RERTR PROGRAM FUEL TESTING AND DEMONSTRATION - AN UPDATE*

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ABSTRACT

The irradiation and postirradiation examination of high-density, reduced-enrichment miniplates and full-sized elements are continuing under the RERTR Program. The emphasis is currently being placed on determining uranium-density/fission-density limits for the highest-density silicide fuels. One whole core demonstration is nearing completion in the FNR and another, using U_3Si_2 fuel, is scheduled to begin in the ORR during the next year. This paper will summarize the progress made during the past year.

INTRODUCTION

The testing and demonstration of high-density fuels under the U.S. Reduced Enrichment Research and Test Reactor (RERTR) Program has continued on several fronts during the past year. Postirradiation examinations (PIE's) of miniplates from the first series irradiated in the ORR have been virtually completed and irradiation of a new series of miniplates has begun. The irradiation to high burnup of several full-sized fuel elements containing high loadings of U_3O_8 or U_3Si_2 in the Oak Ridge Research Reactor (ORR) has been completed, and the elements are awaiting PIE. The irradiation of full-sized plates and elements containing U_3Si_2 or U_3Si has begun in the SILOE and R2 reactors. Also, the irradiation of a cluster of TRIGA pins has concluded in the ORR. In addition to testing fuel plates and elements to determine the irradiation behavior of the various high-density fuels developed, the RERTR Program conducts full-core demonstrations to determine the characteristics of operating cores and to provide data for validation of neutronics analysis methods and codes. The first such demonstration, in the Ford Nuclear Reactor (FNR) at The University of Michigan, is nearing completion. A second demonstration is scheduled to begin in the ORR around July 1985. Details of many of these tests and demonstrations are contained in other papers presented at this meeting. A summary of these results is presented in this paper, along with some specific topics not covered elsewhere.

MINIPLATE TESTING

As reported previously,[1] irradiation of the first series of miniplates was completed on June 13, 1983. The burnups (^{235}U depletions) of plates of most of the modules, determined from the measured isotopic abundances of

^{235}U in the irradiated plates, are listed in Table 1. Fission densites derived from the ^{235}U burnups through the use of ^{235}U fission fractions obtained from EPRI-CELL[2] depletion calculations are generally consistent with fission densities measured by the ^{148}Nd method. However, the ^{148}Nd values appear to be more uncertain in general and, at times, appear to be completely wrong. It should be noted that the burnups listed in Table 1 are considerably higher than the estimated burnups given in Ref. 1. There is an inconsistency between the burnup measured for one sample from one plate of Module 10 and the burnup which would be estimated based upon a fit of the measured values for the other modules. Additional samples will be analyzed, and the measured value given in Table 1 for Module 10 should be considered preliminary.

Results of PIE's of the CNEA miniplates in Module 6 and the ANL miniplates in Modules 10, 13, and 14 are reported in other papers.[3,4] Table 2 is a summary of swelling and blister-threshold-temperature data for these, as well as previously examined, miniplates. The highly loaded (45 to 51 vol%) UAl_2 and U_3O_8 minipl tes in Module 6 behaved very well, with all showing a net decrease in fuel meat volume owing to the high initial porosity which accompanies high volume loading in dispersion fuels. The U_3Si_2 fuel continued to behave excellently up to 97% burnup. The volume loading of the U_3Si fuel appears to influence the swelling rate. Further study will be needed to determine burnup limits for highly loaded U_3Si fuel.

As reported last year,[1] a new series of miniplate irradiations is being performed to establish the performance limits of U_3Si_2 and U_3Si fuels, to determine whether a small copper addition will improve the performance of U_3Si, to show that highly loaded UAl_2 dispersion fuel performs well at medium enrichment, and to investigate the basic behavior of U_6Fe. Table 3 shows the test matrix. The depleted uranium plates are included to investigate neutron-, as opposed to fission-, induced effects. The plates containing medium-enriched uranium (MEU) and high-enriched uranium (HEU) are included to investigate fuel performance for fission densities in excess of those which could be achieved with low-enriched uranium (LEU). Thereby, fuels suitable for use with MEU can be identified, and safety margins can be established for LEU fuels. Irradiation of the new series began on March 7, 1984, and Table 4 gives the current irradiation status.

