DP-MS-76-8
CONF-760622--34

ENDF/B-IV THERMAL DATA TESTING: METHODS, RESULTS, AND RECOMMENDATIONS

by

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An invited paper to be presented to the 1976 Annual Meeting of the *American Nuclear Society* at Toronto. Ontario, Canada, on June 13-18, 1976.

ABSTRACT — The Evaluated Nuclear Data File/Library B (ENDF/B) provides a computer-oriented reference set of evaluated neutron cross sections for thermal and fast reactor applications, photon interactions cross sections, and photon production data. The current evaluations span the energy range from 0 to 20 MeV. This paper presents ENDF/B-IV data testing results from seven organizations on seventeen thermal benchmark experiments. Development and testing of ENDF/B-IV is the latest contribution of the Cross Section Evaluation Group. The file is maintained at, and released through, the National Neutron Cross Section Center at Brookhaven National Laboratory. The ENDF/B-IV predictions for uranium systems are an improvement over ENDF/B-III. Recommendations include extending the benchmark experiments to plutonium, urania, and thoria, and mixed oxide systems and prepare a revised library, ENDF/B-V.

This paper was prepared in connection with work under Contract No. AT(07-2)-1 with the U. S. Energy Research and Development Administration.

DISCLAIMER

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INTRODUCTION (SLIDE 1)

In this paper, I will be reporting on the ENDF/B-IV thermal data testing effort as carried on by the Cross Section Evaluation Working Group. Let me begin, however, by making a few remarks pertaining to the ENDF/B library itself, since some of you may not be acquainted with it.

ENDF/B is an acronym for Evaluated Nuclear Data File/Library B. This library provides a computer-oriented reference set of evaluated neutron cross sections for thermal and fast reactor applications. Library B is distinguished from Library A (which contains partial or multiple evaluations of a particular nuclide) and is used primarily by cross section measurers and evaluators. ENDF/B contains only one evaluation for each material in the library, but each material contains cross sections for all significant reactions. The library contains neutron cross section data and other related nuclear constants, as well as

† The information contained in this article was developed during the course of work under Contract No. AT(07-2)-1 with the U. S. Energy Research and Development Administration.

photon interaction cross sections and photon production data (photons produced by neutron interactions). For generality, the cross sections are stored with the energy variable specified in a continuous (pointwise) form, rather than a particular multigroup structure. Current ENDF/B evaluations span the energy range from 0 to 20 MeV.

New versions of ENDF/B have been released at about a frequency of one every two years to improve its applicability; ENDF/B-IV, the latest version, was released in 1974. Development and testing of ENDF/B are performed by the Cross Section Evaluation Working Group, which is composed of scientists from universities and laboratories throughout the United States and Canada. The file is maintained at, and released through, the National Neutron Cross Section Center at Brookhaven National Laboratory.

One of the activities of the Cross Section Evaluation Working Group (CSEWG) is testing differential ENDF/B cross sections in integral benchmark experiments. In this paper, I will be presenting the ENDF/B-IV data testing results as obtained by the CSEWG Data Testing Subcommittee. These results provide a) a basis for evaluating the merit of ENDF/B-IV in the analysis of thermal systems, and b) a reference to assist evaluators in the development of improved thermal neutron data for ENDF/B-V.

SUMMARY

The ENDF/B-IV calculations for thermal systems were performed by personnel from seven organizations (SLIDE 2): Floyd Wheeler (ANC); Jud Hardy (BAPL); Wolfgang Rothenstein (BNL); Don Craig (CRNL); Odelli Ozer (EPRI); Don Mathews (GA); and Don Finch and myself (SRL).

Seventeen thermal benchmark experiments have been analyzed (SLIDE 3). All the experiments were made at room temperature and were free of fission products. The seventeen experiments were in three categories:

- Five unreflected spheres or uranyl nitrate (93 wt % ^{235}U) solution were analyzed to test the H_2O and ^{235}U cross sections. The ENDF/B-IV calculations for the spheres yielded values of k_{eff} about 0.1% below experiment for the smaller spheres and about 0.3% below experiment for the largest sphere.
- Four H_2O-moderated lattices of slightly enriched uranium rods and three D_2O-moderated lattices of natural uranium rods were analyzed to test the ^{238}U thermal and resonance region capture cross sections in addition to the ^{235}U and moderator cross sections.

  The most rigorous calculations for the H_2O-moderated lattices yielded reasonably good predictions of criticality and measured activation parameters. Typically, however, k_{eff} is somewhat underpredicted, and epithermal ^{238}U capture is overpredicted.

The D_2O-moderated lattices are not as well predicted; on an average, k_{eff} is about 1% low, although epithermal ^{238}U capture is well-predicted. There are significant differences in the values reported by the laboratories for both the H_2O- and D_2O-moderated lattices.

