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PERFORMANCE OF LOW-ENRICHED U_3Si_2 -ALUMINUM DISPERSION
FUEL ELEMENTS IN THE OAK RIDGE RESEARCH REACTOR

by

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ABSTRACT

Six high-density, low-enriched U_3Si_2 -Al dispersion fuel elements have been tested in the Oak Ridge Research Reactor (ORR). The elements were geometrically identical to standard ORR elements. The uranium density in the fuel meat ranged between 4.6 and 5.2 Mg/m³. The elements were fabricated by B&W, CERCA, and NUKEM using their normal materials and fabrication practices, with minor modifications necessitated by the new fuel. The U_3Si_2 contained minor amounts of USi, U_3Si and/or uranium solid solution. The elements were irradiated in a variety of typical core positions. Three elements were irradiated to approximately normal ORR burnup, and three elements were irradiated twice as long, to average burnups of ~80% of the initially contained ²³⁵U, well above the burnups normally achieved in research and test reactors. Peak burnups of 98% were achieved.

Following suitable cooling periods, the elements were subjected to a series of nondestructive and destructive examinations, including visual inspection and dimensional measurements, channel gap thickness measurements, gamma scans, plate thickness measurements, blister threshold temperature tests, metallography, and isotopic burnup analyses. Externally, the elements were essentially unchanged from their as-fabricated condition. The behavior of the fuel was found to be entirely consistent with the known irradiation behavior of the constituent phases. The extremely stable swelling behavior of the U_3Si_2 phase dominated in all cases. The plates showed small, uniform thickness changes, ranging up to 112 μ m in regions of ~98% burnup. Blister threshold temperatures were >550°C, at the upper end of the the range of those of current fuels.

It is concluded that low-enriched U_3Si_2 -Al dispersion fuel elements will perform at least as well in research and test reactors with power densities up to that of the ORR as the highly enriched UAl_x -Al and U_3O_8 -Al dispersion fuels currently being used. There were no indications that use of this fuel under substantially more stringent conditions might be precluded.

Table of Contents

	<u>Page</u>
1. INTRODUCTION	1
2. DESCRIPTION OF FUEL ELEMENTS	2
2.1 General Description	2
2.2 Specifications	3
2.3 As-Fabricated Attributes	7
3. IRRADIATION HISTORY	9
4. POSTIRRADIATION EXAMINATION OF FUEL ELEMENTS	12
4.1 Visual Examination	12
4.2 Dimensional Inspection	12
4.3 Gamma Scanning of Elements	14
4.4 Coolant Channel Gap Thickness Measurements	14
5. EXAMINATION OF FUEL PLATES	14
5.1 Visual Inspection of Plates	15
5.2 Plate Thickness Measurements	15
5.3 Plate Gamma Scanning and Burnup Analysis	17
5.4 Blister Threshold Testing	17
5.5 Toughness of Irradiated Fuel	18
5.6 Metallography	20
6. SUMMARY AND DISCUSSION OF RESULTS	25
7. CONCLUSION	26
ACKNOWLEDGMENTS.....	26
REFERENCES	26

Table of Contents (Cont.)

	<u>Page</u>
APPENDICES	
A. POSTIRRADIATION EXAMINATION STEPS.....	63
B. VISUAL EXAMINATION AND PHOTOGRAPHS.....	66
C. ELEMENT DIMENSIONAL MEASUREMENT DATA.....	72
D. ELEMENT GAMMA SCANS.....	79
E. COOLANT CHANNEL GAP THICKNESS MEASUREMENTS.....	83
F. PLATE THICKNESS MEASUREMENTS.....	88
G. PLATE GAMMA SCANNING DATA AND BURNUP ANALYSIS.....	95
H. PHOTOGRAPHS OF PLATES AFTER BLISTER TESTING.....	114

List of Tables

	<u>Page</u>
I. Materials Used in U_3Si_2 Test Elements.....	3
II. Properties of Aluminum Alloys Specified for ORR LEU Fuel Elements	4
III. Comparison of Homogeneity Tolerances for U_3Si_2 Test Elements.....	6
IV. Reported Average U_3Si_2 Powder Compositions and Impurities.....	8
V. Irradiation History Summary for U_3Si_2 Test Elements.....	10
VI. Estimated Average and Peak Fuel Temperature Drops.....	11
VII. Results of Dimensional Inspection of Irradiated Elements.....	13
VIII. Average Thickness Increase and Burnup.....	16
IX. Results of Blister Anneals of Full-Sized Plates.....	19

List of Figures

	<u>Page</u>
1. Cross Section of Standard 19-Curved-Plate ORR Fuel Element.....	28
2. Basic Core Configurations During Irradiation of U_3Si_2 Elements....	29
3. Axial ^{137}Cs Profiles of Typical High- and Normal-Burnup Plates....	30
4. Photograph of Three Plates After Bending to Evaluate Toughness....	31
5. Sectioning Diagram for Destructive Evaluation of Plates.....	31
6M. Meat Microstructure of U_3Si_2 Miniplates After 90% Burnup (Bu).....	32
7M. Fission Gas Bubble Morphology in U_3Si After 90% Bu.....	32
8M. Meat Microstructure of U_3Si Miniplate After 90% Bu.....	33
9M. Fission Gas Bubble Morphology in U_3Si After 90% Bu.....	33
10M. Meat Microstructure of Irradiated Depleted U_3Si_2 Miniplate.....	34
11M. Detail of Fig. 10M.....	34
12B. Meat Microstructure of Plate BSI-201, at 31% Bu.....	35
13B. Detail of Fig. 12B.....	35
14B. SEM Image of Fuel Meat of Plate BSI-201, at 31% Bu.....	36
15B. Detail of Fig. 14B.....	36
16B. Idem Fig. 15B, BSE Mode.....	36
17B. Meat Microstructure of Plate BSI-201, at 71% Bu.....	37
18B. Detail of Fig. 17B.....	37
19B. SEM Image of Fuel Meat of Plate BSI-201, at 71% Bu.....	38
20B. Detail of Fig. 19B.....	38
21B. Detail of Fig. 19B.....	38
22B. Detail of Fig. 19B.....	38
23B. Meat Microstructure of Plate BSI-202, at 51% Bu.....	39
24B. Detail of Fig. 23B.....	39
25B. Meat Microstructure of Plate BSI-202, at 97% Bu.....	40

List of Figures (Cont.)

	<u>Page</u>
26B. Detail of Fig. 25B.....	40
27B. Detail of Fig. 26B.....	41
28B. SEM Image of Fuel Meat of Plate BSI-202, at 97% Bu.....	41
29B. Idem Fig. 28B, BSE Mode.....	41
30B. SEM Image of Fuel Meat of Plate BSI-202, at 97% Bu, Showing Various Bubble Morphologies.....	42
31B. Idem Fig. 30B.....	42
32B. Idem Fig. 30B.....	42
33B. Idem Fig. 30B.....	42
34B. SEM Image of Fuel Meat in Unirradiated BSI Plate, Showing U_3Si_2 and U_3Si , BSE Mode.....	43
35B. Idem Fig. 34B, Showing U_3Si_2 and U.....	43
36B. Detail of Fig. 35B.....	43
37B. Energy Dispersive X-Ray Spectra Identifying Various Phases in Unirradiated BSI Plate.....	44
38C. Meat Microstructure of Plate CSI-201, at 33% Bu.....	45
39C. Detail of Fig. 38C.....	45
40C. Meat Microstructure of Plate CSI-201, at 67% Bu.....	46
41C. Detail of Fig. 40C.....	46
42C. SEM Image of Fuel Meat of Plate CSI-201, at 67% Bu.....	47
43C. Idem Fig. 42C, BSE Mode.....	47
44C. Detail of Fig. 42C.....	47
45C. Detail of Fig. 42C.....	47
46C. Meat Microstructure of Plate CSI-202, at 55% Bu.....	48
47C. Detail of Fig. 46C.....	48
48C. SEM Image of Fuel Meat of Plate CSI-202, at 55% Bu.....	49
49C. Idem Fig. 48C, BSE Mode.....	49

List of Figures (Cont.)

	<u>Page</u>
50C. Detail of Fig. 48C.....	49
51C. Detail of Fig. 48C.....	49
52C. Meat Microstructure of Plate CSI-202, at 97% Bu.....	50
53C. Detail of Fig. 52C.....	50
54C. SEM Image of Fuel Meat of Plate CSI-202, at 97% Bu.....	51
55C. Idem Fig. 54C, BSE Mode.....	51
56C. Detail of Fig. 54C.....	51
57C. Detail of Fig. 54C.....	51
58C. SEM Image of Fuel Meat in Unirradiated CSI Plate, Showing U ₃ Si in U ₃ Si ₂ Grain, BSE Mode.....	52
59C. SEM Image of Fuel Meat in Unirradiated CSI Plate, Showing Oxy-Carbide Phase (C).....	52
60C. Energy Dispersive X-Ray Spectra Identifying U ₃ Si and U ₃ Si ₂ in Unirradiated CSI Plate.....	52
61N. Meat Microstructure of Plate NSI-201, at 24% Bu.....	53
62N. Detail of Fig. 61N.....	53
63N. SEM Image of Fuel Meat of Plate NSI-201, at 24% Bu.....	54
64N. Idem Fig. 63N, BSE Mode.....	54
65N. Detail of Fig. 63N.....	54
66N. Detail of Fig. 64N.....	54
67N. Meat Microstructure of Plate NSI-201, at 51% Bu.....	55
68N. Detail of Fig. 67N.....	55
69N. SEM Image of Fuel Meat of Plate NSI-201, at 51% Bu.....	56
70N. Idem Fig. 69N, BSE Mode.....	56
71N. Detail of Fig. 69N.....	56
72N. Detail of Fig. 71N, BSE Mode.....	56
73N. Meat Microstructure of Plate NSI-202, at 54% Bu.....	57

List of Figures (Cont.)

	<u>Page</u>
74N. Detail of Fig. 73N.....	57
75N. SEM Image of Fuel Meat of Plate NSI-202, at 54% Bu.....	58
76N. Detail of Fig. 75N.....	58
77N. Detail of Fig. 75N.....	58
78N. Idem Fig. 77N.....	58
79N. Meat Microstructure of Plate NSI-202, at 96% Bu.....	59
80N. Detail of Fig. 79N.....	59
81N. SEM Image of Fuel Meat of Plate NSI-202, at 96% Bu, Showing Various Bubble Morphologies.....	60
82N. Idem Fig. 81N.....	60
83N. Idem Fig. 81N.....	60
84N. SEM Image of Fuel Meat of Unirradiated NSI Plate, BSE Mode.....	61
85N. Idem Fig. 84N.....	61
86N. Detail of Fig. 84N, Showing U_3Si_2 and U_3Si	61
87N. Idem Fig. 86N.....	61

Performance of Low-Enriched U_3Si_2 -Aluminum Dispersion Fuel Elements in the Oak Ridge Research Reactor

1. INTRODUCTION

Since its inception in 1978, the U.S. Reduced Enrichment Research and Test Reactor (RERTR) Program¹ has pursued the development of high-density dispersion fuels as one means of making feasible the conversion of research and test reactors from the use of highly enriched uranium (HEU) fuel to the use of low-enriched uranium (LEU) fuel. At that time the highest density fuels in common use in plate-type research reactor fuel elements were dispersions of uranium aluminide (UAl_x) and uranium oxide (U_3O_8) in aluminum with fuel meat densities of 1.7 Mg U/m^3 and 1.3 Mg U/m^3 , respectively. These two types of dispersion fuels have now been developed and tested for LEU applications up to their practical fabrication limits-- 2.4 Mg U/m^3 for UAl_x and 3.2 Mg U/m^3 for U_3O_8 .²

Although 3.2 Mg U/m^3 is significantly higher than the densities available in 1978, even higher density fuels are needed for the higher performance research and test reactors. To this end the development of fuels consisting of uranium silicide compounds dispersed in aluminum has been pursued. The two highest density uranium silicides are U_3Si and U_3Si_2 , with bulk densities of 15.4 and 12.2 Mg/m^3 and uranium densities of 14.8 and 11.3 Mg U/m^3 , respectively. There is general agreement among the developers and fabricators of aluminum-matrix dispersion fuels that yields of acceptable plates drop rapidly as dispersant loadings are increased beyond 43 to 45 vol%, or 4.8 to 5.1 Mg U/m^3 for U_3Si_2 and 6.3 to 6.7 Mg U/m^3 for U_3Si .

Irradiation testing of the various fuels began with miniature plates (miniplates) to determine basic irradiation behaviors. All miniplate irradiations were performed in the Oak Ridge Research Reactor (ORR) at Oak Ridge National Laboratory (ORNL).³ Successful candidate fuels were then tested in full-sized fuel elements to confirm their good behavior under typical reactor conditions. Early indications of acceptable performance of uranium silicide dispersion fuels led to a decision in 1981 to proceed with the fabrication and irradiation of full-sized, low-enriched uranium silicide fuel elements in the ORR.⁴ At that time U_3Si_2 was chosen because it was much more brittle and, therefore, could be more easily comminuted than U_3Si . That was a fortunate choice because, subsequently, U_3Si_2 was shown to be much more stable under irradiation than U_3Si .^{5,6}

NUKEM,* CERCA,[†] and B&W** each fabricated two U_3Si_2 fuel elements for testing in the ORR under cooperative arrangements in which the RERTR Program provided the low-enriched uranium and the testing and the fabricators provided

*NUKEM GmbH, Hanau, Fed. Rep. of Germany.

[†]Compagnie pour l'Etude et la Réalisation de Combustibles Atomiques, Romans-sur-Isère, France.

**Babcock & Wilcox Company, Lynchburg, Virginia, U.S.A.

the fuel elements, each without cost to the other. Fabrication of the elements was completed in January 1982 by NUKEM, in March 1983 by CERCA, and in October 1983 by B&W. Irradiation of the first element began in May 1982, the final element was removed from the core in December 1984, and the examinations were completed in September 1986.

The elements, their irradiation history, and the results of detailed post-irradiation examinations are described and discussed in this report.

2. DESCRIPTION OF FUEL ELEMENTS

2.1 General Description

The LEU U_3Si_2 test elements were essentially identical to the HEU elements routinely used in the ORR, except for the composition of the fuel meat and, for CERCA and NUKEM, the aluminum alloy compositions of the cladding and side plates. The ORR element is a standard box-type element containing 19 curved fuel plates. A cross section of the fuel box is shown in Fig. 1. The nominal fuel meat thickness is 0.51 mm (0.020 in.), giving nominal cladding thicknesses of 0.38 mm (0.015 in.) and 0.57 mm (0.0225 in.) for the inner and outer plates, respectively.

The ^{235}U loading of the test elements was nominally 340 g, a 19% increase over the 285-g loading of the HEU elements. The fuel meat consisted of uranium silicide particles with the nominal composition of U_3Si_2 dispersed in an aluminum matrix. Based on the nominal fuel meat dimensions, the uranium density of the fuel meat was 4.75 Mg U/m^3 (42 vol% U_3Si_2).^{*} By comparison, the nominal uranium density of the HEU elements is 0.85 Mg U/m^3 (12 vol% U_3O_8).

2.2 Specifications

Each of the three fabricators developed a set of specifications for the U_3Si_2 test elements based upon ORNL specifications for ORR HEU fuel elements. For the most part, each fabricator was allowed to use its standard materials and fabrication and inspection procedures. The materials used in the test elements are listed in Table I. The compositions and properties of the principal aluminum alloys used in the elements are listed in Table II. The greatly increased volume loading of fuel particles in the LEU fuel plates necessitated changes in, or in the interpretation of, several specifications related to the fuel meat.

