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Title: EURATOM Fast Collar for BWR (EFCB) Field Calibration Exercise

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EURATOM Fast Collar for BWR (EFCB) Field Calibration Exercise

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Introduction

A neutron collar for the measurement of fresh BWR fuel assemblies (EFCB) has been designed and built by Los Alamos National Laboratory (LANL) and the Euratom Safeguards Directorate (Euratom). The design was similar to a previous collar designed for the measurement of fresh PWR assemblies [1]. A key feature of both of these collars is that they operate in fast mode (preventing the return of thermal neutrons into the assembly by means of a cadmium liner) to reduce the effect of burnable poisons on the measurement.

The first EFCB was fabricated in Europe and sent to Los Alamos in December 2018, where a calibration exercise was carried out jointly by Los Alamos and Euratom Safeguards staff [2].

The calibration data obtained in Los Alamos were fit with the standard curve of the form

$$y=am/(1+bm)$$

where y is the net doubles count rate, m is ^{235}U loading in g/cm in the assembly, and *a* and *b* are the calibration constants determined by the curve fit. Using the Deming plotting program [3], we determined calibration constants of

$$a = 1.26 \text{ +/- } 0.068$$

$$b = 0.00344 \text{ +/- } 0.00448.$$

This calibration covered a limited range of mass loading, up to 16 g ^{235}U/cm. The “b” parameter is within 1 sigma of zero, indicating the linearity of the calibration. As commercial fuel assemblies have significantly greater ^{235}U linear mass loadings than the LANL assembly, a field exercise in a fuel fabrication plant was carried out to extend the range of this calibration, as was also done in the case for the PWR version of the collar [4]. The current report describes the results of the field calibration exercise that was carried out at the ENUSA Fuel Fabrication Plant in Juzbado, Spain from May 28 to May 31, 2019.

Measurements

All the data were collected and analyzed using INCC [5] using the method described in the collar “bible” [6]. The measurements were made with the C121 AmLi source provided by Euratom. The counting rate from this source in the empty collar was 3008.9 ± 0.77 cps (after background subtraction). In December 2018 the counting rate from the MRC-95 AmLi source was 1848.0 ± 2.8 cps. This makes the source strength of C121 relative to MRC-95 equal to 1.6282 ± 0.0015. The decay of MRC-95 between December

2018 and May 2019 is negligible and was neglected. All LANL collars are related to MRC-95 in order to put all calibrations on an absolute basis (independent of the AmLi source actually used).

The properties of interest for the fuel assemblies that were available are shown in Table 1. Each fuel assembly has 3 vertical zones (high, middle and low) and separate measurements were made on each zone.

Table 1 Nuclear Material Parameters of Fuel Assemblies

Fuel ID	Type ID	High (^{235}U g/cm)	Middle (^{235}U g/cm)	Low (^{235}U g/cm)	High (^{238}U g/cm)	Middle (^{238}U g/cm)	Low (^{238}U g/cm)
1	A	20.088	22.364	24.070	421.02	464.73	497.51
2	A	20.086	22.361	24.067	421.05	464.76	497.55
3	A	20.081	22.355	24.061	420.98	464.69	497.47
4	A	20.065	22.338	24.043	420.82	464.51	497.28
5	B	20.121	22.393	24.053	421.87	465.52	497.42
6	B	20.139	22.413	24.075	422.24	465.93	497.85
7	B	20.147	22.422	24.084	422.21	465.89	497.81
8	B	20.093	22.362	24.019	422.11	465.79	497.70
9	B	20.116	22.387	24.047	421.90	465.56	497.45
10	B	20.113	22.385	24.044	421.85	465.50	497.40
11	B	20.129	22.402	24.062	422.12	465.80	497.72
12	B	20.137	22.410	24.072	422.44	466.15	498.09
13	B	20.113	22.385	24.044	422.03	465.70	497.60
14	B	20.100	22.370	24.029	421.76	465.40	497.29

The details of the burnable poison pin content is given in Table 2 Burnable Poison Information

Table 2 Burnable Poison Information

Assembly type /position	Total pins	Poison pins	Gd_2O_3 Poison %
A low	92	14	7
A middle	86	14	7
A high	78	14	7
B low	92	15	6
B middle	86	13	6
B high	78	13	6

Table 3 shows the counting rates obtained from each of the measurements. Most measurement were for a total time of one hour to have good statistics for the calibration. Two measurements were made with shorter times to see how the uncertainty was affected.

Table 3 Measurement Results from Fuel Assemblies

Date	Time	Item ID	Corrected Doubles	Dbls Err	Total Meas time (min)
05/29/19	13:47:23	1 Low	27.36	0.66	21
05/29/19	14:14:19	1 Low	27.71	0.44	47
05/29/19	16:42:40	1 Low	26.66	0.38	60
05/30/19	10:47:39	3 Low	27.39	0.40	60
05/30/19	13:11:12	3 Mid	25.46	0.40	60
05/30/19	13:31:25	3 High	22.74	0.41	60
05/30/19	16:31:41	9 Low	27.61	0.41	60
05/30/19	17:59:51	9 Mid	25.39	0.41	60
05/30/19	18:15:03	9 High	23.82	0.42	60
05/31/19	09:04:16	6 Low	27.06	0.41	60
05/31/19	11:19:05	6 Mid	25.61	0.41	60
05/31/19	11:33:31	6 High	23.28	0.41	60
05/31/19	13:15:49	4 Low	26.12	0.41	60
05/31/19	15:45:26	4 Mid	26.02	0.41	60
05/31/19	16:00:17	4 High	22.99	0.42	60

Analysis

Initial examination of the data showed that the shape of the Juzbado data was being adversely affected by the heavy metal correction. Reference [6] suggests that the heavy metal correction for BWR fuel should be around 1-2%. With the default values the heavy metal correction was over 3%. Therefore the data was analyzed with a very much reduced heavy metal correction (b=1e-4 rather than 7.24e-4), which reduced the magnitude of the correction and gave the expected behavior. The results are shown in Figure 3. (The effect of the change of this factor should continue to be evaluated as further data is collected.) This change makes no difference to the results of the original LANL measurements because the reference heavy metal loading was set to the LANL assembly value.

