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Application of research reactor environments for validation of the IRDFF-II dosimetry cross section library

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Abstract. Activation data from seven different reactor-based reference neutron fields are examined to provide enhanced validation evidence for the newly released IRDFF-II library. A least-squares based spectrum adjustment methodology is used and rigorous statistical metrics demonstrate the consistency of the set of IRDFF-II dosimetry cross sections. The use of these reactor-based neutron fields provides validation evidence for nine more reactions than have been addressed in the ^{252}Cf(sf) and ^{235}U(th) benchmark validation testing. The use of covers to shift their energy response increases the power of the response validation but makes it challenging to properly capture response correlations.

1 Characterization Methodology

The release of the new International Reactor Dosimetry and Fusion File (IRDFF-II) in 2019 [1] provided the dosimetry community with an updated neutron metrology library that represents a significant advancement in terms of scope, fidelity, and validation. The library includes 115 neutron metrology reactions, cross sections up to 60-MeV, and supports the use of elemental dosimeters where several reaction channels lead to the same residual nuclide. This library provides a complete and consistent set of recommended nuclear data, decay data, and fission product yields.

A critical step involved assembling the set of validation evidence that supports the assertion of fidelity for the metrology library. This evidence plays a role in establishing user confidence in the library. While nuclear data evaluations are developed using the available energy-dependent measurements and nuclear physics model calculations, the independent validation data typically draws upon measurements made in integral neutron fields. Note, the validation data must be independent of considerations that went into the cross-section evaluation itself. The most common metric used for validation is a comparison of the calculated-to-experimental (C/E) ratios for the spectrum-averaged cross sections (SACs) in the well-characterized ^{252}Cf(sf) spontaneous fission and ^{235}U(th) thermal neutron fission benchmark neutron fields. The cross-section evaluation itself is generally based up

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differential measurements and model calculations. While the consideration of integral measurements in these two benchmark neutron fields is not part of the evaluation process, measurements in these two benchmark neutron fields are generally examined by the nuclear data evaluator prior to dosimetry cross section release as part of a validation step. Because activity measurements are typically gathered during a series of irradiations rather than one, another useful measurement is a spectral index (SI), i.e., the ratio of the activity for a given reaction to that for a monitor reaction, and the comparison metric is again a C/E ratio – hence it is now a double ratio. Proper treatment of the uncertainty propagation in this double ratio can be a challenge, e.g., correlation of the spectrum uncertainty contributions that appear in the SI needs to be addressed.

In addition to the SACs and SI, another powerful metric for the validation of a dosimetry cross section is an examination of the consistency of the evaluation with the results from other dosimetry-quality cross sections when considered over a wide range of different neutron fields. The resulting C/E ratios for the activities, when all of the constraints and irradiation normalizations are coherently incorporated, can be used to provide statistically meaningful metrics for evaluation. A common acceptance metric is the joint consideration of: a) the overall chi-squared per degree-of-freedoms (dof), i.e., the number of activity measurements minus the number of any applied constraints/normalizations such as a reference activity for a normalizing reaction; and b) the magnitude of adjustment of the best estimates for the activities and for the energy-dependent neutron spectrum (as a fraction of the associated uncertainty components). This approach uses a least-squares analysis of the combined set of neutron spectrum, dosimetry reaction cross sections, and activity measurement data. Each of these input quantities needs to have an assigned *prior* uncertainty and any correlations between input quantities need to be characterized. While this least squares-based metric has been routinely applied to available experimental data for the high fidelity ^{252}Cf(sf) and ^{235}U(th) benchmark neutron fields, it can also be extended to the wider set of well-characterized research reactor reference neutron fields available within the reactor community. This paper reports on validation evidence for the IRDFF-II library acquired using over 30 different measured reactions acquired in seven different research reactor fields that have been used at Sandia National Laboratories (SNL). We highlight results from this validation activity in research reactor neutron fields, compare to the validation evidence available from the ^{252}Cf(sf) and ^{235}U(th) benchmark neutron fields, and compare the power of the rigorous least square approach to use of the simpler SACS and SI comparison. We also highlight cases where new measurements from research reactors could further improve the scope and fidelity of the validation evidence.