The specifications for fuel plates for the ORR HEU elements required minimum cladding thicknesses of 0.33 mm (0.013 in.) and 0.46 mm (0.018 in.) for

*The 340-g loading for the test elements was chosen to remain below the 350-g maximum loading approved for the ORR in order to avoid possible delays in the irradiation schedule. It is only coincidental that the chosen uranium density is near the practical upper limit for U_3Si_2 fuel.

Table I. Materials Used in U_3Si_2 Test Elements

Part Name	Fabricators		
	B&W	CERCA	NUKEM
Fuel Plate			
Frame	6061	AG 3 NE	AlMg2
Cover	6061	AG 3 NE	AlMg2
Fuel Core			
Fuel	U_3Si_2	U_3Si_2	U_3Si_2
Matrix	MD X75	A5 NE or AL 405	Al-Powder 99.8
Side Plate	6061-T6	AG 3 NE	AlMgSi11, F32
Comb	6061-T6	6061-T6 ^a	AlMgSi11, F32
Pin (Rivet)	4043 or 5356	4043 or 5356 ^a	AlMgSi11, F21
End Adapter	356 Al	356 Al ^a	356 Al ^a
Welding Wire	N/A	AG 3 NE	S-AlSi15

^aSupplied by ORNL/ANL.

Table II. Properties of Aluminum Alloys Specified for
ORR LEU Fuel Elements

Alloy ^a	AlMg2	AG 3 NE	6061	6061-T6	AlMGSil, F32
Composition, wt% ^b					
Al ^c	97.6	96.7	97.6	97.6	97.2
Mg	2.0	2.7	1.0	1.0	0.9
Si	<0.3	<0.3	0.6	0.6	1.0
Cu	<0.05	<0.008	0.28	0.28	<0.05
Cr	<0.3	<0.3	0.2	0.2	<0.25
Mn	<0.05	<0.7	<0.15	<0.15	0.7
Tensile Strength, MPa	>147	235	124	310	>314
Yield Strength, MPa	>59	127	55	276	>255
Hardness (HB)	40	42	30	95	95
Thermal Conductivity, W/m•K	150	130	180	167	170
Heat Capacity, J/kg•K	---	960	896	896	---
Solidus Temperature, °C	620	---	582	582	585
Liquidus Temperature, °C	650	650	652	652	650

^aAll properties are for 0-temper anneal unless listed otherwise.

^bAverage value of composition limit range used.

^cTypical Al contents are provided for comparison purposes only. The specification is for Al to constitute the remainder after accounting for additions and impurities.

the inner and outer plates, respectively. Surface defects with depths up to 0.127 mm (0.005 in.) were allowed, leaving a minimum of 0.20 mm (0.008 in.) of cladding over the fuel meat at any point. With only 12 vol% of fuel in the fuel meat of the HEU plates, it was relatively easy to meet these requirements. At the 42-vol% fuel loading required for the LEU plates, however, the rolling process tends to leave the fuel meat thicker at the ends than in the middle (commonly referred to as a dogbone). This, of course, results in thinner cladding over the dogbones. In addition the large concentration of fuel particles results in an increased probability that several fuel particles will come into contact with each other and that one of them will be pushed into the cladding. Both of these phenomena would have resulted in a reduced yield of plates meeting the original ORR minimum cladding thickness specification. ORNL agreed to a minimum cladding thickness specification of 0.267 mm (0.0105 in.) for the inner fuel plates and 0.40 mm (0.016 in.) for the outer plates. They also agreed to allow a 0.25-mm (0.010-in.) minimum at up to six points in the sections to be examined from any one fuel plate. If the plates exhibited dogbones, the depth of surface defects was limited to 0.076 mm (0.003 in.) in the dogbone region in order to maintain approximately the same absolute minimum cladding thickness as for the HEU fuel plates.

Also related to the high volume loading of fuel in the meat is an increased number of fuel particles at the surface of the fuel compact and, consequently, an increased probability for fuel particles to become dislodged and spread into nominally fuel-free zones during the rolling process. This phenomenon, referred to as fuel flaking or fuel out of zone, is identified by the occurrence of white spots on an x-radiograph of the fuel plate. Although the specifications approved for the LEU elements did not specifically address this new problem, ORNL used realistic criteria in judging the acceptability of plates with fuel out of zone. Since the amount of fission energy liberated in these relatively isolated particles is so small as to preclude any cooling problem, the only concern is the isolation of fission products. In general, it was required that no particle be within 0.5 mm (0.020 in.) of the edges or ends of fuel plates.

Another consequence of the high volume loading of fuel particles in the fuel meat and of the high uranium loading in each fuel particle was a difficulty in achieving as homogeneous a uranium loading as was possible in the HEU fuel meat. In addition, it was necessary to accept the spot size normally associated with each fabricator's scanning equipment since it was impractical to request that special collimators be installed for such limited work under a cooperative arrangement. The homogeneity tolerances to which each fabricator agreed are shown in Table III. It is apparent that the different sets of requirements yield different degrees of homogeneity. All were acceptable to ORNL, however.

Finally, the HEU element specifications required a metallographic grain growth test to verify a metallurgical bond between covers (cladding) and frame. The fabricators were allowed to substitute a bending (delamination) test of a strip of material trimmed from the end of the plate. In addition, it was required that each fuel plate be ultrasonically scanned to detect the

Table III. Comparison of Homogeneity Tolerances for U_3Si_2 Test Elements

	Spot Size		Tolerance	
	Linear, mm	Area, mm ²	Dogbone Region	Non-Dogbone Region ^a
HEU Element	2.0 diam	3.1	+27%/-100%	+27%/-100%
	2.0 × 12.7	25.4	+12%/-100%	±12%
B&W LEU Element	2.0 diam	3.1	+30%/-100%	---
	20 × 2.0 diam ^b	62.8	---	±10%
CERCA LEU Element	3.0 diam	7.1	+27%/-100%	±27%
	5.0 diam	19.6	---	±12%
NUKEM LEU Element	5.6 diam	24.6	+27%/-100%	±12%

^aIn the area between the maximum and minimum core outlines a tolerance of -100% was used in place of the listed negative tolerance.

^bTwenty spots distributed along a 25.4-mm (1.0-in.) line.

presence of non-bond areas in the fuel zone. It was recognized that false non-bond indications might occur from reflections at the fuel-frame interface, so the fabricators were given considerable latitude in interpreting the ultrasonic records in this region. Primary reliance was placed on the blister test to detect non-bonds at the fuel-frame interface.

2.3 As-Fabricated Attributes

The stoichiometric composition of U_3Si_2 , 7.3 wt% Si, was chosen by each fabricator as the nominal composition of the fuel compound. Metallic uranium and silicon were combined by arc-melting to form the fuel alloy. Since it is a practical impossibility to produce a perfectly homogeneous ingot by arc melting, the as-cast ingots consisted of U_3Si_2 as the major phase with minor amounts of USi and uranium solid solution (U_{ss} , also called free uranium). Both CERCA and NUKEM heat treated the ingots for approximately three days at 800°C, as had been the practice at ANL for the U_3Si_2 used in the miniplates. During this heat treatment, most or all of the U_{ss} was converted to U_3Si through the peritectoid reaction. By the time B&W began production, however, it had been decided at ANL that no advantage was to be gained by heat treating U_3Si_2 . Therefore, the B&W fuel was not heat treated. As will be discussed later, a knowledge of the differences in the compositions of the fuel powders used in the elements from the different fabricators was important in understanding the details of the irradiation behavior of the different elements.

The results of chemical and spectroscopic analyses of the fuel powders produced by the three fabricators are given in Table IV. The maximum U_3Si_2 particle size was 150 μm for B&W and NUKEM and 90 μm for CERCA. The quantity of fines (particles smaller than 40 μm for CERCA and NUKEM or 44 μm for B&W) in the powder was 17% for NUKEM, 18% for B&W, and 40% for CERCA.

The minimum cladding thickness specification was discussed in Section 2.2. Smaller values of this parameter were discovered during metallographic examination of plates during fabrication. The following minima were accepted: 0.22 mm (0.0087 in.) for B&W, 0.23 mm (0.0091 in.) for NUKEM, and 0.25 mm (0.0098 in.) for CERCA. One must understand, of course, that the penetration of fuel particles into the cladding is a random process and that the actual minima for the fuel plates assembled into elements are not necessarily the same as those measured in the sections of the plates destructively examined.

Another parameter of importance in understanding the swelling characteristics of the fuel plates is the volume of void in the as-fabricated fuel plates. Void volumes were measured by the fabricators and/or by ANL using the immersion density technique. The results for inner plates were 4.0 vol% for CERCA and 6.8 vol% for NUKEM. The results for outer plates were 7.8 vol% for NUKEM and 9.9 vol% for B&W.

The immersion density measurements mentioned above yield the fuel meat volume of each plate measured. Based upon these measurements, the calculated

Table IV. Reported Average U_3Si_2 Powder Compositions and Impurities

Major Constituent, wt%	Fabricator		
	B&W	CERCA	NUKEM
U	91.8 (91.2-92.3)	92.1	---
Si	7.4 (7.2- 7.7)	---	7.3
Impurity, ppm			
Al	4	---	400
B	5	<10	0.9
C	607	337	400
Cd	<0.5	<10	<5
Co	---	---	<5
Cu	7	---	96
Fe	6	---	550
H	---	13	---
Li	---	<5	<5
N	---	1672	---
Ni	5	---	---
O	806	1290	---
Zn	<2	---	<10

average uranium densities for the fuel plates from each fabricator are 5.2 Mg U/m³ for the CERCA elements, 4.9 Mg U/m³ for the NUKEM elements, and 4.6 Mg U/m³ for the B&W elements, compared to the 4.75 Mg U/m³ nominal uranium density. The as-fabricated uranium densities correspond to fuel volume fractions of 46, 43, and 41 vol% for the CERCA, NUKEM, and B&W fuel, respectively. These density data are consistent with average fuel meat thicknesses determined from metallographic studies by CERCA and B&W--0.49 mm and 0.53 mm, respectively.

3. IRRADIATION HISTORY

The irradiation history of the U₃Si₂ test elements is summarized in Table V. One element of each pair was irradiated to approximately normal (~50% average) burnup in the ORR. The second element was irradiated until more than 75% average burnup was achieved. Element No. NSI-201, one of the first pair of elements to be irradiated, was removed from the core earlier than planned in order to take advantage of two months of cooling during a major maintenance outage so that the postirradiation examination of the element would not be delayed.

The two basic core configurations employed during the irradiation of the U₃Si₂ test elements are shown in Fig. 2. At various times, experiments were replaced with filler pieces or with fuel elements. Although the test elements were not cycled through the core in a normal pattern, they did experience irradiation in a variety of typical core positions.

Although fluxes were measured for only a few of the cores containing these elements, results of calculations of similar cores have been used to estimate the maximum powers and associated heat fluxes and temperatures of the test elements during irradiation. It is estimated that each element produced ~1.3 MW during its first cycle of irradiation, with a peak-to-average power density and heat flux factor of no more than 1.5. The average heat transfer area of the element is 1.39 m², giving average and peak heat fluxes of 0.94 and 1.4 MW/m², respectively. Estimated temperature drops from the center of the fuel meat to the bulk coolant are given in Table VI for various materials and assumptions. The maximum temperature drops given in the table are over-estimates since it took several cycles for the boehmite film to build up to its maximum thickness, by which time the element power had decreased owing to burnup. With an average bulk coolant temperature in the ORR core of ~53°C, it is estimated that peak fuel meat temperatures were between 110 and 130°C during the early cycles of irradiation. Average fuel meat temperatures are estimated to have been ~20 to 25°C less.

The pH and electrical resistivity of the primary coolant during the irradiation of the elements ranged between 5.0 and 6.3 and 0.7×10^4 and 2.5×10^4 Ω·m, respectively.

Table V. Irradiation History Summary for U₃Si₂ Test Elements

Core Position	Irradiation Time, fpd					
	BSI-201	BSI-202	CSI-201	CSI-202	NSI-201	NSI-202
B-3	24.8		25.7	43.1		12.6
B-7		24.8	43.1	25.7		
C-2	27.1	12.5	42.7	9.4		
C-4		174.9	12.6	54.9		29.0
C-5		24.9				70.3
C-6	24.9			112.0		54.9
C-8	12.5	27.1	9.4	42.7		
D-2		12.7			57.0	60.8
D-3		30.0				
D-7	30.0					
D-8	12.7				53.2	57.0
E-2				11.5		
E-8			11.5			
Total	132.0	306.9	145.0	299.3	110.2	284.6
Begin Irrad.	11/23/83	11/23/83	4/28/83	4/28/83	5/27/82	5/27/82
End Irrad.	4/22/84	12/19/84	9/29/83	8/14/84	1/14/83	8/14/84
Total No. of Cycles	8	26	11	26	8	24
Ave. Burnup, ^a % ²³⁵ U	54	77	52	82	35	82
Ave. Burnup, ^b MWd	150	217	144	228	95	231
Ave. Power, MW	1.13	0.71	0.99	0.76	0.86	0.81

^aSee Table VIII.^bBased on the following calculated ²³⁵U burnup rate correlation:

$$\text{Burnup rate (g/MWd)} = 1.2608 - 0.0004103 \cdot \text{Burnup (MWd)}.$$

Table VI. Estimated Average and Peak Fuel Temperature Drops

	Thickness, mm	Thermal Conductivity, W/m·K
Fuel Meat	0.25 ^a	30 - 60 ^b
Cladding	0.38	130 - 180 ^c
Boehmite Layer	0 - 0.025	2.25

Temperature Drops, °C		
	Average (0.94 MW/m ²)	Peak (1.4 MW/m ²)
Fuel Meat		
30 W/m·K	7.8	11.7
60 W/m·K	15.7	23.3
Cladding		
130 W/m·K	2.7	4.1
180 W/m·K	3.8	5.7
Boehmite		
13 μm thick	5.4	8.1
25 μm thick	10.4	15.6
Water Film ^d	27.6	41.2
Total		
Minimum		
(no Boehmite)	38.1	57.0
Maximum	57.5	85.8

^aHalf-thickness.^bR. K. Williams, R. S. Graves, R. F. Domagala, and T. C. Wiencek, "Thermal Conductivities of U₃Si and U₃Si-Al Dispersion Fuels," Proc. 19th International Conference on Thermal Conductivity, Cookeville, Tennessee, USA, October 21-23, 1985, in press.^cSee Table II.^dFilm coefficient calculated using the Dittus-Boelter correlation for a bulk water temperature of 53.3°C.

The accessible channel gaps of the elements were measured at various times during the irradiation of the elements (following each cycle beyond 50% burnup) using the ultrasonic probe described in Ref. 3. In all cases the channel profiles remained essentially unchanged during the course of the irradiations, indicating no abnormal swelling or warping of the plates.

4. POSTIRRADIATION EXAMINATION OF FUEL ELEMENTS

After suitable periods of cooling in the ORR pool following completion of irradiation, the elements were transported to the ORNL High-Radiation-Level Examination Laboratory (HRLEL). All six elements were given the complete nondestructive and destructive examinations outlined in Appendix A. The non-destructive portion consisted of visual examination, dimensional inspection, gamma scanning, and coolant channel measurements. Then, the elements were dismantled, and the plates were visually inspected. Selected plates were measured for thickness and were gamma scanned. Two plates from each element were tested for blister threshold temperature, and one plate from each element was sectioned for microstructural and burnup analyses.

