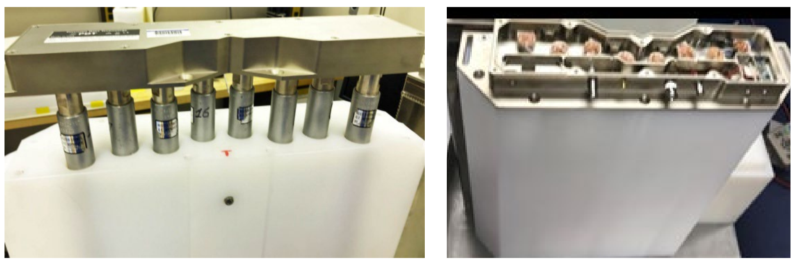

Fig. 2. The ^{3}He tubes in the HDPE moderator with the WWER-1000 notch filler (left), and the open JB (right) with the epoxy sealer in the HV connections for each of the 8 tubes.

The complete FNPC is shown in Fig. 3 where it is assembled around the LANL mockup 15x15 rod PWR fuel assembly. The front slab on the detector is a door that is hinged (see Fig.3 right) to allow fuel assembly insertion through the front of the collar as well as from above.

Fig. 3. The complete collar system that surrounds the LANL mockup fuel assembly where hinges for the removable door are shown (right).

The electronics to support the FPNC are the shift register JSR-15 [5], the optional advanced list mode module (ALMM or PTR-32) [6], and a laptop computer as shown in Fig.4. The alternative data collection with the list mode is being investigated as a more sensitive tool for cosmic-ray spallation rejection in the background. These same electronic modules are in use by the IAEA for the current UNCL and other fielded instruments.

Fig. 4. The electronics for data collection and signal processing are shown with the ALMM (left) and the JSR-15 (right).

4. Experimental Characterization for the Detector

Experiments were performed to check for electronic noise, to gain match the four slabs of the FNPC, and to determine the optimum operating parameters for the system.

4.1 Plateau Curves

After matching the gain is all 4 slabs, a ^{252}Cf source was placed in the center of the detector to measure the plateau curves shown in Fig. 5 (left). The front and back slabs contain 8 ^{3}He tubes, whereas, the two side slabs contain 6 tubes each, thus, the plateaus occur at different count rates. The plateau curve with all four slab for the mockup fuel assembly is shown in Fig. 5 (right). The operating HV of 1260 V is well below the voltage where pileup gamma interference from the ^{238}U begins.

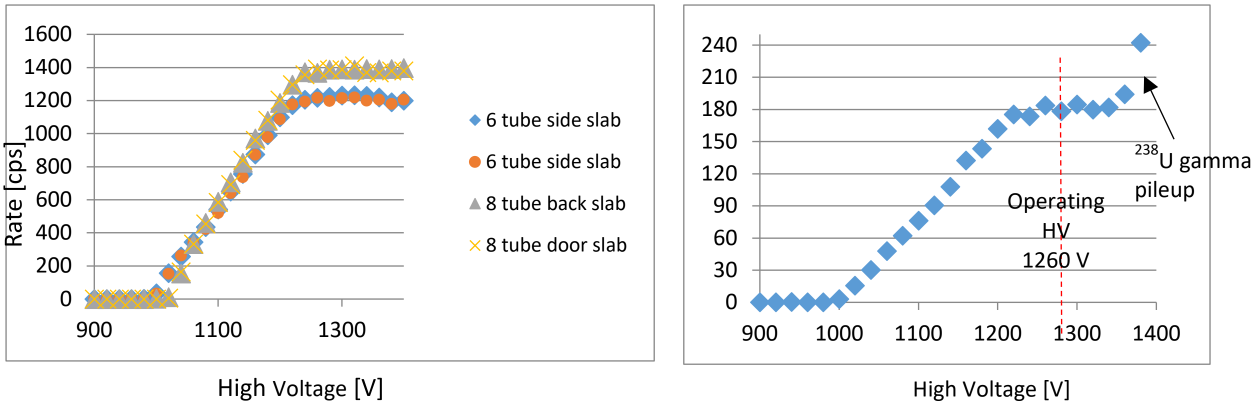

Fig. 5. Plateau curves for the four detector slabs and a ^{252}Cf source after matching the amplifier gains (left), and for all 4 slabs with the fuel assembly in the center.

4.2 Singles Rate Response Profiles

There is a detection efficiency gradient as a function of the axial position in the fuel assembly because the collar detector geometry is open at both ends. We scanned a ^{252}Cf source along the vertical axis in the central tube of the depleted uranium (DU) mockup assembly to measure the efficiency profile that is shown in Fig. 6 (left). The ^{252}Cf source was also scanned in the radial direction with the fuel assembly present, and the singles rate was almost flat with only a 2% increase at the assembly perimeter compared with the center.

In Fig. 6 (right), the singles rate from the passive mockup assembly is shown for the FNPC detector that was raised from near the floor up to the top of the fuel assembly that was sitting near the floor. The count rate decreases at distances above 60 cm because the active region of the fuel assembly no longer completely fills the FNPC cavity. For the subsequent calibration measurements, the distance above the floor was ~ 40 cm to the bottom of the HDPE slabs.

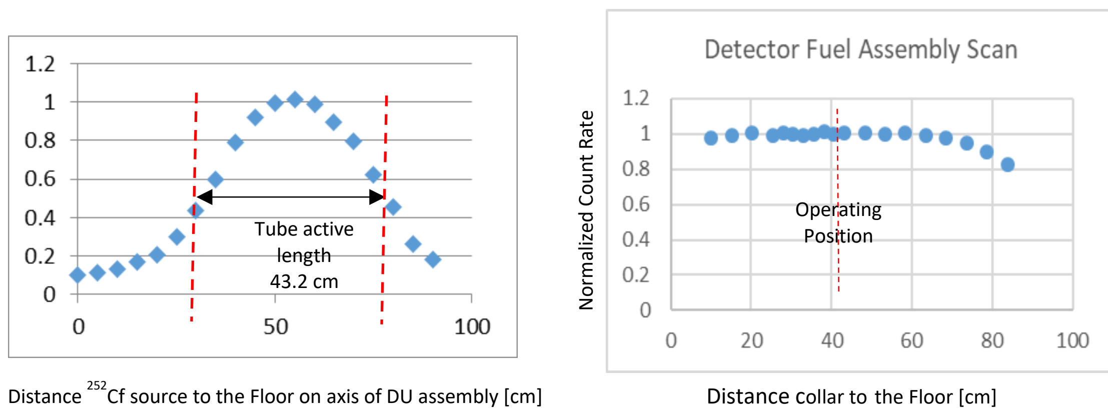

Fig. 6. The efficiency profile where the source is a ^{252}Cf source (left) and the mockup fuel assembly (right) in the central counting position.

4.3 Die-away Time

The die-away time of the detector system with the DU mockup assembly was measured using a ^{252}Cf source located in the center of the fuel assembly. The measurement method was the two gate approach where each gate pair differed by a factor of two. The resulting die-away times are shown in Fig. 7 (left) where we see that the die-away time increases as the gate time interval increases.

Because of the low counting rates for the FNPC, it is useful to increase the gate length until the accidental rate approaches the doubles rate and impacts the statistical error. The longer the gate, the larger the doubles and triples rates as illustrated in Fig. 7 (right). Because the doubles rate is a function of the fuel assembly's linear mass loading LD (g^{235}U/cm), we did measurements after loading the fuel assembly with a representative LD loading (21.9 g^{235}U/cm). With this fuel loading, our optimum gate length was determined by an analysis of the statistical error for many (1000-2000) repeat cycles of 20s each. This "sample based error" method is more accurate than alternatives such as the square root of the counts, and it is a necessity for multiplicity counting that makes use of the triples rates.

