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**Monte Carlo Analysis of the Slightly Enriched
Uranium-D₂O Critical Experiment LTRIIA**

(AWBA Development Program)

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November 1981

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J. Hardy, Jr.
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Bettis Atomic Power Laboratory

Pittsburgh, Pennsylvania

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FOREWORD

The Shippingport Atomic Power Station located in Shippingport, Pennsylvania was the first large-scale, central-station nuclear power plant in the United States and the first plant of such size in the world operated solely to produce electric power. This program was started in 1953 to confirm the practical application of nuclear power for large-scale electric power generation. It has provided much of the technology being used for design and operation of the commercial, central-station nuclear power plants now in use.

Subsequent to development and successful operation of the Pressurized Water Reactor in the Atomic Energy Commission (now Department of Energy, DOE) owned reactor plant at the Shippingport Atomic Power Station, the Atomic Energy Commission in 1965 undertook a research and development program to design and build a Light Water Breeder Reactor core for operation in the Shippingport Station.

The objective of the Light Water Breeder Reactor (LWBR) program has been to develop a technology that would significantly improve the utilization of the nation's nuclear fuel resources employing the well-established water reactor technology. To achieve this objective, work has been directed toward analysis, design, component tests, and fabrication of a water-cooled, thorium oxide-uranium oxide fuel cycle breeder reactor for installation and operation at the Shippingport Station. The LWBR core started operation in the Shippingport Station in the Fall of 1977 and is expected to be operated for about 4 to 5 years or more. At the end of this period, the core will be removed and the spent fuel shipped to the Naval Reactors Expended Core Facility for a detailed examination to verify core performance including an evaluation of breeding characteristics.

In 1976, with fabrication of the Shippingport LWBR core nearing completion, the Energy Research and Development Administration, now DOE, established the Advanced Water Breeder Applications (AWBA) program to develop and disseminate technical information which would assist U.S. Industry in evaluating the LWBR concept for commercial-scale applications. The program is exploring some of the problems that would be faced by industry in adapting technology confirmed in the LWBR program. Information being developed includes concepts for commercial-scale prebreeder cores which would produce uranium-233 for light water breeder cores based on the technology developed to fabricate and operate the Shippingport LWBR core, and other information and technology to aid in evaluating commercial-scale application of the LWBR concept.

All three development programs (Pressurized Water Reactor, Light Water Breeder Reactor, and Advanced Water Breeder Applications) are under the technical direction of the Office of the Deputy Assistant Secretary for Naval Reactors of DOE. They have the goal of developing practical improvements in the utilization of nuclear fuel resources for generation of electrical energy using water-cooled nuclear reactors.

Technical information developed under the Shippingport, LWBR, and AWBA programs has been and will continue to be published in technical memoranda, one of which is this present report.

ABSTRACT

The Savannah River Laboratory LTRIIA slightly-enriched uranium-D₂O critical experiment was analyzed with ENDF/B-IV data and the RCP01 Monte Carlo program, which modeled the entire assembly in explicit detail. The integral parameters δ^{25} and δ^{28} showed good agreement with experiment. However, calculated K_{eff} was 2-3% low, due primarily to an overprediction of U238 capture. This is consistent with results obtained in similar analyses of the H₂O-moderated TRX critical experiments. In comparisons with the VIM and MCNP2 Monte Carlo programs, good agreement was observed for calculated reaction rates in the B²=0 cell.

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MONTE CARLO ANALYSIS OF THE SLIGHTLY ENRICHED
URANIUM-D₂O CRITICAL EXPERIMENT LTRIIA

I. INTRODUCTION

The LTRIIA critical experiment (Ref. 1), which was run at the Savannah River Laboratory, was designed to provide high-quality benchmark data for slightly-enriched (1.1 w/o) uranium-D₂O systems. It was a D₂O-moderated hexagonal assembly of 127 fuel rods on a 7.00-inch triangular pitch, surrounded by a ring of Li-6 rods (Figures 1 and 2). In each fuel rod there were two concentric nickel-coated uranium fuel rings contained between two aluminum cylinders (Figure 2). D₂O filled the annular gaps in the fuel rod assembly. The fuel was uniform axially and 66.648 inches high. Moderator height at critical, with control rods out, was 57.266 inches above the bottom of the fuel. Neutrons escaping from the lattice were captured in the Li-6 border and in a boron plate beneath the fuel, thus minimizing room return.

Measurements (Ref. 1) were made of material buckling (B_m^2) and detailed integral parameters at core center, including the epithermal/thermal ratio of U238 capture (ρ^{28}) and U235 fission (δ^{25}), the ratio of U238 fission to U235 fission (δ^{28}), the ratio of U238 capture to U235 fission (CR*), and the ratio of U238 capture to all fission ($C^\dagger$).

The experiment has been analyzed with ENDF/B-IV data by the RCP01 Monte Carlo program, including a full-core eigenvalue calculation. Section II of this report summarizes the analysis methods and compares calculated results with experiment.

Because the calculated K_{eff} was 2-3% low, the RCP01-calculated reaction rates were checked against two independent Monte Carlo programs, VIM and MCNP2. The latter programs gave reaction rates in excellent agreement with RCP01. (Section III).

FIGURE 1. RCP01 Representation of One-third of the Lattice

FIGURE 2. One-third of a Fuel Cell

Section IV reviews U238 capture and K_{eff} results obtained for the TRX H₂O-moderated slightly enriched uranium lattices. It is concluded that the low calculated K_{eff} for LTRIIA is due mostly to an overestimate of U238 resonance capture which is entirely consistent with a similar overestimate observed for the TRX lattices with ENDF/B-IV data.

Section V presents a number of data sensitivity results, and Section VI summarizes overall results and conclusions. A calculation of the U235 fission neutron age to 1.46 eV in D₂O is described in the Appendix.

II. ANALYSIS METHODS AND RESULTS

The LTRIIA experiment was analyzed by two methods. In the first, a Monte Carlo calculation with the RCP01 program (Ref. 2), the entire assembly was represented explicitly in three dimensions out to, and including the vessel. The only approximations made in the geometry description were small and considered insignificant. They involved homogenization of some of the support structure with surrounding materials. Four independent full-core calculations, of 66000 histories each, were run and then averaged to obtain reaction rates and eigenvalues. A short calculation was run initially to provide a starting source guess.

The full-core calculations were arranged so that an asymptotic region in the center could be edited. Radially, this region comprised the center cell and the two innermost hexagonal rings; axially it spanned the central portion of the fuel, extending approximately 12.4 inches above and below axial center. Integral parameters were calculated for this asymptotic region, to be compared with measurements made at core center.