2 Reactor-based Neutron Fields Addressed for Validation

Table 1 provides a brief description of seven (7) reactor-based neutron reference benchmark fields where validation data has been acquired as part of ongoing work at Sandia National Laboratories. More extensive documentations on these neutron fields and the database of activity measurements can be found in internal SNL reports. Numerical representations of the neutron spectra can be found in International Atomic Energy Agency (IAEA) Nuclear Data Section (NDS) websites [2, 3]. Figure 1 shows the variation seen in these reactor-based neutron spectra compared with the ^{252}Cf(sf) standard benchmark neutron field. This representation uses a lethargy plot, but, since the y-axis is logarithmic to highlight the variation in the thermal portion of the spectra, the areas under the curve do not correspond to equal neutron probability as they would if a linear y-axis were used.

Table 1. Reactor-based Neutron Benchmark Fields Addressed in the Validation.

Field Identifier	Field Description
SPR-III-CC	SPR-III fast burst reactor with a 17-cm central cavity in the fuel and, due to the use of an aluminium insert, a 16.5-cm exposure area for test articles. SPR-III is an unmoderated Godiva-type reactor, a cylindrical assembly of uranium enriched to 93% ^{235}U and alloyed with 10-wgt-% molybdenum.
ACRR-FF-CC-32cl	ACRR central cavity with the 81.28 cm (32-inch) pedestal to place the experiment at the fuel centerline. ACRR is a pulsed pool-type research reactor with a dry central cavity with a minimum full-width half-maximum (FWHM) of 6 ms. It is composed of a 236 element array of UO_2-BeO fuel elements and uses uranium enriched to 35 weight percent ^{235}U with 21.5% weight percent UO_2 and 78.5 weight percent BeO.
ACRR-LB44	ACRR with an insert consisting of a 111.76 cm (44-inch) tall lead and B_4C "bucket" and a 12.7 cm (5-inch) inner diameter experiment location. This environment reduces the down-scattered thermal component of the neutron spectrum as well as the associated gamma exposure.
ACRR-PLG	A 23.5-cm diameter cavity in ACRR with a polyethylene-lead-graphite insert designed to reduce the fast neutron component relative to the total neutron fluence.
ACRR-CdPoly	A19.05 cm (7.5-inch) inner diameter cavity in ACRR with cadmium-polyethylene insert that is used to tailor the neutron spectrum and enhance the gamma ionization component.
FREC-II-FF	A fueled ring external cavity coupled to ACRR that provides a 50.8 cm (20-inch) dry cavity for large experiment packages. The fueled cavity uses a 186-element array of uranium/zirconium-hydride ($UZrH_{1.625}$) fuel elements with 12 weight percent uranium enriched to 20 weight percent ^{235}U.
6"_FBR-leakage	A 15.24 cm (6-inch) leakage position next to a bare 93% enriched ^{235}U assembly with a 3-leg/position aluminium experiment stand. Each of the three exposure positions are symmetric with respect to the control rod positions.

3 Validation Methodology

Table 2 shows the number of dosimetry sensors that were used in a least squares analysis of the seven (7) reactor-based neutron fields. The word "sensor" is used here rather than "monitor" to describe the dosimeters because they often consist of a specific cover material in addition to an activation foil and may consist of multiple reactions that yield the same product that is measured, e.g., fission products in multi-isotope foils. Table 2 also shows the chi-squared per-degree-of-freedom (χ^2/dof) metric and *posteriori* uncertainty fluence values to indicate the quality of the spectrum adjustment and the consistency of the sensor measurements. The least squares spectrum adjustment was performed using the LSL-M2 code [4] using an 89-group energy representation. This table also provides the results of a comparable spectrum adjustment, using the same adjustment code and group structure, for the ^{235}U(th) and ^{252}Cf(sf) standard benchmark neutron spectra.