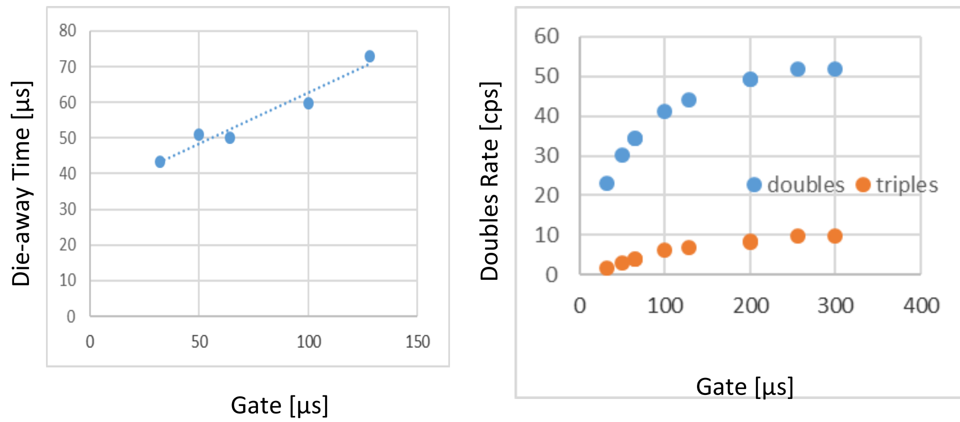

Fig. 7. The die-away times (left) and doubles and triples rates (right) as a function of the gate length where the neutron source is a ^{252}Cf source in the center of the PWR mockup fuel assembly containing DU rods.

4.4 Detector Efficiency

The detector efficiency was measured using a calibrated ^{252}Cf reference source (Cf-12) that had a neutron yield of 11,370 n/s (+/- 1.5%) on May 20, 2019. The measurements were made for the point source in the center of the empty FNPC detector both with and without the 1 mm thick Gd metal liners. The efficiency measurements were repeated with the ^{252}Cf in the center position of the mockup fuel assembly containing 204 rods to show the increased efficiency related to neutron scattering and multiplication in the assembly. Table 2 lists the measured efficiencies for the different detector conditions. The high efficiency of the passive collar is essential for the triples rates that we use for the multiplicity measurements. The key efficiency in Table 2 is the 23.9% for a point source in the center of the empty collar that can be compared with the ~ 12% efficiency for the present UNCL in the passive mode (4 slabs). The passive UNCL is used for MOX fuel assembly verification by the IAEA where the ^{240}Pu effective mass is measured.

Table 2. The efficiencies for ^{252}Cf (11,370 n/s) for different detector conditions.

Detector Status	Gate [us]	Singles [cps]	Doubles [cps]	Triples [cps]	Efficiency
Empty no Gd liners	300	2712	890.6	176.8	**0.239**
Empty with Gd liners	300	2417	734.4	129.6	0.212
Empty with Gd liners	200	2415	712.2	118.7	0.212
109 LEU rods no Gd liners	300	4077	2175.1	884.7	0.357*
109 LEU rods with Gd liners	300	3229	1247	327.9	0.284*

** Includes neutron multiplication and time correlated counts.*

5. Fuel Assembly Measurements

5.1 Mockup fuel assembly characteristics

The LANL 15x15 mockup fuel assembly shown in Fig. 3 contains 204 fuel rod positions and 21 control rod tubes (empty). The array can be loaded with all LEU rods (3.19% enriched), all Du rods (0.22% depleted) or any mixture of the two types of rods. The fuel rods have an active length of 103.5 cm. Because of facility specific nuclear material control regulations, the loading in the low background building (TA-35, building 27) was limited to 109 LEU rods that resulted in a LD of 21.9 $g^{235}U/cm$. The fuel rod loading values that were used in the initial low background measurements are listed in Table 3. The neutron interrogation source term for the passive measurements is the ^{238}U mass that decreases as the enrichment increases, so the induced counting rates are normalized by the source term normalization shown in Table 3 to provide what we have defined as the gross counts. Normalizing to the AmLi source strength has a similar function in the present UNCL systems.

Table 3. Fuel rod loadings for the LANL calibration measurements.

LEU rods 3.19%	^{238}U rods 0.22%	Total $g^{238}U/cm$	Total $g^{235}U/cm$	^{238}U Source Norm.
0	intercept	1215	0	1
0	204	1210	2.66	1.004
30	174	1204	7.95	1.009
48	156	1201	11.13	1.012
59	145	1199	13.07	1.013
60	144	1199	13.25	1.013
80	124	1196	16.78	1.016
90	114	1194	18.54	1.018
100	104	1192	20.31	1.019
109	95	1190	21.9	1.021

5.2 Room background

Los Alamos has an elevation of ~2200 meters above sea-level and the cosmic-ray background is more than an order of magnitude higher that for sea-level facilities. The cosmic-ray spallation background is removed from the measured counts based on the 3-sigma quality control (QC) test of the repeat measurements. The fuel assembly calibration measurements were made in a low-background room that is ~ 12 m below the surface level that provides a background similar to nuclear facilities at sea-level. Prior to moving the fuel assembly into the measurement room (TA-35, B27, R404), the singles rate was 1.0 cps and the doubles and triples rates were essentially zero. With the fuel rods in the room, the singles background was increased to ~ 1.6 cps where the 100 fuel rods were at a distance of 3.5 m from the detector. The doubles and triples rates were < 0.01 cps for the background. Thus, for the subsequent calibration measurements, the room background was negligible (i.e. < 0.5%). For measurements in a fuel fabrication facility, the singles background is expected to be constant on a measurement timescale and in the range of 20-40 cps and the doubles and triples backgrounds < 0.01 cps. Thus, the singles rate background would be measured and subtracted from the fuel assembly rate. The doubles and triples rates would not require a room background subtraction.

5.3 Thermal-neutron Calibration Results

The calibration measurements were made by loading the 15x15 mockup array entirely with DU rods (204 rods at 0.22% depletion) followed by subsequent loadings of 30, 48, 60, 80, 90, 100, and 109 LEU rods as listed in Table 3. The total number of rods was constant at 204 and that provided a heavy metal loading of 1218 g/cm that is similar to typical commercial PWR assemblies (1200-1300 g/cm). The LEU rods were introduced to give a uniform distribution of the enriched rods mixed with the DU rods.

The measurements were performed using a large number of 20s cycles to provide the "sample based" error in the INCC software [7] from the data scatter. The measurements varied from 50x20s to 2000x20s to obtain high precision data with the quality control (QC) 3-sigma rejection on to remove outlier events from the cosmic-ray spallation. The rejection fraction of cycles was only ~ 1.5% of the total cycles in the low-background room that is typical of sea-level facilities.

The measurements were made in both the thermal-neutron mode (no Gd liners), and the fast-neutron mode (with 1 mm Gd liners) operations. The pre-delay was set at 2.0 µs and the gate was 300 µs for the thermal-neutron mode and 200 µs for the fast-neutron mode. For the passive mode measurements with low counting rates, the error associated with the accidental counts is only a small component of the statistical error. The thermal-neutron mode benefited from the longer 300 µs gate because two die-away times corresponding to the initial spontaneous fission followed by the induced fission in the ^{235}U from thermalized neutrons returning from the polyethylene increase the lifetime of the neutrons in the detector system. The measurement results for the singles, doubles, and triples are listed in Table 4. The repeat measurements at the 3 different LD loadings (2.65, 13.07, and 21.89) were made about one month after the initial measurements to demonstrate reproducibility with respect to time, assembly position, and rod positions in the array. The average change for the repeat measurements at the 3 different LD loadings was 0.31%, 0.37%, and 1.2% for the in the measured S, D, and T rates, respectively. These differences are consistent with the counting statistical errors showing the absence of systematic errors components related to electronics drift and fuel assembly position.

The gross counts include both the spontaneous fission reactions from the ^{238}U as well as the induced fission reactions in the ^{235}U and ^{238}U. The net counts correspond to the residual counts after the subtraction from the gross counts of the ^{238}U related counts. The counts related to the ^{238}U corresponds to the zero ^{235}U mass intercept as shown in Table 4 for the singles (S), doubles (D), and triples (T). The uncertainty values are the measured error on average S, D, and T rates for the multiple (~ 1000) repeat 20s cycles.

Table 4. Measured Gross and net rates for the singles (S), doubles (D), and the triples (T) for the passive FNPC in the thermal-neutron mode.