In the second method, denoted RCP01/MUFT7, the infinite-lattice cell was analyzed with RCP01, and leakage corrections were determined from the experimental buckling by MUFT7, a point B_g multigroup program which is an updated version of MUFT5 (Ref. 3). The RCP01 cell eigenvalue calculation represented the fuel cell explicitly in two dimensions (Figure 2). MUFT7 described a homogenized lattice cell, with RCP01-calculated fast (10 MeV-821 keV) and thermal flux-weighting factors applied to the cylindrical cell regions. In

the resonance range, however, absorption was calculated by an integral transport method which used the same detailed cross section profile as RCP01 (Ref. 4). For this, the lattice cell geometry was represented explicitly except that the nickel clad was homogenized with the fuel, and the small ring of D_2O between the inner fuel annulus and the aluminum can was homogenized with the aluminum. The cell boundary was treated as cylindrical, with a diffuse-reflection boundary condition.

Atomic number densities are shown in Table 1 and fuel assembly dimensions in Figure 2.

One test of adequacy for the MUFT7 calculations was to compare the absorption fractions obtained for the unbuckled cell with those from the RCP01 cell calculation. Table 2 shows this comparison. Agreement is good, demonstrating the consistency of the MUFT7 approximations.

Integral parameters calculated with ENDF/B-IV data are shown in Table 3. Except for K_{eff} , agreement between the full-core RCP01 and RCP01/MUFT7 results is very good. The K_{eff} difference of 1.0% can be attributed only partly to statistics, and the measured B_m^2 (which enters the RCP01/MUFT7 calculations, but not the full-core RCP01) is not considered to be significantly in question. The most important factor is thought to be approximations in the homogenization procedure used in the MUFT7 calculation. Similar differences were observed in analysis of the TUPE thorium-U235- H_2O lattices (Ref. 5).

Table 1Atomic Number Densities Used in RCP01 Analyses

	<u>Nuclide</u>	<u>Atomic Number Density (cm⁻³) x 10⁻²⁴</u>
<u>Fuel</u>	U235	53274-03
	U238	47282-01
	U236	11148-04
<u>Aluminum (Can and Structure)</u>	Al	60512-01
	B10	30438-06
<u>Nickel (Clad)</u>	Ni	91331-01
<u>Moderator</u>	D	66291-01
	Ø	33229-01
	H	16614-03
<u>Stainless Steel 306 (Structure)</u>	SS	87775-01
<u>Boral</u>	B10	26984-01
	Al	44997-01
	C12	67459-02
<u>Lithium (Homogenized with some Al clad)</u>	Li6	42084-01
	Al	55436-02

Table 2

Comparison of MUFT7 and RCP01 Reaction Rates
for the Infinite Lattice Cell

	Absorption Rate	
	MUFT7	RCP01 (σ)
<u>Fast Energy Range</u>		
(10 MeV - 0.625 eV)		
U235 Fission	55444-01	56103-01 (0.4%)
U235 Capture	25173-01	25293-01 (0.6%)
U238 Fission	30306-01	30728-01 (0.6%)
U238 Capture	30147+00	29871+00 (0.4%)
U236 Capture	11978-02	11724-02 (3.0%)
<u>Thermal Energy Range</u>		
(0.625 - 0.0 eV)		
U235 Fission	35816+00	35630+00 (0.3%)
U235 Capture	62173-01	62471-01 (0.3%)
U238 Capture	15673+00	15958+00 (0.3%)
U236 Capture	70339-04	71361-04 (0.3%)
K _{eff}	1.08634	1.08511 (0.2%)

Table 3

Comparison of Calculated and
Measured Integral Parameters

Integral Parameter	Calculation		Experiment
	RCP01/MUFT7 ($\pm$ % σ) ^a	Full Core RCP01 ($\pm$ % σ) ^a	
$\rho^{28} = \frac{\text{Epithermal U238 Capture}}{\text{Thermal U238 Capture}}$	2.000 (0.6)	1.990 (1.5)	2.05 $\pm$.09
$\delta^{25} = \frac{\text{Epithermal U235 Fission}}{\text{Thermal U235 Fission}}$	.167 (.9)	.164 (1.4)	.168 $\pm$.004
$\delta^{28} = \frac{\text{All U238 Fission}}{\text{All U235 Fission}}$	.0818 (1.0)	.0824 (1.4)	.086 $\pm$.005
$CR^* = \frac{\text{All U238 Capture}}{\text{All U235 Fission}}$	1.152 (0.6)	1.152 (1.5)	1.147 ^b
$C^\dagger = \frac{\text{All U238 Capture}}{\text{U235 Fission} + \text{U238 Fission}}$ $= CR^*/(1 + \delta^{28})$	1.065 (1.2)	1.064 (3.2)	1.056 $\pm$.007
K_{eff}	.9785 (0.2)	.9690 (0.1)	1.0

^aUncertainties derive from Monte Carlo statistics only (at one standard deviation). They do not reflect eigenfunction shape fluctuations in the full-core analysis.

^bCalculated from the experimental values of $C^\dagger$ and δ^{28} (Ref. 1).

RCP01-calculated integral parameters are in good agreement with experiment except that K_{eff} is 3% low. This is the main problem encountered in the analysis of this experiment. As will be seen below (Section V), the slightly-low calculated δ^{28} is increased 3% by use of the harder U235 fission spectrum adopted for ENDF/B-V. This spectrum, which is based on a Watt shape with $E_p = 2.03$ MeV, has no appreciable effect on the other parameters or on K_{eff} . Some improvement of K_{eff} is afforded by the 0.74% increase of $\bar{\nu}$ (U235) adopted in ENDF/B-V and a slight reduction of U238 resonance capture.

The main reason for the low calculated K_{eff} is that the calculated U238 resonance capture is too high, as can be seen in Figure 3. This shows the calculated sensitivity of K_{eff} to ρ^{28} for variation of U238 resonance capture. For $K_{\text{eff}} = 1.0$, the calculated ρ^{28} would have to be near 1.8, far below the measured value of 2.05 ± 0.09 .

This illustrates the second major problem in interpreting this experiment, namely the difficulty of reconciling the measured ρ^{28} with criticality. The only calculational possibilities would require a reduction of fast leakage (increasing K_{eff} with little effect on other parameters) or a substantial increase of $\bar{\nu}$, neither of which is likely.

