Reactivity and Parameter Measurements in a Coaxial Uranium Fuel-D_2O Moderated Critical Lattice*

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ABSTRACT

Reactivity and reaction rate parameters were measured for a 7-inch triangular pitch lattice of coaxial uranium fuel in a critical, D_2O-moderated reactor. The results were compared with RAHABR computations using ENDF/B-IV cross sections and with an earlier subcritical exponential measurement of the same lattice. Measured and calculated reactivity are in good agreement, however, the calculated ratio of epicadmium ^{238}U captures to subcadmium ^{238}U captures (ρ^{28}) was 10% lower than measured. Indirect verification of the ρ^{28} measurement was obtained by measurement of a new conversion ratio parameter (C^+) defined as the ratio of ^{238}U captures to total fissions. Agreement between measured and calculated inner-to-outer fuel activation ratios suggests that the discrepancy is caused by underprediction of epicadmium captures in ^{238}U or by erroneously high measured values of ρ^{28} and C^+. However, any adjustment of ^{238}U captures to match the measured ρ^{28} will cause the calculated reactivity to be underpredicted. An unresolved concern is that the experimental results do not satisfy an internal consistency criterion based on the two group neutron balance equation even though all known systematic errors have been accounted for and well known experimental techniques are used. Reaction rate parameters from the critical experiment agree with the exponential measurements indicating that the neutron spectra in the measurement regions were closely identical. The measured buckling in the critical facility is 0.52 m^{-2} lower than in the exponential. Other studies have shown systematic differences in reactivity between D_2O critical and exponential measurements.

INTRODUCTION

A fundamental goal of the calculational program at Savannah River Laboratory is to provide accurate representation of reactivity and reaction rates over a wide range of D_2O-thermal reactor lattices. A broad base of experimental evidence is required to evaluate the theoretical methods and differential cross sections

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used for predicting these integral reactor properties. (The most meaningful evaluations occur for lattices with simple geometry and composition so that errors of representation in the theoretical methods are minimized.) Several years ago two different, slightly enriched, coaxial fuel assemblies (Type I and Type II) each were studied in uniform lattices over a range of pitches in the exponential facility (SE) at SRL.[1] The purpose of these experiments was to provide information to assess the performance of the RAHAB[2] code with ENDF/B-IV cross sections. The calculated k_{eff}'s were 4 to 8% low and resonance capture in ^{238}U was consistently overpredicted by as much as 22%. Development later of an improved resonance treatment calculation in the RAHAB code improved agreement with the SE coaxial fuel experiments but significant discrepancies remained. In early 1977, analyses of the SE experiments by use of equations that tested the internal consistency of the data indicated that they may not be valid SRL benchmarks.[3] Possible distortion of the neutron energy spectrum by anisotropic leakage in the small exponential lattice and concern about the accuracy of the reactivity measurement in an exponential suggested the need to repeat several of the experiments in the critical LTR facility at SRL. Accordingly, reactivity and activation parameters have been remeasured for the Mark 15 (Type II) coaxial fuel at a 7-inch triangular pitch in the LTR and preparations are being made to remeasure the Mark 5R (Type I) coaxial fuel at a 7-inch triangular pitch.

In this paper:

- The results of the Mark 15-LTR experiments are reported and compared both with the earlier SE experiments and with computations by the transport theory code RAHABR[4] using ENDF/B-IV cross sections.
- The internal consistency of the Mark 15-LTR data is investigated.
- Measurement of a useful new conversion ratio parameter is described.
- Measurement techniques, corrections to the data, and systematic errors are discussed to illustrate experimental methods and justify the assigned error flags.
- The preliminary results of an experimental investigation of the energy dependence of the ^{238}U subcadmium cross section are presented in the Appendix.

LATTICE DESCRIPTION

The Mark 15 fuel assembly consisted of six stacked, unclad, nickel-plated inner and outer fuel pairs supported by aluminum

housing tubes to produce a uniform, continuous, coaxial fuel column 66.7-inches long. The fuel assembly geometry and composition are summarized in Table 1.

127 Mark 15 assemblies were placed on a 7-inch triangular pitch in the LTR. An outer poison boundary consisting of 1-inch diameter 4.9 wt % Li-Al rods surrounded the lattice to reduce reflector effects and improve the definition of the radial buckling. The lattice arrangement is shown in Figure 1.

The LTR is a stainless steel cylindrical vessel, 10 ft in diameter and 11 ft high with walls 1/4-inch thick. The lattice was supported and spaced on a precision made 1-inch thick aluminum bottom plate positioned about 4-inches above the tank bottom. A bottom poison boundary consisting of two layers of 1/8-inch boral sheet is located 1-1/2-inches beneath the fuel support plate. Top support and spacing was provided by a combination of grid support beams and interlocking spacers. A moderator supply system provides for filling and level control of the D_2O to ± 0.005 cm.

MEASUREMENT PROCEDURES

The satisfactory prediction of reactivity (B_m^2) is taken as the most important criterion in testing a reactor physics code and its associated nuclear data library. Integral reaction rate parameters provide detailed diagnostic information to assist the evaluation. In the Mark 15-LTR experiment integral parameters representative of important reaction rate ratios in the fuel were measured separately for the inner and outer fuel by activation of foil detectors placed within the fuel. Parameters that were derived from experimental data are summarized as follows:

^{238}U (n,γ) Capture Ratio $\rho^{28} = \dfrac{\text{Epicadmium } ^{238}U \text{ Captures}}{\text{Subcadmium } ^{238}U \text{ Captures}}$

^{235}U Fission Capture Ratio $\delta^{25} = \dfrac{\text{Epicadmium } ^{235}U \text{ Fissions}}{\text{Subcadmium } ^{235}U \text{ Fissions}}$

^{238}U Fast Fissions $\delta^{28} = \dfrac{^{238}U \text{ Fissions}}{^{235}U \text{ Fissions}}$