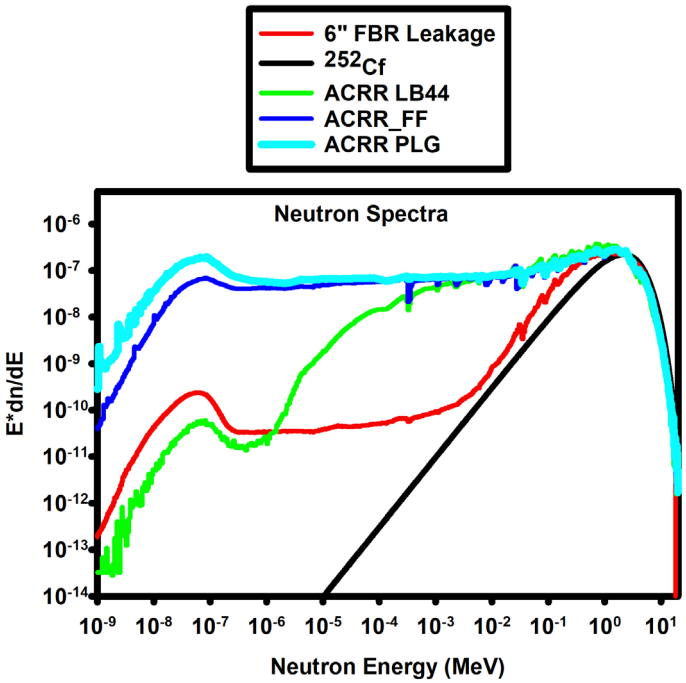

Fig. 1. Comparison of Some Reactor-based Reference Benchmark Neutron Spectra with the ^{252}Cf(sf) Standard Benchmark Neutron Spectrum.

Table 2. Least Squares Adjustment Characteristics.

Field Identifier	Number of Sensors [Reactions/ Covers]	χ^2/dof	Total Fluence (n/cm^2)	Posteriori Uncertainty	
				Total Fluence	>3-MeV fluence
Reference Reactor Fields					
SPR-III-CC	40	2.248	1.377x10^{13}	±1.1%	±3.9%
ACRR-FF-CC-32cl	33	0.8986	3.861x10^{15}	±1.8%	±2.2%
ACRR-LB44	29	1.255	3.590x10^{15}	±1.5%	±5.7%
ACRR-PLG	35	0.9619	3.855x10^{15}	±2.5%	±2.1%
ACRR-CdPoly	31	1.174	1.976x10^{15}	±1.6%	±2.0%
FREC-II-FF	36	0.9402	8.589x10^{14}	±2.1%	±2.3%
6” FBR-Leakage	34	1.363	4.882x10^{14}	±2.7%	±5.1%
Standard Neutron Fields					
^{252}Cf(sf)	48	0.4219	1.008x10^{12}	±0.7%	±0.7%
^{235}U(th)	52	0.9430	1.026x10^{12}	±0.7%	±0.9%

A major benefit of this reactor-based validation data is that it includes dosimetry reactions that have been fielded with various “covers”. Covers are often used with dosimetry foils to attenuate/shift the response of a measured activity and to augment the energy coverage provided by the use of only “bare” foils. The use of the word “sensor” in Table 2 addresses the number of different combinations of a dosimetry reaction and its associated covers. These measurements included use of the following cover geometries:

- "bare" indicating a bare foil with a thickness between 0.0127 and 0.0254 cm (5 and 10 mil);

- "cd" indicating a cylindrical cadmium cover with an areal density of 2.587x10^{-3} atoms/barn;
- "fiss" indicates inner thick cadmium cover, with an areal density of 4.705x10^{-3} atoms/barn, and an outer spherical boron ball. The boron ball is a spherical shell with an outer diameter of 4.76 cm and thickness of 1.03 cm. The B_4C has a density of 2.5 g/cm^3 and used isotopically enriched Boron (91.67% ^{10}B and 8.33% ^{11}B).

A detailed description of the covers and how self-shielding effects are rigorously addressed in the use in the activation measurements can be found in Reference [5].

In addition to activation foils, ^{235}U, ^{238}U, and ^{239}Pu fission foils were also used in the spectrum characterization. The fission foils were in the form of a sintered oxide (uranium oxide-to-metal ratio of 1.995; plutonium ratio of 1.886) measuring approximately 1.27 cm by 0.0762 cm thick and having an approximate mass of 1 gram. The isotopic mixtures of the various fission foils are given in Table 3.

