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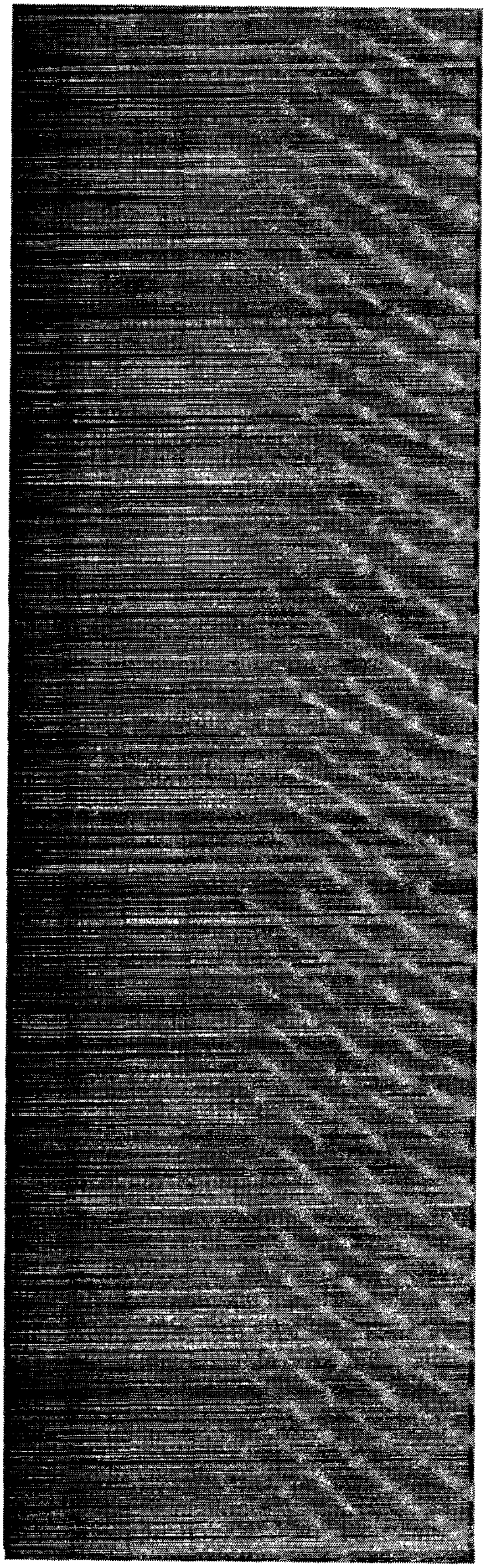

The Underwater Coincidence Counter for Plutonium Measurements in Mixed-Oxide Fuel Assemblies Manual

UNITED STATES PROGRAM
FOR TECHNICAL ASSISTANCE TO IAEA SAFEGUARDS

POTAS

DEPARTMENT OF STATE
DEPARTMENT OF ENERGY
ARMS CONTROL AND DISARMAMENT AGENCY
NUCLEAR REGULATORY COMMISSION

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

Edited by Amy Fulton-Stout, Group CIC-1

This work was supported by the U.S. Department of Energy, Office of Nonproliferation and National Security, International Safeguards Division, and Program for Technical Assistance to IAEA Safeguards.

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LA-13574-M
Manual
(ISPO-375)
UC-706
Issued: May 1999

USER'S MANUAL

The Underwater Coincidence Counter for Plutonium Measurements in Mixed-Oxide Fuel Assemblies

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THE UNDERWATER COINCIDENCE COUNTER FOR PLUTONIUM MEASUREMENTS IN MIXED-OXIDE FUEL ASSEMBLIES

by

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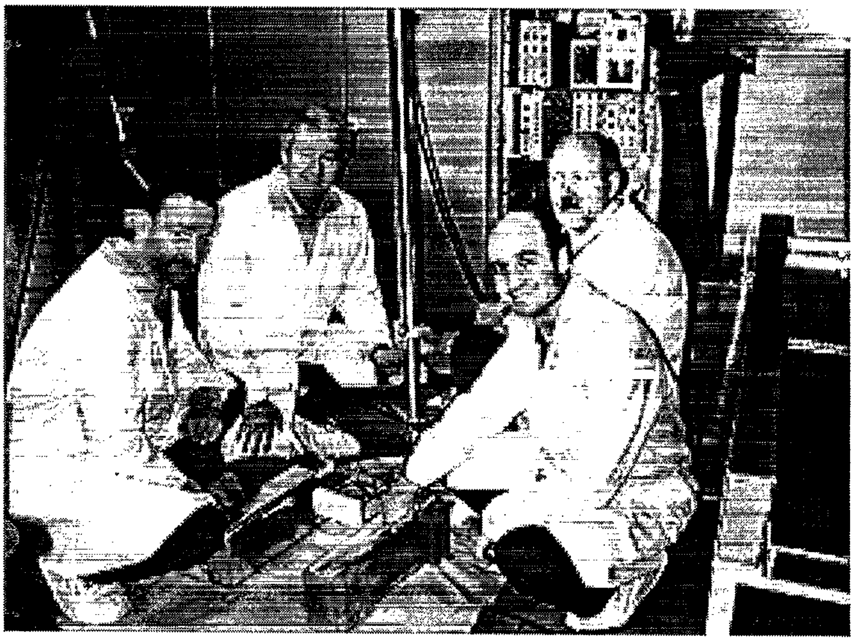
ABSTRACT

This manual describes the Underwater Coincidence Counter (UWCC) that has been designed for the measurement of plutonium in mixed-oxide (MOX) fuel assemblies prior to irradiation. The UWCC uses high-efficiency ^{3}He neutron detectors to measure the spontaneous-fission and induced-fission rates in the fuel assembly. Measurements can be made on MOX fuel assemblies in air or underwater. The neutron counting rate is analyzed for singles, doubles, and triples time correlations to determine the ^{240}Pu effective mass per unit length of the fuel assembly. The system can verify the plutonium loading per unit length to a precision of less than 1% in a measurement time of 2 to 3 minutes. System design, components, performance tests, and operational characteristics are described in this manual.



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

INTRODUCTION The use of fresh uranium-plutonium mixed-oxide(MOX) fuel in light-water reactors is increasing in Europe and Japan, and it is important for inspectors to verify the plutonium content in the fuel for international safeguards purposes. Therefore, an improved underwater coincidence counter (UWCC), shown in Fig. 1, has been developed to verify fresh MOX fuel subassemblies in air or underwater at reactor storage ponds. The UWCC can be configured to measure either boiling-water reactor (BWR) or pressurized-water reactor (PWR) fuel assemblies.

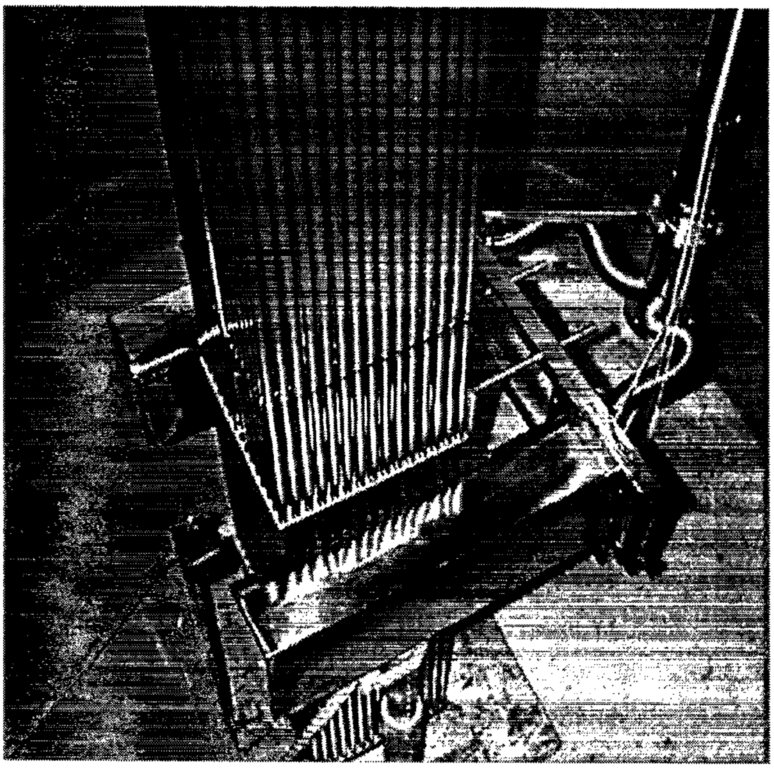


Fig. 1. UWCC positioned around the Los Alamos PWR MOX fuel assembly to provide plutonium verification measurements underwater.

The UWCC uses high-efficiency ^{3}He neutron detectors to measure the spontaneous-fission and induced-fission rates in the fuel assembly. The neutron counting rate is analyzed for singles (S), doubles (D), and triples (T) time correlations to determine the ^{240}Pu effective mass, as well as the reactivity of the fuel assembly. The UWCC can verify the plutonium loading per unit length to a precision of under 1% in a measurement time of 2 to 3 minutes.

Calibration of the UWCC was determined through measurements of MOX fuel in Mol, Belgium, and in Los Alamos. The Mol fuel array allowed calibration measurements up to ^{240}Pu effective loadings of 6.8 g/cm. The Los Alamos MOX fuel allowed the calibration to be extended up to a ^{240}Pu effective loading of 14.83 g/cm.

This manual provides the design specifications, performance tests, operational parameters, and preliminary calibration information for the UWCC.

UWCC DESIGN

The UWCC design was based on MCNP calculations. These calculations attempted to determine the effects of cadmium and to specify the front and back dimensions of polyethylene located around the detectors, which optimize efficiency while reducing the effect of boron concentration. The goals of the UWCC development were:

- 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 and PWR MOX fuel subassemblies,
- insensitivity to detector positioning around a fuel assembly,
- use of standard neutron coincidence shift-register electronics and assay software, and
- compatible size and weight for transportation, field setup, and use.

The selected design for the UWCC (shown in Fig. 2) consists of eight 7.5-atmosphere ^{3}He neutron detectors embedded in polyethylene, with 2.5 cm of polyethylene in front and 3.8 cm 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 UWCC pipe and preamplifier. A stainless-steel backplate contains a pipe holding the PDT-210A dual AMPTEK preamplifier.[1] Stainless steel is used on all external components for decontamination.

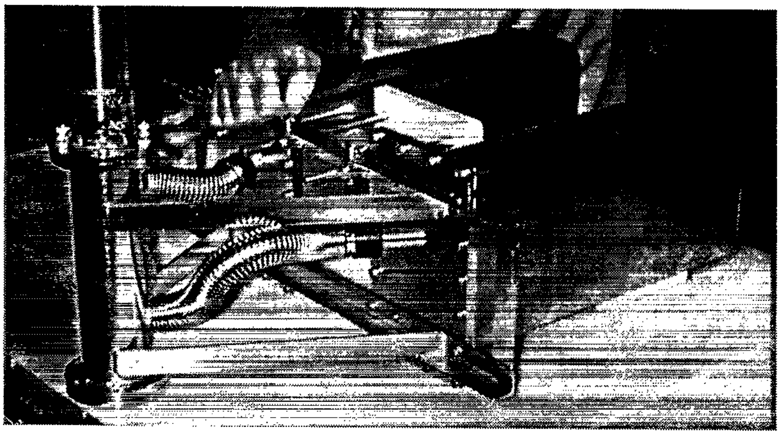


Fig. 2. Underwater Coincidence Counter (UWCC).

In addition to providing improved decontamination, the stainless shell also protects the cadmium liner, which is positioned around the high-density polyethylene on the inside of the shell. The stainless shell is watertight and sealed with standard stainless-steel screws and O rings, permitting measurements to be performed underwater.

To decrease the UWCC sensitivity to varying boron concentrations in the water, we placed a 0.5-mm liner of cadmium inside the stainless-steel forks which completely surrounds the polyethylene containing the detectors. For gamma-ray shielding and neutron absorption, the cadmium liner thickness was increased to 1.0 mm in the location directly between the fuel assembly and the ^{3}He tubes. The cadmium-covered polyethylene contains the ^{3}He detectors, as shown in Fig. 3. Each of the UWCC forks contain four ^{3}He tubes with the specifications listed in Table I.

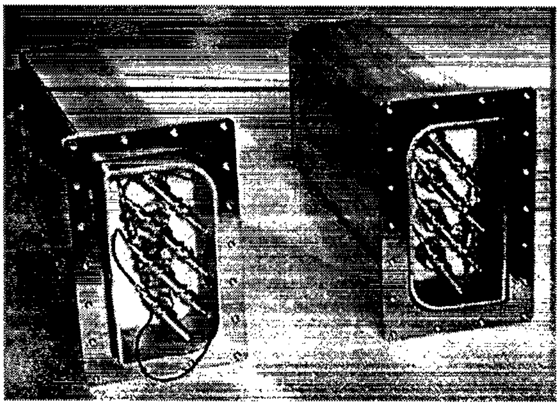


Fig. 3. UWCC forks showing polyethylene and the cabling to the ^{3}He neutron detectors.

