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METALLOGRAPHIC OBSERVATIONS
OF SWELLING IN U_3Si

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METALLOGRAPHIC OBSERVATIONS OF SWELLING IN U_3Si

By

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ABSTRACT

Experimental hollow core U_3Si fuel rods were examined metallographically to determine the type of swelling and the nature of any structural changes in U_3Si irradiated at temperatures between 370 and 570 °C. The initial axial void behaved as designed and filled early in the irradiation to accommodate fuel swelling. Microtearing was identified for the first time as being the primary cause of swelling in U_3Si at these temperatures. Ion bombardment etching proved to be a very effective technique for the examination of irradiated U_3Si .

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METALLOGRAPHIC OBSERVATIONS OF SWELLING IN U_3Si

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INTRODUCTION

This report describes the postirradiation examinations of sections from four experimental hollow core U_3Si fuel rods irradiated in the NRX reactor at Chalk River Nuclear Laboratories. The main objectives of the investigation were the identification of the type of swelling and the structural changes that might have occurred in the fuel rods. The examinations were conducted by Battelle-Northwest at the Pacific Northwest Laboratories as part of a joint effort on a USAEC-AECL cooperative program. Most of the work at PNL consisted of optical and electron microscopy and X-ray diffraction studies, although some density and hardness measurements were made. Feraday et al.⁽¹⁾ have discussed the fuel element behavior at an interim point in the experiment, and Hann et al.⁽²⁾ have reported the results of the X-ray diffraction work.

Economic studies by Pon et al.⁽³⁾ indicated that lower power costs could be obtained by substituting a higher uranium density fuel for UO_2 in heavy water moderated power reactors. After studying several fuel possibilities, Chalk River personnel decided to test in detail U_3Si (U-3.8 wt% Si) because it has a high density (15.58 g/cm^3), low parasitic absorption, and good corrosion resistance in high temperature water in both the unirradiated⁽⁴⁾ and the irradiated condition.^(4,5) Chalder et al.⁽⁶⁾ at Chalk River Nuclear Laboratories have presented economic data that show savings of 0.1 to 0.2 mill/kW-hr if U_3Si is substituted for UO_2 as fuel in CANDU* type reactors. Prototype hollow core fuel elements of U_3Si

* *CANadian Deuterium Natural Uranium*

irradiated under power reactor conditions have demonstrated excellent dimensional stability to exposures of 15,000 MWd/TeU⁽⁷⁾. A detailed metallographic examination of irradiated fuel was needed to better understand the behavior of the test fuel elements and to further improve fuel element performance.

SUMMARY AND CONCLUSIONS

Sections from experimental hollow core U₃Si fuel rods were examined at the Pacific Northwest Laboratories. The type of swelling and structural changes were identified. The following conclusions were reached:

- Swelling in U₃Si at temperatures between 380' °C and 570 °C is initially caused by microtearing similar to that observed in uranium metal. Solid fission product accumulation and the growth of fission gas bubbles contribute relatively little to the swelling at these exposures.
- The original void closes quite early in irradiation because it is initially redistributed as microtears and U₃Si behaves as a quasi-viscous material under irradiation.
- Only a small portion of one irradiated specimen showed any evidence of delineated grain boundaries. The grain structure was probably destroyed by fuel flow and possibly irradiation growth of individual grains (U₃Si is slightly anisotropic).
- Ion bombardment etching gives representative results in U₃Si and is superior to chemical etching if porosity gradients exist.

EXPERIMENTAL PROCEDURE AND OBSERVATIONS

SPECIMENS

The silicon rich (4.01 wt% Si) U_3Si fuel cores were fabricated at the Eldorado Mining and Refining Company by induction melting followed by casting into cored molds. The as-cast structure of U_3Si_2 and uranium was transformed to U_3Si and some residual U_3Si_2 by heat treating at 800 °C for 3 days. The fuel material was slip fitted into Zircaloy-2 sheaths, assembled into elements, and irradiated in the NRX reactor at CRNL. The four sections examined at PNL were cut from elements that were irradiated under the same loop pressure (100 bars) but at slightly different fuel temperatures and effective restraints. All elements initially contained a central void along the axis of the fuel. Three elements started with a 7% void while one started with a 4% void. Effective restraint varied because two elements were clad with 0.7 mm thick sheaths while the other two were clad with 0.45 mm thick sheaths. Pertinent pre- and post-irradiation data for the respective elements are summarized in Table 1.