LD	Gross S	S sigma	Gross D	D sigma	Gross T	T sigma	net S	net D	net T
g^{235}U/cm	[cps]	[cps]	[cps]	[cps]	[cps]	[cps]	[cps]	[cps]	[cps]
0	249.3	0.165	43.5	0.082	6.25	0.077	0	0	0
2.65	256.91	0.178	48.98	0.084	8.2	0.066	7.61	5.23	1.95
2.65	258.02	0.161	49.38	0.081	8.37	0.03	8.72	5.63	2.12
2.65	257.82	0.134	49.31	0.084	8.48	0.066	8.52	5.56	2.23
7.95	272.5	0.143	58.66	0.093	12.22	0.082	23.2	14.91	5.97
11.13	277.78	0.101	62.48	0.112	14.57	0.100	28.48	18.73	8.32
13.07	283.12	0.089	65.83	0.072	15.91	0.066	33.82	22.08	9.66
13.07	282.92	0.149	65.64	0.109	15.99	0.101	33.62	21.89	9.74
13.25	284.96	0.103	66.78	0.076	16.43	0.072	35.66	23.03	10.18
16.78	290.41	0.104	70.14	0.081	18.42	0.079	41.11	26.39	12.17
18.54	293.62	0.108	72.41	0.082	19.47	0.081	44.32	28.66	13.22
20.31	296.42	0.107	74.18	0.85	20.93	0.081	47.12	30.43	14.68
21.9	299.73	0.175	76.34	0.135	21.78	0.139	50.43	32.59	15.53
21.9	298.83	0.109	75.83	0.079	21.9	0.076	49.53	32.08	15.65

Figure 8 shows the gross counting rates for the S, D, and T in the thermal-neutron mode. The measurement precision for the doubles and triples which varied from ~ 0.15-1.0% similar to the size of the data points. We note that the maximum LD for the measurements was 21.9 g^{235}U/cm; whereas, LD as large as ~ 60 g^{235}U/cm can be expected for commercial PWR assemblies. Thus, the net counting rates will significantly increase for measurements on commercial LD loadings.

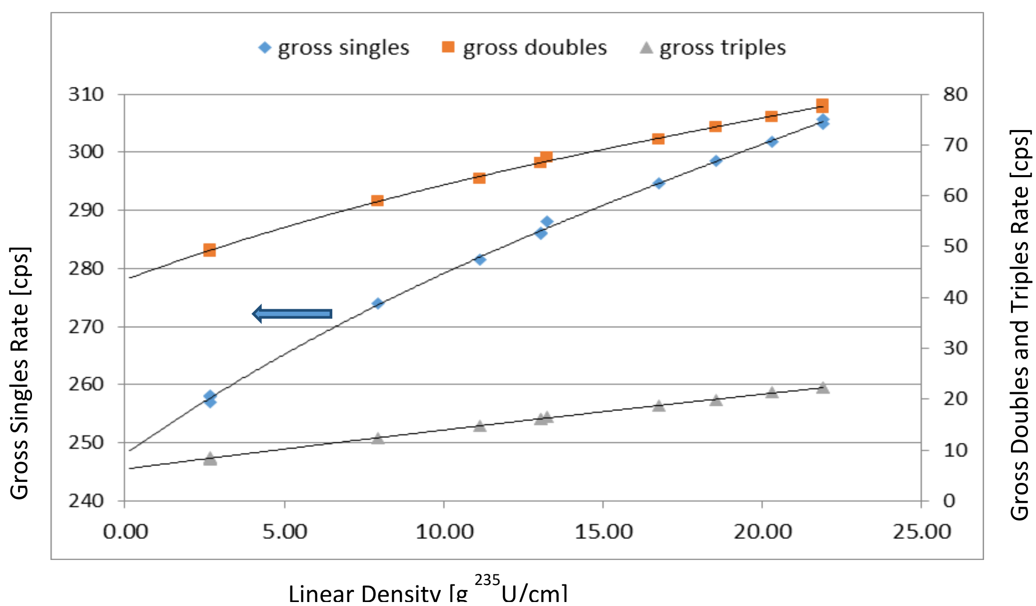

Fig 8. The measured gross counting rates (thermal neutron mode) for the singles, doubles, and triples as a function of the LD in the mockup fuel assembly. The curves are trend-line fits to the data.

Figure 9 shows the data for the net counts after the subtraction of the spontaneous fission and induced fission neutrons from the ^{238}U. We see that the net ^{235}U counts are significantly less than the gross counts, and that has the effect of increasing the statistical error for the net counts. However, when the LD is increased to the loading of the commercial fuel assemblies (~ 60 g^{235}U/cm), the statistical errors are ~ 0.65%, 1.0%, and 2.1 % for the net S, D, and T rates, respectively for a 1000s measurement. These errors were determined via the sample based repeat counts for the multi-cycle data that includes the time correlations in the doubles and triples rates (see Section 8 for error details).

The net triples rates are nearly linear with a straight line through the origin and the linearity is important as we project the triples statistical error to the ^{235}U mass error. The reason for the linear triples curve is that the thermal-neutron absorption in the ^{235}U (self-shielding) is fully compensated by the neutron multiplication that increases the triples by approximately the 3rd power of the multiplication. Also, the ^{234}U (α,n) neutron emission and the hard energy spectrum contribute to the near linear calibration curves.

The statistical errors in the measurements for Fig. 9 are approximately the size of the data points as a result of the long measurement intervals and the stability of the detector system. Several of the measurements were made months apart after moving the detector and reloading the rod positions in the mockup fuel array.

Figure 9 is the most important result of the calibration in that it demonstrates the measured precision for the singles, doubles, and triples, as well as the curvature for the three calibration curves. This excellent precision makes possible the advanced analysis that solves for both the ^{235}U LD and the effective BP content independent of any operator declarations. The primary benefit of the small statistical errors in the thermal-neutron mode is that the measurement time can be reduced to less than 600s and still meet the inspection accuracy requirements.

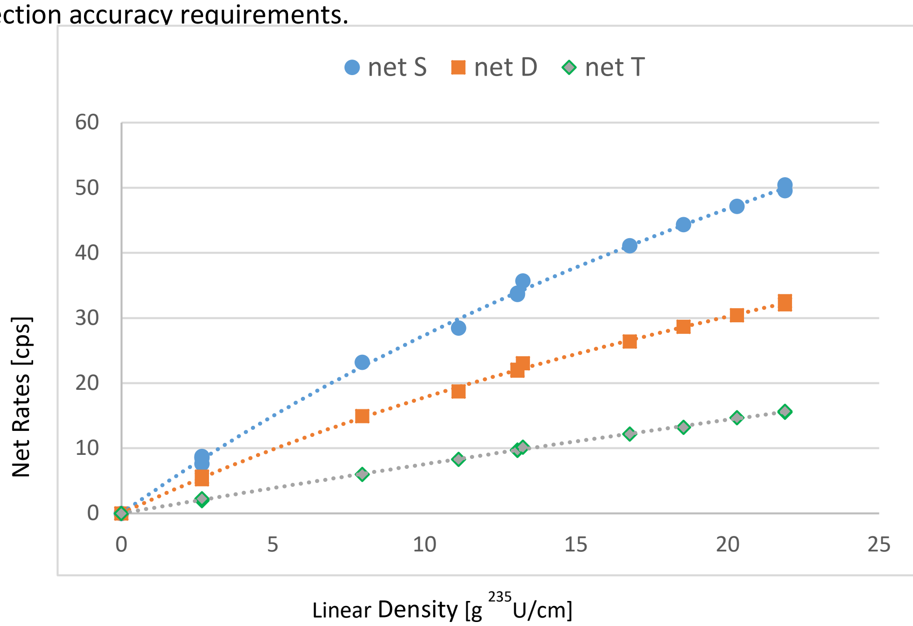

Fig 9. The measured net counting rates (thermal neutron mode) for the S, D, and T as a function of the LD in the mockup fuel assembly.

5.4 Fast-neutron Calibration Results

All of the calibration measurements included data collection with and without the Gd liners. The fast-neutron results are with the Gd liners in place to remove the thermal-neutron region of the neutron slowing-down energy spectrum. In the prior MCNP based study [4], Cd liners were compared with Gd liners and it was shown that the Gd liners reduced the perturbation from the BP rods compared with Cd liners. Thus, all of the present fast-neutron experimental measurements used 1 mm thick Gd liners.

The Gd liner mode runs were performed sequentially with the thermal-neutron mode runs listed in Table 4. Table 5 lists the fast-neutron mode data for the gross and net S, D, and T rates, respectively. The fast-neutron measurements are expected to have less dependence on the BP rod loadings than thermal mode, but at the cost of lower count rates.