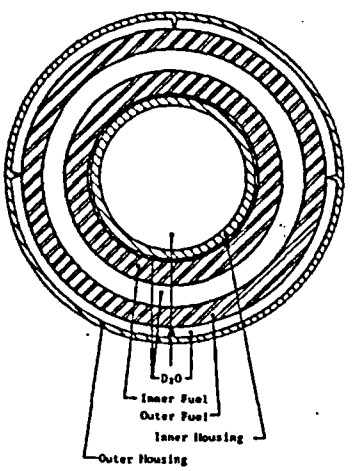
Conversion Ratio Index $C^{+} = \dfrac{^{238}U \text{ Captures}}{\text{Total Fissions}}$

Thermal Neutron Spectral Index $R = \dfrac{[^{176}Lu/^{63}Cu]^{\text{Subcadmium}}_{\text{Fuel}}}{[^{176}Lu/^{63}Cu]^{\text{Subcadmium}}_{\text{Thermal Ref.}}}$

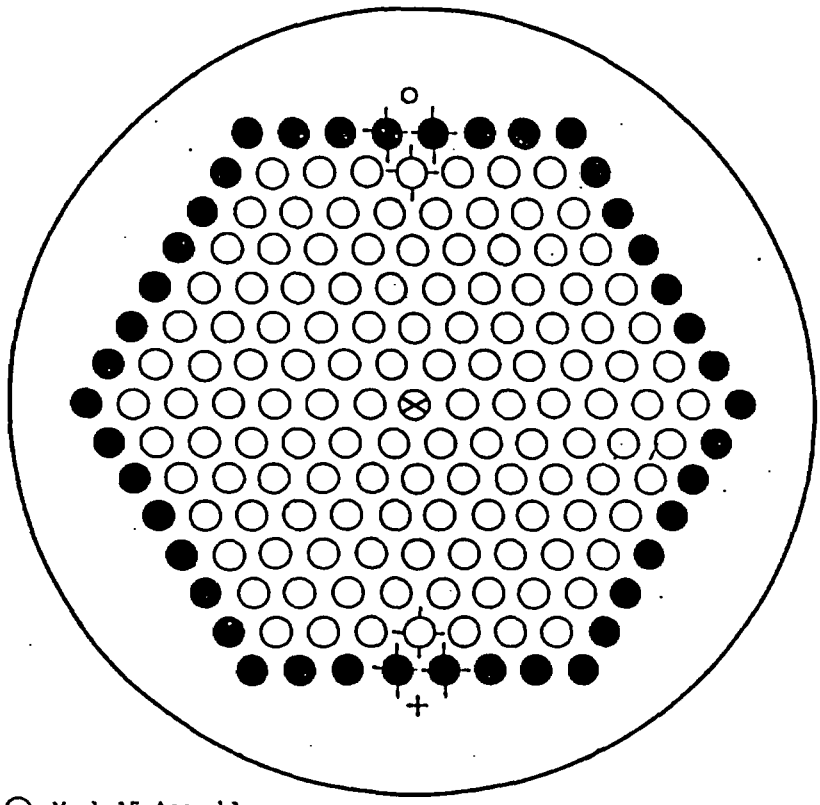
Table 1

Mark 15 Assembly Geometry and Fuel Compositions

Al Inner Housing, inches	
O.D.	2.004
I.D.	1.748
Inner Fuel Slug[a]	
O.D.	2.606
I.D.	2.017
Outer Fuel Slug[a]	
O.D.	3.641
I.D.	3.164
Al Outer Housing	
O.D.	4.050
I.D.	3.950
Fuel Composition, wt %	
^{235}U	1.100
^{238}U	98.877
^{236}U	0.023



a. Dimensions include a 0.0015-inch thick nickel plating on the fuel surfaces.



○ Mark 15 Assembly
● 4.9 wt % Li-Al Poison Rod
⊗ Foil Bearing Mark 15 Assembly
-|- Assembly Removed for Reference Environment
o δ^{28} Reference
\+ Reference Foil Spinner

FIGURE 1. Mark 15 Lattice at 7" Δ Pitch in LTR

Material Buckling, B_m^2

The material buckling was obtained by measuring flux profiles in the critical reactor. Radial and axial curvatures were determined independently and combined to obtain $B_m^2 = B_r^2 + B_z^2$. Flux shape data were obtained from activation of both brass (Cu) bead chains and gold pins placed on the axial center line in the central D_2O region of the fuel assemblies. Extensive flux energy-spectrum mapping of the Mark 1S core was done by bare and cadmium-covered gold pin activations to avoid use of data from regions where the flux curvature was energy dependent (i.e. non-asymptotic). The radial activation data were fitted by a least squares procedure to a J_o function and the vertical data to a cosine function. The data that were used in the fit were examined to eliminate errors due to edge effects. This was accomplished by dropping outermost data points until the effects on the curve fitting were random. In practice this amounted to eliminating only the outermost ring of fuel cells for the radial fit. A check of the lattice uniformity was performed by activation of gold pins at five axial levels in the center of all 127 fuel assemblies. Less than 2% variation was found among equivalent positions indicating that no severe radial or axial flux asymmetry existed in the reactor.

Lattice Parameters

Experimental Arrangement. The foil bearing assembly for the activation experiment was placed at the center of the lattice. It was identical to the other lattice fuel assemblies except that inner and outer fuel pieces with accurately machined central angle slots to accommodate thin, bare, arc shaped foils and 1/2-inch thick filler pieces were located at the center of the fuel column. The shaped foils were fabricated to fit accurately in the slots so the specific activity of the foil represented the average reaction rate in the fuel. Epicadmium activations were obtained from foils placed inside a small (0.375-inch diameter x 0.100-inch thick) cadmium pill box contained in a recess in the lower filler piece about 3-inches from the nearest bare foil. The foil bearing assembly was rotated during irradiation to average any radial flux asymmetry.