METALLOGRAPHY OF UNIRRADIATED U_3Si

Density and volume measurements are used to evaluate total swelling, but these methods reveal little about the nature of the swelling. Metallography can be an extremely useful tool to characterize fuel swelling if representative microscopic observations are obtained. However, interpretation of microscopic observations from atypical areas can impose serious limitations on the techniques as far as explaining behavior on the macroscopic scale. Prior work with irradiated uranium established the effectiveness of ion bombardment etching in removing surface metal that had flowed as a result of mechanical polishing and in revealing the true microstructure. Pitting or selective attack at impurity inclusions by chemical or electrolytic etchants is also

**TABLE 1. Pre- and Postirradiation Data
on U_3Si Fuel and Elements**

Element Number	Linear Heat Rating (W/cm)		Calculated Temperature, °C		Burnup		Nominal Void Size,	Estimate of Initial Porosity,	Clad Thickness,	Average % Volume Increase For Element ^(b)
	Max.	Time Average	Surface		MWd/TeU ^(a)	at. %	%	%	mm	
MJB	550	545	380	540	1620	0.13	7	3.0	0.45	15.7
MJC	520	505	390	540	8980	0.72	7	1.1	0.70	18.7
MJE	565	565	380	565	990	0.079	4	1.2	0.45	8.1
MJL	480	450	375	515	5900	0.47	7	1.6	0.71	16.7

(a) $10,000 \text{ MWd/TU} = 0.8\% \text{ of total atoms fissioned} = 4.06 \times 10^{20} \text{ fission/cm}^3 \text{ of } U_3Si$

(b) *Calculated from an average of three density measurements per element. Postirradiation density values were referred to theoretical values for U_3Si at the silicon content of interest.*

avoided. Battelle-Northwest did not have any prior experience with ion bombardment etching of U_3Si at the time these examinations were initiated. Consequently, some effort was expended to locate a chemical etch that would produce representative structures in both the irradiated and the unirradiated material. Etchants were somewhat limited by safety and handling restrictions associated with hot cell operations. The following etch produced satisfactory results on unirradiated material and was convenient to use in-cell. The etching technique consisted of immersing the polished specimen for 6 to 8 sec in a solution of 3.4g citric acid, 72 cm³ nitric acid, 170 cm³ water, and 1 cm³ 40% hydrofluoric acid. Representative optical microscopy from unirradiated material etched as indicated above is included in Figure 1. The dark particles are residual U_3Si_2 particles in a U_3Si matrix. Ambler⁽⁸⁾ has attributed the striations evident in the individual grains to a martensitic type reaction. An electron micrograph from a negative replica of the chemically etched material shows well defined grain boundaries. Note the rough surface of the U_3Si_2 particle. Compare the micrograph (chemical etch) with one obtained from similar material etched by ion bombardment. Although grain boundaries are evident in the U_3Si , they are not as well defined as those in the chemically etched specimen. Also, the U_3Si_2 particles appear relatively smooth indicating a possible preferential attack by the chemical etch.

METALLOGRAPHY OF IRRADIATED U_3Si

Metallographic specimens were cut from the as-received segments on a wafer saw to avoid introducing artifacts. Larger cut-off saws have occasionally introduced cracks and other artifacts in metallic uranium elements examined at PNL. The sections were placed in stainless steel mounts and ground through 600 grit SiC papers. Polishing was done on an orbital polisher using Linde A ($\alpha-Al_2O_3$) and distilled water on canvas cloth followed by Linde B ($\alpha-Al_2O_3$) and distilled

