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PRE- AND POSTIRRADIATION EVALUATION OF FUEL IN CAPSULE HRB-14

by
C. A. YOUNG

**Prepared under
Contract DE-AT03-76ET35300
for the San Francisco Operations Office
Department of Energy**

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ABSTRACT

Capsule HRB-14 was irradiated jointly by Oak Ridge National Laboratory and General Atomic Company (GA). This report covers the pre- and post-irradiation characterization and evaluation of the GA fuel. The experiment was primarily to characterize the irradiation performance of TRISO-coated low-enriched (Th,U)O₂, UC_{0.7}O_{0.5}, and UO₂ particles and TRISO ThO₂ particles. Twenty cured-in-place fuel rods containing the fuel particles were irradiated at 960° to 1130°C. The fluence was 4.5 to 8.3 x 10²⁵ n/m² (E > 29 fJ)_{HTGR}. The fertile burnup was 4.1% to 8.5% fissions per initial metal atom (FIMA); the mixed oxide burnup was 14.5% to 19.3% FIMA; the uranium fissile burnup was 27.9% to 29.5% FIMA.

The following major conclusions were made on capsule HRB-14 fuel irradiation:

1. The fuel rods were friable because the matrix-coating bond was weak.
2. The pressure vessel failure was <0.1% for the TRISO-coated low-enriched (Th,U)O₂ particles irradiated to a burnup of 15% FIMA and for UC_{0.7}O_{0.5} and UO₂ particles irradiated to a burnup of 29.5% FIMA.
3. The outer pyrolytic carbon (OPyC) coating failure was primarily dependent on the total particle diameter of the fissile, fertile, and inert particles; the average OPyC coating failure was 0.8% for particles <820 μm in diameter.
4. The pressure vessel failure of the TRISO ThO₂ particles increased with OPyC coating failure; the pressure vessel failure was zero

for particles $< 820 \mu\text{m}$ in diameter and irradiated to a burnup of 6.3% FIMA.

5. Palladium attack of the SiC coating was observed in all fissile and ThO_2 particles; rare-earth attack was also detected in the $\text{UC}_{0.7}\text{O}_{0.5}$ particles.

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1. INTRODUCTION

1.1. SCOPE

Capsule HRB-14 was irradiated as part of a continuing cooperative effort between General Atomic (GA) and Oak Ridge National Laboratory (ORNL). The experiment was funded by the Department of Energy-sponsored High Temperature Gas Cooled Reactor (HTGR) Generic Technology Program. The capsule space was divided equally between GA and ORNL. In the GA half of the capsule, TRISO-coated (Th,U)O₂, UC_{0.7}O_{0.5}, and UO₂, containing low-enriched* uranium (LEU), and TRISO ThO₂ particles were irradiated at 1250°C design to peak HTGR irradiation conditions. The particles were bonded in cured-in-place fuel rods. The ORNL half of the capsule tested BISO-coated ThO₂ bonded in molded planchets. The instrumented capsule was irradiated in the removable beryllium (RB) facility of the high flux isotope reactor (HFIR) at ORNL for 10 cycles. The capsule was discharged from the reactor on January 4, 1979 and disassembled at ORNL. The GA fuel was initially examined at ORNL, then shipped to GA to complete the postirradiation examination.

This report describes the pre- and postirradiation characterization and evaluation of the GA fuel.

1.2. OBJECTIVES

The objectives for irradiating capsule HRB-14 are as follows:

1. Verify adequate performance of TRISO ThO₂ particles in fuel rods irradiated to high burnups.

* ~19.5% enriched.

2. Demonstrate that matrix-outer pyrolytic carbon (OPyC) coating interaction can be eliminated by minimizing OPyC porosity in the TRISO ThO_2 particles in cured-in-place fuel rods.
3. Demonstrate successful performance of TRISO LEU $(\text{Th,U})\text{O}_2$ and dense $\text{UC}_{0.7}\text{O}_{0.5}$ particles in fuel rods as a function of neutron exposure and burnup.
4. Verify performance of TRISO LEU $(\text{Th,U})\text{O}_2$ and ThO_2 fuel used in Fort St. Vrain (FSV) fuel test elements (FTEs).
5. Provide TRISO ThO_2 and LEU fuel rods irradiated to peak HTGR burnups for core-heatup-simulation testing.
6. Characterize the dimensional change behavior of cured-in-place fuel rods containing all TRISO-coated particles as a function of fluence and shim content.

2. JUSTIFICATION

The fertile particles for capsule HRB-14 were TRISO-coated ThO_2 . In development work over the past several years, oxide fuels have demonstrated several benefits over carbide fuels. As a result, ThO_2 has replaced ThC_2 as the HTGR reference fertile fuel. The TRISO coating is more retentive of fission products than BISO coatings; consequently, TRISO ThO_2 particles are an attractive alternate to the TRISO ThC_2 fuel in the FSV HTGR. The TRISO ThO_2 batch tested in FSV as the driver fuel for reload segment 1 of the FTEs (Ref. 2-1) was also irradiated in HRB-14 to verify adequate performance.

Capsule HRB-14 tested the OPyC coating properties of the fertile particles. The surface-connected porosity of the OPyC coating of the TRISO ThO_2 particles was varied to demonstrate that matrix-coating interaction can be eliminated, as discussed later in this section. The density and coating rate ranges were to help support the HTGR specification limits.

Many of the TRISO ThO_2 batches for capsule HRB-14 were first tested in capsule HT-34 (Ref. 2-2). This study is being continued in a HRB because

1. A more realistic test is possible under less accelerated irradiation than in the HT capsule.
2. Temperature can be monitored and controlled in the HRB to reduce temperature uncertainty.
3. With its higher fuel loadings and greater test volume, the HRB can test a larger number of particles (improving the statistical confidence of the results) and can test fuel rods rather than unbonded particles.

LEU fissile fuel was selected for capsule HRB-14, because the U.S. recognizes the risks associated with nuclear materials diversion and weapons proliferation. The LEU-thorium HTGR fuel cycle is being developed to meet the special nonproliferation requirements. Fortunately, high-enriched uranium (HEU) fuel development work was largely applicable to LEU fuel. Selecting the fissile kernel was the most important early decision required in the LEU fuel development program, and capsule HRB-14 was the first to irradiate this fuel. An extensive investigation (Ref. 2-3), performed jointly by GA, ORNL, and the Federal Republic of Germany, revealed that a number of performance features can limit LEU fuel more than HEU fuel. These features include (1) kernel migration of oxide particle, (2) plutonium release from failed particles, (3) palladium attack of the SiC coating, and (4) silver release from fuel particles. Primarily because of fuel hydrolysis concern, the LEU system tends to favor oxide-based kernels over carbides.

(Th,U)O₂ and UC_xO_y kernels were selected for the near-term development program to license LEU fuel for HTGRs. A significant amount of data, including data from capsules P13R and P13S (Ref. 2-4), was available on (Th,U)O₂ kernels having a range of thorium to uranium (Th/U) ratios, and the (Th,U)O₂ kernel could be qualified with a minimum incremental effort. A Th/U ratio of 1.0 was selected initially because this fuel type had the highest amount of uranium in the kernel of those fuels with significant irradiation data. Consequently, this fuel was tested in FSV FTE-2, -4, and -6 (Ref. 2-1), and HRB-14 was to verify adequate irradiation performance of the same TRISO (Th,U)O₂ particles for the FTEs.

The (Th,U)O₂ fuel design is not, however, desirable in the long term because of its unfavorable U-238 resonance absorption cross section and its relatively high rate of amoeba migration. Therefore, dense UC_xO_y kernels were selected as a second candidate. The irradiation behavior of these kernels was less well known; however, based on the known behavior of weak-acid resin (WAR) UC_xO_y kernels (Ref. 2-5), good performance was expected. Since no data existed on the effect of the oxygen/uranium (O/U) ratio on

performance of dense UC_xO_y kernels, an O/U ratio of 1.0, which was half way between a pure oxide and a pure carbide, was selected as the design ratio. The actual O/U ratio was 0.5 for the HRB-14 particle batches, because fabricating an O/U ratio of 1.0 was difficult. ORNL (Ref. 2-5) had reported acceptable behavior of WAR kernels with a 1.0 ratio. The presence of a carbide diminishes the release of oxygen, reducing the amoeba migration, but sufficient oxygen is present to maintain the plutonium as the oxide. The greater degree of lumping of the U-238 in UC_xO_y relative to $(Th,U)O_2$ results in favorable neutronic characteristics.

Kernels of UO_2 were not chosen for the near-term development program, because UO_2 fuels exhibit high amoeba migration rates (Ref. 2-6). However, one sample was irradiated in HRB-14 as a migration standard to evaluate the migration of $(Th,U)O_2$ and UC_xO_y kernels. The migration standard reduced the importance of uncertainties of particle temperatures and thermal gradients.

Capsule HRB-14 tested cured-in-place fuel rods as the candidate rod type for the large high-temperature gas-cooled reactor (LHTGR). The experiment particularly evaluated matrix-coating interaction and fuel rod dimensional changes. Matrix-coating interaction can cause the OPyC coating to fail and should be prevented. Irradiation results (Ref. 2-7) on TRISO-coated particles in capsule P13T fuel rods showed that the amount of surface-connected porosity in the OPyC coating influenced the degree of matrix-coating interaction. The HRB-14 experiment was supposed to irradiate OPyC coatings having a range of microporosity to evaluate how porosity affected this interaction. The dimensional change data on the fuel rods containing all TRISO particles were to verify the fuel-rod core-design model (Ref. 2-8). The effect of shim on the dimensional change was studied by testing rods with and without shim.

Another major experiment objective was to provide selected fuel rods for postirradiation core-heatup-simulation testing. This work was to demonstrate that the fuel performance model used in reactor safety analyses of unrestricted core heatup events conservatively predicts particle behavior.

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3. UNIRRADIATED COATED PARTICLES

3.1. DESCRIPTION

Five fissile batches were tested in capsule HRB-14. The kernels were LEU, high-density, 350- μm (Th,U) O_2 , 340- μm $\text{UC}_{0.7}\text{O}_{0.5}$, or 300- μm UO_2 . All five batches had similar coatings, except that the buffer thickness varied to accommodate the different amounts of gases generated during irradiation.

Two (Th,U) O_2 particle batches were tested. Both batches were similar, except that one batch (6155-05-010) had an 86- μm buffer while the other (6155-05-020) had a 110- μm buffer. The thicker buffer batch was irradiated at the higher burnup positions. Batch 6155-05-010 is being tested in FSV FTE-2, -4, and -6 (Ref. 3-1).

Two $\text{UC}_{0.7}\text{O}_{0.5}$ particle batches were tested. Both batches were coated to the same design. Two batches were irradiated rather than one, since batch-to-batch variation may cause differences in irradiation performance. Capsule HRB-14 was the first GA test to irradiate dense UC_xO_y kernels. The O/U ratio was 0.5 rather than 1.0, because an O/U ratio of 1.0 could not be fabricated during early UC_xO_y kernel development.

One TRISO UO_2 particle batch was used as a standard to compare to the TRISO $\text{UC}_{0.7}\text{O}_{0.5}$ and (Th,U) O_2 particle batches.

Eight TRISO ThO_2 particle batches, including five used in capsule HT-34 (Ref. 3-2), were designed to evaluate the irradiation behavior of the OPyC coating. All batches consisted of 450- μm -diam kernels and were coated in the 240-mm pilot plant coater. The primary independent OPyC variables were density and coating rate, as shown in Fig. 3-1.* The liquid gradient

* All figures and tables appear at the end of each section.

densities ranged from 1.80 to 1.95 Mg/m³ and the coating rate from 5 to 8 $\mu\text{m}/\text{min}$. Figure 3-1 also illustrates that the mercury intrusion, or surface-connected porosity, increased with increased coating rate. Mercury intrusion values of ~ 30 to 60 $\mu\text{l}/\text{g}$ OPyC coating were tested to evaluate the effect of OPyC porosity on matrix-coating interaction. Present data (Ref. 3-3) indicate that coatings with >35 $\mu\text{l}/\text{g}$ OPyC may interact more with the matrix, causing higher OPyC coating failure. Since anisotropy is dependent on the coating rate, the Bacon anisotropy factor (Baf_0) values also varied. The 55- μm -buffer particles had a total particle diameter of ~ 800 μm and were representative of the candidate design for the FSV HTGR (Ref. 3-4). This design is also a candidate for an LHTGR (Ref. 3-5). The four thicker buffer batches, to accommodate the larger quantity of fission gas, were placed at the very high burnup positions. These particles had a total particle diameter of ~ 875 μm . All particles were designed to exhibit low pressure vessel failure, assuming that the OPyC coating remained intact. If matrix-coating interaction caused higher OPyC failure in the high porosity batches, increased pressure vessel failure was expected.

Three TRISO-coated inert particle batches were large-diameter particles (~ 1040 μm). The OPyC coating was doped with silicon in two of the batches. OPyC coating failure tends to increase for large-diameter particles (Ref. 3-6). The irradiation performance of the pure OPyC was to be compared to the silicon-doped OPyC coatings.

3.2. FABRICATION

All kernel and coating batches were manufactured in accordance with Ref. 3-7 specifications. Table 3-1 gives the fabrication conditions of the coated particle batches.

The fissile particles contained UO_2 , $\text{UC}_{0.7}\text{O}_{0.5}$, or $(\text{Th},\text{U})\text{O}_2$ kernels made by a gel-supported precipitate process in a GA research and development laboratory. The coatings were deposited in a GA 35-mm i.d. laboratory

coater. The OPyC coating diluent gas was helium. The fissile batches were coated in the laboratory coater rather than the pilot plant coater, because the laboratory kernel process was not set up to make large kernel quantities.

The kernels and coatings of the fertile particles were made in the HTGR pilot plant equipment. A sol-gel process formed the ThO_2 kernels. The coatings were deposited in the 240-mm i.d. dry coater. The coater was loaded with ~17 kg of kernels, and the buffer and inner pyrolytic carbon (IPyC) coatings were deposited. Each batch was then divided in half, and the SiC and OPyC coatings were deposited. The OPyC coating diluent gas was H_2 .

The TRISO inert particles were made from BISO inert particles manufactured at ORNL (batch OR1930-31-32). The GA coatings were made in the 35-mm coater. A second pyrocarbon coating was deposited on the OPyC coating of the BISO particle to make a larger substrate. The SiC and the OPyC coatings were then deposited. One batch had a pure OPyC coating. The two other batches had a silicon-doped OPyC coating (~30 wt % silicon), which was deposited using a mixture of helium, mixed-coating gas, and methyl-trichlorosilane.

3.3. PROPERTIES

All kernel and coated particle batches were extensively characterized prior to irradiation; Table 3-2 summarizes the particle batches; Tables 3-3, 3-4, and 3-5 list the detailed data. Table 3-6 gives the properties which did not meet the design specifications (Ref. 3-7). Figures 3-2 through 3-17 present the microstructures of each particle batch.

The crush strengths of the fissile and fertile particles were measured (see Table 3-5). Each particle was placed between two flat steel plates, and a compressive force was applied. The force was increased until the

particle broke. The maximum force was recorded. A minimum of 50 particles was measured for each batch. The crush strengths of the five fissile batches ranged from 20.7 N (4.6 lb) to 28.7 N (6.4 lb). The two $UC_{0.7}O_{0.5}$ batches were significantly stronger than the three oxide batches. Crush strengths of 19.0 N (4.2 lb) to 31.0 N (7.0 lb) were measured on the TRISO ThO_2 batches. The thick-buffer batches (larger total diameter) were obviously weaker than the 800- μ m particles. The weaker fissile and fertile particle batches tended to have a higher fraction of defective SiC coatings.

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Fig. 3-1. Design test matrix for OPyC coating of TRISO fissile and ThO₂ particles for capsule HRB-14

MP78008-10 (a)

MP78008-11 (b)

MP78008-1 (c)

MP78008-2 (d)

Fig. 3-2. Representative photomicrographs of TRISO coated UO_2 particle batch 6152-01-010 for capsule HRB-14: (a) and (c) bright field; (b) and (d) polarized light (sheet 1 of 2)

L7907-456

(e)

L7907-458

(f)

L7907-462

(g)

Fig. 3-2. Representative photomicrographs of TRISO coated UO_2 particle batch 6152-01-010 for capsule HRB-14: (e), (f), and (g) other examples of kernel extrusion (sheet 2 of 2)

MP77027-7 (a)

MP77027-8 (b)

MP77027-1 (c)

MP77027-2 (d)

Fig. 3-3. Representative photomicrographs of TRISO coated (Th,U)O₂ particle batch 6155-05-010 for capsule HRB-14: (a) and (c) bright field; (b) and (d) polarized light

MP77026-7

(a)

MP77026-8

(b)

MP77026-1

(c)

MP77026-2

(d)

Fig. 3-4. Representative photomicrographs of TRISO coated (Th,U)O₂ particle batch 6155-05-020 for capsule HRB-14: (a) and (c) bright field; (b) and (d) polarized light

MP78009-7

(a)

MP78009-8

(b)

MP78009-1

(c)

MP78009-2

(d)

Fig. 3-5. Representative photomicrographs of TRISO coated $UC_{0.7}O_{0.5}$ particle batch 6157-08-010 for capsule HRB-14: (a) and (c) bright field; (b) and (d) polarized light

MP78007-11

(a)

MP78007-12

(b)

MP78007-2

(c)

MP78007-3

(d)

Fig. 3-6. Representative photomicrographs of TRISO coated $UC_{0.7}O_{0.6}$ particle batch 6157-08-020 for capsule HRB-14: (a) and (c) bright field; (b) and (d) polarized light

MP77024-4

(a)

MP77024-5

(b)

MP77024-1

(c)

MP77024-2

(d)

Fig. 3-7. Representative photomicrographs of TRISO coated ThO_2 particle batch 6252-12 COMP for capsule HRB-14: (a) and (c) bright field; (b) and (d) polarized light

MP77007-7

(a)

MP77007-8

(b)

MP77007-1

(c)

MP77007-2

(d)

Fig. 3-8. Representative photomicrographs of TRISO coated ThO_2 particle batch 6252-13-010 for capsule HRB-14: (a) and (c) bright field; (b) and (d) polarized light

MP77008-7

(a)

MP77008-8

(b)

MP77008-1

(c)

MP7708-2

(d)

Fig. 3-9. Representative photomicrographs of TRISO coated ThO_2 particle batch 6252-14-010 for capsule HRB-14: (a) and (c) bright field; (b) and (d) polarized light

MP77010-8

(a)

MP77010-7

(b)

MP77010-1

(c)

MP77010-2

(d)

Fig. 3-10. Representative photomicrographs of TRISO coated ThO_2 particle batch 6252-16-010 for capsule HRB-14: (a) and (c) bright field; (b) and (d) polarized light

MP77012-7

(a)

MP77012-8

(b)

MP77012-1

(c)

MP77012-2

(d)

Fig. 3-11. Representative photomicrographs of TRISO coated ThO_2 particle batch 6252-17-010 for capsule HRB-14: (a) and (c) bright field; (b) and (d) polarized light

MP77028-7

(a)

MP77028-8

(b)

MP77028-1

(c)

MP77028-2

(d)

Fig. 3-12. Representative photomicrographs of TRISO coated ThO_2 particle batch 6252-18-010 for capsule HRB-14: (a) and (c) bright field; (b) and (d) polarized light

MP77011-7

(a)

MP77022-8

(b)

MP77011-1

(c)

MP77011-2

(d)

Fig. 3-13. Representative photomicrographs of TRISO coated ThO_2 particle batch 6252-19-010 for capsule HRB-14: (a) and (c) bright field; (b) and (d) polarized light

MP77029-7

(a)

MP77029-8

(b)

MP77029-1

(c)

MP77029-2

(d)

Fig. 3-14. Representative photomicrographs of TRISO coated ThO_2 particle batch 6252-20-010 for capsule HRB-14: (a) and (c) bright field; (b) and (d) polarized light

MP77030-7

(a)

MP77030-8

(b)

MP77030-1

(c)

MP77030-2

(d)

Fig. 3-15. Representative photomicrographs of TRISO coated inert particle batch 6351-05-010 for capsule HRB-14: (a) and (c) bright field; (b) and (d) polarized light

MP77031-7

(a)

MP77031-8

(b)

MP77031-5

(c)

MP77031-6

(d)

Fig. 3-16. Representative photomicrographs of TRISO coated inert particle batch 6351-05-020 for capsule HRB-14: (a) and (c) bright field; (b) and (d) polarized light

MP77032-7

(a)

MP77032-8

(b)

MP77032-1

(c)

MP77032-2

(d)

Fig. 3-17. Representative photomicrographs of TRISO coated inert particle batch 6351-05-030 for capsule HRB-14: (a) and (c) bright field; (b) and (d) polarized light