Reference foils used in the ρ^{28} and spectral index measurements were located on a rotating disc in the reflector region of the reactor and were irradiated simultaneously with the foils in the lattice. The measured cadmium ratio (0.032-inch cadmium) for 0.0105-inch thick copper (^{63}Cu) at the reference position was 195. Paired natural and depleted uranium reference foils for the δ^{28} measurement were placed in an isolated 1-inch natural uranium rod also located in the reflector. Fuel assemblies and poison boundary rods were removed in the immediate proximity of these reference positions to increase the thermal-to-fast flux ratio. Refer to Figure 1.

ρ^{28} Measurement. Measurement of the ^{238}U (n,γ) capture ratio (ρ^{28}) was made by the "copper subtraction" method that permits the epicadmium component of the ^{238}U captures in the fuel to be determined without cadmium-covered ^{238}U foils. Bare and cadmium covered 0.0105-inch thick copper foils were used to determine the subcadmium ^{63}Cu captures in the fuel. Thin (0.003 to 0.004-inch thick) bare natural and depleted (0.019 wt % ^{235}U) uranium foils were used to determine the total ^{238}U captures in the fuel. Bare and cadmium covered copper, natural and depleted uranium foils were irradiated in a reference thermal flux to provide a normalization for subcadmium captures. The subcadmium ^{238}U captures in the fuel were obtained by:

$$^{238}U^{\text{Fuel}}_{\text{Subcd}} = {}^{63}Cu^{\text{Fuel}}_{\text{Subcd}} \cdot \frac{^{238}U^{\text{Th Ref}}_{\text{Subcd}}}{^{63}Cu^{\text{Th Ref}}_{\text{Subcd}}}$$

The epicadmium component of the ^{238}U captures was obtained as the difference between the total capture and the thermal capture. Good agreement was obtained by J. Hardy, Jr. et al[5,6] in a comparison of ρ^{28} values measured by the subtraction method and by the direct measurement of the ^{238}U capture cadmium ratio.

Inherent in the subtraction measurement method is the assumption that copper and ^{238}U thermal cross sections are 1/v below 0.625 eV. ENDF/B-IV evaluations show the ^{238}U subcadmium capture cross section departing slightly from 1/v behavior in the upper end of the thermal region (refer to Figure 2 in the Appendix). The cross section in this region is above that given by the 1/v dependence. Calculations show that the effect is to yield ρ^{28} values by the subtraction method that may be about 1-1/2% high for the Mark 15 lattice in this report. Preliminary results of an investigation of the ^{238}U subcadmium cross section are given in the Appendix.

The ^{239}Np decay from ^{238}U capture was counted in the time interval from 2 to 4 days after irradiation to maximize the 2.3-day decay activity of ^{239}Np relative to background fission product activity. The data were obtained with NaI scintillation counters biased to accept gamma energies in the interval from 90 to 116 keV. A simultaneous count representative of fission product decay activity, obtained at an integral bias of 500 keV, was used to correct for the fission product contribution to the counting rate in the window. The ratio of the ^{235}U fission product counting rate in the 90 to 116 keV window to the ^{235}U fission product counting rate at the 500 keV bias was determined from the natural and depleted uranium foils in the thermal reference that were counted with the foils from the lattice. (The ratio for the small contribution from ^{238}U fission products is assumed to be identical to that for ^{235}U.) The fission product corrections for the

depleted and natural uranium foils were about 0.7% and 5% respectively. No systematic differences were noted in the ρ^{28} values between the natural and depleted foil types. Additional confirmation that the fission product correction was treated properly was obtained by counting the 278 keV γ-ray peak of ^{239}Np using a Ge-Li detector. This peak is nearly free of fission product contamination and gamma self-shielding is less important. Normalized ^{239}Np activations agreed within ±1% for the two methods.

An experimentally determined correction factor of 1.0882 was used to convert the average epicadmium specific activity of the two 0.272-inch diameter x 0.0105-inch thick copper foils used in the cadmium pill box in the fuel to the equivalent epicadmium specific activity for a single 0.500-inch diameter x 0.0105-inch thick copper foil under 30 mils of cadmium (dimensionally similar to the arc-shaped bare copper foils contained in the foil). The factor was measured by irradiating copper foils in both geometries under cadmium on a spinner in the center of the SP[1] reactor. The correction simultaneously establishes the effective cadmium energy for the ρ^{28} measurement at 0.625 eV corresponding to 0.030-inch thick cadmium in slab geometry and isotropic flux incident with a 1/E energy dependence; conditions closely approximated in the SP experiment.

An analytical investigation of the sensitivity of ρ^{28} to the cadmium cutoff energy was made for the Mark 15 lattice using RAHABR. A 10% change in the effective cadmium cutoff energy from a reference energy of 0.6325 eV produced only a 1.07% change in the assembly average value of ρ^{28}.

Small corrections of 1% for the inner fuel and 2% for the outer fuel accounted for the increase in ^{238}U resonance capture caused by neutron streaming through the 0.001-inch gap at the interface between foils and fuel where aluminum was placed to prevent fission product contamination of the foils. These corrections were derived from an auxiliary experiment with coaxial fuel in which known gaps of from 0.001 to 0.021 inch were introduced at the foil sites for the ρ^{28} measurement. The normalized epicadmium activation component of each foil was plotted against foil gap thickness and extrapolated to zero gap to obtain the correction. The magnitudes of these corrections are in quantitative agreement with values derived for rods in a study made by R. Sher and S. Fiarman in which they modeled the streaming of resonance neutrons with a Monte Carlo calculation.[6]

Small calculated corrections of about 2% were applied to the measured subcadmium copper and uranium foil activities in the lattice to account for the thermal flux peaking at the foil sites in the fuel. Calculated thermal flux depression factors were used to derive these corrections.[1] The calculational model assumed an isotropic, monoenergetic flux incident on a slab absorber within a cavity.

Other corrections to the experimental data accounted for:

- Differences (~4%) in gamma attenuation in the 90 to 116 keV window count caused by the difference in foil thickness between the natural and depleted uranium foils used in the measurements. (No systematic differences were noted between the 4 depleted uranium and 2 natural uranium foil detectors used to derive ρ^{28} for each of the coaxial fuel tubes.)

