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IMPACT OF NEUTRON ABSORBERS ON THE UNDERWATER NEUTRON COINCIDENCE COUNTER PERFORMANCE

Abstract

The present status of Underwater Coincidence Counter (UWCC) in general and impact of neutron absorbers - mainly boron acid - on the UWCC characteristics and performance in particular are considered. Formal algorithm for assessment of the main system parameters as a functions of boron concentration is presented. Some practical issues of UWCC application at highly borated water are discussed.

Introduction.

An Under Water Neutron Coincidence Counter (UWCC) has been developed for quantitative plutonium axial density verification in fresh light-water reactor (LWR) mixed-oxide (MOX) fuel assemblies stored under water. Original version of the UWCC was just a modification of FORK detector [1,2], where highly resistant to gamma radiation, but relatively neutron insensitive 4 fission chambers were substituted by 4 high-efficiency He3 neutron detectors [3,4]. Later on a new version of the UWCC with 8 He3 detectors, which can be configured to measure either pressurized-water reactor (PWR) or boiling-water reactor (BWR) fuel assemblies was developed by LANL [5]. The measurement and analysis principles are the same for both versions - measured by a standard neutron coincidence electronics (JSR12) singles and doubles are corrected for multiplication using the conventional known-alpha analysis [6] resulting in linear function

$$Dc = Am, \qquad (-1-)$$

where Dc is multiplication corrected doubles rate, m - linear Pu240 effective mass density, and A - calibration parameter. It was expected and experimentally confirmed [3,4,5,7,8], that, unlike to the non-corrected doubles, the multiplication corrected ones most adequately - within 3% uncertainty react to the diversion scenario, where MOX pins are simply removed from the assembly or substituted by pins with low enriched uranium (without plutonium). The multiplication corrected doubles are also practically insensitive to variations in the number and diameter of fuel rods. However, neutron absorbers - boron acid in the pond water (mainly PWR ponds) or poison rods (mainly in BWR assemblies) affect even corrected doubles.

The following is a brief description of both UWCC versions with detailed consideration of the neutron absorbers influence on the UWCC performance.

2. "Old" and "New" UWCC. Calibration Results in Clean and Borated Water.

Initially one "old" type UWCC, PWR configuration, was calibrated in Mol, Belgium in 1990 [4] using a 17x17 mockup array with 6.82 g/cmPu240eff. In clean water the calibration parameter was found to be equal

$$A = 2.00 +/- 0.02 \text{ c/s/g/cm}.$$

The calibration parameter A was measured also in borated water and it was found that it exponentially decreases with boron concentration increase.

This UWCC was successfully used in joint Euratom and IAEA inspection verifications. The proportionality coefficient A value was chosen through interpolation of the experimentally measured A values using the operator declared boron concentrations.

High UWCC sensitivity to boron, which leads to introduction of the empirical boron correction coefficient, is undesirable feature, because requires additional means for verification of the Operator declared boron concentration.

The original UWCC version was just a simplest adaptation of the spent fuel fork detector for new application and was not optimized for the task. Therefore in 1997 LANL developed an upgraded UWCC version [5] with three main improvements.

- Instead of 4 He3 tubes, each of 20c/n/cm^2 efficiency, the new detector contains 8 He3 tubes, each of 40 c/n/cm^2 efficiency, thus increasing the overall UWCC efficiency by about an order of magnitude. Obviously it greatly improved the measurement statistics, which could be important with low plutonium concentration measurements (BWR arrangement). Apart of that the higher efficiency makes it possible to measure triple coincidences in reasonable time (less than 5% uncertainty within 10 minutes measurement time). In principle the third measured value might help to take into account boron and/or poison rods influence, but this option still requires further efforts and investigations with unclear practical results.

- The polyethylene body of the new UWCC fork was wrapped in cadmium to make it less sensitive to boron (on the other hand the detector efficiency decreased also, but it was not important for the new high efficiency version).

- The detector fork can be configured to measure either BWR or PWR fuel assemblies.

The drawback of the new UWCC version is bigger size, weight and price. IAEA has prepared the technical and design specifications for another “intermediate” UWCC version which would presumably combine positive features of both models - the size and weight of old UWCC and high efficiency of the new one. First two detectors manufactured according to the Agency Specifications are ordered from ANTECH Ltd. (UK).