- Five unreflected spheres of plutonium nitrate solutions were analyzed to test the ^{239}Pu cross sections. The calculated values for k_{eff} are typically 1 to 2% above experimental values. Differences between ENDF/B-III and ENDF/B-IV are small.

Now these ENDF/B-IV thermal data testing results will be discussed in more detail. In addition, comparisons of intermediate results, namely, the processed multigroup libraries and calculated fewgroup reaction rates for one of the H_2O-moderated lattices, will be discussed. These comparisons are made to better isolate the effects that data and calculational methods have on calculated integral parameters. This short presentation will only highlight the ENDF/B-IV thermal data testing. A full report of ENDF/B-IV data testing methods, results, and recommendations can be obtained through Brookhaven National Laboratory under document number ENDF-203.[1]

DISCUSSION

Measured Integral Parameters

Unreflected Spheres of Uranyl Nitrate Solution (SLIDE 4)

CSEWG benchmark experiments ORNL-1, -2, -3, -4, and -10 refer to well-documented experiments performed in the early 1960's by R. Gwin and D. W. Magnuson,[2] in which critical compositions were determined for aqueous solutions of ^{235}U in spherical geometry. Complete specifications for these and all other CSEWG benchmark experiments are given in Reference 3. The first four benchmark experiments (SLIDE 4) have the same critical radius, but have $H/^{235}U$ ratios which vary as a function of boric acid content. Benchmark experiments ORNL-1 and ORNL-10 contain no boron. These ORNL experiments were reanalyzed in 1968 by Alan Staub, D. R. Harris, and Mark Goldsmith of BAPL to include small corrections for the presence of the aluminum container, departures from sphericity, and room return.[4] The corrected measurements are useful for testing H_2O fast-scattering data, the ^{235}U fission spectrum, thermal capture and fission of ^{235}U, and thermal absorption of hydrogen. Incidently, prior to these benchmark calculations, the $S(\alpha,\beta)$ thermal-scattering law data for ENDF/B-IV moderators had been tested and found satisfactory for predicting measured integral parameters associated with the diffusion length and pulsed neutron experiments.[5]

The ANC, GA, and SRL results were obtained using S_n theory. The BAPL calculations were P_3 epithermally and double P_1 thermally with Marshak boundary conditions.

The good prediction of criticality for the uranyl (93 wt % ^{235}U) nitrate solutions in Slide 4 implies there are no major deficiencies in the H_2O and ^{235}U cross sections for thermal systems. ENDF/B-IV predictions of criticality for these spheres are about 0.2% higher than ENDF/B-III (in closer agreement with the measurements). The closer agreement can be attributed to the ENDF/B-IV revisions to the ^{235}U cross sections based on the least-squares analysis reported by J. R. Stehn.[6]

Uranium Lattices (SLIDE 5)

Benchmark experiments TRX-1, -2, -3, and -4 correspond to lattices described by J. Hardy, Jr.[7] These lattices contain slightly enriched (1.3%) uranium rods with diameters of 0.4915 cm. Benchmark experiments MIT-1, -2, and -3 are well-documented D_2O lattice experiments performed in the early 1960's at MIT under the Heavy Water Lattice Project.[8] The MIT experiments were performed in a subcritical exponential facility and involved D_2O-moderated lattices of natural uranium rods with diameters of 2.565 cm. In addition to material bucklings, the TRX and MIT series of experiments determined several important activation parameters:

ρ^{28} = The ratio of epithermal-to-thermal ^{238}U captures.

δ^{25} = The ratio of epithermal-to-thermal ^{235}U fissions.

δ^{28} = The ratio of ^{238}U fissions to ^{235}U fissions.

These benchmark experiments directly test the thermal and epithermal cross sections for ^{238}U capture and ^{235}U fissions and the ^{238}U fast fission cross section. They are sensitive to ^{238}U inelastic scattering, the ^{235}U fission spectrum, and the moderator cross sections. By way of comparison, these lattices have a softer neutron spectrum than the lattice of a typical pressurized water reactor (PWR). Thus, for a PWR, the ratio of epithermal-to-thermal ^{235}U fissions is three times greater than for the TRX-1 lattice, which, with the exception of TRX-3, has the hardest spectrum of the benchmark experiment shown in SLIDE 5.

The ENDF/B-IV predictions of criticality for the H_2O-moderated lattices of slightly enriched uranium rods and the D_2O-moderated lattices of natural uranium rods vary appreciably from one laboratory to another. Taken collectively, however, they indicate k_{eff} is underpredicted by approximately 1%; the underprediction is about 0.5% for the more-moderated lattices and increases to about 1.5% as the moderator-to-fuel ratio decreases.