- Differences in the axial elevation of the foils in the experiment. This correction was obtained from a smooth fit of the axial flux derived from bare gold pin activations. With the foil loading centered near the peak of the cosine flux distribution, this correction was less than 1%.

- Small (<1%) differences in foil-to-counter geometry.

Small adjustments obtained from RAHABR calculations were used to convert the measured parameters at 99.61 mol % D_2O to values for 99.75 mol % D_2O.

δ^{25} Measurement. The ^{235}U fission capture ratio (δ^{25}) was measured by activating thin bare and cadmium-covered, dilute ^{235}U-Al foils in the fuel. The fission product gamma activity was measured during the interval from 2 to 4 hours after irradiation by NaI scintillation counters biased at 200 keV. Corrections were made for differences in the axial elevations of the foils, flux peaking at the foil sites in the fuel, foil weight (based on activation calibration) and for counting conditions (i.e., background, deadtime and foil-to-counter geometry differences).

δ^{28} Measurement. The ratio of fissions in ^{238}U to fissions in ^{235}U (δ^{28}) was measured using paired natural and depleted uranium foils in the fuel; 1/2-inch diameter foils of identical composition and thickness were simultaneously irradiated in the δ^{28} reference. The reference was taken as a 1/2-inch recess in the isolated 1-inch natural uranium rod in D_2O. The δ^{28} values for the lattice are based on a δ^{28} reference value of 0.076. This value was obtained by direct measurement using the double fission chamber method for an isolated 1-inch diameter natural uranium rod imbedded in graphite as described in Reference 1. A 7.7% reduction obtained RAHAB cell calculations has been applied to the 0.076 reference value to account for the difference in backscatter between D_2O and graphite.

R Measurement. Bare and cadmium covered lutetium and copper foils were irradiated in the fuel and in the thermal reference. The activation ratio of subcadmium captures in ^{176}Lu (0.14 eV resonance) to subcadmium captures in ^{63}Cu (1/v) within the fuel is a parameter related to the energy distribution of the thermal neutrons. Normalization to the same ratio in the undistorted

Maxwellian spectrum at the thermal reference position provides a spectral index, R, that is a measure of the spectrum hardening in the fuel.

C^+ Measurement. A new procedure was derived for the determination of an important reaction rate parameter (C^+) defined as the ratio of ^{238}U (n,γ) captures to total (^{235}U + ^{238}U) fissions. This parameter is closely related to the modified conversion ratio (C^*) defined as the ratio of ^{238}U (n,γ) captures to ^{235}U fissions. The procedure requires irradiation in the lattice of thick, full ring segments of the actual Mark 15 fuel rather than small sectored foils. The advantages of this measurement over the foil method of measuring the C^* parameter are:

- Positional inaccuracies are minimized
- Azimuthal variations are automatically averaged
- Errors from differential fission product escape are reduced
- No perturbations are introduced from use of foils in the lattice.

C^+ was determined from the relative fission rates and the relative ^{238}U capture rates in "foils" of Mark 15 fuel irradiated simultaneously in the LTR lattice and in the SP thermal column. The "foils"in the lattice consisted of 1/2-inch-long ring sections irradiated as an integral part of the Mark 15 coaxial fuel near the center of the LTR. The "foils" in the thermal reference were 1/2-inch-long (30°-inner; 18°- outer) ring sectors of Mark 15 fuel. These were stacked in linear columns with identical guard pieces at both ends. Following irradiation the relative total fission rate between the lattice and reference "foils" was determined by counting with a Ge-Li detector the 1596-keV photopeak from ^{140}La. The relative ^{239}Np capture rate was measured by counting the photopeak at 278 keV. The full ring segments were placed symmetrically on the axis of the cylindrical Ge-Li detector for counting. The ring sectors were assembled on the same arc as the full rings. Lead rings were placed on the inside and outside of the Mark 15 rings and similarly around the ring sectors to minimize counting of circumferential surface activation. In addition, unirradiated sectors were placed at both ends of the ring sector arc. Counting was done in the interval from 3-8 days after irradiation. The value of C^+ is related to the counting ratios by the expression

$$C^+ = \left(\frac{\Sigma_a{}^{238}}{\Sigma_f{}^{235}}\right)_{\text{Th Ref}} \cdot \frac{[^{239}\text{Np Prod}]_{\text{Lattice}}}{[^{239}\text{Np Prod}]_{\text{Th Ref}}} \cdot \frac{[^{140}\text{La Prod}]_{\text{Th Ref}}}{[^{140}\text{La Prod}]_{\text{Lattice}}}$$

$$\cdot \frac{(1 + f\,\delta^{28})}{(1 + \delta^{28})}$$

Here the right hand ratio which includes the f factor corrects for the difference in fission product yield of ^{140}La between ^{235}U and ^{238}U fission. The δ^{28} value is that measured for each tube (see Table 4). Values of f, $\sigma_a{}^{238}$, $\sigma_f{}^{235}$, g^{235}, and g^{238} used in the determination of C^+ are given in Table 2. Inherent in the measurement is the assumption that the ^{132}Te and ^{140}La fission product yields are independent of neutron energy. A small (<1%) correction for ^{238}U epithermal neutron capture in the thermal reference was measured using bare and cadmium covered depleted uranium foils. A calculated correction of ∿2% also was applied to account for ^{238}U fast fission in the thermal reference.

Inner-to-Outer Fuel Activation Rate Ratios. Inner-to-outer fuel activation rate ratios per unit volume were obtained for ^{238}U epicadmium capture, ^{238}U subcadmium capture, ^{238}U fission, ^{235}U subcadmium fission, ^{235}U epicadmium fission and ^{235}U fission. These ratios were derived as a byproduct of the foil activations for the ρ^{28}, δ^{28}, and δ^{25} measurements.