This new field calibration data together with the original Los Alamos data were fit with the standard curve in the same form as above. We obtained the calibration constants and variances and covariances given in Table 4 and the results are plotted in Figure 1.

Table 4 Calibration parameters obtained from a Deming fit to all data

a	b
1.2979	6.209075E-003
σa	σb

2.790349E-002	1.151896E-003
Var a	
7.786050E-004	
Covar ab	Var b
3.151214E-005	1.326864E-006

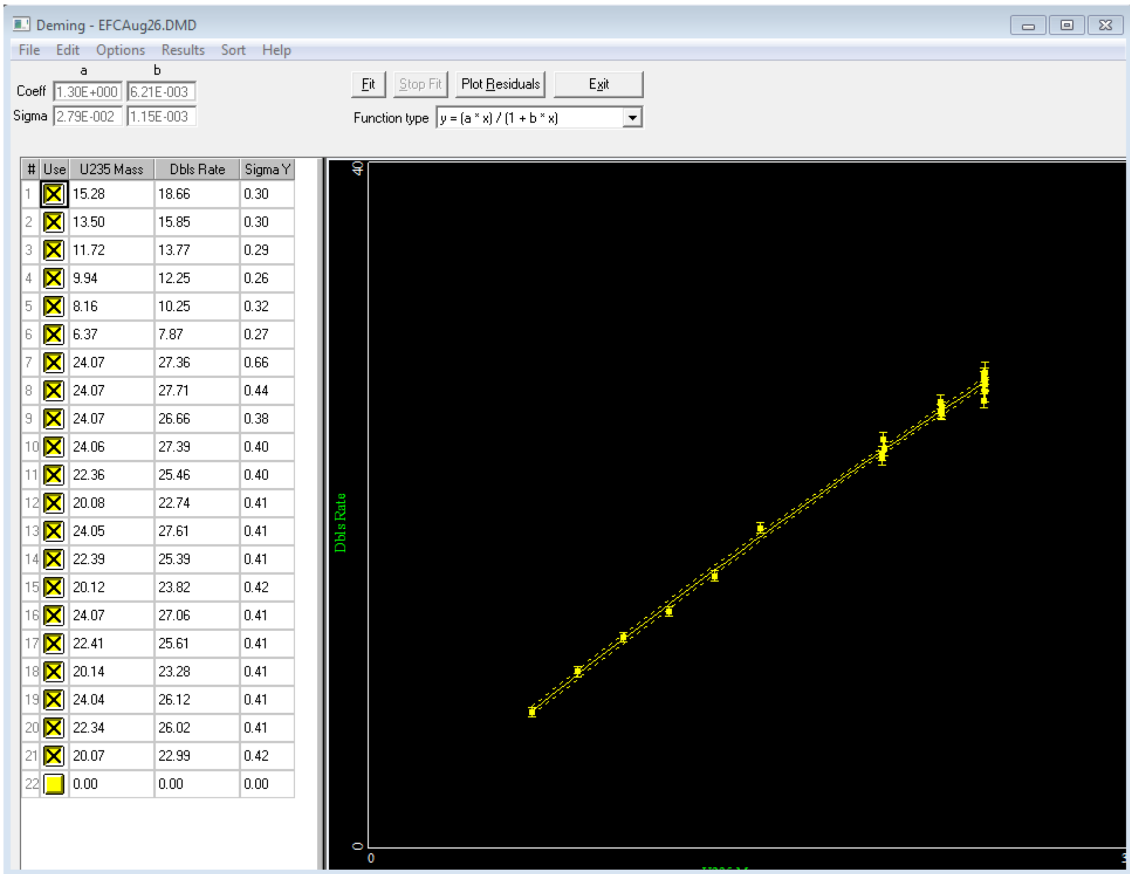

Figure 1 Deming Fit to All Data Points

The new ‘a” parameter is about 3% larger than the value determined from the Los Alamos data alone, but this is compensated to a large extent by the “b” parameter, which is now definitely positive, as the higher mass loadings show more curvature than at lower mass loadings. Figure 2 shows a comparison of the original and new calibrations. The overall change is very small in the region of the original LANL data.

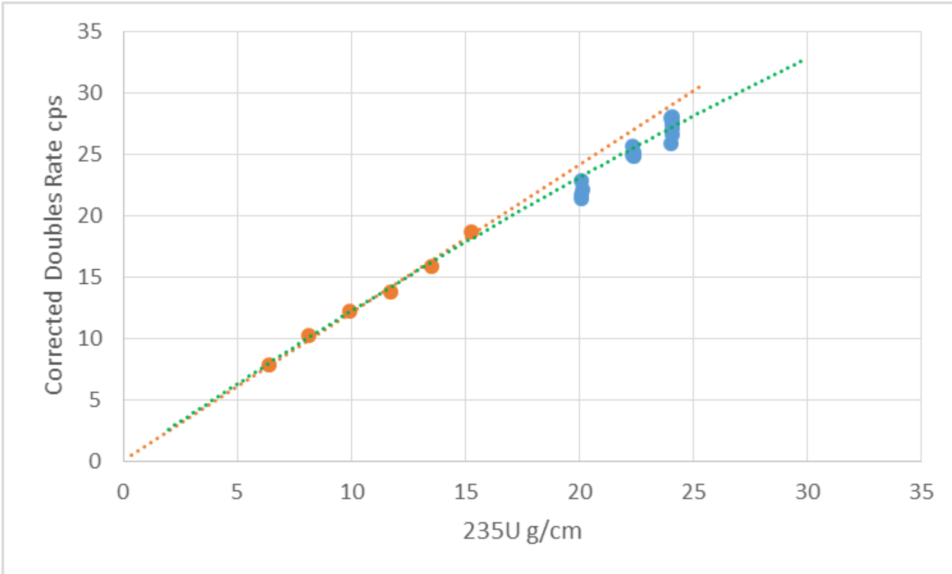

Figure 2 Comparison of initial calibration and new calibration. LANL points and initial calibration are shown in orange, Juzbado data in blue and fit to all data in dotted green.