A calculation of the U235 fission neutron age to 1.46 eV in D₂O produced a value 110.5 cm^2 , in excellent agreement with the measured value, $110 \pm 3 \text{ cm}^2$ (See the Appendix). This supports the adequacy of the fast neutron transport and leakage calculated for LTRIIA.

FIGURE 3. K_{eff} versus Rho28 for LTRIIA

III. COMPARISON OF RCP01 AND OTHER MONTE CARLO RESULTS

In view of the low calculated K_{eff} , it was decided to check the correctness of the RCP01-calculated reaction rates for LTRIIA by comparing them with other independent calculations of high accuracy. As a first step in this direction, the LTRIIA infinite lattice cell was analyzed with the VIM Monte Carlo program by P. F. Rose of Brookhaven National Laboratory *. Cell specifications were exactly the same as for RCP01, and ENDF/B-IV data were used exclusively. VIM described the cell geometry explicitly and represented cross sections in all essential detail provided by ENDF/B.

Reaction rates were edited in four groups for comparison with RCP01. The few-group breakpoints were chosen at the following convenient MUFT-group energies: 10 MeV, 67.4 keV, 3.354 keV, 0.625 eV and 0 eV. These were chosen so that group 2 emphasized the ENDF/B-IV U238 unresolved resonance range (4 keV-40 keV) and group 3 the resolved range (0.625 eV-4 keV).

Results are shown in Table 4 for the major reactions of interest. Agreement between VIM and RCP01 is excellent and within statistics in nearly every case, except for U235 capture in group 2 and U235 fission in group 3. The VIM k_{∞} is 1.0870 ± 0.0035 (σ) compared with 1.0851 ± 0.0022 for RCP01.

The VIM results, except for the common ENDF/B-IV data set, are almost completely independent of RCP01. This includes many features of the cross section representation: VIM uses pointwise data exclusively and preserves the ENDF/B-IV detail in energy and in angle of scatter. Of more importance, the resolved and unresolved resonance treatments, Doppler broadening, geometry representations, neutron transport mechanisms and statistical estimators are independent of RCP01.

*This was undertaken as part of the thermal reactor benchmark testing effort of the Cross Section Evaluation Working Group.

Table 4

Comparison of VIM and RCP01 Four Group Reaction Rates ($B^2 = 0$ Cell)

Group	VIM	RCP01	$\left(\frac{\text{VIM}}{\text{RCP01}} - 1\right) \times 100\%$
<u>U238 Capture</u>			
1	20005-1 (.39) ^a	19881-1 (.56) ^a	+ .62 ± .68
2	49650-1 (.65)	50043-1 (.47)	- .79 ± .80
3	22763+0 (.82)	22879+0 (.48)	- .51 ± .95
1-3	29729+0 (.64)	29871+0 (.4)	- .48 ± .75
4	15918+0 (.62)	15950+0 (.3)	- .25 ± .69
<u>U238 Fission</u>			
1-3	30628-1 (.79)	30728-1 (.6)	- .33 ± .99
<u>U235 Fission</u>			
1	27426-2 (.35)	27355-2 (.44)	+ .26 ± .56
2	29386-2 (.55)	29395-2 (.57)	- .03 ± .79
3	51592-1 (.60)	50426-1 (.49)	+2.3 ± .77
1-3	57273-1 (.54)	56100-1 (.4)	+2.1 ± .67
4	35671+0 (.63)	35630+0 (.3)	+ .11 ± .70
<u>U235 Capture</u>			
1	39706-3 (.43)	39398-3 (.66)	+ .78 ± .79
2	11087-2 (.56)	10685-2 (.56)	+3.8 ± .79
3	24159-1 (.78)	23831-1 (.64)	+1.4 ± 1.1
1-3	25665-1 (.73)	25293-1 (.6)	+1.5 ± .94
4	62350-1 (.62)	62471-1 (.3)	- .19 ± .69
<u>U236 Capture</u>			
1	10575-4 (.40)	10537-4 (.51)	+ .36 ± .65
2	2061-4 (.57)	20226-4 (.55)	+1.9 ± .79
3	1143-2 (4.3)	11273-2 (3.4)	+1.4 ± 5.5
1-3	1174-2 (4.2)	11581-2 (3.0)	+1.4 ± 5.2
4	7153-4 (.62)	71361-4 (.3)	+ .24 ± .69
<u>U236 Fission</u>			
1-3	1429-4 (.64)	14326-4 (.57)	- .25 ± .86

^aPercent uncertainties from Monte Carlo statistics at one standard deviation.

Subsequently, good agreement was also observed for reaction rates calculated with the MCNP2 Monte Carlo program (Ref. 6) by R. E. Prael of Los Alamos (Ref. 7).

Table 5 compares integral parameters calculated for the $B^2=0$ cell by the three Monte Carlo programs. Once again, agreement is generally very good. The high value of ρ^{28} obtained by MCNP2 (with slight effect on CR^* and K_∞) is attributed to its neglect of unresolved resonance shielding.

TABLE 5

Comparison of Calculated Integral
Parameters ($B^2=0$ Cell)

Integral Parameter	Calculated Value ($\pm \% \sigma$)		
	RCP01	VIM	MCNP2
K_∞	1.0851 (.22)	1.0870 (.35)	1.0813 (.09)
ρ^{28}	1.872 (.6)	1.868 (.7)	1.935 (.3)
δ^{25}	.1575 (.9)	.1606 (.8)	.1584 (.3)
δ^{28}	.0745 (1.0)	.0740 (1.0)	.0736 (.4)
CR^*	1.111 (.6)	1.103 (.7)	1.116 (.3)

IV. IMPLICATIONS OF TRX ANALYSIS RESULTS (ρ^{28} AND K_{eff}) FOR LTRIIA

With ENDF/B-IV, RCP01 analyses of the TRX slightly-enriched uranium- H_2O lattices have consistently overpredicted U238 resonance capture (Ref. 8). This has shown up primarily in evaluation of measured ρ^{28} (= U238 capture above 0.625 eV/U238 capture below 0.625 eV) but it is apparent also in calculated K_{eff}^* .

*The four TRX critical experiments are among the thermal reactor benchmarks of the Cross Section Evaluation Working Group.

The situation can be summarized as follows: The ENDF/B-IV-calculated value of ρ^{28} is about 5% above integral experiment, as shown in Table 6. The sensitivity of ρ^{28} to variation of the U238 effective resonance capture integral I_{28} (Ref. 9) is shown in Table 7. These values were obtained by varying the smooth (unshielded) U238 capture cross section so as to reduce I_{28} in the lattice by exactly 1.0b (out of $\sim 15.0b$). Each value shown in Table 7 is the average of two cross section variations which produced nearly the same results, one in the U238 unresolved resonance range (5.5 keV - 25 keV) and the other near thermal energies (0.625 eV-6 eV). Also shown in Table 7 is the K_{eff} sensitivity.