Neg 468-5257

500X

Chemical Etch

10 μ

10 μ

Neg M5127A

Chemical Etch

Neg 5759A

Ion Bombardment Etch

FIGURE 1. Microstructure of Unirradiated U_3Si

water on canvas cloth. A phosphoric bath (5 parts ethylene glycol to 5 parts phosphoric acid to 8 parts ethanol, 8 V, 10-12 sec) was used after each polishing step to remove the worked material. The specimens were etched with the chemical etch described earlier or by ion bombardment (3000-3500 V, 1 ma, 9-10 microns argon, 2 hr). Photomacrographs (Figure 2) of the four specimens were taken after replicas had been stripped from the etched (ion bombardment) surfaces. Two specimens, MJB and MJE, arrived at PNL without cladding, while specimens MJC and MJL were clad. The original void was almost completely closed during irradiation, at least at these locations in the elements. The relative size of the light areas on the specimens is associated with different porosity gradients. No obvious explanation was found for the light rings near the edge of the elements, although the rings could be associated with localized porosity. When the chemical etch described earlier was used, the porosity differences between the edge and the core were large enough to affect etching rates. In fact, it was impossible to avoid preferential attack of the central portions of the specimens before the outer regions were completely etched. Consequently, the bulk of the metallography on irradiated fuel was confined to material etched by ion bombardments. No well-defined grain boundaries were detected in either chemically or ion-bombardment etched fuel.

OPTICAL MICROSCOPY

The representative portion of the optical microscopy in Figure 3 will enable the reader to compare the effects of increasing exposure as well as the differences between the edge and core of each specimen. The edge of specimen MJE appears to be unchanged by irradiation while the center of the element is quite porous. A marked gradient varying from light at the edge to very dark at the center was observed after etching. This same gradient appears light at the center and dark at the

Neg E5167

Specimen MJE
Average Exposure: 990 MWd/TeU

Neg E5199

Specimen MJB
Average Exposure: 1620 MWd/TeU

Neg E5200

Specimen MJL
Average Exposure: 5900 MWd/TeU

Neg E7733

Specimen MJC
Average Exposure: 8980 MWd/TeU

FIGURE 2. *Photomicrographs of Metallographic Sections Cut from Irradiated U_3Si Fuel Elements - Ion Bombardment Etch*

Neg E5168

Specimen MJE

Core

100 μ

Neg E5176

Average Exposure: 990 MWd/TeU

Edge

Neg E5188

Specimen MJB

Core

100 μ

Neg E5195

Average Exposure: 1620 MWd/TeU

Edge

FIGURE 3a. Representative Optical Photomicrographs of Irradiated U_3Si Fuel Elements - Ion Bombardment Etch

Neg E5178

Specimen MJL
Core

Neg E5186

Edge
Average Exposure: 5900 MWd/TeU

Neg E7642

Specimen MJC
Core

Neg E7628

Edge
Average Exposure: 8980 MWd/TeU
Fuel Elements - Ion Bombardment Etch
FIGURE 3b. Representative Optical Photomicrographs of Irradiated U_3Si

edge in Figure 2. We attribute the gradient to porosity differences in the fuel. This effect was more noticeable at the lower exposures. The large, angular black particles located at isolated spots in the fuel are UO_2 particles. A rather large change in the size of residual U_3Si_2 particles was noted as the specimen was scanned from the edge to the center. It is not known whether the difference in particle size was caused by higher fuel temperatures, flow of fuel material, or existed prior to irradiation. The center of specimen MJE shows the original void partially closed by fuel from the outer areas flowing towards the center. In fact, flow lines in the U_3Si matrix are quite evident. The large white precipitates outlining the edges of the original void are believed to be U_3Si_2 particles stabilized by carbon absorbed from the graphite core used during the casting process.

Flow lines are also present in the core of specimen MJB, but the effect is not as apparent as indicated in specimen MJE. The central void is almost closed at this exposure, and the material near the core does not appear to be as porous as that in MJE. Very few cracks were detected in either specimen MJE or MJB.

Specimen MJL, however, contained many macro-cracks (see Figure 3). These cracks are presumed to have occurred during the original sectioning operation at CRNL as the material is relatively brittle at this exposure level. Neither the etching gradient nor flow lines detected in MJE and MJB were observed in specimen MJL. The filigree precipitate evident in isolated clumps is thought to be debris picked up during fabrication.

The core of specimen MJC appears to be more porous (at these magnifications) than the core of specimen MJL, an observation that conflicts with the trend established with MJE and MJB. Perhaps the appearance of MJL is due to a lighter etch. No apparent evidence of a reaction zone between the clad and the fuel was observed in either clad specimen.

