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THE ORR WHOLE-CORE LEU FUEL DEMONSTRATION

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ABSTRACT

The ORR Whole-Core LEU Fuel Demonstration, conducted as part of the U.S. Reduced Enrichment Research and Test Reactor Program, has been successfully completed. Using commerically-fabricated U_3Si_2-Al 20%-enriched fuel elements (4.8 g U/cc) and fuel followers (3.5 g U/cc), the 30-MW Oak Ridge Research Reactor was safely converted from an all-HEU core, through a series of HEU/LEU mixed transition cores, to an all-LEU core. There were no fuel element failures and average discharge burnups were measured to be as high as 50% for the standard elements and 75% for the fuel followers. Experimental results for burnup-dependent critical configurations, cycle-averaged fuel element powers, and fuel-element-averaged ^{235}U burnups validated predictions based on three-dimensional depletion calculations. Calculated values for plutonium production and isotopic mass ratios as functions of ^{235}U burnup support the corresponding measured quantities. In general, calculations for reaction rate distributions, control rod worths, prompt neutron decay constants, and isothermal temperature coefficients were found to agree with corresponding measured values. Experimentally determined critical configurations for fresh HEU and LEU cores radially reflected with water and with beryllium are well-predicted by both Monte Carlo and diffusion calculations.

INTRODUCTION

Early in the history of the U.S. Reduced Enrichment Research and Test Reactor (RERTR) Program the need for a whole-core demonstration of high uranium density LEU fuel was recognized. Plate-type U_3Si_2-Al dispersion fuel was chosen for the demonstration because of it's excellent behavior under irradiation (Ref's. 1 & 2), it's high maximum practical uranium density (4.8 g U/cc), and it's ease of fabrication by commercial suppliers. The primary objectives of the demonstration were:

1. to demonstrate the safe and acceptable behavior of commerically-fabricated 20%-enriched U_3Si_2-Al dispersion fuel (4.8 g U/cc in fuel meat) to ^{235}U burnups greater than 50% in a relatively high power research reactor.

2. to demonstrate the safe transition process from an all-HEU equilibrium core, through a series of mixed HEU/LEU cores, to an all-LEU equilibrium core, and

3. to provide an abundance of core physics data for validating analytical methods, codes and burnup predictions.

The 30-MW Oak Ridge Research Reactor (ORR) was chosen for the demonstration because its high power would provide data for the validation of fuel cycle calculations in relatively short times and because analyses showed that the demonstration would cause only minor changes in the performance of standard ORR experiments. Three international fuel vendors fabricated the U_3Si_2-Al LEU elements for the ORR demonstration. Sixty fuel elements and twelve shim rod assemblies were fabricated by Babcock and Wilcox (USA), and twenty elements each were supplied by CERCA (France) and NUKEM (FRG). Each 19-plate 20%-enriched fuel element had a meat density of 4.8 g U/cc and contained 340 g ^{235}U. The 15-plate fuel followers had a density of 3.5 g U/cc and contained 200 g ^{235}U. HEU (U_3O_8-Al) and LEU fuel elements are of identical geometry.

The demonstration began with an all-HEU reference core (174C) in December 1985. The first three LEU elements were phased into the ORR core at the beginning of January 1986. Following every cycle thereafter, three or four additional LEU elements were inserted into the core while an equal number of HEU elements were discharged. Normally the ORR operated with two nearly identical cores which were alternated between the reactor and the pool to allow for xenon decay. The first all-LEU core (178C) operated in December 1986. With the completion of cycle 179A, the ORR was permanently shut down in March 1987 for reasons entirely unrelated to the demonstration. Table 1 provides a summary of the 30-MW cores used in the demonstration.

Because of this unexpected shutdown, not as many LEU fuel elements were fully irradiated as had been planned initially. Nevertheless, the primary objectives of the demonstration, as stated above, were successfully carried out. Measurements made during the demonstration included core maps of reaction rates, control rod worths, isothermal temperature coefficients, prompt neutron decay constants, and cycle-averaged fuel element powers and ^{235}U discharge burnups. Typical approach-to-critical measurements were also made for fresh HEU and LEU core configurations radially-reflected with both water and beryllium. This report summarizes comparisons of measured and calculated results obtained from the demonstration. However, more details than can be given here are provided in Ref. (3). In addition, results of postirradiation examinations of demonstration fuel elements are given in Ref. (4).

CRITICAL ASSEMBLIES WITH FRESH FUEL

Standard approach-to-critical methods were used to determine critical configurations for cores with unirradiated HEU (93% enriched) and LEU (20% enriched) fuel and radially-reflected with water and with beryllium. This data was used to test analytical models and multigroup cross section generation methods with some results given in Ref. (5).

Figure 1 shows core maps for the ORR fresh fuel critical assemblies. Three of these assemblies (HEU-1, LEU-1, and 179-AX5) were reflected in the radial direction with water. For the HEU-1 core, water occupied grid positions C4 and C6. Core 179-AX5 was an LEU core with the magnetic fusion experiments (MFE) replaced with water. Three assemblies (HEU-2, LEU-2, and 179-AX6) were radially-reflected with beryllium. For the LEU core 179-AX6 the MFE's were replaced with beryllium elements.

The ORR shim rods (SR) consist of an upper cadmium poison section and a lower 15-plate fuel follower section. For these measurements the four shim rods located in positions D4, D6, F4, and F6 were banked together and moved as a unit to achieve criticality. For shim rods withdrawn 15.25 inches the bottom of the cadmium poison section lies on the axial midplane of the core.

Table 2 shows the eigenvalues calculated for each of these experimentally determined critical configurations. Small corrections have been applied to account for temperature differences between the experimental conditions and the temperature at which the cross sections were generated. Neutron absorption in impurities and in minor elements used in the aluminum alloys has been expressed in terms of an equivalent boron concentration. The DIF3D code[6] was used to perform the diffusion calculations where the cadmium poison was treated by a set of effective diffusion parameters.[7] The Monte Carlo results are based on 300,000 neutron histories and were obtained from the continuous energy VIM code.[8] Cross sections for both types of calculations were obtained from ENDF/B Version IV. Table 2 shows that the calculated eigenvalues are in good agreement with the experimentally determined critical configurations, for which k_{eff} is unity.

REACTION RATE DISTRIBUTIONS

Activity distributions were measured by activating thin wires located in water channels between fuel plates. For the fresh fuel criticals gold wires were used for this purpose since the large activation cross section of gold allowed the measurements to be made without significantly activating the fuel. For all the other cores, however, cobalt-vanadium (2 wt% Co) wires were activated for six hours at 300 kw power levels. In general, several wires were located in each fuel element. These cobalt activity measurements had the dual purpose of allowing prediction of maximum fuel power density prior to full power operation of the reactor and of providing reaction rate distributions to compare with calculations. The maximum power densities were used to show that adequate safety margins would be preserved at full power.[9]

Measured and calculated ^{198}Au and ^{60}Co activity distributions averaged over the fuel element have been compared by R. J. Cornella. Some early results are given in Ref. (10). Figure (2) shows the calculated-to-experiment (C/E) ratios for gold wires in the water-reflected fresh fuel cores. The RMS DEV shown in this figure is the root-mean-square deviation of the C/E ratios from unity. Some typical results obtained from Co-V wire data are given in Fig. 3. Note that only those wires irradiated in standard 19-plate fuel elements were used to evaluate the RMS DEV values. In general, measured and calculated ^{60}Co activities, averaged over each fuel element, agree reasonably well.

SHIM ROD WORTHS

Differential shim rod worths were measured in the ORR by the positive period method. Because of intense gamma-ray fields from highly active fuel elements and associated photoneutron sources, however, the reactor had to operate at high enough powers so that temperature-related feedback effects during the reactivity transient were not negligible. Under these circumstances the transient flux never acquires a purely exponential shape characterized by an asymptotic period. Therefore, differential shim rod worths were evaluated from a careful analysis of the measured shape of the initial portion of the time-dependent flux following a positive reactivity insertion. In this region of the curve temperature change effects are still negligible. To further complicate the analysis, delayed photoneutrons contribute to the kinetic response of the reactor and to the value of the effective delayed neutron fraction. The methods used to determine ORR differential shim rod worths from measured time-dependent fluxes were presented at the 1987 RERTR meeting[11] and so will not be repeated here.

Table 3 shows some differential worths measured in several ORR cores using techniques just described. Although the errors are relatively large, most of the C/E ratios are within about

5% of unity. More results may be found in Ref's (3) and (11). Most of the differential shim rod worth measurements were conducted with a coolant flow rate of 1200 gpm. For core 179-AX7, however, measurements were made at both 1200 and 18,000 gpm. These results are reported in Ref. (3) and show that somewhat lower C/E ratios were obtained for the high flow rate conditions. This suggests that the data analysis methods described above did not completely remove temperature-related negative feedback effects and probably accounts for the fact that most of the C/E ratios in Table 3 are somewhat greater than unity.

The total or integral rod worth is obtained by integrating the differential worths from the lower limit (LL) to the upper limit (UL) of rod movement. To carry out these integrations the measured and calculated differential worths were fit to sixth degree polynomials by the least squares process. Results for the D6 shim rod in core 179-AX5 are summarized in Table 4. Also shown in this table are the DIF3D and VIM evaluations of the total D6 rod worth based on eigenvalue calculations for the rod-in and rod-out configurations.

The VIM-Monte Carlo and the DIF3D-diffusion results are in very good agreement. They are also less than 1% larger than the integral worth obtained by integrating the calculated differential worths. However, these integral and total worths are not expected to be exactly the same because of differences in the rod bank positions.

PROMPT NEUTRON DECAY CONSTANT

The prompt neutron decay constant is just the ratio of the effective delayed neutron fraction to the prompt neutron lifetime. Reactor noise methods were used to measure this ratio in several ORR cores.[12] Signals from two fission chambers located on different sides of the core were processed by a Fourier analyzer to obtain the cross-power spectral density as a function of frequency. A least squares analysis of this frequency spectrum determines the break frequency which when multiplied by 2π gives the prompt neutron decay constant. Some preliminary results for the fresh-fueled water-reflected criticals are given in Ref. (13).

Table 5 compares measured and calculated values for the prompt neutron decay constant. Unlike the other cores, 179A used mostly previously irradiated fuel and so had a background contribution from delayed photoneutrons. These delayed photoneutrons must be included in the evaluation of the effective delayed neutron fraction. Table 5 shows the calculated values for the delayed neutron fraction, with and without photoneutrons. This same value for the total delayed neutron fraction (with photoneutrons) was also used in the evaluation of differential shim rod worths in cores 179A and 179-AX7 (Table 3). As can be seen from Table 5, measured and calculated values for the prompt neutron decay constant are in good agreement.