The inner-to-outer fuel total fission ratio per unit volume was obtained as a byproduct of the C^+ measurement. Approximately two weeks after irradiation, with the ^{140}La activity dominant, a measurement of the ratio of the total ^{140}La yield of the inner-to-outer ring was made by monitoring the 1596 keV photopeak with a Ge-Li detector. The measurements were made at different elevations above the detector to study the geometry dependent counting efficiencies between the inner and outer rings. The ^{140}La activity is closely proportional to the fission product yield with only a small correction for the different yield in ^{238}U and ^{235}U fission. The ratio of ^{238}U fissions to ^{235}U fissions used for this correction was obtained from the δ^{28} measurement. The activity ratio was corrected for the difference in volume between the inner and outer fuel rings.

COMPARISON OF RESULTS

LTR and SE Experiments

Material Buckling. A measured value of 7.29 ± 0.06 m^{-2} was obtained for the material buckling from the LTR experiment compared to 7.81 ± 0.30 in the SE after adjustment to comparable conditions (see Table 3). The large (0.51 m^{-2}) discrepancy is outside of experimental uncertainties. Systematic differences in the

Table 2

Constants Used in C^+ Measurements

Decay Chain		$^{140}Ba \rightarrow ^{140}La$
^{235}U Fission Product Yield		0.0636
^{238}U Fission Product Yield		0.0605
f		0.951
	^{235}U	^{238}U
σ_a, b	-	2.70
σ_f, b	582.2	-
g	0.9759	1.000[a]

a. Refer to the section on the energy dependent of the ^{238}U subcadmium capture cross section in the Appendix.

Table 3

Mark 15 Lattice Reactivity at 7-inch Δ Pitch & 99.75 mol % D_2O

	Material Buckling, m^{-2}
LTR Measurement	7.29 ± 0.06[a]
SE Measurement (Ref. 2)	7.81 ± 0.30[b]
RAHABR Computation	7.12 ± 0.20

a. The material buckling measured at 99.61 mol % D_2O has been reduced by 0.16 m^{-2} (based on calculation) to correct to conditions at 99.75 mol % D_2O. Corrections have been applied for the reactivity effects of the activation detectors (estimated to be worth -0.01 m^{-2}) and for the presence of 29 highly perforated, thin wall aluminum guide tubes (for safety and control rods) located at interstitial positions in the lattice (estimated to be worth -0.01 m^{-2}).

b. A small (+0.11 m^{-2}) calculated correction has been applied to convert the SE measurement to the same geometrical lattice conditions as the LTR measurement.

The Mark 15 fuel in the SE measurement was clad with 30 mil thick aluminum and the outside surface of the inner fuel contained 4 thin aluminum ribs. Minor differences in the support tube housing arrangement also existed. The SE geometry is detailed in Reference 1.

Table 4

Mark 15 Lattice Parameters at 7-inch Δ Pitch & 99.75 mol % D_2O

Parameter	Inner Tube			Outer Tube			Assembly Avg.		
	Measurement		RAHABR Calc	Measurement		RAHABR Calc	Measurement		RAHABR Calc
	LTR[a]	SE[b]		LTR[a]	SE[b]		LTR[a]	SE[b]	
ρ^{28}	2.23 ± .04	2.14 ± .04	1.985	1.98 ± .08	1.86 ± .05	1.777	2.05 ± .09	1.97 ± .06	1.856
δ^{25}	0.193 ± .002	0.194 ± .002	0.1936	0.150 ± .003	0.152 ± .003	0.1458	0.168 ± .004	0.168 ± .004	0.1636
δ^{28}	0.107 ± .004	0.103 ± .004	0.0940	0.073 ± .003	0.070 ± .003	0.0660	0.086 ± .005	0.083 ± .005	0.0767
C^{*c}	1.087 ± .009	---	1.031	1.036 ± .008	---	1.009	1.056 ± .007	---	1.017
	(1.094 ± .014)	(1.074 ± .015)		(1.066 ± .029)	(1.030 ± .018)		(1.067 ± .033)	(1.049 ± .022)	
R	1.621 ± .020	1.644 ± .016	---	1.493 ± .030	1.539 ± .023	---	---	---	---

a. Small calculated corrections from RAHABR have been applied to convert the parameters measured in the LTR at 99.61 mol % D_2O to values that would be obtained at 99.75 mol % D_2O.

b. Small calculated corrections from RAHABR have been applied to convert the ρ^{28}, δ^{25} and δ^{28} parameters measured in the SE to the same geometrical lattice conditions as the LTR measurement. (See footnote in Table 3.)

c. Values in parentheses were derived from the expression $C^* = \frac{C^{28}}{F^{25}} \cdot \frac{(1 + \rho^{28})}{(1 + \delta^{25})(1 + \delta^{25})}$.

reactivity measured in an exponential facility and those obtained from critical measurements were reported for the simple case of 1-inch diameter natural uranium rods and rod clusters in D_2O.[7] The differences were found to be dependent on fuel assembly size and the moderator-to-fuel ratio. An extrapolated value of about 0.30 m^{-2} (exponential measurement higher) is obtained for single rods with the same moderator-to-fuel ratio as the Mark 15 at the 7-inch pitch. Efforts to determine the source of systematic error in exponential reactivity measurements have not been successful. The use of reactivity data from D_2O exponential experiments as benchmarks to test analytical methods used in lattice analysis and to evaluate cross section data may no longer be justified with the current state of calculational sophistication.

Lattice Parameters. Parameters measured in the critical LTR reactor are compared with the SE exponential measurements in Table 4. Parameters measured in the SE and LTR agree within the assigned errors. The results indicate that the neutron spectrum is closely identical in the asymptotic regions of the critical and exponential facilities where the measurements were made.

LTR Experiment and RAHABR Computations

Material Buckling. The measured material buckling (7.29 ± 0.06 m^{-2}) in the LTR is in good agreement with the 7.12 ± 0.20 m^{-2} value calculated by RAHABR using ENDF/B-IV cross sections (see Table 3).