4.1 Visual Examination

The elements were examined visually through the cell windows and through the Kollmorgan periscope. All six of the elements appeared to be in excellent condition. With the exception of the oxide film and some handling scratches, the elements appeared to be as fabricated. No abnormal conditions were observed. Photographs obtained of the exterior of the elements and through the coolant channels are contained in Appendix B.

4.2 Dimensional Inspection

The width (between side plate outer surfaces) and stack height (between outer fuel plate outer surfaces) of each element were measured at six axial locations along a central line and along parallel lines near the edges of the element. The measurements were made by positioning the element between opposing dial micrometers at the desired point of measurement and comparing the readings to a standard. By comparing readings from the upper and lower micrometers, bow or twist could be detected. The length of each element was determined by comparison to a standard using a fixture and a dial indicator. No unusual bow, twist, or swelling was observed for any of the elements. Within the accuracy of the in-cell measurements, the dimensions were within the envelope of tolerances allowed for as-fabricated dimensions. A summary of the dimensional measurement result is given in Table VII. Individual measurement results for each element are presented in Appendix C.

Table VII. Results of Dimensional Inspection of Irradiated Elements

	Width,		Stack Height,		Length,	
	mm	in.	mm	in.	mm	in.
Fabrication Tolerance						
Max	76.10	2.996	78.18	3.078	975.1	38.390
Min	75.84	2.986	77.67	3.058	973.5	38.328
Element No.						
BSI-201	76.17	2.999	77.83	3.064	975.0	38.386
	75.72	2.981	78.31	3.083		
BSI-202	76.20	3.000	77.85	3.065	974.8	38.378
	76.05	2.994	77.75	3.061		
CSI-201	76.07	2.995	78.05	3.073	---	---
	75.82	2.985	77.09	3.035		
CSI-202	75.69	2.980	78.10	3.075	974.5	38.367
	75.56	2.975	77.50	3.051		
NSI-201	75.95	2.990	78.10	3.075	974.5	38.365
	75.84	2.986	77.93	3.068		
NSI-202	76.23	3.001	78.26	3.081	975.7	38.413
	76.02	2.993	78.00	3.071		

4.3 Gamma Scanning of Elements

The elements were passed in front of a 432-mm (17-in.)-long collimator with a 0.25 mm × 25.4 mm (0.010 in. × 1.0 in.) aperture, and the gamma spectrum was measured. The detector was either a NaI or a Ge(Li) crystal. During the course of the work, several methods of recording the data were used. Profiles of gamma intensity versus axial position were obtained for integrated energies greater than 0.5 MeV and for a narrow energy window containing the ^{137}Cs peak at 662 keV. At certain positions, complete multichannel energy spectra were obtained using the Ge(Li) crystal.

The primary purpose of these measurements was, in conjunction with the results of the destructive burnup analyses discussed in Section 5.3, to provide data for determining burnups of similar elements not scheduled to be destructively examined. Since all of the present elements were destructively examined, including burnup analysis, these data will not be discussed in detail. The ^{137}Cs profiles are presented in Appendix D.

4.4 Coolant Channel Gap Thickness Measurements

Following removal of the end adapters from the elements, the coolant channel gap thicknesses were measured on either side of the comb along the entire length of each channel. For element NSI-201 the measuring probe was a spring-loaded device containing a linear voltage differential transformer (LVDT). Channel gaps of elements CSI-202, BSI-201, and BSI-202 were measured using a capacitance probe. For elements NSI-202 and CSI-201 neither device was available, and a 2.64-mm (0.104-in.)-diameter wire was rolled between the plates to assure that the channels exceeded the 2.64-mm minimum gap allowed by the specifications.

Tabulated results of the coolant channel measurements are contained in Appendix E. These data indicate that the gaps of all but a few channels everywhere exceeded the as-fabricated minimum dimension. In these few channels, the gap thicknesses at a few isolated points were slightly below this value (but greater than 2.62 mm). No comparable preirradiation data are available to determine changes. The uniformity of the channels indicates that no excessive swelling or warping of the plates occurred during irradiation.

5. EXAMINATION OF FUEL PLATES

The individual plates were removed from the element by cutting through the side plates into the coolant channels using a milling machine. The strips of aluminum clinging to the plate were then easily pulled off without damaging the plate.

5.1 Visual Inspection of Plates

The first examination of the plates following their removal from the element was verification of the plate numbers and a thorough visual inspection. The plates in all elements exhibited some warping and bowing after removal from the element. This is typical of all irradiated elements of this configuration. All of the plates from the six elements appeared to be in good condition with no evidence of blisters, excessive swelling, or any other unusual condition.

5.2 Plate Thickness Measurements

Plate thickness measurements were made by positioning the plate between opposing dial micrometers at the desired point of measurement and comparing the readings to a standard. The indicator tip for the top (convex) surface was a 6.35-mm (1/4-in.)-diam flat and for the bottom (concave) surface was a 3.18-mm (1/8-in.)-diam ball. Measurements were made along tracks at the center and near the sides of the plate. No attempt was made to remove the oxide film from the plates, so its thickness is included in the overall plate thickness. Near the end of the examinations, a new device based on capacitance became available to measure the plate thickness. This device was used to remeasure the thickness of several plates as an overcheck of the micrometer measurements and to supplement some incomplete data. Thicknesses determined with the new device were consistent with the data obtained using the micrometers.

All plates of NSI-201 and NSI-202 were measured at NUKEM's request, since they were the first U_3Si_2 elements to be irradiated. Five plates (in positions 2, 6, 10, 14, and 18) from each of the other four elements were selected for measurement. Plate thickness increases were determined from the thicknesses measured at each position by subtracting the plate thickness measured outside the fuel zone, near the end of the plate. This method at least partially corrects for the oxide film buildup, since the normalization region also has an oxide film, though probably not as thick as one as in the fuel zone, where the heat flux was higher. The average fuel plate thickness increases in the peak- and minimum-burnup regions (based upon the plates in positions 2, 6, 10, 14, and 18) are listed in Table VIII. Swelling profiles for the five plates used for the averages are presented in Appendix F.

Apart from the contribution from the oxide film, plate thickness changes result only from swelling of the fuel meat. Since the fuel meat is well constrained by the frame in the transverse directions, it swells almost exclusively in the thickness direction. The fractional change in fuel meat thickness is, then, equal to the fractional change in fuel meat volume, the number most commonly reported as the fuel meat swelling. Experience with well over 100 miniplates, where both fuel plate thickness changes and fuel meat volume changes were accurately measured, has shown that swelling estimates based on thickness changes are always greater than the actual fuel meat volume changes since the thicknesses are measured between the "high" points on the

Table VIII. Average Thickness Increase and Burnup^a

Element No.	Low-Burnup End			Peak-Burnup Region			Element-Average Burnup, %
	Burnup, %	Thickness Increase, mils μm		Burnup, %	Thickness Increase, mils μm		
BSI-201	28	0 0		69	1.5 38		54
BSI-202	53	0 0		97	1.8 46		77
CSI-201	32	0.1 3		66	1.7 43		52
CSI-202	55 ^b	0.9 23		98	4.4 112		82
NSI-201	19	0.7 18		46	1.0 25		35
NSI-202	53	1.2 30		97	4.1 104		82

^aAverage thickness increases and burnups at the low-burnup end and in the peak-burnup region are average values for the plates in positions 2, 6, 10, 14, and 18. Data from all 19 plates were used in calculating the element-average burnup.

^bBased on analyzed burnup and comparison to other elements because of discrepant data at the low-burnup end.

fuel plate surfaces. The curvature of the ORR fuel plates increases this problem. Therefore, no attempt has been made to calculate volume swelling from the thickness change data. Nevertheless, significant differences in measured thickness change do represent significant differences in the volume swelling of the fuel meat. However, from the point of view of fuel element performance, the overall thickness changes were small compared to the allowed tolerance in the channel gap thickness. This is consistent with the results from the channel gap thickness measurements discussed in Sections 3 and 4.4.

5.3 Plate Gamma Scanning and Burnup Analysis

Five plates from each element (including the one from which burnup samples were taken) were selected for determining the axial burnup profile by gamma scanning. The setup and techniques described in Section 4.3 for full-element scanning were also used for the plates. Complete multichannel energy spectra were obtained with the Ge(Li) crystal at the peak-burnup points of all nineteen plates of each element, with the exception of NSI-201.

Samples for burnup analysis were obtained at the positions of peak and minimum burnup, as determined by the gamma profiles. Following dissolution of the sample, the relative uranium and plutonium isotopic abundances were determined by mass spectrometry. The ^{235}U isotopic abundances before and after irradiation were used, with calculated correlations for changes in the ^{238}U and ^{236}U abundances, to derive the ^{235}U burnup.

Relative plate-average burnups were determined from the individual axial profiles, and the relative plate-to-plate burnup profile in the element was determined from the areas of the 662 keV peak of ^{137}Cs in the multichannel spectra (NaI gamma intensity data used for NSI-201) at the peak-burnup point of each plate. These data were normalized to the results of the destructive burnup analysis to determine the element-average burnup. The results are summarized in Table VIII. Typical profiles are shown in Fig. 3. Typical examples of the gamma scanning data and the complete burnup analysis data and correlations are in Appendix G.

As was mentioned in Section 3, the average burnup of one element from each fabricator was intentionally pushed well beyond the ~50% level normally achieved in reactors using this type of fuel. This resulted in peak burnups of ~98% in each case. Accounting for non- ^{235}U fissions, the fission density in the high-burnup elements ranged between $\sim 1.1 \times 10^{27}$ and $\sim 2.5 \times 10^{27}$ f/m³.

5.4 Blister Threshold Testing

A method which has been used historically to compare the relative irradiation performance of dispersion plate-type research reactor fuels is their resistance to blistering during heating after irradiation. This test, termed the "blister threshold test," is performed by sequentially heating the plate (or portions thereof) to higher and higher temperatures and visually examining the plate after each heating for evidence of blisters. Two plates from each

element were blister threshold tested. The entire plate rather than a plate section was heated to preclude the possibility of fission gas diffusing out of the cut edges rather than causing blisters at these relatively high volume fractions of fuel. The plates were held at the following temperatures for 30 minutes; removed from the furnace, cooled and examined; then heated to the next higher temperature (or removed from testing if blistering was observed): 400, 450, 475, 500, 525, 550, and 575°C. This procedure corresponds closely to the test procedure used previously for the highly enriched, low-volume-fraction uranium aluminide and uranium oxide fuels.

Typical blister threshold temperatures for the highly enriched dispersion fuels in use today range from 480 to >565°C for the uranium aluminide⁷ and from 400 to >550°C for the uranium oxide⁸ fuels. Blister threshold temperatures measured during miniplate tests of high-density, low-enriched uranium aluminide and uranium oxide dispersion fuels developed by the RERT Program ranged from 550 to >550°C and from 450 to >550°C, respectively.⁹ The same type of tests on uranium silicide miniplates yielded blister threshold temperatures of 530°C for U_3Si_2 fuel and 500 to 525°C for U_3Si fuel.⁹

The results of the present tests are presented in Table IX. The blister threshold temperature in each case was in the upper range of that which could have been expected with the established fuels. The appearance of the blisters was similar to that of the small blisters between the cladding and meat which were observed during testing of uranium silicide miniplates. The blister threshold temperatures of these full-sized plates are consistent with the results of the miniplate tests cited above. Photographs of the plates after blistering are contained in Appendix H.

These tests have shown that blister threshold temperatures of low-enriched, high-density uranium silicide fuels are about the same or higher than those of the highly enriched, lower-density uranium aluminide and uranium oxide fuels they are proposed to replace. Therefore, the propensity for blistering in-reactor will be no worse for these new fuels than for those presently in use.

5.5 Toughness of Irradiated Fuel Plates

Owing to the very high volume fraction of fuel particles in the meat following irradiation, some concern was expressed about the brittleness of the fuel and whether the fuel plates might be subject to breaking during handling and shipping. Even though one would expect the cladding and frame, which were fabricated from the same alloys used for HEU fuel plates for many years with no problems, and not the fuel meat to be the major determinant of the toughness of the fuel plate, it was considered prudent to devise a simple test to address this concern in a very qualitative manner.

Therefore, several high-burnup plates were bent to determine their ductility and toughness. The center of a plate was positioned under a mandrel

Table IX. Results of Blister Anneals of Full-Sized Plates

Element No.	Plate Position	Plate No.	Maximum Temperature, °C	Description of Blisters ^a
BSI-201	3	S-3-211-13	575	None
	8	S-3-210-23	575	Typical PI
BSI-202	3	S-3-213-15	550	Typical PI
	8	S-3-212-19	550	Typical PI
CSI-201	4	OSIIW-065	550	Typical PI
	8	OSIIW-054	550	Typical PI
CSI-202	3	OSIIW-044	550	Typical PI ^b
	8	CSIIW-026	550	Typical PI ^c
NSI-201	2	ORR-092	550	None
	8	ORR-100	550	None
	19	ORR-144	550	None
NSI-202	3	ORR-114	550	Typical PI
	9	ORR-123	550	Typical PI

^aTypical PI--typical of postirradiation blisters observed previously in low-volume-fraction fuels (i.e., appear to be discrete blisters between meat and cladding with no "pillowing").

^bSmall blisters off of fuel formed at 500°C.

^cSmall blisters off of fuel formed at 525°C.

(~2.5 mm diam), and, with one end fixed, the plate was bent around the mandrel with the concave surface inward. A plate from CSI-202 broke at about 160° of bend. One plate from BSI-202 broke at about 90° of bend. Another plate from BSI-202 was bent 80° and straightened out completely when the force was removed. A plate from BSI-201, which had experienced significantly less neutron fluence, was bent 80° and straightened out when the force was removed. The same plate was bent again to 90° and recovered to a bend of about 10° when the force was removed. The bent plates are shown in Fig. 4.

Therefore, it can be concluded that U_3Si_2 fuel plates in irradiated elements have more than adequate toughness to maintain their integrity during handling and shipping. The differences in the characteristics of the B&W and CERCA fuel plates demonstrated by the bending test are believed to be related primarily to differences in the cladding.

5.6 Metallography

The outermost of the inner plates on the concave side of each element was sectioned for destructive examination according to the diagram in Fig. 5. The burnup analysis sections were cut from the minimum- and maximum-burnup areas of the plate as determined by the gamma scan profile. Sections were cut immediately adjacent to the burnup analysis sections for optical metallography, Scanning Electron Microscopy (SEM), and Scanning Auger Microscopy (SAM). In order to characterize the unirradiated fuel, a section from one plate produced by each fabricator during the fabrication run for the test elements was also examined.

The metallographic sections were prepared for viewing (transverse to the length direction of the plate) using conventional techniques. The section was mounted in epoxy, ground on progressively finer silicon carbide paper through 600 grit, then vibratorily polished. The vibratory polishing was a three step process. The first and second steps were on a Texmet* cloth with a water medium and 3- μ m and 1- μ m diamond paste respectively. The final polish was on Microcloth* with a thick water slurry of Magomet* for 12 minutes.

The SEM and SAM samples were small discs, approximately 1.5 mm in diameter, punched from the irradiated plates. These discs were split parallel to the cladding surface, yielding two samples of a fracture surface through the fuel meat. The small sample size was needed to reduce gamma activity enough to allow examination outside the hot cell. SEM and SAM examinations of the unirradiated plates were performed on polished metallography samples.