The effects of increasing the exposure seem to have little effect on the appearance of the fuel near the edge of the element. The size of the residual U_3Si_2 particles near the edge appears to decrease with increasing exposure; however, these differences could have existed prior to irradiation. The amount of porosity, which appears as a fine black precipitate at these magnifications, does increase with exposure. The original void begins to close quite early in the irradiation as the flow of fuel material is directed inwards by the combination of clad and coolant restraint. Flow lines that appear at lower exposures are gradually obliterated as the fuel fills the original void. The etching effect is also decreased as the porosity is redistributed on a finer scale.

ELECTRON MICROSCOPY

Electron photomicrographs obtained from replicas of locations near the core and near the edge of each specimen are depicted in Figures 4, 5, 6, and 7. These photomicrographs were obtained from negative replicas; consequently, depressions in the sample surface cast shadows that appear white in the photographs. Conversely, the projections on the specimen surface appear as depressions on the replica and the shadows fall inside rather than outside the object.

Specimen MJE (Figure 4) contained porosity in the U_3Si matrix even near the edge of the specimen. The porosity appears to be rather heterogeneously distributed, on a microscopic scale, in the U_3Si at this low burnup. These are some indications of interconnected porosity along U_3Si_2 particles near the core of the element (Figure 4); however, no porosity was detected in the U_3Si_2 particles. The photographs taken at higher magnifications reveal that the porosity is primarily two dimensional or plate-like in shape. No marked difference between the edge and core was detected on replicas of MJE. On the other hand, specimen MJB (Figure 5) showed a marked

difference between the edge and the core. We were more fortunate in the examination of specimen MJB because we were able to obtain a replica from the very edge of the specimen. The edge of MJB is quite sound and one can see faint outlines of what appears to be U_3Si grain boundaries. Considerable porosity in the form of tears or elongated pores was located in the U_3Si about 2 mm from the specimen edge. The porosity in MJB is more homogeneously distributed (on a microscopic scale) than that observed in MJE. Porosity near the edge of MJB resembles the plate-like tears of MJE but near the center the porosity tends toward elongated pores. At higher exposures (Figure 6), the pores are spherical rather than plate-like in shape, and they appear to be somewhat smaller. The porosity in MJC (Figure 7) at even higher burnups is spherical near the edge but bean-shaped and relatively large near the core. (Note that the photomicrograph of MJC edge is not at the same magnification as others in this series.) One possible explanation for the anomaly is that MJC could have had larger amounts of initial free volume in the segment examined. Consequently, the porosity generated during irradiation in MJC would not be subject to the same restraints which would explain the larger size and the bean shape at the higher burnups. Flow lines were detected in MJC near the core and pores had definitely linked up in long rows along the U_3Si_2 particles (Figure 8). A precipitate of unknown origin is scattered throughout specimens MJB, MJC, and MJL. The precipitate appears to be associated with the U_3Si_2 particles; perhaps, the U_3Si_2 particles are going into solution during irradiation.

Neg 5634 1/2E

Neg 5635B

Neg 5632E

Neg 5633A

Core

Core

FIGURE 4. *Replica Electron Photomicrographs from a Section of Hollow Core U_3Si Fuel Element MJE Irradiated to an Average Exposure of 990 MWd/TeU*

Neg 5796A

Edge

Neg 5796C

Edge

Neg 5796D ~2 mm from Edge

Neg 5797B ~2 mm from Edge

Neg 57190

Core

Neg 5720A

Core

FIGURE 5. *Replica Electron Photomicrographs from a Section of Hollow Core U_3Si Fuel Element MJB Irradiated to an Average Exposure of 2620 MWd/TeU*

*Neg 5628B**Near Edge* *Neg 56280**Near Edge* *Neg 5630B**Core* *Neg 56300**Core*

FIGURE 6. *Replica Electron Photomicrographs From a Section of Hallow Core U_3Si Fuel Element MJL Irradiated to an Average Exposure of 5900 MWd/TeU*

Neg 6460B *Neg 64600* *Neg 6469A**Core* *Neg 6469C**Core*

FIGURE 7. *Replica Electron Photomicrographs From a Section of Hollow Core U_3Si Fuel Element MJC Irradiated to an Average Exposure of 8980 MWd/TeU*