Table I. UWCC Helium-3 Detector Specifications

Detector Parameters	Value
Model number	RS-P4-0811-105
Number of tubes	8
Gas pressure	7.5 atmospheres
Tube cladding	aluminum
Active length	277 mm

PREAMPLIFIER (PDT-210A)

The UWCC uses a dual-channel PDT-210A amplifier with one AMPTEK channel for four ^{3}He detectors. Figure 4 shows the wiring between the ^{3}He tubes and the PDT-210A amplifier. The detectors are cross-wired between the two forks and each AMPTEK channel collects signals from two detectors in each fork. The cable length between the ^{3}He tubes and the PDT-210A amplifier is approximately 45 mm. The amplifier output pulse is set for 50 ns. The distance between the PDT-210A and the shift register should be 20 m or less.

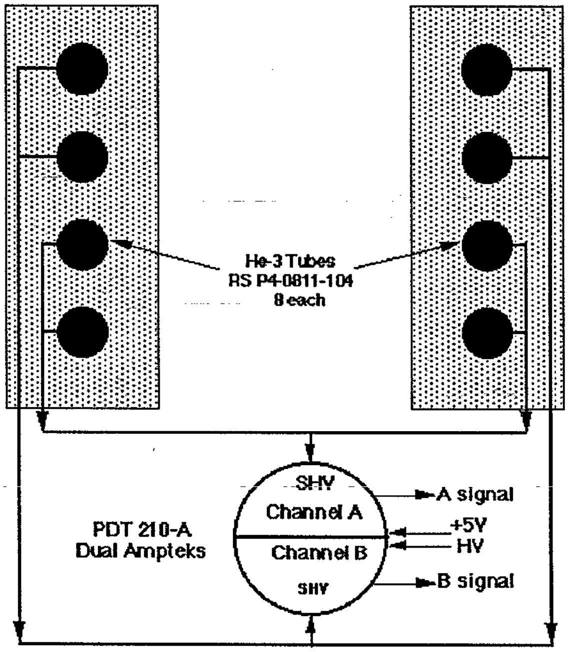


Fig. 4. Wiring from ^{3}He tubes to the PDT-210A amplifier.

A signal summer box, shown in Fig. 5, connects the PDT-210A to the shift-register electronics. The summer box passes HV and +5V from the shift-register module to the PDT-210A and ORs the output of the two digital pulses to produce one pulse stream, which is then fed into the shift register.

COINCIDENCE ELECTRONICS

Commercial shift-register products meeting the requirements for UWCC neutron multiplicity/coincidence measurements with the INCC program are the Advanced Multiplicity Shift Register from Ortec, and the PSR and PSR-B modules from Aquila Technologies. The PSR-B module is shown in Fig. 5.

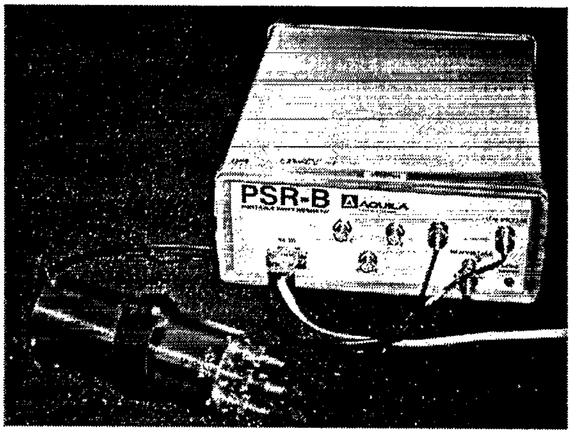


Fig. 5. PSR-B multiplicity shift register connected to the UWCC signal summer box.

The UWCC functions with older coincidence shift-register electronics such as the JSR-11 and JSR-12. Measurements of the neutron singles (S) and doubles (D) are provided by these units.[2] A two-parameter analysis provides fuel-assembly verification but lacks triples flags. Triples measurements are obtained from multiplicity measurements. These also provide information indicating whether measurement conditions are appropriate to declared conditions.

INCC MEASUREMENT PROGRAM

The UWCC is operated using the Integrated Neutron Coincidence Counting (INCC) software program. The program communicates with a shift register through the serial port of a PC computer. The INCC program controls the shift register, sets UWCC operational parameters, and receives neutron singles, doubles, and multiplicity signals. These signals are collected by the shift register.

The INCC program analyzes the UWCC measurement data and displays the results within a few seconds from the time each measurement is completed. Count rates are corrected for detector dead time. The neutron doubles, D, are corrected for multiplication using the known-alpha method.[3] The UWCC measurements provide underwater verification of the ^{240}Pu effective rate of fresh MOX fuel based on a calibration curve, shown in Fig. 6.

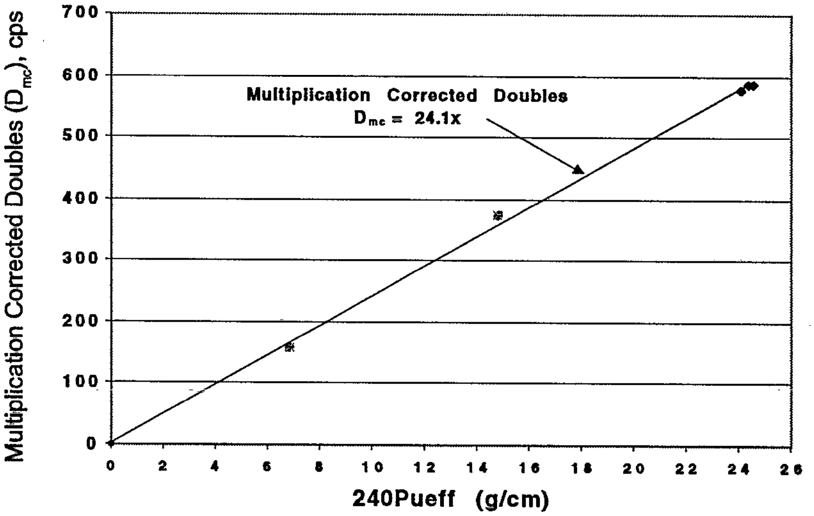


Fig. 6. Calibration curve for PWR MOX fuel verifications in borated water using INCC-corrected doubles measurement data.

HIGH-VOLTAGE PLATEAU

Before measuring the high-voltage plateau for the UWCC, the two PDT-210A channels were matched to have the same gain. Figure 7 shows the plateau curves for channels A and B for the ^{3}He tubes (RS-P4-0811-105). The PDT-210A preamplifier allows the UWCC high-voltage operating bias to be the standard 1680 volts used for safeguards neutron-measurement systems.

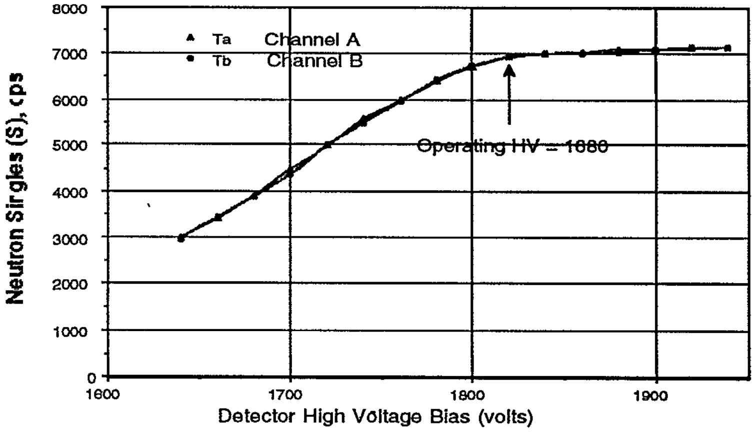


Fig. 7. UWCC detector high-voltage bias plateau curve.

DEAD TIME

The counting rates for the UWCC are high (approximately 100 kHz) for MOX fuel assemblies, which causes a significant electronic deadtime effect. The dead time was measured using two ^{252}Cf sources that had a known absolute ratio of neutron emission rates. The ratio for sources Cf-10 to Cf-4 is 55.6. The deadtime equations for corrected rates for the singles and doubles are given by

$$S(corr.) = S(meas)e^{\frac{\delta S}{4}}$$

$$D(corr.) = D(meas)e^{\delta S}$$

where

$$\delta = (a + b \bullet S \bullet 10^{-6})\ \mu s$$

and the deadtime parameters a/b = 1. The measurement parameters required for the INCC program under the "Setup" heading are listed in Table II.

Table II. UWCC Measurement Parameters Setup

Parameter		UWCC1	UWCC2	UWCC3
Gate Length	µsec	64	64	64
High Voltage	HV	1680	1680	1680
Dieaway Time (air)	τ, µs	38	38	38
Efficiency	ε	0.05	0.05	0.05
Multiplicity Dead Time	d	500	500	500
Deadtime Coefficient	A	2.15	2.18	1.9
Deadtime Coefficient	B	2.15	2.18	1.9
Deadtime Coefficient	C	35	30.5	0
Doubles-Gate Fraction	fg	0.70	0.70	0.70
Triples-Gate Fraction	tg	0.49	0.49	0.49

MULTIPLICITY DEAD TIME

For multiplicity analysis, the deadtime corrections are done with the equations derived by Dytlewski[4] using a constant deadtime value *d*. The value of *d* was determined by measuring several ^{252}Cf sources with different neutron source strengths. The triples/doubles multiplicity ratio should be independent of the neutron source strength after deadtime correction. The value of *d* that gave the best agreement was the maximum value:

$$d \cong 500 \text{ ns.}$$

A multiplicity dead time of 500 ns requires a shift-register gate setting of 64 μs or larger. The additional multiplicity deadtime coefficient C was required for units UWCC1 and UWCC2.

NEUTRON DIEAWAY TIME

The neutron dieaway time τ of the UWCC was measured using source Cf-7. Table III lists the gate widths and the doubles rates and errors. The resulting dieaway time in air is approximately 37 μs for a gate setting of 64 μs.

Table III. Californium (Cf7) UWCC Dieaway Time Measurements in Air

Gate Length (μs)	Parameter	UWCC1
32	Singles, cps	17898
	Doubles, cps	2260
	D_{err}, σ%	0.32
	τ, μs	-
64	Singles, cps	17899
	Doubles, cps	3200
	D_{err}, σ%	0.281
	τ, μs	36.5
128	Singles, cps	17902
	Doubles, cps	3803
	Derr, σ%	0.36
	τ, μs	38.6

Boron in the pool affects the multiplication of the MOX fuel assembly, which in turn affects the dieaway time of the system. Measurements at two dieaway time gate settings can confirm the boron content in a pool. Figure 8 shows the doubles rate versus the gate width for a ^{252}Cf source in air (bottom curve) and a PWR assembly in unborated water (top curve).

In addition to the measurements for a ^{252}Cf source in air, the dieaway time was measured for a PWR MOX fuel assembly in pure water at Los Alamos. This information is provided in Table IV. The dieaway time increases from approximately 38 μs for ^{252}Cf in air to approximately 78 μs for a MOX assembly in pure water. The reason for the increase is the long neutron-multiplication fission chains that occur when a MOX fuel assembly is placed underwater. The induced fissions from multiplication add several neutron-thermalization time intervals to the dieaway time.

Table IV. UWCC Dieaway Time Measurements for a PWR MOX Assembly in Water

Gate Length (μsec)	Parameter	UWCC1
32	Singles, cps Doubles, cps D_{err}, σ% τ, μs	100490 5995 1.264 -
64	Singles, cps Doubles, cps D_{err}, σ% τ, μs	100540 10137 1.144 ~86
128	Singles, cps Doubles, cps Derr, σ% τ, μs	14258 3803 1.259 ~71

Figure 8 shows a graph of the normalized doubles rate as a function of gate width for a ^{252}Cf source in air and a MOX assembly in pure water with the data normalized to unity for at the 32-μs gate width.