Table 5. Gross and net rates for the singles (S), doubles (D), and the (T) for the passive FNPC with measurements in the fast-neutron mode.

g235U/cm	Gross S	S sigma	Gross D	D sigma	Gross T	T sigma	net S	net D	net T	net D+T
	[cps]	[cps]	[cps]	[cps]	[cps]	[cps]	[cps]	[cps]	[cps]	[cps]
0	221.2	0.13	34.268	0.077	4.39	0.045	0	0	0	0
2.65	223.2	0.122	34.73	0.066	4.509	0.044	1.95	0.459	0.119	0.578
2.65	223.2	0.152	34.56	0.07	4.466	0.043	1.99	0.288	0.076	0.363
2.65	223.1	0.152	34.64	0.076	4.525	0.043	1.89	0.368	0.135	0.503
7.95	227.4	0.122	35.63	0.065	4.771	0.045	6.22	1.364	0.381	1.745
11.13	229.2	0.091	35.96	0.046	4.982	0.031	8.00	1.692	0.592	2.284
13.07	230.9	0.089	36.38	0.046	5.007	0.089	9.67	2.115	0.617	2.732
13.07	230.9	0.087	36.38	0.046	5.009	0.029	9.69	2.114	0.619	2.733
13.25	230.9	0.87	36.47	0.046	5.014	0.03	9.7	2.204	0.624	2.828
16.78	233.5	0.087	36.85	0.047	5.218	0.031	12.33	2.582	0.828	3.41
18.54	234.9	0.085	37.18	0.045	5.237	0.029	13.73	2.915	0.847	3.762
20.31	236.1	0.089	37.37	0.048	5.426	0.033	14.85	3.098	1.036	4.134
21.9	237.5	0.17	37.81	0.092	5.39	0.06	16.26	3.538	1.000	4.539
21.9	237.4	0.089	37.6	0.047	5.398	0.031	16.19	3.331	1.008	4.34

Figure 10 shows the plot of the fast-neutron calibration data for the gross counts for the S and D rates. We see that the induced fission rate in the ^{235}U is small compared with the spontaneous fission in the ^{238}U at the LD values less than 21.9 g^{235}U/cm. However, at the higher LD values of ~ 60 g^{235}U/cm, the net rate become useable as illustrated in Fig. 11 with the linear extension to the commercial fuel loadings. This linear extrapolation is based on prior MCNP simulations to the higher mass loadings. The linear shapes of the three curves is a result of the hard neutron spectrum and the buildup of the ^{234}U (α, n) neutrons as the enrichment increases. The linear calibration curves are also predicted from the MCNP simulations [4].

Table 5 also lists the net D+T results that would represent the “Reals” in the original UNCL prior to multiplicity data collection electronics. The D+T rate with linear extension to an LD of 60 g^{235}U/cm gives a net rate of 12 cps for the fast-neutron mode. Longer measurement times (e.g. 600-1000s) are needed for the fast-neutron mode because of the lower counting rates. For future applications, we prefer the thermal-neutron mode for this reason.

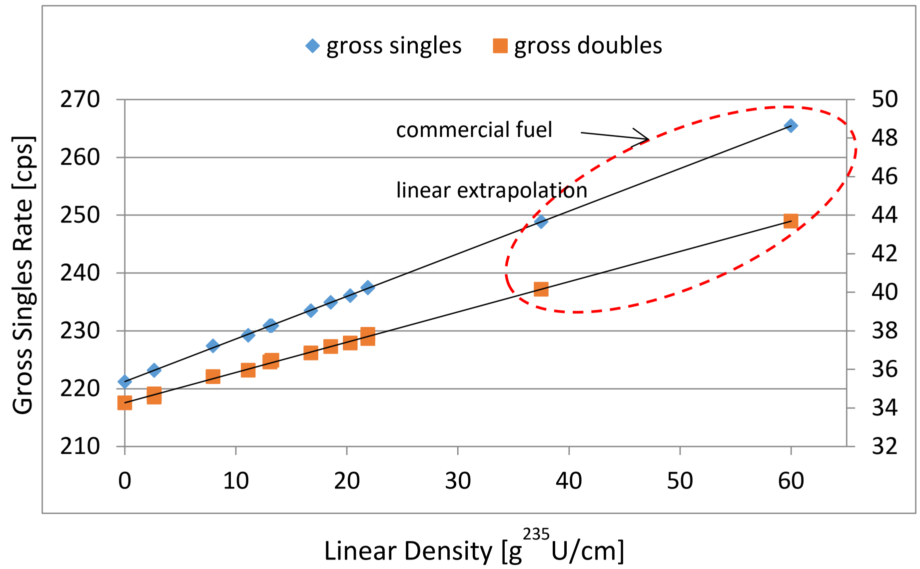

Fig 10. The measured fast neutron gross counting rates for the singles and doubles as a function of the LD in the mockup fuel assembly with a linear trend-line fit to the data.

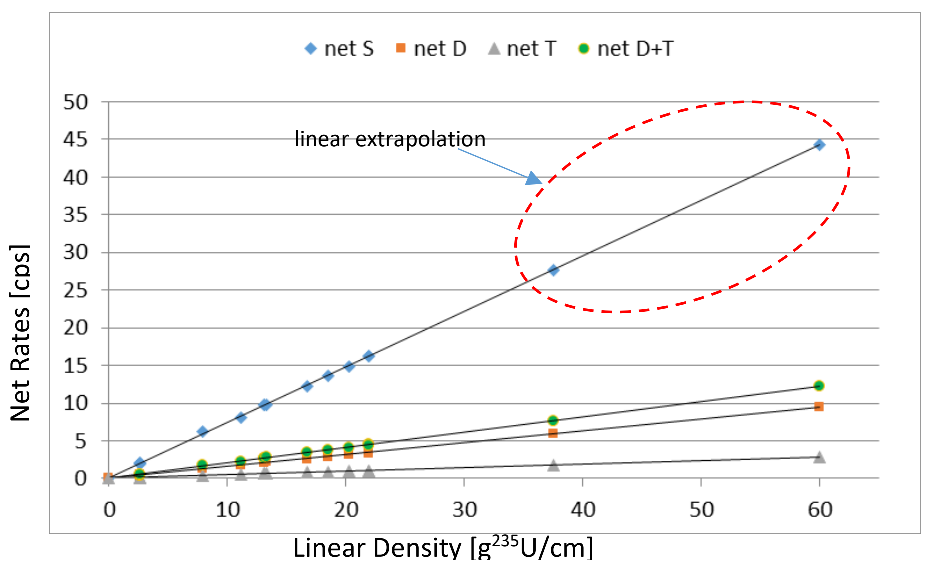

Fig 11. The measured net counting rates for the singles, doubles, and triples as a function of the LD in the mockup fuel assembly showing the calculated linear extension to a LD of 60 g^{235}U/cm

6. Burnable Poison (BP) Rod Effects

The effect of the burnable poisons (BP) rods on the original UNCL was the primary reason for the development of the replacement collar options. The effect of the BP is considerably larger for thermal-neutron interrogation than for the fast-neutron (Cd or Gd Liner) case, and indeed, that was the motivation for the fast-neutron collar developments. A typical thermal-neutron interrogation system will have a BP perturbation of 20-40% on the ^{235}U measurement [1]; whereas, for a fast-neutron interrogation (i.e. with Cd or Gd liners), the BP perturbation is reduced by about a factor of ~ 5 [2]. However, the BP problem is still present, and requires a correction based on the operator's declaration.

The fast-neutron collar (FNCL) under development by the IAEA had an MCNP simulated (A. Di Fulvio[8])^{235}U mass verification perturbation of 9% for a BP rod loading of 24 rods with a 6% Gd fraction. The trend for future fuel assembly design is to increase the BP content to obtain higher burnup reactor fuel. Thus, ignoring BP effect is not a viable option, even for the fast-neutron interrogation systems.

Burnable poison considerations:

- The interrogation-neutron perturbation from the BP rods is entirely determined during the interrogation phase of the measurement, and not during the neutron detection phase. Thus, all collar systems that use AmLi neutron sources imbedded in polyethylene will have essentially the same BP perturbation to the ^{235}U fission rate.
- The subsequent measurement of the BP perturbation will be dependent on the penetrability of the detector system that is different for different detector types and threshold settings. If the measured perturbation is smaller than the induced fission change, it indicates a lack of sensitivity (penetrability) to BP rod locations.
- Neutron scattering in exiting from the fuel assembly lowers the detection efficiency for fast-neutron scintillation type detectors. Thus, the BP rods (as well as LEU rods) locations that are deeper into the fuel assembly are measured with reduced sensitivity because of neutron scattering in exiting the assembly. This effect will be dependent on the neutron cutoff energy chosen for the scintillation detector to reduce gamma ray interference.
- The loading pattern for the BP rods changes both the interrogation perturbation as well as the detection sensitivity where rods near the exterior have a larger effect than rods near the center.
- The "advanced analysis" approach to solve for both the ^{235}U and the BP loading is the only available neutron measurement technique that is completely free of the BP declaration.