ISOTHERMAL TEMPERATURE COEFFICIENT

The isothermal temperature coefficient was measured in core 179-AX7, which was identical to 179A (Fig. 4) except that the MFE's and irradiation (Eu,Ir) experiments were removed. With the coolant at its lowest temperature, shim rods F4 and F6 were withdrawn to their upper limits, B6, D4 and D6 were banked together at a fixed position (12.76"), and B4 was withdrawn to achieve criticality. Because of friction heating by the pumping system, the coolant temperature slowly increased. With about every 3 degree C temperature increase the B4 critical rod position (CRP) was redetermined. Thus, the B4 CRP was measured as a function of coolant temperature in the range from 25 to 45 degrees C. The differential worth of the B4 shim rod was measured over this same rod displacement interval. Since these temperature changes occurred very slowly and because the reactor was subcritical most of the time, the measurements were made under isothermal conditions.

Table 6 summarizes the isothermal temperature coefficient evaluations. The first column shows the differential worth of the B4 shim rod measured over the interval of interest while dL/dT is the slope of the critical rod position versus temperature data. Cross section sets, generated at 23 and 77 degrees C, were used to calculate the temperature coefficient. Within experimental errors, the calculated isothermal temperature coefficient is consistent with the measured one.

BURNUP CALCULATIONS

One of the primary purposes of the whole-core demonstration was to provide data for the validation of fuel cycle calculations. The REBUS-3 code[14] was used to perform three-dimensional non-equilibrium burnup calculations for each of the 22 full power cores used in the demonstration. For each of these calculations the cycle length, expressed in full power days (FPD's), was divided into several subintervals or time nodes (TN's). In order to make use of the control rod movement capability of the REBUS-3 code, shim rod positions at the boundaries of each time node were determined from control rod position histories recorded throughout each burn cycle.

Table 7 gives the calculated eigenvalues corresponding to the experimentally-determined critical configurations for each time node and for each operating core. These eigenvalues have been temperature-corrected to account for small changes between the operating core temperature and the 296K used for cross section generation. The configuration for each of these cores is given in Ref. (3). Table 7 shows that the REBUS-3 code adequately predicts the influence of burnup on the eigenvalues throughout the burn cycle. For these calculations the cadmium poison section of the shim rods was treated by the methods described in Ref. (7).

The REBUS-3 calculations were also used to determine cycle-averaged fuel element powers and fuel-element-averaged ^{235}U burnups. These results will be compared with corresponding measured values in the following sections. Together with the eigenvalues given in Table 7, these comparisons serve to validate the fuel cycle calculations.

CYCLE-AVERAGED FUEL ELEMENT POWERS

After each burn cycle during the whole-core demonstration the fuel elements were removed from the 30-MW ORR to allow for xenon decay while a second core was loaded into the assembly. During these intercycle periods the removed fuel elements were gamma-scanned axially along their centerlines to measure the distribution of the ^{140}La fission product activity. Because of the relatively short half lives of ^{140}Ba and ^{140}La, this information gives a measure of the fission rate densities and so the power densities, that occurred during the previous burn cycle. Thus, the ^{140}La data can be used to determine cycle-averaged fuel element powers. The gamma-scanning apparatus is described in Ref's (9) and (15) while methods used to analyze the data are given in Ref's (3), (16), and (17). As described in Ref. (17), transverse gradient corrections have been applied to the gamma-scanning data.

Table 8 gives the cycle-averaged measured power P(E) and the corresponding C/E ratio for each fuel element in each of the operating cores used in the demonstration. No gamma-scanning data was taken for the fuel elements in the all-HEU reference core 174C. The root-mean-square deviation (RMS DEV) of the departure of the C/E ratios from unity is shown at the bottom of Table 8 for each of the cores. Of the 524 C/E ratios given in this table about 75% differ from unity by 5% or less. Fig. 4 shows some typical core maps of C/E fuel element power ratios.

A careful examination of Table 8 reveals several anomalies. For cores 174D through 175C the C/E power ratios are unusually large in the A-row, especially at location A5. However, this trend tends to disappear for the remaining cores in the demonstration. The Heavy Section Steel Technology (HSST) Experiment was located just outside the core box on the west side of the core (see Fig. 4) for 174D through 175C, but was removed for all the remaining cores. The C/E data suggests that the HSST was not modeled very well in the diffusion calculations even though good eigenvalues (Table 7) were obtained. A number of core pairs with nearly identical configurations (176B-176C, 176D-177A, 177B-177C) show several low C/E ratios in column 5 for one member of the pair but not the other. In almost all of these cases the low C/E ratio corresponds to an HEU fuel element which was not gamma-scanned for ^{137}Cs. As will be discussed in the next section, the ^{235}U mass for these fuel elements is quite uncertain, which may account for this strange C/E behavior. Finally, all the cores beginning with 178C contained only LEU fuel and had the same configuration (see Fig. 4, core 179A). For each of the these cases a large C/E value was obtained at position B3 but very normal ratios at the symmetric position B7. The reason for this behavior is not understood.

FUEL-ELEMENT-AVERAGED ^{235}U BURNUPS

During the demonstration fuel elements discharged from the ORR were gamma-scanned to determine the ^{137}Cs activity distribution. Because of the 30-year half life of ^{137}Cs, this measurement integrates the activity over all previous cycles of operation and so gives count rates proportional to the total fission density within the fuel element. The ^{235}U burnup is directly related to the total fission density. Mathematical details for analyzing the ^{137}Cs gamma-scanning data to determine final ^{235}U fuel element masses and burnups are given in Ref.'s (3) and (16).

Table 9 gives the experimental values for the ^{235}U masses and burnups for all 68 LEU fuel elements used in the demonstration and the corresponding C/E ratios. Similar information is given at the end of this table for the LEU fuel followers. Of the 132 HEU fuel elements used in the demonstration only 3 were cycled into the reactor as fresh fuel. Table 10 summarizes the burnup results for these three HEU fuel elements.

Nearly all of the HEU elements were previously irradiated before the beginning of the whole-core demonstration. Thus, their ^{235}U masses were uncertain at the start of the demonstration. By combining the ^{140}La and ^{137}Cs gamma-scanning data, an experimental value was obtained for the ^{235}U content of the HEU elements at the start of the demonstration. These initial mass values were used in the REBUS-3 burnup calculations. ^{235}U fuel element masses based on the gamma-scanning of HEU fuel elements are given in Ref. (3).

Table 11 gives the average burnup status for each of the LEU fuel elements at the end of the demonstration. Seven of the standard 19-plate fuel elements achieved average burnups in excess of 50% while two of the 15-plate fuel followers had average burnups of nearly 75%. Because of the early shutdown of the ORR, however, 32 Babcock and Wilcox fuel elements and 4 fuel followers remained unirradiated.

Calculated and measured axial distributions of ^{235}U burnups were obtained by dividing the fuel column into six segments of equal height (10.0 cm). Table 12 shows these axial distributions for those LEU fuel elements and fuel followers having average burnups of 50% or greater.

Segment A is at the bottom of the fuel column and segment F at the top. For the 19-plate elements the maximum burnup is about 65% and occurs in segment C. The maximum burnup for the fuel followers is somewhat greater that 90% and occurs in segment F. Since there are only a few data points available in each axial segment, errors in the numerical integrations are relatively large and contribute to an appreciable scatter in the C/E ratios. Segment A in the fuel followers is normally located deep in the axial reflector below the core where both cross sections and neutron fluxes are quite uncertain. This contributes to the large C/E ratios in this region.

At the conclusion of the whole-core demonstration a number of plates were removed from selected fuel elements and fuel followers and gamma-scanned to measure ^{137}Cs activity distributions. In addition, small samples for mass spectrometry analyses were cut from a number of these plates. Analysis of this post-irradiation data provides fuel-element-averaged ^{235}U burnups which are independent of those obtained from the gamma- scanning of full-sized fuel elements (see Table 9). Basically, the plate gamma-scanning data is used to determine the fuel-element-averaged ^{137}Cs activity relative to the activity at the location of the mass spectrometry sample. The measured uranium mass spectrum determines the localized ^{235}U burnup. Thus, the fuel-element-average burnup is the product of these two values. More details of this method are given in Ref. (3).

Results from these burnup analyses are compared with those discussed earlier in Table 13. REBUS-3 calculated values are also included in this table. Generally speaking, ^{235}U burnups for the 19-plate LEU fuel elements obtained by the two independent experimental methods are self-consistent. Likewise, the REBUS-3 calculated values agree reasonably well with these experimental results. For the fuel followers, however, the burnup results based on mass spectrometry are somewhat smaller than those obtained from the earlier evaluations. Uncertainties in the experimental values are in the 2-3% range.

URANIUM AND PLUTONIUM ISOTOPIC MASS RATIOS AS FUNCTIONS OF ^{235}U BURNUP

From the mass spectrometry measurements values for uranium and plutonium isotopic mass ratios were obtained for various ^{235}U burnups. These results are compared with REBUS-3 depletion calculations in Figs. 5-7. The ORNL data were obtained from Ref. 1, appendix G, and refer to the U_3Si_2-Al test elements irradiated in the ORR prior to the whole-core demonstration. The ANL-W data were obtained from mass spectrometry measurements made at the Argonne National Laboratory in Idaho using samples taken from LEU fuel elements used in the whole-core demonstration. Isotopic dilution methods were used to measure the mg Pu/g U for samples with varying degrees of burnup.

Figures 5-7 show that the REBUS-3 calculations follow the measurements remarkably well. However, it does appear that the $^{240}Pu/^{239}Pu$ ratio is over-calculated by about 10% in the 30%-70% ^{235}U burnup range. These calculations are based on ENDF/B-IV data. Changes in the resonance capture data for the plutonium isotopes in ENDF/B-VI are in the direction of improving the $^{240}Pu/^{239}Pu$ ratio without significantly changing the other plutonium mass ratios.

CONCLUSIONS

Although the Oak Ridge Research Reactor was permanently shut down before the planned completion of the Whole-Core LEU Fuel Demonstration, the primary objectives of the program were met.

1. All 68 of the commerically-fabricated U_3Si_2-Al LEU fuel elements (4.8 g/cc U in fuel meat) as well as the 8 LEU fuel followers used in the demonstration performed in a completely safe and acceptable manner without any fuel failures. Seven standard elements and four fuel followers achieved average burnups of 50% or greater. In fact, two of the followers had average ^{235}U burnups of nearly 75% with peak values greater than 90%.

2. The gradual and safe transition from an all-HEU core, through a series of mixed HEU/LEU cores, to an all-LEU core was clearly demonstrated for the 30-MW Oak Ridge Research Reactor.