TABLE 3-1
FABRICATION CONDITIONS OF TRISO PARTICLE BATCHES FOR CAPSULE HRB-14

Parent Batch Data Retrieval No.	Buffer ^(a)		IPyC ^(b)					SiC ^(c)			OPyC ^(b)							
	Coater Charge (kg)	Coating Rate (μm/min)	Coating Rate (μm/min)			Control Temp (°C)	Diluent/ Levitating Gas	Coater Charge (kg)	Coating Rate (μm/min)	Control Temp (°C)	Coater Charge (kg)	Coating Rate (μm/min)			Control Temp (°C)	Coating Gas Volume Fraction	Diluent/ Levitating Gas	Coater Diam (mm)
			Mean	Min	Max							Mean	Min	Max				
Fissile Particle																		
5152-01-010	0.040	30.50	2.73	2.35	3.11	1300	He	0.059	0.14	1700	0.081	3.80	2.83	4.78	1305	0.24	He	35
5155-05-010	0.056	28.67	3.47	2.66	4.28	1316	He	0.163	0.17	1700	0.108	4.89	3.83	5.95	1315	0.32	He	35
6155-05-020	0.103	27.50	3.14	2.45	3.85	1315	He	0.179	0.15	1700	0.120	4.40	3.27	5.53	1315	0.32	He	35
6157-08-010	0.050	28.13	2.47	1.93	3.01	1300	He	0.038	0.21	1700	0.050	3.64	2.95	4.33	1300	0.12	He	35
6157-08-020	0.050	29.03	2.71	2.05	3.37	1300	He	0.038	0.24	1700	0.050	3.60	2.82	4.39	1300	0.12	He	35
Fertile Particle																		
6252-12 COMP ^(d)	17.0	9.25	4.08	3.15	4.99	1360	H ₂ /Ar	~10	0.32	1650	~13	5.33	4.00	6.66	1380	0.37	H ₂ /Ar	240
6252-13-C1C	17.0	9.17	4.10	3.08	5.12	1350	H ₂ /Ar	10.5	0.32	1650	13.6	8.62	6.97	10.27	1400	0.46	H ₂ /Ar	240
6252-14-C1C	17.0	9.54	4.00	2.92	5.08	1360	H ₂ /Ar	10.7	0.31	1650	13.3	8.28	6.53	10.02	1295	0.50	H ₂ /Ar	240
6252-16-C1C	17.0	9.67	4.24	3.22	5.25	1360	H ₂ /Ar	10.7	0.33	1650	13.5	5.56	4.33	6.79	1280	0.42	H ₂ /Ar	240
6252-17-010	17.0	12.86	4.17	3.13	5.21	1330	H ₂ /Ar	22.6	0.23	1650	14.3	5.44	3.91	6.98	1280	0.42	H ₂ /Ar	240
6252-18-010	17.0	12.86	4.17	3.13	5.21	1300	H ₂ /Ar	22.6	0.24	1650	12.8	5.00	3.59	6.41	1405	0.36	H ₂ /Ar	240
6252-19-C1C	17.0	12.86	4.17	3.05	5.29	1330	H ₂ /Ar	22.6	0.23	1650	12.0	7.23	5.46	9.00	1390	0.44	H ₂ /Ar	240
6252-20-C1C	17.0	12.29	4.17	3.13	5.21	1330	H ₂ /Ar	22.6	0.24	1650	14.3	8.57	6.55	10.59	1275	0.53	H ₂ /Ar	240
Inert Particle																		
6351-05-010 ^(e)	0.050	12.88	--	--	--	--	--	0.142	0.13	1700	0.062	4.00	3.21	4.79	1285	0.21	He	35 ^(f)
6351-05-020 ^(e,g)	0.050	12.88	--	--	--	--	--	0.142	0.13	1700	0.062	1.82	1.26	2.38	1315	0.27	He	35
6351-05-030 ^(e,g)	0.050	12.88	--	--	--	--	--	0.142	0.13	1700	0.105	2.19	1.82	2.54	1315	0.27	He	35

(a) Coating gases: deposition gas = C₂H₂; diluent and levitating gas = helium or argon.

(b) Deposition gases: C₂H₂/C₃H₆ (except 6351-05-020 and -030).

(c) Coating gases: deposition gas = CH₃SiCl₃; diluent and levitating gas = H₂.

(d) Composite of 12 batches; values are weighted averages.

(e) Starting substrate was BISO batch 6641-00-020 made at ORNL (ORNL No. OR1930-31-22); GA coated part of IPyC, then the SiC and OPyC coatings.

(f) For coatings deposited at GA.

(g) Deposition gases: C₂H₂/C₃H₆ + CH₃SiCl₃.

TABLE 3-2
GENERAL DESCRIPTION OF TRISO COATED PARTICLE BATCHES FOR CAPSULE HRB-14

Batch No.	Kernel			Coatings										Total Coated Particle				
				Buffer		IPyC		SiC		OPyC								
	Composition	Diameter (μm)	Density (Mg/m ³)	Thickness (μm) ^(a)	Density (Mg/m ³) ^(b)	Thickness (μm)	Density (Mg/m ³) ^(c)	Thickness (μm)	Density (Mg/m ³) ^(c)	Thickness (μm)	Density (Mg/m ³) ^(c)	Anisotropy ^(d) (BAF ₀)	Micro-porosity ^(e) (ml/kg OPyC Coating)	Coating Rate (μm/min)	Diameter (μm)	Defective SiC Coating ^(f) (kg heavy metal/kg heavy metal)	Exposed Heavy Metal ^(g) (kg heavy metal/kg heavy metal)	Fission Gas Release ^(h) (R/B)
Fertile ⁽¹⁾																		
6252-12 COMF	ThO ₂	452	9.88	53	1.11	33	1.85	38	3.22	44	1.85	1.037	24	5.3	786	1.6 × 10 ⁻⁵	1.0 × 10 ⁻⁶	5.3 × 10 ⁻⁶
6252-13-010	ThO ₂	454	9.88	55	1.13	32	1.86	42	3.22	50	1.79	1.030	57	8.6	811	4.3 × 10 ⁻⁴	4.9 × 10 ⁻⁵	1.2 × 10 ⁻⁵
6252-14-010	ThO ₂	451	9.90	62	1.10	32	1.84	37	3.22	48	1.57	1.030	49	8.3	808	2.4 × 10 ⁻³	8.3 × 10 ⁻⁵	4.2 × 10 ⁻⁵
6252-16-010	ThO ₂	455	9.90	58	1.07	36	1.85	39	3.21	50	1.56	1.040	23	6.0	816	8.9 × 10 ⁻⁵	9.8 × 10 ⁻⁶	2.5 × 10 ⁻⁶
6252-17-010	ThO ₂	455	9.78	90	0.93	40	1.79	36	3.22	49	1.95	1.050	24	5.4	882	1.3 × 10 ⁻³	2.1 × 10 ⁻⁵	2.1 × 10 ⁻⁵
6252-18-010	ThO ₂	453	9.78	86	0.93	40	1.79	37	3.22	45	1.83	1.035	28	5.0	868	1.2 × 10 ⁻³	4.6 × 10 ⁻⁶	5.6 × 10 ⁻⁵
6252-19-010	ThO ₂	457	9.78	81	0.93	40	1.79	36	3.21	47	1.92	1.034	41	7.2	870	1.7 × 10 ⁻³	1.4 × 10 ⁻⁴	5.1 × 10 ⁻⁶
6252-20-010	ThO ₂	456	9.78	86	0.93	40	1.79	37	3.21	48	1.98	1.040	51	9.0	874	2.9 × 10 ⁻³	2.5 × 10 ⁻⁴	7.3 × 10 ⁻⁵
Fissile ⁽¹⁾																		
6152-01-010	UO ₂ ^(k)	299	10.55	122	1.15	41	1.91	32	3.21	40	1.87	1.032	21	3.8	769	1.2 × 10 ⁻⁴	1.3 × 10 ⁻³	2.5 × 10 ⁻⁷
6155-05-010	(Th,U)O ₂ ^(k)	357	10.40	86	1.09	34	1.87	36	3.21	46	1.87	1.032	17	4.9	760	1.3 × 10 ⁻⁴	4.8 × 10 ⁻⁸	8.0 × 10 ⁻⁷
6155-05-020	(Th,U)O ₂ ^(k)	360	10.40	110	1.09	32	1.89	36	3.22	48	1.85	1.035	22	4.4	813	1.0 × 10 ⁻⁴	1.7 × 10 ⁻⁶	1.1 × 10 ⁻⁶
6157-08-010	UCO ₂ .71O _{0.56} ^(k)	354	11.91	108	1.20	37	1.88	36	3.21	48	1.93	1.026	13	3.6	810	3.3 × 10 ⁻⁶	1.1 × 10 ⁻⁶	5.9 × 10 ⁻⁸
6157-08-020	UCO ₂ .69O _{0.51} ^(k)	353	12.03	90	1.15	35	1.87	40	3.21	49	1.91	1.029	13	3.6	786	7.0 × 10 ⁻⁷	7.0 × 10 ⁻⁷	6.1 × 10 ⁻⁷
Inert ⁽¹⁾																		
6331-05-010	Carbon	ND ⁽¹⁾	4.13	ND	ND	ND	ND	34	3.17	44	1.89	1.024	5	4.0	1061	ND	ND	ND
6331-05-020 ^(a)	Carbon	ND	3.10	ND	ND	ND	ND	34	ND	40	ND	ND	14	1.8	1037	ND	ND	ND
6331-05-030 ^(a)	Carbon	ND	1.49	ND	ND	ND	ND	36	3.17	23	ND	ND	11	2.2	1003	ND	ND	ND

(a) Measured after SiC coating was deposited.

(b) Determined by mathematical calculation.

(c) Measured by liquid gradient technique.

(d) Measured using the Seibersdorf optical unit at GA.

(e) Determined by the amount of mercury which penetrates the OPyC coating 1.7 to 68.9 MPa (2500 to 10,000 psi).

(f) Measured by burn-leach technique.

(g) Measured by a liquid-leach technique.

(h) Release rate/birth rate for Kr-85m at 1100°C.

(1) Coated in 240-mm coater.

(j) Coated in 35-mm coaters.

(k) Uranium is ~19.5% enriched.

(l) ND = not determined.

(m) OPyC coating is doped with 30 wt % silicon.

TABLE 3-3
KERNEL PROPERTIES OF COATED PARTICLES FOR CAPSULE HRB-14

Coated Particle Data Retrieval No.	Kernel Batch No.	Composition	Uranium Enrichment U-235 (wt %)	Diameter(a) (μm)		Density (Mg/m ³)	Oxygen (wt %)	Carbon (wt %)	Impurities (wt ppm)				Chemical Composition			
				Mean	Standard Deviation				Impurities (wt ppm)				U (wt %)	Th (wt %)	Q/U Atomic Ratio	C/U Atomic Ratio
									B	Fe	Cr	Ni				
Fissile Kernels																
6152-01-010	4122-01-010	UO ₂	19.61	299	8.11	10.55	N/A	58 ppm	N/A	52	11.45	15.7	87.70	N/A	N/A	N/A
6155-05-010	4152-02-010	(Th,U)O ₂	19.66	357	9.90	10.40	N/A	20 ppm	N/A	23	6.35	28.25	44.73	43.93	N/A	N/A
6155-05-020	4152-02-010	(Th,U)O ₂	19.66	360	10.07	10.40	N/A	20 ppm	N/A	23	6.35	28.25	44.73	43.93	N/A	N/A
6157-03-010	4192-02-020	UC _{0.71} O _{0.54}	19.18	354	15.04	11.91	3.40	3.36	N/A	74	8	2	93.23	N/A	0.54	0.71
6157-03-020	4192-02-010	UC _{0.69} O _{0.51}	19.19	353	15.58	12.03	3.21	3.27	N/A	64	8	10	93.16	N/A	0.51	0.69
Fertile Kernels																
6252-12 COMP	90.1-120/ COMP 88 ^(b)	ThO ₂	N/A ^(c)	452	8.15	9.88	N/A	N/A	N/A	55	16.1	40.1	N/A	87.53	N/A	N/A
6252-13-010	4222-09-03C	ThO ₂	N/A ^(c)	454	8.33	9.88	N/A	N/A	N/A	64	16.0	42.4	N/A	87.07	N/A	N/A
6252-14-010	4222-09-04C	ThO ₂	N/A ^(c)	451	9.12	9.90	N/A	N/A	N/A	55	16.1	40.1	N/A	87.53	N/A	N/A
6252-15-010	4222-09-04C	ThO ₂	N/A ^(c)	455	8.43	9.90	N/A	N/A	N/A	55	16.1	40.1	N/A	87.53	N/A	N/A
6252-17-010	4222-09-02C	ThO ₂	N/A ^(c)	455	8.93	9.78	N/A	N/A	N/A	53	12.8	40.2	N/A	87.13	N/A	N/A
6252-13-010	4222-09-02C	ThO ₂	N/A ^(c)	453	8.75	9.78	N/A	N/A	N/A	53	12.8	40.2	N/A	87.13	N/A	N/A
6252-19-010	4222-09-02C	ThO ₂	N/A ^(c)	475	9.16	9.78	N/A	N/A	N/A	53	12.8	40.2	N/A	87.13	N/A	N/A
6252-23-010	4222-09-02C	ThO ₂	N/A ^(c)	456	8.6	9.78	N/A	N/A	N/A	53	12.8	40.2	N/A	87.13	N/A	N/A
Inert Kernels																
6351-05-010	(d)	(d)	N/A	N/A	N/A	4.13	N/A	80.63	N/A	40	N/A	N/A	N/A	N/A	N/A	N/A
6351-05-020	(d)	(d)	N/A	N/A	N/A	3.10	N/A	77.90	N/A	21	N/A	N/A	N/A	N/A	N/A	N/A
6351-05-030	(d)	(d)	N/A	N/A	N/A	1.49	N/A	77.53	N/A	40	N/A	N/A	N/A	N/A	N/A	N/A

(a) Measured by contact X-radiography on ~200 particles.

(b) Composite of two kernel batches.

(c) N/A = not applicable or data not available.

(d) Kernels made at ORNL.

TABLE 3-4
COATING PROPERTIES OF TRISO-COATED PARTICLE BATCHES FOR CAPSULE HRB-14

Parent Batch Data Retrieval No.	Kernel Composition	Buffer			IPyC						SiC			OPyC								
		Thickness(a,b) (μm)		Density (Mg/m^3)	Thickness(b,c) (μm)		Density(d) (Mg/m^3)		BAF _o (e)		Thickness(b) (μm)		Density(d) (Mg/m^3)	Thickness(b) (μm)		Density(d) Mg/m^3		Micro- porosity(f) (ml/kg OPyC)	Oriented Porosity (%)	BAF _o (e)		
		Mean	Standard Deviation		Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation		Mean	Standard Deviation	Liquid Gradient	Bulk			Mean	Standard Deviation	
Fissile Particle																						
6152-01-010	UO ₂	122	20.00	1.15	41	3.07	1.91	4.66×10^{-3}	1.045	0.63×10^{-2}	32	5.55	3.21	40	5.53	1.87	5.08×10^{-3}	1.75	20.78	0	1.032	4.15×10^{-3}
6155-05-010	(Th,U)O ₂	86	13.47	1.09	34	4.27	1.87	6.12×10^{-3}	1.046	0.64×10^{-2}	36	4.20	3.21	46	5.41	1.87	4.08×10^{-3}	1.88	17.18	0	1.032	0.45×10^{-2}
6155-05-020	(Th,U)O ₂	110	12.98	1.09	32	3.89	1.89	1.63×10^{-2}	1.051	0.52×10^{-2}	36	3.69	3.22	48	6.63	1.86	7.0×10^{-3}	1.88	22.38	0	1.035	0.44×10^{-2}
6157-08-010	UC _{0.7} O _{0.5}	108	15.15	1.20	37	4.35	1.88	5.27×10^{-3}	1.036	0.51×10^{-2}	36	4.24	3.21	48	4.92	1.90	1.96×10^{-3}	1.82	13.32	0	1.026	0.48×10^{-2}
6157-08-020	UC _{0.7} O _{0.5}	90	15.41	1.15	35	4.61	1.87	1.0×10^{-2}	1.039	0.50×10^{-2}	40	5.55	3.21	49	5.77	1.91	2.0×10^{-3}	1.62	12.82	0	1.029	0.50×10^{-2}
Fertile Particle																						
6252-12 COMP	ThO ₂	53	11.52	1.11	33(8)	4.37(8)	1.85(8)	$3.0 \times 10^{-2}(8)$	1.062	0.60×10^{-2}	38	2.38	3.22	44	5.67	1.85	3.1×10^{-2}	1.68	23.50	0	1.037	0.41×10^{-2}
6252-13-010	ThO ₂	55	9.67	1.13	32	4.05	1.86	3.23×10^{-2}	1.060	7.20×10^{-3}	42	2.33	3.22	50	4.88	1.79	5.71×10^{-3}	1.61	57.30	0	1.030	2.72×10^{-3}
6252-14-010	ThO ₂	62	12.04	1.10	32	4.41	1.84	2.82×10^{-2}	1.060	0.64×10^{-2}	37	2.48	3.22	48	5.17	1.97	4.56×10^{-3}	1.76	49.43	0	1.040	0.42×10^{-2}
6252-16-010	ThO ₂	58	12.29	1.07	36	4.39	1.85	1.99×10^{-2}	1.060	0.67×10^{-2}	39	2.04	3.21	50	5.65	1.96	2.72×10^{-3}	1.82	23.38	0	1.050	0.49×10^{-2}
6252-17-010	ThO ₂	90	22.32	0.93	40	5.10	1.79	1.37×10^{-2}	1.050	0.77×10^{-2}	36	3.36	3.22	49	7.06	1.95	4.26×10^{-3}	1.80	23.69	0	1.050	0.43×10^{-2}
6252-18-010	ThO ₂	86	19.23	0.93	40	5.10	1.79	1.4×10^{-2}	1.048	0.63×10^{-2}	37	3.50	3.22	45	6.03	1.83	1.28×10^{-2}	1.77	28.47	0	1.035	0.45×10^{-2}
6252-19-010	ThO ₂	84	19.18	0.93	40	5.10	1.79	1.37×10^{-2}	1.052	0.65×10^{-2}	36	3.89	3.21	47	5.45	1.92	8.0×10^{-3}	1.80	40.53	0	1.034	0.44×10^{-2}
6252-20-010	ThO ₂	86	19.17	0.93	40	5.10	1.79	1.37×10^{-2}	1.050	0.56×10^{-2}	37	3.37	3.21	48	5.76	1.98	5.1×10^{-3}	1.74	51.06	2	1.040	0.46×10^{-2}
Inert Particle																						
6351-05-010	Inert	ND(h)	ND	ND	NE	ND	ND	ND	1.038	0.41×10^{-2}	34	5.87	3.17	44	4.71	1.89	5.16×10^{-3}	ND	5.35	ND	1.024	0.52×10^{-2}
6351-05-020 ⁽ⁱ⁾	Inert	ND	ND	ND	NE	ND	ND	ND	ND	ND	34	6.05	ND	40	6.67	1.94	3.01×10^{-3}	ND	13.54	ND	ND	ND
6351-05-030 ⁽ⁱ⁾	Inert	ND	ND	ND	NE	ND	ND	ND	ND	ND	36	4.22	3.17	23	2.00	1.94	2.34×10^{-2}	ND	10.73	ND	ND	ND

(a) Calculated (after SiC coating deposited) by subtracting IPyC thickness from measured buffer-IPyC thickness.

(b) Measured by contact X-radiography on 200 particles.

(c) Measured at BISO stage.

(d) Measured by liquid gradient technique.

(e) Measured with Seibersdorf unit using a 24- μm spot on ~50 particles.

(f) The amount of mercury which penetrates the coatings from 1.7 to 68.9 MPa (250 to 10,000 psi).

(g) Average of 12 batches.

(h) ND = not determined.

(i) OPyC coating doped with ~30 wt % silicon.