The variations in k_{eff} among the various laboratories are due primarily to widely differing methods of calculations (SLIDE 6):

ANC - The TRX lattices were calculated using S_n theory and the RABBLE resonance treatment.

BAPL - The lattice calculations were fully Monte Carlo for the infinite lattice with subsequent leakage corrections based on B_1 calculations.

BNL - The lattices were calculated using the HAMMER integral transport theory code, but the standard Nordheim treatment was replaced by a Monte Carlo resonance treatment.

CRNL - The lattices were calculated using HAMMER with the Nordheim resonance treatment.

EPRI - Benchmark experiment TRX-1 was calculated using HAMMER; the Nordheim resonance treatment was replaced by RABBLE.

GA - The TRX and MIT lattices were calculated using S_n theory with resonance region cross sections obtained from GAND3 and MICROX calculations with two space regions.

SRL - The TRX and MIT lattices were calculated using integral transport theory with the Nordheim resonance treatment. The zero leakage integral transport results were leakage-corrected by subsequent B_1 calculations.

SRL* - The lattices were calculated using the same methods described just above except the Nordheim treatment was replaced by a more-accurate method developed by D. R. Finch.

When the results of all the laboratories are averaged, ρ^{28} is 3 to 5% too high for the H_2O lattices and less than 2% above the measurements for the D_2O lattices (SLIDE 7). The experimental values for the activation parameters on this and the subsequent slides have been revised to be consistent with the recent preliminary corrections reported by Sher, et al.[9] These experimental values may be adjusted further based on additional work by Sher, et al. at Stanford and by Hardy at BAPL. The calculated and measured values of ρ^{28} correspond to a thermal cutoff energy of 0.625 eV. Thus, the observed underprediction of k_{eff} is traceable, at least in part, to an overprediction of epithermal ^{238}U capture. Background of this problem is documented in the proceedings of the March 18-20, 1975, *Seminar on ^{238}U Resonance Capture*, held at BNL, during which the accuracy of the ρ^{28} measurements, ^{238}U differential cross sections measurements, and calculational methods were reviewed.[10]

From this and the preceding slide, residual deficiencies in the ^{238}U resonance region cross sections may occur; however, the most pressing need is to establish the "correct" calculational method. For example, BAPL yields values of k_{eff} that are about 0.7% higher than the average for the H_2O-moderated lattices, whereas ANC and CRNL yield values about 0.5% lower than the average. The BNL calculations of ρ^{28} for the four H_2O-moderated lattices are in general agreement with measurements (even though predictions of criticality are about 1% low). The BAPL and SRL* calculations of ρ^{28} are generally within two standard deviations of the measured ρ^{28} values, and k_{eff} is predicted reasonably close to unity.

When the results from the various laboratories are averaged, the calculated δ^{25} for the TRX lattices are in good agreement with measurement (SLIDE 8). There are, however, significant differences in the reported values of the individual laboratories: CRNL is about 10% higher than experiment, whereas SRL* is about 6% below experiment. For the MIT lattices, averaging the calculated δ^{25} of the various laboratories yields severe overpredictions: 6% for MIT-1 and approximately 20% for MIT-2 and -3. These overpredictions primarily follow from the CRNL and SRL calculations that do not include the effects of shielding of the ^{235}U resonances. The BNL, GA, and SRL* calculations accurately account for this effect and are not far outside the precision of the measurements.

in SLIDE 9, δ^{28} is well-predicted for the H_2O-moderated lattices if the results from the various laboratories are averaged, and is underpredicted significantly for the D_2O-moderated lattices (about 5% for MIT-1, 10% for MIT-2, and 14% for MIT-3). The ENDF/B-IV calculations for δ^{28} are 4 to 5% higher than ENDF/B-III because of the decrease in the ^{238}U inelastic scattering cross section between 1 and 5 MeV.

Overall, the ENDF/B-IV results for the benchmark lattices are in better agreement with experiment than ENDF/B-III; prediction of k_{eff} is almost 1% higher than ENDF/B-III, and ρ^{28} is reduced nearly 5%.

Unreflected Spheres of Plutonium Nitrate Solutions (SLIDE 10)

This slide, describing ENDF/B-IV integral benchmark results, summarizes calculated eigenvalues for five unreflected spheres of plutonium nitrate solution. The first two benchmark experiments in the series were performed by R. C. Lloyd, et al., at Battelle-Northwest in 1966.[11] Benchmark experiments PNL-3, -4, and -5 were performed by F. E. Kruesi, et al., at Hanford in 1952.[12] These experiments, which have hydrogen-to-^{239}Pu atom ratios ranging from 124 to 1204, are useful for testing H_2O scattering data, cross sections for thermal neutron capture and fission by ^{239}Pu, and the ^{239}Pu fission spectrum. Although their inventories are not defined as precisely as more recent experiments, the simplicity of these bare, homogeneous spheres makes them particularly attractive for calculational benchmarks.