Table 3. Isotopic Composition of Fission Foils.

Foil	Isotope	Atom Fraction
Enriched ^{235}U	^{235}U	0.9300
	^{234}U	0.00981
	^{236}U	0.00359
	^{238}U	0.0566
Depleted ^{238}U	^{238}U	0.9979
	^{234}U	0.00001
	^{235}U	0.00205
	^{236}U	0.00004
^{239}Pu	^{239}Pu	0.869965
	^{238}Pu	0.0006798
	^{240}Pu	0.115968688
	^{241}Pu	0.010797
	^{242}Pu	0.00235936
	^{235}U	0.000199946
	^{237}Np	0.00002999
Atom fractions sum to the number of atoms of the prime sensor element is unity. Due to contaminant elements, the total sum may be greater than 1.0.		

Whereas the acceptance metric for the consistency of the composite set of inputs to the least-squares spectrum adjustment was the χ^2/dof metric (as seen in Table 2), we also need to consider a validation metric that highlights the status of specific reactions. There are multiple considerations here – including the C/E ratio for that activity (relative standard deviation relative to a C/E of one as well as the acceptance range for the C/E interval), the measurement accuracy of the activity, and the overall accuracy of the activity determination (including measurement, dosimetry cross section, and prior neutron spectrum). Table 4 shows the criteria adopted for these characteristics and used to label the overall activity determination in a given neutron field as good, acceptable, or poor.

Table 4. Criteria Used to Evaluate the Consistency of a Sensor in a Neutron Field.

#	Metric	Status		
		Good	**Acceptable**	**Poor**
1	C/E	≤2 std. dev.	≤3 std. dev.	> 3 std. dev.
2	C/E Interval	Within [0.9, 1.1]	Within [0.8, 1.25]	Outside [0.8, 1.25]
3	Expt. Unc.	≤ 15%	≤ 30%	>30%
4	Total Unc.	≤ 25%	≤ 40%	> 40%

4 Validation Status for Individual Reactions

Table 5 shows the status of the validation for the reaction/cover combinations in the seven reactor neutron fields. The ^{98}Mo(n,γ) reaction is highlighted as blue in this table because this is a reaction where we have activities measurements, but the cross section is not contained in the IRDFF-II library. In the absence of a dosimetry-quality cross section for this reaction, we used the ENDF/B-VII cross section and its associated COMMARA-2.0 covariance for this analysis. The green highlighting of the sensor name in Table 5 indicates a sensor configuration that augments the validation data gathered in the ^{252}Cf(sf) standard benchmark field. In general, these reactor-based dosimetry results provide good support for the fidelity and consistency of the IRDFF-II library. An examination of the C/E ratios as a function of the median response energy demonstrates that the sensors used in these reactor fields have very good coverage in the thermal and fast regions but lack good coverage in the neutron energy region between 100 keV and 2 MeV.

The median response energy for the various reactions varies with the reactor benchmark field and the cover. However, to aid in identifying potential energy-dependent bias in the sensor response, in Table 5 we have listed the reactions in an approximate response energy-dependent order (low to high with respect to the response of the reaction in the suite of fission reactor environments). Table 5 also presents the C/E ratios for the various neutron fields. The order for the ^{58}Ni(n,p) reaction is an exception to the energy ordering in that it appears first since it is the monitor/reference foil used to normalize the reactor exposure in the series of irradiations used to support the spectrum characterization. A monitor/reference reaction was used in conjunction with multiple separate reactor exposures to avoid attenuation/scattering from stacking multiple foils and to avoid interference of the foils/covers with the free-field neutron spectrum, e.g., when a boron ball was fielded only a single reaction was evaluated and a monitor foil was fielded both inside and outside the boron ball.

Table 5. Reactor-based Neutron Benchmark Fields Addressed in the Validation.