Lattice Parameters. Parameters measured in the LTR are compared with RAHABR (ENDF/B-IV) calculations in Table 4.

The major discrepancies between measured and calculated parameters occur in ρ^{28} and δ^{28} which are calculated about 10% low in both the inner and outer fuel. The discrepancy between measured and calculated δ^{28} will be reduced by ENDF/B-V data as a result of a harder fission spectrum and changes in ^{238}U inelastic scattering. Independent confirmation of the measured values of ρ^{28} was obtained via the C^+ measurement. The C^+ parameter is related to ρ^{28}, δ^{25} and δ^{28} by the expression

$$C^+ = \frac{C^{28}}{F^{25}} \cdot \frac{(1 + \rho^{28})}{(1 + \delta^{25})(1 + \delta^{28})}$$

where

$C^{28} \equiv$ Subcadmium ^{238}U captures in the fuel

$F^{25} \equiv$ Subcadmium ^{235}U fissions in the fuel

Since $\rho^{28} \approx 2.0$ in the Mark 15 lattice, C^+ is sensitive to small percentage changes in ρ^{28}. Therefore the C^+ measurement within 1% accuracy becomes an independent means of verifying the ρ^{28}

measurement. The C^{28} to F^{25} ratio is calculated quite well by RAHABR for this purpose. Values of C^+ derived from parameters by this method are given in Table 4. Agreement with the direct measurement of C^+ is good providing additional confidence in the value of ρ^{28} derived by the foil activation technique.

A comparison of measured and calculated inner-to-outer fuel reaction rate ratios are given in Table 5. The good agreement indicates that the spatial distribution of the neutron energy spectrum is calculated properly in the coaxial fuel by RAHABR. With the inner-to-outer ratios of epicadmium ^{238}U captures and subcadmium ^{238}U captures predicted properly, the 10% discrepancy of ρ^{28} in both the inner and outer fuel suggests either that the resonance capture in ^{238}U is uniformly underpredicted or that the measured ρ^{28} is erroneously high.

The inner-to-outer fuel total fission ratio is related to foil parameters by the expression:

$$(I/0)_{\substack{\text{Total}\\\text{Fission}}} = (I/0)_{\substack{^{235}U\ \text{Subcd}\\\text{Fission}}} \cdot \frac{[(1+\delta^{28})(1+\delta^{25})]_{\text{inner}}}{[(1+\delta^{28})(1+\delta^{25})]_{\text{outer}}}$$

The ratio obtained from this expression is compared with that from the ^{140}La measurement in Table 5. No explanation is available to account for the 5.8% difference between the two values.

CONSISTENCY ANALYSIS

The consistency of the Mark 15 data from the LTR experiment has been tested using a two-energy-group, neutron balance equation[3] that expresses the material buckling (B_m^2) as a function of the integral parameters and calculable cross-section dependent terms. The expression is

$$B_m^2 \left[\frac{D_1\ (\Sigma_{a2} + \Sigma_{r2\to1} + D_2\ B_m^2)}{\Sigma_{f2}\ \Sigma_{r1\to2}} + \frac{D_2}{\Sigma_{f2}}\right] = (\bar{\nu}_a^{25} - 1) +$$

$$(\bar{\nu}_1^{25} - 1)\ \delta^{25} - \bar{\alpha}_2^{25} - \bar{\alpha}_1^{25}\ \delta^{25} +$$

$$(1+\delta^{25})\ [(\bar{\nu}_1^{28} - 1)\ \delta^{28} - (1+\delta^{28})\ C^+ - \zeta]$$

where δ^{25}, δ^{28} and C^+ are the experimentally determined activation parameters. (The equation can be cast in terms of ρ^{28} using the relation given earlier for C^+.)

and

Table 5

Comparison of Measured and Calculated
Inner-to-Outer Fuel Reaction Rate Ratios, 99.61 mol % D_2O

Reaction Rates	Inner-to-Outer Ratio (per unit volume) Measured	Calculated (RAHABR)
epi Cd ^{238}U captures	0.809 ± .018	0.803
sub Cd ^{238}U captures	0.719 ± .007	0.718
^{238}U fissions	1.048 ± .011	1.050
epi Cd ^{235}U fissions	0.911 ± .012	0.940
sub Cd ^{235}U fissions	0.706 ± .010	0.707
^{235}U fissions	0.732 ± .007	0.737
Total fissions	0.801 ± .012[a]	0.756
	0.757 ± .02[b]	

a. Measured by ^{140}La signal from Mark 15 fuel ring pieces.

b. Derived from foil activations by use of the expression:

$$\text{Total Fission} = (I/O)_{\substack{\text{sub Cd } ^{235}U \\ \text{fissions}}} \cdot \frac{(1+\delta^{28})_{\text{inner}}}{(1+\delta^{25})_{\text{outer}}} \cdot \frac{(1+\delta^{25})_{\text{inner}}}{(1+\delta^{25})_{\text{outer}}}$$

$$\zeta = \frac{\text{Total Captures in Materials Other than } {}^{235}U \text{ and } {}^{238}U}{\text{Total } {}^{235}U \text{ Fissions}}$$

$$\bar{\nu}_n = \frac{\overline{\nu\Sigma_f}_n}{\Sigma_{f_n}}$$

$$\bar{\alpha}_n = \frac{\Sigma_{c_n}}{\Sigma_{f_n}}$$

The consistency buckling obtained from this expression using RAHABR (ENDF/B-IV) to generate the cross section dependent terms was 5.42 ± 1.18 m^{-2} compared to the measured buckling of 7.29 ± 0.06 m^{-2}. Assuming that the measured buckling is correct, that the two-group neutron balance expression relating measured parameters to B_m^2 is valid, and that the cross sections are correct, then the discrepancy between the measured buckling and the consistency buckling would be attributed to erroneous experimental parameter(s).