The calculated values of k_{eff} for the plutonium nitrate solutions are 1 to 2% above experimental values. The ANC and GA calculations are in excellent agreement with each other, whereas the SRL results tend to be higher. The ANC, GA, and SRL results were each obtained using the S_4 approximation and multigroup cross sections with P_1 scattering. The explanation for the large difference between the ANC/GA result and the SRL result for PNL-2 is being sought. ENDF/B-II calculations reported by L. E. Hansen and E. D. Clayton yielded higher values of k_{eff} for PNL-2 than for PNL-1, which are consistent with the ENDF/B-IV SRL results.[13] The overprediction of k_{eff} increases as the thermal neutron spectrum hardens. The ENDF/B-IV criticality predictions are somewhat higher than for ENDF/B-III (and ENDF/B-II) due to revisions to the thermal cross sections based on the least-squares analysis reported in Reference 6.

Comparison of Fewgroup Reaction Rates and Multigroup Libraries

To help resolve the origin of the discrepancies among the calculated results, the thermal data testing participants also supplied supplemental fewgroup information for benchmark experiment TRX-1, and edits of the fast and thermal multigroup cross section libraries.

SLIDE 11 is an example of the TRX-1 fewgroup edits. These consist of zero-leakage and leakage-corrected, 4-group reaction rates for $^{235,238}U$ captures and fissions; H, D, ^{16}O, and ^{27}Al captures; and the slowing down source Q. For each energy group there are two columns in the tables: the left column is the reaction rate normalized to be consistent with a thermal ^{235}U fission rate of unity; the right column is the reaction rate divided by the corresponding SRL reaction rate. The upper energy boundaries for the 4-group structure are 10 MeV, 67.379 keV, 3.355 keV, and 0.625 eV. These boundaries are compatible with the MUFT 54-group structure and were selected to match closely the boundaries of the fast cross sections, the unresolved and resolved resonance regions, and the thermal cross sections in the ENDF/B-IV ^{238}U evaluation.

To test the ENDF/B cross section processing codes, multigroup cross section edits for room temperature hydrogen as bound in H_2O, deuterium as bound in D_2O, ^{16}O, ^{27}Al, ^{235}U, and ^{238}U have been compared for the energy bands of the first and fourth groups of the 4-group structure. The fast multigroup structure (Fewgroup 1) consists of the first 20 MUFT groups above 67.379 keV (E_{max} = 10 MeV, 0.25 lethargy intervals); the thermal multigroup structure (Fewgroup 4) consists of the familiar 30-group THERMOS structure.

SLIDE 12 lists the various quantities which are edited for the top 20 MUFT groups. SLIDE 13, which is for the ^{238}U inelastic scattering cross section is an example of one of these edits. In this slide, the SRL cross section is about 10% lower than the ANC, BAPL, and CRNL cross sections. This reduction is caused by the flat weighting spectrum used in the SRL cross section processing. The other laboratories used a more-realistic spectrum weighting that consisted of the fission spectrum coupled to the 1/E energy dependence in the slowing-down region. The BNL cross sections in Groups 1 and 2 are very much larger than those of the other laboratories because of the BNL method for accounting for (n,2n) reactions.

For the 30 THERMOS groups, the neutrons/fission ($\bar{\nu}$) and the fission, capture, and scattering cross sections are edited. SLIDE 14, which is for the deuterium capture cross section, is an example. In this case, the SRL and BNL cross sections differ by 10 to 30%, agreement worsening as energy increases. The SRL cross sections properly match the ENDF/B evaluation. The BNL underestimation has a negligible effect on lattice reactivities because nearly all the captures take place in the uranium and its cladding.

Full documentation of the findings of the comparisons of the fewgroup reaction rates and multigroup libraries is given in ENDF-203.[1] For the most part, the discrepancies are of the type seen on the previous slides, and should be easy to rectify by regenerating the multigroup libraries. Hopefully, after this iteration, the intermediate calculational results and the prediction of the measured integral parameters will both be brought into better agreement.

The most notable differences, however, are in the predictions of ^{238}U resolved resonance capture (SLIDE 15). The differences in k and ρ^{28} observed earlier can be largely attributed to the differences seen on this slide. These differences in ^{238}U resolved resonance capture are more difficult to rectify, since they undoubtedly arise from (a) the different approximations in the various resonance self-shielding models themselves, and (b) the different methods used to incorporate the self-shielding information into the transport calculations. Such differences are difficult to track down and usually involve abandonment of the approximations for more rigor and greater computational cost.