TABLE 3-5
PROPERTIES OF TOTAL COATED PARTICLE BATCHES IN HRB-14 CAPSULE

Coated Particle Data Retrieval No.	Kerrel Composition	Total ^(a) Diameter (µm)		Particle ^(b) Density (Mg/m ³)	Chemical Composition							Fraction Defective					Exposed Heavy Metal			Faceting ^(g) (%)	Crush Strength ^(h) (N)	
		Mean	Standard Deviation		U (wt %)	Th (wt %)	Si (wt %)	C (wt %)	O/U Ratio ^(c) (Atomic)	Impurities (wt ppm)		Coated Particle ^(a)		Burn-Leach ^(d) Test (g heavy metal/ g heavy metal)	Burn-Visual Test ^(e)	Leach Test ^(d) (g heavy metal/ g heavy metal)	Fission Gas Release ^(f)	Mean	Standard Deviation			
										Boron	Fe	Buffer and/ or IPyC	OPyC									
Fissile Particle																						
6152-01-010	UO ₂	769	46.35	2.37	21.35	NA ⁽¹⁾	16.33	55.85	NA	1.41	31	0	0	1.2 x 10 ⁻⁴	NA	1.3 x 10 ⁻³	2.5 x 10 ⁻⁷	1.04	20.7	3.0		
6152-05-010	(Th,U)O ₂	760	31.18	2.83	17.05	16.42	15.43	45.59	NA	1.88	<25	1.5 x 10 ⁻³	0	1.3 x 10 ⁻⁴	NA	7.8 x 10 ⁻⁸	8.0 x 10 ⁻⁷	1.08	24.4	3.3		
6152-05-020	(Th,U)O ₂	813	31.75	2.65	15.25	14.77	15.17	45.19	NA	0.63	42	0	0	1.0 x 10 ⁻⁴	NA	1.7 x 10 ⁻⁶	1.1 x 10 ⁻⁶	1.09	21.4	2.9		
6157-08-010	UCO ₂ 7Co ₂ 5	810	33.65	2.63	30.45	NA	15.83	53.55	0.52	0.65	30	0	0	3.3 x 10 ⁻⁶	NA	1.1 x 10 ⁻⁶	5.9 x 10 ⁻⁸	1.05	28.7	5.4		
6157-08-020	UCO ₂ 7Co ₂ 6	766	32.03	2.76	32.86	NA	15.24	50.69	0.58	0.64	15	0	0	7.0 x 10 ⁻⁷	NA	1.1 x 10 ⁻⁶	6.1 x 10 ⁻⁷	1.06	28.3	4.7		
Fertile Particle																						
6252-12 COMP ^(j)	ThO ₂	766	30.60	3.51	NA	47.63	13.12	32.14	NA	1.46	79	0	0	1.6 x 10 ⁻⁵	4.2 x 10 ⁻⁴	1.0 x 10 ⁻⁶	5.3 x 10 ⁻⁶	1.06	26.4	4.4		
6252-13-010	ThO ₂	811	26.77	3.39	NA	45.00	14.85	33.94	NA	1.98	74	0	1.5 x 10 ⁻³	4.3 x 10 ⁻⁴	9.7 x 10 ⁻⁴	4.9 x 10 ⁻⁵	1.2 x 10 ⁻⁵	1.71	31.0	6.2		
6252-14-010	ThO ₂	8C8	28.94	3.37	NA	46.20	13.20	35.25	NA	1.98	60	0	0	2.4 x 10 ⁻³	4.1 x 10 ⁻³	8.3 x 10 ⁻⁵	4.2 x 10 ⁻⁵	0.86	26.2	3.5		
6252-16-010	ThO ₂	816	29.18	3.37	NA	44.78	13.42	36.37	NA	1.98	60	0	0	8.9 x 10 ⁻⁵	3.7 x 10 ⁻⁴	9.8 x 10 ⁻⁶	2.5 x 10 ⁻⁶	0.67	29.0	5.2		
6252-17-010	ThO ₂	8E2	51.62	2.98	NA	41.65	14.16	39.00	NA	2.28	140	1.5 x 10 ⁻³	0	1.3 x 10 ⁻³	1.3 x 10 ⁻³	2.1 x 10 ⁻⁵	2.1 x 10 ⁻⁵	2.67	23.8	5.4		
6252-18-010	ThO ₂	8E8	44.15	3.00	NA	42.63	13.24	36.30	NA	0.63	<25	3.4 x 10 ⁻³	0	1.2 x 10 ⁻³	2.6 x 10 ⁻³	4.6 x 10 ⁻⁶	5.6 x 10 ⁻⁵	1.08	20.5	3.4		
6252-19-010	ThO ₂	8D0	44.28	3.06	NA	42.81	12.98	37.47	NA	0.63	30	1.5 x 10 ⁻³	0	1.7 x 10 ⁻³	7.6 x 10 ⁻³	1.4 x 10 ⁻⁴	5.1 x 10 ⁻⁶	1.07	19.0	3.1		
6252-20-010	ThO ₂	8D4	44.06	2.98	NA	41.79	13.55	39.65	NA	2.28	87	2.6 x 10 ⁻³	0	2.9 x 10 ⁻³	1.9 x 10 ⁻³	2.5 x 10 ⁻⁴	7.3 x 10 ⁻⁵	6.29	23.6	3.8		
Inert Particle																						
6351-05-010	(c)	10E1	50.83	4.13	NA	NA	19.67	80.63	NA	0.73	40	NA	NA	NA	0	NA	NA	NA	NA	NA		
6351-05-020 ^(k)	(c)	10E7	49.26	3.10	NA	NA	24.10	77.90	NA	0.73	21	NA	NA	NA	NA	NA	NA	NA	NA	NA		
6351-05-030 ^(k)	(c)	10C3	42.16	1.49	NA	NA	24.16	77.53	NA	0.73	40	NA	NA	NA	NA	NA	NA	NA	NA	NA		

(a) Measured after all coatings deposited.

(b) Measured using mercury porosimeter.

(c) Measured by contact X-radiography on ≥200 particles.

(d) 25 g sample leached in ultra leach.

(e) 15 g sample visually examined.

(f) Release/birth rates of Kr-85m at 1100°C.

(g) Percent of particles with >1.20 aspect ratio.

(h) Maximum load to break one particle in compression; ≥50 particles measured.

(i) NA = not applicable or data not available.

(j) Composite of 12 batches.

(k) OPyC coating doped with ~30 wt % silicon.

TABLE 3-6
OUT-OF-DESIGN PROPERTIES OF TRISO COATED PARTICLE FUEL BATCHES FOR CAPSULE HRB-14

Coated Particle Data Retrieval No./Particle Type	Property	Measured Value	Design(a) Value
Fissile			
6152-01-010/ UO ₂ TRISO	% in critical region for SiC coating thickness Inner mean coating thickness Buffer mean coating thickness % in critical region for buffer coating thickness	2.38% 41 μm 122 μm 4.46%	<1%<20 μm 30-40 μm 130-140 μm <1%<85 μm
6155-05-010/ (Th,U)O ₂ TRISO	Buffer mean coating thickness % in critical region for buffer coating thickness	86 μm 3.14%	90-100 μm <1%<59 μm
6155-05-020/ (Th,U)O ₂ TRISO	Buffer mean coating thickness	110 μm	90-100 μm
6157-08-020/ UCO.69O.51 TRISO	Buffer mean coating thickness % in critical region for buffer coating thickness Kernel mean coating thickness	90 μm 14.92 353 μm	110-120 μm <1%<72 μm 330-350 μm
Fertile			
6252-12 COMP/ ThO ₂ TRISO	% in critical region (low) for IPyC coating density % in critical region for buffer coating thickness	14% 8.69%	<2%<1.80 Mg/m ³ <1%<36 μm
6252-13-010/ ThO ₂ TRISO	Fraction defective coated particle OPyC mean coating rate OPyC maximum coating rate SiC mean coating thickness % in critical region for buffer coating thickness	1.5 x 10 ⁻³ 8.62 μm/min 10.27 μm/min 42 μm 3.36%	<1 x 10 ⁻³ >7.5<8.5 μm/min <10.0 μm/min 30-40 μm <1%<36 μm
6252-14-010/ ThO ₂ TRISO	Fraction defective coated particle Fraction defective SiC Fission gas release % in critical region (high) OPyC BAF ₀ measurement % in critical region for buffer coating thickness	1.4 x 10 ⁻³ 2.4 x 10 ⁻³ 4.21 x 10 ⁻⁵ 2.70% 2.6%	<1 x 10 ⁻³ <1 x 10 ⁻³ <3 x 10 ⁻⁵ <1%>1.05 <1%<36 μm
6252-16-010/ ThO ₂ TRISO	OPyC mean coating rate OPyC maximum coating rate % in critical region (high) OPyC BAF ₀ measurement % in critical region for buffer coating thickness	5.56 μm/min 6.79 μm/min 5.1% 5.60%	>4.5<5.5 μm/min <6.5 μm/min <1%>1.06 <1%<36 μm
6252-17-010/ ThO ₂ TRISO	Fraction defective coated particle Total coated particle iron impurity measurement OPyC maximum coating rate % in critical region (high) OPyC BAF ₀ measurement % in critical region for buffer coating thickness	1.5 x 10 ⁻³ 140 ppm 6.98 μm/min 3.2% 3.5%	<1 x 10 ⁻³ <100 ppm <6.5 μm/min <1%>1.06 <1%<45 μm
6252-18-010/ ThO ₂ TRISO	Fraction defective coated particle OPyC coating density % in critical region for buffer coating thickness	3.4 x 10 ⁻³ 1.83 Mg/m ³ 2.38%	1 x 10 ⁻³ 1.78-1.82 Mg/m ³ <1%<45 μm
6252-19-010/ ThO ₂ TRISO	Fraction defective coated particle OPyC coating density OPyC mean coating rate % in critical region for buffer coating thickness	1.5 x 10 ⁻³ 1.92 Mg/m ³ 7.23 μm/min 2.74%	1 x 10 ⁻³ 1.85-1.89 Mg/m ³ >6.0<7.0 μm/min <1%<45 μm
6252-20-010/ ThO ₂ TRISO	Fraction defective coated particle Fraction defective SiC Fission gas release Exposed thorium (leach) OPyC coating density OPyC mean coating rate OPyC maximum coating rate % in critical region (high) OPyC BAF ₀ measurement % in critical region for buffer coating thickness	2.6 x 10 ⁻³ 2.9 x 10 ⁻³ 7.3 x 10 ⁻⁵ 2.5 x 10 ⁻⁴ 1.98 Mg/m ³ 8.57 μm/min 10.59 μm/min 4.3% 2.60%	<1 x 10 ⁻³ <1 x 10 ⁻³ <3 x 10 ⁻⁵ <1 x 10 ⁻⁴ 1.93-1.97 Mg/m ³ >7.5 x <8.5 μm/min <10.0 μm/min <1%>1.05 <1%<45 μm

(a)Ref. 3-7.

4. UNIRRADIATED FUEL RODS

4.1. DESCRIPTION

Capsule HRB-14 irradiated 20 GA cured-in-place fuel rods 12.50 mm in diameter by 9.52 mm thick. These rod dimensions were much smaller than reference HTGR fuel rods because of the limited amount of test space and the decision to test separate fissile and fertile rods. The rods consisted of TRISO-coated fuel and inert particles, H-451 shim particles, and the reference LHTGR matrix. Each rod had a different combination of coated and shim particles. Half the rods contained only fertile particles, and half contained all or primarily fissile particles. (For this report, the rods will be designated either fissile or fertile rods.) The UO_2 and $\text{UC}_{0.7}\text{O}_{0.5}$ fissile rods contained the same amount of thorium (in the form of TRISO ThO_2 particles) as was in the $(\text{Th},\text{U})\text{O}_2$ rods so that heat generations in the rods would be similar throughout the irradiation. One fuel type was used in 14 of the rods to unambiguously determine which particle type failed during irradiation, based on postirradiation fission gas release (FGR) measurements and postirradiation core-heatup-simulation tests. The fissile and fertile rods were alternated along the capsule axis to maintain relatively constant temperatures throughout life and to reduce the axial thermal gradients. The H-451 near-isotropic shim is the prime candidate for the LHTGR and ranged from 0 to 35 vol % in the rods. The TRISO inert particles were added to the rods to achieve the close particle packing, the design fuel loadings (less than in HTGR rods), and shim volume fractions. The composition of the matrix was 47 wt % Ashland A-240 petroleum pitch, 38 wt % Lonza-15 HTR graphite filler, 5 wt % polystyrene, and 10 wt % octadecanol.

ORNL calculated the fuel loadings (Ref. 4-1). The fissile and fertile particle loadings were based on these. Table 4-1 gives the fuel loadings and the particle loadings for the fuel rods.

A minimum of 12 rods was made for each of the 20 rod types. One rod from each type was irradiated in capsule HRB-14. The other rods were either used in the quality control evaluation or placed in storage as historical rods.

4.2. FABRICATION

The green fuel rods for capsule HRB-14 were fabricated according to Ref. 4-2. The fabrication process simulated the HTGR pilot plant process. The four-mold hot-injection press was used. After weighing the particle charges, the particles were blended and dropped into the four cavities. The particle charges were raised in the mold. The mold was heated to 163°C, and each particle bed was injected with preheated matrix to a maximum pressure of 4.86 to 8.72 MPa (705 to 1265 psi). Each set of green rods was cooled and ejected from the mold.

The green rods were fired in 127.5-mm-long H-451 graphite tubes. The graphite was gun-drilled to form a 12.6 mm (0.494 in.) i.d. Nine fuel rods were loaded into each graphite tube. Filter paper was placed between all the fuel rods to prevent the fuel rods from sticking together during carbonization. The two ends of the tube were plugged after rod loading.

The loaded graphite tubes were heat treated in a laboratory induction furnace. The heating rates were (1) 5.2°C/min from room temperature to 820°C, (2) 10.4°C/min from 820° to 1100°C, and (3) 11.1°C/min from 1100° to 1685°C. The temperature was $\geq 1600^\circ\text{C}$ for 95 min. The firing atmosphere was N₂ from start to 1000°C and argon from 1000°C to completion.

After firing, all fuel rods were removed from the graphite tubes. Three slits were made ~120 deg apart along the axis. The graphite tube was split, and the rods were picked out. No rods were pushed out of the crucibles.

4.3. PROPERTIES

The 20 fuel rod types were characterized in the green and fired rod states. Fuel rod properties were measured on the capsule rod and companion rods. The properties measured in companion rods were assumed to be representative of the capsule rod, because they were all made under similar conditions.

The constituents of the fuel rods were coated particles, shim, and matrix. The coated particles were discussed in Section 3. Tables 4-2 and 4-3 give the properties of the shim, matrix raw materials, and matrix batches for capsule HRB-14. Figure 4-1 shows the shim particles.

Tables 4-4 and 4-5 present the properties of the green and fired fuel rods. Table 4-6 identifies the properties of the fuel rod types which did not meet the specifications (Ref. 4-2). Figure 4-2 shows the photomicrographs of a representative fuel rod in capsule HRB-14. Figure 4-3 shows the metallographic cross section and the matrix microstructure of a typical fired rod.

The matrix properties were acceptable. The coke contents ranged from 0.30 to 0.35 and averaged 0.32 g coke/g (coke plus filler). The macroporosity range was 27% to 38% and averaged 31%.

The visual examination of both the green and fired fuel rods indicated that the rods were in good condition before irradiation.

The analysis of the heavy metal contamination and particle failure was based on chlorine leaching, visual inspection, and FGR measurements. Table 4-7 summarizes the data for the as-coated particles and the fuel rods.

The fissile particles in the fissile fuel rods primarily had low particle failure and uranium contamination. The defective SiC coating

fraction was low for all the fuel rods, except rod type 4. This rod had a defective SiC value of 1.9×10^{-3} g U/g U. The FGR values were all low.

The fertile fuel rods were in fair condition. The defective SiC coatings, exposed thorium (measured by chlorine leach), and FGR of the as-coated particle batches were compared to those of the fuel rods. The OPyC and SiC failure increased during fuel rod fabrication for all fuel rods except those containing batches 6252-13-010 and 6252-12 COMP (used as the driver fuel in the FSV fuel test elements). The failure was significantly higher for some of the rods with the thicker buffer batches. Table 4-7 also shows that the defective SiC coatings fraction (up to 3.9×10^{-2}) of the as-coated batches was higher than the specification ($\leq 1 \times 10^{-3}$) for many of the batches. The particle breakage in the fuel rods did not correlate well with the crush strengths of the particles.

Green and fired rods were visually examined to verify the fertile coating failure. Nine green rods were deconsolidated. Table 4-7 shows that the OPyC coating failure was high (up to 4.3×10^{-2}). The majority of the particles with a failed OPyC coating also had a failed SiC coating. The deconsolidated rods were then burned back, and the defective SiC coatings were counted (see Table 4-7). A defective particle appeared yellow, because the buffer and IPyC coatings were at least partially burned off. The visual results were in fairly good agreement with the burn-leach results measured on another companion rod. The fired fuel rods, which were leached with chlorine to measure the exposed thorium, were also burned back and visually examined. The number of defective SiC coated particles were counted. The fraction of defective SiC coatings was in the same range as the exposed thorium values measured by chlorine leach. Therefore, the measured exposed thorium was from surface contamination and particles with failed OPyC plus SiC coatings.

The uranium and thorium loadings were measured analytically for all the fuel rod types. The measured values agreed well with the design values,

except one rod. The uranium content of type 10 measured ~25% higher than design. Apparently, an error was made. The higher loading would cause rod No. 10 to be hotter than the other rods during the irradiation. The design fuel loadings for all rods, except the uranium of rod No. 10 (measured used), were decided upon for use in any postirradiation analytical calculations.

The crush strength of HRB-14 fired fuel rods (9.5 mm long) was measured (see Table 4-8). As a comparison, the crush strength of 9.5- and 19.0-mm-long archive rods from capsules P13R and P13S (Ref. 4-3) were also measured. Selected 19.0-mm P13R/S rods were cut in half with a diamond circular saw to make 9.5-mm-long rods. The compressive strength of each rod was measured in a Material Testing Systems* press. Metal caps were placed on the ends of each fuel rod, and this assembly was lined up between the compression plates. The specimen was compressed at a crosshead speed of 2.1×10^{-6} m/s (0.005 in./min) to compressive failure.

The results of the crush strength measurements show that the uncut HRB-14 fuel rods were 19% weaker (3.97×10^6 Pa) than the 9.5-mm cut P13R/S rods (4.88×10^6 Pa). The actual strength of the HRB-14 rods could be even weaker than the P13R/S rods, because cutting the ends of the rod can weaken the rod (Ref. 4-4). The 9.5- and 19.0-mm-long P13R/S rods had no significant difference. However, comparing the strength of the HRB-14 fuel rods to strengths of longer rods may be inappropriate because of a possible geometry effect (Ref. 4-4). The HRB-14 and the P13R/S 9.5-mm rods had similar compliance or stiffness.

REFERENCES

- 4-1. Thoms, K. R., ORNL private communication, October 6, 1977.
- 4-2. "FMB-3 Fuel Specification for Irradiation Experiments," General Atomic unpublished data.

* Trade name.

- 4-3. Young, C. A., and D. P. Harmon, "Preirradiation Report: Fuel Materials for P13R and P13S Irradiation Capsules," USAEC Report GA-A13026, General Atomic Company, November 1974.
- 4-4. Kovacs, W. J., General Atomic private communication, June 10, 1980.

N77040

Fig. 4-1. Shim particles made from Great Lakes Carbon Company H-451 graphite (batch F0-296) and used in fabrication of HRB-14 fuel rods

SR78032-1

(a)

SR78032-2

(b)

SR78032-3

(c)

SR78032-4

(d)

Fig. 4-2. Photomicrographs of a representative fuel rod inserted in capsule HRB-14: (a) side at 0 deg; (b) side at 180 deg; (c) and (d) ends of rod

MR 78043 - 1 THRU 5

Fig. 4-3. Photomicrographs representative of all fired fuel rods for capsule HRB-14: (a) composite of radial cross section (sheet 1 of 2)

MR78043-6

MR78043-7

Fig. 4-3. Photomicrographs representative of all fired fuel rods for capsule HRB-14: (b) microstructure of fuel matrix (sheet 2 of 2)

TABLE 4-1
PARTICLE AND FUEL LOADINGS FOR CAPSULE HRB-14 FUEL RODS

Fuel Rod No. (7161-014-)	Fissile				Fertile				Inert				H-451 Shim		Fuel Loadings (mg)			
	Batch No.	Weight (g)	Volume Fraction(a)	Number of Particles	Batch No. (6252-)	Weight (g)	Volume Fraction(a)	Number of Particles	Batch No. (6351-05-)	Weight (g)	Volume Fraction(a)	Number of Particles	Weight (g)	Volume Fraction(a)	U		Th	
															Design(b)	Measured(c)	Design(b)	Measured(c)
01-6	None	0	0	0	17-010	0.848	0.243	790	010	0.361	0.163	335	0.340	0.150	0	--	353	351
02-6	6155-05-020	0.307	0.099	410	None	0	0	0	020	0.274	0.120	245	0.794	0.350	46.8	48.6	45.3	ND(d)
03-11	None	0	0	0	20-010	1.016	0.292	975	030	0.259	0.115	265	0.340	0.150	0	--	425	435
04-11	6155-05-020	0.299	0.097	400	None	0	0	0	020	0.280	0.123	250	0.794	0.350	45.7	47.7	44.2	ND
05-3	None	0	0	0	19-010	1.036	0.290	980	010	0.590	0.167	610	0	0	0	--	444	451
06-8	6152-01-010	0.219	0.080	390	18-010	0.105	0.030	100	030	0.234	0.105	240	0.786	0.350	46.7	48.4	44.8	45.1
07-3	None	0	0	0	18-010	1.080	0.038	1050	--	0	0	0	0.586	0.258	0	--	460	462
08-2	6157-08-010	0.162	0.053	220	18-010	0.110	0.032	105	020	0.296	0.132	265	0.786	0.350	49.3	48.8	47.0	50.2
09-4	None	0	0	0	18-010	1.128	0.322	1100	--	0	0	0	0.563	0.248	0	--	481	480
10-8	6157-08-010	0.159	0.050	220	18-010	0.117	0.034	115	010	0.292	0.133	270	0.786	0.350	52.2	65.8	49.7	50.8
11-4	None	0	0	0	13-010	1.151	0.290	1215	030	0.600	0.267	610	0	0	0	--	518	524
12-2	6157-08-010	0.188	0.062	225	18-010	0.128	0.037	125	020	0.265	0.118	235	0.786	0.350	57.4	57.9	54.7	54.4
13-7	None	0	0	0	12 COMP	1.164	0.284	1305	--	0	0	0	0.638	0.281	0	--	554	554
14-1	6157-08-010	0.207	0.068	285	18-010	0.141	0.041	135	010	0.237	0.108	220	0.786	0.350	63.0	64.3	60.2	61.5
15-8	None	0	0	0	12 COMP	1.232	0.300	1380	--	0	0	0	0.601	0.265	0	--	587	585
16-8	6155-05-010	0.412	0.125	635	None	0	0	0	030	0.215	0.095	220	0.794	0.350	70.2	68.9	67.6	ND
17-9	None	0	0	0	14-010	1.368	0.347	1470	020	0.475	0.210	425	0	0	0	--	632	630
18-4	6155-05-010	0.474	0.143	730	None	0	0	0	010	0.135	0.061	126	0.794	0.350	80.8	81.4	77.8	ND
19-7	None	0	0	0	16-010	1.556	0.420	1725	030	0.312	0.139	315	0	0	0	--	741	742
20-5	6157-08-010	0.294	0.096	400	18-010	0.201	0.058	195	020	0.619	0.276	555	0.337	0.150	89.5	87.5	85.5	88.6

(a) Based on design fuel rod dimensions.