Preliminary results of an investigation of the exothermic reaction between uranium silicide and aluminum were presented last year.[1] A more thorough analysis of the data resulted in some small changes in the reported reaction energies. The new values are listed in Table 5, and a complete report of the experiment is contained in Ref. 5. The reason for the differences in reaction energy for different volume loadings of each fuel type is not known. If all of the fuel completely reacted with the aluminum, as would be expected for three heatings, the specific energy release would be the same for a given fuel type. However, since these measurements were made by a differential thermal analysis technique rather than by calorimetry, the energy released during relatively slow reactions might not result in detectable temperature differences. It is reasonable to expect the reaction rate to decrease with increasing volume loading since a smaller fraction of the fuel particles are in intimate contact with the aluminum matrix or cladding and since the aluminum must travel greater distances to react with the fuel particles. Since a greater amount of aluminum is required for complete reaction of the U_3Si than the U_3Si_2, a greater difference would be expected for the U_3Si than for the U_3Si_2, consistent with the data.

If this were the case, the actual reaction energy would be higher than the values measured for the 32 vol% samples. In any case, care should be exercised when using the measured reaction energies in a safety analysis.

FULL-SIZED ELEMENT (PLATE, ROD) TESTING

The irradiation testing of full-sized elements, full-sized plates, and full-sized TRIGA rods has continued in the ORR and the SILOE reactor and has begun in the R2. Table 6 gives the current status of all reduced-enrichment elements scheduled for irradiation in the ORR. During the past year the high-burnup irradiations of one U_3O_8 element containing 3.2 Mg U/m^3 and two U_3Si_2 elements containing 4.8 Mg U/m^3 have been completed. Two additional U_3Si_2 elements have completed their irradiations to normal discharge burnups. All of the elements have performed well, and channel gap measurements have given no indication of excessive swelling. As reported in a separate paper,[6] PIE's of a number of these elements have been completed and have shown the elements to have behaved entirely satisfactorily. The irradiation of high-uranium-loaded TRIGA rods was concluded on August 16, 1984, following a vibration-induced cladding failure. As reported elsewhere,[7] the fuel appears to have performed well to burnups of over 60%.

Table 7 gives the status of reduced-enrichment fuel elements and full-sized fuel plates scheduled for irradiation in European reactors in cooperation with the RERTR Program. The PIE of the elements irradiated in the HFR-Petten has been completed and showed the elements to have behaved satisfactorily. Based upon the satisfactory behavior of the four U_3Si plates irradiated in SILOE, a full-sized U_3Si element is now being irradiated. The four U_3Si plates will be shipped to ANL for destructive examination. Further details of the SILOE irradiation program are given in Ref. 8. The U_3Si_2 elements scheduled for irradiation in the R2 reactor at Studsvik have the same uranium density as the U_3Si_2 elements irradiated in the ORR but have a 50%-thicker meat. Full-power irradiation of these elements will begin following replacement of the R2 vessel. It is anticipated that irradiations of additional uranium-silicide elements will take place in the HFR-Petten and the BR2 reactor at Mol. Joint studies are underway to define the test elements.

WHOLE-CORE DEMONSTRATIONS

A whole-core demonstration in the 2-MW FNR at the University of Michigan is nearing completion. The primary purpose of the demonstration was to provide data for neutronics methods validation. Many data have been obtained from an equilibrium HEU core, fresh and nearly fresh LEU cores, mixed HEU-LEU cores, and a near-equilibrium LEU core. The operational impacts of the change from HEU to LEU fuel have been very small.[9]

A second demonstration with the primary purposes of providing data for validation of LEU fuel cycle calculations and of providing large-scale proof of acceptable performance of production-line U_3Si_2 elements is planned for the ORR. The fuel elements will be the same as the six test elements already irradiated in the ORR, i.e., standard 19-plate elements containing 4.8 Mg U/m^3 in the form of U_3Si_2. Preliminary safety approval was obtained in May 1984 from the Reactor Operations Review Committee (RORC) at Oak Ridge National Laboratory. Consideration of final approval will occur after PIE data is obtained from additional test elements, including some at high burnup; after specific safety calculations have been performed to verify conclusions based on generic studies; and after the effect of fuel fines on thermal conductivity has been investigated. The Department of Energy has approved the procurement of 100 fuel elements from B&W (60), CERCA (20), and NUKEM (20) and 12 shim rod assemblies containing LEU followers from B&W. Contract negotiations are underway, and fuel deliveries are anticipated in time to begin the demonstration in July 1985. The transition from the HEU equilibrium core to the LEU equilibrium core will be made through a series of mixed HEU-LEU cores.