CONCLUSIONS (SLIDE 16)

ENDF/B-IV predictions of the measured integral parameters are significantly improved over those of ENDF/B-III for the uranium systems. These improvements are due primarily to (a) the revisions of the ^{235}U thermal data which raised predictions of k_{eff} for the uranyl nitrate spheres by 0.2%, and (b) the revisions of the ^{238}U resonance capture cross sections (Reference 10, p 122) which raised k_{eff} for the lattices by about 1% and reduced ρ^{28} nearly 5%. Limited testing of the plutonium cross sections has yielded values of k_{eff} that are 1 to 2% high (similar to the ENDF/B-III results).

The differences between the calculational methods are significant. The ENDF/B-IV predictions compared with the measured values of the uranium benchmark experiments are quite close. Effects of uncertainties in the unnormalized calculational methods and in the integral parameter measurements (e.g., ρ^{28}, δ^{25}, and δ^{28}) are becoming as significant as the differences reported for the cross sections themselves.

RECOMMENDATIONS (SLIDE 17)

To ensure continued meaningful testing of the differential data for succeeding ENDF/B versions, the Data Testing Subcommittee of CSEWG should determine the most accurate available calculation method, establish its expected uncertainties in predicting integral parameters, and use this calculation in reporting the results and recommendations of ENDF/B data testing. Processed cross section libraries and intermediate results of the calculations should be checked by the members of CSEWG as a safeguard against errors in processing. Results of more-approximate calculations should also be included in the data testing report to provide a measure of sensitivity to calculational methods.

To define better the measurements of the lattice benchmark experiments, work such as that being done by the groups at Stanford and BAPL should continue.

The range of CSEWG thermal benchmark experiments should be extended to include:

- More experiments for testing plutonium cross sections.
- Uranium oxide and mixed oxide (uranium-plutonium) lattices in H_2O.
- Thorium oxide lattices in H_2O, D_2O, and graphite.

In planning for ENDF/B-V, I recommend that every effort be made to factor in the result of the ^{238}U self-indication transmission measurements in progress at ORNL and RPI. All currently available differential cross section measurements correspond to the infinitely dilute case, not to the heavily self-shielded cases encountered in the integral benchmark experiments. The measurements therefore pertain primarily to the peaks of the cross sections and not to the wings of the resonances where a significant number of the ^{238}U reactions occur. The self-indication transmission measurements would supply differential information for heavily self-shielded cases.

To permit full utilization of the G. de Saussure, et al. ^{238}U capture data,[14] I recommend that this high precision differential data be cast into resonance parameter form. The required neutron widths could be taken from the Columbia transmission measurements[15] or from new transmission experiments that could be performed at the Oak Ridge Electron Linear Accelerator (ORELA).

The shapes of the thermal cross sections for the fissile nuclides ^{233}U, ^{235}U, ^{239}Pu, and ^{241}Pu should be re-evaluated for ENDF/B-V in addition to σ_{2200} values. The least-squares analysis for ENDF/B-IV thermal parameters assumed the same g-factors as the 1969 IAEA review.[6] The need to reanalyze the cross section shapes is indicated, especially in the ENDF/B integral data tests for thermal plutonium systems where k is typically overpredicted by 1 to 2%.

The ENDF/B-V ^{238}U evaluation should avoid the negative scattering cross sections that occur in certain interference valleys of ENDF/B-IV through the use of bound levels, e.g., the picket fence model,[16] and a multilevel resonance formulation.

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SLIDE 1

ENDF/B

- Evaluated Nuclear Data File/Library B
- Computer-oriented
- σ_n, angular and energy distribution of secondary neutrons, FP yields, λ
- Photon interaction and photon production cross sections
- Pointwise rather than multigroup; 0 to 20 MeV
- Developed and tested by CSEWG
- Maintained at NNCSC

SLIDE 2

PARTICIPATING ORGANIZATIONS

- AEROJET NUCLEAR CO. (ANC)
- BETTIS ATOMIC POWER LABORATORY (BAPL)
- BROOKHAVEN NATIONAL LABORATORY (BNL)
- CHALK RIVER NUCLEAR LABS. (CRNL)
- ELECTRIC POWER RESEARCH INSTITUTE (EPRI)
- GENERAL ATOMIC COMPANY (GA)
- SAVANNAH RIVER LABORATORY (SRL)