We are making use of the thermal-neutron results for our "advanced analysis" technique to take advantage of the good statistical results in the thermal neutron measurements. The thermal-neutron mode increases the measured response by about an order of magnitude more than for fast-neutron interrogation, and provides good statistics for the S, D, and T counting rates. The advanced analysis uses the S, D, and T data to solve for both of the variables (^{235}U loading and Gd content) independent of any operator declarations.

6.1 Counting Precision and Errors

A passive mode collar was not considered in the past because of the low counting rates and the large ^{238}U spontaneous fission component. Also, the ^{234}U (α,n) contribution was not recognized at the time. The ^{238}U spontaneous fission neutron emission rate is only 13.6 n/s/kg; however, there are ~ 70 kg of ^{238}U in the active length of the passive collar, so the neutron source term is ~ 1000 n/s. The ~ 24% efficiency would then register ~ 240 cps, and that is consistent with the measured singles rates in Table 4 of 257 cps for DU rods. The singles rate increases to ~ 370 cps for the commercial LD of ~ 60 g^{235}U/cm. Also, the neutron multiplication increases with enrichment and that increases the singles rates and more so for the doubles and triples rates. The net singles rate for the commercial fuel would be ~ 44 cps as illustrated in Fig. 12 for the fast-neutron mode.

The statistical uncertainty in the doubles and triples rates is complicated by the neutron time correlations in the measured rates, and this significantly increases the statistical error. To fully account for this correlated error component, we have measured the relative standard deviation (RSD) by many repeat counts of the same sample so that the actual error is measured. Our measurements were performed with 50x20s to 2000x20s cycles to obtain the actual RSD. Thus, the measured RSD includes time correlations, electronic stability and background variations. For several of the fuel assembly loading, the measurements were repeated months apart and after reloading the fuel assembly, and no normalizations were required. One major advantage of ^{3}He based detector systems is that the electronic stability is good to < 0.1% over extended time spans of months [9].

The statistical errors for the thermal-mode system are significantly smaller than for the fast-neutron mode, because the net signal rates are much higher in the thermal mode. Also, the RSD errors are significantly different for the singles, doubles, and triples measurements. Table 8 summarizes the measured RSD values for both the thermal-neutron and fast-neutron modes of operation. The statistical errors are reduced by the square-root of the measurement time, so we have normalized all of the RSD values in Table 8 to a 1000s total measurement time. We note that this time is less than the typical total time for an active mode measurement with AmLi that would include both the passive measurement plus the active measurement. In Table 8, the measured RSD values were determined at the LD loading of 21.89 g^{235}U/cm, and the RSD values at the higher loadings were calculated by extrapolating the calibration curves based on the MCNP simulations of the rates at the higher mass loadings.

Table 8. Statistical uncertainties for 1000s based the sample based scatter from repeat measurements.

Passive Mode	**Gross S**	**Gross D**	**Gross T**	**Net S**	**Net D**	**Net T**
Thermal-Neutron Mode	**RSD [%]**	**RSD [%]**	**RSD [%]**	**RSD [%]**	**RSD [%]**	**RSD [%]**
LD @ 21.9 $g^{235}U/cm$	0.233	0.709	2.53	1.402	1.665	3.543
LD @ 37.5 $g^{235}U/cm$	0.220	0.645	2.12	0.871	1.220	2.669
LD @ 60 $g^{235}U/cm$	0.210	0.595	1.81	0.654	0.991	2.128
Fast-Neutron Mode						
LD @ 21.9 $g^{235}U/cm$	0.250	0.788	3.66	3.664	8.827	19.58
LD @ 367.5$g^{235}U/cm$	0.244	0.760	3.43	2.198	5.185	11.86
LD @ 60 $g^{235}U/cm$	0.236	0.734	3.22	1.419	3.405	8.16

The key values in Table 8 correspond to the commercial PWR LD loadings of ~ 60 $g^{235}U/cm$ where the errors (1-sigma) are below ~ 2% for the S, D, and T rates for the thermal mode. The errors in Table 8 are based on long repeat measurements that were normalized to 1000s. If the doubles error were calculated via the square-root of the doubles plus accidental counts, the error would be a factor of ~ 1.5 smaller than the values in Table 8. The sample based errors are larger because the doubles and triples rates are correlated in time, and that is true of alternative detector types as well.

In the fast-neutron mode, we would propose using the net singles rate as the primary assay result, and the net doubles rate as confirmatory information because the error in the net singles rate is 1.42%, whereas the doubles error is 3.40%. The triples rate would not be used for the fast-neutron mode because of the large statistical error. We note that the linear calibration shape through the origin of the net singles and doubles calibration curves means that the net counting errors are the same as the ^{235}U mass errors. The total error in the ^{235}U mass would need to be increased in quadrature with the uncertainty in the calibration curve that is less than 1%, and the results for both S and D are well below the ITV target values of 4.5% [10]. Thus, both the singles and doubles accuracies in the fast-neutron mode meet the ITV criteria for the UNCL as applied to fresh LEU fuel assemblies. However, a BP correction based on the Operators declaration would still be needed, because the BP effect on the mass measurement is in the range of 3-10%, and it is systematic so all BP assembly measurements are biased low.

In the thermal-neutron mode, all three observables (S, D, and T) can be used to solve for both the ^{235}U and the effective BP loading. Thus, the Operators BP declaration would not be needed. The statistical error for the ^{235}U mass is below ~ 2%, and the errors are quantified in a separate report on "Advanced Analysis" [11].

6.2 Fuel Assembly Mass Effect

The fuel assembly mass and size effects the measurement results because neutron scattering and the form factor (positioning) inside the neutron collar. Commercial PWR fuel assemblies typically have a 17x17 rod matrix, but there are older reactors that use 14x14 matrix, etc. rod arrays. Also, many of the new reactors have the WWER-1000 hexagonal rod array geometry. The original UNCL made a calibration correction for the heavy metal linear density change called the k_4 correction to the doubles rate in the INCC code [7]. For the passive collar, there are two approaches to account for the change in assembly type and size; 1) introduce k4 type corrections for the singles, double, and triples; or 2) introduce separate "material type" categories for the different assembly types in the calibration files of the software. This second approach could be the easiest to implement. For example, for the IAEA verification of plutonium samples, there are different material types to for the different sample categories, and the INCC code carries the corresponding calibration coefficients.

7. Comparison to the IAEA Fast Neutron Collar (FNCL)

The IAEA has under development a measurement system for LEU fuel assemblies with the goal of replacing the UNCL for inspection activities. The system called the Fast Neutron Collar (FNCL) [12,13] makes use of AmLi neutron interrogation followed by fast-neutron detection using EL-309 liquid scintillation detectors. The system typically uses two or four AmLi neutron sources vs. one to reduce the required measurement time.

For comparison purposes with the passive collar, we have summarized in Table 9 some of the key performance parameters related to both systems that are important for inspection applications including the interrogation source, the statistical error (for 1000s), the BP sensitivity, stability, and the penetrability.

Table 9. Comparison of the passive collar with the IAEA (FNCL)

Parameter	**IAEA Fast-neutron Collar (FNCL)***	**Passive Collar (FNPC)**
Interrogation source	2 or 4 AmLi neutron sources	^{238}U self-interrogation
Detector type	Liquid scintillator (EL-309) (12 pods)	^{3}He tubes (28 tubes)
Doubles precision (RSD% in 1000s)	D ~ 2% precision (TBD via repeat runs). Repeat measurements at field test had a spread in D > 2%. [8]	Net S = 1.42% (via repeat runs, fast neutron) Net D = 3.4% (via repeat runs, fast neutron) Net T = 2.2% (via repeat runs thermal mode) Multiplicity ~ 2% (thermal mode)
Burnable poison (BP) sensitivity	D ~ 5% decrease @ 24 BP rods with 6% Gd [8] Mass defect correction (OID)* ~ 9% @ 24 BP rods with 6% Gd [8]	S ~ 4% decrease @ 24 BP rods with 6% Gd [4], **fast n mode**; OID perturbation at 4% D ~ 10% decrease @ 24 BP rods with 6% Gd [4] mass defect correction ~ 10% **Thermal neutron multiplicity mode requires no BP information**
Stability (24 hour, 72 hour)	D > 1% (TBD via repeat runs) [14] requires daily normalization to ^{137}Cs source	S ~ 0.1% (via repeat runs) D ~ 0.5% (via repeat runs)
Penetrability	Weak response from central rod locations for both LEU and BP rods [8]	More uniform response from all rod locations [4]
Calibration curve	Concave shape gives error increase in calculating ^{235}U mass from doubles [14] as mass loading increases	Linear shape gives no error increase in calculating ^{235}U from net doubles (fast mode)

*OID is defined as Operator Inspector Difference in the measured ^{235}U mass, [10].