3. Numerous experimental measurements validated REBUS-3 fuel cycle predictions. Calculations supported experimentally-determined criticality conditions throughout the burn cycle for each of the 22-full power cores used in the demonstration. REBUS-3 cycle-averaged fuel element powers agreed (usually within 5%) with the measured values. Calculated fuel-element-averaged ^{235}U burnups are in good agreement with results obtained from two independent experimental methods. Measurements of uranium and plutonium mass spectra in discharged fuel elements support the calculations.

4. Standard methods, models and codes successfully accounted for a wide variety of experimental measurements. These included criticality conditions for unirradiated HEU and LEU cores radially-reflected with water and beryllium, differential and integral shim rod worth determinations, prompt neutron lifetime evaluations, reaction rate distributions, and isothermal temperature coefficient measurements.

5. The interpretation of differential shim rod worth measurements in the ORR had to take into account the combined effects of temperature changes during the reactivity transient and delayed photoneutron contributions to the total delayed neutron fraction. Changing temperature effects were eliminated by analyzing the initial shape of the measured time-dependent flux. However, only a rough treatment of delayed photoneutron contributions was possible. Plans to extract an effective set of kinetic parameters from an analysis of the shape of the flux die-away curve following a rod drop had to be abandoned because no such measurements were made before the unexpected shutdown of the reactor. Nevertheless, the rough photoneutron treatment resulted in C/E ratios close to unity for differential shim rod worths and for the prompt neutron decay constant in core 179A.

In view of the above remarks, it is concluded that the goals of the Whole- Core LEU Fuel Demonstration have been successfully achieved.

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Table 1. SUMMARY OF THE 30-MW CORES USED IN THE ORR WHOLE-CORE DEMONSTRATION

CORE	HEU[a]	LEU[a]	CYCLE LENGTH[b]
174C	27+6	0+0	16.840
174D	24+6	3+0	12.855
174E	24+6	3+0	10.623
174F	24+6	3+0	15.428
175A	20+6	7+0	18.518
175B	20+6	7+0	20.305
175C	17+6	10+0	17.389
176A	17+6	10+0	17.244
176B	13+4	14+2	21.864
176C	14+4	14+2	19.436
176D	8+4	17+2	19.446
177A	8+4	17+2	14.773
177B	4+2	21+4	18.516
177C	4+2	21+4	18.411
177D	0+2	24+4	15.334
178A	0+2	24+4	12.101
178B	0+2	25+4	0.644
178C	0+0	26+6	11.138
178D	0+0	26+6	16.356
178H	0+0	26+6	20.277
178J	0+0	26+6	16.502
179A	0+0	26+6	20.169

Table 2. EIGENVALUE CALCULATIONS FOR ORR FRESH FUEL CRITICAL CONFIGURATIONS

CORE	REFLECTOR	MFE's IN?[c]	SHIM ROD Pos. In.[d]	EIGENVALUES VIM	DIF3D
HEU-1	H_2O	Yes	17.21	1.0027±0.0022	0.9981
LEU-1	H_2O	Yes	15.46	0.9966±0.0019	0.9959
179-AX5	H_2O	No	15.48	1.0027±0.0019	1.0002
HEU-2	Be	Yes	17.34	1.0032±0.0020	1.0007
LEU-2	Be	Yes	18.41	1.0018±0.0020	0.9959
179-AX6	Be	No	18.22	1.0022±0.0019	0.9999

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[a] 27+6 means 27 19-plate fuel elements and 6 15-plate fuel followers.
[b] Cycle length in full power (30-MW) days.
[c] The Magnetic Fusion Experiments (MFE's) were designed for irradiation-testing of materials for use in magnetic fusion devices.
[d] Shim rod withdrawal position is relative to the fully inserted reference position.

Table 3. DIFFERENTIAL SHIM ROD WORTHS IN THE ORR[a]

CORE	SHIM ROD	R_i-In.	R_f-In.	% DELTA K/K PER IN. CALC.	C/E
179-AX5	D4	12.00	12.23	0.6098	1.045±0.052
179-AX5	D6	12.00	12.19	0.6120	1.054±0.073
179-AX5	F4	12.00	12.29	0.3588	1.060±0.086
179-AX5	F6	12.00	12.36	0.3583	1.066±0.064
179-AX6	D4	12.00	12.31	0.5769	1.014±0.025
179-AX6	D6	12.00	12.19	0.5727	0.986±0.038
179-AX6	F4	12.00	12.31	0.5682	1.044±0.027
179-AX6	F6	12.00	12.28	0.5717	1.027±0.031
179-AX7	D4	12.00	12.39	0.3958	1.006±0.039
179-AX7	D6	12.00	12.36	0.4287	1.030±0.040
179-AX7	B4	12.00	12.52	0.2455	0.978±0.052
179-AX7	B6	12.00	12.47	0.2718	1.022±0.062
179-AX7	F4	12.00	12.81	0.1476	1.146±0.098
179-AX7	F6	12.00	12.92	0.1656	1.053±0.041

Table 4. D6 INTEGRAL ROD WORTH FOR ORR CORE 179-AX5

INTEGRATION LIMITS, In.[b] LL=0.0	UL=26.56	INTEGRAL WORTH, % DELTA K/K Calc.	Exp.	C/E
		7.239	6.855	1.056

CODE	R-out, In.	R-in, In.	R-bank, In.	K-out	K-in	% DELTA K/K
VIM	26.56	0.0	17.72	1.0400 ±0.0018	0.9666 ±0.0020	7.299 ±0.273
DIF3D	26.56	0.0	17.72	1.0371	0.9641	7.309

[a]These measurements were made with a coolant flow rate of 1200 gpm.
[b]Integration of the differential rod worth from the lower to the upper limit gives the total rod worth.

Table 5. PROMPT NEUTRON DECAY CONSTANT

CORE	DELAYED NEUTRON FRACTION	PROMPT NEUTRON LIFETIME, SEC	PROMPT NEUTRON DECAY CONSTANT[a] CALC.-SEC^{-1}	EXP.-SEC^{-1}	C/E
HEU-1	8.052E-3	47.87E-6	168.2	167.8±0.6	1.0024±0.0036
LEU-1	7.980E-3	41.55E-6	192.0	192.3±1.2	0.9984±0.0062
179A	7.255E-3	55.54E-6	130.6	140.5±0.9	0.9297±0.0060
	7.915E-3[b]	55.54E-6	142.5	140.5±0.9	1.0143±0.0065

Table 6. ISOTHERMAL TEMPERATURE COEFFICIENT

ORR CORE 179-AX7

DELTA K/K/In.	dL/dT, In./°C	ISOTHERMAL TEMPERATURE COEFFICIENT[c] EXP., 1/°C	CALC., 1/°C	C/E
-(1.980±0.091)E-3	(6.78±0.21)	-(1.341±0.075)E-4	-1.301E-4	0.970±0.054

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[a]The prompt neutron decay constant is the ratio of the effective delayed neutron fraction to the prompt neutron lifetime.
[b]Includes estimate of delayed photoneutron contributions.
[c]The measured isothermal temperature coefficient is the product of the differential shim rod worth (DELTA K/K/In.) and the slope (dL/dT) of the critical rod position versus temperature curve.

Table 7. CALCULATED EIGENVALUES CORRESPONDING TO MEASURED CRITICAL CONFIGURATIONS FOR ORR DEMONSTRATION CORES

CORE	CYCLE LENGTH, CL FPD's	TEMPERATURE-ADJUSTED EIGENVALUE BOC	1/3 CL	MOC	2/3 CL	EOC
174C	16.8402	1.0024	0.9999		0.9985	0.9992
174D	12.8554	1.0006		0.9970		0.9960
174E	10.6228	1.0035		0.9966		0.9963
174F	15.4282	0.9918	0.9916		0.9935	0.9936
175A	18.5181	0.9963	0.9974		0.9970	0.9967
175B	20.3049	1.0058	1.0050		1.0040	1.0006
175C	17.3891	1.0001	1.0003		1.0009	1.0019
176A	17.2444	1.0041	1.0034		1.0032	1.0042
176B	21.8645	1.0000	0.9995		0.9992	0.9986
176C	19.4357	0.9952	0.9946		0.9950	0.9936
176D	19.4463	1.0042	1.0049		1.0048	1.0084
177A	14.7731	1.0018	1.0033		1.0030	1.0054
177B	18.5160	1.0018	1.0004		1.0006	0.9996
177C	18.4107	1.0038	1.0028		1.0038	1.0038
177D	15.3341	1.0065	1.0068		1.0070	1.0090
178A	12.1006	1.0006		1.0012		1.0053
178B[a]	0.6445	0.9946				0.9869[a]
178C	11.1377	1.0062		0.9999		0.9996
178D	16.3556	1.0030	1.0006		0.9986	1.0002
178H	20.2765	1.0130[b]	0.9969		0.9975	0.9959
178J	16.5022	0.9981	0.9983		0.9982	0.9978
179A	20.1687	0.9969	0.9990		0.9995	0.9991

[a]Insufficient excess reactivity. EOC control rod positions were not recorded, only estimated.
[b]Calculation neglects ^{135}Xe buildup from the just previous experimental core, 178-EX1.