The ^{235}U mass results calculated using the new calibration are shown in Table 5 and plotted in Figure 3.

Table 5 Measurement Results with Updated Calibration

Date	Time	Item ID	Declared Mass g/cm	Measured Mass g/cm	Mass Uncertainty g/cm	Mass Uncertainty %	Declared -Assay g/cm	Declared -Assay %	Difference (Number of sigma)
5/29/2019	13:47:23	1 Low	24.07	24.26	0.69	2.83	-0.19	-0.77	-0.27
5/29/2019	14:14:19	1 Low	24.07	24.62	0.47	1.92	-0.55	-2.27	-1.18
5/29/2019	16:42:40	1 Low	24.07	23.54	0.41	1.75	0.53	2.20	1.26
5/30/2019	10:47:39	3 Low	24.06	24.28	0.44	1.80	-0.22	-0.93	-0.52
5/30/2019	13:11:12	3 Mid	22.36	22.33	0.42	1.88	0.02	0.10	0.05
5/30/2019	13:31:25	3 High	20.08	19.66	0.41	2.07	0.42	2.10	1.01
5/30/2019	16:31:41	9 Low	24.05	24.51	0.45	1.82	-0.46	-1.92	-1.05
5/30/2019	17:59:51	9 Mid	22.39	22.26	0.42	1.90	0.12	0.55	0.29
5/30/2019	18:15:03	9 High	20.12	20.71	0.42	2.04	-0.60	-2.98	-1.46
5/31/2019	09:04:16	6 Low	24.08	23.95	0.44	1.83	0.12	0.51	0.28
5/31/2019	11:19:05	6 Mid	22.41	22.49	0.42	1.89	-0.08	-0.34	-0.18
5/31/2019	11:33:31	6 High	20.14	20.19	0.41	2.04	-0.05	-0.23	-0.11
5/31/2019	13:15:49	4 Low	24.04	23.00	0.43	1.86	1.05	4.35	2.34
5/31/2019	15:45:26	4 Mid	22.34	22.90	0.43	1.87	-0.56	-2.50	-1.34
5/31/2019	16:00:17	4 High	20.07	19.90	0.42	2.09	0.16	0.81	0.39

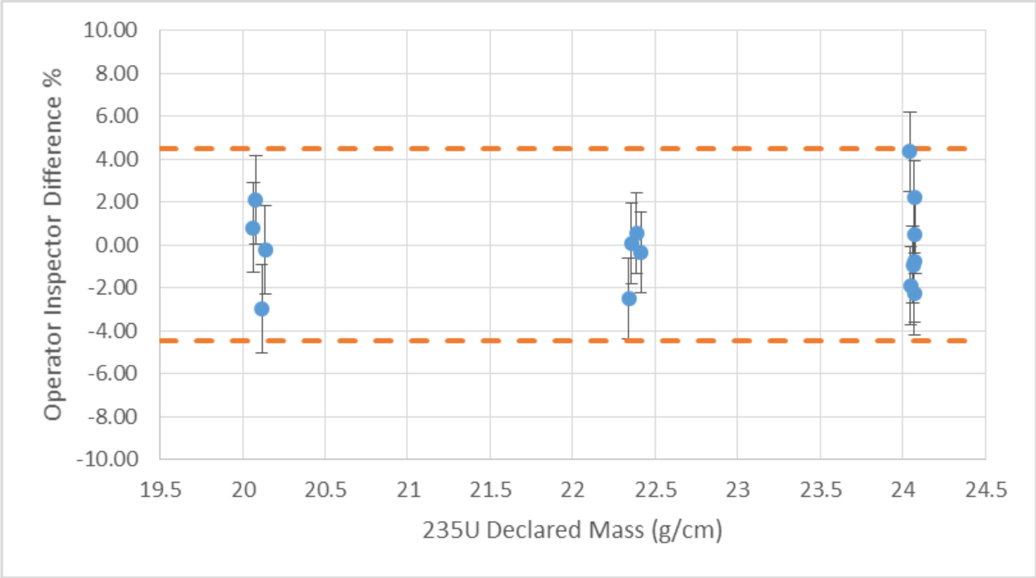

Figure 3 Declared-Measured as a function of ^{235}U mass. The dotted lines correspond to the 2010 ITV values for "LWR fresh fuel without Gd or with a Gd content, not exceeding the calibration range"

The results are good, well within 3 sigma of the declarations and within the 2010 ITV values for UNCL measurements (±4.5% as shown on the figure).

The uncertainty on the ^{235}U mass loading calculated by INCC for the measurement of assembly 1-Low is 2.8% for 21 minutes total measurement time, 1.9% for the 47 minute measurement and 1.8% for the 1 hour measurement. The operator-inspector differences for these shorter measurements are not very different from the 1 hour measurements. This suggests that 47 minute or even 20 minute measurements could give acceptable results, within the 2010 ITV values, for inspection purposes.

Conclusion

This report gives the results of the EFCB field exercise in the ENUSA plant in Juzbado Spain. The intensity of AmLi source C121 relative to MRC-95 was determined. The heavy metal loading correction was modified based on these results to reduce the correction required for the BWR with Cd case. A new calibration curve was produced, which extends the mass range beyond that of the calibration in Los Alamos in 2018. All of the parameters necessary for inspection measurements using INCC have been established.

