LA-UR- 98-3303

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CONF-980733--

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Submitted to: INMM 39th Annual Meeting
July 26-30, 1998
Naples, Florida

Los Alamos
NATIONAL LABORATORY

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The Underwater Coincidence Counter (UWCC)

For Plutonium Measurements in Mixed Oxide Fuels

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ABSTRACT

The use of fresh uranium-plutonium mixed oxide (MOX) fuel in light-water reactors (LWR) is increasing in Europe and Japan and it is necessary to verify the plutonium content in the fuel for international safeguards purposes. The UWCC is a new instrument that has been designed to operate underwater and nondestructively measure the plutonium in unirradiated MOX fuel assemblies. The UWCC can be quickly configured to measure either boiling-water reactor (BWR) or pressurized-water reactor (PWR) fuel assemblies. The plutonium loading per unit length is measured using the UWCC to precisions of less than 1 per cent in a measurement time of 2 to 3 minutes. Initial calibrations of the UWCC were completed on measurements of MOX fuel in Mol, Belgium. The MCNP-REN Monte Carlo simulation code is being benchmarked to the calibration measurements to allow accurate simulations for extended calibrations of the UWCC.

I. INTRODUCTION

An improved underwater neutron coincidence counter (UWCC), Fig. 1, has been developed to verify fresh MOX fuel subassemblies underwater at reactor storage ponds. The counter can be configured to measure both BWR and PWR MOX subassemblies.

Figure 1. (L-R) P. DeBaere (Euratom), G. Eccleston (LANL), I. Cherradi (IAEA), and H. Menlove (LANL), with the UWCC.

Initial UWCC calibration measurements were completed with IAEA and Euratom inspectors in Mol, Belgium on mockup BWR and PWR MOX fuels (Fig. 1). The MOX fuels and measurement configurations were provided at the SCK-CEN facility by the Belgian support program.[1-5] The MOX fuel pins, clad with 304 SS, were 70 cm long, with a 50 cm active length, and a diameter of 0.90 cm. The chemical composition of the pins was UO_2 (97.3 percent with 2 percent enrichment) and PuO_2 (2.7 percent). The $^{240}Pu_{eff}$ was 18.486

percent on 16 February 1998, corresponding to the following plutonium isotopics composition:

• ^{238}Pu	0.054%
• ^{239}Pu	81.218%
• ^{240}Pu	17.582%
• ^{241}Pu	0.689%
• ^{242}Pu	0.456%
• ^{242}Am	2.432%

II. UWCC DESIGN

The initial UWCC design was based on MCNP calculations. Primary goals of the calculations were to determine the effects of cadmium and the front and back dimensions of polyethylene around the detectors to optimize efficiency while reducing the effect of boron concentration on detector efficiency. The design requirements for the UWCC consisted of providing

- Underwater partial defect verifications (< 6% 1 sigma) on fresh MOX fuel assemblies
- Stainless steel cladding for improved decontamination
- Measurement time less than 5 minutes per assembly
- Configurable for measurements of BWR & PWR MOX fuel subassemblies
- Insensitivity to detector positioning around a fuel assembly
- Use of standard IAEA neutron coincidence electronics and assay software
- Compatible size and weight for transportation, field setup and use

Spent-fuel storage ponds have boron contents that range from zero to several thousand parts per million with most ponds containing ~2200 ppm. Increasing the boron concentration in a spent-fuel pond increases the neutron absorption rate, reducing the number of neutrons emitted from a MOX fuel assembly that reach the UWCC--thus resulting in a lower detection efficiency. This efficiency change causes a bias that is a function of the boron concentration. Surrounding the UWCC with a cadmium layer reduces