(b) The design fuel loadings of all rods except the uranium of rod 10 (65.8 mg uranium) were used in the postirradiation analytical calculations.

(c) Measured by X-ray fluorescence and titration.

(d) ND = not determined.

TABLE 4-2
DESCRIPTION OF RAW MATERIALS USED IN FABRICATION OF HRB-14 FUEL RODS

Material (Manufacturer)	Use	Batch No.	Density (Mg/m ³)	Insolubles (%)	Impurities (ppm) ^(a)						Particle Size (μm)	Apparent Crystalline Size ^(b) (Å)
					B	Fe	Ti	V	S	Ash		
KS-15 graphite flour (LONZA Ltd.)	Filler	FO274	ND ^(c)	ND	<0.1	11	<10	<10	<10	135	9.98	1350
Octadecanol	Additive	SCO45	ND	ND	1.0	2	10	<1	<1	153	NA ^(c)	NA
Polystyrene	Additive	SCO44	ND	ND	1.3	2	55	4.0	307	117	NA	NA
Petroleum pitch (Ashland Oil Co.)	Binder	BO28	ND	0.38	<1.0	62	<10	<10	3.1%	1650	NA	NA
Impregnated H-451 graphite powder ^(d) (Great Lakes Carbon Corp.)	Shim	FO296	1.94	ND	0.50	41	1	0.50	6	200	(e)	670

(a) Units are ppm except where noted.

(b) Measured by X-ray diffraction technique.

(c) ND = not determined. NA = not applicable.

(d) Impregnated by Great Lakes Carbon Corp. with furfuryl alcohol.

(e) Sieving analysis +1180 μm -0.7%; +1000 μm -17.2%; +850 μm -36.6%; +710 μm -29.3%; +539 μm -16.0%; +495 μm -0.2%.

TABLE 4-3
PROPERTIES OF FUEL ROD MATRIX BATCHES

Item	Batch MO450	Batch MO460
Composition		
KS-15 graphite filler		
Batch No.	FO274	FO274
Wt %	38	38
A-240 petroleum pitch		
Batch No.	BO28	BO28
Wt %	47	47
Octadecanol		
Batch No.	SC045	SC045
Wt %	10	10
Polystyrene		
Batch No.	SC044	SC044
Wt %	5	5
Filler content ^(a) (wt %)	40.5	39.6
Impurities ^(b) (wt ppm)		
Fe	40	40
Ti + V	8.5	10.5
B	0.5	0.5
S	1912	2056
H ₂ O	16	24

(a) Measured in green matrix.

(b) Measured in fired matrix.

TABLE 4-4
DESCRIPTION OF FUEL RODS FOR CAPSULE HRB-14

Fuel Rod No. (7161-014-)	Cap- sule Posi- tion	Fuel Rod Constituents ^(a)					Green Rod		Matrix			Defective SiC Coatings ^(e)		Exposed Thorium (g Th/g Th)	FGR(g)
		TRISO Particle Batches			Matrix Batch No.										
		Fissile		ThO ₂ Batch No. (6252-)		Inert Batch No. (6351-)									
		Batch No.	Kernel Type				Particle Packing (%)	Matrix Filler Content ^(b) (%)	Coke Content ^(c)	Macro- poros- ity ^(b,d) (%)	Density (Mg/m ³)	U (g U/g U)	Th (g Th/g Th)		
01-6	1	--	--	17-010	05-010	MO450	56.97	40.6	0.318	37.7	0.799	ND ^(h)	6.0 x 10 ⁻³	1 x 1 x 10 ⁻²	2.5 x 10 ⁻⁴
02-6	2	6155-05-020	(Th,U)O ₂	--	05-020	MO450	56.28	42.8	0.326	32.1	0.770	9.0 x 10 ⁻⁶	0	ND	8.5 x 10 ⁻⁴
03-11	3	--	--	20-010	05-030	MO450	57.52	41.8	0.317	38.9	0.802	ND	8.5 x 10 ⁻³	5.7 x 10 ⁻³	2.5 x 10 ⁻⁴
04-11	4	6155-05-020	(Th,U)O ₂	--	05-020	MO450	56.57	41.3	0.333	28.6	0.794	1.9 x 10 ⁻³	1.4 x 10 ⁻³	ND	2.2 x 10 ⁻⁶
05-3	5	--	--	19-010	05-010	MO450	58.14	40.6	0.317	30.4	0.819	ND	1.6 x 10 ⁻²	1.3 x 10 ⁻²	2.5 x 10 ⁻⁴
06-8	6	6152-01-010	UO ₂	18-010	05-030	MO460	68.46	40.4	0.309	34.6	0.958	1.5 x 10 ⁻⁵	1.9 x 10 ⁻²	ND	<1.0 x 10 ⁻⁶
07-3	7	--	--	18-010	--	MO450	57.02	42.7	0.330	26.5	0.791	ND	4.3 x 10 ⁻³	1.2 x 10 ⁻³	2.5 x 10 ⁻⁴
08-2	8	6157-08-010	UCO _{0.7} O _{0.5}	18-010	05-020	MO460	56.51	40.3	0.323	36.1	0.735	5.0 x 10 ⁻⁶	7.4 x 10 ⁻⁵	ND	4.6 x 10 ⁻⁶
09-4	9	--	--	18-010	--	MO450	57.22	41.0	0.319	26.8	0.799	ND	6.4 x 10 ⁻³	1.6 x 10 ⁻³	2.5 x 10 ⁻⁴
10-8	10	6157-08-020	UCO _{0.7} O _{0.6}	18-010	05-010	MO460	55.34	39.7	0.353	32.2	0.782	7.0 x 10 ⁻⁶	0	ND	6.0 x 10 ⁻⁷
11-4	11	--	--	13-010	05-030	MO450	58.23	41.4	0.304	27.4	0.806	ND	6.2 x 10 ⁻⁶	1.6 x 10 ⁻⁴	2.5 x 10 ⁻⁴
12-2	12	6157-08-010	UCO _{0.7} O _{0.5}	18-010	05-020	MO460	56.68	39.8	0.324	36.1	0.737	2.5 x 10 ⁻⁵	1.4 x 10 ⁻²	ND	1.1 x 10 ⁻⁶
13-7	13	--	--	12 COMP	--	MO450	57.02	41.7	0.331	27.7	0.798	ND	6.3 x 10 ⁻⁴	2.2 x 10 ⁻⁴	2.5 x 10 ⁻⁴
14-1	14	6157-08-010	UCO _{0.7} O _{0.5}	18-010	05-010	MO460	56.79	40.1	0.321	35.4	0.733	7.0 x 10 ⁻⁶	5.8 x 10 ⁻³	ND	3.6 x 10 ⁻⁷
15-8	15	--	--	12 COMP	--	MO450	56.80	41.1	0.316	29.8	0.799	ND	3.9 x 10 ⁻⁴	1.7 x 10 ⁻⁴	2.5 x 10 ⁻⁴
16-8	16	6155-05-010	(Th,U)O ₂	--	05-030	MO450	56.69	42.8	0.311	30.4	0.759	2.7 x 10 ⁻⁶	4.2 x 10 ⁻⁵	ND	2.6 x 10 ⁻⁷
17-9	17	--	--	14-010	05-020	MO450	58.65	42.2	0.307	27.5	0.807	ND	3.6 x 10 ⁻³	6.9 x 10 ⁻⁴	2.5 x 10 ⁻⁴
18-4	18	6155-05-010	(Th,U)O ₂	--	05-010	MO450	56.24	41.8	0.318	31.6	0.771	3.0 x 10 ⁻⁶	0	ND	3.8 x 10 ⁻⁷
19-7	19	--	--	16-010	05-030	MO450	59.10	40.9	0.311	29.1	0.822	ND	1.8 x 10 ⁻³	2.8 x 10 ⁻³	2.5 x 10 ⁻⁴
20-5	20	6157-08-010	UCO _{0.7} O _{0.5}	18-010	05-020	MO460	56.18	41.0	0.340	32.5	0.762	8.0 x 10 ⁻⁶	2.1 x 10 ⁻²	ND	3.8 x 10 ⁻⁶

(a) FO296 shim used in all rods except No. 5, 9, 17, and 19.

(b) Measurement made on companion rod.

(c) Calculation: (coke wt) + (coke + filler wt).

(d) Determined from metallographic cross section of rod.

(e) Measured with a burn-leach technique.

(f) Measured by chlorine leach technique.

(g) Release/birth Kr-85m at 1100°C.

(h) ND = not determined.

TABLE 4-5
WEIGHTS AND DIMENSIONS OF HRB-14 FUEL RODS

Capsule Position	Rod No.	Green Rod			Fired Rod		
		Dimensions (mm)		Weight (g)	Dimensions (mm)		Weight (g)
		Length	Diam		Length	Diam	
1	7161-014-01-6	9.40	12.44	2.186	9.34	12.45	1.926
2	-02-6	9.74	↓	2.038	9.84	12.45	1.757
3	-03-11	9.31		2.261	9.39	12.44	1.997
4	-04-11	9.69		2.042	9.82	12.43	1.763
5	-05-3	9.21		2.243	9.10	12.46	2.002
6	-06-8	9.44		1.966	9.53	12.45	1.676
7	-07-3	9.55		2.312	9.62	12.44	2.047
8	-08-2	9.55		1.994	9.61	12.45	1.705
9	-09-4	9.58		2.343	9.58	12.44	2.070
10	-10-8	9.77		2.048	9.83	12.44	1.748
11	-11-4	9.20		2.372	9.09	12.48	2.122
12	-12-2	9.54	12.43	2.008	9.64	12.44	1.721
13	-13-7	9.53	12.44	2.451	9.60	12.44	2.184
14	-14-1	9.51	↓	2.011	9.60	12.45	1.720
15	-15-8	9.57		2.490	9.55	12.44	2.212
16	-16-8	9.67		2.072	9.75	12.44	1.787
17	-17-9	9.13		2.461	9.18	12.41	2.214
18	-18-4	9.48	↓	2.053	9.58	12.43	1.772
19	-19-7	9.11	12.43	2.568	8.99	12.45	2.330
20	↓ -20-5	9.83	12.44	2.138	9.94	12.46	1.851

TABLE 4-6
OUT-OF-DESIGN PROPERTIES FOR CAPSULE HRB-14 FUEL RODS

Items	Property - Rod Type	Measured Value	Design Value(a)	Items	Property - Rod Type	Measured Value	Design Value(a)
1	Impurities of matrix (ppm)			5	Green rod dimensions		
	Residual ash	7245	<3000		Length (mm)		
	Sulfur	1984	<1300		Type 5	9.18	9.52 ± 0.25
2	Fraction defective SiC coating				11	9.14	9.52 ± 0.25
	Fissile (g U/g U)				17	9.10	9.52 ± 0.25
	Type 4	1.9 x 10 ⁻³	<1 x 10 ⁻³		19	9.13	9.52 ± 0.25
	Fertile (g Th/g Th)				20	9.83	9.52 ± 0.25
	Type 1	6.0 x 10 ⁻³	<1 x 10 ⁻³	6	Heating rate up to 1000°C	5.2	6-10
	3	8.5 x 10 ⁻³	<1 x 10 ⁻³		(°C/min)		
	5	1.6 x 10 ⁻²	<1 x 10 ⁻³	7	Exposed Th (g Th/g Th)		
	7	4.3 x 10 ⁻³	<1 x 10 ⁻³		Type 1	1.1 x 10 ⁻²	<1 x 10 ⁻⁴
	9	6.4 x 10 ⁻³	<1 x 10 ⁻³		3	5.7 x 10 ⁻³	<1 x 10 ⁻⁴
	17	3.6 x 10 ⁻³	<1 x 10 ⁻³		5	1.3 x 10 ⁻²	<1 x 10 ⁻⁴
	19	1.8 x 10 ⁻³	<1 x 10 ⁻³		7	1.2 x 10 ⁻³	<1 x 10 ⁻⁴
3	Macroporosity (%)				9	1.6 x 10 ⁻³	<1 x 10 ⁻⁴
	Type 1	37.7	<35		11	1.6 x 10 ⁻⁴	<1 x 10 ⁻⁴
	3	38.9	<35		13	2.2 x 10 ⁻⁴	<1 x 10 ⁻⁴
	8	36.1	<35		15	1.7 x 10 ⁻⁴	<1 x 10 ⁻⁴
	12	36.1	<35		17	6.8 x 10 ⁻⁴	<1 x 10 ⁻⁴
4	Fuel loadings				19	2.8 x 10 ⁻³	<1 x 10 ⁻⁴
	Uranium type 10	+26%	±5%				
	Thorium type 8	+7%	±5%				

(a) Ref. 4-2.

TABLE 4-7
SUMMARY OF PARTICLE FAILURE AND CONTAMINATION DATA OF HRB-14 AS-COATED PARTICLES AND RODS

Fuel Rod Type	Coated Particles Batch No.		Defective SiC Coatings						Fraction of Defective OPyC Coatings(d)	Exposed Heavy Metal			FCR(g)	
			Particles			Fuel Rods(c)				Particles(e)		Fertile Fuel Rod(c,f)		
			Fertile (6252-)	Fissile(a) (g U/g U)	Fertile		Leach(a)						Visual(b,d) (Fertile Rods)	
	Leach(a) (g Th/g Th)	Visual(b)			Fissile (g U/g U)	Fertile (g Th/g Th)								
Fissile	Fertile (6252-)	(g U/g U)	(g Th/g Th)	Visual(b)	Fissile (g U/g U)	Fertile (g Th/g Th)	Visual(b,d) (Fertile Rods)	(g U/g U)	(g Th/g Th)	(g Th/g Th)	Particle Batch	Fuel Rod(c)		
Fertile Rods														
1	--	17-010	--	1.3×10^{-3}	1.3×10^{-3}	--	6.0×10^{-3}	5.0×10^{-3}	6.3×10^{-3}	--	2.1×10^{-5}	1.1×10^{-2}	2.1×10^{-5}	$2.5 \times 10^{-4}(1)$ 5.1×10^{-5}
3	--	20-010	--	2.9×10^{-3}	1.9×10^{-3}	--	8.5×10^{-3}	9.2×10^{-3}	4.1×10^{-3}	--	2.5×10^{-4}	5.7×10^{-3}	7.3×10^{-5}	
5	--	19-010	--	1.7×10^{-3}	7.6×10^{-3}	--	1.5×10^{-2}	3.9×10^{-2}	4.3×10^{-2}	--	1.4×10^{-4}	1.3×10^{-2}	5.1×10^{-6}	
7	--	18-010	--	1.2×10^{-3}	2.6×10^{-3}	--	4.3×10^{-3}	4.8×10^{-3}	6.7×10^{-3}	--	4.6×10^{-6}	1.2×10^{-3}	5.6×10^{-5}	
9	--	18-010	--	1.2×10^{-3}	2.6×10^{-3}	--	6.4×10^{-3}	2.7×10^{-3}	1.8×10^{-3}	--	4.6×10^{-6}	1.6×10^{-3}	5.6×10^{-5}	
11	--	13-010	--	4.3×10^{-4}	9.7×10^{-4}	--	6.2×10^{-3}	8.2×10^{-4}	6.6×10^{-3}	--	4.9×10^{-5}	1.6×10^{-4}	1.2×10^{-5}	
13	--	12 COMP	--	1.6×10^{-5}	4.2×10^{-4}	--	6.3×10^{-4}	0	7.7×10^{-4}	--	1.0×10^{-6}	2.2×10^{-4}	5.3×10^{-6}	
15	--	12 COMP	--	1.6×10^{-5}	4.2×10^{-4}	--	3.9×10^{-4}	ND(h)	ND	--	1.0×10^{-6}	1.7×10^{-4}	5.3×10^{-6}	
17	--	14-010	--	2.4×10^{-3}	4.1×10^{-3}	--	3.5×10^{-3}	2.7×10^{-3}	4.1×10^{-3}	--	8.3×10^{-5}	5.9×10^{-4}	4.2×10^{-5}	
19	--	16-010	--	8.9×10^{-5}	3.7×10^{-4}	--	1.9×10^{-3}	ND	ND	--	9.8×10^{-6}	2.8×10^{-3}	2.5×10^{-6}	
Fissile Rods														
2	6155-05-020(j)	--	3.5×10^{-4}	$1.8 \times 10^{-4}(k)$	--	9.0×10^{-6}	$<10^{-7}(k)$	ND	ND	7.8×10^{-8}	3.3×10^{-6}	--	1.1×10^{-6}	8.5×10^{-7}
4	6155-05-020(j)	--	3.5×10^{-4}	$1.8 \times 10^{-4}(k)$	--	1.9×10^{-3}	$1.4 \times 10^{-3}(k)$	ND	ND	7.8×10^{-8}	3.3×10^{-6}	--	1.1×10^{-6}	2.2×10^{-6}
6	6152-01-010	18-010	1.4×10^{-4}	1.2×10^{-3}	2.6×10^{-3}	1.5×10^{-5}	1.9×10^{-2}	ND	ND	1.3×10^{-3}	4.6×10^{-6}	--	2.5×10^{-7}	1.0×10^{-6}
8	6157-08-010	18-010	3.2×10^{-6}	1.2×10^{-3}	2.6×10^{-3}	5.0×10^{-6}	7.4×10^{-5}	ND	ND	1.1×10^{-6}	4.6×10^{-6}	--	5.9×10^{-8}	4.6×10^{-6}
10	6157-08-020	18-010	7.0×10^{-7}	1.2×10^{-3}	2.6×10^{-3}	7.0×10^{-6}	$<10^{-7}$	ND	ND	1.1×10^{-6}	4.6×10^{-6}	--	6.1×10^{-7}	6.0×10^{-7}
12	6157-08-010	18-010	3.2×10^{-6}	1.2×10^{-3}	2.6×10^{-3}	2.5×10^{-5}	1.4×10^{-2}	ND	ND	1.1×10^{-6}	4.6×10^{-6}	--	5.9×10^{-8}	1.1×10^{-6}
14	6157-08-010	18-010	3.2×10^{-6}	1.2×10^{-3}	2.6×10^{-3}	7.0×10^{-6}	5.8×10^{-5}	ND	ND	1.1×10^{-6}	4.6×10^{-6}	--	5.9×10^{-8}	3.6×10^{-7}
16	6155-05-010(j)	--	4.0×10^{-4}	$2.7 \times 10^{-6}(k)$	--	2.7×10^{-6}	$4.2 \times 10^{-5}(k)$	ND	ND	1.5×10^{-7}	$<10^{-7}$	--	8.0×10^{-7}	2.6×10^{-7}
18	6155-05-010(j)	--	4.0×10^{-4}	$2.7 \times 10^{-6}(k)$	--	3.0×10^{-6}	$<10^{-7}(k)$	ND	ND	1.5×10^{-7}	$<10^{-7}$	--	8.0×10^{-7}	3.8×10^{-7}
20	6157-08-010	18-010	3.2×10^{-6}	1.2×10^{-3}	2.6×10^{-3}	8.0×10^{-6}	2.1×10^{-5}	ND	ND	1.1×10^{-6}	4.6×10^{-6}	--	5.9×10^{-8}	3.8×10^{-6}

(a) Sample burned in air and leached in ultra leach.

(b) Sample burned in air and visually examined for defects.

(c) All data for fired fuel rods except where noted.

(d) Green fuel rod deconsolidated to visually measure OPyC coating failure, then particles burned back to visually measure defective SiC coatings.

(e) Leached in ultra leach.

(f) Measured by chlorine leach technique.

(g) Release/birth rates of Kr-85m at 1100°C; indicates exposed thorium for fertile samples and exposed uranium for fissile samples.

(h) ND = not determined.