Table 8. SUMMARY OF ORR FUEL ELEMENT POWER C/E RATIOS

CORE:	174D			174E			174F			175A			175B		
LOC	FE	P(E)-MW	C/E	FE	P(E)-MW	C/E	FE	P(E)-MW	C/E	FE	P(E)-MW	C/E	FE	P(E)-MW	C/E
A2	T519	0.670	1.009	T527	0.630	1.096	T547	0.683	1.057	T521	0.589	1.104	T534	0.663	1.049
A3	T530	0.859	0.991	T521	0.766	1.086	T549	0.768	1.122	T537	0.798	1.055	T531	0.802	1.061
A4	T554	1.038	1.006	T557	0.975	1.078	T544	1.014	1.056	T525	0.971	1.047	T552	0.976	1.051
A5	C021	1.055	1.097	C021	1.049	0.993	C024	1.065	1.127	C027	1.025	1.136	N001	1.022	1.151
A6	T555	0.995	1.029	T545	0.984	1.071	T541	0.996	1.065	T561	0.990	1.041	T556	0.967	1.063
A7	T540	0.823	0.990	T534	0.780	1.104	T515	0.759	1.103	T538	0.8[illegible]	1.051	T546	0.787	1.067
A8	T503	0.644	0.984	T500	0.565	1.095	T519	0.564	1.137	T527	0.599	1.076	T547	0.608	1.061
B3	T501	0.980	1.003	T465	0.927	0.994	T503	0.996	1.006	T500	0.890	0.998	T491	0.944	0.984
B5	T455	1.007	1.046	T458	1.040	0.988	T416	1.043	0.983	T454	0.969	1.000	T417	1.004	1.006
B7	T497	0.889	0.962	T505	0.891	1.023	T522	0.945	0.965	T535	0.921	0.957	T484	0.901	0.979
C2	C022	1.170	1.038	C022	1.177	0.969	C025	1.194	1.033	C028	1.154	1.011	N002	1.211	0.986
C4	T526	1.225	0.987	T507	1.142	1.012	T508	1.150	1.016	T528	1.111	0.989	T530	1.154	0.978
C5	T419	1.161	0.956	T420	1.107	1.010	T453	1.049	1.055	T473	1.068	1.003	T456	1.128	1.003
C6	T535	1.214	0.945	T528	1.206	0.973	T530	1.129	1.041	T540	1.163	0.974	T515	1.167	0.974
C8	C023	1.135	0.915	C023	1.134	0.952	C026	1.127	0.999	C029	1.076	1.010	N003	1.113	0.976
D2	T379	0.771	0.993	T368	0.750	0.981	T408	0.769	0.979	T328	0.739	1.032	T439	0.709	1.020
D3	T548	1.262	0.984	T529	1.282	0.965	T533	1.249	0.991	C021	1.215	1.006	C024	1.294	0.973
D5	T434	1.073	0.965	T396	1.161	0.924	T426	1.049	0.988	T364	1.041	0.974	T460	1.186	0.955
D7	T539	1.214	0.921	T559	1.138	0.937	T560	1.219	0.970	C022	1.183	1.002	C025	1.231	0.976
D8	T469	0.784	0.920	T475	0.748	1.016	T430	0.755	0.992	T418	0.724	0.971	T523	0.742	0.986
E2	T515	0.883	0.989	T517	0.887	0.946	T532	0.909	0.986	C023	0.921	1.001	C026	0.949	0.992
E4	T537	1.174	0.980	T531	1.180	0.969	T518	1.164	0.993	T558	1.235	0.947	T553	1.251	0.929
E5	Ir			Ir			Ir			Ir			Ir		
E6	T549	1.200	0.950	T536	1.257	0.961	T542	1.182	0.992	T548	1.223	0.954	T554	1.205	0.953
E8	T556	1.037	0.924	T561	1.058	0.948	T562	0.996	0.977	C030	0.980	0.998	N004	0.983	0.985
F3	T516	0.771	0.939	T464	0.731	0.877	T479	0.732	0.968	T487	0.700	0.939	T445	0.705	0.962
F5	T459	0.848	0.967	T493	0.870	0.965	T443	0.813	0.984	T461	0.870	0.923	T489	0.815	0.932
F7	T514	0.791	0.910	T523	0.766	0.935	T492	0.776	0.986	T422	0.740	0.937	T495	0.678	0.984
RMS-DEV:			0.048			0.054			0.055			0.050			0.047

Note: HEU fuel elements (FE) are identified with the letter T. LEU fuel elements are identified with the letters C (CERCA), N (NUKEM) and B (Babcock and Wilcox).

Table 8. SUMMARY OF ORR FUEL ELEMENT POWER C/E RATIOS (Continued)

CORE:	175C			176A			176B			176C			176D		
LOC	FE	P(E)-MW	C/E	FE	P(E)-MW	C/E	FE	P(E)-MW	C/E	FE	P(E)-MW	C/E	FE	P(E)-MW	C/E
A2	T538	0.694	1.036	T546	0.698	0.976	T507	0.523	0.996	T510	0.542	1.031	Be		
A3	T517	0.802	1.073	T536	0.841	0.997	T537	0.741	0.972	T520	0.692	1.001	T538	0.700	1.008
A4	T562	1.024	1.040	T541	1.004	0.986	T558	0.905	0.969	T542	0.784	0.982	C021	0.792	0.999
A5	N007	1.084	1.114	N005	1.305	1.045	T551	0.942	0.982	T559	0.843	0.993	C022	0.790	1.055
A6	T545	0.984	1.041	T557	1.002	0.984	T550	0.873	0.997	T532	0.773	0.989	C023	0.771	1.061
A7	T543	0.834	1.058	T539	0.815	1.022	T549	0.701	0.989	T554	0.662	0.993	T548	0.691	1.049
A8	T524	0.624	1.067	T534	0.656	0.984	T521	0.551	0.999	T514	0.502	0.998	Be		
B3	T497	0.908	1.004	T499	1.015	0.952	C021	1.057	1.002	C024	1.008	1.022	C027	1.114	1.007
B5	T470	1.029	0.984	T486	1.055	0.994	T425	0.941	0.957	T432	0.904	0.887	T442	1.085	0.857
B7	T482	0.910	0.947	T501	0.907	0.941	C030	1.069	0.971	N001	1.005	0.934	C028	1.019	0.989
C2	N008	1.132	1.046	N006	1.232	1.010	B041	1.254	0.975	B045	1.256	1.002	B048	1.292	1.015
C4	T519	1.155	0.990	T485	1.125	1.022	C027	1.357	1.019	N004	1.322	0.990	N008	1.484	0.979
C5	T496	1.137	1.074	T506	1.246	0.972	T484	1.013	0.985	T444	0.908	0.979	T429	1.196	0.875
C6	C023	1.323	1.029	C026	1.392	1.009	C028	1.267	1.007	N002	1.206	0.978	N007	1.393	0.971
C8	N009	1.116	0.964	N010	1.151	1.005	B042	1.138	0.978	B046	1.133	0.945	B049	1.183	0.996
D2	T457	0.775	0.993	T509	0.837	0.964	T480	0.824	0.963	T474	0.862	1.009	T483	0.840	0.995
D3	C030	1.274	1.011	N001	1.325	0.972	N008	1.286	1.003	N006	1.297	1.019	B041	1.414	0.985
D5	T400	1.080	0.991	T455	1.081	0.982	T410	1.028	0.954	T488	1.148	0.804	T447	1.133	0.901
D7	C028	1.152	0.974	N002	1.193	0.993	N007	1.168	0.980	N010	1.174	0.959	B042	1.285	0.964
D8	T464	0.724	0.892	T494	0.771	0.998	T349	0.751	0.974	T405	0.794	0.870	T481	0.849	0.933
E2	C029	0.942	1.015	N003	0.995	0.973	B043	1.064	0.991	B047	1.131	1.036	B043	1.128	1.017
E4	C021	1.161	0.998	C024	1.200	0.979	N009	1.286	0.968	N005	1.368	0.961	B044	1.288	1.029
E5	Ir			Ir			IR			T401	0.994	0.888	Al		
E6	C022	1.102	1.017	C025	1.144	1.022	C029	1.138	1.019	N003	1.231	0.976	N009	1.230	0.989
E8	C027	0.947	0.949	N004	0.970	1.019	B044	1.046	0.983	N011	1.096	0.979	B050	1.176	0.983
F3	T498	0.759	0.935	T495	0.705	0.922	C022	0.879	0.985	C025	1.001	0.989	C030	1.005	0.999
F5	T504	0.797	0.949	T505	0.788	0.968	T495	0.826	0.892	T448	0.923	0.899	T477	0.910	0.910
F7	T511	0.734	0.935	T513	0.688	0.975	C023	0.858	0.997	C026	0.957	0.987	C029	0.985	0.997
RMS-DEV:			0.051			0.029			0.029			0.062			0.054

Note: HEU fuel elements (FE) are identified with the letter T. LEU fuel elements are identified with the letters C (CERCA), N (NUKEM) and B (Babcock and Wilcox).

Table 8. SUMMARY OF ORR FUEL ELEMENT POWER C/E RATIOS (Continued)

CORE:	177A			177B			177C			177D			178A		
LOC	FE	P(E)-MW	C/E	FE	P(E)-MW	C/E	FE	P(E)-MW	C/E	FE	P(E)-MW	C/E	FE	P(E)-MW	C/E
A2	Be			Be			Be			Be			Be		
A3	T553	0.759	1.025	T420	0.538	0.984	T443	0.564	1.001	Be			Be		
A4	C024	0.833	1.023	C027	0.723	1.019	N001	0.723	1.074	B048	0.877	0.975	B051	0.882	1.000
A5	C025	0.843	1.030	C028	0.755	1.018	N002	0.734	1.087	B050	0.839	1.014	B053	0.851	1.044
A6	C026	0.820	1.035	C029	0.717	1.041	N003	0.720	1.077	B095	0.901	1.002	C033	0.875	1.044
A7	T518	0.713	1.042	C030	0.629	1.080	N004	0.642	1.097	Be			Be		
A8	Be			Be			Be			Be			Be		
B3	N004	1.191	0.968	N008	1.015	0.998	N006	1.003	1.044	B043	1.126	0.953	B047	1.080	0.951
B5	T475	0.972	0.965	T390	0.924	0.896	T482	0.860	0.974	C028	1.031	0.975	N002	1.082	0.995
B7	N002	1.078	0.944	N007	0.958	0.963	N011	1.026	0.990	B044	0.979	1.019	N010	0.904	1.008
C2	B051	1.329	0.983	B095	1.308	0.957	C033	1.212	1.036	C036	1.249	0.958	C038	1.091	0.957
C4	N006	1.541	0.962	B041	1.487	0.907	B045	1.376	1.006	C027	1.188	0.989	N001	1.254	0.998
C5	T492	1.227	0.953	T397	1.089	0.879	T500	1.014	0.941	C021	1.068	1.011	C024	1.156	1.020
C6	N010	1.448	0.957	B042	1.336	0.950	B046	1.329	0.985	C029	1.153	0.991	N003	1.201	1.000
C8	B052	1.220	0.994	B096	1.127	1.006	C034	1.122	1.027	C037	1.118	1.015	C039	1.019	0.912
D2	T416	0.857	0.933	C021	0.977	0.979	C024	0.918	1.076	B041	1.017	0.979	B045	0.907	0.987
D3	B045	1.466	0.954	B048	1.520	0.901	B051	1.370	1.001	N008	1.171	0.967	N006	1.141	0.985
D5	T466	1.145	0.933	T419	1.115	0.850	T507	0.948	0.971	C022	1.167	0.996	C025	1.266	1.007
D7	B046	1.308	0.956	B049	1.268	0.961	B052	1.272	0.967	N009	1.116	0.936	N005	1.182	0.975
D8	T422	0.822	0.959	C023	0.917	1.015	C025	0.911	1.044	B042	1.011	1.012	B046	0.957	0.996
E2	B047	1.165	0.965	C032	1.221	0.985	N012	1.160	1.023	N013	1.176	0.939	N014	1.000	0.942
E4	N011	1.376	0.953	B050	1.499	0.891	B053	1.363	0.970	C030	1.244	0.951	N004	1.234	0.982
E5	Al			Al			Al			C023	1.095	1.015	C026	1.149	1.032
E6	N005	1.261	0.956	B043	1.271	0.961	B047	1.220	1.002	N007	1.203	0.985	N011	1.409	1.000
E8	B053	1.177	0.972	N013	1.157	0.994	N014	1.122	1.023	N015	1.213	0.978	N018	1.141	0.977
F3	N001	1.043	0.935	B044	1.163	0.929	N010	0.996	1.029	B096	1.284	0.886	C034	1.092	0.957
F5	T458	0.937	0.824	C022	1.041	0.967	C026	1.004	1.022	B049	1.329	0.934	B052	1.328	0.973
F7	N003	0.996	0.967	N009	1.014	0.972	N005	0.953	1.042	C032	1.224	0.948	N012	1.208	0.974
RMS-DEV:			0.052			0.064			0.045			0.039			0.033

Note: HEU fuel elements (FE) are identified with the letter T. LEU fuel elements are identified with the letters C (CERCA), N (NUKEM) and B (Babcock and Wilcox).