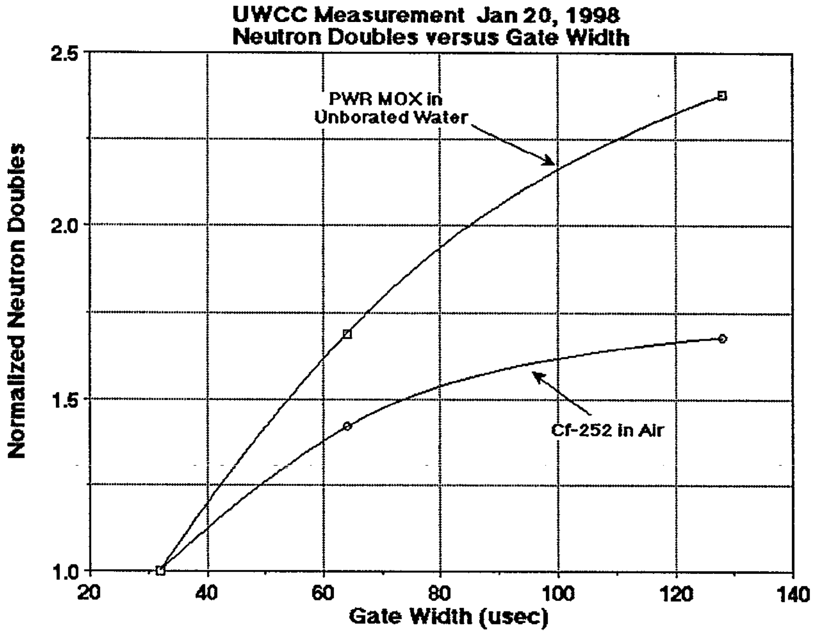
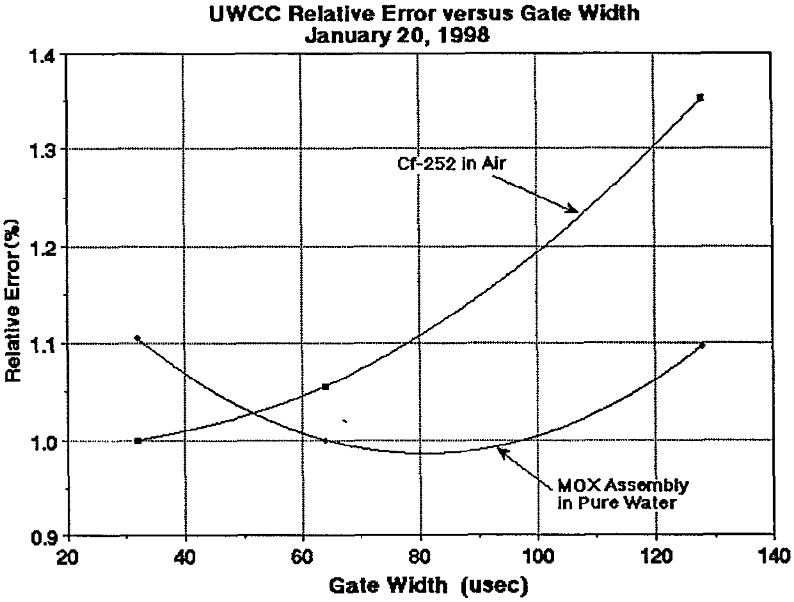


Fig. 8. Doubles rate versus the coincidence gate width for the UWCC in air with a ^{252}Cf source and in water from a PWR MOX fuel assembly.

Figure 9 shows the relative counting statistical error versus the gate length for the same cases (air and water). The error is a minimum for a gate setting at approximately 80 μs in water.

For the case of MOX fuel in borated water, the dieaway time is slightly higher than for air (approximately 40 μs). Since most MOX fuel assemblies are stored in borated water, we have chosen a gate setting of 64 μs for applications of the UWCC to MOX fuel assemblies. A gate increase to 128 μs would result in a doubling of the counting time needed to obtain the same counting statistics obtained statistics obtained for the 64-μs gate.

Fig. 9. Relative statistical error for the doubles rate versus gate setting for ^{252}Cf in air and for a PWR MOX fuel assembly in water.



EFFICIENCY

The efficiency of the UWCC was measured by placing a calibrated ^{252}Cf source in the center of the active zone. The measured efficiency in air was 3.6% (PWR mode) for a ^{252}Cf point source centered in the UWCC. For the BWR geometry, the efficiency for a ^{252}Cf source in air increases because the two forks are moved closer together compared to the PWR configuration, resulting in an efficiency of 5.1%. Because of the extended geometry and the neutron absorption in the water, the average efficiency for spontaneous fission neutrons emitted over the geometry of a fuel assembly will be considerably less than this value.

The ^{3}He tubes in the UWCC have active lengths of 280 mm compared with 152 mm for the modified fork. The extra length was designed to provide more efficiency and to make the counting rate less sensitive to the movement of the fuel assembly relative to the fork during the measurement. The primary drawback to these larger fork arms is the increased weight for the UWCC.

The nylon bumper on the back of the UWCC is used to position fuel assemblies in the center of the maximum counting profile. The bumper has two positions, which are determined by a set screw. The bumper is extended for BWR assemblies and retracted for PWR assemblies.

Tests were performed to determine the change in counting rate as a function of moving the fuel assembly away from the bumper and out of the measurement area of the forks (see Fig. 10.) A 2-cm gap between the fuel and the bumper results in an approximately 1% change in the D_{mc} rate. Both the totals and the doubles rates have larger variations with position than the D_{mc}. The plutonium calibration is based on the D_{mc} rate.

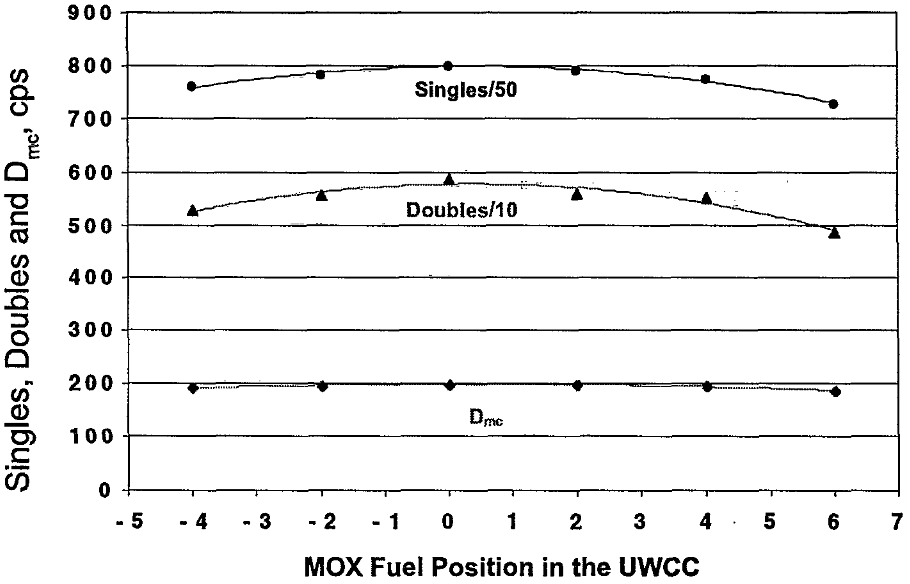


Fig. 10. UWCC neutron singles, doubles, and multiplication-corrected doubles response vs position (cm) of the PWR MOX fuel assembly along the length of the UWCC arms.

MULTIPLICATION CONSTANT

For the conventional two-parameter known-alpha analysis of neutron coincidence data, the constant ρ_0 represents a nonmultiplying sample and is defined as:

$$\rho_0 = \frac{R}{T}(1+\alpha)$$

where α is the calculated ratio of alpha-particle-induced neutrons to spontaneous-fission neutrons. Because R is directly proportional to the gate fraction f_g for the doubles rate, we have ρ_0 at an approximate efficiency of $* f_g$. We cannot measure ρ_0 because we do not have a nonmultiplying fuel assembly with the geometry of a PWR or BWR fuel assembly. The value of ρ_0 is directly proportional to the efficiency; therefore, the higher efficiency of the BWR configuration will result in a higher ρ_0 for BWRs than for PWRs.

The value of ρ_0 can be determined using MCNP calculations to obtain the neutron leakage multiplication (M_L) of the assembly in water. The ρ_0 is selected to give agreement between the MCNP value of M_L and the two-parameter analysis of M_L.

In Table V, we have used the same value of ρ_0 for air, pure water, and borated water for a given fuel type to provide consistency during setup of the INCC program and for field measurements. Actually, ρ_0 increases as the boron in the water increases because the boron shortens the dieaway time and results in a larger fraction of neutrons appearing within the gate width.

Table V. UWCC Multiplication Constants

Parameter	BWR	PWR
ρ_0 in air f_g in air	0.026 0.75@64 µs	0.019 0.75@64 µs
ρ_0 in pure water f_g in pure water	0.026 0.53@64 µs	0.019 0.53@64 µs
ρ_0 in 2200 ppm B f_g in 2200 ppm B	0.026 0.73@64 µs	0.019 0.73@64 µs

The MCNP-REN analysis of the PWR MOX fuel assembly provides values for ρ_0 that vary from 0.014 for unborated water to 0.020 for 2200 ppm of boron. The boron concentration can be checked and estimated using the doubles ratio from two gate measurements when a MOX fuel assembly is being measured. We have selected a single ρ_0 value corresponding to 2200-ppm boron concentration. The ρ_0 is selected to give the true M_L for the assembly in borated water. Since the majority of fresh MOX fuel assemblies are stored in approximately 2200-ppm borated water, the borated water value of ρ_0 was used.

CROSS-CALIBRATION

Calibrating the UWCC using a MOX fuel assembly allows other UWCCs to be cross-calibrated using a ^{252}Cf source positioned in the center of the UWCC. A reference count rate for cross-calibration is obtained by placing a ^{252}Cf source with a calibrated neutron-emission rate at the center of the UWCC active zone (see Fig. 11.) The rates are listed in Table VI for both PWR and

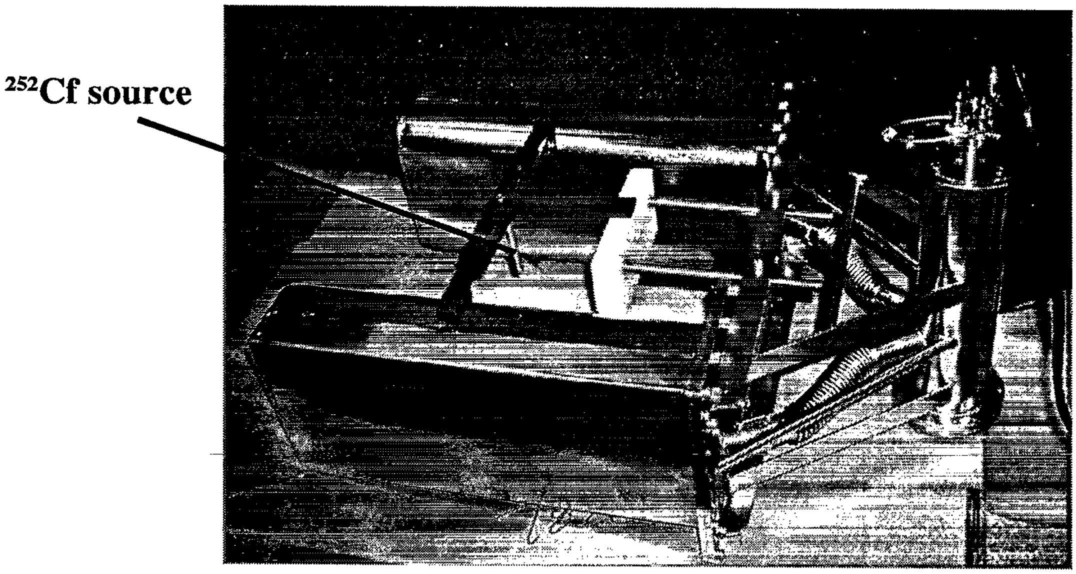


Fig. 11. UWCC cross-calibration geometry and ^{252}Cf source-holding fixture.

BWR geometries. The data in Table VI are also corrected for dead time. The UWCC parameters used for the measurements are listed in Table IV.

When performing a cross-calibration, care must be taken to avoid neutron reflection from the table or floor supporting the UWCC. The UWCC should be positioned about one meter above the floor and at least a meter away from the walls. A metal pushcart was used to support the UWCC when collecting the cross-calibration data shown in Table VI. A special fixture, shown in Fig. 11, is supplied with the UWCC to hold the ^{252}Cf source in the center of the active zone. The fixture adjusts to both BWR and PWR geometries.

Table VI. ^{252}Cf (Cf-8) Reference Rates for Cross-Calibration

UWCC Configuration	Singles (S) cps	Doubles (D) cps
PWR	4092	178.3 ± 0.05
BWR	5800	350.6 ± 2.9

BORON EFFECTS

The multiplication constant ρ_0 is dependent on the boron in the water because the boron decreases the die-away time (τ) for neutrons in the fuel assembly. This decrease in τ results in an increase in the gate fraction *fg* given by:

$$fg = e^{-PD/\tau}\left(1 - e^{-G/\tau}\right)$$

where

PD = pre-delay (3 μs),

G = gate length (64 μs), and

τ = die-away time.