Neg 64630 *Neg 64633* *Neg 6464A*

FIGURE 8. *Replica Electron Photomicrographs of U_3Si Fuel Element MJC Showing Linked Up Pores Along Edges of U_3Si_2 Particles*

RESULTS

The data from the present work indicate that initial fuel swelling occurs near the central void as large tears. At the same time the fuel begins to flow towards the center of the element in a quasi-viscous manner. The flow is undoubtedly directed by the combined restraints of cladding and system pressure. As burnup and fuel movement increase additional microtears form in the fuel somewhat removed from the central void. Eventually the original free volume is redistributed in the fuel as microtears that probably contain relatively little fission gas. Additional burnup causes these tears to spheroidize into pores that decrease in size until they are either consumed by lattice expansion caused by the accumulation of solid fission product atoms or reach radii that place them in equilibrium with any fission gas present.

DISCUSSION

Bleiburg and Jones⁽⁹⁾ observed volume increases of 3.5 to 4.1% in U_3Si irradiated unrestrained in NAK capsules at temperatures less than 250 °C. Swelling was independent of exposure between 0.01 and 0.104 at.% BU and was attributed to irradiation induced disordering. No grain boundaries or X-ray diffraction lines were detected.

Kittel and Smith⁽¹⁰⁾ irradiated cast and extruded U_3Si specimens in NAK capsules. Swelling amounted to about 4% in cast specimens irradiated to burnups of 0.09 at.% to 0.35 at.% at center temperatures of 200 to 700 °C. The extruded specimens swelled less but were irradiated at lower center temperatures (180 °C max.) and to lower exposures (0.13 at.% BU max.).

Howe⁽¹¹⁾ irradiated solid U_3Si rods clad in Zr-2 to burnups of 0.096 at.% at center temperatures of 580 to 660 °C. Swelling increased rapidly above 0.048 at.% Bu to 7% at the

highest exposures. The volume increases were attributed to fission gas porosity rather than disordering because: (1) swelling was too large to be caused solely by the disordering mechanism, and (2) swelling did not saturate at low burnups.

MacEwan and Bethune⁽¹²⁾ detected irradiation induced disordering in U_3Si irradiated at 100 °C to exposures of only 0.12×10^{-3} at.%. X-ray diffraction patterns showed that the modified bc tetragonal structure had changed to a disordered fcc structure with a 0.6% decrease in X-ray density. Immersion density measurements showed a volume increase of 2.3%. Diffraction patterns from specimens of higher exposure indicated a trend toward an amorphous structure. Annealing at progressively higher temperatures indicated recovery of the bc tetragonal structure started at approximately 250 °C and was complete at 500 °C. Volume increases were almost completely recovered by annealing between 210 °C and 255 °C. The fact that Hann et al⁽²⁾ detected no structural transformation in U_3Si fuel irradiated to 0.47 at.% BU is consistent with the work of MacEwan and Bethune⁽¹²⁾ because irradiation temperatures were high enough to anneal out any irradiation induced disordering.

Swelling in U_3Si at temperatures ranging from 380 to 570 °C appears to be initially caused by the nucleation and propagation of microtears. These microtears are very similar in appearance to those detected by Leggett et al.^(13,14) and Angerman and Caskey⁽¹⁵⁾ in uranium metal irradiated between 370 °C and 500 °C. Several possible mechanisms exist that could contribute to the nucleation and propagation of microtears in U_3Si . In general, two mechanisms have been proposed for a variety of materials: (1) grain boundary sliding, and (2) vacancy condensation. Some controversy exists in the literature as to which mechanism is operative. The nucleation of voids by vacancy condensation has been supported by