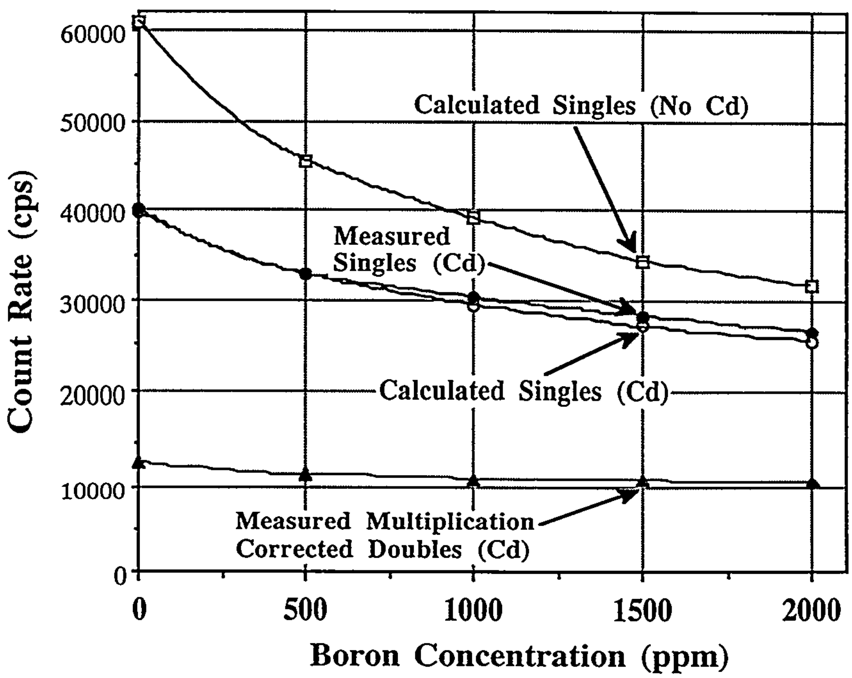

Figure 2. MCNP simulation of UWCC measurements on a 17 x 17 MOX PWR fuel assembly with and without a cadmium cover.

the bias. The cadmium removes thermal neutrons, similar to boron, as they enter the UWCC reducing the effect of varying boron concentration. Figure 2 shows neutron singles as a function of boron concentration from an MCNP simulation of a 17-pin by 17-pin MOX PWR fuel assembly surrounded by an UWCC.[6] MCNP results are plotted for the UWCC with and without cadmium. Cadmium covering the UWCC flattens the efficiency response compared to no cadmium and removes the efficiency bias due to changing boron concentration. Experimental measurements corresponding to the cadmium covered UWCC is also shown in Fig. 2. The multiplication-corrected doubles (D_{mc}), in Fig. 2, is relatively flat between 500 and 2250 ppm boron, indicating that only two calibration curves are needed for the UWCC to cover ponds with no boron and ponds that contain above 500 ppm boron.

The selected design for the UWCC consists of eight 7.5-atmosphere helium-3 neutron detectors embedded in polyethylene; 2.5 cm in front and 3.8 cm. of polyethylene behind the detectors. Four detectors are located in each of the UWCC forks. The polyethylene is wrapped in cadmium and located in a watertight stainless steel enclosure. A stainless steel bellows allows signal cables to be connected between the detectors and the standard spent fuel. A stainless steel backplate contains a pipe holding the PDT-210 dual AMPTEK preamplifier. Stainless steel is used on all external components to improve decontamination.

III. UWCC CHARACTERISTICS

The UWCC has a movable configuration allowing the forks to be moved to fit either PWR or BWR fuel geometries. UWCC measurements use the standard equipment and procedures used for passive neutron coincidence measurements, such as the high-level neutron coincidence counter (HLNC)[7]. The electronics consist of a PC computer running the IAEA neutron coincidence code (INCC) or the Los Alamos neutron coincidence code (NCC). The computer is connected to standard neutron coincidence shift register or multiplicity electronics modules, which are cabled to the UWCC detectors. The commercial version of the UWCC is available from Holbrooks Development and Manufacturing[8], Inc., USA.

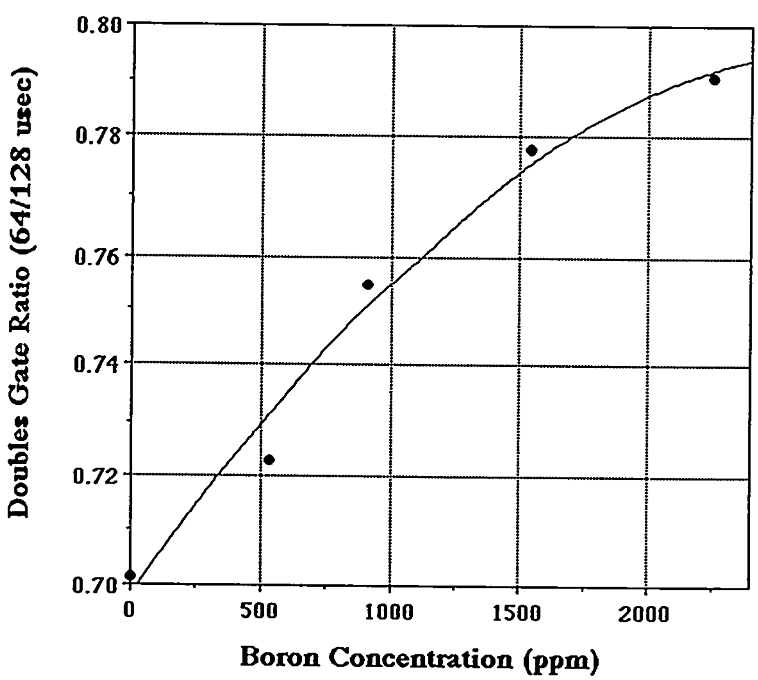

Figure 3. . Calibration of boron concentration vs double gate ratio for a 17x 17 PWR fuel assembly.