Figure 12 shows a plot of *fg* versus τ for the UWCC for gate lengths of 32, 64, and 128 μs. The τ values for pure water and borated water were measured for a PWR MOX assembly and the values are indicated in Fig. 12. The resulting changes in the *fg* values change the effective ρ_0 by approximately 37%.

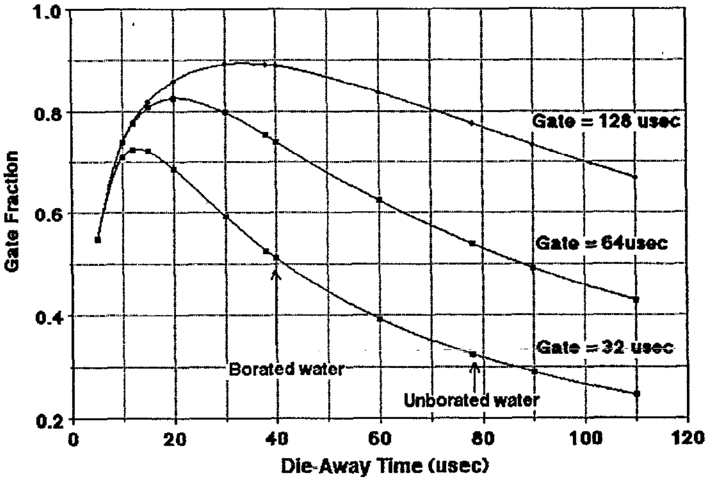


Fig. 12. The UWCC gate fraction vs dieaway time for gates of 64 and 128 μs.

BORON EFFECTS ON UWCC MEASUREMENTS

Spent-fuel storage ponds have boron contents that range from zero to several thousand ppm, with most ponds containing approximately 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 and resulting in a lower counting rate. This rate change causes a calibration change that is a function of the boron concentration. Surrounding the UWCC with a cadmium layer removes thermal neutrons that are similar to boron as they enter the UWCC, reducing the effect of varying boron concentrations. Figure 13 shows the UWCC neutron singles rate as a function of boron concentration from a 17-pin X 17-pin MOX PWR fuel assembly. The MCNP results are plotted for the UWCC with and without cadmium. Cadmium covering the UWCC flattens the efficiency response compared to no cadmium, and it reduces the efficiency changes due to changing boron concentration. The UWCC-measured D_{mc} in Fig. 13 is relatively flat (between 1000- and 2250-ppm boron), indicating that two D_{mc} calibration curves are sufficient for the UWCC to cover unborated and borated ponds.

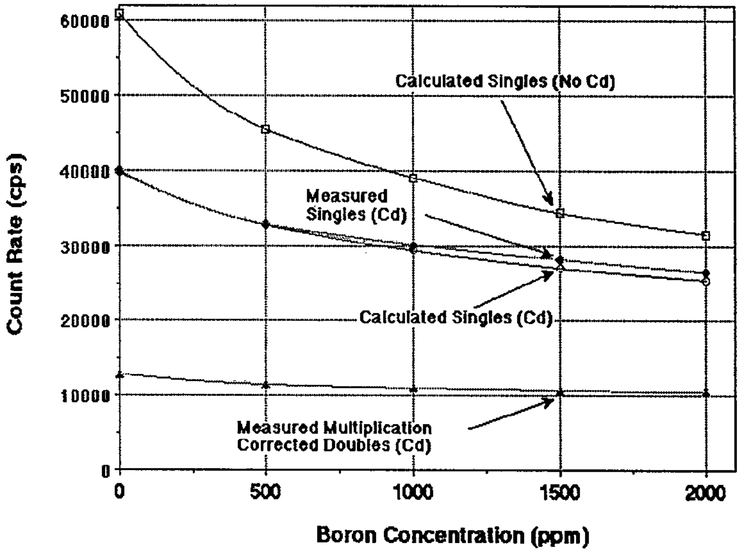


Figure 13. MCNP simulation of UWCC measurements on a 17 X 17 MOX PWR fuel assembly with and without a cadmium cover.

Figure 13 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 a 17 X 17 PWR MOX fuel assembly.

BORON CONCENTRATION MEASUREMENT

For MOX fuel assemblies stored underwater, the boron content can be confirmed from a dieaway time τ ratio measurement when a fuel assembly is located in the UWCC. The boron concentration in parts per million is determined with the UWCC by measuring a fuel assembly at two shift-register gate settings. This is possible since the boron concentration affects the die-away time and not the efficiency of the UWCC. The shift-register gate settings are changed in the INCC program in the "Measurement Parameters," located under the "Settings" file menu. The normal doubles-rate measurement, D_{64}, takes place with a 64-µs gate setting. If a second doubles-rate measurement, D_{128}, of approximately 5 minutes is made with a second shift-register gate setting of 128 µs, then the boron concentration can be determined.

The doubles gate ratios, D_{64}/D_{128}, confirm the boron concentrations as shown in Fig. 14. The doubles gate ratio is expected to be approximately 0.79 for a boron concentration of 2200 ppm.

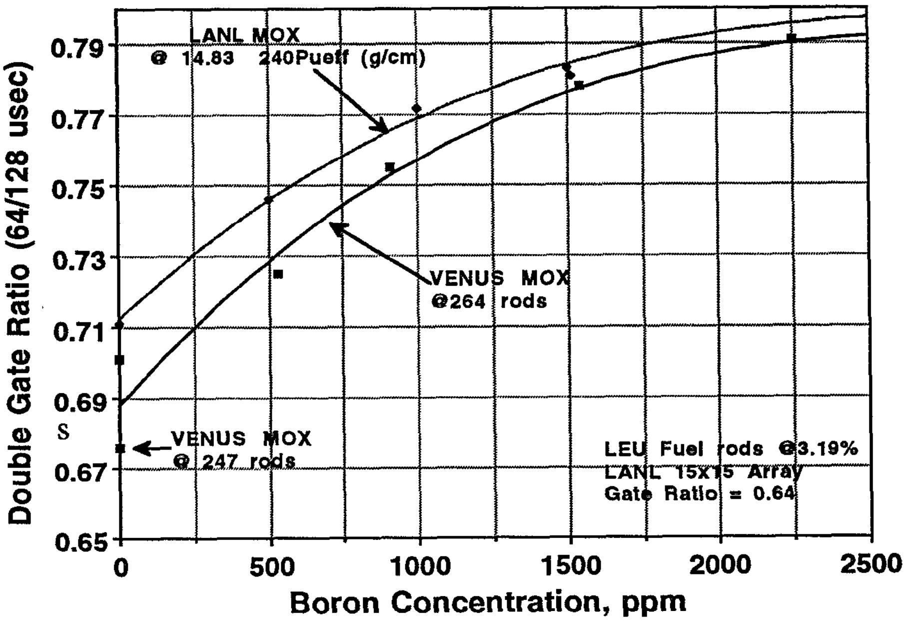


Fig. 14. Doubles gate ratio (D_{64}/D_{128}) vs boron concentration.

MOL FUEL DESCRIPTION

Figure 15 shows the UWCC positioned around the PWR MOX fuel array in Mol, Belgium.[5] The active length of the plutonium in the Mol fuel rods is 50 cm. The isotopics for the fuel are given in Table VII.

Table VII. Mol MOX Fuel Isotopics

	16-Jan-1998
^{238}Pu	0.054 %
^{239}Pu	81.218 %
^{240}Pu	17.582 %
^{241}Pu	0.689 %
^{242}Pu	0.456 %
^{241}Am	2.432 %
$^{240}Pu_{eff}$	0.02575 g/cm/pin
MOX Array	15 x 15 = 204 pins
$^{240}Pu_{eff}$	6.798 g/cm/array

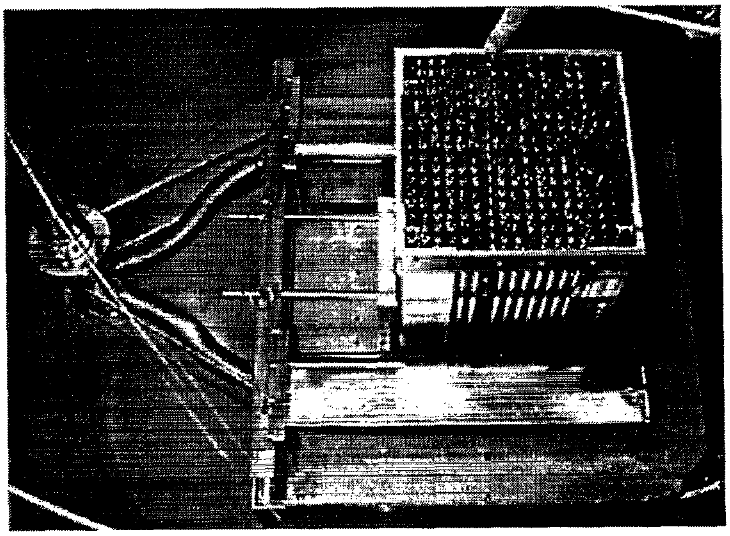


Fig. 15. Mol PWR MOX fuel array positioned underwater in the UWCC. Two rows of fuel pins are removed from the array.

LANL FUEL DESCRIPTION

The Los Alamos PWR MOX fuel assembly is a 15-pin X 15-pin array, shown in Fig. 16. (Refer also to Appendix A.) The isotopic specifications for the MOX rods are listed in Table VIII below. For the full 204-rod array (204 fuel rods and 21 empty control-rod channels) the linear plutonium loading is 14.83 g ^{240}Pu$_{eff}$/cm. The UWCC is 17.3 cm tall and it is sensitive to the fuel for about 10 cm beyond the top and bottom of the detector arms. The measured fuel region extends over a height of about 37 cm. In the case of the Los Alamos MOX fuel assembly, this corresponds to approximately 2.5 kg of plutonium.

Table VIII. Los Alamos MOX Fuel Isotopics

	15-Jan-1998
^{238}Pu	0.673 %
^{239}Pu	77.580 %
^{240}Pu	17.799 %
^{241}Pu	2.367 %
^{242}Pu	1.581 %
^{241}Am	4.734 %
^{240}Pu$_{eff}$	0.0727 g/cm/pin
MOX Array	15 X 15 = 204 pins
^{240}Pu$_{eff}$	14.83 g/cm/array

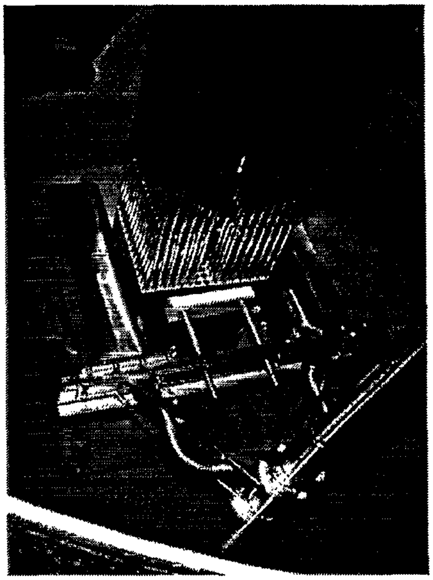


Fig. 16. UWCC calibration geometry with the Los Alamos 15-pin X 15-pin MOX fuel assembly.

CALIBRATION

Calibration of the UWCC was obtained from measurements of MOX fuel rods located at the SCK-CEN facility in Mol, Belgium and at Los Alamos. These measurements provide calibration data for two different types of MOX fuel rods and fuel arrays. The calibrations at Mol were performed in pure water and for five boron concentrations (530, 909, 1540, 2160, and 2250 ppm). Both PWR (17-pin X 17-pin array) and BWR (9-pin X 9-pin array) fuel arrays were used for the measurements at the VENUS facility. Borated and unborated calibrations were performed at Los Alamos. The Los Alamos PWR MOX fuel array is a 15 X15 configuration and the fuel contains more than twice the plutonium (14.83g ^{240}Pu$_{eff}$/cm) compared to the Mol fuel array (6.80g ^{240}Pu$_{eff}$/cm).

MOX PIN REMOVAL

The effects of plutonium loss through pin-removal load were determined starting with full MOX arrays. The full MOX fuel arrays in Mol, Belgium (17 X 17 = 264 pins) and in Los Alamos (15 X 15 = 204 pins) were measured. Pins were then removed from selected interior rows to reduce the plutonium content. Measurements were made for the case where water replaced the MOX rods. One set of measurements were collected with UO_2 fuel rods (containing a depleted-uranium content of 0.2%) replacing the MOX rods. The neutron singles and neutron doubles rates are dependent on the specific configurations. The multiplication correction removes this dependence. The multiplication-corrected neutron doubles rate versus the ^{240}Pu-effective content is a straight line.