J. N. Greenwood,⁽¹⁶⁾ and J. N. Greenwood et al.⁽¹⁷⁾ Balluffi and Seigle⁽¹⁸⁾ suggested that voids were nucleated by lattice vacancies and grow by the migration of vacancies from the grain boundaries to the void. Ratcliffe and Greenwood⁽¹⁹⁾ concluded from their study of cavitation in magnesium that cavity growth depends on a supply of vacancies from grain boundaries and that deformation mechanisms do not contribute. Ratcliffe and Greenwood also surmised that structural changes induced during deformation do not influence cavity nucleation. Hull and Rimmer⁽²⁰⁾ suggested that void nuclei might be stress induced, and they developed a theory for void growth based on diffusion of atom from the surface of voids along the grain boundaries. Sinclair⁽²¹⁾ subjected bubble raft "crystals" to repeated shearing action and observed holes nucleated by vacancy condensation. Vacancies throughout the model were collected by dislocations and eventually transferred to the void, leaving the adjacent material depleted of vacancies. McLean⁽²²⁾ proposed that existing holes could serve as void nuclei and could grow in a material with a supersaturation of vacancies by the sliding action of grain boundaries enlarging cavities located on grain boundaries and thus form favored sites for vacancy precipitation. Cottrell⁽²³⁾ in his review paper supported the hypothesis that grain boundary sliding nucleated voids which grow by atom diffusion from the voids through the lattice or along a grain boundary. Hyam and Sumner⁽²⁴⁾ concluded nucleation and growth of voids in irradiated beryllium tested in tension was due to enhanced diffusion of vacancies to bubbles from grain boundaries subjected to local intergranular tensile stresses. Stress-induced growth of the bubbles was thought to result in large cavities which eventually link up to form large grain boundary cracks. MacEwan and Bethune⁽¹²⁾ proposed a nucleation mechanism for U_3Si based on fission spikes producing a disordered region and

localized deformation of the matrix. The disordered structure would quickly revert to the denser tetragonal structure leaving an excess of vacancies or microtears in the original core of the fission spike. Agglomeration of these cavities could form larger voids; however, the appearance of the microtears in U_3Si at low exposures does not suggest a simple agglomeration mechanism for void propagation. In addition, Scaife and James⁽²⁵⁾ gave evidence that intergranular cavities formed during creep-rupture tests of niobium stabilized stainless steel do not grow by vacancy condensation but by grain boundary sliding.

The authors believe the microtears are nucleated by the condensation of vacancies as voids or at pre-existing voids and are propagated by the anisotropic expansion of individual grains due to irradiation growth because U_3Si is slightly anisotropic. Kittel and Smith⁽¹⁰⁾ measured irradiation growth coefficients in extruded U_3Si comparable to those found for uranium that had been rolled at 300 °C and quenched from the beta phase. However, we cannot provide evidence in the present work that microtears are located on grain boundaries since no well defined grain boundaries were detected; nor can we provide conclusive evidence for a microtear nucleation mechanism. The present study was limited to replica techniques with a lower resolution limit of 200Å. Additional work utilizing transmission electron microscopy should provide some insight into the nucleation mechanism. Examination of specimens irradiated under known and closely controlled temperatures and pressures⁽²⁶⁾ might reveal the location of the microtears.

Several different mechanisms appear to contribute to swelling in U_3Si at low exposures:

- Solid fission product accumulation - a temperature insensitive mechanism that contributes relatively little to the total swelling.

- Disordering of the bc tetragonal lattice to a disordered fcc structure - apparently saturates (2.3% AV/V) at very low exposures (0.12×10^{-3} at.% BU) and begins to anneal out above 250 °C.
- Nucleation and growth of fission gas bubbles - a contributing factor, but not a major one at low exposures or below 600 °C.
- Microtearing - the major contributor to swelling in unrestrained fuel irradiated between 375 °C and 565 °C.