Acknowledgements

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References

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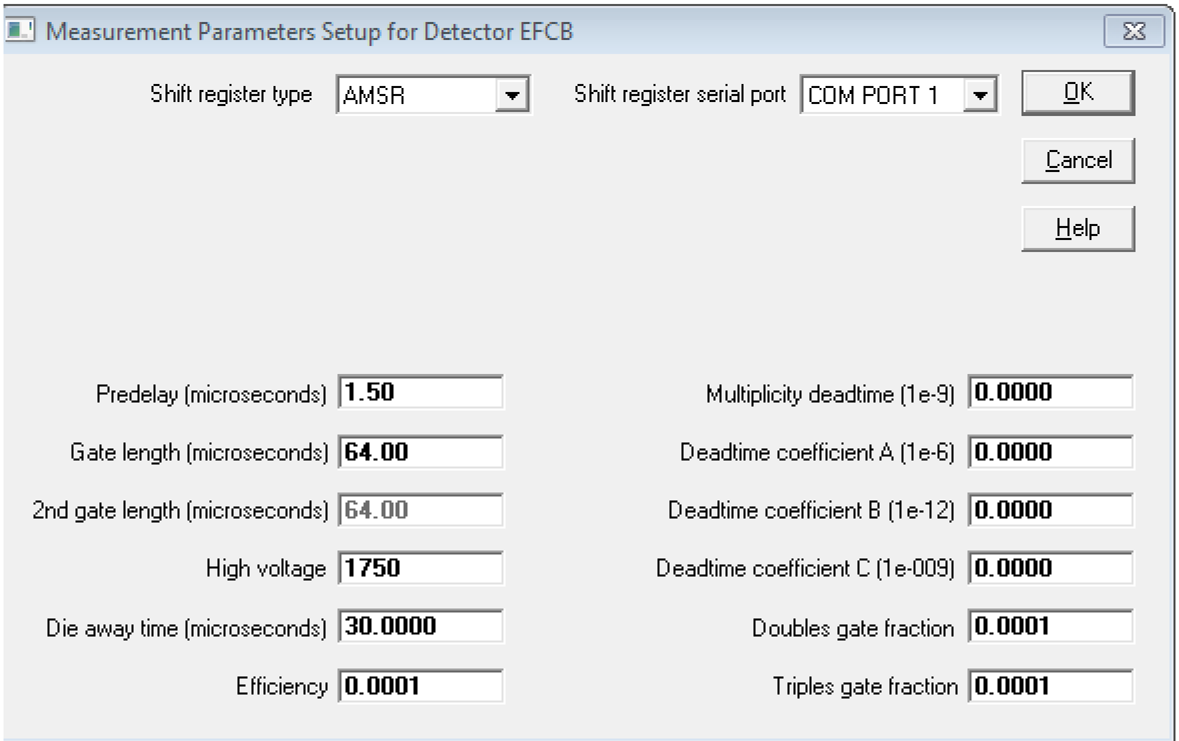
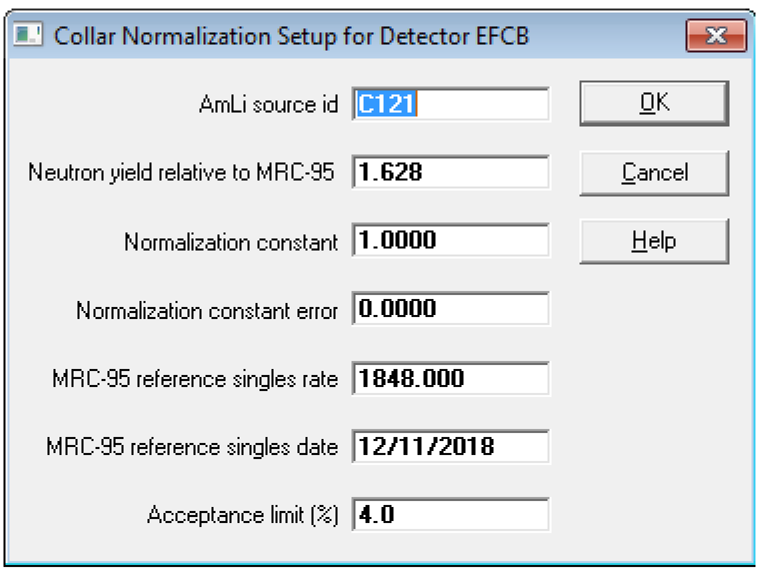
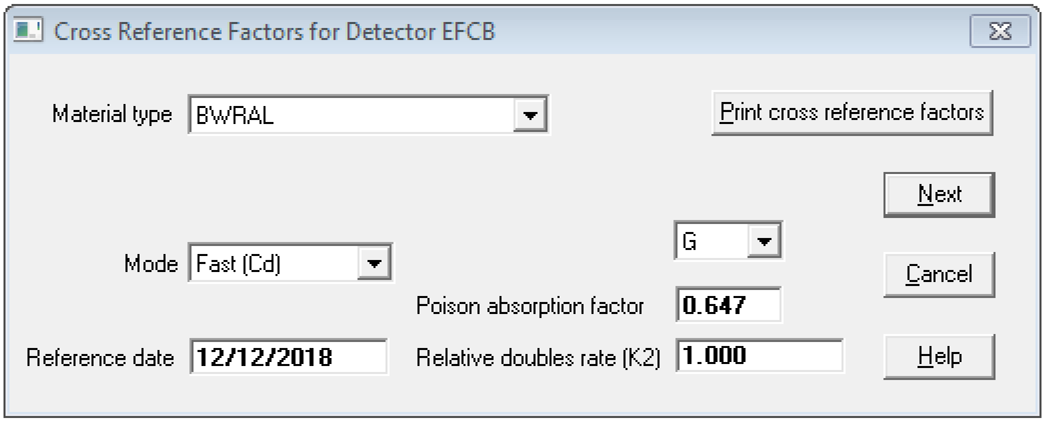
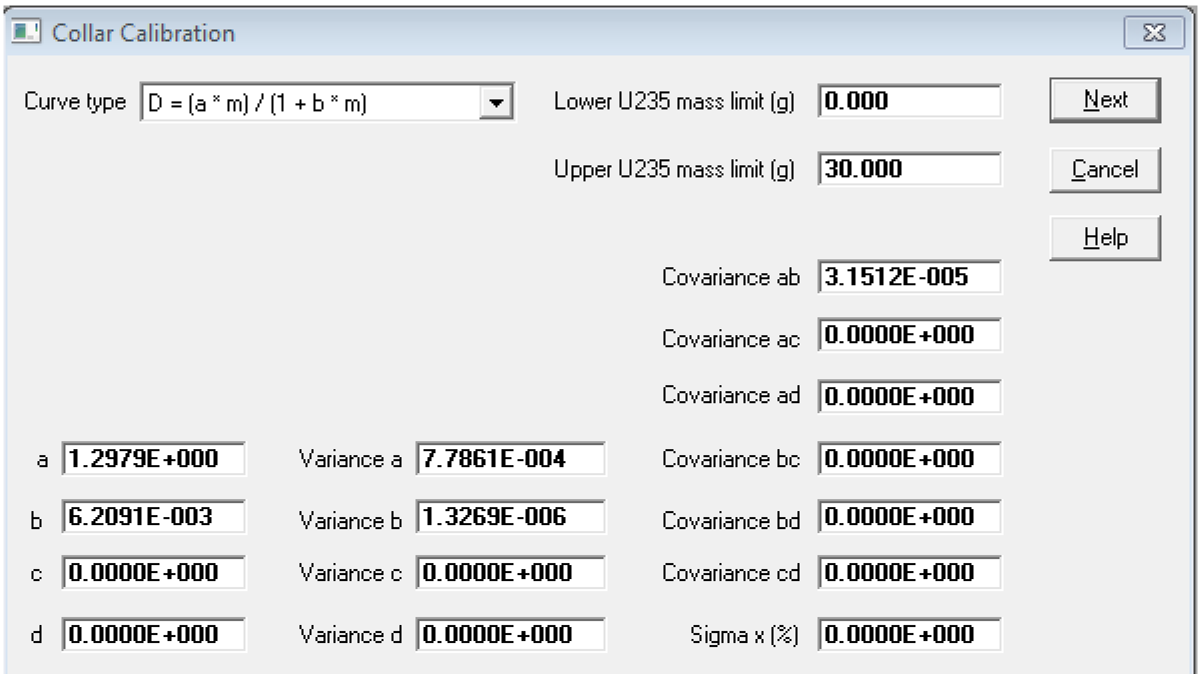
6. H.O. Menlove, J. E. Stewart, S. Z. Qiao, T. R. Wenz and G.P.D. Verrecchia, “Neutron Collar Calibration and Evaluation for Assay of LWR Fuel Assemblies Containing Burnable Neutron Absorbers”, Los Alamos National Laboratory Report LA-11965-MS November 1990.