SUMMARY

The irradiation testing of reduced-enrichment fuels under the RERTR Program is progressing well. Basic irradiation-behavior data to high burnup have been obtained from miniplates for high volume loadings of UAl_x, UAl_2, and U_3O_8 and for intermediate volume loadings of U_3Si_2 and U_3Si. A second series of miniplate irradiations is underway to extend the volume loading and fission density range of the data. Irradiations of full-sized fuel elements of all fuel types are underway or completed. PIE's of many of them have been completed and have shown the fuels to have performed well. The whole core demonstration in the FNR is nearing completion and has provided much core physics and operational data. The operational impacts of the change from HEU to LEU fuel have been small. Planning for a whole-core demonstration using U_3Si_2 fuel in the ORR is proceeding. Preliminary safety approval has been obtained, and contract negotiations for fuel procurement are underway.

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Table 1. ^{235}U Burnups Achieved During First Series of Miniplate Irradiations

Module	Fabricator	Fuel Type	Measured Burnup, %
1	EG&G, ORNL	UAl_x, U_3O_8	93.5
2	ORNL, ANL	U_3O_8, U_3SiAl	86.5
3	ANL	U_3SiAl, U_3Si	34.0
4	EG&G, ORNL, ANL	UAl_x, U_3O_8, U_3SiAl, U_3Si	95.9
5	ORNL	U_3O_8	80.1
6	CNEA	UAl_2, U_3O_8, U_3Si	89.0
7	ANL	U_3Si_2, U_3SiAl, U_3Si	90.2
8	NUKEM	UAl_x, U_3O_8	90.3
9	CNEA, ORNL	UAl_x, U_3O_8	97.9
10	ANL	U_3SiAl, U_3Si	71.9(84)+
13	ANL	U_3SiAl	- (86)+
14	ANL	U_3Si_2*	97.1

*Two plates from Module 7 reinserted.

+Estimate based on fit of measured values from other modules.

Table 2. Summary of Swelling and Blister-Threshold Temperature Data for High-Density Dispersion Fuels (From PIE of Miniature Fuel Plates).

Fuel Type	Fabricator*	Density Range, Mg/m^3 Low	Density Range, Mg/m^3 High	Enrichment	No. of Plates	Fission Density Range, $10^{27}/m^3$ Low	Fission Density Range, $10^{27}/m^3$ High	Swelling Range, % $\Delta V/V_m$ Low	Swelling Range, % $\Delta V/V_m$ High	Blister-Threshold Temperature, °C
UAl_x	C	1.47		45.1	1	1.3		4.3		-
UAl_x	E	1.88	1.95	40.2	4	1.1	1.5	-0.3	0.6	550 - 565
UAl_x	E,N	2.13	2.31	39.8 - 40.2	6	1.3	1.8	1.9	3.4	550 - 561
UAl_x	E	1.88	1.99	19.9	3	0.8	0.9	0.7	2.9	>550
UAl_x	E,N,C	2.14	2.33	19.9 - 27.3	6	1.0	1.1	-1.7	4.0	>550
UAl_x	C	2.48	2.52	20.2	2	1.1		-3.9	-3.3	>550
UAl_2	C	2.99	3.09	19.8	5	1.3		-7.2	-2.7	475 - 500
U_3O_8	O,N	2.40	2.46	39.7 - 45.0	3	1.7	2.0	2.9	9.7	470
U_3O_8	O	2.77		45.0	1	2.3		P+		
U_3O_8	O	3.10		45.0	3	2.1	2.5	11.2	P+	
U_3O_8	O,N,C	2.30	2.48	19.5 - 27.3	9	0.8	1.1	0.0	2.0	490 - >550
U_3O_8	O	2.76	2.79	19.5	11	0.9	1.2	-0.7	1.3	>550
U_3O_8	O,N,C	2.91	3.13	19.5 - 27.3	16	1.0	1.6	-3.8	12.6	478 - 550
U_3O_8	C	3.49	3.58	19.7	3	1.5		-5.4	-3.4	450
U_3Si_2	A	3.72	3.76	19.9	4	1.6		3.7	4.3	530
U_3Si_2	A	3.72	3.75	19.9	2**	1.8		6.8	7.1	-
U_3Si	A	4.79	4.83	19.9	5	0.7		0.1	0.8	510
U_3Si	A	4.77	4.81	19.9	6	2.0	2.2	8.9	11.8	500
U_3Si	C	5.18	5.20	19.8	2	2.2		10.3	11.4	500
U_3Si	A	5.65	5.72	19.9	4	1.6		0.7	7.6	525
U_3Si	C	6.10		19.8	1	2.6		20.4		-