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REFERENCES

1. M. A. Feraday, G. H. ChaZder, and K. D. Cotnam. Nuclear Applications, vol. 4, no. 3, p. 148. 1968.
2. C. R. Hann, R. D. Leggett, M. A. Feraday, and G. H. ChaZder. J. Nucl. Mater. vol 31, p. 114. 1969.
3. G. A. Pon, W. B. Lewis, L. R. Haywood, D. B. Primeau, G. J. Phillips, and E. E. Merlo. "Prospective D_2O -Moderated Power Reactors;" Proceedings of International Conference on Peaceful Uses of Atomic Energy, Geneva, vol. 5, P/10, p. 333. 1964.
4. W. T. Bourns. A Literature Survey of U_3Si Corrosion, AECL-2609. ChaZk River NucZear Laboratories, ChaZk River, Ontario, March 1967.
5. M. A. Feraday, G. M. Allison, J. F. R. Ambler, G. H. ChaZder, and J. J. Lipsett. In-Reactor Performance of Defected Zircaloy-Clad U_3Si Fuel Elements in Pressurized and Boiling Water Coolants, AECL-3106. ChaZk River Nuclear Laboratories, ChaZk River, Ontario, May 1968.
6. G. H. ChaZder, W. T. Bourns, M. A. Feraday, and J. Veeder. U_3Si as a NucZear Fuel, AECL-2874. ChaZk River NucZear Laboratories, ChaZk River, Ontario, May 1967.
7. G. H. ChaZder. Unpublished Data. ChaZk River NucZear Laboratories, ChaZk River, Ontario, May 1969. Personal Communication.
8. J. F. R. Ambler. J. Nucl. Mater., vol. 22, p. 112. 1967.
9. M. L. Bleiburg and L. J. Jones. "The Effects of Pile-Irradiation on U_3Si ," Trans. AIME, vol 212, p. 758. December 1958.
10. J. H. Kittel and K. F. Smith. Effects of Irradiation on Some Corrosion-Resistant Fuel Alloys, ANL-5640. Argonne National Laboratory, Argonne, Illinois, May 1960.
11. L. M. Howe. Irradiation Behavior of Enriched U_3Si Elements Sheathed in Zircaloy-2, AECL-984, ChaZk River NucZear Laboratories, ChaZk River, Ontario, January 1960.
12. J. R. MacEwan and B. Bethune. Irradiation Damage in U_3Si , SM-120/H-3. Presented at IAEA Conference on Radiation Damage in Reactor Materials, Vienna, Austria, June 2-6, 1969.

13. R. D. Leggett, T. K. Bierlein, and B. Mastel. Irradiation Behavior of High Purity Uranium, HW-79559. Available from Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia, November 1963.
14. R. D. Leggett, T. K. Bierlein, B. Mastel, and H. A. Taylor. Basic Swelling Studies, BNWL-SA-154. Battelle-Northwest, Richland, Washington, 1965. Also: "Basic Swelling Studies," Radiation Effects, edited by W. F. Sheely, ----- AIME. Gordon & Breach, 1967. vol. 37, p. 303.
15. C. L. Angerman and C. R. Caskey. "Swelling of Uranium by Mechanical Cavitation," J. Nucl. Mater., vol. 13, no. 2, p. 102. 1964.
16. J. N. Greenwood. "Intercrystalline Cracking of Metals," Bull. Inst. Metals, p. 104. 1952.
17. J. N. Greenwood, D. R. Miller, and J. W. Suiter. "Intergranular Cavitation in Stressed Metals," Acta Met., vol. 2. March 1954.
18. R. W. Balluffi and L. L. Seigle. "Growth of Voids in Metals During Diffusion and Creep," Acta Met. vol. 5, p. 449. August 1957.
19. R. T. Ratcliffe and G. W. Greenwood. "The Mechanism of Cavitation in Magnesium During Creep," Phil. Mag., vol. 12, p. 59. 1965.
20. D. Hull and D. E. Rimmer. "The Growth of Grain-Boundary Voids Under Stress," Phil. Mag., vol. 4, p. 673. 1959.
21. G. M. Sinclair. "Fatigue Fracture," Fracture of Engineering Materials. American Society of Metals, Metals Park, Ohio, 1964. p. 185.
22. D. McLean. Grain Boundaries in Metals. Oxford University Press, Amen House, London, 1957. p. 333.
23. A. H. Cottrell. "Intercrystalline Creep Fractures," Iron Steel Institute, Spec. London Report, no. 70, 1961.
24. E. D. Hyam and G. Sumner. "Irradiation Damage to Beryllium," Radiation Damage in Solids. IAEA, Vienna, 1962.
25. E. C. Scaife and P. L. James. "Influence of Environment on Intergranular Cavitation," Metal Science J., vol. 2, p. 217. 1968.
26. C. R. Hann. Unpublished Data. Battelle-Northwest, Richland, Washington, June 1969.

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