APPENDIX A INCC Setup for EFCB with C-121

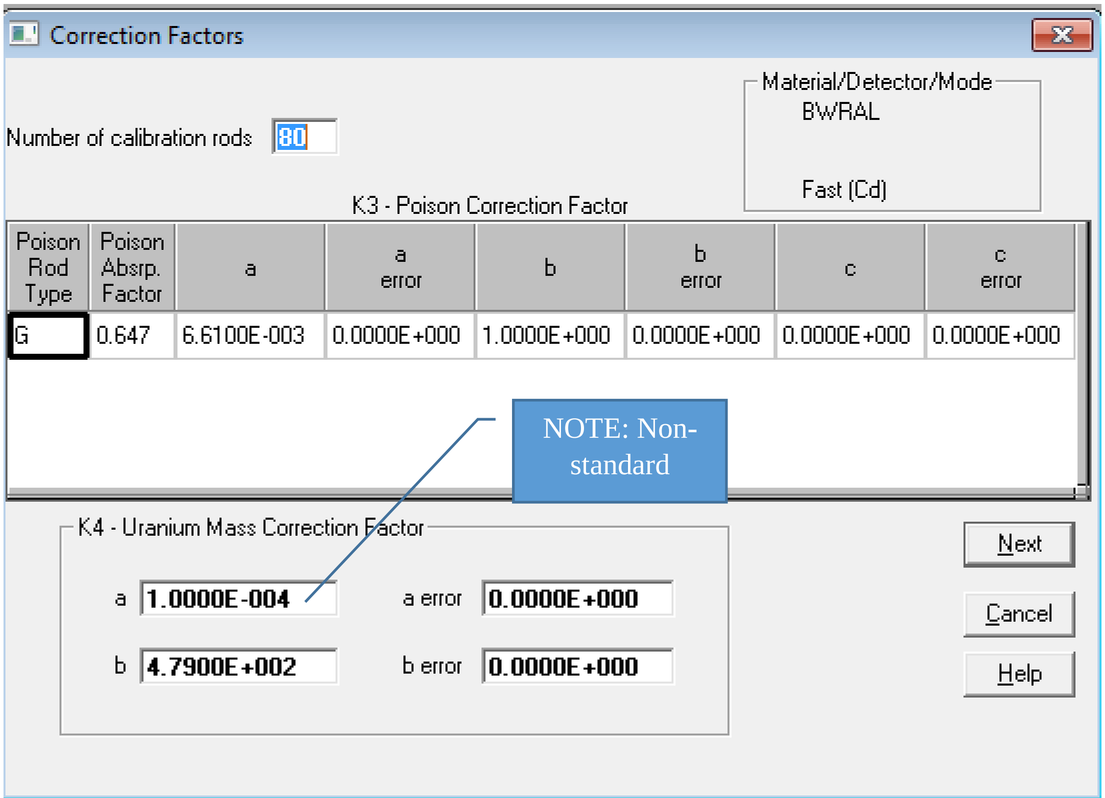


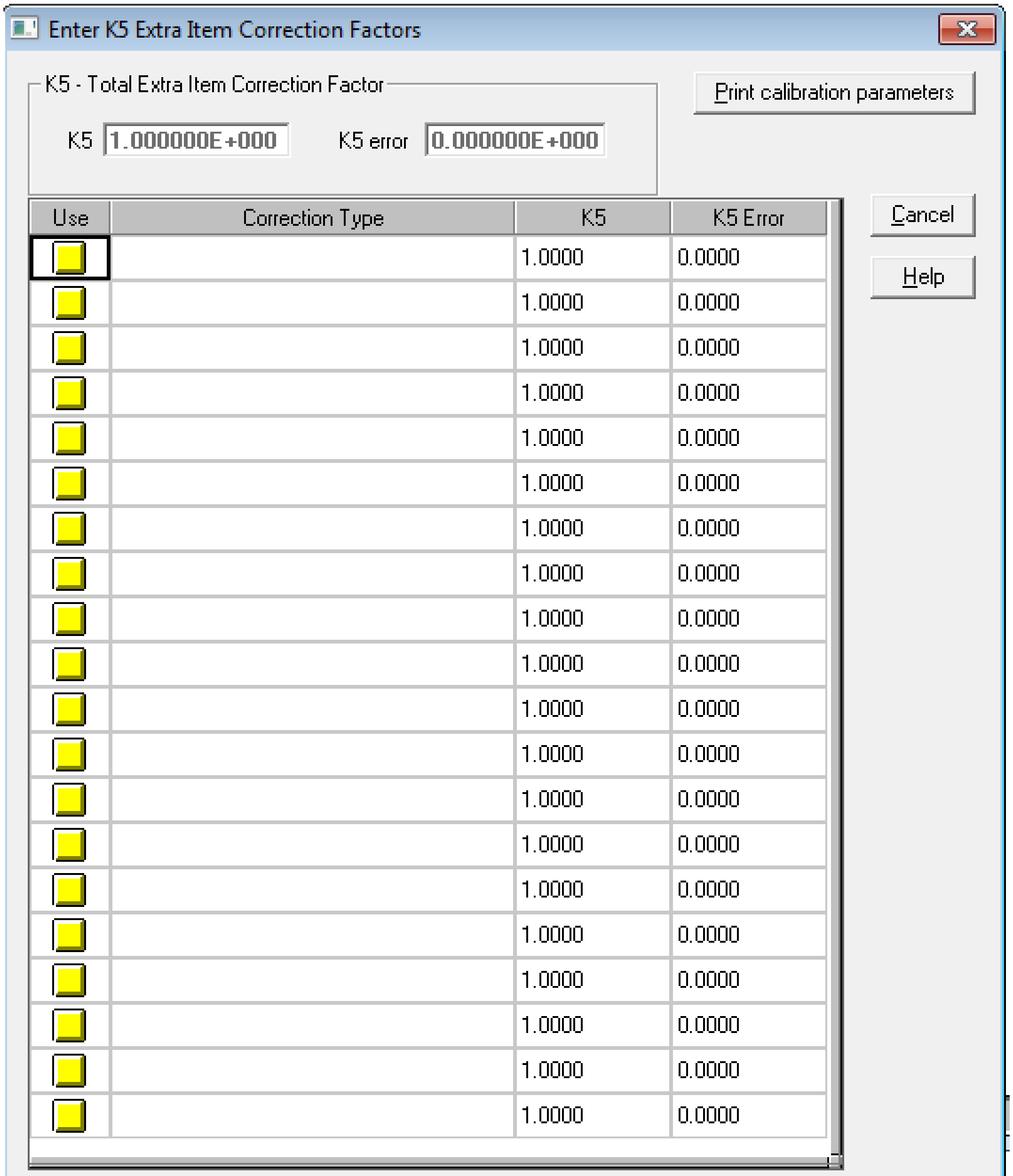






Calibration curve fitting Juzbado and LANL data


Correction Factors
Material/Detector/Mode
BWRAL
Fast (Cd)
Number of calibration rods 80
K3 - Poison Correction Factor
Poison Rod Type | Poison Absrp. Factor | a | a error | b | b error | c | c error
G | 0.647 | 6.6100E-003 | 0.0000E+000 | 1.0000E+000 | 0.0000E+000 | 0.0000E+000 | 0.0000E+000
NOTE: Non-standard
K4 - Uranium Mass Correction Factor
a 1.0000E-004
a error 0.0000E+000
b 4.7900E+002
b error 0.0000E+000
Next
Cancel
Help


Enter K5 Extra Item Correction Factors
K5 - Total Extra Item Correction Factor
K5 1.000000E+000
K5 error 0.000000E+000
Print calibration parameters
Cancel
Help
Use
Correction Type
K5
K5 Error
1.0000 0.0000
1.0000 0.0000
1.0000 0.0000
1.0000 0.0000
1.0000 0.0000
1.0000 0.0000
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APPENDIX B Example INCC Output

INCC 5.1.2

```
                 Facility:  WSAF
 Material balance area:  WSAF
          Detector type:  EFC
              Detector id:  EFCB
         Electronics id:  AMSR
 Inventory change code:
            I/O code:
     Measurement date:  19.05.31  16:13:34
       Results file name:  95VQ1334.VER
     Inspection number:  ETI w21
            Item id:  Assembly#4 High
