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In-field Calibration of a Fast Neutron Collar for the Measurement of Fresh PWR Fuel Assemblies

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Abstract

A new neutron collar has been designed for the measurement of fresh LEU fuel assemblies. This collar uses “fast mode” measurement to reduce the effect of burnable poison rods on the assay and thus reduce the dependence on the operator’s declaration. The new collar design reduces effect of poison rods considerably. Instead of 12 pins of 5.2% Gd causing a 20.4% effect, as in the standard thermal mode collar, they only cause a 3.2% effect in the new collar. However it has higher efficiency so that reasonably precise measurements can be made in 25 minutes, rather than the 1 hour of previous collars. The new collar is fully compatible with the use of the standard data collection and analysis code INCC. This report describes the calibration that was made with a mock-up assembly at Los Alamos National Laboratory and with actual assemblies at the AREVA Fuel fabrication Plant in Lingen, Germany.

Introduction

Neutron collars are used by international inspectorates to determine the amount of ^{235}U in fresh LWR fuel assemblies. Standard neutron collars [1] can operate in two modes: “fast” and “thermal”. In fast mode (using cadmium liners), thermal neutron are excluded from the assembly and the measurement results are not very sensitive to the presence of neutron poison loaded pins. In thermal mode, the thermal neutrons are affected by the presence of poison rods leading to significant effects, requiring corrections. These corrections depend on the declaration of the operator, reducing the independence of the inspectors’ measurements. The thermal mode signal is much higher than the fast mode signal and can give statistically acceptable results in ~600 seconds compared with ~1 hr for the fast mode. This report describes the calibration of a new fast neutron collar designed to use fast mode to reduce the effect of poison pins on verification measurements but with increased efficiency to reduce the measurement times to those normally used on inspection. The work was done in cooperation with the safeguards division of the European Commission and so the new collar is named the Euratom Fast Collar (EFC). The motivation and design work is presented in reference 2. Reference 1 describes how the measured count rate of the detector is corrected for AmLi source strength, electronic stability, efficiency, poison rods effects and heavy metal effects as well as other perturbing factors. These will be discussed below. INCC [3] is the normal software that is used to collect and analyze neutron collar data. The results of this work have been formulated to fit into this existing INCC data analysis framework.

Initial Measurements at LANL

Figure 1 shows the horizontal cross section of the EFC from the Monte Carlo design. After the EFC was fabricated, test measurements were made using a mock-up fresh PWR fuel assembly and AmLi source N169 at LANL. The neutron emission of this source is 1.25 relative to MRC-95 [4]. The MRC-95 reference Singles rate on 6th February2014 was 2353.4 cps. The predelay was set at 1.5μs and the gate width 32μs. No deadtime correction was carried out because the counting rates are so small. The setup for assembly measurement is shown in Figure 2. The data from the measurement of the LANL assemblies is shown in Tables 1 and 2.

Table 1 Data for Mock-up Fuel Assembly Configurations at LANL

Item	Average enrichment	#LEU pins	#DU pins	#poison pins	U235/cm	U238/cm
PWR 0.80	0.8	40	164	0	9.75	1205.3
PWR 0.80	0.8	40	164	0	9.75	1205.3
PWR 1.09	1.09	60	144	0	13.29	1201.7
PWR 1.09	1.09	60	144	0	13.29	1201.7
PWR 1.68	1.68	100	104	0	20.36	1194.6
PWR 1.68	1.68	100	104	0	20.36	1194.6
PWR 1.97	1.97	120	84	0	23.90	1191.1
PWR 1.38	1.38	80	124	0	16.82	1198.2
PWR 0.51	0.51	20	184	0	6.21	1208.8
PWR 0.22	0.22	0	204	0	2.67	1212.3
1.97(12)	1.97	108	84	12	23.78	1185.6
1.68(12)	1.67	88	104	12	20.24	1189.2
1.68(8)	1.67	92	104	8	20.28	1191.0
1.68(4)	1.67	96	104	4	20.32	1192.8