(i) Group of rods measured at once.

(j) (Th,U)O₂ kernels.

(k) Thorium measured in fissile particle.

TABLE 4-8
CRUSH STRENGTHS OF HRB-14 AND P13R/S FUEL RODS

Capsule	Rod No.	Rod Type	Description	Maximum Crush Strength (10^6 Pa)			Compliance (10^8 Pa)		
				Rods	Mean	Standard Deviation	Rods	Mean	Standard Deviation
HRB-14 ↓	4243-1	04	Uncut	4.38	3.97	0.43	1.36	1.83	0.65
	4252-3	16	9.5 mm	4.20			2.65		
	4254-1	18	long	4.61			2.30		
	4288-1	06	↓	3.52			1.03		
	4289-4	08	↓	3.47			1.40		
	4292-2	10	↓	3.69			1.61		
	4296-2	12	↓	3.71			1.58		
	4299-3	14	↓	4.19			2.78		
P13R/S(a) ↓	2176-3A	R/S 1-B	Cut	5.67	4.88	0.62	1.45	1.42	0.49
	2176-3B	R/S 1-B	9.5 mm	4.45			2.09		
	2178-1A	R/S 1-B	long(b)	3.84			1.16		
	2179-1A	R/S 1-C	↓	5.10			1.65		
	2179-1B	R/S 1-C	↓	4.46			0.99		
	2179-3A	R/S 1-C	↓	5.03			1.19		
	2180-2A	R/S 1-C	↓	4.85			0.80		
	2180-2B	R/S 1-C	↓	5.64			2.01		
	2178-4	R/S 1-B	Uncut	5.00	4.62	0.74	2.72	2.80	0.28
	2179-4	R/S 1-C	19.0 mm	5.47			3.22		
	2185-2	R/S 5-B	long(b)	4.18			2.63		
	2185-3	R/S 5-B	↓	3.84			2.63		

(a) Description of fuel rods given in Ref. 4-4.

(b) The matrix for P13R/S rods was 65% A-240 petroleum pitch, 30% 6353 graphite flour, and 5% octadecanal.

5. IRRADIATION CAPSULE PARAMETERS

5.1. DESIGN

The fuel for capsule HRB-14 was contained in a single graphite magazine extending the length of the capsule. The space was shared equally by GA and ORNL, as Fig. 5-1 shows in a schematic fuel layout. The ORNL specimens, which were molded graphite planchets, occupied the top half. Each planchet was 2.50 mm thick and 12.50 mm in diameter. The GA samples were bonded fuel rods, 9.52 mm thick and 12.50 mm in diameter. The loaded magazine was doubly contained within two stainless steel containment vessels.

The experiment was instrumented to monitor capsule parameters. Eight chromel/alumel thermocouples were inserted into the graphite magazine to monitor the graphite temperature. Although the fuel temperatures were not directly measured, they were calculated from the measured graphite temperatures. Temperature was controlled under changing reactor conditions by varying the gas mixture of the sweep-gas system. The sweep gas was sampled periodically to monitor the FGR from the fuel specimens during irradiation. Since HRB-14 was a one-cell capsule, the FGR measurement only indicated the overall fuel performance.

5.2. OPERATING HISTORY

Capsule HRB-14 was inserted into the RB position of HFIR on May 20, 1978 and discharged on January 4, 1979 after 10 cycles. ORNL was in charge of the capsule operation. The capsule operated for an equivalent 5124 h at 100-MW reactor power (Ref. 5-1). Table 5-1 presents the capsule operating history.

5.3. THERMAL ANALYSIS

ORNL performed the in-pile thermal analysis of capsule HRB-14 using the preirradiation design data (ORNL did not perform postirradiation thermal analysis). Figures 5-2 through 5-4 give the complete temperature histories (Ref. 5-1) of fuel rods No. 2, 10, and 17, which were next to graphite thermocouples. The figures show the centerline and surface fuel rod temperatures and the midwall graphite sleeve temperature.

GA calculated the time-average surface, centerline, and volume temperatures of all the fuel rods. The time-average temperatures of fuel rods No. 2, 10, and 17 were calculated based on the ORNL thermal analysis. The temperatures of the three rods were plotted as a function of capsule position. The points fell on a straight line. The time-average temperatures of the other 17 rods were determined from the graph. Table 5-2 gives the results. The average centerline and volume temperatures ranged from 1025° to 1190°C and 960° to 1130°C, respectively. Table 5-2 also gives the estimated uncertainty in the fuel rod temperature (Ref. 5-2).

5.4. FLUENCE AND BURNUP ANALYSIS

ORNL calculated the fast fluence for the HRB-14 fuel rods (Ref. 5-1). Table 5-3 lists the fluences. The fluence was 8.3 and $4.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} for rod positions 1 and 20, respectively.

Table 5-3 gives the burnups calculated by GA. Radiochemical methods measured the burnups on three fissile and three fertile samples. Appendix A details the calculations. The computer program CURIE calculated the burnups and fission product inventories of all samples. The cross sections of the heavy metal isotopes for the CURIE program were adjusted until the measured and calculated values agreed well. The adjusted set of cross sections was used to calculate all the sample burnups. The fertile burnups were 4.1% to 8.5% fissions per initial metal atom (FIMA); the (Th,U)O₂ burnups were 14.5% to 19.3% FIMA; and the straight uranium samples were 22.9% to 29.5% FIMA.

REFERENCES

- 5-1. Homan, F. J., and P. R. Kasten, "Gas-Cooled Reactor Programs, High Temperature Gas-Cooled Reactor Base-Technology Program, Annual Progress Report for Period Ending December 31, 1979," DOE Report ORNL-5643, Oak Ridge National Laboratory, July 1980.
- 5-2. Ketterer, J. W., General Atomic personal communication, September 1980.

Fig. 5-1. Fuel layout for capsule HRB-14

Fig. 5-2. Fuel rod temperature history for rod No. 2, capsule HRB-14. The graphite temperature was measured by a thermocouple in the graphite near rod No. 2.

Fig. 5-3. Fuel rod temperature history for rod No. 10, capsule HRB-14. The graphite temperature was measured by a thermocouple in the graphite near rod No. 10.

Fig. 5-4. Fuel rod temperature history for rod No. 17, capsule HRB-14. The graphite temperature was measured by a thermocouple in the graphite near rod No. 17.

TABLE 5-1
REACTOR OPERATING HISTORY^(a) FOR CAPSULE HRB-14

HFIR Cycle	Cycle Dates				Irradiation Time ^(b) (h)	
	Begin		End		During Cycle	Accumulated
	Day	Time	Day	Time		
162	5/20/78	0240	6/11/78	0157	527	527
163	6/12/78	1533	7/4/78	2020	531	1058
164 ^(c)	7/6/78	1615	7/30/78	2350	515	1573
165	7/31/78	1752	8/22/78	0100	510	2083
166	8/22/78	1909	9/13/78	0400	513	2596
167	9/15/78	1824	10/6/78	2115	506	3102
168	10/7/78	1650	10/29/78	0000	511	3613
169 ^(d)	10/29/78	1735	11/22/78	0225	502	4115
170	11/22/78	2147	12/14/78	0140	507	4622
171	12/14/78	1945	1/4/79	1759	502	5124

(a) Reference 5-1.

(b) Irradiation time is given in equivalent hours at 100 MW.

(c) Reactor was shut down from 2100, July 24, 1978 to 1408, July 27, 1978. The reactor also operated at reduced power on numerous occasions during this cycle due to weather conditions.

(d) Reactor was shut down from 0815, November 13, 1978 to 1830 November 15, 1978.

TABLE 5-2
TIME-AVERAGED TEMPERATURES OF HRB-14 FUEL RODS

Rod Position	Time-Averaged Temperature (°C)		
	Surface	Centerline (a)	Volume (b)
1	1035	1190	1130
2	1030	1180	1105
3	1020	1170	1095
4	1015	1165	1090
5	1005	1155	1080
6	1000	1145	1070
7	990	1135	1065
8	985	1130	1055
9	975	1120	1050
10	970	1110	1040
11	960	1100	1030
12	955	1095	1025
13	945	1085	1015
14	940	1075	1010
15	930	1065	1000
16	925	1060	990
17	915	1050	985
18	910	1040	975
19	900	1030	965
20	895	1025	960

(a) The 1σ uncertainty in the fuel rod centerline temperature is 12.5% based on a propagation of errors analysis using the following estimated uncertainties: heat generation in fuel rod $\pm 10\%$, in graphite $\pm 4\%$; thermal conductivity in fuel rod $\pm 15\%$, in graphite $\pm 5\%$, in sweep gas $\pm 10\%$; dimensions of fuel rod $\pm 2\%$, of graphite $\pm 5\%$, of thermocouple radial location $\pm 5\%$; and thermocouple temperature $\pm 3\%$ (Ref. 5-2).

(b) Volume temperature = (surface + centerline) $\div$ 2.

TABLE 5-3
NEUTRON FLUENCES AND BURNUPS OF SAMPLES

Capsule Position	Fast Fluence ^(a) ($\times 10^{25}$ n/m ²) (E > 29 fJ) _{HTGR}	Burnup (% FIMA) ^(b)	
		Fertile	Fissile
1	8.3	8.5	--
2	8.2	--	19.3
3	8.1	8.4	--
4	8.1	--	19.1
5	8.0	8.2	--
6	7.8	8.0	29.5
7	7.6	7.8	--
8	7.5	7.6	28.6
9	7.3	7.3	--
10	7.1	7.1	27.8
11	6.9	6.9	--
12	6.6	6.6	26.4
13	6.4	6.3	--
14	6.2	6.0	26.1
15	5.9	5.7	--
16	5.6	--	15.4
17	5.3	5.0	--
18	5.0	--	14.5
19	4.8	4.4	--
20	4.5	4.1	22.9

(a) Calculated at ORNL (Ref. 5-1).

(b) Calculated at GA.

6. RESULTS OF POSTIRRADIATION EXAMINATION

6.1. DISASSEMBLY AND VISUAL EXAMINATION

Capsule HRB-14 was disassembled in the High Radiation Level Examination Laboratory at ORNL. The primary containment was cut open at both ends, and the graphite sleeve was extracted from the containment.

The graphite sleeve contained the GA fuel rods and the ORNL wafers. The mechanical press to push out the fuel rods did not have a force gauge to measure the actual force to be applied to the fuel column. In order not to apply excessive force, a simple procedure was used. A 113-N (25.5-lb) weight was placed on the external manipulator handle. This force was transmitted through the manipulator to the mechanical press handle. A gauge measured the maximum force in the press to be 400 N (90 lb) because of the mechanical advantage. The graphite sleeve was secured in the mechanical press for fuel rod extraction. A graphite plug was placed next to the end fuel rod (No. 20) to protect it. The maximum force resulting from the 113-N (25.5-lb) weight was applied to the fuel column, but the fuel rods did not move. To reduce the column length, the graphite sleeve was then circumferentially cut 178 mm (7 in.) from the end next to the ORNL samples. As the sleeve was severed, seven wafers fell out. The wafers were in good condition. Half of the sleeve now contained only the 190-mm length of GA fuel rods. It was secured in the press, and force was applied. The rods began to move easily using less than the maximum force [400 N (90 lb)]. As rod No. 1 protruded from the cut end of the sleeve, the rod was gently held with tweezers to remove it. Rod No. 1 began to crumble. A V-trough was placed against the sleeve, and rod No. 1 was pushed onto it. Figure 6-1 shows the condition of rod No. 1 on the trough. The other rods were pushed out. All rods were intact as they came out of the sleeve; however, some rods began to crumble as they slid along the trough. Figure 6-2 shows the column of rods being pushed out.

Some of the fuel rods were contaminated with particles from other rods. Rods No. 11, 17, and 19 were most likely contaminated because of how they were handled during unloading. The other rods were less likely to have been contaminated.

The primary containment, gas inlet tube, and graphite sleeve were visually examined. All appeared to be in good condition. No signs of oxidation or other corrosion were on the surfaces.

Table 6-1 gives the results of the visual examination of the fuel rods. The fuel rods were examined at ORNL after unloading and at GA after shipping. The ORNL examination indicated that the fuel rods were very friable. The rods did not break into pieces, but rather, crumbled and debonded. Five fuel rods were essentially a pile of loose particles. Four rods were partially intact. Nine were intact but had significant debonding. Figures 6-3 through 6-22 show the condition of the fuel rods after unloading at ORNL and after shipping to GA.

GA performed a visual examination to determine particle failure (see Table 6-1). The failure was measured on the surface of the intact rods (No. 2, 3, and 4) or the loose particles. The failure reported was the total failure for all the particle types in the debonded rods divided by the total number of particles counted. The OPyC coating failure was significant and ranged from 3% to 45%. The OPyC failure appeared to be irradiation induced, as shown in Figs. 6-3 through 6-22. The SiC failure was 0.7% to 9%.

6.2. FISSION GAS RELEASE (FGR)

Fission gas retention characteristics of the fuel rods before and after irradiation were evaluated by neutron activation in the GA TRIGA reactor facility. Preirradiation measurements of the fissile fuel were made as part of the quality control evaluation to determine the amount of heavy metal contamination in the fuel specimens prior to irradiation. The post-

irradiation measurements were primarily to measure the average fuel failure in each fuel rod.

6.2.1. Technique

FGR measurements were made by irradiating fuel specimens in a graphite tube furnace designed to fit into a fuel element position of the TRIGA reactor core (Ref. 6-1). The furnace allowed measurements to be made at high temperatures, independent of the power generated in the fuel. The rods were irradiated at appropriate power levels for 0.5 h to produce $\sim 10^{14}$ fissions in each fuel specimen. During irradiation, the released fission gases were swept with helium into a liquid-nitrogen-cooled charcoal trap. The trapped gases were assayed for fission product isotopes by gamma-ray spectroscopy (Ref. 6-2) using a Ge(Li) detector and a 4096-channel analyzer. The fission product isotope birth fractions were calculated using the neutron flux in the TRIGA core and the end-of-life (EOL) fissionable material loadings. The amount of the EOL fuel loading for each specimen was determined by expressing the sum of the weights of all remaining fissionable material (U-233, U-235, Pu-239, and Pu-241) in terms of equivalent U-235, producing the equivalent Kr-85m yield (Ref. 6-3). The Kr-85m isotope was selected as the reference isotope, because it has a short half-life (4.4 h) and its gamma-ray energy peak can easily be resolved. A reference temperature of 1100°C was used for analysis of fuel failure levels. The preirradiation release/birth (R/B) data obtained under nonsteady-state conditions were corrected to steady-state production rates (multiplied by a factor of 1.9). However, the postirradiation R/B values were not corrected to steady-state production rates, because a study showed that the R/B values obtained for irradiated fuel in the 0.5-h TRIGA irradiation were essentially steady-state values (Ref. 6-4).

6.2.2. Calculation of In-Service Fuel Failure Levels

The FGR during TRIGA activation came from two sources: (1) as-fabricated heavy metal contamination outside the particle coatings and

(2) fuel particles which failed before and during (in-pile) irradiation, as shown by the following equation:

$$R/B_{EOL} = R/B_{\text{failed fuel}} + R/B_{EOL(U)} + R/B_{EOL(Th)} \quad , \quad (6-1)$$

where R/B_{EOL} = measured postirradiation FGR,

$R/B_{\text{failed fuel}}$ = FGR from in-pile failed fuel particles,

$R/B_{EOL(U)}$ = FGR at EOL from as-fabricated uranium contamination and failed particles (fissile rods only),

$R/B_{EOL(Th)}$ = FGR at EOL from as-fabricated thorium contamination and failed fertile particles.

Uranium and thorium contamination and failed particles in the fuel rods were measured before irradiation. The difference between the FGR at EOL resulting from as-fabricated contamination and failed particles and the measured postirradiation FGR (R/B_{EOL}) is the FGR from fuel particles that failed during irradiation.

Equation 6-1 calculated FGR resulting from in-pile fuel particle failure for each fuel rod specimen. Table 6-2 gives these results. The FGR from the exposed uranium and thorium from the as-fabricated fuel rods was calculated using the following equations:

$$R/B_{EOL(U)} = [R/B_{EOL(U)}] (X_{\text{fissile}}) \quad , \quad (6-2)$$

$$R/B_{EOL(Th)} = (R/B_{EOL})_{\text{cont}} + (R/B_{EOL})_{\text{pre-fail}} \quad , \quad (6-3)$$

$$(R/B_{EOL})_{\text{cont}} = (5.0 \times 10^{-5}) (X_{\text{fertile}}) \quad , \quad (6-4)$$

$$(R/B_{EOL})_{\text{pre-fail}} = [(Th_E) - (2 \times 10^{-4})] [(r/b_f)_{\text{fertile}}] \times (X_{\text{fertile}}) \quad , \quad (6-5)$$

where $(R/B_{EOL})_{cont}$ = FGR from as-fabricated thorium contamination,

$(R/B_{EOL})_{pre-fail}$ = FGR from failed fertile particles as-fabricated,

$R/B_{BOL}(U)$ = measured preirradiation FGR from the as-fabricated uranium contamination and failed fissile particles,

X = fraction of fissions that occurred in fissile or fertile particles at EOL,

r/b_f = fractional gaseous release from Kr-85m at 1100°C from failed fissile or fertile particles, and

Th_E = preirradiation exposed thorium (chlorine leach) from the as-fabricated thorium contamination and failed fertile particles.

The beginning of life (BOL) R/B from exposed uranium and thorium was determined to calculate their contributions to the R/B_{EOL} . The actual R/B from the uranium [$R/B_{BOL}(U)$] was measured on the unirradiated fissile rods (see Eq. 6-2). The preirradiation R/B from thorium [$R/B_{BOL}(Th)$] was only measured on rods No. 13 and 15 containing batch 6252-12 COMP, because the amount of thorium per rod was too small for activation analysis. For fertile rod No. 13 (Table 6-2), Eq. 6-2 was used, except that the fertile particle data were substituted for the fissile data called for in Eq. 6-2.

The $R/B_{BOL}(Th)$ was estimated for all the other rods containing thorium (rods No. 1, 3, 6, 7, 8, 9, 10, 12, 18, and 20). As discussed in Section 4.3, all the fertile batches, except 6252-12 COMP and 6252-13-010, in the unirradiated rods had failed particles and contamination, based on the chlorine leach data. The two exceptions had only contamination. (See Table 4-7 for summary of data.) For the rods containing failed fertile particles, the failed particles and contamination contributed to the $R/B_{BOL}(Th)$ (see Eq. 6-3). For those rods, the $R/B_{BOL}(Th)$ from contamination was assumed to be constant for all rods and the same as the R/B measured (5×10^{-5} R/B Kr-85m) in the two rods containing 6252-12 COMP (see Eq. 6-4). The

$R/B_{\text{BOL}}(\text{Th})$ from as-fabricated failed particles was estimated from the exposed thorium measured by chlorine leaching. Since the exposed thorium also came from contamination and failed particles, the contribution from thorium contamination was subtracted from the exposed thorium. Table 6-2 shows that the average contamination from batches 6252-12 COMP and 6252-13-010 was 2×10^{-4} g Th/g Th. The contamination was assumed to be constant for all rods. Therefore, the failure fraction of fertile particles was the exposed thorium value minus 2×10^{-4} g Th/g Th (see Eq. 6-5).

The fraction of fissions occurring in each isotope at EOL was determined by summing the weights of all remaining fissionable material (U-233, U-235, Pu-239, and Pu-241), normalized to the thermal fission yields of Kr-85m.

The in-pile particle failure fraction was calculated for each sample using the following equations:

$$F_{\text{fissile}} = \frac{R/B_{\text{failed fuel}}}{(X_{\text{fissile}}) [(r/b_f)_{\text{fissile}}]}, \quad (6-6)$$

$$F_{\text{fertile}} = \frac{R/B_{\text{failed fuel}}}{(X_{\text{fertile}}) [(r/b_f)_{\text{fertile}}]}, \quad (6-7)$$

where F = in-pile fuel failure fraction of fissile or fertile particles.

The most recent data on r/b_f (Ref. 6-5) give the following equation as an estimate for the burnup dependence for failed ThO_2 (for Kr-85m at 1100°C):

$$r/b_f = 0.0013 + 0.0018 (\% \text{ FIMA})^{0.9} \quad (6-8)$$

Equation 6-8 calculated the r/b_f of the fissile and fertile particles. This equation was based on ThO_2 particles with burnups up to ~12% FIMA. The

oxide fissile kernels in HRB-14 were irradiated to burnups as high as 33% FIMA. Since Eq. 6-8 may not be valid at these burnups or compositions, the r/b_f calculated for 12% FIMA was assumed for the fissile particles. This assumption would give a higher failure fraction (more conservative) using Eq. 6-6.