The burnable poison perturbation is a function of the BP rod locations where rods near the center have less impact than rods near the outside. Thus, the 24 BP rod configuration in Table 9 provides a more representative BP distribution and perturbation result than configurations with a smaller number of BP rods.

The MCNP simulations are more accurate for the relative BP effect than experimental measurements because the perturbation per BP rod is typically less than the statistical uncertainty in the experimental doubles rates. The BP perturbations listed in Table 9 were obtained from the MCNP calculations from the Di Fulvio paper [8].

8. Conclusions

This report provides the detector design, performance measurements, preliminary calibration, and measurement uncertainties for the fast-neutron passive collar (FNPC) that is used to measure the ^{235}U linear density in PWR type fuel assemblies. The current development is unique from prior systems that are used to verify the ^{235}U content in fuel assemblies in that it does not require the use of an external interrogation source such as AmLi. The self-interrogation is accomplished by using the ^{238}U spontaneous fission neutrons to induce the fission reactions in the ^{235}U that coexists in the same fuel pellets. The primary advantages of the passive collar are:

- No radioactive source required
- Two measurements (passive plus active) with the associated source handling are not required
- Shorter measurement times using singles rates (better precision)
- Independent of operation declaration of poison content for multiplicity analysis
- Very adaptable to unattended mode operation

The measured neutron efficiency of the FNPC is 24% for a ^{252}Cf source located in the center, and that is significantly higher than prior neutron collar systems. The UNCL in the passive mode (i.e. 4 sides) is ~ 12% efficient. The high efficiency for the FNPC provides useful statistical results (~ 2%) in measuring times of 600s for the net singles rate in the fast-neutron mode. The doubles precision for 1000s was 3.4% in the fast-neutron mode and 1.0% in the thermal-neutron mode. Because of the linear shape of the net fast-neutron results (see Fig. 12), the RSD % error for the net rates (singles and doubles) and the ^{235}U mass statistical % error are approximately the same. The uncertainties in the measured rates need to be combined with the calibration error (~ 1%) to get the total error in the mass. This total error in the ^{235}U mass is also referred to as the Operator-Inspector-Difference (OID) in the mass where the ITV target value for the UNCL is 4.5% [10]. The passive neutron collar can exceed this target in < 600s.

One of the primary reasons for the present development was to remove the requirement to make a BP rod correction based on the operator's declaration. The evaluation of the advanced analysis capability to independently solve the multiplicity data (singles, doubles, and triples) for both the ^{235}U mass and the effective burnable poison content (regardless of the BP rod configuration) gave good results with a statistical error for the ^{235}U mass of ~ 2% in 1000s. MCNP calculations in the paper by A. Di Fulvio at the Univ. of Mich. for the IAEA's FNCL [8] showed that the ^{235}U mass defect error for a BP loading of 24 rods with 6% Gd was ~ 9%. In the fast-neutron mode, the FNPC mass deficit for the same BP rod configuration was ~ 10% for the doubles and ~ 4% for the singles [4]. The singles have a smaller BP perturbation because of the ^{234}U (α,n) neutron contribution that is immune to the BP content, and the singles have less change in the neutron multiplication than the doubles rate. For the AmLi interrogation systems, the error in the ^{235}U LD is larger than the error in the doubles rate because of the doubles curve concave shape. The present multiplicity analysis method is the only neutron based measurement approach that is truly independent of the poison rod problem. We also note that for some fuel assembly verifications prior to shipping, control rods are in the assemblies in addition to BP rods for criticality control. The advanced analysis method can handle this condition; whereas, the fast-neutron measurement systems cannot.

The bottom line in the comparison of the passive collar to the IAEA's FNCL is that the error in the ^{235}U mass defect is approximately the same for both systems in the fast-neutron doubles mode (3-4% in 1000s). However, for the FNPC, the ^{235}U mass defect statistical error decreases to ~ 1.7% when using the singles rate. We note that the use of the singles rate with the room background subtraction needs to be verified by future field tests of the passive collar. The background subtraction should not significantly impact the net singles error, because the expected room background neutron rates (20-40 cps) are only a minor fraction of the fuel assembly singles rate. Both systems (in the fast mode) would need to make similar BP corrections based on the operator's declaration. However, the preferred mode of operation for the passive collar is the thermal-neutron mode using multiplicity analysis where no information related to the BP content is needed, and the passive collar ^{235}U mass defect statistical error is ~ 2%.

The second key objective in the passive collar development was to reduce inspector time at the nuclear facilities. The passive system is less complex and with no radioactive source handling than the alternative active-neutron interrogation systems, and that makes the potential for unattended mode application more practical. The unattended mode would have the advantage of reducing the inspection time for IAEA verification of the fresh fuel assemblies. A summary of the experiments and analysis to help evaluate the unattended mode of operation are provided in Appendix A of this report, and more complete information is provided in a separate report [15] under this project (PWP 24.1.3.1, Task 4).

Future work should include a field test of the passive collar that would easily include both attended and unattended mode data collection in parallel where the inspector presence could be part time. The signal output from the passive collar would be split to go to a JSR-15 as well as the list mode module (e.g. ALMM or PTR-32). The data accumulation in list mode would be continuous, and in parallel, the JSR-15 would log in the traditional info for the fuel assembly ID, start times, etc. The calculated singles, doubles, and triples rates in the JSR-15 from INCC would be subsequently compared with the list mode analysis for the same time periods. This type of hybrid data collection could provide useful information as the IAEA evaluates the potential for future unattended mode operation for the instrument.

9. Acknowledgements

The authors would like to thank the NNSA's Office of International Nuclear Safeguards (NA-241) for the funding for this work.

10. References

[1] Menlove, H. O., et. al. "Neutron Collar Calibration and Evaluation containing Burnable Neutron Absorbers", Los Alamos National Laboratory Report, LA-11965-MS, (1990).
[2] Gariazzo, Claudio, Rodeo-II summary report from Argonne National Laboratory (2019).

[3] Root, M. A., et al. "Using the Time-Correlated Induced Fission Method to Simultaneously Measure the 235U Content and the Burnable Poison Content in LWR Fuel Assemblies." *Nuclear Technology*, 2018, pp. 1–14.
[4] Margaret Root, William Geist, Anthony Belian, and Howard Menlove, "Fast Neutron Passive Collar Project Year End Report". Los Alamos National Laboratory Report, LA-UR-18-29560, (2018).
[5] JSR-15 Shift Register electronic module produced by Canberra Industries, Meriden, CT. www.canberra.com/contact
[6] Mathew Newell, advanced list mode module (ALMM), private communication January (2019).
[7] W. Harker, M. Krick, and J. Longo "INCC Software User's Manual," Los Alamos National Laboratory document LA-UR-01-6761 (rev) (November 2005).
[8] A. Di Fulvio, T. H. Shin, S. D. Clarke, S. A. Pozzi, "Effect of the detector type on the performance of a simulated fast-neutron uranium collar foe non-destructive assay of fresh fuel assemblies", paper presented at the 2019 INMM Annual Meeting in Palm Desert, CA, July (2019).
[9] D. Henzlova, et. al. "Results of the Evaluation and Comparison of Alternative Neutron Detectors for Potential 3He Replacement for Nuclear Safeguards Applications", Los Alamos National Laboratory Report, LA-12-00837, (2012).
[10] International Target Values 2010 for Measurement Uncertainties in Safeguarding Nuclear Materials, ESARDA Bulletin, Number 48, ISSN 0393-3029 (2012).
[11] Root, et.al. "Advanced Analysis to Determine Both the U-235 and Gadolinium Content in Fresh PWR Fuel Assemblies". LANL report in preparation (2019).
[12] Tae-Hoon Lee, Alice Tomanin, Jonathon, Beaumont, "Liquid Scintillator Based Fast Neutron Coincidence Counter for Fresh Nuclear Fuel Measurements", ANS Workshop, Santa Fe, NM, Sept 30, (2016).
[13] J. Beaumont, Lee, T. H., Mayorov, M., Tintori, C., Rogo, F., Angelucci, B., Corbo, M., A fast-neutron coincidence collar using liquid scintillators for fresh fuel verification, J RadioanalNuclChem 314, pp. 803–812 (2017).
[14] A. Tomanin, L. Bourva, J. Beaumont, P. De Baere, et. al. "Inter-Comparison Exercise for the Safeguards Verification of Fresh PWR Fuel Assemblies using Fast and Thermal Neutron Coincidence Collars", ESARDA Symposium, 16th May 2019, Stresa, Italy.
[15] M. Root, et. al. , "Verification of fresh LWR fuel assemblies using the Passive Unattended Neutron Collar " LANL Draft Report (2019).