A comprehensive comparative UWCC calibration exercise with both UWCC types and configurations was performed in MOL, Belgium in 1998 [7,8]. Later on a “new” UWCC in PWR configuration was calibrated at LANL with much higher linear plutonium density (6.8 g/cm Pu240eff in MOL and 14.83 g/cm of Pu240eff at LANL). The calibration results together with all essential system parameters are summarized in the Table 1.

Table 1. Calibration of “old” and “new” UWCC.

Parameter	Old PWR UWCC	Old BWR UWCC	New LANL UWCC, PWR config.	New LANL UWCC, BWR config.
Gate, mcs	128	128	64	64
Predelay, mcs	4.5	4.5	3.0	3.0
Dead-time coefficients	a = 4.5mcs b = 4.5 mcs^2	a = 4.5 mcs b = 4.5mcs^2	a = 2.18mcs b = 2.18mcs	a = 2.18 mcs b = 2.18mcs
ρo	0.0043	0.0043	0.019	0.019
A1, c/s/g/cm clean water	1.99	2.32	33	32
A2, c/s/g/cm 2250 ppm	1.32	1.66	24.1	27
A1/A2	1.51	1.40	1.37	1.19

Comments to the Table 1:

- new LANL UWCC has in average about 15 times higher efficiency for corrected doubles than that of old UWCC version. It means, that for the same statistical uncertainty the required measurement time with new UWCC is about 5-6 time less;

- in spite of cadmium shielding the new UWCC is still sensitive to boron (A1/A2 ratio is 1.37 for PWR and 1.19 for BWR configuration respectively).

3. Formal Consideration of Boron Influence.

Boron affects all important for multiplication correction algorithm parameters, like multiplication, detection efficiency, die-away time (coincidence gate fraction), and ρo - the doubles/totals ratio for a hypothetic non-multiplying MOX fuel assembly. The ρo is directly proportional to the detection efficiency "ε" and the coincidence gate fraction "f", which is a function of the die-away time "τ". The die-away time and, hence, the coincidence gate fraction can be directly measured.

$$\rho_o = 0.873 * \varepsilon * f, \qquad (-2-)$$

$$f = \exp(-p/\tau)\,[\,1 - \exp(-G/\tau)\,], \qquad (-3-)$$

$$\tau = -64 / \mathrm{Ln}\,[\,R(128)/R(64) - 1\,]; \qquad (-4-)$$

where:
"p" and "G" - predelay and gate length (3 and 64 for new UWCC),
R(128) and R(64) are doubles count rates at 128 mcs and 64 mcs coincidence gate lengths respectively.

Note, that the die-away time measurement does not require any assumptions or constants, but does require two relatively long measurements because of the nature of the above relation.

The ρo parameter cannot be directly measured, therefore it is estimated through MCNP calculations. For original "old" UWCC the recommended value is 0.0043 [3] (presumably calculated for clean water and PWR fork with 128 mcs gate width), and for new UWCC the recommended value is 0.019, calculated for PWR configuration with 64 mcs gate width in borated (2200ppm) water [5]. For consistency of the INCC [10] software setup parameters the ρo is recommended to keep fixed the same independently on the boron concentration and even on the PWR/BWR configuration. Therefore the actual multiplication (M) and, hence, the calibration parameter A values may differ from those, calculated by the known-alpha formalism.

Using directly measured values of the die-away time (coincidence gate fraction), the known-alpha formalism and expression (-2-) it is possible to estimate how all main parameters change with boron concentration.
It will be demonstrated on the new UWCC in PWR configuration - the most often used UWCC version.

Assuming the MCNP analysis correctly estimated the ρo = 0.019 for 2200 ppm and, hence, the multiplication M obtained from the known-alpha algorithm (M=1.81) is true value, one can find the "true" values for M, ε, ρo from mutual solution of:

$$T(x)/ T(2200) = \varepsilon(x)*M(x) / \varepsilon(2200)*M(2200), \qquad (-5-)$$

$$a*M(x)^2 + b*M(x) = [R(x)/T(x)]*(1+\alpha) / \rho o(x), \qquad (-6-)$$

where:

T(x) and T(2200) - totals rates at 2200 ppm, and “x” ppm boron concentrations,
$a = 2.062(1+\alpha)$, $b = 1-a$,
$\rho o = 0.873\ f(x)\ \varepsilon(x)$.