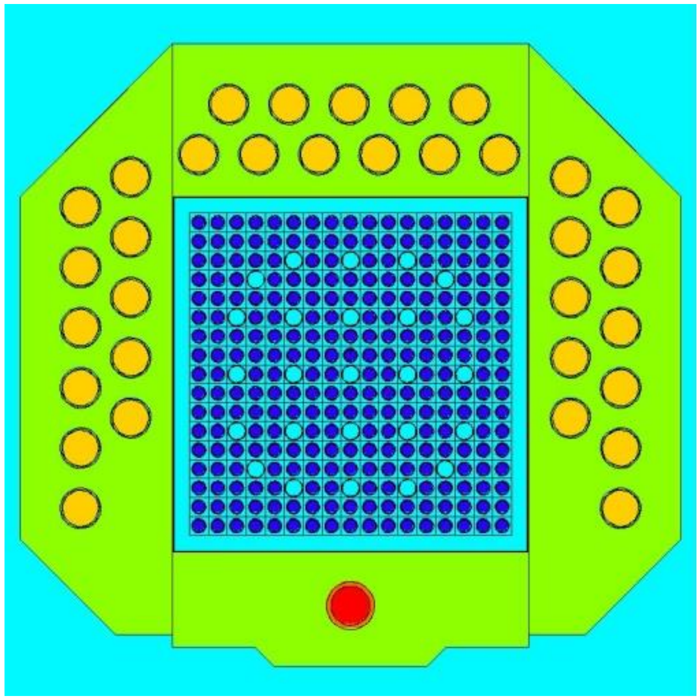

Figure 1 Horizontal cross-section of the EFC. (^{3}He tubes are shown in yellow, the AmLi source in red and polyethylene in green.)

Figure 2 EFC during measurement of Fuel Assembly Mock-up

Table 2 Measurement data for LANL Mock-up Assemblies (Singles background 42.2 ± 0.4 cps, Doubles background 0.055± 0.03 cps)

Meas Date 2014	Meas Time	Item ID	Singles	Singles Error	Doubles	Doubles Error	Collar Doubles	Collar Dbls Err
4 Feb	15:32:31	PWR 0.22	162.8	1.4	18.9	0.47	4.7	0.63
4 Feb	15:04:03	PWR 0.22	162.0	1.4	19.4	0.47	3.6	0.66
4 Feb	13:44:44	PWR 0.51	167.7	0.7	21.0	0.23	4.9	0.38
4 Feb	10:29:03	PWR 0.80	162.7	1.2	19.5	0.40	8.1	0.62
4 Feb	10:02:58	PWR 0.80	163.2	1.1	20.2	0.36	7.8	0.60
4 Feb	11:34:32	PWR 1.09	169.6	0.7	21.0	0.22	10.6	0.34
4 Feb	11:07:02	PWR 1.09	169.6	1.4	19.1	0.47	12.6	0.64
3 Feb	16:45:46	PWR 1.38	170.9	1.2	20.7	0.43	14.0	0.36
6 Feb	17:06:52	PWR 1.68	186.5	1.2	21.4	0.42	15.7	0.35
6 Feb	10:19:38	PWR 1.68	175.5	1.2	22.6	0.41	14.6	0.35
6 Feb	09:43:38	PWR 1.68	172.9	1.0	20.7	0.35	15.3	0.67
3 Feb	16:00:51	PWR 1.68	170.8	1.3	20.6	0.45	15.3	0.68
3 Feb	15:33:22	PWR 1.68	172.9	1.3	19.5	0.43	16.2	0.66
5 Feb	10:07:58	PWR 1.97	174.7	1.1	21.3	0.37	17.0	0.65
4 Feb	17:47:05	PWR 1.97	176.6	1.0	21.9	0.36	17.6	0.31
3 Feb	14:54:21	PWR 1.97	173.6	1.3	19.6	0.43	19.0	0.65

Field Test Measurements

Measurements of fresh PWR fuel assemblies were made at the Areva Fuel Fabrication Plant in Lingen, Germany. A photograph of the measurement setup is shown in Figure 3. The assemblies were centered as far as possible in the detector cavity. The AmLi interrogation source used was C-270, which, according to [1] has an emission rate of 1.382 relative to MRC-95. The measured data is shown in Table 3.