Before proceeding with a discussion of the results of the metallographic examinations, some data obtained from miniplate irradiations that preceded the present full-sized fuel element experiments will be briefly reviewed. An example of the meat microstructure of a U_3Si_2 miniplate after >90% burnup is

*Texmet, Microcloth, and Magomet are trademarks of Buehler, Ltd.

shown in Fig. 6M.* Some of the noteworthy features in this optical micrograph are the absence of fission gas bubbles and the fact that all of the as-fabricated porosity has been consumed by fuel particle swelling. Fuel-aluminum interaction was limited to a narrow zone around the U_3Si_2 particles with a thickness about equal to the range of fission product recoils in aluminum. SEM examination of fractured fuel particles reveals a gas bubble morphology typical of pure U_3Si_2 , as shown in Fig. 7M. The very uniform distribution of small gas bubbles that show no tendency to interlink is the reason for the stable swelling behavior of U_3Si_2 .

The microstructural changes in U_3Si miniplates resulting from irradiation to high burnups are quite different, as shown in Fig. 8M. Fission gas bubbles are clearly visible in the optical micrograph. The bubble morphology, more clearly shown in the SEM images in Fig. 9M, reveals a basic difference in fission gas behavior between U_3Si and U_3Si_2 . The fission gas bubbles in U_3Si are clearly not uniformly distributed and vary widely in size. The large bubbles are growing rapidly and linking up, resulting in a much larger fuel swelling rate than that of U_3Si_2 . As will be shown further on in this report, the fuel in the full-sized U_3Si_2 plates exhibits characteristics of both U_3Si_2 and U_3Si .

Several uranium silicide miniplates fabricated with depleted uranium were irradiated to determine the effects of neutrons, as opposed to fission fragments, on the fuel. Figs. 10M and 11M clearly show that irradiation-enhanced diffusion has occurred.

The microstructure of the fuel as it changes during irradiation is discussed in alphabetical order for the three fabricators, beginning with the low-burnup plate in each case, followed by the high-burnup plate, and concluding with some observations on unirradiated fuel. The micrographs used in the discussion represent the typical fuel condition observed under the microscope. The serial number of the fuel element rather than that of the specific fuel plate from which the sample came is used for simplicity; plate numbers are the same as those from which burnup samples were taken (See Appendix G, Table G.8). Burnups are those measured for samples taken adjacent to the metallographic sections. Thickness changes are averaged for five plates from the element in order to reduce the considerable scatter in the data.

The B&W fuel meat microstructure at the low-burnup (31%) end of plate BSI-201 is shown in Figs. 12B-16B. A large fraction of the as-fabricated porosity is still present, and the fuel swelling that has taken place is easily accommodated by these pores. This is consistent with the fact that no

*A large number of photomicrographs are presented in this section, grouped by fabricator. So that each figure can easily be associated with the fabricator in the discussions to follow, a letter designating the fabricator has been appended to the remaining figure numbers, as follows: M - Miniplates (fabricated by ANL); B - B&W; C - CERCA; N - NUKEM.

thickness increase has occurred at this end of the plate. A narrow interaction zone between fuel particles and aluminum, as well as the rounding of the pores by radiation-enhanced diffusion, can be seen in Fig. 13B. Except for the somewhat-more-extensive Al-fuel interaction inside some of the particles, the structure is similar to that of irradiated depleted U_3Si_2 miniplates shown in Figs. 10M-11M. Figure 14B is a typical SEM image taken at the low-burnup end of the plate. The fuel appears free of fission gas bubbles at this magnification and the smoothed as-fabricated porosity is clearly evident. However, at higher magnification, areas containing small fission gas bubble populations were found in a few fuel particles, as shown in Figs. 15B and 16B. Figure 16B was taken using the backscatter electron (BSE) detector in order to show the different phases in the fuel more clearly. In this figure, as well as in the backscatter images to follow, the image intensity is proportional to the atomic number of the material. The light phase containing the small bubbles is, therefore, the highest U-Si phase present whereas the other extreme shading, black, represents matrix aluminum.

A considerably larger number of fission gas bubbles have formed in the fuel at the high-burnup (71%) end of plate BSI-201, and the fuel swelling has nearly consumed all as-fabricated porosity; only a few pores (the irregularly shaped ones in Figs. 17B and 18B) remain. Fuel swelling has resulted in a plate thickness increase of 38 μm at this location. The fuel has essentially three different phases with regards to gas bubble morphology: (1) the lighter phase that appears to be bubble free; (2) a light grey phase containing many very small bubbles; and (3) isolated irregular clusters of larger bubbles. SEM images, shown in Figs. 19B-22B, more clearly distinguish two very different bubble morphologies. The areas containing irregular, larger-sized bubbles look similar to U_3Si fuel observed in the miniplates, while areas containing dense and uniform small bubbles appear identical to U_3Si_2 .

The low-burnup end of plate BSI-202 reached a burnup of 51%. No thickness increase was measured at this location, and the fuel microstructure is not much different from that of the low-burnup end of plate BSI-201, as shown in Figs. 23B and 24B.

The high-burnup (97%) end of plate BSI-202 had a measured thickness increase of 46 μm , and, indeed, the fuel microstructure has somewhat-more-developed fission gas bubbles. As was the case at 71% burnup in plate BSI-201, three distinct phases exist in the fuel (see Figs. 25B-27B). The SEM images in Figs. 28B-33B show examples of the fission gas behavior in these three fuel phases. The major phase has a bubble morphology characteristic of pure U_3Si_2 (Fig. 33B), while parts of several fuel particles have either a characteristic U_3Si bubble morphology (Figs. 30B and 31B) or, as shown in Fig. 32B, a total absence of bubbles and apparent brittle properties reminiscent of UAl_4 .

The different fission gas behavior in parts of the ostensibly pure U_3Si_2 fuel grains can be understood through the results of a detailed microscopic examination of an unirradiated fuel plate. As shown in Figs. 34B-36B, the

fuel particles are not single-phase U_3Si_2 ; rather, they contain both U_3Si and U , as determined by energy dispersive x-ray analysis (Fig. 37B). The Si-to-U ratios of phases A and B identify them as, respectively, U_3Si_2 and U_3Si , while the absence of Si in phase C indicates U_{ss} . Therefore, the U_3Si and U_3Si_2 show their characteristic irradiation behaviors, and the U_{ss} presumably reacts with Al during irradiation to form the stable UAl_4 compound. UAl_4 is indeed very stable and has never been found to contain fission gas bubbles. Therefore, the presence of U_{ss} in the as-fabricated fuel appears not to be detrimental to the performance of the fuel plate. This is consistent with the results of miniplate tests of UAl_2 fuel containing U_{ss} in the as-fabricated condition.¹⁰ Even though the U_3Si was found to contain all the larger bubbles, its amount is such that no continuous network of large bubbles can develop, even at the very high burnup attained in these plates. It has been established in miniplate irradiations that interparticle linkup of larger bubbles is a prerequisite for possible large swelling in U_3Si .

The low-burnup (33%) end of plate CSI-201 may have just begun to show a thickness increase (3 μm was measured at this location). This may owe to the lower as-fabricated porosity of the CERCA plates (4%) than for the B&W plates (9 to 10%). Indeed the microstructure shown in Figs. 38C and 39C illustrates the rather low residual porosity at this burnup compared to that in the B&W plates discussed before (cf. Figs. 12B and 13B). The narrow interaction zone at the fuel particle surface is also seen in this fuel, but no significant amount of fuel-Al reaction phase inside the fuel particles is present.

The high-burnup (67%) end of plate CSI-201, with a thickness increase of 43 μm , has a fuel microstructure in which the fuel swelling has completely consumed the as-fabricated porosity and in which the fuel particles have begun to develop fission gas bubbles (see Figs. 40C and 41C). This is shown in more detail in the SEM images in Figs. 42C-45C. The phase in which larger bubbles occur (presumably U_3Si) is more dispersed, in a stringy or lacy manner, than in the B&W fuel.

The fuel microstructure at the low-burnup end (55%) of plate CSI-202 is very similar to that of plate CSI-201 (see Figs. 46C-51C). The thickness increase at this location is 23 μm .

The high-burnup (97%) end of plate CSI-202 has a measured thickness increase of 112 μm , more than twice that of the B&W plate. The fuel microstructure shows basically the same two-phase fission gas morphology seen in plate BSI-202, with the U_3Si -type bubbles more evenly distributed throughout the fuel (see Figs. 52C-57C). The total fission gas bubble volume appears to be significantly larger than that seen in the B&W plates, as would be expected from the much larger thickness increase experienced by the CERCA plates. Some of this larger thickness increase is attributable to the 4% porosity of the CERCA fuel meat compared to the 9-10% porosity of the B&W fuel meat, but the largest part of the difference undoubtedly owes to a larger amount of U_3Si in the CERCA plates.

The fission gas bubble behavior is, in fact, consistent with the as-fabricated fuel microstructure. The CERCA fuel did contain more U_3Si than did the B&W fuel (compare, for example, Figs. 58C and 34B), and it was more finely distributed than in the B&W fuel. The CERCA fuel did not contain U_{ss} because it had been heat treated, hence the absence of the UAl_4 -like phase in the irradiated plate. It did, however, contain a powdery, grey phase (see Fig. 59C) which, by means of Auger Electron Spectroscopy, was found to contain oxygen and carbon in addition to U, Si, and Al. No trace of this material was found in the irradiated plates and it is assumed that it reacted in-pile to form a compound not distinguishable from the common fuel phases.

The fuel microstructure of the low-burnup (24%) end of NUKEM plate NSI-201 (shown in Figs. 61N-66N) was essentially the same as that of the low-burnup plates discussed before. The fuel consisted of U_3Si_2 with a somewhat coarsely distributed (compared to the CERCA fuel) second phase. The amount of second phase in this fuel appeared to be the highest of the three, albeit still minor. The second phase, and the tendency for gas bubbles to occur first in this phase, is more clearly illustrated in the microstructure at the high-burnup (51%) end of plate NSI-201, shown in Figs. 67N-72N. SAM analysis of the irradiated fuel positively identified the light phase containing the irregular bubbles in Fig. 72N as U_3Si , while the remainder of the fuel was identified as U_3Si_2 .

The fuel at the low-burnup (54%) end of plate NSI-202, shown in Figs. 73N-78N, had the expected microstructure, with the beginning of small uniform bubble formation in U_3Si_2 (see Figs. 77N-78N) and continued irregular bubble development in U_3Si (see Fig. 76N). The high-burnup (96%) end of plate NSI-202, shown in Figs. 79N and 80N, had a measured thickness change of 104 μm . The fission gas bubble morphology is rather similar to that of the other high-burnup plates with a two-phase behavior, as clearly illustrated in Figs. 81N-83N.

As was the case for the B&W and CERCA fuels, the fission gas behavior can be traced to the microstructure of the as-fabricated fuel. The SEM images in Figs. 84N-87N show a major, dark grey, brittle phase, identified by energy dispersive x-ray analysis as U_3Si_2 , interlaced with a more ductile light phase, U_3Si . The light phase occurs primarily in the largest fuel particles, acting as a bond during grinding, due to its more ductile properties. As indicated before, the NUKEM fuel appears to contain slightly more U_3Si than the CERCA fuel, and because this fuel was heat treated, it does not contain U_{ss} . It also does not contain the powdery oxy-carbide-like phase found in the CERCA fuel.

In conclusion, the metallographic observations are consistent with the relatively small plate thickness increases experienced during irradiation. The swelling is primarily caused by formation of two distinct fission gas bubble morphologies. The by-far-major phase, U_3Si_2 , developed a very uniform and dense distribution of submicron-sized bubbles, characteristic of this

fuel. The second silicide phase, U_3Si , which occurred in different amounts in the three fuels, developed its characteristic coarse, non-uniform bubble morphology. The amount of U_3Si and its larger swelling account, with the as-fabricated porosity, for the variability in overall plate swelling between plates of the different fabricators.

The similarity of the average thickness changes in the high-burnup regions of elements CSI-202 and NSI-202 suggest that differences in bubble morphology may not be as great as comparison of Figs. 52C and 79N seem to indicate. Since only one section from the high-burnup region of CSI-202 was examined, there is a possibility that the section was atypical.

The non- U_3Si_2 phases present in the fuels are a result of fabrication practices. It is not possible, on a commercial scale, to produce a perfectly homogeneous alloy with the exact composition of a line compound such as U_3Si_2 . Heat treatment of the ingots employed by CERCA and NUKEM and not by B&W would explain the absence of U_{ss} in their fuel. The oxy-carbide-like phase present in the CERCA fuel could be related to the larger amount of fuel fines (with much larger surface-to-volume ratio) used by CERCA. However, the U_{ss} phase found in the B&W plates and the oxy-carbide-like phase in the CERCA plates evidently react with aluminum during irradiation and have no deleterious effects on the swelling behavior of the fuel.

6. SUMMARY AND DISCUSSION OF RESULTS

The postirradiation examination of these low-enriched U_3Si_2 fuel elements confirmed the excellent behavior experienced during their irradiation and expected from previous miniplate tests. The dimensional examinations, visual examinations, coolant channel measurements, and destructive examinations revealed no abnormalities or evidence of undesirable behavior.

In general, the microstructures were as expected from previous miniplate irradiations, revealed no abnormal conditions, and were consistent with the measured thickness increases. No, or very little, swelling was measured for the areas where fabrication porosity remained. The CERCA and NUKEM plates, which contained more of the U_3Si phase, showed more areas where large gas bubbles were beginning to form and more thickness change. The B&W plates, which contained some U_{ss} as fabricated and less U_3Si , showed fewer areas with large bubbles forming and less thickness change. The U_{ss} apparently converted to UAl_4 during irradiation and retained the gas.

These minor differences in postirradiation microstructure reflect the differences in fabrication practices of the manufacturers at the various times of fabrication. For example, when NUKEM fabricated the first two U_3Si_2 elements, it was not known that U_3Si behaved differently under irradiation than U_3Si_2 and that it might be desirable to control the amount of U_3Si in the fuel powder. The results of the metallographic examinations presented and

discussed in Section 5.6 have concentrated on these differences because, through their explanations, the overall understanding of the effects of the different phases on irradiation behavior has been confirmed.

The completely satisfactory behavior of these six U_3Si_2 fuel elements in the ORR, three of which were operated to >75% burnup, must be emphasized. The swelling of the fuel plates was stable and small in comparison to allowed fabrication tolerances for coolant channel gap thicknesses, even at 98% burnup of the ^{235}U and 2.5×10^{27} f/m³. The variety of as-fabricated attributes of the fuel meat--most importantly, the different fuel phases present and the different fuel meat porosities and densities--appear to cover the range of attributes to be expected in U_3Si_2 fuel elements fabricated in the future.

7. CONCLUSION

Postirradiation evaluations of low-enriched U_3Si_2 fuel elements irradiated in the ORR have confirmed their expected satisfactory performance. Peak burnups ranged up to 98%--far above that expected from normal reactor operation. Externally, the elements were essentially unchanged from their as-fabricated condition, both dimensionally and visually. The plates showed small, uniform thickness changes. Blister threshold temperatures were at the upper end of the range of those typical of current fuels.

It is concluded from the results of these tests that low-enriched U_3Si_2 -aluminum dispersion fuel elements will perform at least as well in research and test reactors with power densities up to that of the ORR as the highly enriched UAl_x -aluminum and U_3O_8 -aluminum dispersion fuels currently being used. There were no indications that use of this fuel under substantially more stringent conditions might be precluded.