*Fabricators: ANL, EG&G Idaho, ORNL, NUKEM, CNEA.

+Indicates that plates "pillowed" during irradiation.

**2 of 4 plates listed in preceding line reirradiated to higher burnup.

Table 3. Test Matrix for the Second Series of Miniplate Irradiations

Fuel Type	Density, Mg U/m^3	Enrichment*	Number of Plates	Under Irrad. in Module 17	18	22
UAl_2	3.0	M	2			
U_3Si_2	4.4	D	1			
	5.0 - 5.7	L	11	3	8	
	3.9 - 5.1	M	4			1
	1.7	H	2			1
U_3Si	5.7	D	1			
	6.2 - 7.2	L	18	2	4	8
	4.5 - 6.4	M	5	5		
	2.0	H	2	2		
U_3SiCu	6.0 - 7.0	L	6			
	4.0	M	2			
$U_3Si_{1.5}$	5.3 - 6.3	L	6			
	4.0	M	2			
U_6Fe	6.7	D	1			
	7.0 - 8.0	L	3			2

*D:0.2%, L:19.4-19.8%, M:40.1-44.8%, H:92.6-93.0%

Table 4. Status of Second Series of Miniplate Irradiations (September 28, 1984)

Module	Est. Burnup, %	Fuel Type	Est. Max. Fiss. Dens. for Enrichment, $10^{27}/m^3$ L	M	H
17	40	U_3Si_2	0.9		
		U_3Si	1.3	2.3	1.6
18	50	U_3Si_2	1.2		
		U_3Si	1.3		
19	15	U_3Si_2		0.5	0.5
		U_3Si	0.5		
		U_6Fe	0.5		

Table 5. Energy Released from the Exothermic Reaction of Uranium Silicide and Aluminum

Fuel Type	Volume Loading, vol%	Reaction Energy, kJ/kg
U_3Si_2	32	349 ± 44
U_3Si_2	45	304 ± 18
U_3Si	32	486 ± 54
U_3Si	45	379 ± 13

Table 6. Status of Full-Sized Fuel Elements Scheduled for Irradiation in the ORR (Start of Cycle 169-G, September 28, 1984)