The summary of the respective calculations is presented in Table 2.

Table 2. New UWCC PWR configuration measurements. Raw measurement data are taken from [4]. Pu240eff = 14.83 g/cm, $\alpha = 1.203$

ppm	T,c/s	D,c/s	M	Dc	A	τ	f	ε	ρo
0	125790	16275	2.32	433	29.2	80	0.53	0.038	0.0176
1500	83630	6902	1.90	378	25.5	47	0.70	0.031	0.0189
2200	77660	5605	*1.80*	371	*25.0*	44	0.73	*0.030*	*0.0190*

The Table 2 data show that boron reduces multiplication and efficiency. Boron also reduces the die-away time, and as a result the coincidence gate fraction increases faster than efficiency decreases - finally the ρo parameter slowly increases. The calibration constant A can be expressed as

$$A = C * \rho o * \varepsilon = C' * f * \varepsilon^2; \qquad (-7-)$$

where C = 43,700 and C’ = 38,150 are constants.

To get A independent on the boron concentration increase of “f” must exactly compensate fall of squared efficiency which is unlikely achievable even at high boron concentrations - that is why while the calibration parameter for clean water at “true” ρo value is considerably less (A=29.2) than that obtained with “fixed” ρo (A=33) it is still higher than A=25.1 at 2200 ppm. Therefore the fixed value of the ρo is practically justified.

The principal difference between old and new UWCC is that the new UWCC is wrapped in cadmium, which makes it less sensitive to boron (but not to the extent when the boron can be neglected). Therefore for old UWCC the efficiency falls faster than coincidence gate fraction increase (opposite to the new UWCC) and as a result the ρo is falling down as it is illustrated in Table 3.

Table 3. Old UWCC PWR Configuration Measurements [7]. Pu240eff = 6.80 g/cm, $\alpha = 0.681$. Gate length = 128 mcs.

Ppm	T,c/s	D,c/s	M	Dc	A	τ	f	ε	ρo
0	19380	1870	*3.673*	13.49	*1.99*	118	0.637	*0.0077*	*0.0043*
1540	10450	530	3.020	7.27	1.06	66	0.800	0.0050	0.0035
2250	9060	390	2.896	6.14	0.91	56	0.829	0.0046	0.0033

The same estimations can be performed for BWR configuration, but it is less interesting, because BWR MOX assemblies are normally stored in clean water.

Similar mechanism can be assumed for the case of the neutron poison/absorber rods, but formal consideration is not possible yet, because there are not enough experimental measurement data.

4. Practical Consideration.

As it was already noted the ρo parameter is recommended [5] to keep the same for clean and borated water, and it seems to be a reasonable proposal, because the calibration parameter A changes with boron concentration anyway. On the other hand A shows a saturation tendency at high boron concentrations, as it is demonstrated on Fig.1

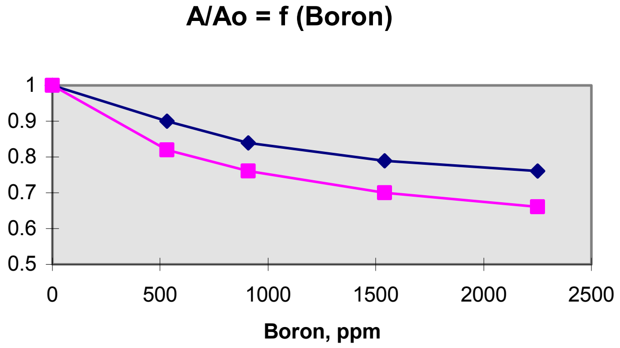

Fig. 1 Change of calibration parameter with boron concentration. Upper line is new UWCC, PWR configuration, lower line is old UWCC, PWR design.

Assuming that:

- in reality the pond water either does not contain boron at all, or contains more than 2000 ppm boron, and
- the calibration constant “A” is about the same for any boron concentration exceeding 2000 ppm,

it is enough to perform the calibration measurements and obtain the calibration parameter values only for clean and for highly borated water (>2000 ppm).

This approach was successfully used in real measurements with boron concentration “exceeding 2000 ppm” [9].