SLIDE 3

ENDF/B-IV BENCHMARK RESULTS

- UNREFLECTED SPHERES OF URANYL NITRATE SOLUTIONS

  SMALL SPHERES: k_{eff} ∿0.1% LOW

  LARGEST SPHERE: k_{eff} ∿0.3% LOW

- H_2O- AND D_2O-MODERATED URANIUM LATTICES

  H_2O: REASONABLY WELL PREDICTED

  D_2O: k_{eff} ∿1% LOW

- UNREFLECTED SPHERES OF PLUTONIUM NITRATE SOLUTION

  k_{eff} 1 to 2% HIGH

SLIDE 4

URANYL NITRATE SPHERES (ENDF/B-IV)

			k_{eff}			
BENCHMARK	RADIUS, cm	$H/^{235}U$	ANC	BAPL	GA	SRL
ORNL- 1	34.595	1378	1.0025	0.9983	1.0012	0.9996
ORNL- 2	34.595	1177	1.0018	0.9980	1.007	
ORNL- 3	34.595	1033	0.9984	0.9949	0.9978	
ORNL- 4	34.595	971	0.9998	0.9963	0.9989	0.9976
ORNL- 10	61.011	1835	0.9988	0.9957	0.9982	0.9951

SLIDE 5

CRITICALITY OF URANIUM LATTICES (ENDF/B-IV)

A. H_2O-Moderated Lattices

BENCHMARK	MOD/FUEL	k_{eff} ANC	BAPL	BNL	CRNL	EPRI	GA	SRL	SRL*
TRX-1	2.35	0.9827	0.9954	0.9880	0.9824	0.9903	0.9855	0.9871	0.9921
TRX-2	4.02	0.9893	0.9996	0.9921	0.9898		0.9961	0.9924	0.9967
TRX-3	1.00		0.9965	0.9935					
TRX-4	8.11		0.9962	0.9974					

B. D_2O-Moderated Lattices

BENCHMARK	MOD/FUEL	k_{eff} BNL	CRNL	GA	SRL	SRL*
MIT-1	20.74	0.9825	0.9829	0.9972	0.9851	0.9912
MIT-2	25.88	0.9807	0.9829	1.0006	0.9856	0.9902
MIT-3	34.59	0.9820	0.9850	1.0076	0.9879	

SLIDE 6

METHODS

LABORATORY	NEUTRON TRANSPORT METHOD (CODE)	RESONANCE SELF-SHIELDING
ANC	S_n (SCAMP)	RABBLE
BAPL	MONTE CARLO (RCP)	MONTE CARLO
BNL	INTEGRAL (HAMMER)	MONTE CARLO
CRNL	INTEGRAL (HAMMER)	NORDHEIM
EPRI	INTEGRAL (HAMMER)	RABBLE
GA	S_n (DTF-IV)	GAND3/MICROX
SRL	INTEGRAL (RAHAB)	NORDHEIM
SRL*	INTEGRAL (RAHAB)	METHOD OF D. R. FINCH

SLIDE 7

RATIO OF EPITHERMAL-TO-THERMAL ^{238}U CAPTURES

BENCH-	ρ^{28}								
MARK	EXP	ANC	BAPL	BNL	CRNL	EPRI	GA	SRL	SRL*
TRX-1	1.324 ±0.020	1.426	1.362	1.367	1.433	1.344	1.407	1.402	1.365
TRX-2	0.842 ±0.015	0.8903	0.859	0.846	0.882		0.881	0.858	0.839
TRX-3	3.027 ±0.05		3.19	3.07					
TRX-4	0.485 ±0.01		0.500	0.491					
MIT-1	0.523 ±0.008			0.502	0.528		0.529	0.541	0.515
MIT-2	0.419 ±0.002			0.413	0.433		0.431	0.443	0.422
MIT-3	0.330 ±0.004			0.318	0.337		0.331	0.344	

SLIDE 8

RATIO OF EPITHERMAL-TO-THERMAL ^{235}U FISSIONS

BENCH-	δ^{25}								
MARK	EXP	ANC	BAPL	BNL	CRNL	EPRI	GA	SRL	SRL*
TRX-1	0.0995 ±0.001	0.1005	0.0992	0.0993	0.111	0.0966	0.0982	0.1014	0.0946
TRX-2	0.0622 ±0.0007	0.0615	0.0610	0.0611	0.067		0.0606	0.0617	0.0577
TRX-3	0.232 ±0.003		0.244						
TRX-4	0.0365 ±0.0004		0.0353						
MIT-1	0.0465 ±0.0019			0.0466	0.0520		0.0469	0.0534	0.0475
MIT-2	0.0328 ±0.003			0.0380	0.0424		0.0382	0.0436	0.0390
MIT-3	0.0266 ±0.0010			0.0297	0.0327		0.0293	0.0336	