Figure 17 shows the the D_{mc} rate versus the ^{240}Pu-effective linear loadings in unborated water.

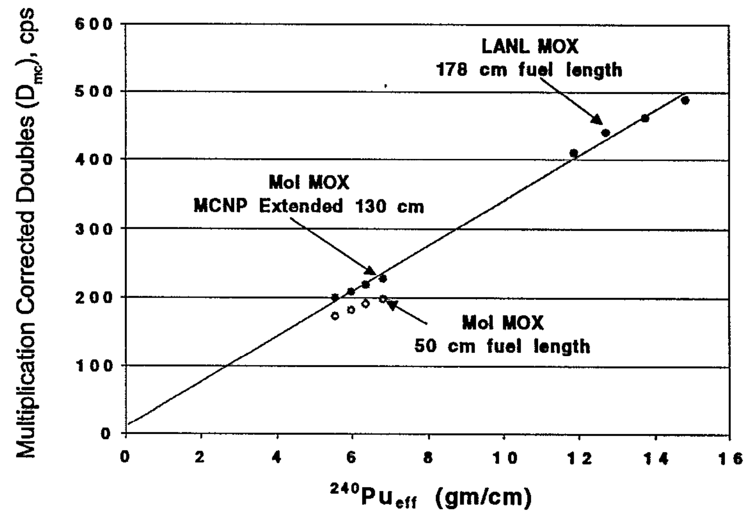


Fig. 17. Multiplication-corrected neutron doubles (D_{mc}) for PWR MOX fuel arrays in Mol, Belgium and Los Alamos in unborated water.

The same ρ_0 (0.19) was used for both the fresh water and the borated water calibration measurements. This value of ρ_0 is required for verification measurements when using the calibration curve in Fig. 17. The limited length of the Mol MOX fuel (50 cm) shows an end effect that has been corrected using MNCP calculations that extend the fuel to a length of 130 cm. The end effect is negligible for the borated water case.

Figure 18 compares the triples with doubles for the Los Alamos MOX fuel array which was measured in 1500-ppm boron and extrapolated to 2200-ppm boron. The triples precision is 2–4% in 10 minutes. Counting periods of about 10 minutes might be required to make quantitative use of the triples count. The triples rate as a function of the ^{240}Pu-effective mass is shown in Fig. 18. The ratio of T/D and T/S could be used to resolve *anomalous* results or differences between the calibration condition and the field condition. The ratio of T/D approximately equal to e and T/S approximately equal to e^2 is a function of the efficiency and the size and configuration of the fuel assembly that could be evaluated using these ratios.

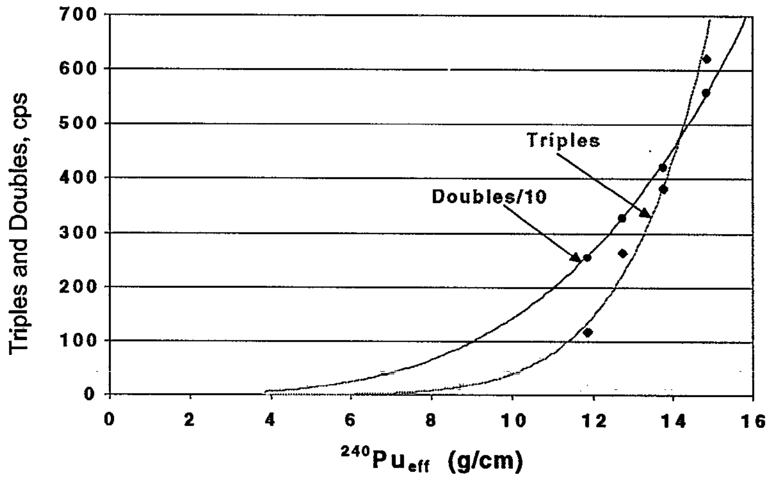


Fig. 18. Neutron triples and doubles/10 versus $^{240}Pu_{eff}$ for PWR MOX fuel in 2200-ppm borated water.

Plutonium-calibration measurements are based on the D_{mc} results shown in Fig. 17 for pure water and Figs. 19 and 20 for borated water. The LANL MOX fuel array was measured in 500-, 1000-, and 1500-ppm boron and the data were extrapolated to the 2200-ppm boron values shown in Fig. 19. Figure 20 contains measurement data for field inspection trials of PWR MOX fuels which have much larger loadings plutonium compared to the Mol and LANL MOX calibration pins. The calibration data in Fig. 20 provide a straight calibration line through the origin, $D_{mc} = 24.1\ x$, which is dependent on the multiplication constant ρ_0. We estimated the ρ_0 listed in Table V for PWR assemblies to be 0.19. The same ρ_0 must be used for calibration and subsequent assay, and its absolute value is important only where the multiplication M must be correctly determined.

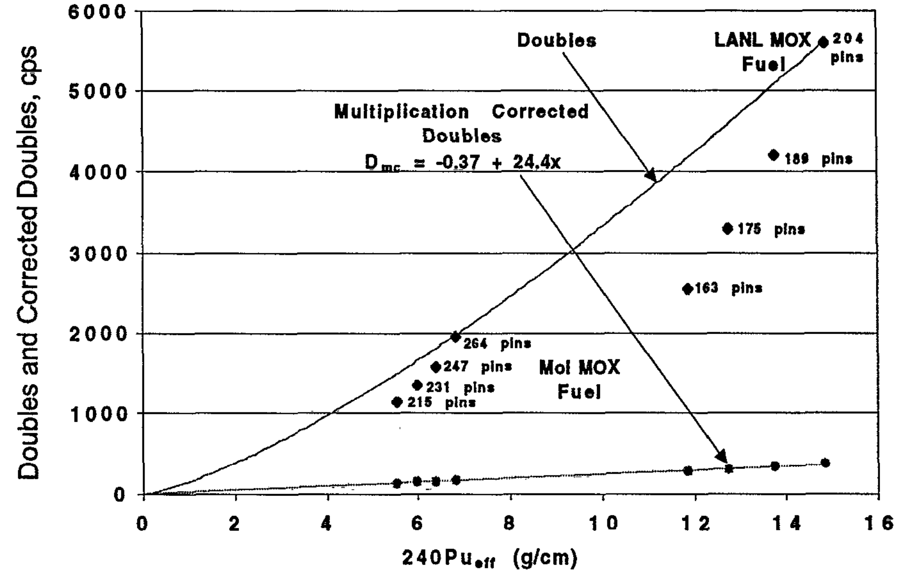


Fig. 19. Neutron doubles (D) and multiplication corrected neutron doubles (D_{mc}) for PWR MOX fuel arrays in Mol, Belgium and Los Alamos in 2200-ppm borated water.

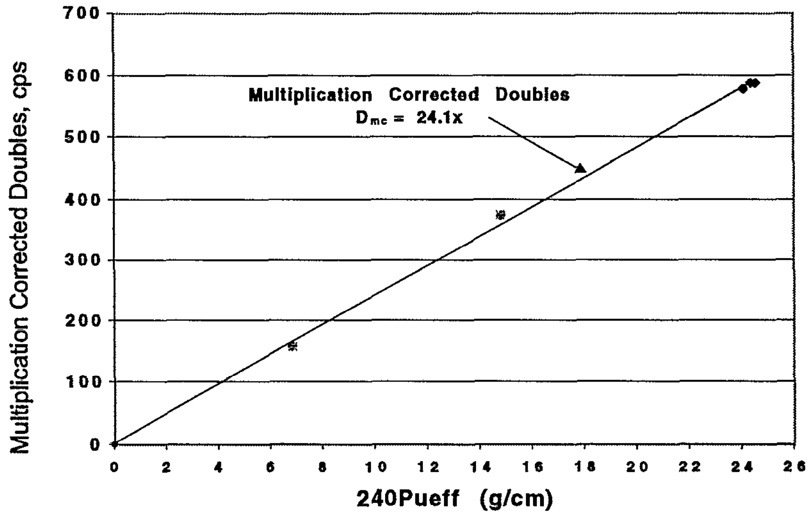


Fig. 20. Multiplication corrected neutron doubles calibration for a PWR MOX fuel array in Mol, Belgium, Los Alamos and inspection field measurements in 2200-ppm borated water.

UWCC AIR MEASUREMENTS

The UWCC can measure MOX fuel in air to verify the $^{240}Pu_{eff}$ content in a manner similar to the passive neutron coincidence collar.[6] We calibrated the UWCC in air using the Mol and Los Alamos MOX fuel assemblies. The Mol fuel pins are 50 cm in active length and show an end effect compared to the 177.8 cm active-length fuel rods at Los Alamos. The neutron doubles and D_{mc} from air measurements are shown in Fig. 21. The D_{mc} precision is better than 1% in 10 min. The line has a negative intercept because rod removal decreases both the plutonium source term and the efficiency from neutron backscattering from the ends of the fuel rods. The triples rate in air is low (8 ± 7 cps) so the T measurement would require very long counting times, so is generally not useful.

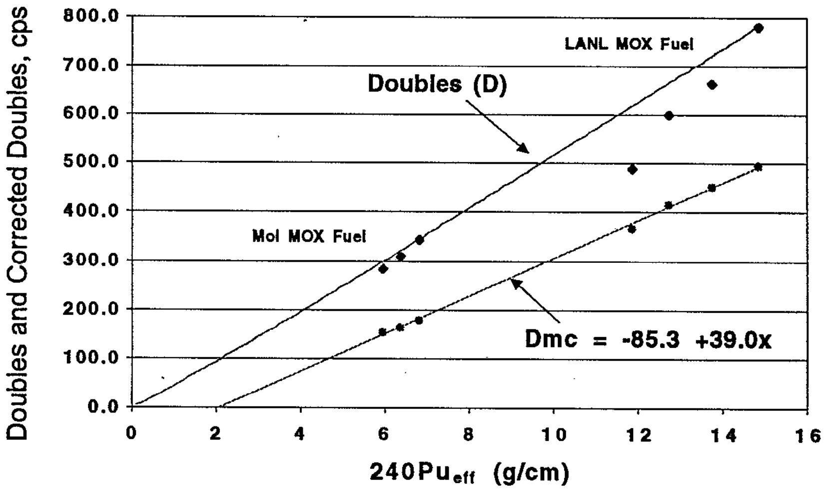


Figure 21. Neutron doubles and multiplication corrected doubles calibration for PWR MOX fuel in air.

CALIBRATION RESULTS

The UWCC measures full arrays of MOX rods and is able to verify if MOX rods have been removed. Calibration results for full arrays of MOX rods in 2200 ppb boron go through origin and have a linear line of $D_{mc} = 24.1$ x.

In most of the calibration configurations where pins were removed, water replaced the space from a rod removal. However, for two of the configurations, low-enriched uranium rods (3.3% ^{235}U) were substituted for the MOX rods. The effects of these pin changes are detected by UWCC measurements.

The plutonium verification measurements are normally based on the D_{mc} calibration, and the counting precision for D_{mc} is better than 1% in 1 to 2 minutes. Two-parameter analysis using the known-alpha correction technique removes multiplication effects from the doubles measurements. For cases where LEU-fuel pins are substituted for MOX-fuel pins, the known-alpha correction removes the multiplication effect created by the LEU pins and permits verification of assemblies even in the presence of LEU-pin substitution. Additionally, the measurement uncertainties required for two-parameter analyses can be obtained within about one order-of-magnitude reduction of counting time compared to the time needed to measure the triples.

SUMMARY

The UWCC can be used to measure the $^{240}\mathrm{Pu}_{\mathrm{eff}}$ per unit length in PWR and BWR MOX fuel assemblies stored under water or in air. Verifications are based on calibration curves of D_{mc} versus $^{240}\mathrm{Pu}_{\mathrm{eff}}$ per unit length. This correction produces a straight-line calibration curve and has been determined from measurements on two different MOX fuel arrays. The statistical precision for D_{mc} is better than 1% for a two-minute count. The UWCC can detect the removal of approximately 1% of the plutonium for a relative measurement and 2–3% of the plutonium for an absolute measurement, depending on how closely the unknown matches the calibration assembly.

The D_{mc} calibration makes the measurements relatively insensitive to differences between the calibration condition and the field condition. The calibration is insensitive to the number of fuel rods, diameter, pitch, cladding, and LEU content. Separate calibrations are required for pure water and borated water. If separate ρ_0 values corresponding to pure and borated water measurements are used, then the calibrations will overlap. To limit the potential for error in measurements and reduce the chance of an inconsistent ρ_0 value, the same value (Table V) is recommended for all measurements.