Table 6-2 gives the calculated in-pile failure fractions of the fissile and fertile particles. Rods No. 2 and 4, which were irradiated to ~19% FIMA, had TRISO (Th,U)O₂ failure of 9.4×10^{-3} and 1.6×10^{-2} , respectively. The (Th,U)O₂ particles irradiated to 14.5% FIMA (rod No. 18) had a failure fraction of 4.3×10^{-4} . The failure fractions of the TRISO ThO₂ particles were calculated to be zero to 2.7×10^{-2} . Batch 6252-18-010 had a failure fraction of zero and 1.0×10^{-2} in fertile rods No. 9 and 7. If all the failure in fissile rods No. 6, 8, 10, 12, and 20 were from fertile batch 6252-18-010, the fertile failure fraction was zero to 2.2×10^{-2} . Batch 6252-12 COMP (rod No. 13) irradiated in the FSV test elements had zero failed particles and performed the best overall of the fertile batches.

6.3. METALLOGRAPHY

GA performed a metallographic examination on 15 fuel rods. The intact and debonded rods were mounted, ground, and polished in the metallographic hot cell. After grinding, the mount was usually reimpregnated with mounting compound to reduce kernel pullout during polishing. Two or more polished sections were prepared from 11 mounts to increase the number of particles examined. All specimens were examined under bright-field illumination and polarized light with a Lietz metallograph.

6.3.1. Fuel Rod Matrix

The fuel rod matrix was examined metallographically on the three intact fuel rods. Figures 6-23 through 6-25 show the matrix microstructure. The microstructure visually appeared in good condition.

The matrix macroporosity, which is composed of voids $\geq 50 \mu\text{m}$, was measured on six polished sections of the three rods. Table 6-3 lists the results. The postirradiation macroporosity ranged from 37% to 49%. The macroporosity increased from 22% to 52% during irradiation. The increase in macroporosity indicated that the carbonaceous matrix phase densified. The values for rod No. 6 show a wide variation in macroporosity. Figures 6-23 through 6-25 show the macroporosity after irradiation.

Table 6-3 shows that the matrix pulled away or debonded from the OPyC coating of most of the particles. The cross sections (Figs. 6-23 through 6-25) show the matrix debonding. Figure 6-26 illustrates the matrix pulling away from the OPyC coating at a higher magnification.

No matrix-coating interaction was observed in the three intact rods.

6.3.2. Fissile Particles

The TRISO (Th,U)O₂, UO₂, and UC_{0.7}O_{0.5} particles were examined metallographically in eight fuel rods. One rod (No. 4) was intact, and seven were partially or completely debonded. Table 6-4 gives the results.

The performance of the OPyC coating was very good. Seven fissile samples had zero failure. The (Th,U)O₂ particles in rod No. 4 had an OPyC failure of 4.6%. Figure 6-27 shows that the failure appeared to be irradiation induced. Under polarized light, the OPyC coating of all samples appeared relatively isotropic.

All eight samples showed zero pressure vessel failure (no SiC coating failure). A few particles had cracks in the SiC coating, but these were attributed to metallographic preparation. Figures 6-28 through 6-31 show examples of intact fissile particles.

The IPyC coatings of all fissile samples were in good condition. The cracking ranged from zero to 3.0%. The IPyC coating debonded from the SiC

coating in zero to 7.7% of the particles. Under polarized light, the IPyC coatings of all samples appeared relatively isotropic.

The buffer cracking was dependent on the kernel composition. No cracking was seen in the UO_2 and $(\text{Th,U})\text{O}_2$ particles (two batches). The $\text{UC}_{0.7}\text{O}_{0.5}$ particles from both batches had 10% to 71% buffer cracking.

The microstructure and shape of the three kernel types were evaluated and compared. The $(\text{Th,U})\text{O}_2$ kernels retained their round shape. The $(\text{Th,U})\text{O}_2$ kernels (Fig. 6-28) irradiated at 1080°C to a burnup of 19.1% had relatively large pores which varied in size. Small areas of a white metallic phase were visible. The $(\text{Th,U})\text{O}_2$ kernels irradiated at 990°C to a burnup of 15.1% FIMA had small pores which were more uniform in size. The UO_2 kernels (Fig. 6-30) were still round, but slight deformation had occurred. The UO_2 microstructure was similar to the high burnup $(\text{Th,U})\text{O}_2$ kernels. The $\text{UC}_{0.7}\text{O}_{0.5}$ kernels generally retained their shape, as shown in Fig. 6-31. However, 2.4% to 20.2% of the $\text{UC}_{0.7}\text{O}_{0.5}$ kernels extruded into the buffer. Table 6-4 indicates that the extrusion increased with decreasing temperature. Figure 6-32 gives examples of the kernel extrusion. The maximum extrusion distance was the thickness of the buffer coating. Sometimes the kernel appeared to penetrate an intact buffer, and at other times, the kernel extruded into cracks in the buffer. However, the kernels did not extrude into the buffer cracks in the majority of particles. The microstructure of $\text{UC}_{0.7}\text{O}_{0.5}$ kernels irradiated at the higher burnups varied, as shown in Fig. 6-31. The kernels had areas of a very fine porosity and/or areas of relatively large pores which varied in size. The kernels irradiated to the lowest burnup (see Fig. 6-29) had small uniform pores.

Table 6-5 summarizes the observed chemical attack of the SiC coating. The attacks in the TRISO $(\text{Th,U})\text{O}_2$ and UO_2 particles irradiated at $\sim 1155^\circ\text{C}$ (peak temperature) to a burnup of 19.1% and 29.5% FIMA, respectively, were very similar. A localized SiC attack caused by palladium (see Section 6.4) was observed in 8% of the particles, and the penetration was $\sim 2\text{ }\mu\text{m}$. Figure 6-33 gives an example. No SiC attack was observed in the $(\text{Th,U})\text{O}_2$ particles

(rod No. 16) irradiated at 1060°C to a burnup of 15.4% FIMA. However, palladium had concentrated in small localized regions at the SiC-IPyC interface.

SiC attack was seen in 3.7% to 22.9% of the TRISO $\text{UC}_{0.7}\text{O}_{0.5}$ particles in rods No. 8, 10, 12, and 14. The maximum penetration was 9 μm . The appearance of the attack was more like rare-earth attack, as shown in Fig. 6-34. The attack was spread out along the SiC coating on one side of the particle. Fission products were in the IPyC coating adjacent to the reaction zone. The $\text{UC}_{0.7}\text{O}_{0.5}$ particles (rod No. 20) irradiated at 1025°C to a burnup of 22.9% FIMA had no SiC attack and no fission products in the IPyC coating. However, localized regions of palladium were again seen at the SiC-IPyC interface of those particles.

Localized external contamination attacked the outside surface of the SiC coating of one TRISO UO_2 particle (1% of sample population). Figure 6-35 shows the chemical attack which was assumed to be caused by iron. The maximum penetration was 9 μm . The attack did not cause failure of the SiC coating, based on the metallographic examination.

Kernel migration was observed in the TRISO UO_2 rod irradiated at 1145°C to a burnup of 29.5% FIMA. Figure 6-33 shows the maximum migration of ~16 μm . Kernel migration was seen in four other particles (5% of sample population).

6.3.3. Fertile Particles

GA examined the TRISO ThO_2 particles in 13 fuel rods. All rods were partially or completely debonded. Table 6-4 gives the results of the metallographic examination.

The OPyC coating failure was 1.5% to 29.1%. The failure appeared to be irradiation induced, as shown in Fig. 6-36. The failure was generally higher for the samples exposed to the higher temperatures and fluences.

Under polarized light, the OPyC coating appeared relatively isotropic for all samples (see Fig. 6-37).

GA evaluated the total coating failure of the particles. Figure 6-37 presents an example of an intact particle, and Fig. 6-38 shows a failed particle. The OPyC plus SiC coating failure was zero to 2.4%. The failure occurred in three high-burnup samples which had the 85- μ m buffer coatings. This failure was assumed to be pressure vessel failure (see Fig. 6-38).

GA examined the IPyC and buffer coatings. The IPyC failure was 8% to 70%. The IPyC coating debonded from the SiC coating in 11% to 85% of the particles. The higher exposure particles had high failure and debonding. Under polarized light, the IPyC coatings were relatively isotropic. The buffer coating cracked in 6% to 26% of the particles.

The ThO₂ kernels were in good condition. No kernel migration was observed. They retained their shape, except for a few kernels which extruded slightly into buffer cracks. The microstructure of the high burnup and temperature samples showed a high concentration of pores. No grain boundaries were visible. The kernels irradiated to a burnup of $\leq 5.7\%$ FIMA had less porosity, and the grain boundaries were visible. Figure 6-37 shows an example of both types of microstructures.

A white metallic phase was found in the void of the SiC coating of one particle from rods No. 1 and 7. Figure 6-39 shows one of them.

The SiC coating was attacked by palladium (see Section 6.4) in 4.0% of the TRISO ThO₂ particles irradiated in rod No. 1 at 1190°C to a burnup of 8.5% FIMA. Table 6-5 lists the results. The attack was localized in all particles, and the maximum penetration was 14 μ m. In one particle, the reaction zone was also spread out along the SiC coating. Figure 6-40 gives examples.

6.3.4. Inert Particles

GA examined the TRISO inert particles in 13 fuel rods. One rod (No. 4) was intact, and 12 rods were partially or completely debonded. Table 6-4 gives the results.

The OPyC and the OPyC plus SiC failure was very high for all these inert batches. The OPyC coating failure was 28% to 100%. The OPyC plus SiC failure was 2% to 57%. Batch 6351-05-030 (silicon-doped) had the highest OPyC and SiC failure. Figures 6-41 and 6-42 show examples of the failure in silicon-doped and non-doped batches. The OPyC coating failure appeared to be irradiation induced. The SiC coating failure was assumed to be an artifact of grinding and polishing.

The TRISO inert particles occasionally had a long circumferential crack in the SiC coating. Figure 6-43 gives an example. This type of crack was also observed in the unirradiated particles.

6.4. ELECTRON MICROPROBE

ORNL performed an electron microprobe examination on a TRISO ThO₂ particle from rod No. 1, a TRISO UO₂ particle in rod No. 6, and a TRISO UC_{0.7}O_{0.6} particle in rod No. 10. One or two small areas from each particle were scanned for the following elements: uranium, cerium, neodymium, palladium, ruthenium, molybdenum, silicon, and chlorine. Figures 6-44 through 6-46 give the results.

SiC chemical attack was observed in TRISO ThO₂ particles irradiated at 1190°C to a burnup of 8.5% FIMA. Figure 6-44 shows that the white metallic phase in the SiC reaction zone was palladium. No chlorine was measured.

The UO₂ particle was irradiated at 1145°C to a burnup of 29.5% FIMA. Figure 6-45(a,b,c,d) shows the kernel results. Uranium, cerium, and neodymium were spread uniformly in the kernel. Molybdenum and ruthenium were

concentrated together in small areas. Palladium was concentrated separately in small areas in the kernel. Figure 6-45(e,f,g) shows an area where the SiC coating was slightly attacked. The white metallic specs were palladium. No cerium, neodymium, or chlorine were detected at the SiC coating.

The $UC_{0.7}O_{0.5}$ particle was irradiated at $1110^{\circ}C$ to a burnup of 27.8% FIMA. Figure 6-46(a,b,c,d) shows that uranium and neodymium were spread throughout the kernel. Palladium had concentrated slightly. Figure 6-46(e, f,g) presents an area where the SiC was attacked. Neodymium, cerium, and palladium were distributed along the reaction zone. No chlorine was detected.

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N79030

Fig. 6-1. Fuel rod No. 1 after being pushed out of the graphite sleeve

R75771

(a)

R75772

(b)

Fig. 6-2. Unloading of fuel rods from sleeve: (a) fuel rods on V-trough and end of sleeve in fuel rod extractor press; (b) severe debonding of rod No. 11 (in center)

S7907-65

S7907-66

S7907-67

S7907-68

Fig. 6-3. Photographs of fuel rod 7161-014-01-6 irradiated in HRB-14 position No. 1 to a fast fluence of $8.3 \times 10^{25} \text{ n/cm}^2 (E > 29 \text{ fJ})_{\text{HTGR}}$ at a volume average temperature of 1130°C . Note the OPyC failure and OPyC plus SiC failure in (b), (c), and (d). The OPyC failure appears to be irradiation induced.

SR78003-1

(a)

S7907-9

(b)

SR78003-3

(c)

S7907-12

(d)

Fig. 6-4. Photographs of fuel rod 7161-014-02-6 irradiated in HRB-14 position No. 2 to a fast fluence of $8.2 \times 10^{25} \times 10 \text{ n/cm}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at a volume average temperature of 1105°C : (a) and (c) side and end views of unirradiated rod; (b) and (d) side end views of rod after irradiation (sheet 1 of 2)

S7907-10

Fig. 6-4. Photographs of fuel rod 7161-014-02-6 irradiated in HRB-14 position No. 2 to a fast fluence of $8.2 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at a volume average temperature of 1105°C : (e) surface of rod. Note OPyC failure. (sheet 2 of 2)

R75780

(a)

S7907-45

(b)

S7907-41

(c)

S7907-39

(d)

Fig. 6-5. Photographs of fuel rod 7161-014-03-11 irradiated in HRB-14 position No. 3 to a fast fluence of $8.1 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$) HTGR at a volume average temperature of 1095°C : (a) rod after unloading; (b), (c), and (d) rod after shipping (sheet 1 of 2)

S7907-40

(e)

S7907-46

(f)

Fig. 6-5. Photographs of fuel rod 7161-014-03-11 irradiated in HRB-14 position No. 3 to a fast fluence of $8.1 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at a volume average temperature of 1095°C : (e) surface of rod. Note OPyC plus SiC failure. (sheet 2 of 2)

SR78031-1

(a)

S7907-24

(b)

SR78031 3

(c)

S7907-20

(d)

Fig. 6-6. Photographs of fuel rod 7161-014-04-11 irradiated in HRB-14 position No. 4 to a fast fluence of $8.1 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at a volume average temperature of 1090°C : (a) and (b) side and end view of unirradiated rod; (c) and (d) side and end view of rod after irradiation (sheet 1 of 2)

S7907-19

(e)

S7907-22

(f)

Fig. 6-6. Photographs of fuel rod 7161-014-04-11 irradiated in HRB-14 position No. 4 to a fast fluence of $8.1 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$) HTGR at a volume average temperature of 1090°C : (e) and (f) surface of rod. Note OPyC failure and OPyC plus SiC failure. The OPyC failure appears to be irradiation induced. (sheet 2 of 2)

R75778

(a)

S7907-38

(b)

S7907-32

(c)

Fig. 6-7. Photographs of fuel rod 7161-014-05-3 irradiated in HRB-14 position No. 5 to a fast fluence of $8.0 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$)_{HTCR} at a volume average temperature of 1080°C: (a) rod after unloading; (b) and (c) rod after shipping

R75777

(a)

S7907-25

(b)

S7907-27

(c)

S7907-28

(d)

Fig. 6-8. Photographs of fuel rod 7161-014-06-8 irradiated in HRB-14 position No. 6 to a fast fluence of $7.8 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}_{\text{HTGR}}$) at a volume average temperature of 1070°C : (a) rod after unloading; (b), (c), and (d) rod after shipping. Note OPyC failure on rod surface (c) and in inert particle (d).

R75776

(a)

S7907-51

(b)

S7907-47

(c)

S7907-49

(d)

Fig. 6-9. Photographs of fuel rod 7161-014-07-3 irradiated in HRB-14 position No. 7 to a fast fluence of $7.6 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at a volume average temperature of 1065°C: (a) rod after unloading; (b), (c), and (d) rod after shipping (sheet 1 of 2)

S7907-48

(e)

S7907-55

(f)

Fig. 6-9. Photographs of fuel rod 7161-014-07-3 irradiated in HRB-14 position No. 7 to a fast fluence of $7.6 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$) HTGR at a volume average temperature of 1065°C : (e) and (f) surface of rod. Note OPyC failure. The OPyC failure appears to be irradiation induced. (sheet 2 of 2)

R75775

(a)

S7907-70

(b)

S7907-73

(c)

S7907-76

(d)

Fig. 6-10. Photographs of fuel rod 7161-014-08-2 irradiated in HRB-14 position No. 8 to a fast fluence of $7.5 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at a volume average temperature of 1055°C : (a) rod after unloading; (b), (c), and (d) rod after shipping. Note OPyC plus SiC failure in (d).

R75774

(a)

S7907-13

(b)

S7907-15

(c)

S7907-16

(d)

Fig. 6-11. Photographs of fuel rod 7161-014-09-4 irradiated in HRB-14 position No. 9 to a fast fluence of $7.3 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at a volume average temperature of 1050°C : (a) rod after unloading; (b), (c), and (d) rod after shipping. Note OPyC failure and OPyC plus SiC failure in (c) and (d). The OPyC failure appears to be irradiation induced.

R75773

(a)

S7907-61

(b)

S7909-62

(c)

S7907-57

(d)

Fig. 6-12. Photographs of fuel rod 7161-014-10-8 irradiated in HRB-14 position No. 10 to a fast fluence of $7.1 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$) HTGR at a volume average temperature of 1040°C : (a) rod after unloading; (b), (c), and (d) rod after shipping

S7907-59

Fig. 6-13. Photograph of fuel rod 7161-014-11-4 irradiated in HRB-14 position No. 11 to a fast fluence of $6.9 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at a volume average temperature of 1030°C. Condition of rod after shipping.

R75789

(a)

S7907-77

(b)

S7907-78

(c)

S7907-80

(d)

Fig. 6-14. Photographs of fuel rod 7161-014-12-2 irradiated in HRB-14 position No. 12 to a fast fluence of $6.6 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at a volume average temperature of 1025°C : (a) rod after unloading; (b), (c), and (d) rod after shipping. Note OPyC failure in (d).

R75790

(a)

S7907-82

(b)

S7907-84

(c)

S7907-86

(d)

Fig. 6-15. Photographs of fuel rod 7161-014-13-7 irradiated in HRB-14 position No. 13 to a fast fluence of $6.4 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at a volume average temperature of 1015°C : (a) rod after loading; (b), (c), and (d) rod after shipping. Note OPyC failure in (d). The OPyC failure appears to be irradiation induced.

R75791

(a)

S7907-88

(b)

S7907-87

(c)

S7907-89

(d)

Fig. 6-16. Photographs of fuel rod 7161-014-14-1 irradiated in HRB-14 position No. 14 to a fast fluence of $6.2 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$) HTGR at a volume average temperature of 1010°C : (a) rod after unloading; (b), (c), and (d) rod after shipping. Note OPyC failure in (d). The OPyC failure appears to be irradiation induced.

S7907-1

S7907-2

S7907-4

S7907-6

Fig. 6-17. Photographs of fuel rod 7161-014-15-8 irradiated in HRB-14 position No. 15 to a fast fluence of $5.9 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$) HTGR at a volume average temperature of 1000°C . Note OPyC failure and OPyC plus SiC failure in (b), (c), and (d). The OPyC failure appears to be irradiation induced.

R75785

(a)

S7907-92

(b)

S7907-20

(c)

S7907-93

(d)

Fig. 6-18. Photographs of fuel rod 7161-014-16-8 irradiated in HRB-14 position No. 16 to a fast fluence of $5.6 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$) HTGR at a volume average temperature of 990°C : (a) rod after unloading; (b), (c), and (d) rod after shipping. Note OPyC plus SiC failure in (d).

S7907-60

Fig. 6-19. Photograph of fuel rod 7161-014-17-9 irradiated in HRB-14 position No. 17 to a fast fluence of $5.3 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at a volume average temperature of 985°C. Condition of rod after shipping.

R75786

(a)

S7907-98

(b)

Fig. 6-20. Photographs of fuel rod 7161-014-18-4 irradiated in HRB-14 position No. 18 to a fast fluence of $5.0 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at a volume average temperature of 975°C : (a) rod after unloading; (b) rod after shipping

S7907-102

S7907-106

S7907-103

S7907-104

Fig. 6-21. Photographs of fuel rod 7161-014-19-7 irradiated in HRB-14 position No. 19 to a fast fluence of $4.8 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$) HTGR at a volume average temperature of 965°C . Note OPyC failure and OPyC plus SiC failure in (b), (c), and (d).

S7907-108

S7907-111

Fig. 6-22. Photographs of fuel rod 7161-014-20-5 irradiated in HRB-14 position No. 20 to a fast fluence of $4.5 \times 10^{25} \text{ n/cm}^2$ ($E > 29 \text{ fJ}$) HTGR at a volume average temperature of 960°C . Condition of rod after shipping. Note OPyC failure in (b).