Appendix A

Passive Collar Unattended Mode Measurement Summary

The passive collar can be used in the unattended mode to save inspector time at nuclear facilities. This Appendix provides a summary of measurements that were performed with the FNPC in the unattended mode on April-May, 2019 to evaluate the sensitivity of the singles (s), doubles (D), and triples (T) rates to rod removals and substitutions. For unattended mode operation, the passive system has the following advantages over active mode systems (i.e. AmLi interrogation source):

- No radioactive source
- No double measurement (passive plus active) with the associated source handling
- Better sensitivity to rod removals
- Continuous (24/7) data collection for potential SNM movement in the facility to supplement C/S.

The singles rate is sensitive to any changes in the room neutron background; whereas, the doubles and triples rates are not. All three rates provide useful signatures in the passive mode and the falsification of the time correlated signals would be very difficult. The measured rates are very sensitive to rod removals or replacements by dummy rods of steel, lead, or empty, etc. because both the self-interrogation source (^{238}U) and the induced fission rate in the ^{235}U decrease. However, if the replacement rods contain uranium, the change per rod is reduced substantially because the ^{238}U spontaneous fission contribution returns.

To demonstrate the sensitivity of the S, D, and T rates to the rod removals, a series of measurements were performed using the mockup PWR fuel assembly. In the 15x15 rod array shown in Fig. A.1, the fuel rods were uniformly removed from the full fuel assembly that contained 204 fuel rods (109 LEU and 95 DU rods) in 3 steps of 10 LEU rod per step. Continuous data was collected in 20s cycles for approximately 4 hours between steps as illustrated in Fig. A.2 for the singles, Fig. A.3 for the doubles, and Fig. A.4 for triples. The heavy shaded bands in the graphs represent the statistical scatter (± 1-sigma) for a 600s subinterval of the data. The light shaded bands represent the ± 2-sigma scatter for the data.

Fig. A.1. The passive collar during fuel rod exchange (left) and the mockup PWR fuel assembly (right) with the central 30 LEU rods replaced by DU rods.

The singles rates show the most absolute deviation due to the removal of 10 rods; however, the percent deviation is larger for the doubles (0.85%/rod) and the triples (1.15%/rod) than for the singles (0.59%/rod). This is because the neutron multiplication decrease is larger for doubles and triples than singles. We note that one rod represents ~ 0.49% of the uranium in the assembly. It is important to note that the removal of 10 rods is easy to see in the doubles and triples rates as well as the singles. Even the 20s data points for the doubles show the change for the 10 rod removals. This demonstartes that these rates (both D and T) could also be useful in future analysis.

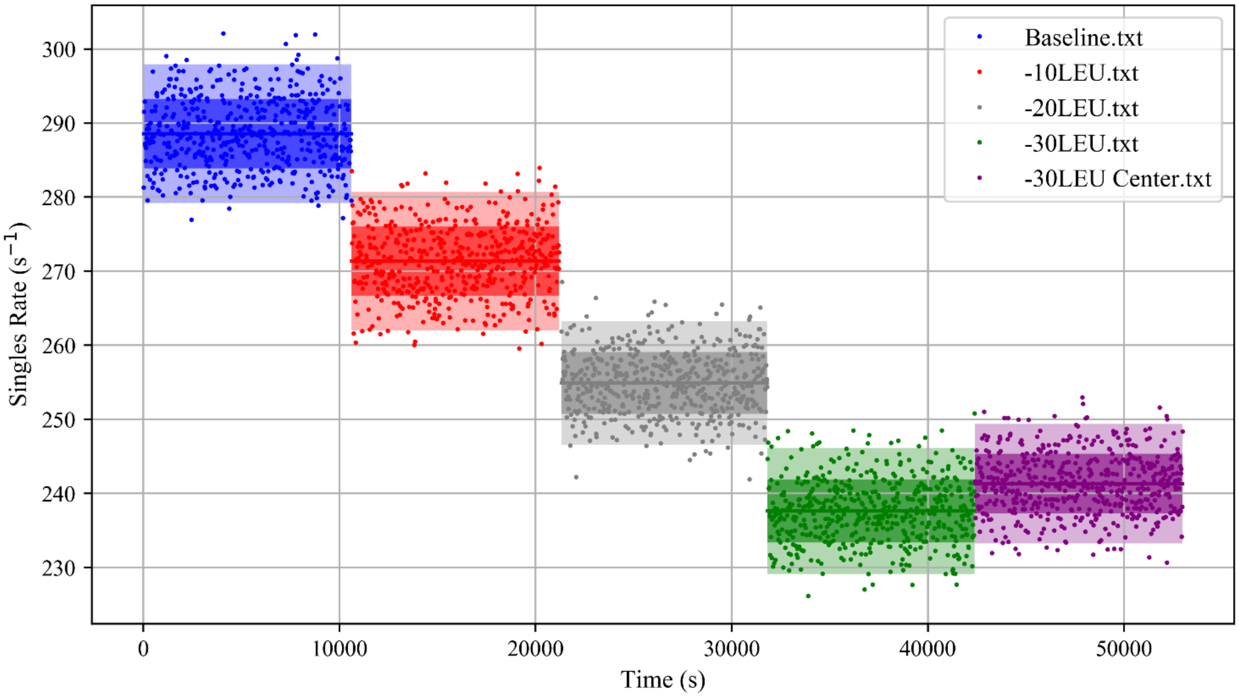

Fig. A.2. Continuous data collection for the measured singles rates (20s/point) during fuel rod removal steps of 10 LEU rods per step in the mockup PWR fuel assembly.

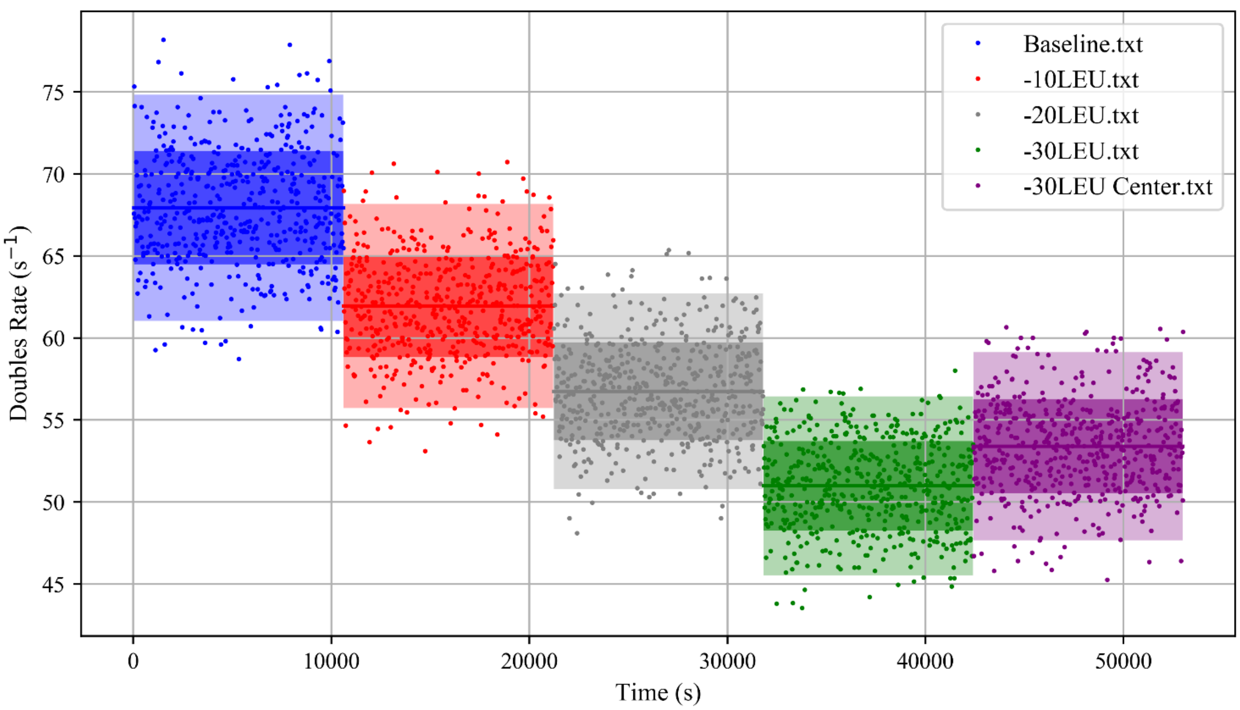

Fig. A.3. Continuous data collection for the measured doubles rates (20s/point) during fuel rod removal steps of 10 LEU rods per step in the mockup PWR fuel assembly.