          Stratum id:  AUG19
        Bias uncertainty:  0.0000
   Random uncertainty:  0.0000
Systematic uncertainty:  0.0000
  Relative std deviation:  0.0000
        Material type:  BWRAL
Original declared mass:  20.065
   Measurement option:  Verification
         Data source:  Database
           QC tests:  On
   Error calculation:  Sample method
   Accidentals method:  Measured
      Inspector name:  AT-DL-CR
            Comment:

        Isotopics id:  Default
 Isotopics source code:  OD
             Pu238:    0.0000 +-   0.0000      0.0000 +-   0.0000
             Pu239:    0.0000 +-   0.0000      0.0000 +-   0.0000
             Pu240:  100.0000 +-   0.0000    100.0000 +-   0.0000
             Pu241:    0.0000 +-   0.0000      0.0000 +-   0.0000
             Pu242:    0.0000 +-   0.0000      0.0000 +-   0.0000
           Pu date:  00.01.01                19.05.31
             Am241:    0.0000 +-   0.0000      0.0000 +-   0.0000
           Am date:  00.01.01                19.05.31

           Predelay:      1.50
        Gate length:     64.00
     2nd gate length:     64.00
        High voltage:   1750
       Die away time:     30.0000
          Efficiency:      0.0001
 Multiplicity deadtime:      0.0000
Coefficient A deadtime:      0.0000
Coefficient B deadtime:      0.0000
Coefficient C deadtime:      0.0000
```