The appropriate calibration curve (borated versus unborated) is selected based on the operator's boron declaration. The boron loading can be verified by calculating the doubles ratio (see Fig. 14) from a measurement on a fuel assembly with two gate settings of 64 to 128 µs.

ACKNOWLEDGMENTS

The work reported in this manual was supported by the United States Department of Energy/International Safeguards Division (DOE/NN-44) and the United States Program of Technical Assistance (POTAS) to the International Atomic Energy Agency (IAEA).

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APPENDICES

A. PWR Fuel Array Mockup

B. UWCC Measurements of Fresh PWR MOX Fuel in Unborated Water

C. UWCC Measurements of Fresh PWR MOX Fuel in Borated Water

D. UWCC Measurements of Fresh PWR MOX Fuel in Air

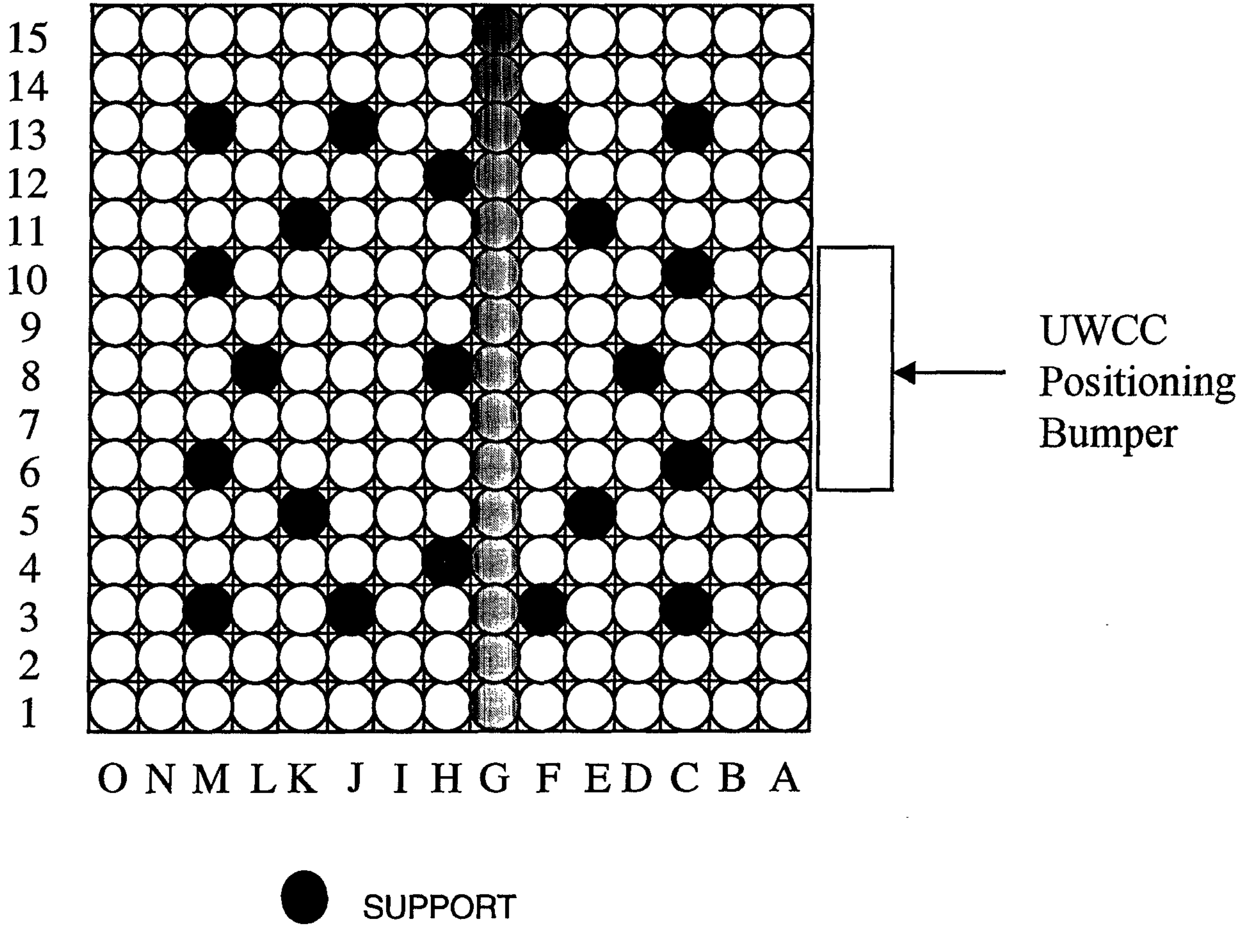
E. UWCC Cross-Calibration Data

F. UWCC User Procedures

G. INCC Setup and Operational Steps for UWCC Measurements

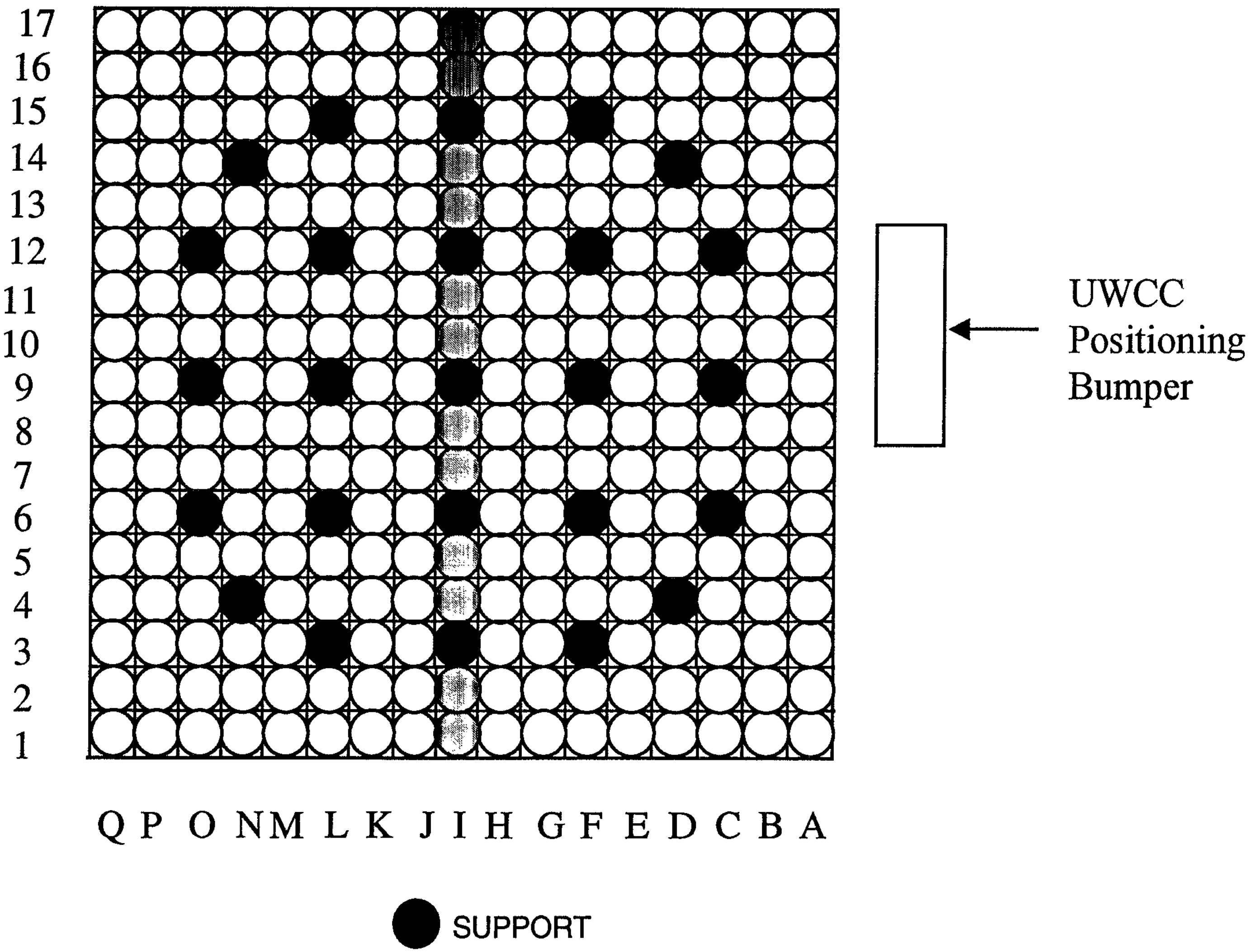
Appendix A: PWR Fuel Array Mockup

Los Alamos 15 × 15 PWR Fuel Array



Appendix A: PWR Fuel Array Mockup

Mol 17 x 17 PWR Fuel Array



Appendix B: UWCC Measurements of Fresh PWR MOX Fuel in Unborated Water

UWCC Measurements of PWR MOX fuel in unborated water	Fuel Type	Number of MOX Rods	Pu Linear Density (g/cm)	240Pueff Linear Density (g/cm)	Gate Width (us)	Measure Time (sec)	Totals Rate (c/s)	Totals-Rate Error (c/s)	Doubles Rate (c/s)	Doubles-Rate Error (c/s)	Triples Rate (c/s)	Triples- Rate Error (c/s)	Multiplica-tion Corrected Doubles Rate (c/s)	Multiplica-tion Corrected Doubles Rate Error (c/s)
PWR Full Array 264 MOX pins 50 cm Rod length	Mol	264	36.77	6.80	64	960	40011	7.9	5869.8	20.9	1224.2	23.9	197.88	0.29
PWR 17 MOX pins removed from Row G	Mol	247	34.41	6.36	64	3800	38446	3.9	5647.3	10.1	1156.4	11.3	190.04	0.14
PWR 33 MOX pins removed from Row G, Column 7	Mol	231	32.18	5.95	64	600	36470	9.6	5281.7	23.9	1081.1	26.1	181.31	0.34
PWR 215 MOX Pins 33 pins removed from Row G, Col 7,1	Mol	215	29.95	5.54	64	600	34679	9.3	4988.8	22.6	979.6	24.1	172.88	0.32
PWR 17 LEU (3.3%) pins placed in row G	Mol	247	34.41	6.36	64	600	37837	9.8	5522.5	24.9	1147.4	27.7	187.52	0.35
PWR 204 pin full array	LANL	204	67.23	14.83	64	900	125876	15.0	16369.5	71.7	2892.2	125.8	488.55	0.84
PWR 204 pin full array	LANL	204	67.23	14.83	64	900	125791	15.0	16275.0	71.5	3063.4	125.7	489.20	0.85
PWR 15 MOX pins removed from Row 7	LANL	189	62.29	13.74	64	3360	119546	7.5	15641.3	35.0	2880.7	60.0	462.87	0.41
PWR 29 MOX pins removed from Row 7 , Col G	LANL	175	57.68	12.72	64	900	112868	14.0	14434.9	63.0	2734.7	105.6	440.93	0.76
PWR 41 MOX pins removed from rows 7 & 10, Col G	LANL	163	53.72	11.85	64	900	105010	13.5	13330.3	58.0	2090.7	94.1	411.42	0.70

Increase Mol Measurements based on MCNP-REN ratio of Mol 130cm/50cm Fuel length	Fuel Type	Number of MOX Rods	Pu Linear Density (g/cm)	240Pueff Linear Density (g/cm)	Gate Width (us)	Measure Time (sec)	Totals Rate (c/s)	Totals Rate Error (c/s)	Doubles Rate (c/s)	Doubles Rate Error (c/s)	Triples Rate (c/s)	Triples Rate Error (c/s)	Multip Correct Doubles Rate (c/s)	Multip Corrected Doubles Rate Error (c/s)
PWR Full Array 264 MOX pins 130 cm Rod length	Mol	264	36.77	6.80	64	960	48649	7.9	8199.2	20.9	2131.5	23.9	227.31	0.29
PWR 17 MOX pins removed from Row G 130 cm Rod leng	Mol	247	34.41	6.36	64	3800	46745	3.9	7888.4	10.1	2013.5	11.3	218.30	0.14
PWR 33 MOX pins removed from Row G, Col 7 130 cm Rc	Mol	231	32.18	5.95	64	600	44343	9.6	7377.7	23.9	1882.4	26.1	208.28	0.34
PWR 215 MOX Pins 33 pins removed from Row G, Col 7,1	Mol	215	29.95	5.54	64	600	42166	9.3	6968.6	22.6	1705.6	24.1	198.59	0.32
PWR 204 pin full array	LANL	204	67.23	14.83	64	900	125791	15.0	16275.0	71.5	3063.4	125.7	489.20	0.85
PWR 15 MOX pins removed from Row 7	LANL	189	62.29	13.74	64	3360	119546	7.5	15641.3	35.0	2880.7	60.0	462.87	0.41
PWR 29 MOX pins removed from Row 7 , Col G	LANL	175	57.68	12.72	64	900	112868	14.0	14434.9	63.0	2734.7	105.6	440.93	0.76
PWR 41 MOX pins removed from rows 7 & 10, Col G	LANL	163	53.72	11.85	64	900	105010	13.5	13330.3	58.0	2090.7	94.1	411.42	0.70

Appendix C. UWCC Measurements of Fresh PWR MOX Fuel in Borated Water.