The sensitivity of B_m^2 to small variations in the Mark 15 reaction rate parameters has been investigated using the consistency equation in the form:

$$C_1 (B_m^2)^2 + C_2 B_m^2 - C_2 = 0$$

where

$$C_1 = \frac{D_1 D_2}{\Sigma_{f2} \Sigma_{r1\to2}}$$

$$C_2 = \frac{D_1 (\Sigma_{a2} + \Sigma_{r2\to1})}{\Sigma_{f2} \Sigma_{r1\to2}} + \frac{D_2}{\Sigma_{f2}}$$

$$C_3 = (\bar{\nu}_2^{25} - 1) + \delta^{25} (\bar{\nu}_1^{25} - 1 - \bar{\alpha}_1^{25}) - \bar{\alpha}_2^{25} +$$

$$(1 + \delta^{25}) \left[(\bar{\nu}_1^{28} - 1)\, \delta^{28} - \frac{C^{28}}{F^{25}} \frac{(1 + \rho^{28})}{(1 + \delta^{25})} - \zeta\right]$$

here

$\frac{C^{28}}{F^{25}}$ is the ratio of ^{238}U thermal captures to ^{235}U thermal fissions

Sensitivity coefficients are summarized in Table 6. Also shown in Table 6 is the percent change required to force internal consistency for each of several variables. Small changes in ρ^{28}

Table 6

Sensitivity Analysis of Consistency Equation
for Mark 15 Lattice at 7-Inch Δ Pitch

Variable	Change in B_m^2, m^{-2} / 1% Change in Variable	% Change in Variable To Force Consistency
ρ^{28}	-0.21	-8.8
δ^{25}	0.043	43.0
δ^{28}	0.035	52.9
C_1	-0.011	-168.0
C_2	-0.053	-34.9
C_3	-0.053	34.9

have a significant effect on B_m^2 while other variables are much less important. In fact most of the 25% discrepancy between the measured buckling and the consistency buckling could be resolved by a 6.5% decrease in the measured ρ^{28}. Not only would this satisfy the consistency criteria but it would also improve agreement between the measured and calculated values of ρ^{28}. However, corrections have been applied for all known systematic errors in the ρ^{28} measurement. A conservative 2% error flag is assigned to ρ^{28}_{inner} where the standard deviation of the mean for the six foils used in the measurement was ±0.3% and a 4% error flag is assigned to ρ^{28}_{outer} where the standard deviation of the mean for the five foils used in the measurement was ±2.0%. The most likely source of error, reflected in the count rate variation for the foil detectors in the fuel, is the accuracy of the geometrical fit of the foil and fuel segments in the machined window slot of the fuel. Some measure of this error is obtained from an earlier study[8] using foils in a 1/2-inch diameter natural uranium rod to investigate the effect of radial misalignment. As expected, the activations lost due to indentation were nearly offset by those gained in the protruding section. The net effect was to give activation results ∿0.2% lower than the correct values for a 0.005-inch radial misalignment. The effect of foil misalignment is more severe in coaxial fuel, particularly in the outer fuel where the thermal flux gradient is steep, and this probably accounts for the larger spread in activation results for the foils in the outer fuel.

The overall consistency of results with the independent C^+ measurement technique and the general agreement in results from experiments at different laboratories suggests that there are no serious systematic errors in the measurement and correction techniques for the determination of ρ^{28} (Reference 9). However, any adjustment of the calculated ρ^{28} would destroy the good agreement between measured and calculated reactivity.

SUMMARY AND CONCLUSIONS

- Although measured and calculated buckling for the Mark 15-LTR critical is in good agreement, a significant discrepancy exists in ρ^{28} that cannot be resolved within experimental errors.
- Agreement between measured and calculated inner-to-outer fuel activation ratios suggests that the ρ^{28} discrepancy is most likely a result of the underprediction of epicadmium captures in ^{238}U. However, adjustment of ^{238}U captures to correct ρ^{28} will cause the buckling to be underestimated.
- The Mark 15-LTR experiment does not meet the internal consistency criterion using RAHABR with ENDF/B-IV cross sections to generate the cross section dependent terms.

- The use of D_2O exponential experiments as valid benchmarks is compromised by systematic error in B_m^2 although nuclear parameters are in agreement with critical experiments.

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APPENDIX

Energy Dependence of ^{238}U Subcadmium Capture Cross Section

The energy dependence of the ^{238}U capture cross section in the thermal and near thermal energy region is important since it enters into the basic computation of lattice bucklings and reactivities. It is particularly important for massive ^{238}U bearing assemblies at low moderator-to-fuel ratios. Absorption hardening and a hard spectrum combine to shift a larger fraction of the neutron induced reactions to the upper end of the thermal region where this cross section is most uncertain. Knowledge of the

energy dependence of the cross section is also essential to compare conversion ratio (C^* or C^+) measurements to direct cadmium ratio (ρ^{28}) measurements. Such comparisons rely on calculations of the subcadmium ratio of ^{238}U fissions both in the thermal reference and in the lattice. Measurements of the ^{238}U cadmium ratio (ρ^{28}) by the indirect method also depend sensitively on the ^{238}U cross section shape. A computation must be made of the ratio of ^{238}U to 1/v activations in the thermal reference flux to the same ratio for subcadmium neutrons in the lattice. For this application it has generally been assumed (including values in this report) that ^{238}U is closely 1/v and that the two ratios are the same.

Figure 2 shows three shape dependences that have been used at SRL. The 1/v dependence has been assumed for analysis of various activation experiments. The values listed as SRL "STANDARD" assumes a low lying negative energy resonance. The choice of energy and partial widths is such as to give good agreement with D_2O-Uranium lattice buckling measurements at SRL. The ENDF/B-IV values assume negative energy levels so far removed from thermal energies that they have essentially no effect on the shape.

An experimental program has been devised to investigate this energy dependence. The experimental technique utilizes a well-thermalized neutron flux which is thermally heated to selected temperatures. Pairs of multilayer packets of alternating copper and ^{238}U foils are simultaneously irradiated under thin gadolinium filters in the heated flux and irradiated bare in a well-thermalized flux at room temperature. Cadmium covered foils provide corrections for the small epicadmium component in both cases. The relative copper and ^{238}U activations are counted in a Ge-Li detector under conditions designed to minimize errors in the activation ratios.