Figure 3 EFC Mounted on Cart with Fresh Fuel Assembly in Measurement Position

Table 3 Measured Values for Fresh Fuel Assemblies (assemblies in bottom 8 rows contain 12 burnable poison rods with 8% Gd))

Meas Date (2014)	Meas Time	Item ID	Singles Bkg	Singles Bkg Error	Doubles Bkg	Dbls Bkg Error	Act Singles Bkg	Act Singles Bkg Error	Singles	Singles Error	Doubles	Doubles Error	Count Time	Collar Doubles	Collar Dbls Err
23 Sept	13:28:50	Z	19.2	0.36	0.007	0.012	2941.8	4.0	185.4	1.2	16.7	0.37	200	34.5	0.71
23 Sept	14:09:26	3	19.2	0.36	0.007	0.012	2941.8	4.0	181.5	1.2	16.4	0.37	200	35.3	0.70
23 Sept	14:37:05	A	19.2	0.36	0.007	0.012	2941.8	4.0	184.3	1.2	15.8	0.36	200	35.9	0.70
23 Sept	15:06:43	P1	19.2	0.36	0.007	0.012	2941.8	4.0	185.4	1.2	16.2	0.37	200	35.8	0.70
24 Sept	11:14:06	P1 (rpt)	19.2	0.36	0.007	0.012	2941.8	4.0	188.5	0.9	17.1	0.27	400	34.4	0.51
24 Sept	11:47:10	P1 (rpt)	19.2	0.36	0.007	0.012	2941.8	4.0	194.7	1.2	17.3	0.38	200	35.5	0.72
25 Sept	10:48:43	6	16.1	0.33	-0.007	0.015	2941.8	4.0	182.3	1.0	16.5	0.30	300	34.7	0.58
25 Sept	13:59:15	L	16.1	0.33	-0.007	0.015	2941.8	4.0	182.7	1.0	15.7	0.30	300	35.7	0.57
25 Sept	15:15:33	J	16.1	0.33	-0.007	0.015	2941.8	4.0	192.6	1.0	16.3	0.30	300	35.3	0.58
24 Sept	10:14:53	N	19.2	0.36	0.007	0.012	2941.8	4.0	186.1	1.2	15.9	0.36	200	34.5	0.71
24 Sept	10:32:19	N (rpt)	19.2	0.36	0.007	0.012	2941.8	4.0	180.6	0.9	16.3	0.26	400	34.1	0.51
24 Sept	15:10:10	R	19.2	0.36	0.007	0.012	2941.8	4.0	185.3	1.2	16.7	0.37	200	35.7	0.74
24 Sept	15:27:46	R (rpt)	19.2	0.36	0.007	0.012	2941.8	4.0	188.2	0.9	16.8	0.27	400	34.9	0.53
25 Sept	11:27:16	F1	16.1	0.33	-0.007	0.015	2941.8	4.0	178.3	0.9	15.5	0.29	300	35.5	0.58
25 Sept	12:09:50	F1 (rpt)	16.1	0.33	-0.007	0.015	2941.8	4.0	182.2	1.0	16.2	0.30	300	35.3	0.59
25 Sept	13:19:57	F3	16.1	0.33	-0.007	0.015	2941.8	4.0	180.4	1.0	15.6	0.29	300	35.0	0.58
25 Sept	14:36:12	F	16.1	0.33	-0.007	0.015	2941.8	4.0	189.4	1.0	16.8	0.31	300	34.1	0.59

Data Analysis

The expected calibration curve is of the form:

$$D = \frac{am}{1 + bm}$$

where D is the Doubles rate and m is the ^{235}U mass/cm.

The calibration coefficients from the initial MCNP simulations were 'a'= 0.8512 and 'b'=0.0032 [2].

The measured data from LANL was processed as described in [1]. The LANL data was fit to this formula by keeping the 'b' value from MCNP constant and varying 'a'. The resulting value of 'a' was 0.803 when each point was weighted with its relative error squared. (NOTE: A correction factor k5=1.015 was used for the effect of the stainless steel guide tubes in the LANL mock-up assembly. This factor was not used for the field trial assemblies.). The original MCNP calibration curve and the curve fitted to the LANL data are shown in Figure 4. There is a 6% difference between the two curves at 50 g/cm ^{235}U (typical PWR assembly value). Part of this difference can be attributed to the uncertainty of the absolute AmLi source strength.