UWCC Measurements of PWR MOX fuel at 1500 and 2200 ppm Boron Concentrations	Fuel Type	MOX Rods	Pu Linear Density (g/cm)	240Pueff Linear Density (g/cm)	Boron (ppm)	Gate Width (us)	Measure Time (sec)	Totals Rate (c/s)	Totals-Rate Error (c/s)	Doubles Rate (c/s)	Doubles-Rate Error (c/s)	Triples Rate (c/s)	Triples-Rate Error (c/s)	Multiplication Corrected Doubles Rate (c/s)	Multiplication Corrected Doubles-Rate Error (c/s)
PWR 2200 ppm Boron	Mol	264	36.77	6.80	2250	64	900	26111	6.2	2256.0	12.5	332.1	11.8	158.97	0.34
PWR 2200 ppm Boron 17 MOX pins removed from Row G	Mol	247	34.41	6.36	2250	64	600	23203	7.0	1820.0	13.4	239.8	11.8	146.50	0.41
PWR 2200 ppm Boron 33 MOX pins removed Row G, Col	Mol	231	32.18	5.95	2250	64	4140	21185	2.5	1557.0	4.6	181.8	3.9	137.03	0.15
PWR 2200 ppm Boron 48 MOX pins removed Row G Col	Mol	215	29.95	5.54	2250	64	600	19351	6.3	1329.3	10.9	139.9	8.8	128.30	0.39
PWR 1500 ppm Boron	LANL	204	67.235096	14.83	1500	64	750	83631	12.4	6901.9	46.0	961.8	69.2	385.62	0.94
PWR 1500 ppm Boron 15 MOX pins removed Row 7	LANL	189	62.291339	13.74	1500	64	750	73169	11.4	5598.4	39.3	676.4	55.8	346.78	0.88
PWR 1500 ppm Boron, 29 pins removed Row 7, Col G	LANL	175	57.677165	12.72	1500	64	750	65686	10.7	4546.9	34.5	534.5	46.8	322.65	0.87
PWR 1500 ppm Boron, 41 pins removed Row 7, Col G	LANL	163	53.72216	11.85	1500	64	750	58183	10.0	3735.4	30.0	359.3	38.6	293.47	0.83

MCNP-REN Calculations and Extrapolations Borated water PWR MOX fuel	Fuel Type	MOX Rods	Pu Linear Density (g/cm)	240Pueff Linear Density (g/cm)	Boron (ppm)	Gate Width (us)	Measure Time (sec)	Totals Rate (c/s)	Totals-Rate Error (c/s)	Doubles Rate (c/s)	Doubles-Rate Error (c/s)	Triples Rate (c/s)	Triples-Rate Error (c/s)	Multiplication Corrected Doubles Rate (c/s)	Multiplication Corrected Doubles-Rate Error (c/s)
Mol Array 264 MOX pins 130cm Rod Length	Mol	264	36.77	6.80	2250	64		26304	55.0	1972	115.0			168.5	
Extend to 130cm 17 MOX pins removed from Row G	Mol	247	34.41	6.36	2250	64	600	23375	7.0	1591	13.4	239.8	11.8	155.27	0.41
Extend to 130cm 33 MOX pins removed Row G, Col 7	Mol	231	32.18	5.95	2250	64	4140	21342	2.5	1361	4.6	181.8	3.9	145.24	0.15
Extend to 130cm 48 MOX pins removed Row G Col 7, 11	Mol	215	29.95	5.54	2250	64	600	19494	6.3	1162	10.9	139.9	8.8	135.99	0.39
Extrapolate 1500 ppm Measurement to 2200 ppm Boron (fu	LANL	204	67.235096	14.83	2200	64	750	**77656**		**5605.0**		**622.3**		**372.15**	
Extrapolate to 2200 ppm boron (15 MOX pins removed Ro	LANL	189	62.291339	13.74	1500	64	750	**66878**		**4203.4**		**382.0**		**332.9**	
Extrapolate to 2200 ppm boron (29 pins removed Row 7, C	LANL	175	57.677165	12.72	1500	64	750	**59386**		**3291.8**		**265.4**		**307.7**	
Extrapolate to 2200ppm boron (41 pins removed Row 7, Co	LANL	163	53.72216	11.85	1500	64	750	**52083**		**2561.6**		**117.0**		**279.2**	

Appendix D: UWCC Measurements of Fresh PWR MOX Fuel in Air.

Air Measurement LANL & Mol Fuel Array PWR MOX fuel	Fuel Type	Number of MOX Rods	Pu Linear Density (g/cm)	240Pueff Linear Density (g/cm)	Gate Width (us)	Measure Time (sec)	Totals Rate (c/s)	Totals-Rate Error (c/s)	Doubles Rate (c/s)	Doubles-Rate Error (c/s)	Triples Rate (c/s)	Triples Rate Error (c/s)	Multip Correct Doubles Rate (c/s)	Multip Corrected Doubles Rate Error (c/s)
PWR Full Array 264 MOX pins 50 cm Rod length	Mol	264	36.77	6.80	64	600	18064	5.7	343.5	9.1	8.2	6.8	180.2	1.3
PWR 17 MOX pins removed from Row G	Mol	247	34.41	6.36	64	5580	16441	1.8	309.7	2.7	7.6	1.9	164.4	0.4
PWR 33 MOX pins removed from Row G, Col 7	Mol	231	32.18	5.95	64	4620	15242	1.9	285.2	2.7	10.0	1.9	152.7	0.4
PWR 204 pin full array	LANL	204	67.23	14.83	64	1050	61075	7.6	782.0	22.0	8.1	37.5	493.7	4.1
PWR 15 MOX pins removed from Row 7	LANL	189	62.29	13.74	64	1050	55110	9.4	665.0	21.4	15.3	30.4	451.0	4.2
PWR 29 MOX pins removed from Row 7, Col G	LANL	175	57.68	12.72	64	1050	50602	6.0	600.7	18.1	25.3	18.9	415.5	3.6
PWR 42 MOX Pins removed Rows 7 and 10, Col G	LANL	163	53.72	11.85	64	1050	46092	7.9	490.4	18.3	5.7	20.3	366.8	18.3

NOTE: Rod count on the measurements in rows 11 and 12 was off. There are 41 rods out with row 7,10 and col G pulled.

* MOX rod in one position in col. G

Appendix E. UWCC Cross-calibration Data.

Note: Cross-calibrations in air should be performed with the UWCC unit sitting on a cart and away from surfaces that would bias the cross-calibration measurements caused by neutron reflections.

UWCC measurements in 1500 ppm boron on the LANL PWR 204 pin MOX Fuel Array

Detector	High Voltage	Pre delay usec	Gate Width (us)	Dead time A	Dead time B	PWR fuel MOX Rods	Boron ppm	240Pueff Linear Density (g/cm)	Assay Time (sec)	Totals Rate (c/s)	Totals-Rate Error (c/s)	Doubles Rate (c/s)	Doubles-Rate Error (c/s)	Doubles Ratios UWCCx/UWCC3	Triples Rate (c/s)	Triples-Rate Error (c/s)	Multiplication-Corrected Doubles Rate (c/s)	Multiplication-Corrected Doubles Rate Error (c/s)
UWCC1[a]	1740	3	64	2.6	2.6	204	1500	14.83	750	85671	12.7	7087.1	47.9	1.027	1268.8	91.5	389.14	0.96
UWCC2	1680	3	64	1.92	1.92	204	1500	14.83	700	84826	12.9	6819.5	48.2	0.988	959.9	73.4	389.34	1.00
UWCC3	1680	3	64	1.9	1.9	204	1500	14.83	750	83631	12.4	6901.9	46.0	1.000	1022.5	70.4	380.22	0.93
UWCC2	1680	3	128	1.92	1.92	204	1500	14.83	750	84712	12.5	8850.5	69.9	1.004	1666.8	145.5	352.76	1.06
UWCC3	1680	3	128	1.9	1.9	204	1500	14.83	750	83624	12.4	8813.3	68.9	1.000	1684.7	144.7	347.08	1.03

[a] The UWCC received an upgraded preamp (PDT210-A), compared to the original model, to increase gain and allow the high voltage (HV) to be lowered from 1740 volts to the standard 1680 volts used for coincidence counting measurements. UWCC-1 that was delivered to the IAEA corresponds to the cross-reference data for Cf-8 in air.

UWCC measurements in air on a wood benchtop[b] using ^{252}Cf source number 8

UWCC1	1680	3	64	0	0	N/A	0	Cf-8	1000	5988	0.7	254.0	0.7	0.973	4.6	0.3	-	-
UWCC2	1680	3	64	0	0	N/A	0	Cf-8	1000	5816	1.0	247.4	0.7	0.950	4.4	0.3	-	-
UWCC3	1680	3	64	0	0	N/A	0	Cf-8	1000	6046	1.4	261.1	1.3	1.000	5.1	0.6	-	-

[b] Cross-calibrations are biased if performed on different benchtops, or benchtop positions, where the neutron reflection is changed

UWCC measurements in air on a metal Cart[c] using ^{252}Cf source number 8

UWCC1	1680	3	64	2.15	2.15	N/A	0	Cf-8	1000	5065	1.0	188.1	0.8	0.985	3.8	0.3	-	-
UWCC2	1680	3	64	2.18	2.18	N/A	0	Cf-8	1000	4920	1.0	188.1	0.8	0.949	3.7	0.3	-	-
UWCC3	1680	3	64	2.18	2.18	N/A	0	Cf-8	1000	5113	1.0	188.1	0.8	1.000	4.2	0.3	-	-

[c] Cross-calibrations were performed with the UWCC on a cart and away from adjacent walls to minimize neutron reflections.

Appendix F
UWCC User Procedures

UWCC USER PROCEDURES

There are two operational modes that use the UWCC:

A. Portable mode, in which the UWCC is shipped to the inspection site and configured, inserted, then removed from the reactor pool after each inspection visit; and

B. Fixed installation in the fuel-storage pool.

The user procedure described below covers operational mode A. Operational mode B is a subset of mode A.

The UWCC is operated using the IAEA neutron coincidence counting software (INCC) program. The electronics to support the UWCC are the same as those used for the HLNC-2 and the AWCC (i.e., a JSR-12 and a PC). Any of the shift-register or multiplicity electronics units may be used with the UWCC. The particular unit used is specified in the INCC setup program. Also, this program contains the setup information for the gate, predelay, HV, deadtime constants, etc. These can be entered into the INCC program or set on the electronics unit, if manual setup is required, prior to the field exercise.

The first step in collecting UWCC verification measurements is to configure the mechanical pieces, connect the wiring to the shift-register electronics, and then to the computer. Following system configuration, electronic tests are performed and the UWCC can be placed into the pool. In the case of fixed installations, the system would be maintained in the pool and all electronic wiring would be in place. Once the UWCC is in the pool, electronics checks and observations are performed so that verification measurements can correctly ensure that the unit is operating properly and hasn't been damaged.

The UWCC detector head and cables are shipped in a reusable fiberglass case with rolling wheels. The detector pipe sections that clamp together to reach the appropriate depth in the water are shipped in tubes or boxes that are about 2-m long. The detector head contains the dual PDT-210A preamplifier and is pre-assembled and sealed up to the point of the cable disconnect to the extension pipes. The contents in the detector shipping container include:

- the UWCC detector head (configured to the PWR or BWR measurement geometry),
- the protective fabric sleeves for the arms of the fork,
- the approximately 20-m of cable run to reach between the head and the OR (sum) coupling box surface electronics,

- the OR box to combine the two signal lines from the PDT-210A amplifier to feed into the JSR-12,
- the approximately 40-cm cable extension between the OR box and the JSR-12,
- a clamp to attach the UWCC pipes to the side rail or bridge rail, and
- all necessary tools for assembly.

The contents in the electronic shipping container include:

- the JSR-12 electronics,
- shift-register connection cable between the JSR-12 and computer,
- computer containing the INCC software program, and
- power supply and cables for the computer and printers if used.