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Fig. 1. Cross Section of Standard 19-Curved-Plate ORR Fuel Element.

Configurations 161-C Through 167-A, 5/27/82 Through 2/23/84

Configurations 167-C Through 170-C, 3/07/84 Through 12/19/84

Fig. 2. Basic Core Configurations During Irradiation of U_3Si_2 Elements.

Fig. 4. Photograph of Three Plates After Bending to Evaluate Toughness.

DIMENSIONS IN MILLIMETERS

Fig. 5. Sectioning Diagram for Destructive Evaluation of Plates.

Fig. 6M. Meat Microstructure of U₃Si₂ Miniplate After 90% Burnup (Bu).

Fig. 7M. Fission Gas Bubble Morphology in U₃Si₂ After 90% Bu.

Fig. 8M. Meat Microstructure of U₃Si Miniplate After 90% Bu.

Fig. 9M. Fission Gas Bubble Morphology in U₃Si After 90% Bu.

R-79833

200 μm

Fig. 10M. Meat Microstructure of Irradiated Depleted U_3Si_2 Miniplate.

R-79828

40 μm

Fig. 11M. Detail of Fig. 10M.

R-79940

200 μ m

Fig. 12B. Meat Microstructure of Plate BSI-201, at 31% Bu.

R-79941

40 μ m

Fig. 13B. Detail of Fig. 12B.

Fig. 14B. SEM Image of Fuel Meat of Plate BSI-201, at 31% Bu.

Fig. 15B. Detail of Fig. 14B.

Fig. 16B. Idem Fig. 15B, BSE Mode.

R-79942

200 μ m

Fig. 17B. Meat Microstructure of Plate BSI-201, at 71% Bu.

R-79943

40 μ m

Fig. 18B. Detail of Fig. 17B.

Fig. 19B. SEM Image of Fuel Meat of Plate BSI-201, at 71% Bu.

Fig. 20B. Detail of Fig. 19B.

Fig. 21B. Detail of Fig. 19B.

Fig. 22B. Detail of Fig. 19B.

Fig. 23B. Meat Microstructure of Plate BSI-202, at 51% Bu.

Fig. 24B. Detail of Fig. 23B.

Fig. 25B. Meat Microstructure of Plate BSI-202, at 97% Bu.

Fig. 26B. Detail of Fig. 25B.

40 μm
Fig. 27B. Detail of Fig. 26B.

Fig. 28B. SEM Image of Fuel Meat of Plate BSI-202, at 97% Bu.

Fig. 29B. Idem Fig. 28B, BSE Mode

Fig. 30B. SEM Image of Fuel Meat of Plate BSI-202, at 97% Bu, Showing Various Bubble Morphologies.

Fig. 31B. Idem Fig. 30B.

Fig. 32B. Idem Fig. 30B.

Fig. 33B. Idem Fig. 30B.

Fig. 34B. SEM Image of Fuel Meat in Unirradiated BSI Plate, Showing U_3Si_2 and U_3Si , BSE Mode.

Fig. 35B. Idem Fig. 34B, Showing U_3Si_2 and U.

Fig. 36B. Detail of Fig. 35B.

(A, U_3Si_2)

(B, U_3Si)

(C, U)

Fig. 378. Energy Dispersive X-Ray Spectra Identifying Various Phases in Unirradiated BSI Plate.

R-79547

200 μ m

Fig. 38C. Meat Microstructure of Plate CSI-201, at 33% Bu.

R-79550

40 μ m

Fig. 39C. Detail of Fig. 38C.

R-79554

200 μ m

Fig. 40C. Meat Microstructure of Plate CSI-201, at 67% Bu.

R-79555

40 μ m

Fig. 41C. Detail of Fig. 40C.

Fig. 42C. SEM Image of Fuel Meat of Plate CSI-201, at 67% Bu.

Fig. 43C. Idem Fig. 42C, BSE Mode.

Fig. 44C. Detail of Fig. 42C.

Fig. 45C. Detail of Fig. 42C.

R-79955

200 μ m

Fig. 46C. Meat Microstructure of Plate CSI-202, at 55% Bu.

R-79956

40 μ m

Fig. 47C. Detail of Fig. 46C.

Fig. 48C. SEM Image of Fuel Meat of Plate CSI-202, at 55% Bu.

Fig. 49C. Idem Fig. 48C, BSE Mode.

Fig. 50C. Detail of Fig. 48C.

Fig. 51C. Detail of Fig. 48C.

R-79957

200 μ m

Fig. 52C. Meat Microstructure of Plate CSI-202, at 97% Bu.

R-79958

40 μ m

Fig. 53C. Detail of Fig. 52C.

Fig. 54C. SEM Image of Fuel Meat of Plate CSI-202, at 97% Bu.

Fig. 55C. Idem Fig. 54C, BSE Mode.

Fig. 56C. Detail of Fig. 54C.

Fig. 57C. Detail of Fig. 54C.

Fig. 58C. SEM Image of Fuel Meat in Unirradiated CSI Plate, Showing U_3Si in U_3Si_2 Grain, BSE Mode.

Fig. 59C. SEM Image of Fuel Meat in Unirradiated CSI Plate, Showing Oxy-Carbide Phase (C).

(A, U_3Si)

(B, U_3Si_2)

Fig. 60C. Energy Dispersive X-Ray Spectra Identifying U_3Si and U_3Si_2 in Unirradiated CSI Plate.

Fig. 61N. Meat Microstructure of Plate NSI-201, at 24% Bu.

Fig. 62N. Detail of Fig. 61N.

Fig. 63N. SEM Image of Fuel Meat of Plate NSI-201, at 24% Bu.

Fig. 64N. Idem Fig. 63N, BSE Mode.

Fig. 65N. Detail of Fig. 63N.

Fig. 66N. Detail of Fig. 64N.

Fig. 67N. Meat Microstructure of Plate NSI-201, at 51% Bu.

Fig. 68N. Detail of 67N.

Fig. 69N. SEM Image of Fuel Meat of Plate NSI-201, at 51% Bu.

Fig. 70N. Idem Fig. 69N, BSE Mode.

Fig. 71N. Detail of Fig. 69N.

Fig. 72N. Detail of Fig. 71N, BSE Mode.

R-79559

200 μ m

Fig. 73N. Meat Microstructure of Plate NSI-202, at 54% Bu.

R-79558

40 μ m

Fig. 74N. Detail of Fig. 73N.

Fig. 75N. SEM Image of Fuel Meat of Plate NSI-202, at 54% Bu.

Fig. 76N. Detail of Fig. 75N.

Fig. 77N. Detail of Fig. 75N.

Fig. 78N. Idem Fig. 77N.

Fig. 79N. Meat Microstructure of Plate NSI-202, at 96% Bu.

Fig. 80N. Detail of Fig. 79N.

Fig. 81N. SEM Image of Fuel Meat of Plate NSI-202, at 96% Bu, Showing Various Bubble Morphologies.

Fig. 82. Idem Fig. 81N.

Fig. 83N. Idem Fig. 81N.

Fig. 84N. SEM Image of Fuel Meat of Unirradiated NSI Plate, BSE Mode.

Fig. 85N. Idem Fig. 84N.

Fig. 86N. Detail of Fig. 84N Showing U_3Si_2 and U_3Si .

Fig. 87N. Idem Fig. 86N.

APPENDIX A
POSTIRRADIATION EXAMINATION STEPS

NONDESTRUCTIVE PIE

1. Visual Inspection

Purpose: To observe general appearance and photograph.

- a. Observe general external appearance.
- b. Note any unusual features.
- c. Photograph element exterior with close-ups of unusual features.
- d. Photograph through channels with element backlighted.

2. External Dimensions

Purpose: To determine dimensional changes during irradiation.

- a. Measure major external dimensions (length, width, depth).
- b. Determine amount of warp, twist, or bow.

3. Gamma Scanning of Full Element

Purpose: To determine relative longitudinal burnup (fission product) distribution for entire element and to determine relative burnup from element to element.

- a. Scan using Ge(Li) detector and multichannel analyzer for fission-product peaks in the energy range 100 to 1400 keV, including ^{106}Ru and ^{137}Cs .
- b. Scan longitudinally in 1.0-in. increments along centerline of element.

4. Measure Channel Gaps

Purpose: To detect unusual amounts of plate swelling or warping.

- a. Remove end fittings.
- b. Measure channel gaps on both sides of comb.

DESTRUCTIVE (FULL) PIE

1-4. Same as above.

5. Dismantling of Element

Purpose: To prepare plates for individual examination.

- a. Separate individual fuel plates from side plates.

6. Visual Inspection of Plate

Purpose: To detect blisters or other unusual features.

- a. Observe general external appearance of each plate and note any unusual features.
- b. Photograph typical plates (2 or 3) and any areas of unusual features.

7. Thickness Measurements

Purpose: To provide data for estimation of plate swelling. Since measured thickness changes always overestimate the volume change (only the "high" points on the surface are measured), these measurements will serve mainly to show that no unexpected swelling has occurred.

- a. Measure thickness at ~24 points on plates Nos. 1, 5, 9, 13, and 17, including at least two points outside the fuel meat zone.
- b. Measure thickness at conspicuous spots.

8. Gamma Scanning

Purpose: To Determine relative longitudinal and transverse burnup (fission-product) distributions.

- a. Perform analog scan longitudinally along centerline for all plates, for both integral above 0.5 MeV and ^{137}Cs .
- b. Perform multichannel spectrum measurements along centerline at peak, as determined from analog scan, at 6 in. below peak, and at 10 in. above peak for plates Nos. 1, 5, 9, 13, and 17.
- c. Perform analog scan transversely at peak of longitudinal scan, at 6 in. below peak, and at 10 in. above peak for plates Nos. 1 and 9, for both integral above 0.5 MeV and ^{137}Cs .

9. Blister Testing

Purpose: To determine the threshold temperature for the formation of blisters. The threshold temperature will be measured by the standard technique of heating the entire plate in a furnace to a specified temperature, holding at that temperature for approximately 30 minutes and removing the plate for visual examination. The sequence is repeated for successively higher temperatures until blistering is observed.

- a. Blister test two plates (Nos. 2 and 8).
- b. If results are not consistent, test also plate No. 18.

10. Metallography

Purpose: To confirm that the behavior of the fuel is as expected, based upon previous examinations of miniplates.

- a. Obtain two sections (high- and low-burnup) from the plate (other than No. 1) showing the highest burnup.
- b. Perform optical metallographic examination.

11. Burnup Analysis

Purpose: To determine the absolute number of fissions (burnup). These data will be used with gamma scanning data to assign absolute burnups to each element.

- a. Obtain burnup samples from high- and low-burnup regions of plate sectioned for metallography.
- b. Perform U and Pu isotopic analyses.
- c. Determine burnup and fission density based on ^{235}U isotopic abundance.

APPENDIX B

VISUAL EXAMINATION AND PHOTOGRAPHS

All elements were visually examined for damage and evidence of swelling or distortion. All of the elements appeared to be in good condition. All showed a corrosion film and some handling marks. Looking through the coolant channels with backlighting showed the coolant channels to be uniform with no evidence of plate swelling or distortion. Photographs through the coolant channels vary in quality due to varying lighting, whether or not the end boxes had been removed, and differing reflectivities of the oxide film. However, all the elements were judged to be in excellent condition based on the visual examinations. Photographs of the elements are presented below.

Figure B.1. Element BSI-201 After Removing End Boxes. (R-79655)

Figure B.2. Element BSI-202 After Removing End Boxes. (R-79657)

Figure B.3. Element CSI-201 with End Boxes Attached. (Y-197349)

Figure B.4. Element CSI-202 with End Boxes Attached. (R-79659)

Figure B.5. Element NSI-201 with End Boxes Attached. (Y-193260)

Figure B.6. Element NSI-202 with End Boxes Attached. (Y-200764)

Figure B.7. View Through Coolant Channels of Element BSI-201 After Removal of End Boxes. (R-79656)

Figure B.8. View Through Coolant Channels of Element BSI-202 After Removal of End Boxes. (R-79658)

Figure B.9. View Through Coolant Channels of Element CSI-201 After Removal of End Boxes. (Y-197813)

Figure B.10. View Through Coolant Channels of Element CSI-202 After Removal of End Boxes. (R-79660)

Figure B.11. View Through Coolant Channels of Element NSI-202 Before Removal of End Boxes. (Y-200765)

APPENDIX C

ELEMENT DIMENSIONAL MEASUREMENT DATA

This appendix presents the backup data for the element dimensions reported in Table VII. The method of measuring the elements is discussed in the text. The maximum and minimum reading for stack height and width are reported in Table VII. To determine if the element was bowed, the upper and lower dial indicator readings were plotted as a function of length and examined for nonlinearity. To determine twist, the upper and lower dial indicator readings were plotted and examined to see the departure from parallel of the front, back, and center tracks from top to bottom.

Table C.1. Dimensional Measurements -- Element BS1-201

			FOR TWIST					
		Stack	Indicator Readings					
Location	Height	Width		Upper	Lower	Total	Width	
<u>(in. from top)</u>	<u>(in.)</u>	<u>(in.)</u>		<u>(in.)</u>	<u>(in.)</u>	<u>(in.)</u>	<u>(in.)</u>	
Back	5	3.0738	2.9918	<u>AT TOP</u>				
	10	3.0813	2.9882					
	15	3.0788	2.9897	BACK	0.1370	0.2845	0.4215	2.9955
	20	3.0770	2.9906	CENTER	0.1381	0.2864	0.4245	2.9985
	25	3.0746	2.9909	FRONT	0.1348	0.2860	0.4208	2.9948
	30	3.0744	2.9915					
Center	5	3.0638	2.9954	<u>AT BOTTOM</u>				
	10	3.0683	2.9889					
	15	3.0667	2.9913	BACK	0.1652	0.2530	0.4182	2.9822
	20	3.0671	2.9917	CENTER	0.1614	0.2574	0.4188	2.9828
	25	3.0645	2.9913	FRONT	0.1561	0.2619	0.4180	2.9820
	30	3.0834	2.9924					
Front	5	3.0765	2.9950	<u>LENGTH</u>				
	10	3.0838	2.9895	<u>(in.)</u>				
	15	3.0827	2.9812					
	20	3.0852	2.9821	38.386				
	25	3.0841	2.9818					
	30	3.0839	2.9824					

Table C.2. Dimensional Measurements -- Element BSI-202

		FOR TWIST					
		Stack	Indicator Readings				
Location		Height	Width	Upper	Lower	Total	Width
<u>(In. from top)</u>		<u>(In.)</u>	<u>(In.)</u>	<u>(In.)</u>	<u>(In.)</u>	<u>(In.)</u>	<u>(In.)</u>
Back	5	3.0699	3.0003	<u>AT TOP</u>			
	10	3.0772	2.9932				
	15	3.0742	2.9952	BACK	0.1408	0.2830	0.4238
	20	3.0737	2.9944	CENTER	0.1419	0.2836	0.4255
	25	3.0706	2.9945	FRONT	0.1432	0.2812	0.4244
	30	3.0679	2.9948				
Center	5	3.0648	2.9972	<u>AT BOTTOM</u>			
	10	3.0628	2.9944				
	15	3.0608	2.9958	BACK	0.1859	0.2359	0.4218
	20	3.0647	2.9949	CENTER	0.1853	0.2369	0.4222
	25	3.0612	2.9950	FRONT	0.1834	0.2384	0.4218
	30	3.0626	2.9954				
Front	5	3.0824	2.9968	<u>LENGTH</u>			
	10	3.0849	2.9934	(In.)			
	15	3.0855	2.9959				
	20	3.0879	2.9952	38.378			
	25	3.0863	2.9951				
	30	3.0856	2.9948				

Table C.3. Dimensional Measurements -- Element CSI-201

FOR TWIST							
Location		Stack	Indicator Readings				
		Height	Width	Upper	Lower	Total	Width
(in. from top)		(in.)	(in.)	(in.)	(in.)	(in.)	(in.)
Back	5	3.0703	a	AT TOP			
	10	3.0832					
	15	3.0835	BACK	0.2252	0.3005	0.5257	2.9914
	20	3.0784	CENTER	0.2278	0.2970	0.5248	2.9905
	25	3.0778	FRONT	0.2295	0.2942	0.5237	2.9894
	30	3.0715					
Center	5	3.0616	AT BOTTOM				
	10	3.0734					
	15	3.0731	BACK	0.2455	0.2841	0.5296	2.9953
	20	3.0531	CENTER	0.2468	0.2756	0.5224	2.9881
	25	3.0349	FRONT	0.2459	0.2738	0.5197	2.9854
	30	3.0615					
Front	5	3.0531	LENGTH				
	10	3.0698	(in.)				
	15	3.0708					
	20	3.0675	a				
	25	3.0576					
	30	3.0614					

^a Width and length data unusable because of faulty calibration. Width data from twist measurements used.