Table 8 shows the change of ENDF/B-IV I_{28} required to bring calculated ρ^{28} into agreement with experiment for each TRX lattice. The average is $-0.75 \pm 0.30b$, a $4.9\% \pm 2.0\%$ reduction of I_{28} .

Figure 4 shows values of I_{28} for these lattices, calculated with ENDF/B-IV data, as a function of $\sqrt{\left(\frac{S}{M}\right)^*} \equiv \sqrt{\left(\frac{S}{M}\right) (1-C)}$. $\left(\frac{S}{M}\right)$ is the surface-to-mass ratio of the uranium fuel rod in cm^2/gm , and $1-C$ is the Dancoff factor for the lattice. The values of $1-C$ used to compute $\left(\frac{S}{M}\right)^*$ values in Table 8 were obtained from Ref. 9**.

For each assembly, I_{28} was obtained from the RCP01 calculation for the infinite lattice cell, as follows: In each RCP group g , RCP01 edits a "heterogeneous resonance integral" (Ref. 2, p. 273). For U238 this is

**Note that no attempt has been made to calculate $\left(\frac{S}{M}\right)^*$ for the double-annulus LTRIIA fuel. The point in Figure 4 has been placed on the line at $I_{28} = 11.5b$.

Table 6Comparison of Calculated and Measured ρ^{28} in TRX Lattices

<u>Assembly</u>	<u>W/U^a</u>	<u>ρ^{28}</u>		
		<u>Measured</u>	<u>Calculated</u>	<u>Calc./Meas.</u>
TRX3	1.0	3.03 $\pm$.05	3.18 $\pm$.01	1.050 $\pm$.018
1	2.35	1.320 $\pm$.021	1.396 $\pm$.004	1.058 $\pm$.017
2	4.02	.837 $\pm$.016	.867 $\pm$.004	1.036 $\pm$.020
4	8.11	.481 $\pm$.011	.507 $\pm$.003	1.054 $\pm$.025
AV				1.050 $\pm$.020

Table 7

Sensitivity of ρ^{28} and K_{eff} to Change of U238
Effective Resonance Capture Integral

<u>Assembly</u>	<u>$\frac{\Delta \rho^{28} / \rho^{28}}{\Delta I_{28}}$ (%/barn)</u>	<u>$\frac{\Delta K_{eff} / K_{eff}}{\Delta \rho^{28} / \rho^{28}}$</u>
TRX 3	8.10	-.119
1	6.82	-.192
2	6.22	-.128
4	5.82	-.103
LTRIIA	8.62	-.289

^aW/U denotes the water/uranium volume ratio.

Table 8

Change in ENDF/B-IV Calculated U238 Effective Resonance
Integral Required to Reproduce Measured ρ^{28}

Assembly	$\left(\frac{S}{M}\right)^*$ (cm/gm ^{1/2})	Calculated I_{28} (barns)	ρ^{28} $\left(\frac{\text{calc}}{\text{exp}} - 1\right) \times 100\%$	Implied Change	
				$\Delta I_{28}(\text{b})$	$\Delta I_{28}/I_{28}$ (%)
TRX3	.369	13.72	5.0 ± 1.8	-.62 ± .22	-4.6 ± 1.6
1	.430	15.46	5.8 ± 1.7	-.85 ± .25	-5.6 ± 1.7
2	.450	16.01	3.6 ± 2.0	-.58 ± .32	-3.7 ± 2.0
4	.461	16.51	5.4 ± 2.5	-.93 ± .43	-5.8 ± 2.7
AV				-.75 ± .30	-4.9 ± 2.0
LTRIIA	--	11.5			

NOTE: $\left(\frac{S}{M}\right)^* = \left(\frac{S}{M}\right) (1-C)$, where $\left(\frac{S}{M}\right)$ is the surface-to-mass ratio of the uranium fuel rod in cm²/gm and (1-C) is the Dancoff factor for the lattice.

FIGURE 4. Effective resonance integral of U238 versus $\sqrt{\left(\frac{S}{M}\right)^*}$.
 Solid points show values of I_{28} required to provide
 agreement with measured ρ^{28} in each TRX lattice.

$$R.I._{28}^g(\text{het}) = -\ln \left(1 - \frac{A_{\text{tot}}^g}{p^g} \right) \times \frac{A_{28}^g(\text{res})}{A_{\text{tot}}^g} \quad (\text{Eqn. 1})$$

where $A_{28}^g(\text{res})$ is the U238 resonance absorption in group g

A_{tot}^g is all absorption in group g

p^g is the absorption escape probability down to group g:

$$p^g = 1 - \sum_{g'=1}^{g-1} A_{\text{tot}}^{g'}$$

Finally,

$$I_{28}(\text{barns}) = \sum_g R.I._{28}^g(\text{het}) \times \left(\frac{\xi \Sigma_s}{N^{28}} \right)^g + I_{28}(\text{smooth}) \quad (\text{Eqn. 2})$$

where $\left(\frac{\xi \Sigma_s}{N^{28}} \right)^g$ is the total $\xi \Sigma_s$ per U238 atom in the cell:

$$\left(\frac{\xi \Sigma_s}{N^{28}} \right)^g = \frac{\sum N^i \xi^i \sigma_s^i V^i}{N^{28} V^{28}} \quad (\text{Eqn. 3})$$

$\left(\frac{\xi \Sigma_s}{N^{28}} \right)^g$ was dominated by hydrogen and showed little variation over groups where most of the U238 capture occurred. Hence it was possible to sum over groups:

$$I_{28} = \left(\frac{\xi \Sigma_s}{N^{28}} \right)_{\text{Av}} \left(\sum_g R.I._{28}^g(\text{het}) \right) + I_{28}(\text{smooth})$$

In the case of the LTRIIA (but not for TRX lattices), there are significant spatial flux variations across the cell in the resonance range. Although these were not accounted for (in Eqn. 3) they are thought not to significantly affect the result for I_{28} in LTRIIA.