Table 8. SUMMARY OF ORR FUEL ELEMENT POWER C/E RATIOS (Continued)

CORE:	178C			178D			178H			178J			179A		
LOC	FE	P(E)-MW	C/E	FE	P(E)-MW	C/E	FE	P(E)-MW	C/E	FE	P(E)-MW	C/E	FE	P(E)-MW	C/E
A2	Be			Be			Be			Be			Be		
A3	C029	0.505	1.106	N003	0.539	1.067	B041	0.539	1.053	B045	0.573	1.027	N016	0.727	0.996
A4	N015	0.792	1.039	N018	0.818	1.014	N016	0.734	1.046	B054	0.826	1.010	B082	0.860	0.974
A5	N019	0.832	1.086	B098	0.806	1.042	B082	0.851	1.041	B086	0.872	1.030	N002	0.693	1.023
A6	B095	0.687	1.140	C033	0.717	1.092	N019	0.784	1.049	C040	0.792	1.044	B083	0.850	0.993
A7	C030	0.466	1.167	N004	0.505	1.096	N009	0.478	1.132	N010	0.528	1.064	B097	0.692	1.025
A8	Be			Be			Be			Be			Be		
B3	B048	0.765	1.162	B051	0.800	1.138	C032	0.794	1.153	C033	0.813	1.147	C036	0.854	1.103
B5	N009	0.837	1.116	N010	0.925	1.032	B042	0.872	1.071	B046	0.955	1.012	B041	0.930	0.986
B7	B050	0.771	1.057	B053	0.843	0.982	N013	0.825	1.008	C034	0.854	0.996	C037	0.895	0.981
C2	N016	0.987	0.973	B054	1.005	0.977	B083	1.007	0.968	B087	0.997	0.987	C035	1.023	0.977
C4	N007	0.981	1.101	N005	1.030	1.071	B043	1.003	1.092	B047	1.081	1.036	B048	1.102	1.026
C5	C027	0.971	1.066	N001	1.048	1.023	N007	0.971	1.060	N005	1.028	1.031	B042	1.062	1.005
C6	N008	0.953	1.040	N006	1.005	1.004	B044	1.018	1.015	N011	1.011	1.036	B049	1.065	0.995
C8	C031	0.940	0.944	C040	0.975	0.921	B084	0.930	0.973	B088	0.973	0.943	N017	0.988	0.937
D2	C032	0.920	0.995	N014	0.941	1.008	C037	0.923	1.021	C039	0.934	0.969	N020	0.962	0.983
D3	B041	0.957	1.088	B045	1.027	1.047	B048	1.010	1.081	B051	1.067	1.039	B095	1.029	1.041
D5	C028	1.053	1.076	C024	1.032	1.034	N008	0.994	1.095	N006	1.052	1.067	B043	1.110	1.011
D7	B042	1.065	0.969	B046	1.091	0.975	B049	1.074	0.988	B052	1.090	0.990	B096	1.094	0.989
D8	B096	0.942	0.976	C034	0.939	1.001	N015	0.962	1.000	N018	0.986	0.987	C031	0.932	1.024
E2	N020	1.016	0.962	B100	1.069	0.903	B097	0.967	0.979	B100	0.966	0.971	B084	0.974	0.952
E4	B049	1.198	1.030	B052	1.268	0.987	B096	1.249	1.020	N012	1.206	1.039	B050	1.080	0.999
E5	B043	1.173	1.038	B047	1.238	1.009	B050	1.226	1.034	B053	1.263	1.014	B044	1.060	1.023
E6	B044	1.275	0.962	N011	1.260	0.986	B095	1.348	1.001	N014	1.341	1.009	C032	1.248	1.011
E8	B097	1.119	0.939	B099	1.116	0.942	B085	1.074	0.994	B089	1.128	0.954	B085	1.007	0.994
F3	C036	1.099	0.938	C038	1.129	0.933	C031	1.078	0.978	B099	1.051	0.986	N015	0.943	0.996
F5	N013	1.251	0.987	N012	1.298	0.964	C036	1.226	1.040	C038	1.227	1.038	N013	1.119	1.005
F7	C037	1.202	0.932	C039	1.341	0.855	N020	1.195	0.975	B098	1.229	0.943	N019	1.095	0.996
RMS-DEV:			0.079			0.062			0.058			0.045			0.030

Note: HEU fuel elements (FE) are identified with the letter T. LEU fuel elements are identified with the letters C (CERCA), N (NUKEM) and B (Babcock and Wilcox).

Table 9. MEASURED LEU FUEL ELEMENT ^{235}U MASSES AND BURNUPS

CERCA FUEL ELEMENTS

FE	IRRADIATION HISTORY	FINAL MASS (GM) & BURNUP (%)			
		MASS(E)	C/E	BU(E)	C/E
C021	177D-C5 177B-D2 176D-A4 176B-B3 175C-E4 175A-D3 174E-A5 174D-A5	168.0	0.996	50.58	1.004
C022	177D-D5 177B-F5 176D-A5 176B-F3 175C-E6 175A-D7 174E-C2 174D-C2	173.2	0.980	49.05	1.021
C023	177D-E5 177B-D8 176D-A6 176B-F7 175C-C6 175A-E2 174E-C8 174D-C8	177.2	0.995	47.87	1.006
C024	178D-D5 178A-C5 177C-D2 177A-A4 176C-B3 176A-E4 175B-D3 174F-A5	165.9	0.983	51.20	1.016
C025	178A-D5 177C-D8 177A-A5 176C-F3 176A-E6 175B-D7 174F-C2	183.5	1.000	46.02	1.000
C026	178A-E5 177C-F5 177A-A6 176C-F7 176A-C6 175B-E2 174F-C8	189.3	0.992	44.33	1.010
C027	178C-C5 178B-C5 177D-C4 177B-A4 176D-B3 176B-C4 175C-E8 175A-A5	180.0	0.992	47.07	1.009
C028	178C-D5 178B-D5 177D-B5 177B-A5 176D-B7 176B-C6 175C-D7 175A-C2	179.2	1.007	47.13	0.995
C029	178C-A3 178B-A3 177D-C6 177B-A6 176D-F7 176B-E6 175C-E2 175A-C8	192.7	1.009	43.16	0.992
C030	178C-A7 178B-A7 177D-E4 177B-A7 176D-F3 176B-B7 175C-D3 175A-E8	196.1	0.987	42.33	1.017
C031	179A-D8 178H-F3 178C-C8	273.9	1.007	19.22	0.982
C032	179A-E6 178H-B3 178C-D2 178B-D2 177D-F7 177B-E2	222.9	1.000	34.24	1.005
C033	178J-B3 178D-A6 178A-A6 177C-C2	262.4	0.999	22.83	1.005
C034	178J-B7 178D-D8 178A-F3 177C-C8	262.5	0.994	22.80	1.019
C035	179A-C2	313.9	1.002	7.42	1.015
C036	179A-B3 178H-F5 178C-F3 178B-F3 177D-C2	248.9	0.989	26.58	1.037
C037	179A-B7 178H-D2 178C-F7 178B-F7 177D-C8	254.6	1.005	24.90	0.992
C038	178J-F5 178D-F3 178A-C2	276.6	0.998	18.41	1.021
C039	178J-D2 178D-F7 178A-C8	282.9	0.996	16.80	1.022
C040	178J-A6 178D-C8	302.0	1.007	10.91	0.968

Table 9. MEASURED LEU FUEL ELEMENT ^{235}U MASSES AND BURNUPS (Continued)

NUKEM FUEL ELEMENTS

FE	IRRADIATION HISTORY	FINAL MASS (GM) & BURNUP (%)			
		MASS(E)	C/E	BU(E)	C/E
N001	178D-C5 178A-C4 177C-A4 177A-F3 176C-B7 176A-D3 175B-A5	188.4	0.994	44.42	1.012
N002	179A-A5 178A-B5 177C-A5 177A-B7 176C-C6 176A-D7 175B-C2	187.2	1.009	44.79	0.993
N003	178D-A3 178A-C6 177C-A6 177A-F7 176C-E6 176A-E2 175B-C8	199.5	1.002	41.16	1.001
N004	178D-A7 178A-E4 177C-A7 177A-B3 176C-C4 176A-E8 175B-E8	201.1	0.986	40.69	1.024
N005	178J-C5 178D-C4 178A-D7 177C-F7 177A-E6 176C-E4 176A-A5	180.5	1.003	46.75	1.000
N006	178J-D5 178D-C6 178A-D3 177C-B3 177A-C4 176C-D3 176A-C2	172.8	1.009	49.02	0.994
N007	178H-C5 178C-C4 178B-C4 177D-E6 177B-B7 176D-C6 176B-D7 175C-A5	168.7	1.006	50.22	0.997
N008	178H-D5 178C-C6 178B-C6 177D-D3 177B-B3 176D-C4 176B-D3 175C-C2	161.6	1.005	52.32	0.999
N009	178H-A7 178C-B5 178B-B5 177D-D7 177B-F7 176D-E6 176B-E4 175C-C8	182.3	1.021	46.21	0.979
N010	178J-A7 178D-B5 178A-B7 177C-F3 177A-C6 176C-D7 176A-C8	191.4	1.029	43.55	0.966
N011	178J-C6 178D-E6 178A-E6 177C-B7 177A-E4 176C-E8	195.3	1.030	42.56	0.960
N012	178J-E4 178D-F5 178A-F7 177C-E2	242.0	1.008	28.60	0.987
N013	179A-F5 178H-B7 178C-F5 178B-F5 177D-E2 177B-E8	225.0	1.005	33.63	0.996
N014	178J-E6 178D-D2 178A-E2 177C-E8	250.5	1.007	26.09	0.989
N015	179A-F3 178H-D8 178C-A4 178B-A4 177D-E8	254.7	1.009	24.88	0.980
N016	179A-A3 178H-A4 178C-C2 178B-C2	284.1	1.007	16.21	0.980
N017	179A-C8	313.8	1.008	7.44	0.941
N018	178J-D8 178D-A4 178A-E8	285.0	1.002	16.18	0.987
N019	179A-F7 178H-A6 178C-A5	279.6	0.997	17.52	1.027
N020	179A-D2 178H-F7 178C-E2	274.8	0.993	19.17	1.031