Boron in the pool affects the multiplication of the MOX fuel assembly, which in turn affects the die-away time of the system. Measurements at two die-away time gate settings provide a direct measure of the boron concentration. These measurements are obtained by changing the die-away time setting in the INCC program. Fig. 3 is a plot of the correlation between the boron concentration and the doubles coincidence ratio (64 μs/128 μs gates) measured by the UWCC on the 17 x 17 PWR MOX fuel assembly.

IV. COINCIDENCE CALIBRATION AND MULTIPLICITY MEASUREMENTS

Fig. 4 is a photograph showing the UWCC positioned underwater around the 17x17 MOX PWR fuel assembly in Mol, Belgium. The measurement configuration in this photograph shows 33 MOX pins that have been removed from one row and one column. Calibration measurements were completed for a series of MOX pin removals for the cases of 0 ppm and 2250 ppm boron in the water. The measurement data are contained in Table I.

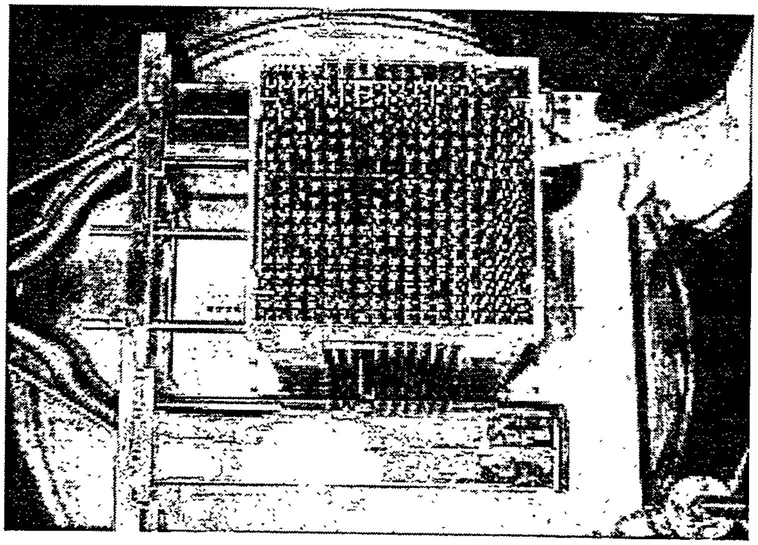

Figure 4. UWCC positioned underwater around a 17 x 17 MOX PWR fuel assembly.

UWCC measurements of the neutron doubles (D), triples (T), and multiplication-corrected doubles (Dmc) rates versus $^{240}Pu_{eff}$ are shown in Fig. 5 for the 17x17 PWR fuel array. As seen in Fig. 5, a large nonlinear effect occurs in both the doubles and triples from the high multiplication of the MOX fuel underwater. Applying a multiplication correction, Dmc, to the doubles produces a linear calibration curve that is independent of multiplication.