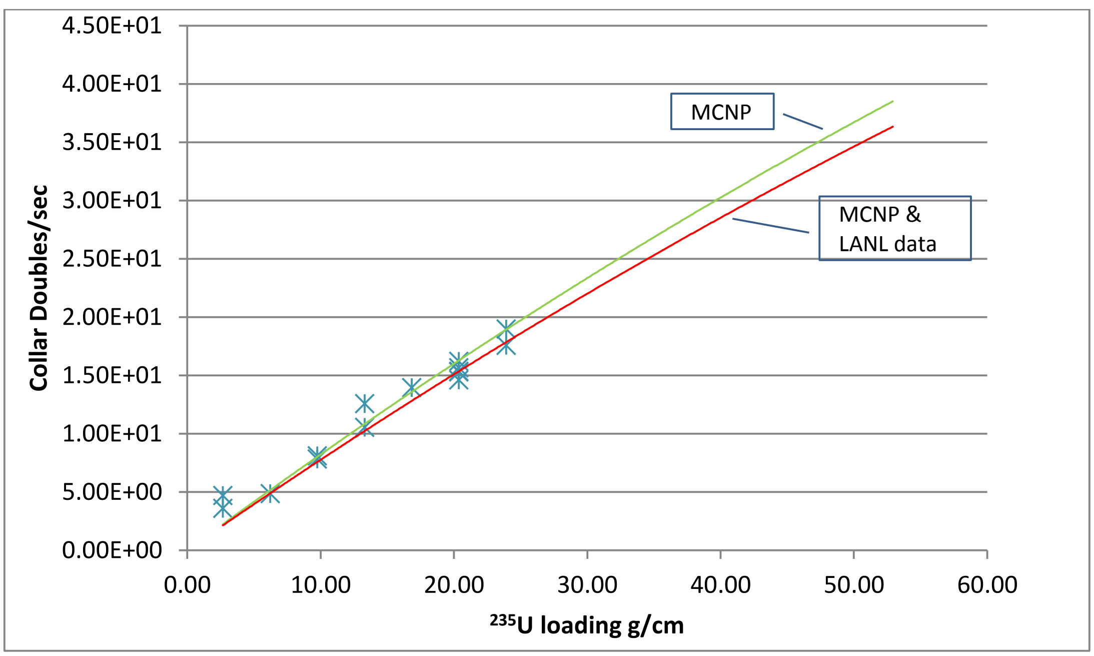

Figure 4 Comparison of MCNP simulation results and curve fitted to LANL data

The field test data, which extends to a much higher mass range, was analyzed in the same way. The poison rods correction parameters were: poison absorption factor 0.07, ‘a’ = 9.7×10^{-3} and ‘b’=1.0 [5]. The other INCC settings were as follows:

Relative Doubles rate (k2) =1.000 reference date 7 February 2014

Uranium Mass Correction Factor (k4) ‘a’=3.89e-4 and ‘b’=1.215e+3 (defaults)

A weighted fit to both sets of data (LANL and field test), gives calibration constants of ‘a’= 0.86385±1.66e-02 and ‘b’=5.54e-3±5.095e-04 (covariance(ab) = 8.2434e-6). The fitting screen from the Deming program [6] is shown in the appendix. Figure 5 shows the calibration curves from the LANL data (labeled “MCNP+LANL”) and the final fit (labeled “fit”) for all measured data. Figure 6 shows the high mass region in more detail. The difference between the field trial measurements and the previous fit to the LANL data is only 2.5% at 50 g/cm ^{235}U. We can also see that the poison correction that was used performs well, as both the poisoned and unpoisoned assembly results fit well on the same curve. When we analyze the field trial data with the final fitted curve the rms uncertainty of the field trial results is 2.4% and the rms deviation from the declaration is 2.1%.