Reaction	Cov.	Reactor-based Neutron Benchmark Field						
		SPR-III CC	ACRR-FF-CC	ACRR-LB44	ACRR-PLG	ACRR-CdPoly	FREC-II-FF	FBR 15.25 cm (6-inch) Leakage
Ni58p	bare	---	1.00 ± 4.5%	1.00 ± 14.%	1.00 ± 3.9%	1.00 ± 4.6%	1.00 ± 5.1%	1.00 ± 12.%
	cd	1.00 ± 11.%						
Sc45g	bare		1.14 ± 28.%	1.17 ± 15.%	1.25 ± 32.%	0.94 ± 16.%	0.88 ± 21.%	
	cd	0.994 ± 8.6%	1.12 ± 16.%		1.10 ± 16.%		1.01 ± 13.%	
	fiss	1.052 ± 8.1%						
Mn55g	bare		1.07 ± 23.%	1.196 ± 6.4%		0.97 ± 8.3%	0.89 ± 19.%	
	cd	0.803 ± 8.0%	1.07 ± 8.5%		1.06 ± .3%			
	fiss	1.083 ± 8.2%						
Au197g	bare	0.840 ± 6.6%	1.07 ± 25.%	1.04 ± 11.%		1.06 ± 29.%	0.93 ± 16.%	
	cd	0.930 ± 6.7%	1.09 ± 28.%		1.07 ± 28.%		0.95 ± 21.%	
	fiss			1.057 ± 6.4%				
In115g	bare							1.14 ± 9.2%
	cd							
	fiss							
Ag109g	bare		1.31 ± 16.%			1.09 ± 18.%	1.04 ± 14.%	1.28 ± 10.%
	cd		1.21 ± 18.%					1.04 ± 11.%
	fiss							
Mo98g	bare			1.111 ± 9.9%			0.97 ± 11.%	1.14 ± 14.%
	cd					1.02 ± 13.%	0.96 ± 11.%	1.17 ± 15.%
	fiss			1.287 ± 8.1%				
Na23g	bare	1.127 ± 11.%	1.16 ± 25.%		1.27 ± 30.%	1.04 ± 12.%	1.02 ± 21.%	1.35 ± 16.%
	cd	1.074 ± 11.%	1.08 ± 11.%		1.15 ± 12.%		1.2 ± 11.%	0.84 ± 16.%
	fiss	1.18 ± 11.%						
Fe58g	bare		1.10 ± 23.%	1.096 ± 8.1%	1.24 ± 29.%	0.97 ± 8.9%	0.88 ± 21.%	1.11 ± 17.%
	cd	1.106 ± 12.%	1.03 ± 8.9%		1.11 ± 9.0%		0.99 ± 10.%	
	fiss			1.18 ± 13.%				
Co59g	bare		1.23 ± 20.%	1.49 ± 14.%	1.24 ± 27.%	1.28 ± 11.%	0.89 ± 18.%	