Figure 3 shows the ENDF/B-IV normalized activation ratios for a range of neutron temperatures and gadolinium thicknesses. The calculations assume isotropic flux incident on infinite slabs. (Thin detectors are used for these illustrations, but the actual foil packet conditions are included in the analysis of the experiments.) A preliminary experiment has been completed with the "heated" flux at room temperature and with a gadolinium filter surface density of 0.000145 atoms/barn. The experimental ratio of ^{238}U to Cu activations in the "heated" flux to the bare foil activations in the reference flux was 1.012 ± 0.004 compared to 1.0148 calculated from ENDF/B-IV, 1.000 for a 1/v dependence, and a quantity less than unity for the SRL "STANDARD" cross sections. These preliminary results agree with the ENDF/B-IV structure within the experimental errors.

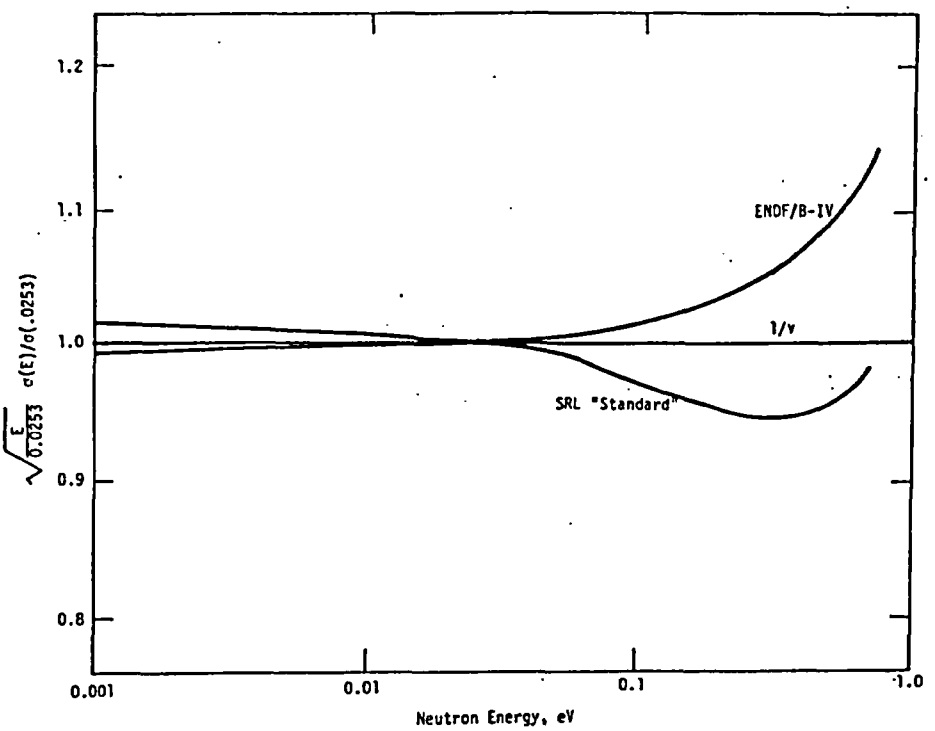

FIGURE 2. Energy Dependence of ^{238}U Capture Cross Section

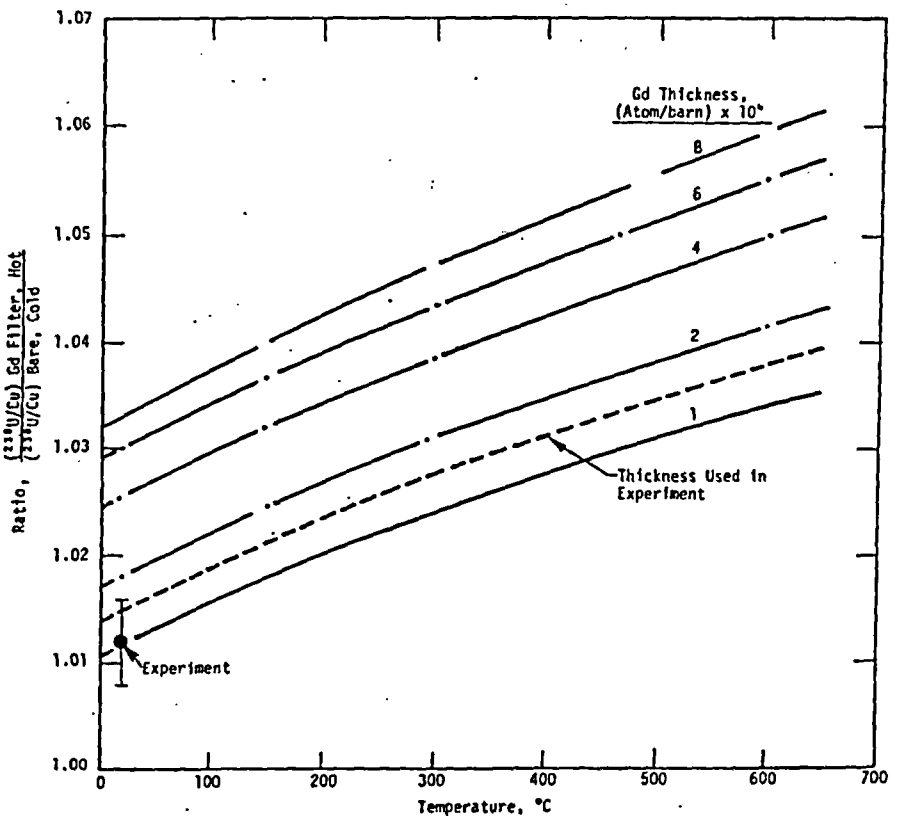

FIGURE 3. Activation Ratios for $^{238}U/Cu$ Using ENDF/B-IV