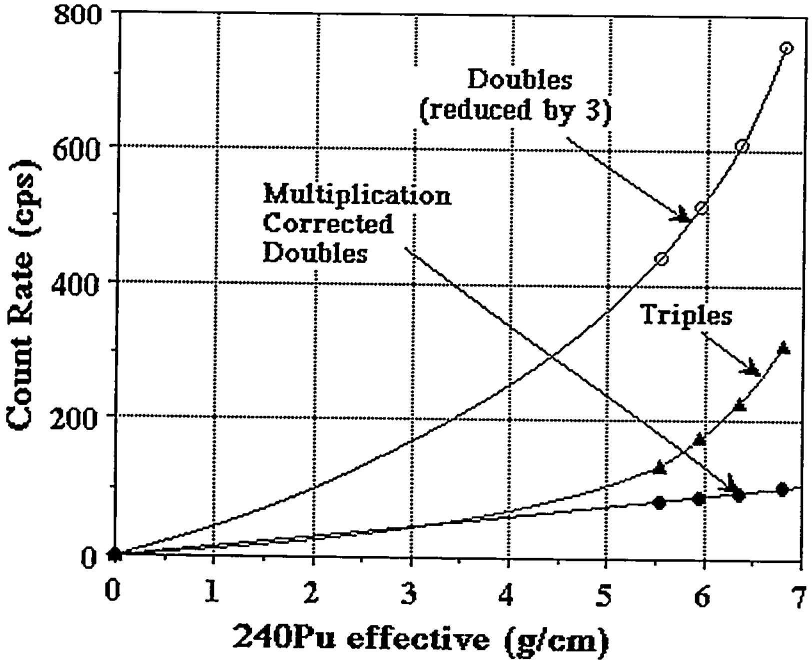

Figure 5. Measured Doubles, Triples and Dmc versus $^{240}Pu_{eff}$ from a 17 x 17 PWR fuel array underwater containing 2250 ppm boron.

MCNP-REN benchmark simulations are in progress to test the capability of the code to accurately simulate UWCC measurements of fresh MOX fuel.[6] Fig 6 is a plot of the measured neutron doubles rates versus $^{240}Pu_{eff}$ for the 17x17 PWR MOX fuel array for boron concentrations of 0 and 2250 ppm boron. The uncertainty in the measured doubles are within the plotted points. MCNP simulations along with the calculated uncertainties are shown in the plots.

MCNP simulations show close agreement with the experimental measurements.

Two multiplication-corrected doubles calibration curves versus $^{240}Pu_{eff}$ for the PWR MOX fuel are shown in Fig. 7, corresponding to no boron and to the maximum (2250 ppm) boron concentration in the water. The calibrations are plots of measured data versus loss of MOX fuel pins. Data were collected corresponding to reducing the MOX fuel pin loadings from a full fuel assembly containing 264 pins to an assembly containing 247, 231 and 215 pins, respectively. Measurements were also collected with 17-3.3% LEU fuel rods substituted for 17-MOX pins to study the effects of replacing plutonium with ^{235}U on UWCC measurements. Substituting ^{235}U for plutonium results in a decreased response compared to just removing the MOX pins. Also, the D_{mc} effectively corrects the changes in multiplication corresponding to ^{235}U fissions in the substituted uranium rods and also corrects for multiplication effects due to the MOX pin removals.

The measured Dmc in unborated water fits a straight calibration line which is above the calibration line for the case when 2250 ppm boron is in the water as shown in Figure 7. The line for unborated water does not have a zero intercept because as MOX rods are removed, the additional interior water that replaces the rods causes the neutron die-away time

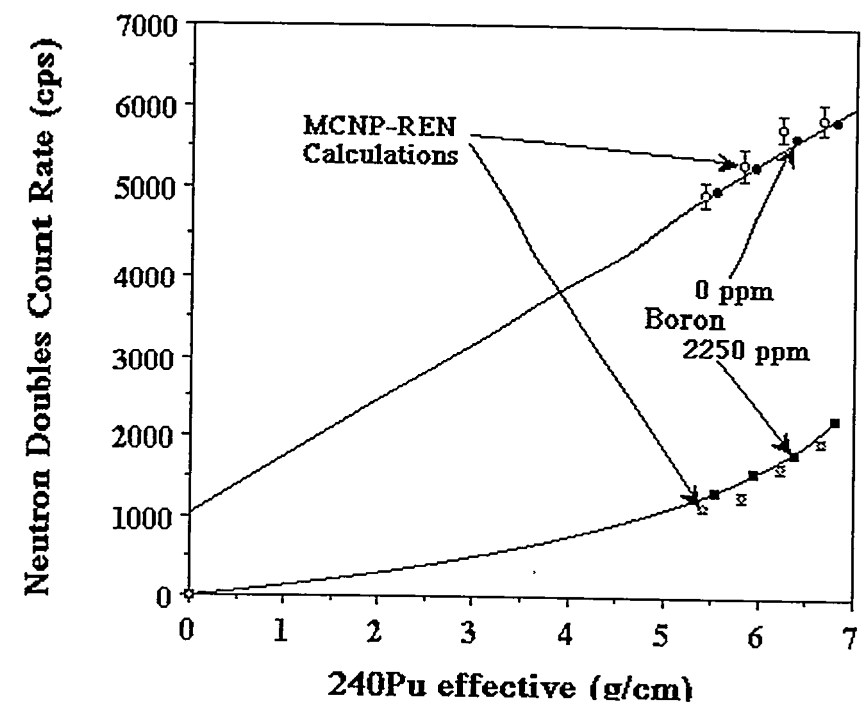

Figure 6. Comparison of MCNP-REN simulations to doubles measurements on 17X17 MOX PWR fuel.