L7907-258

(a)

L9707-266 thru-270

(b)

Fig. 6-23. Representative photomicrographs of fuel rod 7161-014-03-11 irradiated in HRB-14 position No. 3 to a fluence of $8.1 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1095°C: (a) matrix structure; (b) composite of radial cross section

L7907-419

(a)

L-7907-289 thru-294

(b)

Fig. 6-24. Representative photomicrographs of fuel rod 7161-014-04-11 irradiated in HRB-14 position No. 4 to a fluence of $8.1 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1090°C: (a) matrix structure; (b) composite of radial cross section

L7907-48

(a)

L7907-68 thru-73

(b)

Fig. 6-25. Representative photomicrographs of fuel rod 7161-014-06-8 irradiated in HRB-14 position No. 6 to a fluence of $7.8 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1070°C: (a) matrix structure; (b) composite of radial cross section

L7907-49

L7907-51

Fig. 6-26. Typical examples of matrix debonding from the OPyC coating of TRISO particles in the intact fuel rods from capsule HRB-14

L7907-378

(a)

L7907-379

(b)

Fig. 6-27. Example of OPyC coating failure of TRISO (Th,U)O₂ particle (6155-05-020) irradiated in rod No. 4 at 1090°C to a fluence of 8.1×10^{25} n/cm² ($E > 29$ fJ)_{HTGR}: (a) bright field; (b) polarized light

L7907 360

(a)

L7907.361

(b)

Fig. 6-28. Example of TRISO (Th,U)O₂ particle (6155-05-020) irradiated in rod No. 4 at 1090°C to a burnup of 19.1% FIMA and a fluence of $8.1 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}: (a) bright field; (b) polarized light

L7907-585

L7907-506

Fig. 6-29. Example of total particle and kernel microstructure of TRISO $\text{UC}_{0.7}\text{O}_{0.5}$ particle (6157-08-010) irradiated in rod No. 20 at 960°C to a burnup of 22.9% FIMA and a fluence of $4.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}

L7907-392

(a)

L7907-393

(b)

Fig. 6-30. Example of TRISO UO_2 particle (6152-01-010) irradiated in rod No. 6 at 1070°C to a burnup of 29.5% FIMA and a fluence of $7.8 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$) HTGR: (a) bright field; (b) polarized light

L7907-483

(a)

L7907-485

(b)

Fig. 6-31. Examples of total coated particles and kernel microstructures of TRISO $\text{UC}_{0.7}\text{O}_{0.5}$ particles (6157-08-010 and 6157-08-020): (a) and (b) particles irradiated at $\sim 1050^\circ\text{C}$ to a burnup of 28% FIMA and a fluence of $\sim 7.3 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} (sheet 1 of 2)

L7907-326

(c)

L7907-328

(d)

L7907-363

(e)

Fig. 6-31. Examples of total coated particles and kernel microstructures of TRISO $UC_{0.7}O_{0.5}$ particles (6157-08-010 and 6157-08-020): (c), (d), and (e) other examples (sheet 2 of 2)

L7907-441

(a)

L7907-443

(b)

L7907-445

(c)

Fig. 6-32. Maximum extrusion of $UC_{0.7}O_{0.5}$ kernel (6157-08-20) irradiated in rod No. 10 at $1040^{\circ}C$ to a burnup of 27.8% FIMA

L7907-198

L7907-201

Fig. 6-33. Kernel migration of 16 μm and palladium attack (maximum penetration of $\sim 2 \mu\text{m}$) of SiC coating in TRISO UO_2 particle (6152-01-010) irradiated in rod No. 6 at 1145°C to a burnup of 29.5% FIMA for 5124 h

L7907-467

L7907-471

L7907-469

Fig. 6-34. Example of rare earth and palladium attack of SiC coating in TRISO $\text{UC}_{0.7}\text{O}_{0.5}$ particle (6157-08-020) irradiated in rod No. 10 at 1110°C to a burnup of 27.8% FIMA. Note the fission products in IPyC coating.

L7907-133

(a)

L7907-162

(b)

L7907-160

(c)

L7907-161

(d)

Fig. 6-35. Attack of outside surface of SiC coating of TRISO UO_2 particle (6152-01-010) irradiated in rod No. 6 at 1070°C : (a), (b), and (c) bright field; (d) polarized light

L7907-178

(a)

L7907-179

(b)

Fig. 6-36. Example of OPyC and IPyC coating failure and debonding of IPyC in TRISO ThO_2 particle (6252-20-010) irradiated in rod No. 3 at 1095°C to a fluence of $8.1 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}: (a) bright field; (b) polarized light

L7907-121

(a)

L7907-122

(b)

L7907-692

(c)

L7907-693

(d)

Fig. 6-37. Example of intact TRISO ThO_2 particle showing kernel microstructure: (a) and (b) particle (6252-20-010) irradiated in rod No. 3 at 1090°C to a burnup of 8.4% FIMA; (c) and (d) particle (6252-14-010) irradiated in rod No. 17 at 985°C to a burnup of 5.0% FIMA. Note: (a) and (c) are bright field and (b) and (d) are polarized light.

L7907-667

Fig. 6-38. Example of pressure vessel failure in TRISO ThO₂ particle (6252-17-010) irradiated at 1130°C to a fluence of 8.3×10^{25} n/m² ($E > 29$ fJ)_{HTGR} and a burnup of 8.5% FIMA

L7907-660

L7907-662

Fig. 6-39. Example of metallic phase (probably silicon) in void of SiC coating of TRISO ThO₂ particle (6252-18-010) rod No. 7 irradiated at 1065°C to a fluence of $7.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}

L7907-687

(a)

L7907-688

(b)

Fig. 6-40. Palladium attack in TRISO ThO₂ batch (6252-17-010): (a) and (b) irradiated to a burnup of 8.5% FIMA at a centerline temperature of 1190°C in rod No. 1 (sheet 1 of 2)

L7907-682

(c)

L7907-680

(d)

Fig. 6-40. Palladium attack in TRISO ThO₂ batch (6252-17-010): (c) and (d) other examples of palladium attack (sheet 2 of 2)

L7907-629

(a)

L7907-630

(b)

Fig. 6-41. Example of failure of non-doped OPyC coating of TRISO inert batch (6351-05-010) irradiated in rod No. 20 at 960°C to a fluence of $4.9 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}: (a) bright field; (b) polarized light

L7907-64

(a)

L7907-65

(b)

Fig. 6-42. Example of OPyC and SiC coating failure of Si-doped TRISO inert batch (6351-05-030) irradiated in rod No. 6 at 1070°C to a fluence of $7.8 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}: (a) bright field; (b) polarized light

L7907-479

L7907-480

Fig. 6-43. Example of a long circumferential crack in SiC coating of TRISO inert particle (6351-05-010) irradiated at 1040°C to a fluence of $7.1 \times 10^{25} \text{ n/m}^2$ ($E > fJ$)_{HTGR}

L7907-682

(a)

N80028-2

(b)

N80028-1

(c)

N80028-3

(d)

Fig. 6-44. Results of electron microprobe examination in SiC reaction area of a TRISO ThO₂ particle irradiated in fuel rod No. 1: (a) optical light photomicrograph; (b) back-scattered electron image; (c) scan of Si Kα; (d) scan of Pd Lα

L7907-40

(a)

N80029-7

(b)

N80029-4

(c)

N80029-5

(d)

N80029-3

(e)

N80029-1

(f)

N80029-2

(g)

N80029-6

(h)

Fig. 6-45. Results of electron microprobe examination of kernel of a TRISO UO_2 particle irradiated in fuel rod No. 6: (a) optical light photomicrograph; (b) back-scattered electron microprobe image; (c) scan of U $M\alpha$; (d) scan of Nd $L\alpha$; (e) scan of Mo $L\alpha$; (f) scan of Ru $L\alpha$; (g) scan of Ce $L\alpha$; (h) scan of Pd $L\alpha$ (sheet 1 of 2)

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L7907-74

(i)

N80029-9

(j)

N80029-10

(k)

N80029-8

(l)

Fig. 6-45. Results of electron microprobe examination of kernel of a TRISO UO₂ irradiated in fuel rod No. 6: (i,j,k,l) SiC reaction area; (i) optical light photomicrograph; (j) back-scattered electron image; (k) scan of Si K α ; (l) scan of Pd L α (sheet 2 of 2)

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L7907-738

(a)

N80025-1

(b)

N80025-2

(c)

N80025-4

(d)

N80025-3

(e)

Fig. 6-46. Results of electron microprobe examination of kernel of a TRISO $UC_{0.7}O_{0.5}$ particle irradiated in fuel rod No. 10: (a) optical light photomicrograph; (b) back-scattered electron image; (c) scan of U $M\alpha$; (d) scan of Nd $L\alpha$; (e) scan of Pd $L\alpha$ (sheet 1 of 2)

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Fig. 6-46. Results of electron microprobe examination of kernel of a TRISO $\text{UC}_{0.7}\text{O}_{0.5}$ particle irradiated in fuel rod No. 10: (f,g,h,i,j,k,l,m) SiC reaction area; (f) optical light photomicrograph; (g) back-scattered electron image; (h) scan of U $\text{M}\alpha$; (i) scan of Si $\text{K}\alpha$; (j) scan of Ce $\text{L}\alpha$; (k) scan of Pd $\text{L}\alpha$; (l) scan of Nd $\text{L}\alpha$; (m) scan of Cs $\text{L}\alpha$ (sheet 2 of 2).

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TABLE 6-1
RESULTS OF VISUAL EXAMINATION

Rod Posi- tion	TRISO Coated Particle Batches				H-451 Shim Content (Volume Fraction)	Variables of Fertile OPyC Coatings			Si-Doping of OPyC of Inert Batches	Matrix Batch No.	Irradiation Conditions		Visual Examination			
	Fissile		ThO ₂ Batch No. (6232-)	Inert Batch No. (6351-)		Density (g/cm ³)	Micro- porosity (ml/kg OPyC)	Coating Rate (μm/min)			Volume Av Temp (°C)	Fast Fluence (10 ²⁵ n/m ²) (E > 29 fJ) _{HTGR}	ORNL Examination	GA Examination		
													General Condition	General Condition (After Shipment)	Observed Failure ^(a) (%)	
															OPyC	SiC
1	--	--	17-01	05-010	0.150	1.96	23.69	5.44	No	M0450	1130	8.3	Completely debonded ^(c)	Same	45	0.7
2	6155-05-020	(Th,U)C ₂	--	05-020	0.350	N/A ^(b)	N/A	N/A	Yes	M0450	1105	8.2	Good condition	Same	6 particles ^(d)	1 particle ^(d)
3	--	--	20-01	05-030	0.150	1.98	51.06	8.57	Yes	M0450	1095	8.1	Intact, debonding	More debonding	25 particles ^(d)	2 particles ^(d)
4	6155-05-020	(Th,U)C ₂	--	05-020	0.350	N/A	N/A	N/A	Yes	M0450	1090	8.1	Good condition	Same	11 particles ^(d)	0 ^(d)
5	--	--	19-010	05-010	0	1.92	40.53	7.23	No	M0450	1080	8.0	Intact, debonding	~2/3 rod debonded	34	2
6	6152-01-010	UO ₂	18-010	05-030	0.350	1.83	28.47	5.00	Yes	M0460	1070	7.8	Intact, debonding	More debonding	51	9
7	--	--	18-010	--	0.258	1.83	28.47	5.00	N/A	M0450	1065	7.6	Intact, debonding	Broke in half	17	0
8	6157-08-010	UCO ₂ 0.5	18-010	05-020	0.350	1.83	28.47	5.00	Yes	M0460	1055	7.5	~1/2 rod debonded ^(e)	Same	10	2
9	--	--	18-010	--	0.248	1.83	28.47	5.00	N/A	M0450	1050	7.3	Intact, debonding	~2/3 rod debonded	9	0
10	6157-08-020	UCO ₂ 0.6	18-010	05-010	0.350	1.83	28.47	5.00	No	M0460	1040	7.1	Intact, debonding	~1/3 rod debonded	24	0
11	--	--	13-010	05-020	0	1.79	57.30	8.62	Yes	M0450	1030	6.9	Completely debonded ^(e)	Same	ND ^(b)	ND
12	6157-08-010	UCO ₂ 0.5	18-010	05-020	0.350	1.83	28.47	5.00	Yes	M0460	1025	6.6	Intact, debonding	2/3 rod debonded	8	0
13	--	--	12 COMP	--	0.281	1.85	23.50	5.33	N/A	M045C	1015	6.4	Intact, debonding	2/3 rod debonded	3	0
14	6157-08-010	UCO ₂ 0.5	18-010	05-010	0.350	1.83	28.47	5.00	No	M046C	1010	6.2	1/2 rod debonded ^(c)	Completely debonded	14	0
15	--	--	12 COMP	--	0.265	1.85	23.50	5.33	N/A	M045C	1000	5.9	Rod dropped-debonded	Completely debonded	ND	ND
16	6155-05-010	(Th,U)O ₂	--	05-050	0.350	N/A	N/A	N/A	Yes	M045C	990	5.6	~1/2 rod debonded ^(c)	Completely debonded	39	3
17	--	--	14-010	05-020	0	1.97	49.43	8.28	Yes	M045C	985	5.3	Completely debonded ^(e)	Same	ND	ND
18	6155-05-010	(Th,U)O ₂	--	05-010	0.350	N/A	N/A	N/A	No	M0450	975	5.0	Intact, debonding	~1/2 rod debonded	5	0
19	--	--	16-010	05-030	0	1.96	23.38	5.56	Yes	M0450	965	4.8	Completely debonded ^(e)	Same	14	8
20	6157-08-010	UCO ₂ 0.5	18-010	05-020	0.150	1.83	28.47	5.00	Yes	M0460	960	4.5	Completely debonded ^(c)	Same	3	3

(a) Observed failure divided by total number of particles counted; particle types not distinguished in rod.

(b) N/A = not applicable; ND = not determined.

(c) Rod crumbled when handled.

(d) Number of failed particles on surface of intact rod.

(e) Rod debonded as was pushed along in the V-through.

TABLE 6-2
RESULTS OF CALCULATED GASEOUS FISSION PRODUCT RELEASE

Rod No.	Fraction Fissions ^(a)		r/b _f		Total R/B _{EO} L ^(c)	R/B _{BOL} ^(c) of Uranium	Calculated R/B _{EO} L of Uranium	BOL Thorium Contamination ^(d) (g Th/g Th)	R/B _{EO} L of Thorium		Calculated R/B Failed Fuel	Calculated In-Pile Failure Fraction	
	Fissile	Fertile	Fissile ^(b)	Fertile					Contamination ^(e)	Defective Particles ^(f)		Fissile	Fertile
1	0	1	--	0.014	5.8×10^{-4}	--	--	1.1×10^{-2}	5.0×10^{-5}	1.5×10^{-4}	3.8×10^{-4}	--	0.027
2	1	0	0.018	--	1.7×10^{-4}	8.5×10^{-7}	8.5×10^{-7}	--	--	-	1.7×10^{-4}	0.0094	--
3	0	1	--	0.014	3.5×10^{-4}	--	--	5.7×10^{-3}	5.0×10^{-5}	7.7×10^{-3}	2.2×10^{-4}	--	0.016
4	1	0	0.018	--	3.0×10^{-4}	2.2×10^{-6}	2.2×10^{-6}	--	--	--	3.0×10^{-4}	0.017	--
5	0	1	--	0.013	4.2×10^{-4}	--	--	1.3×10^{-2}	5.0×10^{-5}	1.7×10^{-4}	2.0×10^{-4}	--	0.015
6	0.118	0.882	0.018	0.013	2.0×10^{-4}	2.5×10^{-6}	3.0×10^{-7}	1.4×10^{-3}	4.4×10^{-5}	1.4×10^{-5}	1.4×10^{-4}	0(g)	0.012(g)
7	0	1	--	0.013	2.0×10^{-4}	--	--	1.4×10^{-3}	5.0×10^{-5}	1.6×10^{-5}	1.3×10^{-4}	--	0.010
8	0.130	0.870	0.018	0.012	3.0×10^{-4}	4.6×10^{-6}	6.0×10^{-7}	1.4×10^{-3}	4.4×10^{-5}	1.2×10^{-5}	2.4×10^{-4}	0(g)	0.023(g)
9	0	1	--	0.012	2.8×10^{-5}	--	--	1.4×10^{-3}	5.0×10^{-5}	1.4×10^{-5}	0	--	0
10	0.158	0.842	0.018	0.012	2.5×10^{-5}	6.0×10^{-7}	9.5×10^{-8}	1.4×10^{-3}	4.2×10^{-5}	1.2×10^{-5}	0	0(g)	0
12	0.126	0.874	0.018	0.011	9.2×10^{-5}	1.1×10^{-6}	1.4×10^{-7}	1.4×10^{-3}	4.4×10^{-5}	1.2×10^{-5}	3.5×10^{-5}	0(g)	0.0036(g)
13	0	1	--	0.011	8.0×10^{-6}	--	--	(h)	$5.0 \times 10^{-5(1)}$	0	0	--	0
18	1	0	0.018	--	8.1×10^{-6}	3.8×10^{-7}	3.8×10^{-7}	--	--	--	7.7×10^{-6}	4.3×10^{-4}	--
20	0.210	0.790	0.018	0.008	1.9×10^{-4}	3.8×10^{-6}	8.0×10^{-7}	1.4×10^{-3}	4.0×10^{-5}	7.6×10^{-6}	1.4×10^{-4}	0(g)	0.022(g)

(a) Values normalized to Kr-85m thermal fission yields.

(b) Based on burnup of 12% FIMA.

(c) Kr-85m measured at 1100°C in TRIGA reactor.

(d) Measured by chlorine leach technique.

(e) Assumed preirradiation R/B from contamination was 5.0×10^{-5} for all fertile samples.

(f) Derived from BOL thorium contamination values after subtracting out 2×10^{-4} g Th/g Th for contamination for all fertile samples.

(g) Calculated assuming all fission gas release came from failed fertile particles, because no failed $UC_{0.7}O_{0.5}$ and UO_2 particles observed in metallographic examination.

(h) Not used in calculation.

(i) R/B_{BOL} of Kr-85m measured at 1100°C in LINAC reactor; this was the only fertile sample measured for R/B_{BOL}.

TABLE 6-3
RESULTS OF MATRIX EXAMINATION OF CAPSULE HRB-14 FUEL RODS

Rod Position	Measure- ment	Irradiation Conditions		Macroporosity ^(a) (%)			Matrix Separated from Particle ^(c) (%)		
		Volume- Average Tempera- ture (°C)	Fluence (10 ²⁵ n/m ²) (E > 29 fJ) _{HTGR}	Measured		Change ^(b)			
				Pre- irra- dia- tion	Post- irra- dia- tion		Fissile	Fertile	Inert
3	1	1095	8.1	38.90	47.48	+22	--	75	100
4	1	1090	↓	28.60	43.50	+52	100	--	100
4	2	1090	↓	28.60	37.36	+31	ND ^(d)	--	ND
6	1	1070	7.8	34.60	47.05	+36	99	ND	100
6	2	1070	↓	34.60	43.58	+26	ND	ND	ND
6	3	1070	↓	34.60	49.30	+42	ND	ND	ND

(a) Determined by point-count method on metallographic cross section (radial) composite of fuel rod.

(b) Calculation: $\text{postirradiation} - \text{preirradiation} \div \text{preirradiation macroporosities} \times 100$.

(c) Percent of particles for which matrix has debonded from OPyC.

(d) ND = not determined.

TABLE 6-4
RESULTS OF METALLOGRAPHIC EXAMINATION

Rod No.	Irradiation Conditions				Fissile								Fertile								Inert			
	Temp(a) (°C)	Fluence [(10 ²⁵ n/m ²) (E > 29 fJ) _{HTCR}]	Burnup (% FIMA)		Batch No.	Number of Particles Examined	Buffer Failure (%)	IPyC		OPyC Failure (%)	OPyC + SiC Failure (%)	Kernel Extrusion(b)	Batch No. (6252-)	Number of Particles Examined	Buffer Failure (%)	IPyC		OPyC Failure (%)	OPyC + SiC Failure (%)	Batch Number (6351-05-)	Number of Particles Examined	OPyC Failure (%)	OPyC + SiC Failure (%)	
			Fissile	Fertile				Debonding from SiC (%)	Failure (%)							Debonding from SiC (%)	Failure (%)							
1	1130	8.3	--	8.5	--	--	--	--	--	--	--	17-010	151	26.5	85.4	69.5	29.1	1.3	010	53	68.0	3.8		
3	1095	8.1	--	8.4	--	--	--	--	--	--	--	20-010	92	6.5	59.8	45.6	13.0	0	030	50	100	48.0		
4	1090	8.1	19.1	--	6155-05-020	87	0	3.4	0	4.6	0	0	--	--	--	--	--	--	020	89	33.7	6.7		
5	1080	8.0	--	8.2	--	--	--	--	--	--	--	19-010	164	11.6	73.8	62.8	12.8	2.4	010	90	73.3	13.3		
6	1070	7.8	29.5	8.0	6152-01-010	100	0	6.0	3.0	0	0	0	18-010	22	ND ^(c)	ND	ND	9.1	0	030	156	100	57.1	
7	1065	7.6	--	7.8	--	--	--	--	--	--	--	18-010	244	11.2	58.0	35.7	12.3	2.0	--	--	--	--		
8	1055	7.5	28.6	7.6	6157-08-010	39	10.3	7.7	0	0	0	0	18-010	ND	ND	ND	ND	ND	020	59	42.4	5.1		
10	1040	7.1	27.8	7.1	6157-08-020	83	42.2	0	1.2	0	0	2.4	18-010	34	ND	ND	ND	20.6	0	010	128	46.1	5.5	
12	1025	6.6	26.4	6.6	6157-08-010	87	18.4	1.1	1.1	0	0	9.2	18-010	46	ND	ND	ND	6.5	0	020	81	28.4	3.7	
14	1010	6.2	26.1	6.0	6157-08-010	107	15.9	0.9	1.9	0	0	10.3	18-010	48	ND	ND	ND	4.2	0	010	45	28.9	2.2	
15	1000	5.9	--	5.7	--	--	--	--	--	--	--	--	12 COMP	196	0	26.1	18.5	2.6	0	--	--	--	--	
16	990	5.6	15.4	--	6155-05-010	107	0	0	0	0	0	0	--	--	--	--	--	--	030	52	100	48.1		
17	985	5.3	--	5.0	--	--	--	--	--	--	--	--	14-010	288	25.3	26.7	21.2	5.2	0	020	56	50.0	35.7	
19	965	4.8	--	4.4	--	--	--	--	--	--	--	--	16-010	137	10.9	10.9	8.0	1.5	0	030	47	59.6	38.3	
20	960	4.5	22.9	4.1	6157-08-010	89	70.3	0	0	0	0	20.2	18-010	38	ND	ND	ND	13.2	0	020	118	36.4	16.9	

(a) Time-averaged volume temperature.