On the basis of experiment and calculation (Ref. 10, 11), I_{28} is found to be practically a linear function of $\sqrt{\left(\frac{S}{M}\right)^*}$ over a wide range. This means that it does not depend on the detailed shape of the absorber (e.g., slab or rod). Furthermore it is independent of moderator, and there is a close equivalence between isolated rods ($C=0$) and rods in lattices (Ref. 10). Thus, despite the differences of moderator and of fuel element shape for LTRIIA (compared to TRX), I_{28} is not much different than for TRX lattices and should show nearly the same sensitivity to changes of U238 capture cross section.

The integral ρ^{28} measurements are strongly supported by the corresponding K_{eff} values (Table 9). This can be seen in Figure 5, which shows K_{eff} plotted versus the calculated U238 capture rate above 0.625 eV. Included also is the zero-leakage limit of K_{eff} inferred from analysis of homogeneous U235-H₂O critical experiments (Ref. 12).

It is apparent that the I_{28} changes required to obtain agreement with measured ρ^{28} bring TRX K_{eff} values into excellent agreement with each other and with the infinite medium of U235-H₂O. The resultant bias of -0.5% is attributed to a low value of $\bar{\nu}$ for U235. This pattern of consistency strongly supports all of the individual results involved.

Two comments need to be made about the K_{eff} values of Figure 5. First, the K_{eff} sensitivity to U238 resonance capture should increase in tighter lattices and this is observed for TRX-1 ($W/U = 2.35$) and TRX-2 ($W/U = 4.0$), which are full lattices, as shown by the dashed line in Figure 5. TRX-3 and TRX-4 depart from this line because they are two-region lattices (Ref. 10). For example, the TRX-3 assembly is dominated by the large UO₂ driver lattice, and this has a much smaller U238 capture rate than does the $W/U = 1.00$ inner test lattice.

Second, the ENDF/B-IV fission spectrum of U235 is too soft, which causes leakage to be underpredicted. This shows up in K_{eff} values of homogeneous U235-H₂O critical assemblies (Ref. 12). However, in the TRX lattices, which have ~20% leakage, the leakage error is almost exactly counterbalanced by an underprediction of U238 fission. Hence the ENDF/B-IV U235 fission spectrum error has no visible effect on K_{eff} values of these assemblies.

Table 9
 K_{eff} Changes Implied by the ρ^{28} Measurements

Assembly	ENDF/B-IV K_{eff}	ΔK_{eff}^*	Resultant K_{eff}
TRX3	.9899 $\pm$.0012	+ .0059	.9958 $\pm$.0012
1	.9837 $\pm$.0010	+ .0110	.9947 $\pm$.0010
2	.9894 $\pm$.0013	+ .0046	.9940 $\pm$.0013
4	.9880 $\pm$.0016	+ .0055	.9935 $\pm$.0016
			AV .9945 $\pm$.0006
LTRIIA RCP01/MUFT 7	.9785 $\pm$.0020	+ .0183	.9968 $\pm$.0020
Full RCP01	.9690 $\pm$.0010	+ .0183	.9871 $\pm$.0010

*Change of K_{eff} implied by the ΔI_{28} required to obtain agreement with measured ρ^{28} for each TRX lattice (Table 8). For LTRIIA, ΔK_{eff} results from $\Delta I_{28} = -0.75b$, the average from Table 8.

FIGURE 5. K_{eff} versus U238 Capture Fraction for Uranium-H₂O lattices and LTRI A.

In LTRIIA, the sensitivity of ρ^{28} to U238 effective resonance integral is 8.62%/barn, slightly greater than in the tightest TRX lattice (see Table 7). The K_{eff} sensitivity is substantially greater, which largely accounts for the low calculated K_{eff} . In fact, as shown in Figure 5, the LTRIIA RCP01/MUFT7 K_{eff} is fully consistent with the picture obtained from the H_2O -moderated TRX lattices. A 0.75b reduction of the U238 effective resonance integral brings the LTRIIA eigenvalue up to 0.9968, slightly above the TRX values. This excellent consistency of LTRIIA with TRX lattice results, shown in Figure 5, may be partly fortuitous since the full-core RCP01 eigenvalue would be increased only up to .9871.

V. ADDITIONAL STUDIES, INCLUDING SENSITIVITIES AND DATA VARIATIONS. AGE IN D_2O

Several important data sensitivities for LTRIIA were determined by MUFT calculations. These included the following:

- (1) Change the U235 Fission spectrum from ENDF/B-IV (a Maxwellian shape with $\bar{E} = 1.985$ MeV) to SPEC(30), a Watt prompt spectrum with $\bar{E} = 2.027$ MeV, plus a delayed spectrum which is a Maxwellian with $\bar{E} = 0.450$ MeV (Ref. 12). This Watt spectrum is almost identical to the U235 fission spectrum in ENDF/B-V.
- (2) Change the U235 fission spectrum from ENDF/B-IV to the Steen Standard Model with $\bar{E} = 2.073$ MeV (Ref. 13). This spectrum is significantly harder than SPEC(30) although based on the same differential data.
- (3) Reduce the U238 effective resonance capture integral I_{28} by 0.75b, by reduction of the smooth capture cross section in the energy range from 2 keV - 6.5 eV.

The effects of these variations are shown in Table 10. The harder Watt and Standard-model prompt fission spectra increase δ^{28} by 2.8% and 5.5% respectively through an increase of the U238 fission rate. They have negligible effect on other parameters, including K_{eff} .

The 0.75b reduction of I_{28} substantially improves K_{eff} and has little effect on δ^{25} . It reduces ρ^{28} , C^* and C^+ below experiment, but measured

values are thought to be too large. They are, at least, incompatible with $K_{\text{eff}} = 1.0$ unless there should be a significant reduction in fast leakage or a large increase of $\bar{\nu}$ for U235, neither of which is likely.

The fourth variation in Table 10 shows the effect of changing B_m^2 from $7.45 \times 10^{-4} \text{ cm}^{-2}$ to $7.29 \times 10^{-4} \text{ cm}^{-2}$. Except for K_{eff} , the consequences are negligible. The experimental B_m^2 uncertainty of $\pm 0.06 \times 10^{-4} \text{ cm}^{-2}$ (Ref. 1) implies an 0.07% uncertainty of K_{eff} .

The fifth variation in Table 10 shows the effect of using the preliminary ENDF/B-V U238. Version V differs from Version IV mainly in the representation of inelastic scattering and in parameters for the low energy resonances. There is negligible effect on integral parameters.