Doubles gate fraction: 0.0001
Triples gate fraction: 0.0001

Normalization constant:	1.0000	+-	0.0000
Passive singles bkgrnd:	12.268	+-	0.129
Passive doubles bkgrnd:	0.017	+-	0.007
Passive triples bkgrnd:	-0.000	+-	0.000
Passive scaler1 bkgrnd:	0.000		
Passive scaler2 bkgrnd:	0.000		
Active singles bkgrnd:	19.887	+-	0.245
Active doubles bkgrnd:	0.017	+-	0.007
Active triples bkgrnd:	-0.000	+-	0.000
Active scaler1 bkgrnd:	0.000		
Active scaler2 bkgrnd:	0.000		

Number passive cycles: 20
Count time (sec): 30

Number active cycles: 100
Count time (sec): 30

Active messages

Collar: failed stratum rejection limits

Passive results

Singles:	64.150	+-	0.341
Doubles:	7.003	+-	0.180
Triples:	1.114	+-	0.134
Quads:	0.413	+-	0.123
Quads/Triples:	0.257	+-	0.053
Scaler 1:	0.000	+-	0.000
Scaler 2:	0.000	+-	0.000

Active results

Singles:	2670.074	+-	0.971
Doubles:	41.064	+-	0.573
Triples:	4.783	+-	0.224
Quads:	0.760	+-	0.139
Quads/Triples:	0.122	+-	0.029
Scaler 1:	0.000	+-	0.000
Scaler 2:	0.000	+-	0.000

Collar results

AmLi source id: C121
Mode: Fast (Cd)

Declared U235 mass (g):	20.065	+-	0.0000
Declared U238 mass (g):	420.823	+-	0.0000

Declared length:	1.000 +- 0.0000
Declared total rods:	78
Declared total poison rods:	14
Declared poison rod type:	G
Declared poison %:	7.000 +- 0.0000
k0 (source yield factor):	0.615 +- 0.0026
k1 (stability factor):	1.000 +- 0.0000
k2 (detector response factor):	1.000 +- 0.0030
k3 (poison factor):	1.094 +- 0.0000
k4 (uranium factor):	1.004 +- 0.0000
k5 (other correction factor):	1.000 +- 0.0000
K (total correction factor):	0.675 +- 0.0020
Corrected net doubles:	22.990 +- 0.4161
U235 mass (g):	19.902 +- 0.4160
Declared - assay U235 mass (g):	0.163 +- 0.4160
Declared - assay U235 mass (%):	0.811 +- 2.0731

Collar calibration parameters

Equation:	D = (a * m) / (1 + b * m)
a:	1.297900e+000
b:	6.209100e-003
c:	0.000000e+000
d:	0.000000e+000
variance a:	7.786100e-004
variance b:	1.326900e-006
variance c:	0.000000e+000
variance d:	0.000000e+000
covariance ab:	3.151200e-005
covariance ac:	0.000000e+000
covariance ad:	0.000000e+000
covariance bc:	0.000000e+000
covariance bd:	0.000000e+000
covariance cd:	0.000000e+000
sigma x:	0.000000e+000
number of calibration rods:	80
poison rod type:	G
poison absorption factor:	0.647
poison correction factor a:	6.610000e-003
poison correction factor a error:	0.000000e+000
poison correction factor b:	1.000000e+000
poison correction factor b error:	0.000000e+000
poison correction factor c:	0.000000e+000
poison correction factor c error:	0.000000e+000
U mass correction factor a:	1.000000e-004
U mass correction factor a error:	0.000000e+000
U mass correction factor b:	4.790000e+002
U mass correction factor b error:	0.000000e+000
item correction factor:	1.000000e+000
item correction factor error:	0.000000e+000
reference date:	18.12.12

relative doubles rate: 1.000000e+000

K5 item correction factors

Passive cycle rate data

Cycle	Singles	Doubles	Triples	Mass	QC Tests
1	65.565	6.917	0.676	0.000	Pass
2	66.698	6.783	0.671	0.000	Pass
3	62.998	7.650	1.966	0.000	Pass
4	62.598	6.217	0.678	0.000	Pass
5	64.665	6.483	0.627	0.000	Pass
6	64.598	7.083	1.266	0.000	Pass
7	64.565	6.617	0.629	0.000	Pass
8	64.532	13.617	46.345	0.000	Fail outlier test
9	65.465	6.117	0.461	0.000	Pass
10	64.498	6.317	0.670	0.000	Pass
11	64.698	6.750	0.822	0.000	Pass
12	62.432	7.083	2.178	0.000	Pass
13	62.365	7.517	1.390	0.000	Pass
14	65.332	7.483	0.665	0.000	Pass
15	64.665	6.583	1.210	0.000	Pass
16	60.965	6.817	1.284	0.000	Pass
17	63.798	5.850	0.392	0.000	Pass
18	63.198	6.550	1.496	0.000	Pass
19	65.365	7.783	1.140	0.000	Pass
20	63.165	8.183	1.541	0.000	Pass
21	65.365	9.283	2.519	0.000	Pass