Table C.4. Dimensional Measurements Element CSI-202

			FOR TWIST				
		Stack	Indicator Readings				
Location		Height	Width	Upper	Lower	Total	Width
<u>(in. from top)</u>		<u>(in.)</u>	<u>(in.)</u>	<u>(in.)</u>	<u>(in.)</u>	<u>(in.)</u>	<u>(in.)</u>
Back	5	3.0567	2.9793	<u>AT TOP</u>			
	10	3.0732	2.9795				
	15	3.0786	2.9783	BACK	0.1616	0.2718	2.9794
	20	3.0799	2.9777	CENTER	0.1588	0.2776	2.9824
	25	3.0738	2.9779	FRONT	0.1515	0.2840	2.9815
	30	3.0579	2.9802				
Center	5	3.0511	2.9790	<u>AT BOTTOM</u>			
	10	3.0636	2.9784				
	15	3.0726	2.9773	BACK	0.1723	0.2622	2.9805
	20	3.0750	2.9751	CENTER	0.1611	0.2729	2.9800
	25	3.0658	2.9760	FRONT	0.1493	0.2829	2.9782
	30	3.0694	2.9798				
Front	5	3.0645	2.9790	<u>LENGTH</u>			
	10	3.0771	2.9788	(in.)			
	15	3.0829	2.9790				
	20	3.0842	2.9761	38.367			
	25	3.0799	2.9765				
	30	3.0684	2.9782				

Table C.5. Dimensional Measurements -- Element NSI-201

		FOR TWIST					
		Stack		Indicator Readings			
Location	Height	Width		Upper	Lower	Total	Width
(in. from top)	(in.)	(in.)		(in.)	(in.)	(in.)	(in.)
Back 5	-	-	<u>AT TOP</u>				
10	-	-					
15	-	-	BACK	0.2151	0.1609	0.3760	2.9870
20	-	-	CENTER	0.2155	0.1598	0.3753	2.9863
25	-	-	FRONT	0.2162	0.1589	0.3751	2.9861
30	-	-					
Center 5	3.0681	2.9865	<u>AT BOTTOM</u>				
10	3.0736	2.9876					
15	3.0726	2.9844	BACK	0.2150	0.1641	0.3791	2.9901
20	3.0741	2.9843	CENTER	0.2134	0.1654	0.3788	2.9898
25	3.0754	2.9843	FRONT	0.2116	0.1672	0.3788	2.9898
30	3.0734	2.9898					
Front 5	-	-	<u>LENGTH</u>				
10	-	-	(in.)				
15	-	-					
20	-	-	38.365				
25	-	-					
30	-	-					

Table C.6. Dimensional Measurements -- Element NSI-202

FOR TWIST								
		Stack	Indicator Readings					
Location		Height	Width	Upper	Lower	Total	Width	
<u>(in. from top)</u>		<u>(in.)</u>	<u>(in.)</u>	<u>(in.)</u>	<u>(in.)</u>	<u>(in.)</u>	<u>(in.)</u>	
Back	5	-	-	<u>AT TOP</u>				
	10	-	-					
	15	-	-	BACK	0.2365	0.3004	0.5369	2.9930
	20	-	-	CENTER	0.2461	0.2992	0.5453	3.0014
	25	-	-	FRONT	0.2382	0.2982	0.5364	2.9925
	30	-	-					
Center	5	3.0709	3.0014	<u>AT BOTTOM</u>				
	10	3.0751	2.9940					
	15	3.0796	2.9938	BACK	0.2521	0.2860	0.5381	2.9942
	20	3.0815	2.9940	CENTER	0.2488	0.2888	0.5376	2.9937
	25	3.0809	2.9933	FRONT	0.2455	0.2821	0.5276	2.9837
	30	3.0746	2.9937					
Front	5	-	-	<u>LENGTH</u>				
	10	-	-	<u>(in.)</u>				
	15	-	-					
	20	-	-	38.413				
	25	-	-					
	30	-	-					

APPENDIX D

ELEMENT GAMMA SCANS

Figures D.1 through D.3 show the strip chart records produced when scanning the fuel elements using a NaI detector and a narrow energy window containing the ^{137}Cs 662-keV peak. The gamma intensity is in relative units for each element separately.

Fig. D.1. BSI Element Gamma Scans, 0.6 - 0.7 MeV.

Fig. D.2. CSI Element Gamma Scans, 0.6 - 0.7 MeV.

Fig. D.3. NSI Element Gamma Scans, 0.6 - 0.7 MeV

APPENDIX E

COOLANT CHANNEL GAP THICKNESS MEASUREMENTS

Table E-1. BSI-201 Coolant Channel Measurements

<u>Channel</u>	<u>Bottom Side (mils)</u>				<u>Top Side (mils)</u>			
	<u>Max.</u>	<u>Min.</u>	<u>Avg.</u>	<u>At Peak Burnup</u>	<u>Max.</u>	<u>Min.</u>	<u>Avg.</u>	<u>At Peak Burnup</u>
1	121.0	114.1	116.2	116.1	121.0	114.2	116.5	117.1
2	120.0	114.5	116.2	116.5	121.0	114.5	116.2	116.4
3	117.0	114.2	115.8	115.5	118.1	115.0	116.8	117.2
4	114.0	110.0	111.2	111.0	115.1	109.0	111.0	109.9
5	118.0	115.1	116.8	117.6	118.9	113.3	117.7	118.0
6	115.0	109.8	111.2	110.3	116.2	109.5	111.0	110.2
7	117.0	113.4	115.0	114.3	118.8	113.5	115.8	114.5
8	118.8	116.5	118.0	118.8	119.7	115.2	118.0	119.0
9	113.1	110.5	112.0	111.5	114.0	111.5	112.6	111.6
10	117.5	112.8	115.2	116.0	114.8	112.0	113.2	113.0
11	116.0	109.7	114.0	113.6	116.0	111.7	113.6	113.1
12	118.0	112.4	113.9	113.3	114.5	110.7	112.5	112.4
13	115.7	108.7	113.6	115.4	115.1	110.3	113.0	113.7
14	125.0	121.5	123.4	122.7	111.1	105.6	109.6	111.0
15	123.2	114.6	119.3	120.5	115.0	108.8	111.3	109.1
16	120.3	106.3	113.4	114.7	118.4	115.1	117.2	116.9
17	116.0	107.8	111.6	110.3	117.3	113.0	114.8	113.4
18	116.5	105.0	112.0	111.7	117.8	109.8	114.3	114.4
	Average			115.0	Average			113.9

Table E-2. BSI-202 Coolant Channel Measurements

Channel	Bottom Side (mils)				Top Side (mils)			
	Max.	Min.	Avg.	At Peak Burnup	Max.	Min.	Avg.	At Peak Burnup
1	120.0	114.3	116.0	117.5	120.0	112.7	115.2	115.4
2	117.0	111.5	113.5	114.0	115.0	110.0	113.0	112.9
3	114.8	111.4	112.6	113.3	114.0	111.0	112.2	112.9
4	115.3	111.0	112.3	112.3	117.0	111.0	112.0	111.9
5	120.4	114.9	115.9	115.7	115.4	112.0	112.8	113.2
6	113.4	111.0	112.2	113.2	115.0	110.9	112.0	112.2
7	119.7	116.0	116.6	116.5	115.2	113.3	114.4	115.2
8	116.0	111.9	114.1	114.3	115.0	112.1	113.1	113.5
9	116.0	113.3	114.2	114.2	115.6	112.8	113.7	114.1
10	115.6	113.0	113.7	114.3	115.4	112.9	114.0	113.3
11	116.0	110.8	112.5	112.0	115.6	112.0	112.7	112.5
12	116.3	113.7	114.8	115.0	116.5	114.2	115.4	114.5
13	111.6	107.5	109.0	108.8	112.3	107.6	109.1	108.9
14	119.0	113.2	117.5	117.7	121.0	113.7	118.0	115.9
15	121.1	116.3	117.4	117.7	119.8	115.1	117.0	116.7
16	110.0	106.7	108.6	108.1	110.5	105.3	108.1	107.7
17	116.5	115.3	116.9	118.1	117.0	112.2	114.6	115.8
18	113.7	109.6	112.4	111.9	114.4	106.4	110.8	112.5
	Average			114.1	Average			113.3

Table E-3. CSI-202 Coolant Channel Measurements

Channel	Bottom Side (mils)				Top Side (mils)			
	Max.	Min.	Avg.	At Peak Burnup	Max.	Min.	Avg.	At Peak Burnup
1	115.0	104.0	112.3	111.9	120.0	112.8	115.2	113.6
2	111.6	103.3	108.0	108.6	112.5	106.2	108.8	108.9
3	112.0	104.8	107.4	107.5	112.0	103.8	107.0	106.2
4	115.0	106.6	110.0	108.8	114.0	105.4	108.0	107.1
5	113.0	105.7	108.7	108.9	112.5	106.4	108.8	109.1
6	112.9	110.4	111.9	111.4	112.0	106.1	108.6	108.4
7	113.8	107.3	110.7	111.0	111.6	106.3	108.1	107.8
8	113.6	107.4	110.2	111.0	111.4	105.8	108.4	108.4
9	114.6	110.2	113.1	113.6	113.3	106.5	109.5	109.6
10	111.3	107.4	109.4	109.2	112.7	108.1	110.5	111.2
11	110.2	106.2	108.6	108.2	112.2	108.8	109.6	109.7
12	112.8	109.4	112.0	111.8	115.0	108.2	111.3	111.3
13	111.4	107.9	109.6	109.4	110.3	106.2	109.2	110.3
14	114.2	110.6	112.1	112.0	113.0	109.2	111.2	110.0
15	115.1	111.0	113.0	113.6	113.1	111.7	112.4	112.5
16	120.0	117.7	119.1	120.0	115.3	113.0	114.6	115.2
17	119.0	113.6	117.6	116.2	115.1	111.8	113.6	114.2
18	123.4	120.0	122.1	123.0	116.8	109.4	115.8	116.6
	Average			112.0	Average			110.6

Table E-4. NSI-201 Coolant Channel Measurements

Channel	Bottom Side (mils)				Top Side (mils)			
	Max.	Min.	Avg.	At Peak Burnup	Max.	Min.	Avg.	At Peak Burnup
1	116.0	108.0	109.2	109.2	117.0	108.0	114.6	109.5
2	106.4	103.0	104.7	104.5	108.7	104.2	107.2	106.7
3	112.0	104.0	106.0	104.6	109.0	103.2	105.2	104.1
4	110.0	108.0	109.3	109.1	109.8	107.2	108.7	108.8
5	110.0	105.0	107.6	107.3	109.7	105.3	107.5	107.1
6	109.2	107.2	108.6	108.1	109.1	107.0	108.2	107.5
7	109.0	105.0	107.0	106.5	109.0	105.0	107.0	105.9
8	111.0	108.3	109.1	109.3	111.0	108.2	109.6	109.8
9	108.0	105.0	105.2	105.3	107.5	104.3	105.5	104.7
10	109.6	107.5	108.9	108.8	109.8	107.8	109.2	109.2
11	109.3	106.7	108.2	107.7	110.0	107.0	108.4	107.1
12	110.2	108.1	109.5	108.9	110.4	108.5	109.5	108.8
13	109.8	106.9	108.3	108.3	105.5	104.0	104.7	105.6
14	112.2	109.3	111.0	110.6	108.7	106.8	107.8	107.7
15	111.6	108.5	110.0	109.5	124.0	105.9	107.0	106.0
16	115.5	110.0	114.3	114.7	124.0	108.0	109.7	109.8
17	113.2	108.8	112.0	112.3	124.0	106.5	107.0	106.1
18	107.3	101.8	103.2	102.7	106.0	102.5	103.9	104.0
	Average			108.2	Average			107.1

APPENDIX F

PLATE THICKNESS MEASUREMENTS

This appendix presents the backup data for the plate thickness increases reported in Table VIII. The methods of measuring plate thickness are discussed in the text. In general, the plate thickness was measured at 26 locations on the plate. Along the length of the plate in eight locations, the thickness was measured in the center of the plate and near both edges. Two measurements were taken 1/4-inch from the top of the plates over the unfueled region. In calculating average thickness change for plate swelling, only the center measurements were used because of the additional uncertainties in the measurements near the edges due to the angle of the plate between the dial indicator tips. Since burnup is not uniform, thickness increases are compared at two locations--the maximum- and minimum-burnup locations. The minimum-burnup location is near the top of the plate and only the measurement at the 1-inch point was included. The peak-burnup region is larger and the 13- and 16-inch measurements were averaged. Although all plates of NSI-201 and NSI-202 were measured, only those plates in positions 2, 6, 10, 14, and 18 were included in the averages since only the plates in those positions were measured for the other four elements.

Table F.1
Element BSI-201
Plate Thickness and Incremental Thickness Compared to Ends (mils)

Distance From Top of Plate in.	Plate S-3-211-15 Position 2		Plate S-3-211-3 Position 6		Plate S-3-210-19 Position 10		Plate S-3-210-9 Position 14		Plate S-3-210-1 Position 18	
	<u>t*</u>	<u>Δt</u>	<u>t*</u>	<u>Δt</u>	<u>t*</u>	<u>Δt</u>	<u>t*</u>	<u>Δt</u>	<u>t*</u>	<u>Δt</u>
1/4	50.7	-	49.9	-	50.3	-	49.1**	-	49.9	-
1	50.7	0	49.9	0	50.3	0	49.8**	0.7	49.9	0
4	50.6	-0.1	49.7	-0.2	50.4	0.1	49.8	0.7	50.8	0.9
7	50.6	-0.1	49.8	-0.1	51.1	0.8	50.0	0.9	51.6	1.7
10	50.9	0.2	49.7	-0.2	51.8	1.5	50.5	1.4	52.7	2.8
13	50.6	-0.1	49.7	-0.2	52.0	1.7	51.0	1.9	53.2	3.3
16	50.9	0.2	50.3	0.4	52.1	1.8	51.0	1.9	53.7	3.8
19	50.7	0	49.6	-0.3	52.2	1.9	51.1	2.0	54.3	4.4
22	-	-	-	-	51.0	0.7	50.8	1.8	54.2	4.3

Average at 1 inch (low-burnup end) 0.1 mil

Average at 13 to 16 inches (peak-burnup region) 1.5 mils

*Plate thickness calculated by adding thickness change from plate end to preirradiation end tab thickness.