Element No.[a]	Fuel Type	No. of Plates	Enrichment, %	Present Location	Initial U Dens., Mg/m^3	Initial ^{235}U, g	^{235}U Depletion, %	Irrad. Compl.	PIE In Prog.	PIE Compl.
T291X	U_3O_8	19	45.0	Pool-R[d]	1.7	280	56	10/13/81		X
T292X	U_3O_8	19	45.0	HRLEL[b]	1.7	280	72(70)[c]	4/16/82		X
T293X	U_3O_8	19	45.0	Reproc.	1.7	280	55	10/11/82		e
T294X	U_3O_8	19	45.0	Reproc.	1.7	280	58	6/22/82		e
NLE451	UAl_x	19	44.9	HRLEL	1.7	284	73(75)[c]	10/11/82		X
NLE452	UAl_x	19	44.9	Pool-R	1.7	284	59	6/22/82		X
CLE451	UAl_x	19	44.9	Pool-R	1.7	282	76(71)[c]	11/18/82		X
CLE452	UAl_x	19	44.9	Pool-R	1.7	282	56	4/16/82		X
CLE453	UAl_x	19	44.9	HRLEL	1.7	284	75	9/15/83	X	
NLE201	U_3O_8	13	19.6	C-5	2.3	340	64			
NLE202	U_3O_8	13	19.6	A-8	2.3	340	9			
CLE201	UAl_x	13	19.8	A-2	2.1	312	7			
CLE202	UAl_x	13	19.8	C-6	2.3	336	65			
CLE203	U_3O_8	18	19.7	Pool	3.2	326	74	4/22/84		
CLE204	U_3O_8	18	19.7	HRLEL	3.2	326	57	9/29/83	X	
NSI201	U_3Si_2	19	19.7	HRLEL	4.8	340	49(41)[c]	1/14/83		X
NSI202	U_3Si_2	19	19.7	Pool	4.8	340	82	8/14/84		
CSI201	U_3Si_2	19	19.8	HRLEL	4.8	339	56	10/13/83	X	
CSI202	U_3Si_2	19	19.8	Pool	4.8	339	82	8/14/84		
BSI201	U_3Si_2	19	19.8	Pool	4.8	339	55	4/22/84		
BSI202	U_3Si_2	19	19.8	C-4	4.8	339	76			

[a]First letter in element no. designates fabricator: Babcock & Wilcox (B), CERCA (C), NUKEM (N), or Texas Instruments (T).
[b]High Radiation Level Examination Laboratory (PIE).
[c]Depletion in parentheses based upon preliminary evaluations of measurements.
[d]Awaiting shipment for reprocessing.
[e]No PIE planned.

Table 7. Status of Full-Sized Fuel Elements Scheduled for Irradiation in the European Reactors (October 4, 1984)

Reactor	Element No.	Fabricator	Fuel Type	Enrichment, at.%	Present Location	Initial U Dens., Mg/m^3	Initial ^{235}U, g	^{235}U Depletion, at.%	Remarks
HFR	LC-01-CD	CERCA	UAl_x	19.8	Hot Lab	2.1	330	73	Irrad. completed 4/11/83
HFR	LC-02	CERCA	UAl_x	19.8	Hot Lab	2.1	329	48	Irrad. completed 10/4/82
HFR	LN-01-CD	NUKEM	U_3O_8	19.6	Hot Lab	2.1	328	74	Irrad. completed 2/14/83
HFR	LN-02	NUKEM	U_3O_8	19.6	Hot Lab	2.1	328	45	Irrad. completed 6/7/82
SILOE	SARU001	CERCA	UAl_x	44.8	a	2.2	420	50	Irrad. completed 11/81
SILOE	b	CERCA	U_3Si	19.8	Pool	c	c	>55	Irrad. completed 11/83
SILOE	SDJZ001	CERCA	U_3Si	19.8	Core	6.0	507	0	Irrad. began 10/84
SILOE	b	CERCA	U_3Si_2	19.8	Core	d	d	17	Irrad. began 7/84
SILOE	e	CERCA	U_3Si_2	19.8	e	5.2	~430	-	
R2	BW-004	B&W	U_3Si_2	19.8	Pool	4.8	488	0	In core 6/84 for flux meas.
R2	BW-005	B&W	U_3Si_2	19.8	f	4.8	~490	-	
R2	f	CERCA	U_3Si_2	19.8	f	4.8	~490	-	
R2	f	NUKEM	U_3Si_2	19.8	f	4.8	~490	-	

[a] PIE completed at CEN-Saclay; now at CEN-Grenoble awaiting shipment for reprocessing.

[b] Four plates in special irradiation element.

[c] Plate loadings are 5.5 and 6.0 Mg U/m^3 (20.2 and 22.1 g ^{235}U).

[d] Plate loadings are 2.0, 3.6, 5.2, and 5.3 Mg U/m^3 (7.5, 13.2, 18.7, 19.1 g ^{235}U).

[e] One element; fabrication scheduled during 1984.

[f] One element; fabrication scheduled during 1985.