Active cycle rate data

Cycle	Singles	Doubles	Triples	Mass	QC Tests
1	2672.513	61.317	4.153	0.000	Fail outlier test
2	2663.013	38.150	4.754	0.000	Pass
3	2660.680	47.883	6.086	0.000	Pass
4	2651.113	44.117	1.993	0.000	Pass
5	2663.880	37.617	2.846	0.000	Pass
6	2676.980	37.383	4.920	0.000	Pass
7	2663.613	48.217	4.689	0.000	Pass
8	2670.113	46.150	3.630	0.000	Pass
9	2669.513	43.783	5.660	0.000	Pass
10	2667.147	44.583	3.835	0.000	Pass
11	2663.280	25.283	1.221	0.000	Pass
12	2648.580	48.650	57.024	0.000	Fail outlier test
13	2669.847	41.050	6.179	0.000	Pass
14	2679.780	46.950	6.914	0.000	Pass
15	2676.847	27.883	4.318	0.000	Pass
16	2664.613	43.350	3.902	0.000	Pass
17	2660.447	35.617	0.994	0.000	Pass
18	2679.747	32.917	7.618	0.000	Pass
19	2668.113	45.083	4.413	0.000	Pass
20	2674.880	43.883	0.568	0.000	Pass

21	2658.413	48.450	-0.609	0.000	Pass
22	2681.313	42.383	5.442	0.000	Pass
23	2667.713	50.483	1.638	0.000	Pass
24	2676.547	39.083	3.722	0.000	Pass
25	2656.147	38.883	4.009	0.000	Pass
26	2677.113	47.717	6.241	0.000	Pass
27	2673.713	35.017	4.675	0.000	Pass
28	2666.147	34.150	4.158	0.000	Pass
29	2665.713	43.750	4.495	0.000	Pass
30	2671.613	34.817	4.401	0.000	Pass
31	2657.147	36.717	6.349	0.000	Pass
32	2671.013	36.183	3.709	0.000	Pass
33	2668.280	37.750	5.004	0.000	Pass
34	2701.713	42.417	4.928	0.000	Pass
35	2681.380	32.050	5.808	0.000	Pass
36	2659.480	36.917	6.792	0.000	Pass
37	2671.780	40.317	0.812	0.000	Pass
38	2671.247	34.317	5.701	0.000	Pass
39	2674.947	37.117	9.108	0.000	Pass
40	2666.647	47.583	6.535	0.000	Pass
41	2660.713	35.517	5.352	0.000	Pass
42	2660.180	45.183	7.078	0.000	Pass
43	2673.047	34.717	5.656	0.000	Pass
44	2676.213	37.650	1.770	0.000	Pass
45	2655.947	37.150	2.988	0.000	Pass
46	2673.913	49.183	2.532	0.000	Pass
47	2675.080	47.850	5.751	0.000	Pass
48	2667.247	38.550	4.549	0.000	Pass
49	2665.180	37.083	4.722	0.000	Pass
50	2686.047	49.983	7.833	0.000	Pass
51	2672.513	32.350	2.023	0.000	Pass
52	2652.713	39.950	5.152	0.000	Pass
53	2676.847	41.483	4.504	0.000	Pass
54	2659.480	47.117	5.055	0.000	Pass
55	2658.347	35.717	2.524	0.000	Pass
56	2679.780	33.483	0.461	0.000	Pass
57	2687.847	42.483	5.775	0.000	Pass
58	2686.213	45.883	0.652	0.000	Pass
59	2669.913	46.783	3.540	0.000	Pass
60	2678.013	39.450	3.673	0.000	Pass
61	2678.647	47.950	6.935	0.000	Pass
62	2672.847	54.617	7.688	0.000	Pass
63	2672.313	44.750	2.739	0.000	Pass
64	2672.913	34.050	8.014	0.000	Pass
65	2673.813	39.583	6.652	0.000	Pass
66	2674.847	37.150	2.958	0.000	Pass
67	2669.747	40.417	8.789	0.000	Pass
68	2661.680	35.250	1.587	0.000	Pass
69	2685.713	42.750	4.888	0.000	Pass
70	2669.747	37.617	4.503	0.000	Pass
71	2683.847	42.417	6.672	0.000	Pass

72	2653.380	43.650	2.640	0.000	Pass
73	2676.080	37.017	3.375	0.000	Pass
74	2664.780	46.217	7.170	0.000	Pass
75	2653.580	37.217	5.407	0.000	Pass
76	2650.447	45.783	7.376	0.000	Pass
77	2660.013	38.117	3.021	0.000	Pass
78	2667.080	43.117	6.991	0.000	Pass
79	2662.680	35.750	4.541	0.000	Pass
80	2652.580	47.850	4.226	0.000	Pass
81	2670.513	48.717	2.996	0.000	Pass
82	2665.847	31.750	4.212	0.000	Pass
83	2678.280	39.683	5.220	0.000	Pass
84	2695.480	51.017	9.316	0.000	Pass
85	2679.580	53.083	10.808	0.000	Pass
86	2686.547	43.583	2.450	0.000	Pass
87	2658.147	47.550	6.755	0.000	Pass
88	2675.180	40.717	7.310	0.000	Pass
89	2666.780	45.617	4.521	0.000	Pass
90	2670.280	44.450	9.506	0.000	Pass
91	2669.047	43.983	4.557	0.000	Pass
92	2678.247	45.050	8.508	0.000	Pass
93	2658.913	36.517	4.172	0.000	Pass
94	2666.447	44.250	6.097	0.000	Pass
95	2674.913	39.117	9.970	0.000	Pass
96	2686.413	35.917	4.693	0.000	Pass
97	2670.347	44.917	3.937	0.000	Pass
98	2662.447	33.117	4.335	0.000	Pass
99	2672.547	47.450	3.391	0.000	Pass
100	2667.680	43.817	3.537	0.000	Pass
101	2671.980	39.550	3.908	0.000	Pass
102	2668.113	31.683	3.317	0.000	Pass