	cd		1.35 ± 13.%		1.21 ± 12.%		1.16 ± 12.%	
	fiss							
W186g	bare		1.05 ± 17.%	1.168 ± 4.4%		1.02 ± 20.%	0.80 ± 15.%	1.06 ± 12.%
	cd	0.818 ± 10.%						
	fiss							
Cu63g	bare			1.140 ± 8.9%	1.20 ± 28.%	1.03 ± 8.5%	0.83 ± 19.%	0.93 ± 12.%
	cd	1.04 ± 12.%			1.14 ± 8.5%		1.07 ± 8.2%	
	fiss							
Nb93g	bare							
	cd					1.17 ± 18.%		
	fiss							
U235f	bare							1.33 ± 13.%
	cd	1.046 ± 5.4%						1.08 ± 13.%
	fiss	1.090 ± 5.4%	0.94 ± 4.4%	1.046 ± 5.3%	0.96 ± 3.4%	1.05 ± 3.5%	0.96 ± 4.2%	1.27 ± 13.%
Pu239f	bare							1.15 ± 13.%
	cd	1.110 ± 5.3%						0.90 ± 13.%
	fiss	1.166 ± 5.3%	1.08 ± 5.0%	1.007 ± 6.8%	1.09 ± 4.1%		1.04 ± 4.8%	1.02 ± 13.%
Np237f	bare							
	cd	1.119 ± 6.4%						1.11 ± 14.%
	fiss	1.104 ± 6.4%	1.08 ± 5.0%	1.03 ± 10.8%		1.15 ± 4.7%	0.98 ± 4.0%	1.33 ± 14.%
In115nm	bare	1.069 ± 9.4%		0.96 ± 14.%	0.93 ± 6.5%	0.96 ± 6.5%	0.95 ± 8.4%	0.93 ± 9.6%
	cd							
U238f	bare							1.16 ± 15.%
	cd	1.047 ± 9.3%						1.06 ± 15.%
	fiss	1.04 ± 9.3%	0.98 ± 4.9%	1.07 ± 14.7%	1.02 ± 4.0%		0.94 ± 4.2%	1.25 ± 15.%
Ti47p	bare		0.98 ± 4.7%	1.05 ± 13.6%	0.98 ± 4.7%	0.98 ± 4.7%	0.97 ± 5.0%	1.03 ± 11.%
	cd	1.10 ± 10.2%						
S32p	bare	0.99 ± 11.8%	0.99 ± 5.1%	1.02 ± 15.0%	1.02 ± 5.1%	1.01 ± 5.1%	0.92 ± 5.1%	1.05 ± 13.%
	cd							
Zn64p	bare		0.96 ± 4.8%		0.99 ± 4.7%	0.99 ± 4.6%	0.97 ± 14.%	1.00 ± 12.%
	cd	1.08 ± 11.8%						
Fe54p	bare		0.96 ± 4.2%	1.05 ± 14.4%	1.01 ± 4.5%	0.99 ± 4.0%	1.01 ± 4.2%	1.02 ± 12.%
	cd	1.05 ± 11.8%						
Al27p	bare					0.95 ± 4.4%		
	cd	1.138 ± 14.%						
Co59p	bare	0.98 ± 14.5%		1.02 ± 17.1%		0.99 ± 5.2%		
	cd		1.02 ± 7.2%		1.00 ± 5.0%		0.96 ± .8%	
Ti46p	bare		1.01 ± 4.7%	1.06 ± 17.5%	1.04 ± 4.4%	1.04 ± 4.4%	1.05 ± 5.5%	1.03 ± 13.%
	cd	1.05 ± 14.7%						
Ni60p	bare		1.01 ± 6.6%	1.05 ± 18.3%				
	cd				0.98 ± 5.0%			
Cu63a	bare	0.97 ± 16.2%			0.83 ± 9.0%			
	cd					0.90 ± 6.1%		
Fe56p	bare		0.98 ± 4.8%	1.06 ± 18.1%	1.00 ± 4.8%	1.00 ± 4.7%	1.04 ± 6.3%	1.09 ± 15.%
	cd	1.08 ± 17.1%						
Ti48p	bare		1.05 ± 5.2%	1.06 ± 18.5%	1.05 ± 5.1%	1.04 ± 5.0%	1.07 ± 5.9%	1.09 ± 15.%
	cd	1.11 ± 17.0%						
Mg24p	bare		1.04 ± 5.0%		1.09 ± 4.7%	1.05 ± 4.8%	1.11 ± 6.6%	1.13 ± 16.%
	cd	1.12 ± 18.9%						
Al27a	bare		1.02 ± 4.9%	1.06 ± 20.5%	1.04 ± 4.8%	1.06 ± 4.6%	1.08 ± 6.4%	1.06 ± 16.%
	cd	1.07 ± 18.0%						
Nb932	bare	1.11 ± 20.9%	0.97 ± 5.1%	1.10 ± 16.3%	1.07 ± 4.8%	0.99 ± 5.0%	1.08 ± 6.8%	1.12 ± 17.%
	cd							
Co592	bare	1.09 ± 19.9%		1.21 ± 23.7%		1.05 ± 19.%		
	cd				1.08 ± 19.%			
Mn552	bare	1.001 ± 26.%		1.12 ± 29.5%	1.02 ± 26.%	1.10 ± 17.%		
	cd						1.11 ± 16.%	
	fiss	1.13 ± 24.7%						
Zr902	bare		1.08 ± 9.4%		1.09 ± 8.4%	1.05 ± 8.2%	1.00 ± 9.5%	1.02 ± 16.%
	cd	1.14 ± 18.8%						
Ni582	bare	1.02 ± 19.8%						
	cd				1.12 ± 11.%			