SLIDE 9

RATIO OF ^{238}U FISSIONS TO ^{235}U FISSIONS

BENCH-MARK	δ^{28}								
	EXP	ANC	BAPL	BNL	CRNL	EPRI	GA	SRL	SRL*
TRX-1	0.0934 ±0.0020	0.0957	0.0948	0.0939	0.0937	0.0940	0.0965	0.0959	0.0935
TRX-2	0.0687 ±0.002	0.0691	0.0678	0.0663	0.0661		0.0700	0.0680	0.0645
TRX-3	0.165 ±0.004		0.177						
TRX-4	0.0472 ±0.0007		0.0477						
MIT-1	0.0617 ±0.0020			0.0570	0.0554		0.0607	0.0591	0.0618
MIT-2	0.0630 ±0.0017			0.0554	0.0539		0.0585	0.0570	0.0600
MIT-3	0.0631 ±0.0012			0.0539	0.0527		0.0559	0.0552	

SLIDE 10

PLUTONIUM NITRATE SPHERES (ENDF/B-IV)

BENCHMARK	RADIUS, cm	H/^{239}Pu	k_{eff}		
			ANC	GA	SRL
PNL-1	19.509	698	1.0232	1.0225	1.0289
PNL-2	19.509	124	1.0196	1.0201	1.0354
PNL-3	22.700	1204	1.0028	1.0021	1.0029
PNL-4	22.700	911	1.0105	1.0102	1.0123
PNL-5	20.126	578	1.0160	1.0169	1.0227

SLIDE 11

NORMALIZED REACTION RATES FOR FISSION

ISOTOPE/LAB		GROUP 1		GROUP 2		GROUP 3		GROUP 4	
^{235}U	ANC	0.008407	1.016781	0.004089	1.051836	0.086038	0.997339	1.000000	1.000000
	BAPL	0.008284	1.001962	0.004062	1.044989	0.084102	0.974901	1.000000	1.000000
	BNL	0.008195	0.991148	0.004100	1.054673	0.084337	0.977617	1.000000	1.000000
	CRNL	0.008550	1.034077	0.004677	1.203155	0.096481	1.118396	1.000000	1.000000
	EPRI								
	SRL	0.008268	1.000000	0.003887	1.000000	0.086268	1.000000	1.000000	1.000000
	SRL*	0.008001	0.967711	0.003828	0.984778	0.079936	0.926603	1.000000	1.000000
^{238}U	ANC	0.097791	0.991712	0.0	0.0	0.0		0.0	
	BAPL	0.097215	0.985873	0.0	0.0	0.0		0.0	
	BNL	0.096497	0.978588	0.00005	0.850937	0.0		0.0	
	CRNL	0.100204	1.016186	0.00005	0.864339	0.0		0.0	
	EPRI								
	SRL	0.098608	1.000000	0.00006	1.000000	0.0		0.0	
	SRL*	0.095517	0.968650	0.00005	0.844460	0.00005		0.0	

NORMALIZED REACTION RATES FOR NU*FISSION

ISOTOPE/LAB		GROUP 1		GROUP 2		GROUP 3		GROUP 4	
^{235}U	ANC								
	BAPL	0.021604	1.003143	0.009837	1.044957	0.203424	0.974883	2.418789	0.999994
	BNL	0.021327	0.990266	0.009927	1.054514	0.203994	0.977619	2.418797	0.999998
	CRNL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	EPRI	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	SRL	0.021537	1.000000	0.009413	1.000000	0.208655	1.000000	2.418802	1.000000
	SRL*	0.020840	0.967646	0.009271	0.984852	0.193352	0.926616	2.418800	0.999999
^{238}U	ANC								
	BAPL	0.274011	0.986593	0.0		0.0		0.0	
	BNL	0.271819	0.978698	0.000012	1.063671	0.0		0.0	
	CRNL								
	EPRI								
	SRL	0.277765	1.000000	0.000012	1.000000	0.000009	1.000000	0.0	
	SRL*	0.269070	0.968802	0.000012	1.055574	0.000010	1.125946	0.0	

SLIDE 12

QUANTITIES EDITED (20 MUFT GROUPS)

Symbol	Cross Section Type
σ_{el}	elastic scattering, barns
σ_c	capture, barns
σ_f	fission, barns
σ_{in}	inelastic scattering, barns
$\sigma_{n,2n}$	(n,2n), barns
$\bar{\mu}$	cos. scattering angle (lab.)
$\bar{\nu}$	neutrons/fission
χ	fission spectrum