Table 4 Measurement Results for Fresh PWR Fuel Assemblies (Assemblies in bottom 8 rows contain 12 burnable poison rods with 8% Gd))

Item ID	Collar Declared Mass g	Dcl mass/cm g/cm	Collar Measured Mass g	Collar Mass Error g	Mass Error %	Collar Declared-Assay g	Collar Dcl-Asy %
Z	19354	52.91	18743	510	2.72%	611	3.2
3	19258	52.65	19339	508	2.63%	-80	-0.4
A	19302	52.77	19766	515	2.61%	-464	-2.4
P1	19303	52.78	19686	514	2.61%	-383	-2.0
P1	19303	52.78	18708	375	2.00%	595	3.1
P1	19303	52.78	19430	525	2.70%	-127	-0.7
6	19254	52.64	18874	419	2.22%	379	2.0
L	19258	52.65	19574	427	2.18%	-317	-1.6
J	19263	52.67	19286	427	2.22%	-23	-0.1
N	18888	51.64	18790	511	2.72%	97	0.5
N	18888	51.64	18499	371	2.01%	388	2.1
R	18907	51.69	19585	538	2.75%	-678	-3.6
R	18907	51.69	19003	387	2.03%	-97	-0.5
F1	18923	51.74	19434	431	2.22%	-511	-2.7
F1	18923	51.74	19324	432	2.23%	-401	-2.1
F3	18910	51.70	19091	427	2.24%	-181	-1.0
F	18947	51.80	18480	426	2.30%	467	2.5