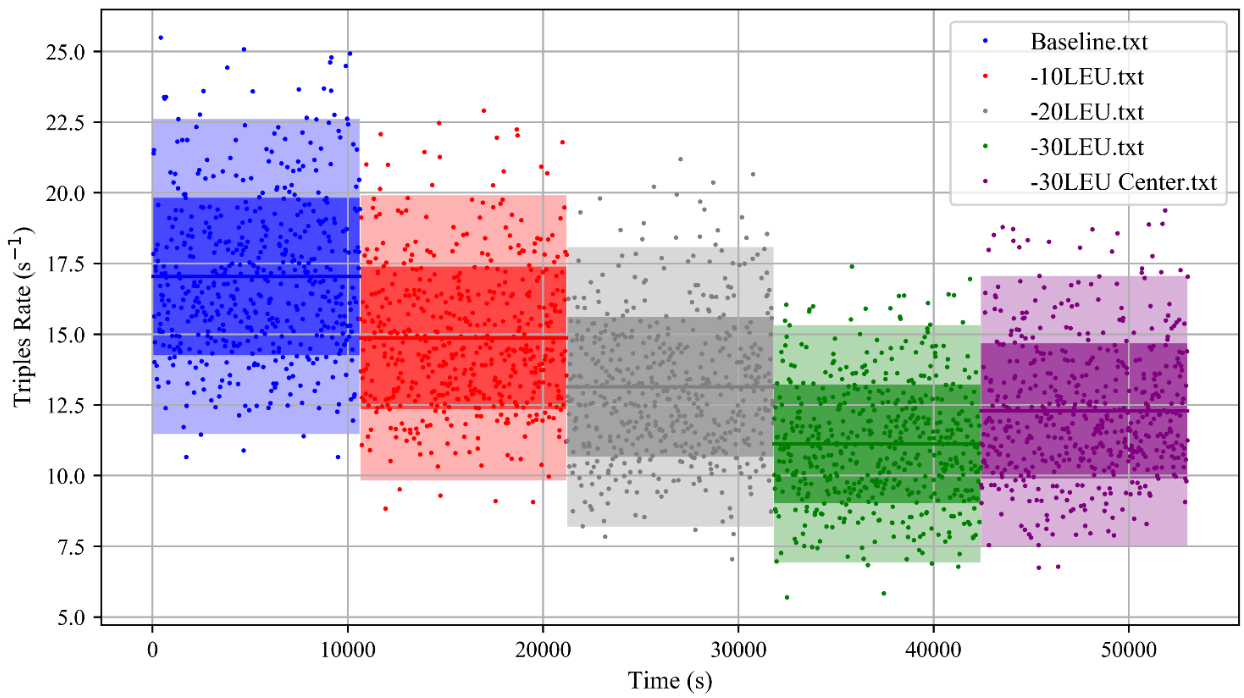

Fig. A.4. Continuous data collection for the measured triples rates (20s/point) during fuel rod removal steps of 10 LEU rods per step in the mockup PWR fuel assembly.

Measurements were also performed where DU rods were substituted for the LEU rods. In this case, the ^{238}U spontaneous fission rate has a small increase with the DU substitution, so the net effect from the rod exchange is considerably smaller that for the data shown in Figs. A.2-A.4. Figure A.5 shows the doubles rates for the same rod exchange pattern as for the prior exchanges. The decrease in the doubles rates from the change are about a factor of 4 smaller than for the empty, steel and Pb substitutions. However, the decrease is still clearly visible for a 600s subinterval of the data for the 10 fuel rod change.

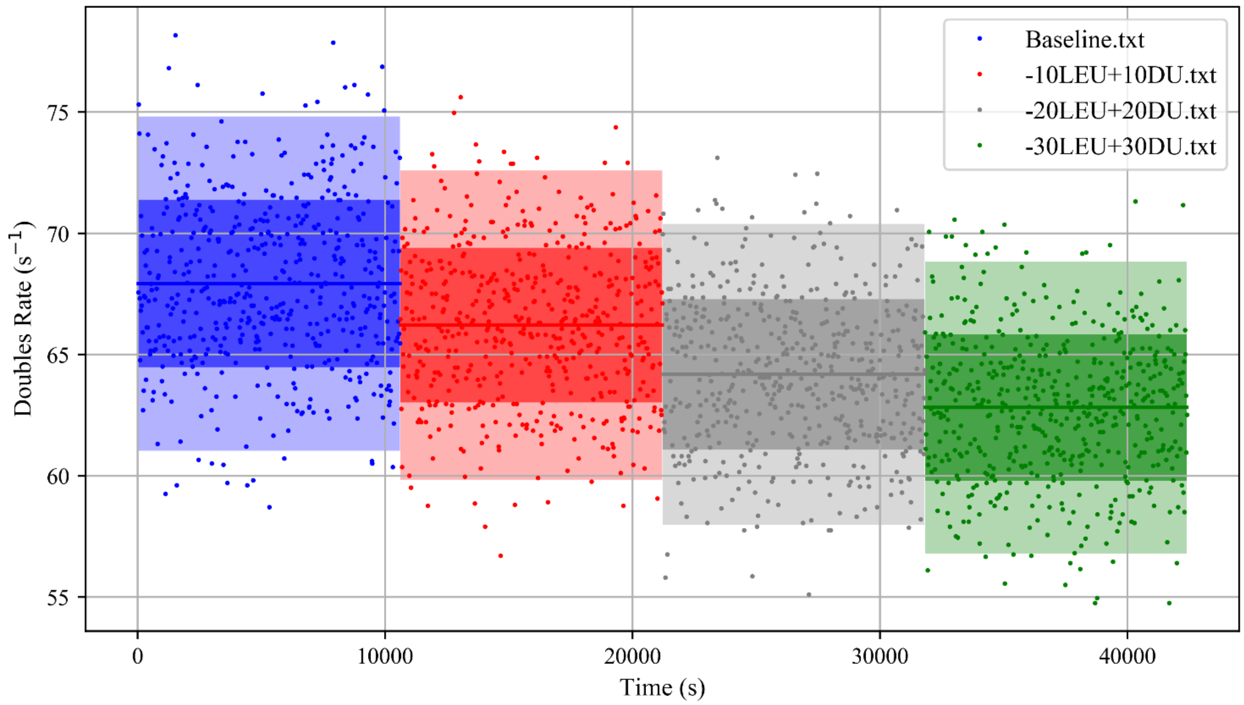

Fig. A.5. Continuous data collection for the measured doubles rates (20s/point) during fuel rod substitution steps of 10 LEU rods per step with the DU rod replacements. For the 4th step, 20 rods were exchanged.

Conclusions

The continuous data collection at LANL with the passive collar over a several week period provided data that demonstrated the utility of using the passive system in the unattended mode. The sensitivity to rod removal and substitutions is better than for active mode neutron systems because both the neutron source term and the induced fission rates decrease with the rod removals. However, if DU rods are available for the substitution, the perturbation is significantly reduced. The sensitivity was good for all 3 correlated signatures (S, D, and T), so falsifying the correlated data would be very difficult. The doubles rates showed the best sensitivity to the removals where the sensitivity (> 3-sigma change) in 600s was less than 2 rods for removals with replacements by steel, Pb, or empty rods. However, if DU rods are used for the substitution, the sensitivity was < 9 rods in 600s. Longer measurement analysis intervals would further improve the sensitivity levels.

A future field test where the data would be split to a shift register (AMSR or JSR-15) for attended mode analysis as well as a list mode module (PTR-32) for unattended continuous collection would be very valuable to better understand list mode data collection and unattended operation. During the field test, the operation of the FNPC detector would be continuous (including overnight) for the several days of fuel assembly measurements. The unattended mode operation during a field test would provide the IAEA with valuable data that could support reduced inspection time at nuclear facilities.

A separate more detailed report on the unattended mode passive collar is available [15].