Table 9. MEASURED LEU FUEL ELEMENT ^{235}U MASSES AND BURNUPS (Continued)

BABCOCK AND WILCOX FUEL ELEMENTS

FE	IRRADIATION HISTORY	FINAL MASS (GM) & BURNUP (%)			
		MASS(E)	C/E	BU(E)	C/E
B041	179A-B5 178H-A3 178C-D3 178B-D3 177D-D2 177B-C4 176D-D3 176B-C2	174.6	1.002	48.50	1.001
B042	179A-C5 178H-B5 178C-D7 178B-D7 177D-D8 177B-C6 176D-D7 176B-C8	167.7	1.019	50.54	0.984
B043	179A-D5 178H-C4 178C-E5 178N-E4 177D-B3 177B-E6 176D-E2 176B-E2	165.1	1.011	51.44	0.990
B044	179A-E5 178H-C6 178C-E6 178B-E6 177D-B7 177B-F3 176D-E4 176B-E8	169.9	1.003	50.04	0.997
B045	178J-A3 178D-D3 178A-D2 177C-C4 177A-D3 176C-C2	208.9	0.990	38.38	1.021
B046	178J-B5 178D-D7 178A-D8 177C-C6 177A-D7 176C-C8	203.2	1.022	40.06	0.972
B047	178J-C4 178D-E5 178A-B3 177C-E6 177A-E2 176C-E2	203.4	0.991	40.16	1.014
B048	179A-C4 178H-D3 178C-B3 178B-D8 177D-A4 177B-D3 176D-C2	196.1	0.992	42.16	1.016
B049	179A-C6 178H-D7 178C-E4 178B-B3 177D-F5 177B-D7 176D-C8	189.8	1.010	44.16	0.988
B050	179A-E4 178H-E5 178C-B7 178B-B7 177D-A5 177B-E4 176D-E8	196.0	1.004	42.37	0.993
B051	178J-D3 178D-B3 178A-A4 177C-D3 177A-C2	232.7	0.992	31.57	1.017
B052	178J-D7 178D-E4 178A-F5 177C-D7 177A-C8	222.3	1.009	34.42	0.990
B053	178J-E5 178D-B7 178A-A5 177C-E4 177A-E8	230.2	1.011	32.09	0.982
B054	178J-A4 178D-C2	299.6	1.009	11.63	0.953
B082	179A-A4 178H-A5	295.2	1.001	13.16	0.992
B083	179A-A6 178H-C2	292.3	1.004	13.77	0.991
B084	179A-E2 178H-C8	291.0	1.008	14.15	0.973
B085	179A-E8 178H-E8	287.7	0.998	15.37	1.010
B086	178J-A5	321.4	0.999	5.48	1.009
B087	178J-C2	320.2	0.997	5.81	1.043
B088	178J-C8	319.8	1.003	5.94	0.956
B089	178J-E8	316.4	1.003	6.66	0.998
B095	179A-D3 178H-E6 178C-A6 178B-A6 177D-A6 177B-C2	224.7	0.990	33.71	1.025
B096	179A-D7 178H-E4 178C-D8 178B-A5 177D-F3 177B-C8	216.8	1.018	36.25	0.969
B097	179A-A7 178H-E2 178C-E8	281.5	1.006	17.19	0.974
B098	178J-F7 178D-A5	300.3	0.990	11.68	1.073
B099	178J-F3 178D-E8 178B-E8	297.5	0.994	12.49	1.041
B100	178J-E2 178D-E2 178B-E2	297.4	1.006	12.27	0.978

Table 9. MEASURED LEU FUEL ELEMENT ^{235}U MASSES AND BURNUPS (Continued)

BABCOCK AND WILCOX FUEL FOLLOWER ELEMENTS

FE	IRRADIATION HISTORY	FINAL MASS (GM) & BURNUP (%)			
		MASS(E)	C/E	BU(E)	C/E
UB001	178J-F4 178H-F4 178D-F4 178C-F4 178B-B4 178A-B4 177D-B4 177C-B4 177B-B4 177A-D4 176D-D4 176C-D4 176B-D4	50.57	1.039	74.72	0.987
UB002	178J-F6 178H-F6 178D-F6 178C-F6 178B-B6 178A-B6 177D-B6 177C-B6 177B-B6 177A-D6 176D-D6 176C-D6 176B-D6	50.32	1.042	74.84	0.986
UB003	179A-F4 178J-B4 178H-B4 178D-B4 178C-B4 178B-D4 178A-D4 177D-D4 177C-D4 177B-D4	80.56	1.010	59.72	0.993
UB004	179A-F6 178J-B6 178H-B6 178D-B6 178C-B6 178B-D6 178A-D6 177D-D6 177C-D6 177B-D6	81.08	1.009	59.46	0.994
UB005	179A-B4 178J-D4 178H-D4 178D-D4 178C-D4	119.9	1.013	40.04	0.982
UB006	179A-B6 178J-D6 178H-D6 178D-D6 178C-D6	120.5	1.006	39.76	0.991
UB007	179A-D4	175.9	1.006	12.07	0.957
UB008	179A-D6	175.0	1.009	12.51	0.939

Note: FF's UB001, UB002, UB003, and UB004 were gamma-scanned with the Ge(Li) detector. Results for the UB005, UB006, UB007, and UB008 FF's are based on gamma scans obtained with the NaI detector.

Table 10. MEASURED HEU FUEL ELEMENT ^{235}U MASSES AND BURNUPS

FUEL ELEMENT	IRRADIATION HISTORY		FINAL MASS (gm) AND BURNUP (%) MASS(E)	C/E	BU(E)	C/E
T556	175B-A6	174D-E8	242.0	1.002	15.10	0.988
T561	175A-A6	174E-E8	247.4	0.998	13.18	1.014
T562	175C-A4	174F-E8	241.6	1.001	15.22	0.998

Table 11. AVERAGE ^{235}U BURNUP STATUS OF ORR LEU FUEL ELEMENTS[a]

RANGE %	19-PLATE STANDARD FUEL ELEMENTS CERCA	NUKEM	B&W	TOTAL	15-PLATE B&W FUEL FOLLOWERS
70-75	0	0	0	0	2
50-60	2	2	3	7	2
45-50	5	3	1	9	0
40-45	3	6	5	14	1
35-40	0	0	2	2	1
30-35	1	1	4	6	0
25-30	1	2	0	3	0
20-25	3	1	0	4	0
15-20	3	4	2	9	0
10-15	1	0	7	8	2
5-10	1	1	4	6	0
0	0	0	32	32	4
	—	—	—	—	—
Total:	20	20	60	100	12

[a]Based on results from the gamma-scanning of full-sized fuel elements.

Table 12. AXIAL DISTRIBUTION OF ^{235}U BURNUPS

FUEL ELEMENT	LAST CORE-POSITION	QUANTITY	AXIAL SEGMENT[a] A	B	C	D	E	F	TOTAL[b]
C021	177D-C5	BU(E)-%:	48.28	59.26	62.94	58.46	45.62	29.25	50.58
		C/E:	1.040	1.031	1.016	0.996	0.960	0.942	1.004
C024	178D-D5	BU(E)-%:	49.98	60.57	63.56	59.24	44.93	29.20	51.20
		C/E:	1.036	1.037	1.030	1.000	0.991	0.973	1.016
N007	178H-C5	BU(E)-%:	48.55	59.82	64.33	58.13	43.40	27.22	50.22
		C/E:	1.021	1.011	0.985	0.993	0.989	0.968	0.997
N008	178H-D5	BU(E)-%:	50.87	62.77	66.48	60.14	45.20	28.50	52.32
		C/E:	1.006	1.005	0.994	1.004	0.994	0.977	0.999
B042	179A-C5	BU(E)-%:	47.98	61.43	64.84	59.14	44.73	24.88	50.54
		C/E:	1.031	0.979	0.969	0.963	0.949	1.068	0.984
B043	179A-D5	BU(E)-%:	48.35	63.35	65.77	59.52	44.97	26.31	51.44
		C/E:	1.048	0.966	0.970	0.976	0.976	1.056	0.990
B044	179A-E5	BU(E)-%:	47.00	59.95	63.21	58.37	45.03	26.67	50.04
		C/E:	1.055	0.990	0.979	0.972	0.962	1.067	0.997
UB001[c]	178J-F4	BU(E)-%:	40.10	67.74	82.87	88.86	90.41	78.31	74.72
		C/E:	1.097	0.956	0.954	0.963	0.958	1.052	0.987
UB002[c]	178J-F6	BU(E)-%:	37.20	65.18	82.78	90.44	91.98	81.46	74.84
		C/E:	1.215	1.004	0.955	0.943	0.935	1.002	0.986
UB003[c]	179A-F4	BU(E)-%:	23.57	47.81	66.89	77.42	80.99	61.63	59.72
		C/E:	1.103	0.974	0.936	0.936	0.937	1.175	0.993
UB004[c]	179A-F6	BU(E)-%:	21.77	46.33	65.33	76.79	80.99	65.56	59.46
		C/E:	1.224	1.015	0.956	0.936	0.927	1.089	0.994

[a]Each fuel segment is 10.0 cm in height. Segment A is located at the bottom of the core.
[b]Fuel-element-averaged burnup.
[c]LEU 15-plate fuel follower element.

Table 13. SUMMARY OF MASS SPECTROMETRY - ^{137}Cs GAMMA SCAN ANALYSES FOR ORR FUEL ELEMENTS AND FUEL FOLLOWERS

FUEL ELEMENT	PLATE	MASS SPEC. SAMPLE LOC. FROM TOP OF PLATE, In.	^{235}U BURNUP (%), METHOD CALC.	MASS SPEC.	SCANNING[a]
B043	2	16.05	50.93	51.79±1.29	51.44±1.03
	2	4.05		46.82±1.17	
	10	16.05		51.97±1.30	
C024	2	16.05	52.02	53.62±1.34	51.20±1.02
	2	4.05		53.47±1.34	
	10	16.05		50.87±1.27	
N007	2	16.05	50.07	50.67±1.27	50.22±1.00
	2	4.05		48.81±1.22	
	10	16.05		50.60±1.26	
B041	2	16.05	48.55	49.22±1.23	48.50±0.97
C025	2	16.05	46.02	46.55±1.16	46.02±0.92
N006	2	16.05	48.73	51.02±1.28	49.02±0.98
T490	2	4.05	45.3[b]	48.86±1.22	48.40±0.97
	2	9.05		49.36±1.23	
	2	16.05		50.40±1.26	
	2	21.05		48.97±1.22	
UB002[c]	2	6.55	73.79	70.72±1.77	74.84±1.50
	2	20.55		76.89±1.92	
	8	6.55		68.21±1.71	
UB005[c]	2	5.05	39.32	37.12±1.30	40.04±0.80
	8	5.05		37.01±1.30	

[a]Based on gamma-scanning of full-sized fuel elements (see Table 9).
[b]This result is an ORR estimate. It depends on burnups in pre-demonstration cores for which no calculations are available.
[c]This is a 15-plate fuel follower element.