**Values determined by capacitance measuring device. Preirradiation end tab measured 50.3.

Table F.2
Element BSI-202
Plate Thickness and Incremental Thickness Compared to Ends (mils)

Distance From Top of Plate in.	Plate S-3-212-3 Position 2		Plate S-3-213-3 Position 6		Plate S-3-212-15 Position 10		Plate S-3-212-7 Position 14		Plate S-3-211-19 Position 18	
	<u>t*</u>	<u>Δt</u>	<u>t*</u>	<u>Δt</u>	<u>t*</u>	<u>Δt</u>	<u>t*</u>	<u>Δt</u>	<u>t*</u>	<u>Δt</u>
1/4	50.8	-	49.9**	-	50.1**	-	50.1	0	50.4	-
1	50.8	0	49.9**	0	50.1**	0	50.1	0	50.4	0
4	51.3	0.5	49.9	0	50.4	0.3	51.2	1.1	51.2	0.8
7	52.1	1.3	50.2	0.3	50.9	0.8	52.7	2.6	51.8	1.4
10	52.6	1.8	50.5	0.6	51.4	1.3	52.1	2.0	51.4	1.0
13	52.7	1.9	50.8	0.9	51.5	1.4	53.3	3.2	51.6	1.2
16	53.3	2.5	50.8**	0.9	51.5**	1.4	53.5	3.4	51.5	1.1
19	53.3	2.5	50.6	0.7	51.8	1.7	53.5	3.4	51.5	1.1
22	53.0	2.2	50.6	0.7	51.9	1.8	52.0	1.9	52.2	1.8

Average at 1 inch (low-burnup end) 0

Average at 13 to 16 inches (peak-burnup region) 1.8 mils

*Plate thickness calculated by adding thickness change from plate end to preirradiation end tab thickness.

**Plate thickness corroborated by new capacitance measuring device.

Table F.3
Element CSI-201
Plate Thickness and Incremental Thickness Compared to Ends (mils)

Distance From Top of Plate in.	Plate OSIEW-087		Plate OSIIW-061		Plate OSIIW-047		Plate OSIIW-052		Plate OSIIW-083	
	Position 1		Position 5		Position 9		Position 13		Position 17	
	<u>t</u>	<u>Δt</u>	<u>t</u>	<u>Δt</u>	<u>t</u>	<u>Δt</u>	<u>t</u>	<u>Δt</u>	<u>t</u>	<u>Δt</u>
1/4	*	-	*	-	*	-	*	-	*	-
1		0.5		1.2		-0.9		-0.6		0.5
4		1.3		0.6		0.5		1.0		0.5
7		1.6		0.6		0.5		1.2		1.4
10		2.3		0		1.1		2.1		1.0
13		2.8		0.7		1.3		2.7		0.9
16		2.8		0.4		1.5		3.0		1.3
19		2.7		1.7		2.2		2.6		0.9
22		2.9		0.6		1.4		2.2		1.4
Average at 1 inch (low-burnup end)			0.1 mil							
Average at 13 to 16 inches (peak-burnup region)			1.7 mils							

* Actual plate thicknesses are not calculated due to erroneous standard readings. Thickness changes are measured relative to the plate thickness at 1/4" over the unfueled region.

Table F.4
Element CSI-202
Plate Thickness and Incremental Thickness Compared to Ends (mils)

Distance From Top of Plate in.	Plate OSIIW-085 Position 2		Plate OSIIW-079 Position 6		Plate OSIIW-063 Position 10		Plate OSIIW-039 Position 14		Plate OSIIW-075 Position 18	
	<u>t*</u>	<u>Δt</u>	<u>t*</u>	<u>Δt</u>	<u>t*</u>	<u>Δt</u>	<u>t*</u>	<u>Δt</u>	<u>t*</u>	<u>Δt</u>
1/4	50.0	-	50.0	-	50.4	-	49.2	-	49.4	-
1	51.0	1.0	50.5	0.5	50.9	0.5	49.7	0.5	49.6	0.2
4	51.4	1.4	52.6	2.6	52.6	2.2	50.5	1.3	51.6	2.2
7	52.9	2.9	52.6	2.6	53.1	2.7	51.7	2.5	53.3	3.9
10	53.6	3.6	53.9	3.9	53.5	3.1	52.2	3.0	54.4	5.0
13	55.8	5.8	55.2	5.2	53.6	3.2	53.3	4.1	54.9	5.5
16	52.8	2.8	55.2	5.2	53.8	3.4	53.0	3.8	54.1	4.7
19	52.2	2.2	54.4	4.4	53.6	3.2	52.4	3.2	53.7	4.3
22	50.5	0.5	53.3	3.3	54.6	4.2	50.9	1.7	53.6	4.2

Average at 1 inch (low-burnup end) 0.5 mil

Average at 13 to 16 inches (peak-burnup region) 4.4 mils

*Plate thickness calculated by adding thickness change from plate end to preirradiation end tab thickness.

Table F.5
Element NSI-201
Plate Thickness and Incremental Thickness Compared to Ends (mils)

Distance From Top of Plate in.	Plate ORR-92 Position 2		Plate ORR-97 Position 6		Plate ORR-102 Position 10		Plate ORR-106 Position 14		Plate ORR-110 Position 18	
	t^*	Δt	t^*	Δt	t^*	Δt	t^*	Δt	t^*	Δt
1/4	49.2	-	48.7	-	49.0	-	49.0	-	49.2	-
1	48.8	-0.4	49.8	1.1	50.1	1.1	49.8	0.8	50.2	1.0
4	48.9	-0.3	50.0	1.3	50.1	1.1	50.1	1.1	50.0	0.8
7	48.7	-0.5	50.0	1.3	50.0	1.0	50.0	1.0	50.2	1.0
10	48.8	-0.4	50.1	1.4	50.0	1.0	50.3	1.3	50.3	1.1
13	49.4	0.2	50.2	1.5	50.1	1.1	50.2	1.2	50.2	1.0
16	49.2	0	50.0	1.3	50.1	1.1	50.0	1.0	50.3	1.1
19	49.2	0	49.9	1.2	50.1	1.1	50.3	1.3	50.4	1.2
22	49.7	0.5	50.1	1.4	50.0	1.0	50.3	1.3	50.5	1.3

At average at 1 inch (low-burnup end) 0.7 mil

At average at 13 to 16 inches (peak-burnup region) 1.0 mils

*Plate thickness based on comparison to standard with thickness change calculated from plate end tabs postirradiation measurement.

Table F.6
Element NSI-202
Plate Thickness and Incremental Thickness Compared to Ends (mils)

Distance From Top of Plate in.	Plate ORR-120 Position 7		Plate ORR-121 Position 8		Plate ORR-131 Position 15		Plate ORR-139 Position 17		Plate ORR-140 Position 18	
	t*	Δt	t*	Δt	t*	Δt	t*	Δt	t*	Δt
1/4	50.6	-	50.0	-	51.1	-	50.7	-	51.2	-
1	51.8	1.2	51.6	1.6	51.7	0.6	52.0	1.3	51.7	0.5
4	52.8	2.2	53.4	3.4	52.4	1.3	52.4	1.7	53.2	2.0
7	53.0	2.4	57.8	2.8	53.0	1.9	52.9	2.2	54.4	3.2
10	53.6	3.0	53.4	3.4	54.0	2.9	53.5	2.8	55.5	4.1
13	54.3	3.7	54.2	4.2	54.5	3.4	53.9	3.2	56.2	5.0
16	55.0	4.4	54.7	4.7	54.5	3.4	54.6	3.9	56.7	5.5
19	55.1	4.5	54.5	4.5	55.0	3.9	54.5	3.8	56.6	5.4
22	55.6	5.0	54.1	4.1	54.2	3.1	54.0	3.3	56.8	5.6

Average at 1 inch (low-burnup end) 1.0 mil

Average at 13 to 16 inches (peak-burnup region) 4.1 mils

*Plate thickness based on comparison to standard with thickness change calculated from plate end tabs postirradiation measurement.

APPENDIX G

PLATE GAMMA SCANNING DATA AND BURNUP ANALYSIS

Correlation of Gamma Scanning and Burnup Data - As discussed in the text, several methods of taking and recording gamma scanning data were used over the course of this work. The gamma scan profile was used to select the axial minimum- and maximum-burnup locations for the burnup analysis samples. Full width sections were removed from one plate of each element at these locations and analyzed by mass spectrometry to determine the burnup (see below). To obtain the average burnup at the low- and maximum-burnup positions, the ^{137}Cs peak as measured by the NaI crystal and strip chart was used. The chart readings at the minimum were averaged and the ratio of the average to the reading of the analyzed plate was multiplied by the analyzed burnup value. The same method was used for finding the average burnup at the axial maximum. To find the average burnup along the length of the plates (and hence elements), the chart readings were averaged along the length of the charts at one-inch intervals (about 35 readings per chart). This gives a bias toward a low average since the minimum-to-maximum ratios of the readings are consistently lower than those of the analyzed burnups. Such a discrepancy could result if a plate had different transverse burnup profiles at the minimum- and maximum-burnup positions since only the central part of the plate was scanned while the entire width of the plate was averaged in the burnup analyses. The same five plates were used for the minimum- and maximum-burnup location averages as were used for the thickness measurements.

The data obtained using the Ge(Li) detector and the multichannel analyzer are believed to be more accurate than the analog data obtained using the NaI crystal for determining the burnup profile through an element. Therefore, these data were used for elements BSI-201, BSI-202, CSI-201, and NSI-202. As explained in Table G.4, the multichannel data appeared to be discrepant for the plate in position 18 of CSI-202. Multichannel data were not obtained for all plates of NSI-201. The analog data were used for these two elements. The element was assumed to have the axial profile of the plate from which the burnup analysis sample was taken, and the analyzed maximum burnup was used. The data and correlation calculations are presented in Tables G.1 through G.6. Examples of the analog gamma scan charts are shown in Figs. G.1 through G.6.

Burnup Calculation from Isotopic Analysis - The isotopic composition of the uranium and plutonium after irradiation can be used to calculate the burnup or percentage depletion of the original ^{235}U in the elements. The isotopic abundance data as determined by mass spectrographic analysis are presented in Table G.7.

The burnup can be expressed in terms of the pre- and postirradiation ^{235}U isotopic abundances, as shown in the following. Let

- B = fractional ^{235}U depletion (burnup),
 A_0 = fractional ^{235}U atomic abundance prior to irradiation,
 A = fractional ^{235}U atomic abundance after irradiation,
 C = $^{238}\text{U}/^{235}\text{U}$ atomic depletion ratio during irradiation,
 and D = $^{236}\text{U}/^{235}\text{U}$ atomic depletion ratio during irradiation
 (negative quantity).

Now,
$$B = 1 - \frac{AN}{A_0 N_0},$$

where N_0 and N represent the pre- and postirradiation uranium atom densities. If ΔN^5 represents the change in ^{235}U atom density during irradiation,

$$N = N_0 - (1 + C + D)\Delta N^5$$

and
$$B = 1 - \frac{AN_0 - (1 + C + D)A\Delta N^5}{A_0 N_0}$$

$$= 1 - A/A_0 + (1 + C + D)AB.$$

Therefore,
$$B = \frac{1 - A/A_0}{1 - (1 + C + D)A} \quad (1)$$

The parameters C and D have been derived from the results of integral transport cell calculations performed at ANL by M. M. Bretscher and R. J. Cornella. They behave as follows:

B	LEU			MEU	
	C	D	C	D	
0.54	0.13	-0.16	0.06	-0.16	
0.76	0.15	-0.15	0.07	-0.16	
0.89	0.18	-0.15	0.08	-0.15	
0.96	0.22	-0.14	0.10	-0.15	
0.98	0.26	-0.14	0.10	-0.14	

It appears that C and D are not particularly sensitive to the uranium density. There is obviously a dependence of C on the enrichment; however, there is a very weak dependence of B on either C or D , as indicated by Eq. 2, since A is small (<0.20 for LEU).

$$\frac{\partial B}{\partial C} = \frac{\partial B}{\partial D} = \frac{AB}{1 - (1 + C + D)A} \quad (2)$$

Therefore, the calculations from which C and D are derived do not have to be extremely accurate.

As used in Eq. 1, A and A_0 are atomic ratios while the enrichment, e, is a weight ratio. The relationship between A_0 and e_0 is

$$A_0 = \frac{1}{1 + 0.98736(1/e_0 - 1)} \quad (3)$$

The fission density due to ^{235}U fission alone (F_{DU}) can be derived as follows:

$$B = \frac{N_F + N_C}{N}$$

where N_F , N_C , and N are the densities of ^{235}U fissions, ^{235}U captures, and originally contained ^{235}U atoms, respectively.

$$N_F + N_C = N_F(1 + \alpha)$$

where α = the ^{235}U capture-to-fission ratio.

$$N = \frac{6.022 \times 10^{21} \rho_U e}{235.04}$$

Therefore, substituting the symbol F_{DU} for N_F ,

$$F_{\text{DU}} = \frac{2.562 \times 10^{21} \rho_U e B}{1 + \alpha}$$

Assuming an average value of 0.19 for α over the burnup of the fuel,

$$F_{\text{DU}} = 2.15 \times 10^{21} \rho_U e B \quad (\text{fissions/cm}^3). \quad (4)$$

Integral transport cell depletion calculations, performed at ANL by R. J. Cornella, provided the ^{235}U fission fraction as a function of ^{235}U depletion. The cumulative fission fraction is plotted as a function of ^{235}U burnup in Fig. G.8 for 20%-enriched (LEU) and 45%-enriched (MEU) fuel. The result of Eq. (4), divided by the appropriate fission fraction, gives the absolute fission density. Burnups, fission fractions, and fission densities of the analyzed samples are given in Table G.8.

It was the intent early in the RERTR Program to determine absolute fission densities based upon ^{148}Nd measurements. The results of such determinations were found to be unreliable, for undetermined reasons. Therefore, acquisition and use of ^{148}Nd data were abandoned.

Table G.1.
Element BSI-201
Burnup Analysis Plate S-3-210-1, Position 18

Calculation of Plate Average

	<u>^{137}Cs, 10³ Cts/s</u>	<u>Burnup % ^{235}U Depletion</u>
Minimum	22.5	$\frac{22.5}{24.0} \times 31.5 = 29.5$
At Top Analysis Point	24.0	31.5
Maximum (Bottom Analysis Point)	62.5	70.9
Average	48.4	$\frac{48.4}{62.5} \times 70.9 = 54.9$

Calculation of Element Average

<u>Plate Position</u>	<u>^{137}Cs, 10³ Cts/s</u>		
	<u>Minimum</u>	<u>Maximum</u>	<u>Average</u>
2	21.0	62.5	48.3
6	21.0	57.0	44.9
10	20.5	60.0	45.5
14	21.5	61.5	47.3
18	<u>22.5</u>	<u>62.5</u>	<u>48.4</u>
Average	21.3	60.7	46.9
Correlated Average Burnup	$\frac{21.3}{22.5} \times 29.5 =$ 28.0	$\frac{60.7}{62.5} \times 70.9 =$ 68.9	$\frac{46.9}{48.4} \times 54.9 =$ 53.2

^{137}Cs peak measured by multichannel analyzer gave the following counts/s at the maximum-burnup position for plates 1 through 19: 141.8, 156.1, 157.9, 150.0, 148.9, 146.3, 154.5, 152.1, 146.9, 149.0, 154.2, 150.9, 155.0, 150.7, 154.6, 152.5, 162.9, 154.3, and 151.9. The average of 152.1 correlates to an element average burnup of 54.1% using all 19 plates.