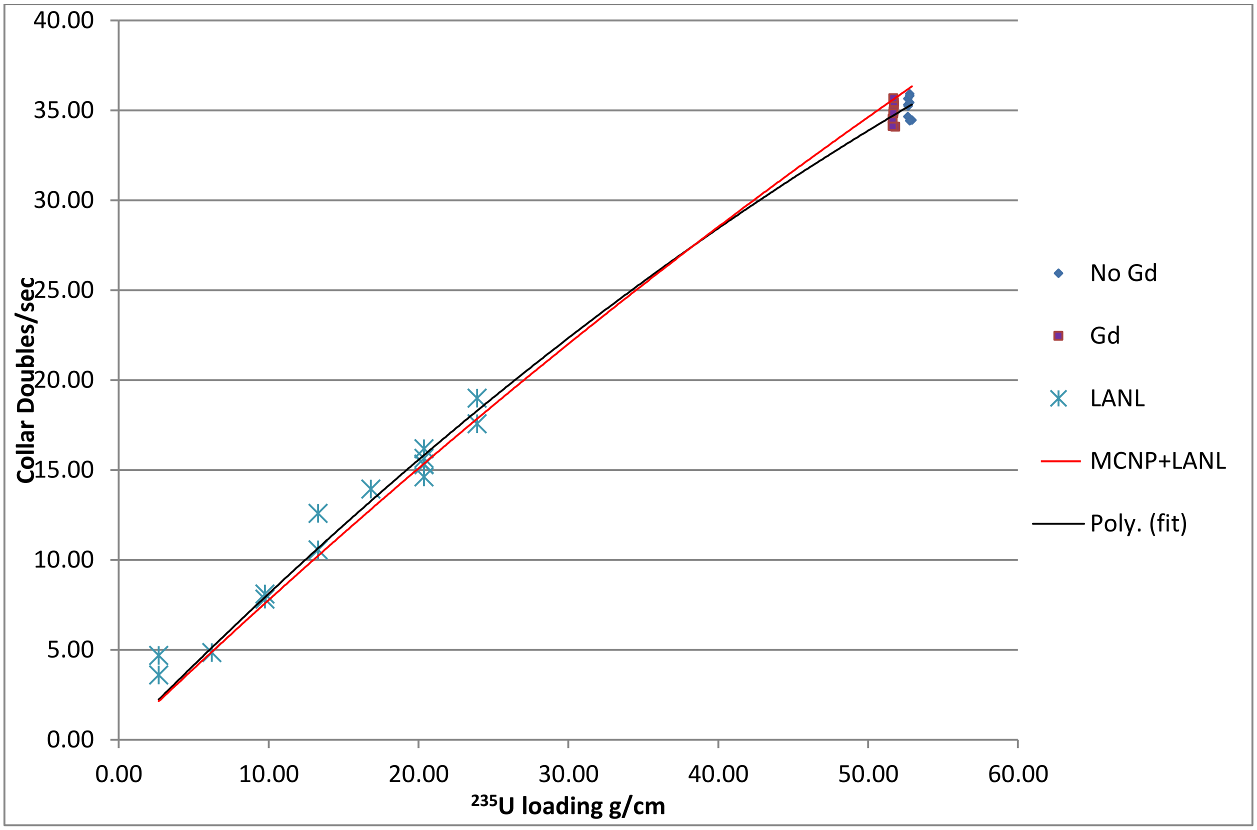

Figure 5 Results for LANL and Field Test Data

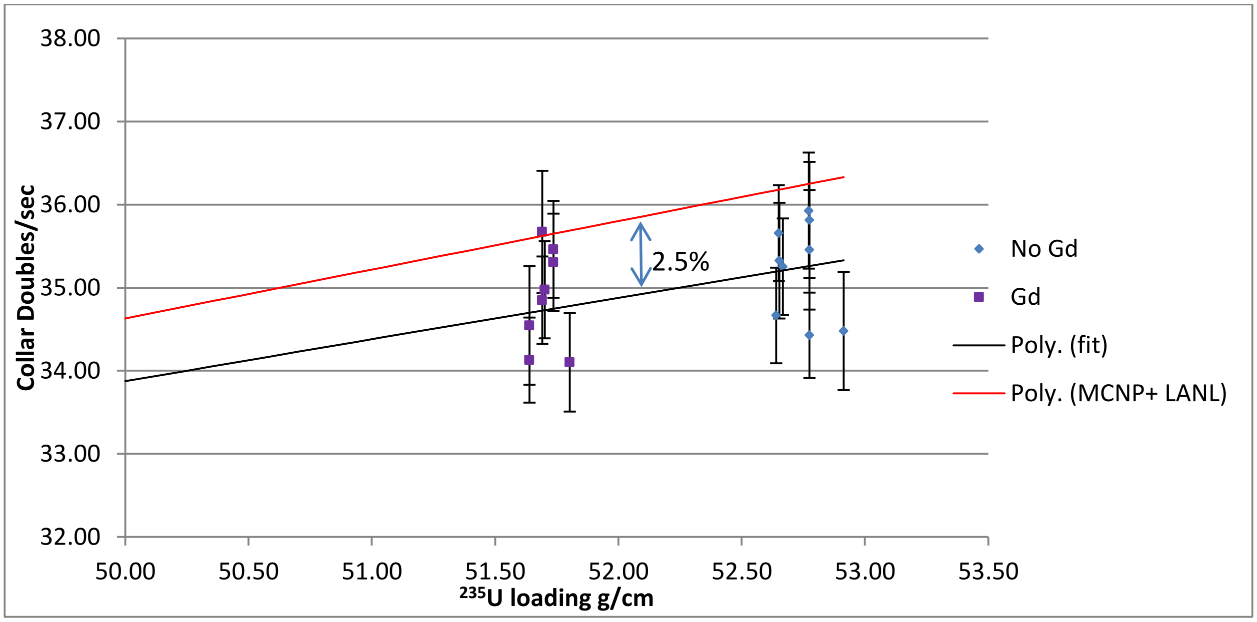

Figure 6 Comparison of Measured Data for PWR assemblies and the extrapolation of the LANL fit in the high mass region

Measurement time

With this collar, the division of the total measurement time into the passive measurement time and active measurement time is important to optimize the overall statistical uncertainty. For in-field measurements it is convenient to measure the passive rate for 1/3 of the active rate [5], so that, for example, the passive measurement could be 20 × 15 seconds and the active measurement could be 60 × 15 seconds, making a total measurement time of 20 minutes. (The time per cycle has to be the same for both measurements in INCC and 20 cycles is a reasonable minimum in order to obtain reliable error estimates). The results for 3 different measurement times are shown in Figure 7. The uncertainty varies, as expected, as inversely proportional to the square root of the measurement time.