Table 10
Some Important Integral Parameter Sensitivities

Parameter	% Change of Parameter				
	(1) Fission Spectrum →	(2) Fission Spectrum →	(3) $\Delta I_{28} =$	(4) $\Delta B_m^2 =$	(5) U238 →
	<u>SPEC(30)</u>	<u>Std. Model</u>	<u>-0.75b</u>	<u>$-.16 \times 10^{-4} \text{ cm}^{-2}$</u>	<u>ENDF/B-VP</u>
ρ^{28}	+ .02	+ .14	-6.49	-.12	-.10
δ^{25}	+ .06	+ .12	+ .45	-.11	-.36
δ^{28}	+2.80	+5.48	-2.02	-.17	+ .54
C^*	+ .02	+ .07	-4.43	-.07	-.10
C^+	- .20	- .35	-4.28		-.14
K_{eff}	+ .05	+ .16	+1.87	+ .19	+ .02

An additional study was undertaken to check the energy mesh and representation of U238 resonances. RCP01 describes resonance cross sections by detailed profiles in an RCP-group structure, with 1000 uniformly-spaced energies in each group. These profiles are superimposed on a small MUFT-group-averaged background absorption cross section. In the LTRIIA calculations, cross sections were described in a 33 RCP-group structure, and U238 p-wave resonances were smoothed over MUFT groups. Over the resolved resonance range for U238 (1-4000 eV) there were ~ 25000 energies, and the mesh spacing varied from ~ .01 eV to ~ 0.6 eV.

This cross section representation has been found to be adequate for TRX lattices. It was checked for LTRIIA by the following series of RCP01 cell calculations which used a preliminary version of ENDF/B-V U238:

- (1) 33 RCP-group library. U238 p-wave resonances smoothed over MUFT groups.
- (2) 58 RCP-group library. U238 p-wave resonances smoothed over MUFT groups.
- (3) 58 RCP-group library. U238 p-wave resonances represented explicitly.
- (4) 100 RCP-group library. U238 p-wave resonances represented explicitly.

The additional RCP groups were added to the 33 group library in the resolved resonance range. With 58 RCP groups, the mesh was uniformly 0.1 eV from 1230 eV to 4000 eV. Below 1230 eV it was held the same as for the 33 group library--generally much finer than 0.1 eV. The RCP 100-group structure reduced the mesh to 0.05 eV over the range 400 eV-4000 eV; below 400 eV the 33-group mesh was retained and it was generally much finer than 0.1 eV.

When the p-wave resonances are described explicitly, it must be ensured that the p-wave resonance integral is accurately preserved, and this puts more stringent demands on the energy mesh because the resonances are generally very narrow. That mesh differences of cross sections are small can be inferred from the dilute resonance integrals obtained directly from the RCP01 cross section profiles, as shown in Table 11.

The fast U238 capture rates in the infinite lattice cell are shown in Table 12. There may be slight effects visible, but the most detailed representation (100 RCP01 groups, explicit p-waves) is not statistically different from the base case. Thus the 33 group structure with smoothed U238 p-wave capture is adequate for these studies.

VI. SUMMARY OF RESULTS AND CONCLUSIONS

The LTRIIA slightly enriched uranium-D₂O critical experiment was analyzed by two methods: full-core RCP01 Monte Carlo and RCP01/MUFT7. Reaction rates and integral parameters obtained by the two methods agree very well except that the full-core K_{eff} is 1% below RCP01/MUFT7. This difference can be due only partly to statistics and to the measured B_m^2 used by MUFT7; it is attributed mainly to leakage differences stemming from homogenization approximations used in the MUFT7 calculation.

Table 11
Effects of Energy Mesh and U238 P-Wave
Representation on U238 Dilute Resonance Integrals
(Pre1. ENDF/B-V U238)

<u>Library</u>	<u>Dilute Resonance Integral (b)</u>
(1) 33 RCP groups Smoothed p-wave resonances*	278.837
(2) 58 RCP groups Smoothed p-wave resonances	278.832
(3) 58 RCP groups Explicit p-wave resonances	278.831
(4) 100 RCP groups Explicit p-wave resonances	278.833

*The resolved p-wave resonance integral is 0.8102b.

Table 12
Effects of Energy Mesh and U238 P-wave Representation
on U238 Fast Capture Rate in the LTRIIA Cell
 (Prel. ENDF/B-V U238)

<u>Number of</u> <u>RCP01 Groups</u>	<u>U238 P-wave</u> <u>Representation</u>	<u>U238 Capture</u> <u>Rate (> 0.625 eV)</u>	<u>% Change</u>
33	Smoothed	.29986 (.25%) ^a	(Base)
58	Smoothed	.29767 (.25%)	-.73 ± .35
58	Explicit	.29723 (.26%)	-.88 ± .35
100	Explicit	.29895 (.26%)	-.30 ± .35

^aUncertainties are from Monte Carlo statistics at one standard deviation.

Compared to experiment, the full-core RCP01 K_{eff} is 3% low. This is attributed mostly to an overestimate of U238 resonance capture. Such an overestimate is entirely consistent with the following situation observed in TRX U-H₂O assemblies (Section IV):

In the RCP01 analysis of four TRX lattices, ENDF/B-IV data overpredict ρ^{28} (the ratio of fast to thermal U238 capture rates) by 5%. This suggests the need for a 0.75b reduction of I_{28} , the RCP01-calculated U238 effective resonance capture integral. Such a reduction is strongly supported by the TRX K_{eff} values--it brings them into line with each other and with the zero-leakage K_{eff} for homogeneous U235-H₂O assemblies (Figure 5). There remains a bias of -0.5% which is attributed to a low $\bar{\nu}$ for U235 in ENDF/B-IV.

Since I_{28} for LTRIIA is not much below values for the TRX lattices, it is reasonable to expect that approximately a 0.75b reduction of I_{28} should be required for LTRIIA also. Such a change brings the RCP01/MUFT7 calculated K_{eff} up to 0.997, fully consistent with the TRX lattices (Figure 5). Such consistency may be partly fortuitous since the full-core RCP01--which should be more accurate--comes up only to 0.987.

The $\bar{\nu}$ of U235 for ENDF/B-V is 2.4366, 0.74% above Version IV. Such an increased $\bar{\nu}$ would raise the full-core eigenvalue (with $\Delta I_{28} = -0.75b$) to 0.994.

The calculated values of δ^{25} and δ^{28} show good agreement with experiment. The harder U235 fission spectrum adopted for ENDF/B-V improves calculated δ^{28} . The changes of U238 inelastic scattering adopted in ENDF/B-V do not affect integral parameters. The suggested reduction of I_{28} by 0.75b does not significantly affect the agreement of δ^{28} and δ^{25} with experiment.