SLIDE 13

COMPARISON OF FAST CROSS SECTIONS FOR ^{238}U ----- INELASTIC

Group	SRL	ANC	BAPL	BNL	CRNL
1	0.5575E 00	0.6210E 00	0.6219E 00	0.3348E 01	0.6160E 00
2	0.1653E 01	0.1824E 01	0.1850E 01	0.2557E 01	0.1807E 01
3	0.2484E 01	0.2492E 01	0.2491E 01	0.2490E 01	0.2490E 01
4	0.2503E 01	0.2502E 01	0.2502E 01	0.2502E 01	0.2502E 01
5	0.2509E 01	0.2509E 01	0.2509E 01	0.2509E 01	0.2509E 01
6	0.2493E 01	0.2493E 01	0.2493E 01	0.2493E 01	0.2493E 01
7	0.2500E 01	0.2501E 01	0.2501E 01	0.2500E 01	0.2501E 01
8	0.2585E 01	0.2586E 01	0.2586E 01	0.2585E 01	0.2585E 01
9	0.2444E 01	0.2441E 01	0.2443E 01	0.2445E 01	0.2445E 01
10	0.2144E 01	0.2143E 01	0.2136E 01	0.2145E 01	0.2146E 01
11	0.1950E 01	0.1949E 01	0.1951E 01	0.1953E 01	0.1952E 01
12	0.1751E 01	0.1752E 01	0.1751E 01	0.1753E 01	0.1753E 01
13	0.1554E 01	0.1555E 01	0.1551E 01	0.1556E 01	0.1557E 01
14	0.1350E 01	0.1351E 01	0.1346E 01	0.1353E 01	0.1352E 01
15	0.1776E 01	0.1177E 01	0.1175E 01	0.1179E 01	0.1179E 01
16	0.1034E 01	0.1035E 01	0.1033E 01	0.1036E 01	0.1036E 01
17	0.8946E 00	0.8958E 00	0.8928E 00	0.8975E 00	0.8977E 00
18	0.7011E 00	0.7032E 00	0.6978E 00	0.7066E 00	0.7062E 00
19	0.4692E 00	0.4710E 00	0.4664E 00	0.4731E 00	0.4730E 00
20	0.2853E 00	0.2868E 00	0.2830E 00	0.2884E 00	0.2883E 00

SLIDE 14

COMPARISON OF THERMAL CROSS SECTIONS FOR D-D_2O
----- CAPTURE

Group	SRL	BNL
1	0.5200E-02	0.4600E-02
2	0.2600E-02	0.2300E-02
3	0.1733E-02	0.1533E-02
4	0.1300E-02	0.1150E-02
5	0.1040E-02	0.9200E-03
6	0.8667E-03	0.7667E-03
7	0.7429E-03	0.6571E-03
8	0.6500E-03	0.5750E-03
9	0.5778E-03	0.5111E-03
10	0.5200E-03	0.4593E-03
11	0.4727E-03	0.4131E-03
12	0.4332E-03	0.3744E-03
13	0.3999E-03	0.3421E-03
14	0.3713E-03	0.3146E-03
15	0.3465E-03	0.2911E-03
16	0.3238E-03	0.2697E-03
17	0.3021E-03	0.2494E-03
18	0.2816E-03	0.2304E-03
19	0.2625E-03	0.2128E-03
20	0.2446E-03	0.1967E-03
21	0.2281E-03	0.1817E-03
22	0.2116E-03	0.1669E-03
23	0.1952E-03	0.1525E-03
24	0.1792E-03	0.1384E-03
25	0.1636E-03	0.1250E-03
26	0.1488E-03	0.1122E-03
27	0.1347E-03	0.1003E-03
28	0.1215E-03	0.8929E-04
29	0.1093E-03	0.7956E-04
30	0.9818E-04	0.7046E-04

SLIDE 15

^{238}U RESOLVED RESONANCE CAPTURE
(Differences from SRL)

ANC	1-1/2% lower
BAPL	6% lower
BNL	4% lower
CRNL	1-1/2% higher
EPRI	6% lower
SRL*	4-1/2% lower

SLIDE 16

CONCLUSIONS

- ENDF/B-IV improved over ENDF/B-III for uranium systems
  - Better ^{235}U thermal data
  - Better ^{238}U resonance parameters
- k_{eff} 1-2% high for plutonium systems (similar to ENDF/B-III)
- Significant differences between calculational methods

SLIDE 17

RECOMMENDATIONS

- Calculational Methods
  - Determine most accurate method
  - Establish uncertainties in calculations
- Benchmark Experiments
  - Further definition of lattice measurements
  - More experiments
- Differential Measurements
  - ^{238}U self indication transmission measurements
  - Cast ^{238}U ORNL capture measurements into resonance parameters
- Cross Section Evaluation
  - Re-evaluate thermal σ for fissile nuclides
  - Avoid negative scattering cross sections in resonance interference valleys