ORR FRESH FUEL CRITICALS

	1	2	3	4	5	6	7	8	9
A	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O
B	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O
C	H_2O	H_2O	MFE	FE	FE	FE	MFE	H_2O	H_2O
D	H_2O	H_2O	FE	SR	FE	SR	FE	H_2O	H_2O
E	H_2O	H_2O	FE	FE	FE	FE	FE	H_2O	H_2O
F	H_2O	H_2O	FE	SR	FE	SR	FE	H_2O	H_2O
G	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O

Water-reflected cores HEU-1
[no fuel elements (FE) in C-4 and C-6],

LEU-1, and 179-AX5 (without MFE's).

	1	2	3	4	5	6	7	8	9
A	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O
B	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O
C	H_2O	Be	MFE	Be	Be	Be	MFE	Be	H_2O
D	H_2O	Be	Be	SR	FE	SR	Be	Be	H_2O
E	H_2O	Be	Be	FE	FE	FE	Be	Be	H_2O
F	H_2O	Be	Be	SR	FE	SR	Be	Be	H_2O
G	H_2O	Be	Be	Be	Be	Be	Be	Be	H_2O

Beryllium-reflected cores HEU-2, LEU-2, and
179-AX6 (without MFE's)

Fig. 1 Critical Configurations for Fresh Fuel.

ORR CORE HEU–1

AVERAGE C/E RATIOS FOR IRRADIATED WIRES

	1	2	3	4	5	6	7	8	9
A	Water	Water	Water	Water	Water	Water	Water	Water	Water
B	Water	Water	Water	Water	Water	Water	Water	Water	Water
C	Water	Water	MFE	Water	0.98	Water	MFE	Water	Water
D	Water	Water	1.02	SR	1.09	SR	0.97	Water	Water
E	Water	Water	1.06	1.04	1.05	0.94	0.89	Water	Water
F	Water	Water	****	SR	1.01	SR	0.90	Water	Water
G	Water	Water	Water	Water	Water	Water	Water	Water	Water

RMS DEV = 0.063

ORR CORE LEU–1

AVERAGE C/E RATIOS FOR IRRADIATED WIRES

	1	2	3	4	5	6	7	8	9
A	Water	Water	Water	Water	Water	Water	Water	Water	Water
B	Water	Water	Water	Water	Water	Water	Water	Water	Water
C	Water	Water	MFE	1.00	1.03	1.02	MFE	Water	Water
D	Water	Water	1.02	SR	1.08	SR	1.00	Water	Water
E	Water	Water	0.96	0.99	0.97	0.98	0.92	Water	Water
F	Water	Water	0.94	SR	1.12	SR	0.96	Water	Water
G	Water	Water	Water	Water	Water	Water	Water	Water	Water

RMS DEV = 0.051

Fig. 2 Results from Gold Wire Activations.

ORR CORE 177–AX1

AVERAGE C/E RATIOS FOR IRRADIATED WIRES

	1	2	3	4	5	6	7	8	9
A	Be	Be	0.82	0.94	0.98	1.02	1.00	Be	Be
B	Be	Be	0.94	SR 0.98	0.93	SR 1.26	0.95	Be	Be
C	Be 0.80	1.02	MFE	1.00	0.95	1.02	MFE	0.98	Be
D	Be	0.97	1.01	SR 1.05	0.97	SR 1.55	0.99	0.99	Be
E	Be	0.97	HFED	1.07	Al	1.02	Al	1.00	Be 0.84
F	Be	Be	1.13	SR 1.02	1.08	SR	1.03	Be	Be
G	Be	Be	Be	Be	Be 0.88	Be	Be	Be	Be

RMS DEV = 0.058

ORR CORE 179–A

Average C/E Ratios for Irradiated Wires

	1	2	3	4	5	6	7	8	9
A	DF	Be	0.97	0.98	0.94	0.95	0.94	Be	DF
B	Eu	Ir	0.91	SR	0.90	SR	0.91	Ir	Eu
C	Be	1.01	MFE	0.98	0.97	0.98	MFE	0.90	Be
D	Eu	1.04	1.04	SR	0.99	SR	0.97	0.98	Eu
E	Be	1.02	Al	1.05	1.06	1.02	Ir	1.00	Be
F	Eu	Ir	1.03	SR	1.01	SR	1.08	Be	Eu
G	DF	Be	Be	Be	Be	Be	Be	Be	DF

RMS DEV = 0.050

Fig. 3 Results from Cobalt-Vanadium Wire Activations

ORR CORE 174D

Cycle-Averaged Power C/E Ratios

	1	2	3	4	5	6	7	8	9	
A	Be	1.009	0.991	1.006	1.097	1.029	0.990	0.984	Be	
B	Be	Be	1.003	SR	1.046	SR	0.962	Be	Be	
C	Be	1.038	MFE	0.987	0.956	0.945	MFE	0.915	Be	
D	Eu	0.993	0.984	SR	0.965	SR	0.921	0.920	Eu	N
E	Be	0.989	HFED	0.980	Ir	0.950	Ir	0.924	Be	
F	Eu	Be	0.939	SR	0.967	SR	0.909	Be	Eu	
G	Be	Be	Be	Be	Be	Be	Be	Be	Be	

E

ORR CORE 176A

Cycle-Averaged Power C/E Ratios

	1	2	3	4	5	6	7	8	9	
A	Be	0.976	0.997	0.966	1.045	0.984	1.022	0.984	Be	
B	Be	Be	0.952	SR	0.994	SR	0.941	Be	Be	
C	Be	1.010	MFE	1.022	0.972	1.009	MFE	1.005	Be	
D	Be	0.964	0.972	SR	0.982	SR	0.993	0.996	Be	N
E	Be	0.973	HFED	0.979	Ir	1.022	Al	1.019	Be	
F	Eu	Be	0.922	SR	0.968	SR	0.975	Be	Eu	
G	Be	Be	Be	Be	Be	Be	Be	Be	Be	

E

ORR CORE 177D

Cycle-Averaged Power C/E Ratios

	1	2	3	4	5	6	7	8	9	
A	DFE	Be	Be	0.975	1.014	1.002	Be	Be	DFE	
B	Be	Be	0.953	SR	0.975	SR	1.019	Be	Be	
C	Be	0.958	MFE	0.989	1.011	0.991	MFE	1.015	Be	
D	Be	0.979	0.967	SR	0.996	SR	0.966	1.012	Be	N
E	Be	0.939	HFED	0.951	1.015	0.985	Al	0.978	Be	
F	Be	Be	0.886	SR	0.934	SR	0.948	Be	Be	
G	DFE	Be	Be	Be	Be	Be	Be	Be	DFE	

E

ORR CORE 179A

Cycle-Averaged Power C/E Ratios

	1	2	3	4	5	6	7	8	9	
A	DFE	Be	0.996	0.974	1.023	0.993	1.025	Be	DFE	
B	Eu	Ir	1.103	SR	0.986	SR	0.981	Ir	Eu	
C	Be	0.977	MFE	1.026	1.005	0.995	MFE	0.937	Be	
D	Eu	0.983	1.041	SR	1.011	SR	0.989	1.024	Eu	N
E	Be	0.952	Al	0.999	1.023	1.011	Ir	0.994	Be	
F	Eu	Ir	0.996	SR	1.005	SR	0.996	Be	Eu	
G	DFE	Be	Be	Be	Be	Be	Be	Be	DFE	

E

All LEU Core

Fig. 4 Cycle-Averaged Power C/E Ratios for Several ORR Cores.

SR=Shim Rod Assemblies, MFE=Magnetic Fusion Experiments, Ir and Eu=Iridium and Europium Irradiation Facilities, HFED=Mini-Plate Irradiation Facilities, Be=Beryllium Reflector Element, and DFE=Dummy Fuel Element. LEU fuel elements are enclosed with thick black lines except for 179A which is an all LEU core.