Analysis of the measured U235 fission neutron age to 1.4 eV in D₂O gives excellent agreement with experiment (Appendix). This supports the adequacy of RCP01 neutron transport and leakage calculations for LTRIIA.

The RCP01-calculated reaction rates in the LTRIIA infinite lattice cell were compared in four groups with rates calculated by the VIM and MCNP2 Monte

Carlo programs. Both programs described the cell geometry exactly and used strictly pointwise cross sections in all essential detail specified by ENDF/B-IV. The VIM and MCNP2 rates showed generally good agreement with RCP01. This strongly supports the correctness of the RCP01 results, including data processing.

The measured ρ^{28} and C^* seem to be incompatible with criticality. It is suspected that there must be an undiscovered error in the U238 capture measurement.

In summary, the RCP01 analysis of the LTRI A U-D₂O critical assembly produces results that are fully consistent with those for the TRX U-H₂O assemblies. The low eigenvalue is attributed mostly to an excess of U238 resonance capture for ENDF/B-IV equivalent to 0.75b in I_{28} . With such a correction and the 0.74% increased $\bar{\nu}$ of U235 in ENDF/B-V, the full-core eigenvalue becomes 0.994.

The differential cross section data for U238 have been greatly improved in the past few years (Ref. 14). However, very little reduction of U238 capture has been obtained with ENDF/B-V. It is not clear whether the current uncertainties of data can fully accommodate the required $\Delta I_{28} = -0.75b$. There may be some contribution from methods, for example, basic questions about the representation of resonance cross section profiles.

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APPENDIXCALCULATION OF THE U235 FISSION NEUTRON AGE TO
1.46 eV IN D₂O

1. Introduction

The U235 fission neutron age to indium resonance energy (1.46 eV) in D₂O was calculated with ENDF/B-IV data. Three Bettis programs were used to obtain independent assessments: MUFT7, RCP01, and PACER. The calculated age is compared with experiment (Ref. A1, A2) and with calculations performed by H. Alter and C. L. Dunford of Atomics International (Ref. A3, A4). Sensitivity of the age to a few important data variations was also determined.

2. Measurements

The U235 fission neutron age to indium resonance energy (1.46 eV) in D₂O was measured in the mid-1950's by R. N. Olcott (Ref. A1) at Los Alamos and by J. W. Wade (Ref. A2) at Savannah River.

Olcott measured the age in 99.8%-pure D₂O by activation of cadmium-covered indium foils. Activations were measured as a function of distance from a small sphere of enriched uranyl nitrate, with a source multiplication of about eight, placed at the center of a 35-inch diameter sphere of D₂O. The activation distribution, from ~11 to 41 cm, gave a good fit to the Fermi-Age expression $A(r) = e^{-r^2/4\tau}$ from which was obtained an age $\tau = 111 \pm 1 \text{ cm}^2$.

Wade measured the age to indium resonance in 99.8%-pure D₂O, in D₂O-H₂O mixtures (99.0, 98.4, 95.3, 94.0, 91.8 and 48.6 mole % D₂O) and in pure H₂O. Measurements were made in the five-ft. diam. x seven-ft. high tank of an exponential facility driven by the SP reactor, a small enriched-uranium graphite pile which supplied thermal neutrons to a fission plate (a source disc 1.0 in. diam. x 0.05-in. thick of ~90% enriched uranium). Cadmium covered indium foils were activated over a distance from ~6 to 50 cm from the source. In order to eliminate background, traverses were made with and without the source in place. Corrections were applied to account for the finite size of source and detectors, and for indium activation above 1.46 eV.

The age was determined from its definition as one-sixth the ratio of second to zeroth moments of the flux at energy E from a point source:

$$\tau_{\phi}(E) = \frac{1}{6} \frac{\int_0^{\infty} r^2 \phi(r, E) dV}{\int_0^{\infty} \phi(r, E) dV}$$

(This is more general than the Fermi-Age expression used by Olcott.) In terms of the measured activation shape A(r)

$$\tau_{\phi}(1.46 \text{ eV}) = \frac{1}{6} \frac{\int_0^{\infty} r^4 A(r) dr}{\int_0^{\infty} r^2 A(r) dr}$$

(The extra factor of r^2 converts the measured foil activation A(r) to all activation in a spherical shell at radius r.) τ was determined from a smooth fit to the corrected measured activations $r^4 A(r)$ and $r^2 A(r)$.

Curves were extrapolated to infinity, assuming $\phi \sim \frac{e^{-r/\lambda}}{r^2}$ with λ determined from experiment at $r = 30\text{--}50$ cm. This extrapolation was worth 13% for $\int_0^{\infty} r^4 A dr$ and 1% for $\int_0^{\infty} r^2 A dr$.

The result for 99.8%-pure D_2O was $\tau = 109 \pm 3 \text{ cm}^2$. The uncertainty stems mainly from the extrapolation.

It may be noteworthy that Wade's result for H_2O is $31.0 \pm 2 \text{ cm}^2$, well above the currently accepted value $26.4 \pm 0.3 \text{ cm}^2$. There is no particular reason to question his D_2O result, however, because the D_2O measurement is subject to somewhat different errors, and is probably easier, than the H_2O measurement.

3. Calculations

The age was calculated with the programs MUFT7, RCP01 and PACER (a modified version of RCP01). Data were from ENDFB-IV. Atomic number densities were the same as used by Alter (Ref. A3, A4), specifying D_2O of 99.75% purity (i.e., with 0.25 mole % H_2O):

	N (Atoms/b-cm)
Oxygen	3309-1
Hydrogen	1700-3
Deuterium	6604-1
U235 fission spectrum	--

For convenience, the age was calculated to 1.44 eV, the breakpoint between XAP groups 54 and 55. This is trivially different from the indium resonance peak energy of 1.46 eV. Details of the individual calculations are as follows.

(a) MUFT7

The flux from a U235 fission source in an infinite medium of D₂O was calculated for three bucklings: $B^2 = 0, 0.0001$ and 0.0002 cm^{-2} . The flux age to 1.44 eV was obtained from the average flux ϕ in XAP groups 54 and 55 (of 57), as follows (Ref. A5):

$$\tau_{\phi} = - \left. \frac{\partial}{\partial B^2} \frac{\phi(B^2)}{\phi(0)} \right]_{B^2 = 0}$$

$$= \frac{\frac{1}{2} [(\phi_0 - \phi_1) - (\phi_1 - \phi_2)] + (\phi_0 - \phi_1)}{\phi_0 \times \Delta B^2}$$

where $\Delta B^2 = 0.0001$; ϕ_0 , ϕ_1 and ϕ_2 are the fluxes for the respective bucklings. A similar procedure was used to obtain the slowing down age τ_q .

