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**POST-IRRADIATION EXAMINATION OF $U_3Si_{1.6}Al$
DISPERSION FUEL ELEMENT LC04***

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ABSTRACT

An LEU $U_3Si_{1.6}$ -Al dispersion fuel element with a fuel loading of 5.5 g cm^{-3} was irradiated in the HFR at Petten and performed well to a total burnup of 66% and a peak burnup of 85%. The swelling behavior of the fuel was similar to that observed in previous U_3Si_x irradiation experiments. The resulting fuel plate thickness increases and associated changes in coolant channel cross-sections were well within acceptable limits.

INTRODUCTION

A low-enrichment uranium (LEU) irradiation test (SIMONE project) was performed in the 45 MW Petten High-flux Reactor (HFR) as part of the Reduced Enrichment for Research and Test Reactor (RERTR) program. The participants in the SIMONE project were:

- Argonne National Laboratory (ANL), who provided the fuel material and who will take care of the ultimate disposal of the irradiated fuel elements.
- Joint Research Centre of the European Communities (JRC), who performed the test irradiations variations and who financed all work in connection with these irradiations.
- Babcock and Wilcox Company (B&W), USA, and "Compagnie pour l'Etude et la Realisation de Combustibles Atomique" (CERCA), France, who each provided two of the test elements, and
- The Netherlands Energy Research Foundation (ECN), The Netherlands, who prepared and carried out the test program under contract with JRC.

The purpose of the irradiation program was to demonstrate the reliable and safe behavior of high-density U_3Si_2 -Al and $U_3Si_{1.6}$ -Al type fuel elements under conditions which are typical for medium powered material testing reactors up to a burnup level of 70%. Four LEU elements with an enrichment of 20% have been tested. Two of the elements contained U_3Si_2 -Al and the other two contained $U_3Si_{1.6}$ -Al as fuel matrix. Dimensions and other experimental details for the most highly-loaded element are given in Fig. 1 and Table I.

All irradiations have been completed and the information prior to and during the experiment has been reported in several ECN reports. The final phase of the SIMONE experiment consisted of detailed post-irradiation examination of one plate from one of the two $U_3Si_{1.6}$ -Al elements, LC04. This examination is the subject of the present paper.

TABLE I EXPERIMENTAL PARAMETERS FOR ELEMENT LC04, PLATE NO. 1	
Fuel Composition	$U_3Si_{1.6}$
Fuel Mass Loading	5.51 g cm ⁻³
Fuel Volume Fraction	47.6%
As-fabricated Porosity	6%
Meat Al	A5 NE
Cladding Al	AG5 NE
Plate Thickness	1.91 mm
Meat Thickness	0.67 mm

POST-IRRADIATION EXAMINATION RESULTS FROM PLATE NO. 1

After removal from element LC04, plate No. 1 was gamma scanned and its thickness was measured at several locations. Subsequently metallographic sections were cut from the plate. The location of these examinations are indicated in Fig. 2.

Gamma Scanning

Pulse height analysis was performed for four long half-life fission product isotopes using a Ge/Li detector. The corrected data were fit with a least squares curve over the axial range of the fuel meat and are summarized in Table II. The curves for ^{137}Cs are shown separately in Fig. 3. The values in Fig. 3 were used to calculate the burnup and fission density at the locations of the thickness measurements and metallography. A total element burnup of 66.3% and a +10% correction for plate No. 1 relative to the element average, based on flux-density measurements, were employed.

- (A) SIDE PLATES (2)
- (B) OUTER FUEL PLATES (2)
- (C) INNER FUEL PLATES (18)
- (D) FUEL MEAT $UxSi_2y-Al$ (20)
- (E) CADMIUM WIRES (40)
- (F) NEUTRON FLUENCE DETECTORS (4)
- (G) COOLING GAPS (19)

Figure 1. Geometry of the LEU-silicide Test Elements

Figure 2. Positions for: Thickness Measurements (1-15), Gamma Scans (I, II, III), Metallography (A, B, C), on Plate No. 1 From Element LC04