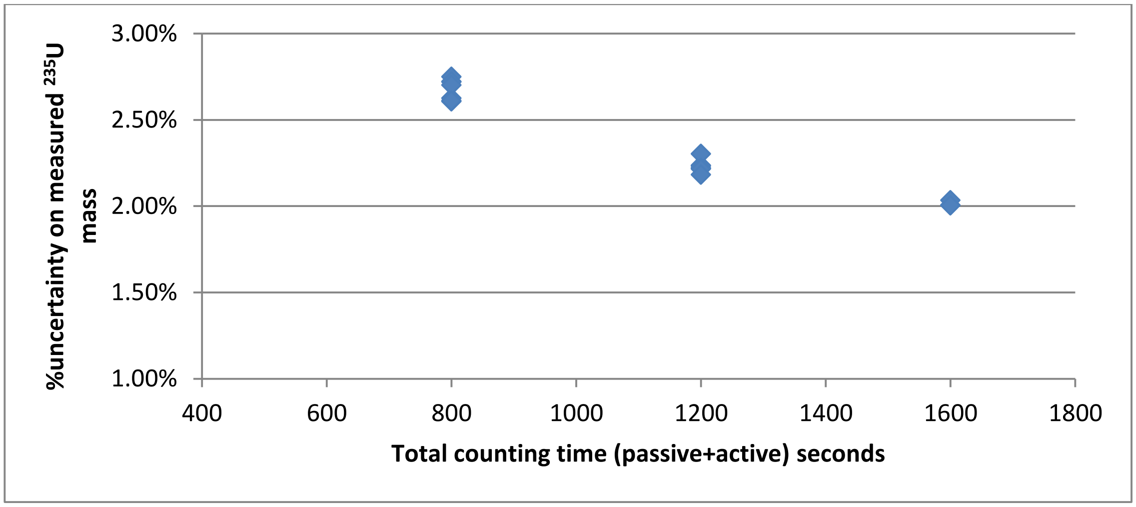

Figure 7 Uncertainty in mass as a function of measurement time

Conclusion

The new collar design reduces effect of poison rods considerably. Instead of 12 pins of 5.2% Gd causing a 20.4% effect, as in the standard thermal mode collar, they only cause a 3.2% effect in the new collar. The measurement time (active + passive) can be 20 minutes instead of 1 hour to obtain a measurement uncertainty of about 2%.

These results were obtained by using the existing version of INCC with existing algorithms.

This collar was specifically designed for the assay of fresh PWR fuel assemblies. WWER-1000 fuels assemblies have a similar size but a hexagonal shape. It is very likely that a small change in the geometry of this collar could allow equally good assay of fresh WWER-1000 assemblies. This could be effectively determined by Monte Carlo simulations similar to those that were so effective for this PWR collar design.

An approach similar to that use for the design of this collar could also be used for an instrument to measure BWR assemblies.