(b) RCP01

The slowing down age to 1.44 eV was calculated by the RCP01 option to obtain first, second and fourth moments of neutron production about the problem origin. For this purpose an artificial, purely-fissionable nuclide was added to the D₂O. It had $\sigma_f = 0$ above 1.44 eV, and $\sigma_f = 1 \times 10^9 \text{ b}$ below 1.44 eV, so that every neutron slowing below 1.44 eV was absorbed immediately. In the RCP01 problem, there was a small source region at the origin in a large medium of D₂O.

The slowing down age across 1.44 eV was obtained from the RCP01-calculated second and zeroth moments of the artificial neutron production. Four independent calculations, of 12,000 histories each, were run to obtain an

estimate of the uncertainty in τ_q . The flux age to indium resonance was inferred from the MUFT7-calculated difference:

$$\tau_\phi(1.44 \text{ eV}) - \tau_q(1.44 \text{ eV}) = 3.864 \text{ cm}^2.$$

(c) PACER

Neutrons were tracked from a point source in an infinite medium of D_2O . At the point where the neutron energy dropped below 0.625 eV, its weight (w_i) and the distance from the source (r_i) were recorded. The slowing-down age to 0.625 eV was obtained directly as a sum over all histories:

$$\tau_q(0.625 \text{ eV}) = \frac{1}{6} \times \frac{\sum w_i r_i^2}{\sum w_i}$$

A total of 12,000 histories were run. The flux age to 1.44 eV was obtained from the MUFT7-calculated difference:

$$\tau_\phi(1.44 \text{ eV}) - \tau_q(0.625 \text{ eV}) = -1.918 \text{ cm}^2.$$

4. Results

Table A1 shows the flux age to 1.44 eV for a $^{11235}\text{U}$ fission source in D_2O , calculated with ENDF/B-IV data. Agreement with the measured age is excellent.

The effects of selected data variations were calculated with MUFT7 and are shown in Table A2. The age is quite insensitive to reasonable variations of the $^{11235}\text{U}$ fission spectrum shape and mean energy.

The age in D_2O , and higher moments, were calculated with the TYCHE-IV Monte Carlo program by C. L. Dunford and H. Alter (Ref. A3) with ENDF/B-I data, and by H. Alter (Ref. A4) with ENDF/B-II data. In both cases, a Cranberg fission spectrum with mean energy 1.979 MeV was used. Results are shown in Table A3.

For comparison, the MUFT7 age calculation was repeated with the Cranberg fission spectrum and ENDF/B-II cross section data. (The deuterium is material 1120, the same as ENDF/B-IV; the oxygen is material 1013.) The Cranberg fission spectrum is

$$f(E) = 0.453 \exp\left(\frac{-E}{0.965}\right) \sinh(2.29E)^{1/2}.$$

This is of the same form as the Watt spectrum which is represented in ENDF/B as

$$f(E) \sim e^{-E/a} \sinh(bE)^{1/2}.$$

The spectrum was generated by ETØMX from this formula with $a = 0.965$ MeV and $b = 2.29 \text{ Mev}^{-1}$. The MUFT7 calculation produced an age $\tau_p = 111.7 \text{ cm}^2$, which is 0.8% higher than the TYCHE-IV result $(110.8 \pm 0.2 \text{ cm}^2)$. The difference is well within the uncertainty of the measured value.

Table A1

Comparison of Calculated and Measured Values of the
U235 Fission Neutron Age to Indium Resonance Energy in D₂O

<u>Calculation</u>	$\tau_{\phi}(1.44 \text{ eV})$ <u>(cm²)</u>
MUFT7	110.5
PACER	110.0 $\pm$.01
RCP01	110.4 $\pm$ 1.2
 <u>Experiment</u>	
Olcott (Ref. A1)	111 $\pm$ 1
Wade (Ref. A2)	109 $\pm$ 3
	<hr/>
AV	110 $\pm$ 3

Table A2

Effect of Nuclear Data Variations
on the Calculated Age in D₂O (MUFT7)

<u>Date Set</u>	<u>$\tau_{\phi}(1.44 \text{ eV})$ (cm²)</u>
Base Calculation (ENDF/B-IV Fission spectrum is Maxwellian, $\bar{E} = 1.985 \text{ MeV}$)	110.513
Fission Spectrum Variations:	
Maxwellian, $\bar{E} = 2.00 \text{ MeV}$	110.727
Watt, $\bar{E} = 2.00 \text{ MeV}$	110.666
Watt, $\bar{E} = 2.029 \text{ MeV}$ plus delayed neutrons, SPEC(30)	110.900

Table A3

TYCHE-IV Values for the U235 Fission
Neutron Age and Higher Moments in D₂O

	ENDF/B-II (Ref. A4)	ENDF/B-I (Ref. A3)
$\tau^\phi(1.44 \text{ eV}) \text{ (cm}^2\text{)}$	110.8 $\pm$ 0.2	117.6 $\pm$ 0.2
$M_4^\phi \text{ (}\times 10^5 \text{ cm}^4\text{)}$	8.98 $\pm$ 0.05	10.03 $\pm$ 0.05
$M_6^\phi \text{ (}\times 10^9 \text{ cm}^6\text{)}$	2.11 $\pm$ 0.03	2.45 $\pm$ 0.03

Note that the high age obtained by Dunford and Alter with ENDF/B-I data is due to the ENDF/B-I deuterium, which had $\sigma_s = 3.18\text{b}$ in the lower keV range, compared to the value $\sigma_s = 3.35\text{b}$ used in ENDF/B-II-IV (material 1120). The low value of σ_s in ENDF/B-I was previously found to seriously perturb the calculation of $\rho^{02} = \text{epithermal thorium capture/thermal thorium capture}$ in the ETA-I and ETA-II lattices (Ref. A6, p. 26). Since slowing down competes directly with thorium resonance capture* the low σ_s caused an $\sim 5\%$ overprediction of thorium resonance capture.

These comparisons lend support to our treatment of neutron transport in D_2O , and suggest that the low eigenvalue calculated for LTRIIA is due to other factors (most likely an overestimate of U238 resonance capture).

*The resonance escape probability for the lattice is $p \sim e^{-I_c/\xi\sigma_s}$, where I_c is the effective resonance capture integral per thorium atom and $\xi\sigma_s$ is the slowing down power per thorium atom.

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