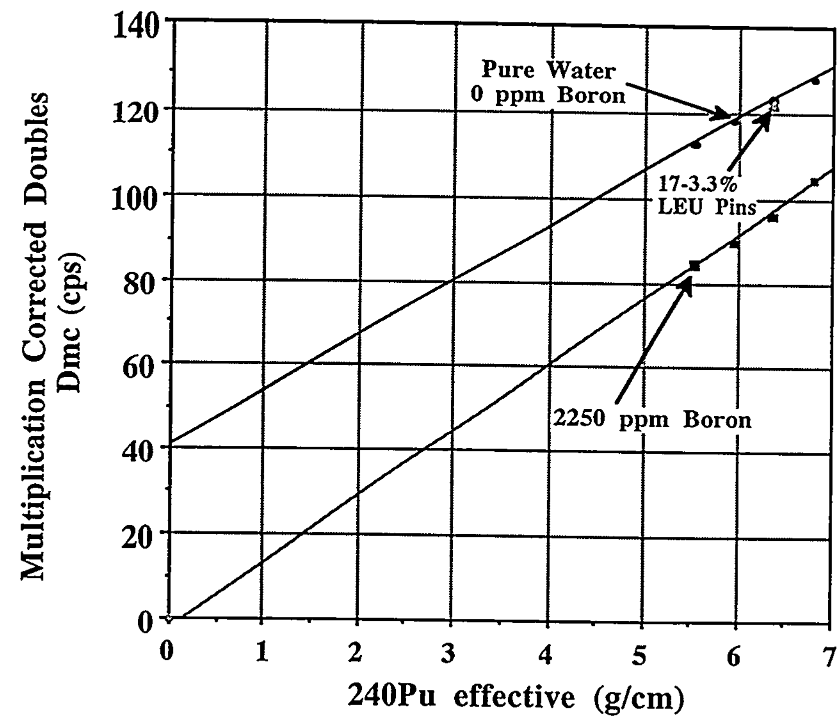

Figure 7. Measured calibration curves for 17X17 PWR MOX fuel underwater with 0pmm and 2250 ppm boron.

to increase. The resulting reduction in the gate fraction reduces the effective ρ_o and increases the multiplication-corrected doubles. This gate fraction change is much smaller for borated water, and the borated calibration line has an intercept near the origin.

IAEA verification of fresh MOX fuel subassemblies requires the ability to detect pin removals or substitutions, relative to a full MOX assembly, at partial defect (6% 1 sigma) levels. This represents detecting 16 pins out of 264 pins in a 17x17 PWR MOX assembly. As shown in Fig. 7 and listed in Table I the UWCC is able to measure the effects of MOX fuel pin loss or substitution at the partial defect level in a two- to three-minute measurement.

Neutron multiplicities can be measured using the UWCC on underwater MOX fuel assemblies. High multiplication of the MOX fuel creates long fission chains which enables relatively low-efficiency counters such as the UWCC (3-4%) to obtain useful neutron triples information. However, in short two- to three-minute counting times, the triples events from multiplicity measurements have larger uncertainties, Table I, compared to the multiplication corrected doubles measurements for a given count time. The triples information is most sensitive to multiplication and boron effects, as shown in Fig 5, and can serve to flag anomalous effects that do not match calibration conditions.

V. MOX FUEL MEASUREMENTS IN AIR

The UWCC has sufficient detection efficiency to provide measurements of fresh MOX fuel assemblies in air. Fig. 8 is a plot showing the measured D_{mc} versus $^{240}Pu_{eff}$ loading of the PWR MOX fuel assembly in air. The capability to use the same UWCC for both air and underwater measurements provides advantages. In some cases the UWCC might be useful in measuring MOX fuel while stored in air awaiting movement to underwater storage in a pond. Air measurements also have potential use for shipper-receiver verification and comparison to calibration measurements at the MOX fuel fabrication facility.