TABLE II
SUMMARY OF GAMMA SCANNING RESULTS FOR PLATE NO. 1
FROM ELEMENT LC04

Nuclide	Line Number	Average Number of Counts	Maximum Number of Counts	Position of Maximum	Peaking Factor (% of Aver.)
^{144}Ce	1	36358.1	41184	309.88	113.3
	2	36258.9	41435	307.63	114.3
	3	37861.2	42877	303.43	113.2
	All	36826.1	42877	303.43	116.4
^{134}Cs	1	61356.6	84318	295.64	137.4
	2	58519.4	80624	295.66	137.8
	3	61094.4	83763	292.97	137.1
	All	60323.5	84318	295.64	139.8
^{106}Ru	1	4985.4	6368	298.37	127.7
	2	4908.7	6277	296.06	127.9
	3	5022.1	6439	290.86	128.2
	All	4972.1	6439	290.86	129.5
^{137}Cs	1	79690.7	93665	302.68	117.5
	2	77717.9	91808	303.87	118.1
	3	80046.1	93882	295.48	117.3
	All	79151.6	93882	295.48	118.6

Thickness Measurements

The thickness of the fuel plate was measured with a Mitutoyo thickness gauge with an accuracy of 0.005 mm. The results and a least squares fit through them are shown in Fig. 3.

Metallography

The samples were cut with a diamond impregnated blade, mounted in epoxy, ground, and polished with a final polish of 1/4 μm diamond paste. Figure 4 is a representative cross-sectional view of the boehmite $\text{Al}_2\text{O}_3 \cdot (\text{H}_2\text{O})$ layer over the fuel region in the plate as well as outside the fuel region at the top of the plate. The boehmite layer thickness in the fuel region is about 45 μm at both the top and center section but only half as thick outside the fuel region. Approximately one-half of this layer represents aluminum consumed by the oxidation reaction. Thus, the boehmite layer contributes significantly to the plate thickness increase. The microstructures at the three sample locations are shown in Figs. 5, 6, and 7. The familiar fuel-Al interaction phase $\text{U}(\text{AlSi})_3$ is present at all locations. There are a few oxide inclusions at the edge of the meat section that were introduced during fabrication, and, except for the lowest burnup top end of the meat, all as-fabricated porosity has been consumed by fuel swelling. The most significant microstructural feature is the relatively large gas bubble porosity in the fuel particles. The bubble morphology is very similar to that previously observed in other U_3Si_x fuel and indeed is similar to stoichiometric U_3Si as well.

Figure 3. Axial γ -activity (a) and Plate Thickness Profiles (b) of Plate No. 1, LC04

Figure 4. Cross-section of Boehmite Layer over Fuel Region (lower) and Outside Fuel Region (upper)

Figure 5. Microstructure at Center (pos. B) of Plate No. 1, LC04

Figure 6. Microstructure at Center Edge (pos. A) of Plate No. 1, LC04

Figure 7. Microstructure at Top End (pos. C) of Plate No. 1, LC04

DISCUSSION AND CONCLUSIONS

Fuel Swelling

Swelling of the fuel particles is the more meaningful entity for evaluation and comparison of the irradiation behavior of various fuel compounds and fuel element designs. The most accurate determination of fuel swelling involves chemical removal of any oxide from the fuel plate, measurement of the change in density of the plate by the Archimedean method, and determination of residual as-fabricated porosity in the meat by metallography. This procedure was not possible for the present experiment; therefore, three different, albeit less accurate, methods were used to derive the magnitude of fuel swelling.

From Plate Thickness Measurements

It has been established that, except for the contribution of the boehmite layer on the plate surface, the increase in plate thickness is equal to the increase in meat, or core, volume. That is, there is no change in plate length or width and no significant change in the density of aluminum cladding or aluminum in the meat. Assuming that the boehmite, $\text{Al}_2\text{O}_3 \cdot (\text{H}_2\text{O})$ with a density of 3.01 cm^{-3} , is of stoichiometric composition, one half of the layer thickness represents aluminum cladding consumed by the oxidation reaction. Thus the meat volume change is:

$$\frac{\Delta V^m}{V_o^m} = \frac{\Delta \text{th plate} - 2 \left(\frac{1}{2} \text{th boehmite} \right)}{\Delta \text{th}^m}$$

where $\text{th}^{\text{boehmite}}$ is the thickness of the boehmite layer determined by metallography (see Fig. 4).

The fuel volume change is:

$$\frac{\Delta V^F}{V_o^F} = \left[\frac{\Delta V^m}{V_o^m} - \frac{V_o^P - V^P}{V_o^m} \right] \frac{V_o^m}{V_o^F}$$

where V^P is the residual as-fabricated porosity determined by metallography. The results for three axial locations on the plate are shown in Table III.

Quantitative Metallography

Computerized image analysis on three 300X micrographs taken on section 'B' at the center of the plate was done to determine the post-irradiation fuel volume fraction. The results are shown in Table IV.