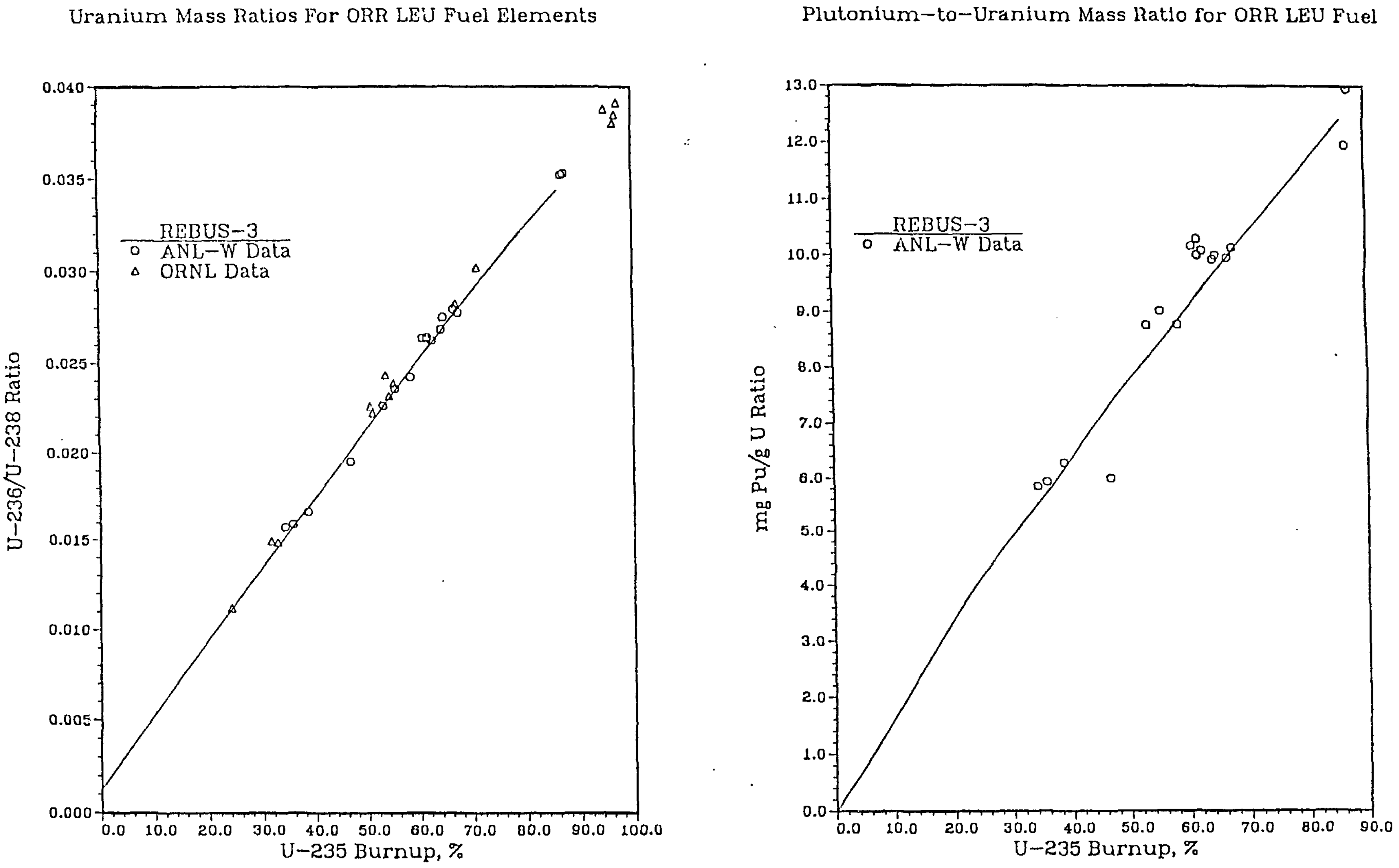


Fig. 5 Uranium and Plutonium Mass Ratios for ORR LEU Fuel Elements

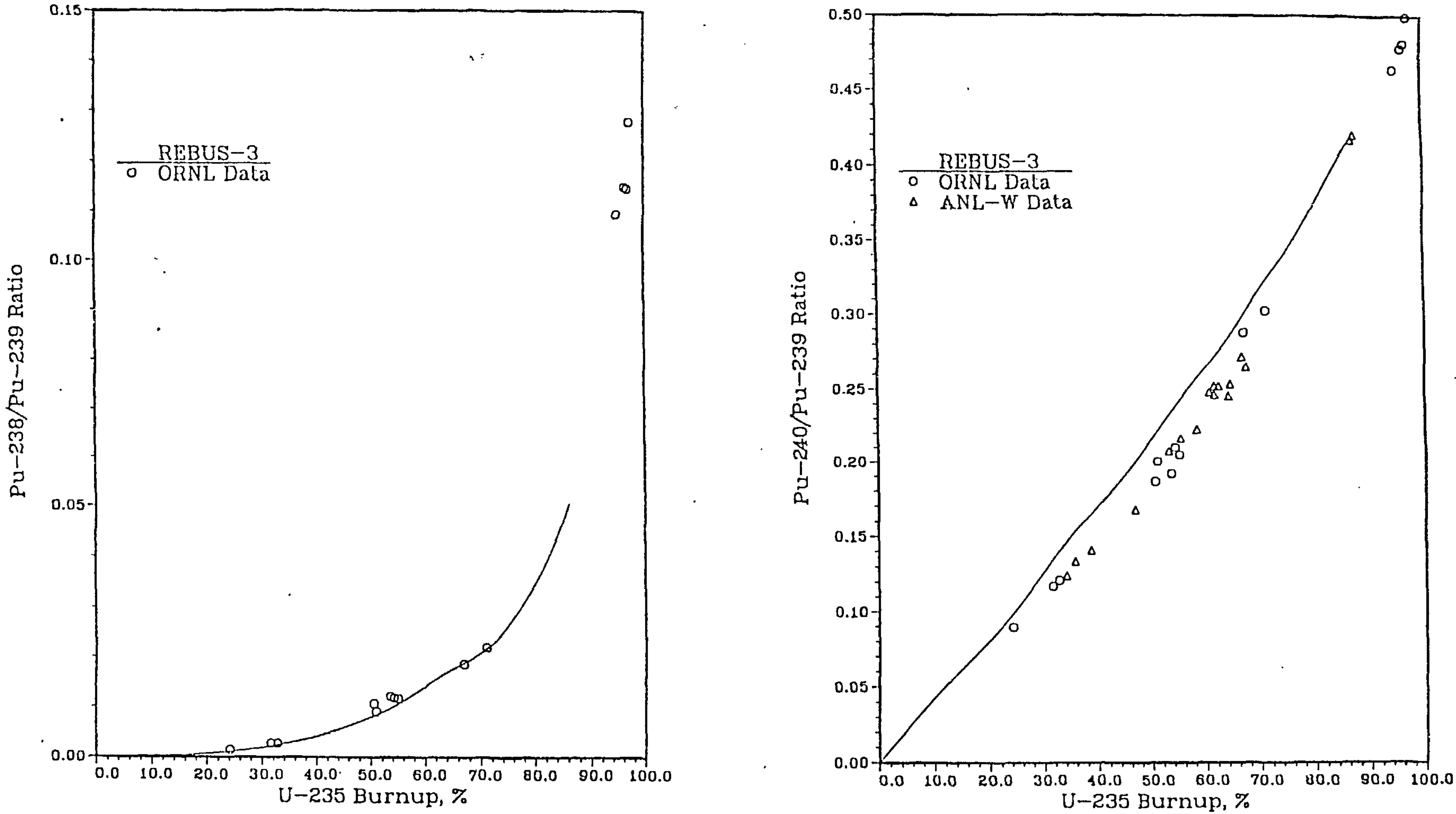
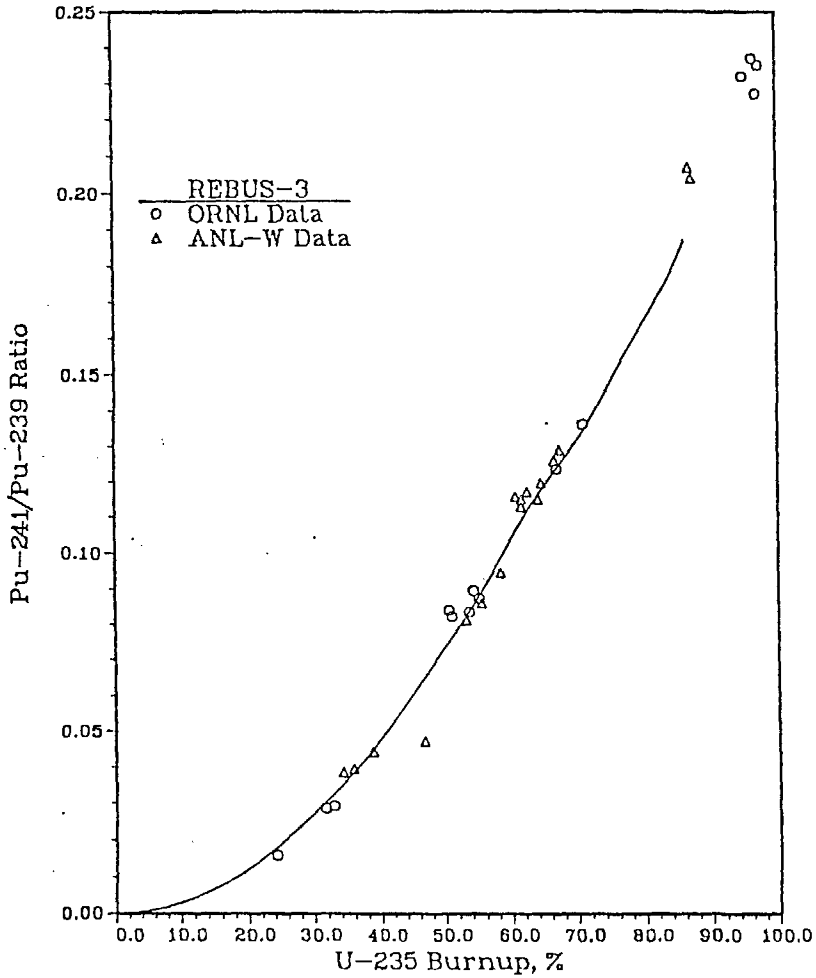


Fig. 6 Plutonium Mass Ratios for ORR LEU Fuel Elements



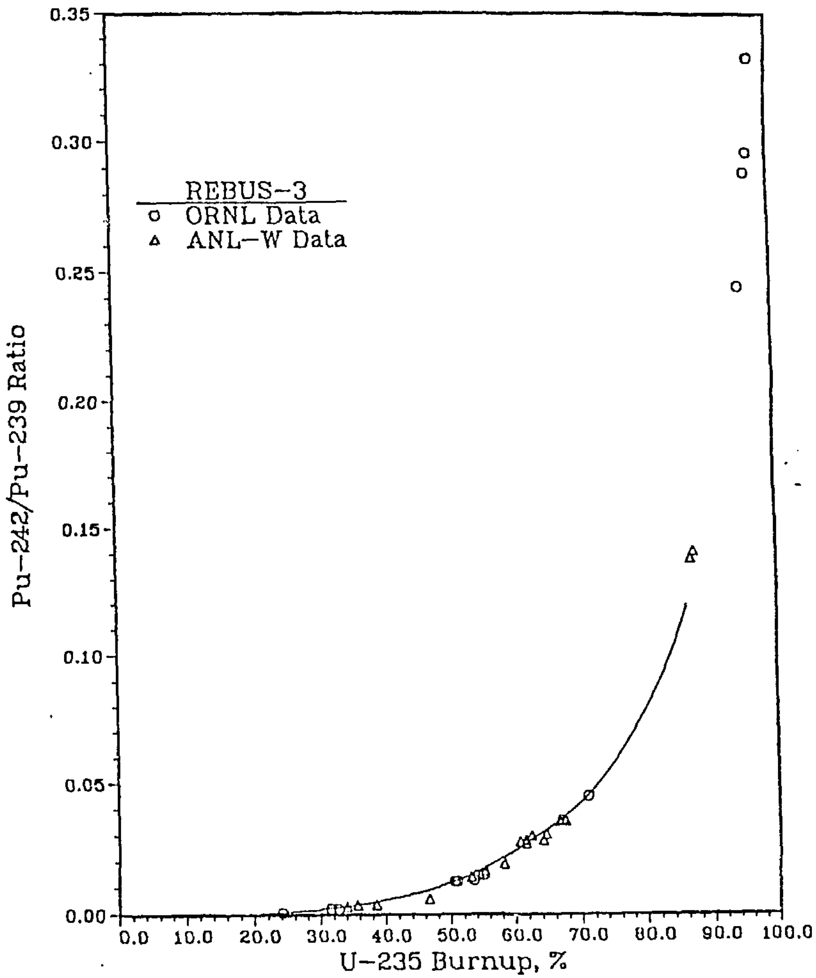


Fig. 7 Plutonium Mass Ratios for ORR LEU Fuel Elements