Nevertheless, the correctness of the assumption that A does not change at high boron concentrations requires experimental confirmation, especially keeping in mind, that at present in a number of facilities the boron concentration is very high.

The measurements recently performed with new LANL UWCC show that for very high boron concentrations the calibration parameter must be further reduced, as it is illustrated on the fig. 2. According to the data available, after 2000 ppm the calibration parameter A goes down approximately proportionally to the boron concentration, and empirical relation for boron concentration $B > 2200$ ppm: $A = 28.7 - 0.0021 * B$.

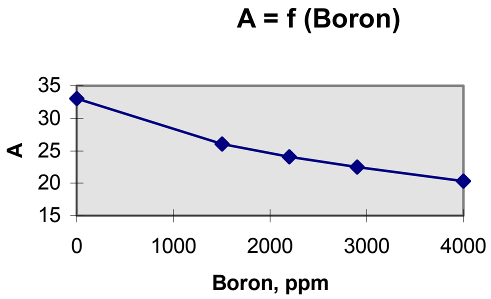

Fig. 2. Calibration parameter A as a function of the boron concentration. New UWCC, PWR configuration.

Semi-quantitative confirmation of the declared boron concentration can be done through the die-away time measurement. The die-away time decreases with boron concentration, as it can be seen from Table 2. For new PWR configured UWCC the die-away time in clean water is about 80+/-5 mcs, while at 1500 ppm boron it comes down to 50+/-5 mcs, and at "over 2000 ppm boron" [9] - to 45+/-5 mcs. Unfortunately there are no experimentally measured die-away time estimations for very high boron concentrations, but it can be assumed, that it will continue to decrease slowly.

The die-away time and hence the boron concentration estimation requires two relatively long measurements. For better than 10% uncertainty two measurements of about 15 minutes each are required. It may cause some problems in real inspection verification due to the time limits.

As it was already noted the boron directly affects neutron multiplication, and it seems to be feasible to use multiplication parameter as an indicator of the boron concentration. Being a direct product of the known-alpha procedure, the leakage multiplication M is automatically determined as a result of every verification measurement with acceptable accuracy. Fig. 3 demonstrates this for new UWCC in PWR configuration.

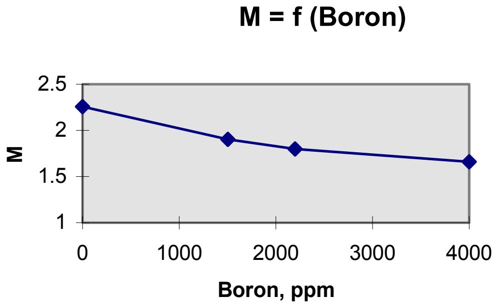

Fig. 3. Multiplication as a function of boron concentration.

It could be *provisionally* proposed to set the INCC known-alpha software calibration parameter A according to the operator declared boron concentration and Fig. 2. The consistency check of the operator declared boron concentration can be made by comparison of the multiplication factor M produced by the INCC software when the measurement is completed, with the value corresponding to the operator declared boron concentration, presented at Fig. 3. The acceptance criterion could be +/- 0.03 of the "measured-expected" M difference. The above proposal is based on very limited experience, and further experimental results are required for evaluation of possible methods for independent confirmation of the declared boron concentration.

At first approximation the influence of neutron absorbers ("followers") in highly borated water can be presumably neglected, and it was already confirmed in actual measurements.

For BWR application the boron influence consideration seems to be of low priority because usually (?) BWR MOX assemblies are stored in clean water. On the other hand most of BWR MOX assemblies contain poison rods which introduce similar effects, and it was observed at real inspections. Further investigations are required.

Conclusion

UWCC performance tests and application experience has shown that this specific version of the neutron coincidence technique is really capable for partial defect test of underwater stored LWR MOX fresh fuel assemblies. The influence of boron acid on the UWCC performance has been intensively investigated in a number of specially prepared tests and the results were successfully implemented in actual verification activities. Nevertheless further experimental results are required for evaluation of possible methods for independent confirmation of the declared boron concentration. Possible options could be based on the estimation of the leakage multiplication or on the die-away time measurements. Further investigations are required also for quantitative assessment of poison rods influence at verification of BWR type MOX fuel assemblies.

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