UWCC ASSEMBLY AND CHECKOUT PROCEDURES

1. Open the box containing the detector pipe sections and lay out the necessary lengths of pipe to reach the fuel assemblies.

2. Open the fiberglass case that contains the UWCC detector head box and remove the UWCC measurement head, OR (sum) coupling box, signal cables, and fork protective fabric sleeves.

3. Carefully set the UWCC on a foam pad or piece of plastic. Note that the welds on the thin stainless steel (SS) cladding of the UWCC could crack if the UWCC is not handled carefully. If these welds are damaged and/or cracked, the UWCC could leak and the unit would be inoperable.

4. Check the UWCC configuration to ensure that the fork positions and the nylon bumper are set in the correct positions for the type of fresh MOX fuel (PWR or BWR) to be verified.

5. Pull the 20m signal cable bundle through the SS pipe segments and then clamp the pipe segments together to form a 6 to 7m long tube that has the cable bundle threaded inside the tube.

6. Pull about 1m of extra signal cable out of the pipe end and attach the cable connectors to the identified locations at the top of the UWCC (signal A, signal B, +5V, and the HV). Attach the other end of the cable connectors to the identified locations on the OR coupling box.

7. Attach the two fork protective fabric sleeves to the arms of the UWCC.

8. Make sure that the detector head is on a padded surface, to avoid damaging the welds on the SS cladding. Carefully tip the UWCC on its side so that the long SS pipe can be attached to the top flange of the detector head.

9. Have the facility operator attach lifting straps to the detector head and the long pipe so that it can be lifted into the water. Have several inspectors or facility staff help guide the system into the water. Keep the open end of the SS pipe and cable bundle on the side of the pool.

10. Observe that there are no air bubbles coming from the detector head or the pipe joints. Air bubbles would indicate a leak.

11. After the SS pipe is vertical, attach the clamps that will support the UWCC to the side rail or to the bridge crane.

12. Extend the signal cable bundle to the location of the JSR-12 and computer. Attach the cables to the OR box and the OR box to the JSR-12 using the labels on the cables and OR box.

13. Turn on the JSR-12 in the manual mode and repeat step 6; however, in this case the neutron signal will approach zero because of the water shielding around the UWCC.

14. Attach the JSR-12 to the computer using the RS-232 cable.

INCC PROGRAM SETUP

15. The UWCC is operated with the INCC program. The INCC program should be configured prior to field measurements. If the INCC program has not been configured and set up, refer to Appendix F for detailed procedures on setting INCC measurement parameters, etc.

16. Turn on the computer and the JSR-12 and review the INCC measurement parameter settings under the Setup / Measurement Parameters option. Check that the correct shift-register type is selected (JSR-12 or other shift register if used).

17. Using the **Acquire / Rates Only** option collect 3 measurements of 10 seconds each to check the operation of the UWCC. Following the measure, select the **Reports / Rates Only** option and review the output file to check that the predelay, gate length, high voltage, dieaway time, and deadtimes are all correctly set. Review the singles, doubles, and triples counts to check that the UWCC is correctly counting.

18. Check and select the correct facility type, MBA, and detector ID (i.e., UWCC1) under the **Setup/ Facility/ Inspection** option.

19. Select or input the isotopics information under the **Setup / Isotopics** option for the MOX-fuel assemblies to be verified.

20. Set the calibration analysis method for the verification. Under the **View** option select Maintain. Under the **Maintain / Calibration** option select "Analysis methods", then select the "Material type" and "Calibration curve" for the passive-analysis method.

21. Check the passive calibration curve parameters and curve t2ype by selecting **Maintain / Calibration / Passive Calibration Curve.** The curve type should be of the form "D = a+b*m+c*m^2+d*m^3." The UWCC calibration is a linear relationship with a zero intercept between the multiplication corrected doubles (D_{mc}) and the $^{240}Pu_{eff}$ (g/cm) loading of a full MOX fuel assembly. Therefore, the calibration constants $a = c = d = 0.0$ and only the constant b has a value which is dependent on the type of MOX fuel assembly (PWR or BWR) and the boron content in the pool (0- or 2200 ppm). The calibration constant for PWR MOX fuel, shown in Fig. 20, in a pond containing 2200 ppm boron is $b = 25.1$ c/s/g/cm

BACKGROUND MEASUREMENT

22. Using the **Acquire / Background** option, collect 10 cycles of 30-sec background counts. The data source for this measurement should be "Shift register." The UWCC should be under the water in the measurement configuration with no fuel assembly inserted in the unit.

FRESH MOX FUEL VERIFICATION

23. Have the operator center a fresh MOX fuel assembly into the UWCC and position it up against the polyethylene bumper.

24. Using the **Acquire / Verification** option, input the "item id", "material type", "declared mass" and then collect 6 cycles of 30-sec verification counts. Note that the "item id" must clearly identify the particular measurement and assembly because it is the key identifier that will be used to reanalyze, report, and review verification measurements. Appendix F provides guidance on defining "item id" names.

BORON CONTENT CONFIRMATION MEASUREMENT

25. Keep the MOX fuel assembly in position in the UWCC. The boron concentration in the pool can now be easily confirmed with a second measurement using a gate-width of 128 µs on the MOX assembly that was measured in step 23. Select the **Setup / Measurement Parameters** option and check that the *Gate length (microseconds)* was set at 64 for the measurement in step 23. Change the gate length to 128 and repeat the measurement performed in step 10.

26. Determine the doubles gate ratio (D_{64}/D_{128}) by taking the ratio of doubles counts for the 64-us gate measurement D_{64} to the doubles count for the 128 µs gate measurement, D_{128}. Using this ratio and referring to Fig. 14, confirm the boron concentration in ppm in the pool and check it against the operator information.

27. Select the **Setup / Measurement Parameters** option, reset the gate length (microseconds) back to 64, and then continue MOX fuel confirmation measurements.

DECONTAMINATION AND REPACKING

28. Once all verification measurements are complete the UWCC can be decontaminated by the operator, if necessary, and removed from the pond and disassembled and packed for shipment. The decontamination of the equipment would follow the operator's normal procedures; however, the fabric covers for the arms are to be discarded after use.

Appendix G
INCC Setup and Operational Steps for UWCC Measurements

Load the INCC Program.

1. Click on "**Start**" in lower left corner of screen.
2. Mouse select - **Programs / INCC 3.XY / INCC 3.XY**

XY = INCC version number

Setup UWCC Measurement Parameters

Set the INCC to allow access to Maintenance mode parameters

1. Mouse select - **View / Maintain**
2. Check that "**Maintain**" appears on the bar menu at the top of the screen.

File View Setup Maintain Acquire Reanalyze Report Tools Window Help

Setup Measurement Parameters for Detector UWCC3 (unit 3).

1. Select - **Maintain / Detector Add/Delete**
2. Select - **Add Detector**

Shift register serial port	Select	**COM 1**
Detector id	type	**UWCC3**
	Select	**OK**
Shift register type	Select	**JSR-12**
Predelay	type	**3.0**
Gate length	type	**64.0**
High voltage	type	**1680**
Die away time	type	
Die away time	type	
Efficiency	type	**0.0**
Deadtime coefficient A	type	**2.18**
Deadtime coefficient B	type	**2.18**
Deadtime coefficient C	type	**0.0**
Doubles gate fraction	type	**0.7**
Triples gate fraction	type	**0.49**
	Select	**OK**
	Select	**OK**

Input facility type and two MBAs for a borated and an unborated fuel pond.

3. Select - **Maintain / Facility Add/Delete**
4. Select - **Add Facility**

Facility	type	**PWR**
Facility description	type	**Reactor**
	Select	**OK**

5. Select - **Maintain / MBA Add/Delete**
6. Select - **Add material balance area**

Material balance area	type	**P1**
Material balance area description	type	**Pond unborated**
	Select	**OK**

7. Select - **Add material balance area**

Material balance area	type	**P2**
Material balance area description	type	**Pond with 2200 ppm B**
	Select	**OK**
	Select	**OK**

Setup two material types for PWR MOX (PMOX) and BWR MOX (BMOX).

8. Select - **Maintain / Material Type Add/Delete**
9. Select - **Add material type**

Material type	type	**PMOX**
	Select	**OK**

10. Select - **Add material type**

Material type	type	**BMOX**
	Select	**OK**
	Select	**OK**

Select facility and measurement parameters for UWCC verifications at a PWR facility which has fresh MOX fuel in a pond containing 2200 ppm boron.

1. Select - **Setup / Facility/Inspection...**

Facility	Select	**PWR Reactor**
MBA	Select	**P2 Pond with 2200 ppm B**
Detector id	Select	**UWCC3**
	Select	**OK**

Setup UWCC Calibration parameters to verify PWR MOX fuel in 2200 ppm Boron

1. Select - **Maintain / Calibration... / Passive Calibration Curve...**

Material type	Select	**PMOX**
Curve type	Select	**D = a+b*m+c*m^2+d*m^3**
a	type	**0.0**
b	type	**25.1**
c	type	**0.0**
d	type	**0.0**
	Select	**OK**

Specify analysis methods for the verification measurement of PWR MOX.

2. Select - **Maintain / Calibration... / Analysis Methods...**

Material type	Select	**PMOX**
Passive Calibration curve	Select	X in box
Passive Known alpha	Select	X in box
	Select	**OK**
Normal analysis method	Select	Dot “calibration curve”
Backup analysis method	Select	X “Known alpha”
	Select	**OK**

3. Select - **Maintain / Calibration... / Known Alpha...**

Material type	Select	**PMOX**
Alpha weight	type	**1.0**
Rho zero	type	**0.014**
k	check	**2.166**
	Select	**OK**

Collecting background data prior to verification measurements.

1. Select - **Acquire / Background...**

Comment	type	**PWR background data**
Count time (secs)	type	**30**
Use number of cycles	Select	**Dot**
Number of cycles	Select	**10**

QC tests	Select	**X in box**
Data source	Select	**Shift register**
	Select	**OK**

Collecting Verification Data for PWR MOX fuel in 2200 ppm boron.

1. Select –**Acquire / Verification...**

MBA	Select	**P2 Pond with 2200 ppm B**
Item id	type	***Measurement id****
Material type	Select	**POX**
	Select	**Isotopics...**
Isotopics id	Select	**ISO1**
	Select	**OK**
	Select	**OK**
Declared mass (g)	type	***240Pueff (g/cm) number***
Comment	type	**PWR MOX Fuel ID#**
Count time (secs)	type	**30**
Use number of cycles	Select	**Dot in circle**
Number Cycles	type	**6**
Data source	Select	**Shift register**
QC tests	Select	**X in box**
	Select	**OK**

* refer to the end of this Appendix for suggestions on defining clear id names.

2. Repeat the step above to collect additional verification measurements for different PWR and fuel assemblies. Change the **Measurement id** and **Comment** for each new verification.

Suggested Measurement id Names

The INCC program stores measurement filesin a database and each file is identified with a *measurement id* (12 characters) plus the date and time when the measurement occurred or when the data was reanalayzed. It is possible, therefore, to have a number of different measurements or a measurement with a number of reanalysis that all have the same name and the only difference would be in the date and time of each measurement or reanalysis. For this reason, confusion may occur in locating and identifying individual files if care is not taken in developing a unique and clear naming convention for the measurement ids.

One example occurs in reanalysis of measurement data. For example,take the case of *measurement id*: **PWRMOX1** that was collected on *date*: 98.07.22 and *time*:15:45:40 and was then later reanalyzed twice using different deadtimes that were changed using the measurement parameters file for each reanalysis. In this example, there would now be three files called **PWRMOX1** in the database and under the INCC program **Reanalyze** option what would be seen is a listing of three files each with the same name tand ;the only difference would be in the times which would be 15:45:40, 15:45:41, 15:45:42. In this case it is difficult to tell which deadtime was used with which file and what their differences are.

We therefore recommend that a naming convention be established prior to verification measurements to establish unique measurement id names thatwill allow the measurement data from past inspections to be easily identified and located for post analysis, print out, plotting, etc.

Listed below is a possible naming convention

SxxxFyyyBzzzz

where

S indicates the fuel serial number follows
where xxxx is the fuel serial number

F indicates the type of MOX fuel where F is replaced by P for PWR and by B for BWR
yyy is the declared 240Pueff loading in grams per cm
For example, a loading of 14.8 g/cm of 240Pueff would be F148

B is the boron loading in the fuel pond
zzzz is the parts per million boron content in the water

0000	pure water
0500	500 ppm
1000	
1500	
2000	
2500	

Using this convention the measurement id name, **P1826F148B2200,** would represent a PWR MOX fuel assembly with serial number 1826 containing 14.8 g/cm of $^{240}Pu_{eff}$ stored in a pond containing 2200 ppm boron.

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