Table G.2.
Element BSI-202
Burnup Analysis Plate S-3-211-19, Position 18

Calculation of Plate Average

	<u>^{137}Cs, 10^3 Cts/s</u>	<u>Burnup % ^{235}U Depletion</u>
Minimum	115	$\frac{115}{115} \times 50.5 = 50.5$
At Top Analysis Point	115	50.5
Maximum (Bottom Analysis Point)	315	97.3
Average	259	$\frac{259}{315} \times 97.3 = 80.0$

Calculation of Element Average

Plate Position	<u>^{137}Cs, 10^3 Cts/s</u>		
	<u>Minimum</u>	<u>Maximum</u>	<u>Average</u>
2	115	320	269
6	130	310	265
10	125	310	262
14	120	310	260
18	<u>115</u>	<u>315</u>	<u>259</u>
Average	121	313	263
Correlated Average Burnup	$\frac{121}{115} \times 50.5 =$ 53.1	$\frac{313}{315} \times 97.3 =$ 96.7	$\frac{263}{259} \times 80.0$ 81.2

^{137}Cs peak measured by multichannel analyzer gave the following counts/s at the maximum-burnup position for plates 1 through 19: 239.2, 250.2, 237.5, 264.2, 252.5, 239.5, 231.4, 253.0, 226.1, 235.4, 248.8, 240.1, 233.3, 245.9, 228.4, 233.3, 243.8, 250.3, and 252.1. The average of 242.4 correlates to an element average burnup of 77.5% using all 19 plates.

Table G.3.
Element CSI-201
Burnup Analysis Plate OSIIW-084, Position 18

Calculation of Plate Average

	<u>^{137}Cs, 10^3 Cts/s</u>	<u>Burnup % ^{235}U Depletion</u>
Minimum	17.0	$\frac{17.0}{17.5} \times 32.7 = 31.8$
At Top Analysis Point	17.5	32.7
Maximum (Bottom Analysis Point)	45.5	66.9
Average	36.7	$\frac{36.7}{45.5} \times 66.8 = 54.0$

Calculation of Element Average

<u>Plate Position</u>	<u>^{137}Cs, 10^3 Cts/s</u>		
	<u>Minimum</u>	<u>Maximum</u>	<u>Average</u>
2	17.0	46.0	38.0
6	17.0	43.5	34.7
10	16.5	45.0	36.0
14	17.0	44.0	34.6
18	<u>17.0</u>	<u>45.5</u>	<u>36.7</u>
Average	16.9	44.8	36.0
Correlated Average Burnup	$\frac{16.9}{17.0} \times 31.8 =$ 31.6	$\frac{44.8}{45.5} \times 66.8 =$ 65.8	$\frac{36.0}{36.7} \times 54.0 =$ 53.0

^{137}Cs peak measured by multichannel analyzer gave the following counts/s at the maximum-burnup position for plates 1 through 19: 714.2, 575.8, 662.1, 646.8, 568.6, 541.5, 545.9, 610.9, 584.9, 608.4, 602.0, 615.6, 594.2, 600.7, 604.2, 607.2, 611.1, 627.4, and 656.5. The average of 609.4 correlates to an element average burnup of 52.4% using all 19 plates.

Table G.4.
Element CSI-202
Burnup Analysis Plate OSIIW-075, Position 18

Calculation of Plate Average

	<u>^{137}Cs, 10^3 Cts/s</u>	<u>Burnup % ^{235}U Depletion</u>
Minimum	105	$\frac{105}{105} \times 55.0 = 55.0$
At Top Analysis Point	105	55.0
Maximum (Bottom Analysis Point)	290	96.6
Average	245	$\frac{245}{290} \times 96.6 = 81.6$

Calculation of Element Average

<u>Plate Position</u>	<u>^{137}Cs, 10^3 Cts/s</u>		
	<u>Minimum</u>	<u>Maximum</u>	<u>Average</u>
2	115	300	251
6	130	300	246
10	135	290	240
14	130	295	241
18	<u>105</u>	<u>290</u>	<u>245</u>
Average	123	295	245
Correlated Average Burnup	$\frac{123}{105} \times 55.0 =$ 64.4	$\frac{295}{290} \times 96.6 =$ 98.3	$\frac{245}{245} \times 81.7 =$ 81.7

^{137}Cs peak measured by multichannel analyzer gave the following counts/s at the maximum-burnup position for plates 1 through 19: 259.6, 232.6, 239.8, 235.8, 251.7, 248.4, 249.0, 235.6, 257.5, 240.1, 242.9, 236.0, 237.4, 234.9, 235.8, 232.2, 237.7, 228.8, and 239.9. The average of 240.8 was not used to correlate to an average element burnup because the value for plate 18 is obviously low and results in unphysically high burnups for many of the plates.

Table G.5.
 Element NSI-201
 Burnup Analysis Plate ORR-93, Position 3

Calculation of Plate Average

	<u>$^{137}\text{Cs}, 10^3 \text{ Cts/s}$</u>	<u>Burnup % ^{235}U Depletion</u>
Minimum	21.5	$\frac{21.5}{23.0} \times 24.1 = 22.5$
At Top Analysis Point	23.0	24.1
Maximum (Bottom Analysis Point)	55.0	50.9
Average	43.0	$\frac{43}{55} \times 50.9 = 39.8$

Calculation of Element Average

<u>Plate Position</u>	<u>$^{137}\text{Cs}, 10^3 \text{ Cts/s}$</u>		
	<u>Minimum</u>	<u>Maximum</u>	<u>Average</u>
1	21.0	51.0	40.1
2	20.0	53.5	41.5
3	21.5	55.0	43.0
4	19.0	52.0	39.6
5	18.5	50.5	38.5
6	17.0	47.0	35.9
7	16.5	47.0	35.7
8	21.5	54.0	42.0
9	16.5	46.0	34.6
10	19.0	52.0	39.6
11	15.5	45.0	33.8
12	16.0	45.5	34.5
13	17.0	48.5	37.2
14	16.0	46.0	34.8
15	17.0	48.5	36.5
16	16.5	46.5	35.5
17	16.5	47.0	35.7
18	16.5	47.5	35.8
19	<u>21.0</u>	<u>54.5</u>	<u>41.9</u>
Average	18.0	49.3	37.7
(Plates 2, 6, 10, 14, 18)	17.7	49.2	37.5
Correlated Average Burnup (19 Plates)	$\frac{18.0}{21.5} \times 22.5 =$ 18.9	$\frac{49.3}{55.0} \times 50.9 =$ 45.6	$\frac{37.7}{43.0} \times 39.8 =$ 34.9
(Plates 2, 6, 10, 14, 18)	18.5	45.5	34.7

Table G.6.
Element NSI-202
Burnup Analysis Plate ORR-140, Position 18

Calculation of Plate Average

	<u>^{137}Cs, 10^3 Cts/s</u>	<u>Burnup % ^{235}U Depletion</u>
Minimum	22.0	$\frac{22.0}{22.5} \times 54.2 = 53.0$
At Top Analysis Point	22.5	54.2
Maximum (Bottom Analysis Point)	49.0	96.4
Average	43.4	$\frac{43.4}{49.0} \times 96.4 = 85.4$

Calculation of Element Average

<u>Plate Position</u>	<u>^{137}Cs, 10^3 Cts/s</u>		
	<u>Minimum</u>	<u>Maximum</u>	<u>Average</u>
2	20.0	48.5	41.9
6	22.0	50.0	43.3
10	22.5	50.0	44.1
14	22.5	50.0	43.7
18	<u>22.0</u>	<u>49.0</u>	<u>43.4</u>
Average	21.8	49.5	43.3
Correlated Average Burnup	$\frac{21.8}{22.0} \times 53.0 =$ 52.5	$\frac{49.5}{49.0} \times 96.4 =$ 97.4	$\frac{43.3}{43.4} \times 85.5 =$ 85.3

^{137}Cs peak measured by multichannel analyzer gave the following counts/s at the maximum-burnup position for plates 1 through 19: 102.5, 97.4, 100.4, 98.0, 98.5, 100.0, 93.5,, 95.6, 97.8, 97.0, 95.4, 94.5, 92.9, 92.8, 95.4, 96.5,, 99.3, 100.9, and 100.0. The average of 97.3 correlates to an element average burnup of 82.4% using all 19 plates.

Table G.7. Final Isotopic Composition of Uranium and Plutonium

Element Number	BSI-201		BSI-202	
Plate Number	S-3-210-1		S-3-211-19	
	<u>Top</u>	<u>Bottom</u>	<u>Top</u>	<u>Bottom</u>
²³⁴ U	0.111	0.097	0.104	0.068
²³⁵ U	14.62	6.81	11.01	0.700
²³⁶ U	1.254	2.73	1.962	3.737
²³⁸ U	84.01	90.37	86.92	95.495
²³⁸ Pu	0.240	1.46	0.833	5.86
²³⁹ Pu	86.91	66.41	77.28	45.53
²⁴⁰ Pu	10.18	20.09	14.42	22.74
²⁴¹ Pu	2.48	9.05	6.49	10.70
²⁴² Pu	0.187	3.00	0.973	15.16

Element Number	CSI-201		CSI-202	
Plate Number	OSIIW-084		OSIIW-075	
	<u>Top</u>	<u>Bottom</u>	<u>Top</u>	<u>Bottom</u>
²³⁴ U	0.110	0.100	0.107	0.068
²³⁵ U	14.400	7.644	10.11	0.852
²³⁵ U	1.253	2.537	2.092	3.67
²³⁸ U	84.237	89.718	87.69	95.41
²³⁸ Pu	0.236	1.271	0.889	5.41
²³⁹ Pu	86.566	68.216	75.81	47.19
²⁴⁰ Pu	10.472	19.638	15.53	22.72
²⁴¹ Pu	2.530	8.427	6.63	10.71
²⁴² Pu	0.196	2.448	1.135	13.97

Element Number	NSI-201		NSI-202		NSI-202
Plate Number	ORR-093		ORR-140		ORR-145
	<u>Top</u>	<u>Bottom</u>	<u>Top</u>	<u>Bottom</u>	<u>Outside Plate, #1 Near Peak</u>
²³⁴ U	0.111	0.104	0.107	0.068	0.078
²³⁵ U	15.820	10.830	10.168	0.893	1.238
²³⁵ U	0.932	1.935	2.031	3.626	3.580
²³⁸ U	83.138	87.131	87.694	95.413	95.104
²³⁸ Pu	0.134	0.701	0.894	5.423	4.792
²³⁹ Pu	90.276	76.659	75.386	47.211	49.442
²⁴⁰ Pu	8.086	15.362	15.841	22.574	20.773
²⁴¹ Pu	1.432	6.308	6.753	11.191	12.567
²⁴² Pu	0.071	0.969	1.126	13.601	12.424

Table G.8. Burnups and Fission Densities of Analyzed Sample

Element Plate Pos.	BSI-201 S-3-210-1		BSI-202 S-3-211-19	
	Top	Bottom	Top	Bottom
ρ_U	4.60	4.60	4.60	4.60
e	0.1987	0.1987	0.1987	0.1987
A_0	0.2007	0.2007	0.2007	0.2007
A	0.1462	0.0681	0.1101	0.0070
C	0.12	0.14	0.13	0.25
D	-0.17	-0.15	-0.16	-0.14
B	0.315	0.709	0.505	0.973
FD_U	0.6	1.4	1.0	1.9
FF	0.966	0.920	0.947	0.851
FD	0.6	1.5	1.0	2.2

Element Plate Pos.	CSI-201 OSI1W-084		CSI-202 OSI1W-075	
	Top	Bottom	Top	Bottom
ρ_U	5.20	5.20	5.20	5.20
e	0.1986	0.1986	0.1986	0.1986
A_0	0.2006	0.2006	0.2006	0.2006
A	0.1440	0.0764	0.1011	0.0085
C	0.12	0.14	0.13	0.23
D	-0.17	-0.16	-0.16	-0.14
B	0.327	0.669	0.550	0.966
FD_U	0.7	1.5	1.2	2.1
FF	0.965	0.926	0.942	0.856
FD	0.8	1.6	1.3	2.5

Element Plate Pos.	NSI-201 ORR-93		NSI-202 ORR-140		NSI-202 ORR-145 Outside Plate, Near Peak
	Top	Bottom	Top	Bottom	
ρ_U	4.90	4.90	4.90	4.90	4.90
e	0.1969	0.1969	0.1969	0.1969	0.1969
A_0	0.1989	0.1989	0.1989	0.1989	0.1989
A	0.1582	0.1083	0.1017	0.0089	0.0124
C	0.12	0.13	0.13	0.23	0.21
D	-0.17	-0.16	-0.16	-0.14	-0.14
B	0.241	0.509	0.542	0.964	0.950
FD_U	0.5	1.1	1.1	2.0	2.0
FF	0.965	0.926	0.942	0.856	0.856
FD	0.5	1.1	1.2	2.3	2.3

Fig. G.1. Typical Gamma Scans of Plates from BSI-201, 0.6 - 0.7 MeV.

Fig. G.2. Typical Gamma Scans of Plates from BSI-202, 0.6 - 0.7 MeV.

Fig. G.3. Typical Gamma Scans of Plates from CSI-201, 0.6 - 0.7 MeV.

Fig. G.4. Typical Gamma Scans of Plates from CSI-202, 0.6 - 0.7 MeV.

Fig. G.5. Typical Gamma Scans of Plates from NSI-201, 0.6 - 0.7 MeV.

Fig. G.6. Typical Gamma Scans of Plates from NSI-202, 0.6 - 0.7 MeV.

Fig. G.7. Transverse Gamma Scans of Plates from NSI-201, 0.6 - 0.7 MeV.

Fig. G.8. Calculated Cumulative ^{235}U Fission Fraction as a Function of ^{235}U Burnup.

APPENDIX H

PHOTOGRAPHS OF PLATES AFTER BLISTER TESTING

**Figure H.1. Blister on Plate S-3-201-23 from Element BSI-201
After Heating to 575°C. (R-79721)**

**Figure H.2. Blisters on Plate S-3-213-15 from Element BSI-202
After Heating to 550°C. (R-79722)**

**Figure H.3. Blisters on Plate S-3-212-19 from Element BSI-202
After Heating to 550°C. (R-79729)**

**Figure H.4. Blisters on Plate OSIIW-054 from Element CSI-201
After Heating to 550°C. (R-79727)**

Figure H.5. Blisters on Plate OSIIW-065 from Element CSI-201
After Heating to 550°C. (R-79728)

Figure H.6. Blisters on Plate OSIIW-044 from Element CSI-202
After Heating to 550°C. (R-79731)

Figure H.7. Blisters on Plate OSIIW-026 from Element CSI-202
After Heating to 550°C. (R-79730)

Figure H.8. Blisters on Plate ORR-114 from Element NSI-202
After Heating to 550°C. (R-79735)

Figure H.9. Blisters on Plate ORR-123 from Element NSI-202
After Heating to 550°C. (R-79734)

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