TABLE III
AVERAGE MEASURED THICKNESS INCREASES AND CALCULATED SWELLING
VALUES OF PLATE NO. 1 FROM ELEMENT LC04

	Total Av. Δth^{Pl} μm	Boehmite μm	Net Δth^{Pl} μm	ΔV^m %	ΔV^F %	Bu, %	FD^F $10^{27} m^{-3}$
Top Fuel	75	45	30	4	20	47	2.5
Center Fuel	150	45	105	14	<u>43</u>	84	4.4
Bottom Fuel	105	45	60	8	30	66	3.4

TABLE IV
VOLUME FRACTIONS IN FUEL MEAT (%) MEASURED BY
QUANTITATIVE IMAGE ANALYSIS ON METALLOGRAPHIC SECTION B

Micrograph	Gas Bubbles	Unreacted Fuel	Fuel-Al Interaction	Matrix Al	Residual As-fabricated Porosity	Total, %
7	8.6	40.3	35.9	15.2	0	100
6	9.5	46.3	28.0	16.2	0	100
5	6.5	43.4	29.4	20.1	0	100
Average	8.3	43.3	31.1	17.3	0	100

The fuel-Al interaction phase is $U(AlSi)_3$ with a density of 7.1 g cm^{-3} . Thus the 31.1% interaction phase corresponds to 16.2% unreacted fuel. The post-irradiation fuel volume fraction is thus:

$$8.3 + 43.3 + 16.2 = 67.8\%$$

or

$$\frac{\Delta V^F}{V_o^F} = \frac{67.8 - 47.6}{47.6} = \underline{44\%}$$

Metallographic Measurement

A third determination involves a simple measurement of the meat thickness on 20X and 100X micrographs. The average thickness change at the center of the plate (section B) is $96 - 76 = 10 \mu m$ representing a meat volume increase of

$$\frac{\Delta V^m}{V_o^m} = 13\%$$

or

$$\frac{\Delta V^F}{V_o^F} = \underline{40\%}$$

Thus the three methods yield respectively

43%, 44%, and 40%

for fuel swelling at the center of the plate.

The average fuel swelling for the fission densities at the top, center, and bottom locations of the plate are plotted in Fig. 8 together with other silicide swelling data from fuel plates with similar fuel volume loadings, i.e., ~45 vol. %.

It is clear from Fig. 8 that the fuel swelling measured for the present experiment is similar to that obtained with other mixed silicide irradiations. Moreover it is also similar to that of single phase U_3Si . It appears that the U_3Si phase dominates the swelling behavior of the 2-phase fuel. The observed coarse gas bubble morphology in the metallographic sections is consistent with this conclusion.

Channel Gap Measurements

The ultimate effect of fuel swelling is, with the addition of boehmite formation, a reduction in the coolant channel width. The coolant channel width was monitored throughout the irradiation by means of an ultrasonic probe. Figure 9 shows the change in the average coolant cross-section as measured after each reactor run. There is an initial decrease of approximately 2% corresponding to 50 μm . This decrease is probably due to boehmite formation. At higher burnup there is a further slight monotonic decrease due to fuel swelling. However, if the thickness data from plate No. 1 are applied to the entire element, twice-as-large a change in average coolant cross-section is calculated as indicated in Fig. 9. This discrepancy might be explained by the pattern of change in individual coolant channels shown in Fig. 10. It appears that the channel width in the left half of the element decreases commensurate with the measured plate thickness changes, but in the other part of the element the channels change little and some even increase in width. This can only be explained if a net outward bow of the fuel plates has taken place. The channel widening due to bowing has the effect of reducing the average decrease in channel cross-section resulting from swelling and boehmite formation.

Conclusions

The irradiation behavior of the $U_3Si_{1.6}$ -Al fuel in the SIMONE experiment was excellent to a total element burnup of 66% and fuel swelling was similar to previously tested U_3Si_x . There also appears to be no difference in the irradiation behavior of $U_3Si_{1.6}$ and U_3Si for the fuel plate design and irradiation conditions employed.

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Figure 8. Fuel Swelling in Plate No. 1, from $\text{U}_3\text{Si}_{1.6}$ -Al Fuel Element LC04 (experiment SIMONE), Compared with Other Silicide Swelling data

Figure 9. Survey of Average Fuel Element Coolant Channel Section of Assembly LC04 as a Function of Burnup

Figure 10. Average Coolant Channel Widths of Fuel Assembly LC04

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