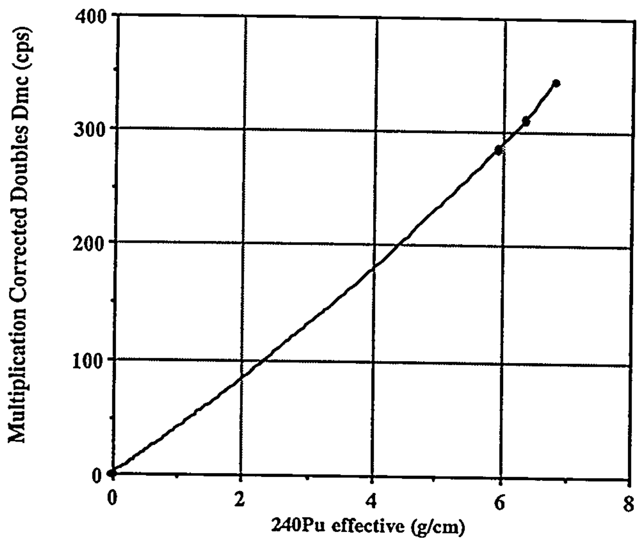

Figure 8. UWCC measurements of a 17 x 17 PWR fuel assembly in air.

VI. CONCLUSIONS

The UWCC provides the capability to obtain bias defect verifications of fresh MOX PWR and BWR fuels with quick (2-3 min) measurement times. The counter was designed to be relatively independent of boron concentration (500-2250 ppm) in spent-fuel ponds, is stainless steel clad for decontamination, and is compatible with standard spent-fuel fork pipe connections.

The boron concentration can be readily determined from the ratio of measured doubles responses at two gate settings. This determination is important to differentiate between no boron in the pond versus more than 500-ppm boron in the pond where different calibration curves are required.

Underwater measurements of MOX fuel assemblies produce large nonlinear coincidence and multiplicity responses due to the high multiplication and long fission chains. The nonlinear coincidence multiplication is effectively removed using the doubles multiplication correction, D_{mc}. This correction calibrates the $^{240}Pu_{eff}$-fuel assembly loading against the D_{mc} and allows partial defect measurements to be verified on unknown MOX fuel assemblies. The doubles correction removes multiplication effects and the effects of substitution with uranium-enriched rods, providing a linear plutonium calibration allowing MOX verification.

Table I. UWCC Measurements on 17x17 MOX PWR Fuel Array

UWCC PWR MOX Fuel Measurements	Number of MOX Rods	$^{240}Pu_{eff}$ (g/cm)	Meas. Time (sec)	Single Rate (c/s)	Double Rate (c/s)	Double Rate Error (c/s)	D_{mc} Rate (c/s)	D_{mc} Rate Error (c/s)	Triple Rate (c/s)	Triple Rate Error (c/s)
0 ppm Boron	264	6.80	960	40011	5869.8	20.9	128.56	0.20	1123.5	22.0
0 ppm Boron 17 MOX pins removed	247	6.36	3800	38446	5647.3	10.1	123.46	0.09	1064.7	10.4
0 ppm Boron 17 LEU (3.3%) pins substituted for MOX pins	247	6.36	600	37837	5522.5	24.9	121.83	0.23	1057.6	25.6
0 ppm Boron 33 MOX pins removed	231	5.95	600	36470	5281.7	23.9	117.81	0.23	999.3	24.2
0 ppm Boron 48 MOX pins removed	215	5.54	600	34679	4988.8	22.6	112.34	0.22	908.8	22.4
530 ppm Boron	264	6.80	240	32911	3945.1	32.6	114.98	0.40	685.9	31.9
530 ppm Boron	264	6.80	600	32887	3963.6	20.6	114.64	0.25	682.5	20.1
909 ppm Boron	264	6.80	480	30185	3252.1	20.7	110.15	0.29	511.2	19.4
1540 ppm Boron	264	6.80	960	28168	2754.5	13.4	106.88	0.21	444.8	12.3
2160 ppm Boron	264	6.80	51420	26470	2329.8	1.7	104.75	0.03	313.9	1.5
2250 ppm Boron	264	6.80	900	26111	2256.0	12.5	104.08	0.23	313.6	11.1
2250 ppm Boron 17 MOX pins removed	247	6.36	600	23203	1820.0	13.4	96.07	0.28	227.8	11.2
2250 ppm Boron 33 MOX pins removed	231	5.95	4140	21185	1557.0	4.6	89.96	0.10	173.4	3.7
2250 ppm Boron 48 MOX pins removed	215	5.54	600	19351	1329.3	10.9	84.33	0.27	134.0	8.4

ACKNOWLEDGEMENTS

This work reported in this paper was supported by the United States Department of Energy/International Safeguards Division (DOE/NN44) and The United States Program of Technical Support (POTAS) to the International Atomic Energy Agency (IAEA).

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