Acknowledgements

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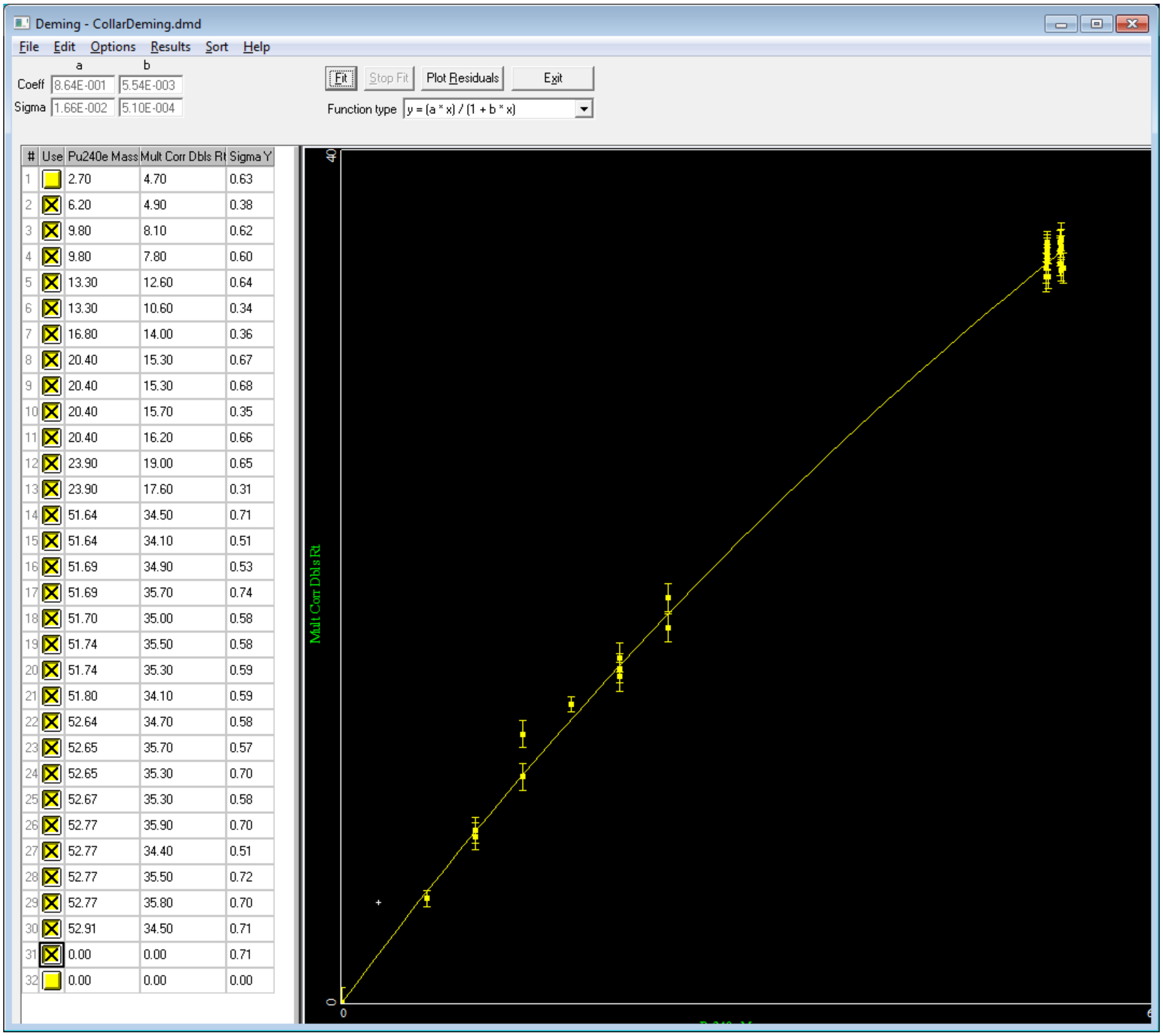
APPENDIX Details of Deming Fit to data



#	Use	Pu240e Mass	Mult Corr Dbls Rt	Sigma Y
1		2.70	4.70	0.63
2	X	6.20	4.90	0.38
3	X	9.80	8.10	0.62
4	X	9.80	7.80	0.60
5	X	13.30	12.60	0.64
6	X	13.30	10.60	0.34
7	X	16.80	14.00	0.36
8	X	20.40	15.30	0.67
9	X	20.40	15.30	0.68
10	X	20.40	15.70	0.35
11	X	20.40	16.20	0.66
12	X	23.90	19.00	0.65
13	X	23.90	17.60	0.31
14	X	51.64	34.50	0.71
15	X	51.64	34.10	0.51
16	X	51.69	34.90	0.53
17	X	51.69	35.70	0.74
18	X	51.70	35.00	0.58
19	X	51.74	35.50	0.58
20	X	51.74	35.30	0.59
21	X	51.80	34.10	0.59
22	X	52.64	34.70	0.58
23	X	52.65	35.70	0.57
24	X	52.65	35.30	0.70
25	X	52.67	35.30	0.58
26	X	52.77	35.90	0.70
27	X	52.77	34.40	0.51
28	X	52.77	35.50	0.72
29	X	52.77	35.80	0.70
30	X	52.91	34.50	0.71
31	X	0.00	0.00	0.71
32		0.00	0.00	0.00