Three reactions in the IRDFF-II library were flagged with a poor status in any one of the first six neutron fields, i.e., Ag109g, Na23g, and Co59g [Mo98g had a poor status but was not included in the IRDFF-II library as it did not have a dosimetry-quality cross section with covariance matrix]. However, five reactions in the 15.24 cm (6-inch) FBR leakage field were flagged as “poor”. This indicates that the spectrum characterization in this field should be re-examined. In this spectrum characterization, foil exposures were fielded on different legs of the 3-legged exposure fixture – locations that were expected to represent equivalent positions based upon geometric considerations. However, it is possible that the

small differences in the reactor control-rod configuration during the reactor operation invalidated this assumption of an identical exposure symmetry and may have invalidated the assumption of equal spectra in each of the three legs of the test fixture.

In many of the cases where "poor" sensor status was indicated in Table 5, the same reaction had been fielded with two different covers – and only one of the configurations was flagged as poor. This suggests that the treatment of the cover correction should be reviewed in more detail. While a high-fidelity cover correction was used [5], the energy-dependent cover corrections need to be reviewed in more detail to verify that they correctly correspond to the modelled adjoint source geometry, e.g., foil thickness and impurity description. This reanalysis of the shielding correction factors is currently underway. Another possibility is that the lack of consideration in the methodology for the correlation between the same reaction as fielded with different covers was responsible for some of the conflict. While it is not easy to derive an *a priori* activity correlation between the sensors for these cases, a correlation can be derived *a posteriori* and then used to check on the sensitivity of the spectrum adjustment to this input correlation. Steps are underway to examine this possibility – along with a more in-depth study of the sensitivity of the spectrum adjustment to the general *a priori* activity correlation, e.g., based upon the uncertainty due to the energy efficiency calibration of the HPGe detector or in the uncertainty in the mass determination when using a single foil to obtain activities from different reactions. In addition, the sensitivity to the specific least squares code, the use of a Gaussian or a log-normal adjustment, and use of a finer 640-group energy structure as opposed to the current 89-group structure, are all aspects that are being examined in more depth.

While no dosimetry reaction stands out as discrepant in the composite collection of neutron fields, we see that there can be some conflict between thermal neutron sensitive sensors when the same reaction is fielded using different covers.

As seen from the Table 2 entries, the composite number of dosimetry reactions available in the ^{252}Cf(sf) and ^{235}U(th) benchmark fields exceeded the number of sensors gathered in any of the reactor fields. However, reactor fields were able to supply validation data for 14 reactions that were not addressed in existing ^{252}Cf(sf) data. If one were to look at reactor-based evidence that addresses reactions not examined in either the ^{252}Cf(sf) or ^{235}U(th) benchmark fields, there were 9 new reactions addressed, i.e., ^{23}Na(n,γ), ^{45}Sc(n,γ), ^{55}Mn(n,γ), ^{nat}Fe(n,X)^{54}Mn, ^{nat}Fe(n,X)^{56}Mn, ^{58}Fe(n,γ), ^{59}Co(n,γ), ^{109}Ag(n,γ), and ^{186}W(n,γ). So, the reactor validation testing served to increase our confidence in some of the capture reaction cross sections.

5 Conclusion

This analysis has extended the validation evidence for the IRDFF-II library to address measurements from seven different reactor-based reference benchmark neutron fields. Whereas the ^{252}Cf(sf) and ^{235}U(th) benchmark validation data typically just used the bare foils, this reactor-based testing has employed "covers" to shift the energy response of the sensor and provide additional validation evidence. While the use of "covers" on the foils increases the energy coverage of the sensors used for spectrum validation and yields good validation evidence, some issues associated with the methodology of using a given reaction with different "covers" in a single spectrum adjustment still need to be studied in more detail.

The use of a least squares approach improves our ability to address uncertainties in the neutron spectrum and provide validation evidence, in the form of C/E ratios, that have smaller uncertainty band than does the use of simple SACs or SI approaches when a consideration is given to the proper propagation of uncertainties.

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