(b) Kernel extruded into cracks of buffer coating.

(c) ND = not determined.

TABLE 6-5
MEASUREMENTS OF SiC ATTACK IN TRISO-COATED PARTICLES IRRADIATED IN CAPSULE HRB-14

Sample No.	Kernel Type	Irradiation Conditions			Fraction of Particles with SiC Attack	Penetration of Fission Products in SiC Coating		
		Temp ^(a) (°C)	Burnup (% FIMA)	Time (h)		Number of Measurements	Average Penetration (μm)	Measurements ^(b) (μm)
1	ThO ₂	1130	8.5	5124	0.040	6	8	5,7,7,7,11,14
4	(Th,U)O ₂	1090	19.1	5124	0.080	7	2	1,2,2,2,2,2,3
6	UO ₂	1070	29.5	5124	0.080	8	2	1,1,2,2,2,2,2,2
8	UC _{0.7} O _{0.5}	1055	28.6	5124	0.102	4	3	2,3,3,3
10	UC _{0.7} O _{0.5}	1100 ^(c)	27.8	5124	0.229	19	5	3,3,3,3,3,3,3,4,4,4,4,4,5,6,6,6,7,7,9
12	UC _{0.7} O _{0.5}	1025	26.4	5124	0.126	11	3	2,3,3,3,3,3,3,3,4,4,5
14	UC _{0.7} O _{0.5}	1010	26.1	5124	0.037	4	3	2,3,3,4

(a) Time-averaged volume temperature of fuel rod.

(b) Measured on metallographic polished sections.

(c) Estimated to be 60°C higher than prediction from thermal analysis.

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7. DISCUSSION OF POSTIRRADIATION RESULTS

7.1. FUEL ROD PERFORMANCE

The fuel rods irradiated in capsule HRB-14 were extremely friable; 18 of the 20 fuel rods were partially or completely debonded. No fuel rod dimensions were measured. Objective 6 (Section 1.2) was not met, because fuel rod dimensional change data could not be determined. Objective 5, which was to provide fuel rods for core-heatup-simulation testing, was partially fulfilled by this experiment. One (Th,U)O₂ fuel rod and unbonded fuel particles are available for the heating tests.

Objective 2 was to evaluate matrix-coating interaction. This objective was only partially met because of the particle debonding. No matrix-coating interaction was observed in the particles in the intact and debonded rods. However, matrix-coating interaction may have occurred in the debonded rods but went undetected. Fuel rods No. 3, 4, and 6 were intact, and the metallographic examination indicated no interaction between the matrix and OPyC coating of the particle batches. Interaction was expected in TRISO ThO₂ batch 6252-20-010 (rod No. 3), because the microporosity was 51 $\mu\text{l/kg}$ of OPyC coating. Matrix-coating interaction was observed in TRISO-coated batches with microporosities of ≥ 35 ml/kg of OPyC coating (Ref. 7-1). A weak matrix-coating bond could have caused this difference (see Section 7.2.1.1). In the debonded fuel rods, the OPyC coating failure of the fertile particles was no higher in the high microporosity particles than in the low ones.

Even though the fuel rods were friable, the rods were intact in the graphite crucible at the end of the irradiation. The rods debonded during unloading from the graphite sleeve. Therefore, the fuel rods maintained their integrity to a fluence of 8.3×10^{25} n/m² ($E > 29$ fJ)_{HTGR}, which is greater than the peak HTGR fluence. Friable rods, as seen in HRB-14, would

not be detrimental to the irradiation performance of a fuel element as long as the rods remained intact during the irradiation.

GA examined the cause of the fuel rod friability. The following fuel rod properties were judged unlikely to be the cause. The coke content was within a narrow range of 0.30 to 0.35 and was acceptable (Ref. 7-1). The macroporosity was 27% to 39% and was acceptable (Ref. 7-1). The fired matrix impurities were low. The matrix density, microporosity, and filler content were similar to fuel rods irradiated in previous irradiation experiments. The fabrication of the green rods, the heat treatment, and the firing atmosphere were in agreement with those of previous capsule fuel rods.

GA evaluated the effect of the constituents of the fuel rods on friability. Two matrix batches were used, and debonding was observed in both. The rods had none or varying amounts of fissile, fertile, inert, and shim particles. Some rods had no inert particles; others had no shim particles. No one particle type appeared to have caused the particle debonding. The OPyC coating failure of the fertile and the inert particles was probably not the primary cause, because the Pl3T rods (Ref. 7-2) were strong even though some rods had higher OPyC failure than in HRB-14. However, high OPyC failure may have contributed to the rod friability.

Rod friability was observed in all the fuel rods. The primary cause had to be some attribute which was similar for all the rods. The attributes were narrowed down to the rod length and the matrix. The rods were short (12.50 mm long). Since the rod properties, required by the specification (Ref. 7-3), were similar to those measured in longer rods irradiated in previous capsules, the length is a less likely cause. Also, the rods did not break up by cracks propagating along the length of the rod. In this case, shorter rods would have affected the rod integrity. Instead, the HRB-14 rods crumbled into fragments. This behavior indicated that the matrix-to-particle bond was weak. The metallographic examination verified this (see Table 6-4). The matrix separated from the majority of particles. Figure 6-6 gives examples. The matrix had also pulled away from the shim

particles. The matrix macroporosity increased 22% to 52% during irradiation. This result supports the metallographic observations. The increase in porosity was at least partially attributed to voids which developed between the matrix and particles as the matrix shrank away from the tightly packed bed of particles. Since the particles were not bonded well to the matrix, the particles debonded when the fuel rods were handled during unloading from the capsule.

The weak bonding between the matrix and the OPyC coating at the TRISO particles and the shim was apparently attributed to the matrix. The matrix phase holds the rod together. The crush strengths of the HRB-14 unirradiated rods were 19% weaker than capsules P13R and P13S rods cut to the same length. The P13R and P13S rods were not friable after irradiation (Ref. 7-4). Apparently, the HRB-14 matrix did not bond as well to the particles as the matrix did in the P13R and P13S fuel rods. The composition of the HRB-14 rods was the same as that used in several previous capsule fuel rods, such as in capsule P13T (Ref. 7-2). This matrix composition did not cause the rods from previous capsules to be friable. That the actual composition of the two HRB-14 batches was the wrong composition is possible but unlikely. The matrix microstructure may have differed subtly because of the heat treatment procedure. However, the actual cause of the weak coating matrix bond is uncertain.

7.2. COATED PARTICLE PERFORMANCE

7.2.1. Mechanical Performance

7.2.1.1. OPyC Coating. The OPyC coating performance was evaluated based upon the metallographic examination (see Table 6-4). The OPyC coating failure was low for the fissile particles and high for the fertile and inert particles. Since all the particle types were TRISO coated, the OPyC coating behavior was not dependent upon kernel type. Therefore, the general OPyC coating performance of all HRB-14 particles was compared as a group, except

for the two silicon-doped TRISO inert batches. These batches were compared only to the non-doped TRISO inert batch.

The OPyC coating failure apparently increased with fast neutron fluence, as shown in Fig. 7-1. Since temperature also increased with increasing fluence, the failure could also be attributed to temperature. The results of capsules P13R and P13S (Ref. 7-4) showed that failure was a function of both fluence and temperature. (For the following discussions, note that when fluence increased, the temperature increased.) The inert particles had the highest OPyC failure, and the failure obviously increased with fluence. The fertile particles had the next highest OPyC coating failure. The fissile particles had zero OPyC failure, except for the OPyC coatings exposed to the highest fluence.

Figure 7-1 shows that the OPyC coating failure was also dependent on total particle diameter. The failure was then plotted as a function of diameter. Figure 7-2 shows that the failure increased with the total particle size. Particles with diameters of $<820\text{ }\mu\text{m}$ had the lowest OPyC coating failure (average of 0.8%). The $1060\text{-}\mu\text{m}$ -diam particles had excessive OPyC failure, and the failure was also dependent on the fluence. A size effect was observed in earlier irradiation capsules (Ref. 7-5). The same TRISO inert particles were also irradiated in capsule HRB-15B, and a size effect was observed (Ref. 7-6).

The OPyC coating failure was compared to microporosity. Microporosity has been found to influence the OPyC coating behavior (Ref. 7-1). The present HTGR specification is 13 to $32\text{ }\mu\text{l/kg}$ of OPyC coating. Figure 7-3 shows no strong correlation of failure and microporosity. Failure occurred within the specification range. The highest failure (inert TRISO particles) was in particles with the lowest microporosity (outside the specification range). However, these particles had the largest diameters. Higher failure was expected in high microporosity particles because of matrix-coating interaction. Figure 7-3 shows this did not occur, possibly because the matrix-

OPyC-coating bond was weak. If the matrix-coating bond had been strong, higher OPyC failure may have occurred in the high microporosity particles.

Figure 7-4 graphs the microporosity and failure of all with diameters $< 820 \mu\text{m}$ to eliminate the size effect. The average failure of all particles within the HTGR microporosity specification was 0.8%, much less than the expected OPyC failure of 3.0% for HTGR particles (Ref. 7-1).

GA tested a range of densities and optical anisotropies for fertile particle OPyC coatings. Figure 7-5 shows that the OPyC failure did not correlate with density in the range of 1.76 to 1.98 Mg/m^3 . Figure 7-6 shows that OPyC failure also did not correlate with BAF_0 in the range of 1.036 to 1.050. The lack of correlation is not surprising, because the size effect was the dominating cause of OPyC failure, and a relatively narrow range of densities and anisotropies was tested.

Figure 7-7 is a graph of OPyC failure versus coating gas volume fraction. The HTGR specification requires a value of ≥ 0.25 . Some samples with coating gas volume fractions < 0.25 had no OPyC failure, and some samples with ≥ 0.25 values had high OPyC coating failure. The lack of correlation was apparently because the size effect was the predominant cause of the OPyC coating failure (Fig. 7-2).

GA also evaluated the OPyC coatings by particle type. The fissile particles performed well. OPyC failure (4.6%) occurred only in the $(\text{Th,U})\text{O}_2$ particles irradiated to a fluence of $8.1 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}. No failure was observed in $(\text{Th,U})\text{O}_2$ batch 6155-05-010 irradiated to a fluence of $5.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}. This batch is being irradiated in the FSV FTE-2, -4, and -6 (Ref. 7-7). The UO_2 and $\text{UC}_{0.7}\text{O}_{0.5}$ batches had no OPyC coating failure. The average fissile OPyC failure was 0.6%, much lower than the expected OPyC failure (3.0%) for HTGR particles (Ref. 7-1).

The OPyC coating failure of the TRISO ThO_2 particles was much higher in the 875- μm -diam particles than in the 800- μm particles. Within the fluence

range of 4.5 to $6.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}, the OPyC coating failure averaged 8.0% for the 868- μm -diam particles and 3.1% for the $\sim 800\text{-}\mu\text{m}$ particles. Batch 6252-12 COMP, which is the driver fuel for the FSV test elements (Ref. 7-7), had the second lowest OPyC failure (2.6%). Batches 6252-12 COMP and 6252-16-010 had $\sim 800\text{-}\mu\text{m}$ diameters and were representative of the candidate design of TRISO ThO₂ particles for the FSV HTGR (Ref. 7-8). The average OPyC coating failure of these two batches was 2.0% in particles irradiated at 965° and 1000°C to fluences of 4.8 and $5.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}. This failure was less than the expected failure (3.0%) for HTGR particles (Ref. 7-1).

The OPyC failure was 20.6% for the TRISO ThO₂ particles in rod No. 10. This failure was higher than in other rods with the same particle batch, possibly because the uranium loading was 26% higher than design. A rough calculation indicated that the rod time-average temperature could have been 120°C higher than the temperature reported in this document (the design loading was used in the thermal analysis). The actual temperature of rod No. 10 was most likely between the two temperatures.

The OPyC coating failure of the inert particles was extremely high (up to 100%). The highest failure was observed in the silicon-doped batch 6351-05-030. The one obvious explanation why the failure was higher in this batch than in the other silicon-doped batch was that the OPyC coating was much thinner (23 μm) than the other batch (40 μm). The OPyC failure of the silicon-doped batch 6351-05-020 and the non-doped batch 6351-05-010 were similar.

7.2.1.2. Particle Integrity. The present fuel performance requirement states that fuel meeting all requirements of particle design and missing and defective coating specifications shall have no more than 0.5% pressure vessel failure after irradiation at 1250°C to $8 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} and/or a burnup of 78% FIMA for HEU fissile particles and/or 7.5% FIMA for fertile particles (Ref. 7-9). Since HRB-14 fissile particles were LEU, the requirements were assumed to be the same.

A metallographic examination and a FGR test measured the particle integrity. Table 7-1 reports the results and shows that the particle failure measured on the same rod differs for the two tests. FGR was measured on all rod particles. The metallographic examination examined only one plane of <40% of the total population. Therefore, the FGR results better indicate the true particle failure in the rod. This discussion will use the FGR results where both rod tests were made.

GA predicted the particle failure of the TRISO fissile and fertile particles. The TRISO particle stress model used a Monte Carlo routine. The predicted failure was based on an apparent failure stress of 33 MPa (4800 psi). Table 7-1 reports the predicted failure.

The overall irradiation performance of the fissile fuel was good. No pressure vessel failure (OPyC plus SiC coating failure) was observed in the metallographic examination in all the UO_2 and the $\text{UC}_{0.7}\text{O}_{0.5}$ particles. The observed failure was less than predicted. Failure of 4×10^{-4} and zero was measured for the $(\text{Th},\text{U})\text{O}_2$ particles (batch 6155-05-010) irradiated to a burnup of ~15% FIMA and a centerline temperature of ~1070°C and was in good agreement with predictions. This batch will be tested to about the same conditions in the FSV FTE-6 (Ref. 7-10). The low failure shows that batch 6155-05-010 will perform adequately in the test element. This HRB-14 result meets part of objective 4 (Section 1.2). The $(\text{Th},\text{U})\text{O}_2$ batch irradiated to a fluence of $8.2 \times 10^{25} \text{ n/m}^2$ and a burnup of 19% FIMA had 0.9% and 1.7% failure measured by FGR. The failures were higher than the HTGR requirement of 0.5% and the predicted failure of <0.1%. This was the only case in which the observed failure was higher than predicted, and the reason for the underprediction was not apparent.

In summary, the HRB-14 results fulfilled most of the requirements of objective 3, which were to show adequate performance of $(\text{Th},\text{U})\text{O}_2$ and $\text{UC}_{0.7}\text{O}_{0.5}$ fuel over the capsule range of fluences and burnups.

The irradiation performance of the fertile particles was not as good as expected, based on the capsule design. Table 7-1 and Fig. 7-8 show the results. Table 7-1 shows fair agreement between the metallographic examination and the FGR measurements. The ThO₂ particles irradiated at the higher burnups were designed with thicker buffer coatings to keep the pressure vessel failure <0.5%. The in-pile pressure vessel failure of the HRB-14 rods was zero to 2.7%. In 8 out of 10 samples, the observed failure was higher than predicted. Figure 7-8 can explain the cause of the high in-pile failure. All failure occurred in 875- μ m-diam particles with thick-buffer coatings. These particles also had high OPyC coating failure, as discussed previously. The pressure vessel performance model predicts that, when the OPyC coating fails, the SiC coating is more likely to fail, because the OPyC coating reduces the SiC tensile stress. This would explain the increased failure. Also, the larger diameter TRISO ThO₂ particles had ~23% lower particle crush strengths (Section 3.3) on the average than the smaller diameter particles. Figure 7-8 shows that the 800- μ m particles (candidate for the FSV HTGR) had zero failure. The HRB-14 results partially fulfill objective 1 (Section 1.2); the results showed adequate performance of the candidate design particles. Batch 6252-12 COMP irradiated at 1085°C to a burnup of 6.3% FIMA had zero pressure vessel failure. This batch is the driver fuel for the FSV FTE-1 through -8 and will be exposed to peak conditions (Ref. 7-10) similar to those of HRB-14. The HRB-14 results fulfill objective 4 (Section 1.2); the results show that this TRISO ThO₂ batch will perform adequately in the test elements.

The TRISO inert particles performed poorly. The OPyC plus SiC failure was highest in silicon-doped batch 6351-05-030, which also had the highest OPyC failure. The OPyC plus SiC failure was 38% to 57%. The failure of the other silicon-doped batch was 4% to 36%. The OPyC plus SiC failure for the non-doped batch was 2% to 13%. Six unirradiated rods were burned back and visually examined for defective SiC coatings. Only one out of 1890 inert particles had a defective SiC coating. Therefore, rod fabrication did not cause the SiC failure; since the kernels were inert, no pressure vessel failure occurred. These two facts support the conclusion that the SiC

coating failure was an artifact of grinding and polishing the metallographic mount. The high OPyC coating failure probably contributed to the polishing damage of the SiC coating.

7.2.2. Chemical Performance

7.2.2.1. SiC Coating Attack. The metallographic examination showed chemical attack in the fissile and fertile particles. Two types of attack were observed. A localized attack occurred in the TRISO ThO₂, UO₂, and (Th,U)O₂ particles. The electron microprobe examination revealed palladium at the reaction zone. This type of attack was detected in TRISO ThO₂ particles irradiated in capsule HT-34 (Ref. 7-11) and in HEU fissile particles irradiated in several capsules including capsule Pl3Q (Ref. 7-12). The second type of attack was spread along the surface of the SiC on one side of the particle and was only seen in the UC_{0.70}O_{0.5} particles. The electron microprobe examination showed that the rare earths and palladium were in the reaction zone. Rare-earth attack has been observed in HEU fuel (Ref. 7-13). The rare-earth elements were not retained completely in the UC_{0.70}O_{0.5} kernel, because the O/U ratio was not high enough. This is in agreement with ORNL data on WAR UC_xO_y particles (Ref. 7-14). The attack of the SiC coating did not cause coating failure, based on the metallographic examination.

The attack of the SiC coating in HRB-14 was compared to the predicted amount of SiC thinning (Ref. 7-15). Figure 7-9 shows the penetration distances of the fission products measured on all the particles as a function of temperature (see Table 6-5). The temperature used for rod No. 10 was corrected by adding 60°C to the reported temperature. This was halfway between the maximum temperature and the temperature calculated from the in-pile thermal analysis, as discussed in Section 7.2.1. Figure 7-9 also gives the 90% confidence bounds for the SiC thinning model (based on square root of time). The SiC attack in the UC_{0.70}O_{0.5} particles was higher than in the UO₂ or (Th,U)O₂ particles and was generally higher than the upper bound of the predicted thinning. The attack in the UO₂ and (Th,U)O₂ particles was within the 90% confidence of the predicted SiC thinning. The amount of

thinning in the ThO_2 particles was also higher than the upper bound of the predicted thinning and agreed better with the $\text{UC}_{0.7}\text{O}_{0.5}$ data than with the fissile oxide data. A number of factors may have caused the scatter in the data and the difference between observed and predicted values. The uncertainty in the calculated fuel rod temperatures and the SiC attack measurements are two factors. Also, the SiC thinning calculations used the time-average volume temperature. In reality, each particle was running at a different temperature, depending on its rod position.

The chemical attack of the SiC coating in the TRISO ThO_2 particles was unexpected, because the number of palladium atoms per particle was roughly an order of magnitude less than in the LEU fissile particles, and the attack had not been observed in other irradiation experiments, except recently in capsule HT-34 (Ref. 7-11). Both capsules were irradiated in HFIR, where the thermal neutron flux is very high. Table 7-2 gives the palladium atoms per particle for some of the samples irradiated in HRB-14. The TRISO ThO_2 particles in rods No. 1 and 3 had 7.4 and 7.3×10^{14} palladium atoms/particle. SiC attack was observed in rod No. 1 but not in rod No. 3, which was exposed to about the same irradiation conditions. The reason for this is not known. SiC attack was observed in capsule HT-34 (Ref. 7-11) in ThO_2 particles having 6×10^{14} palladium atoms/particle. The results of HRB-14 and HT-34 agree. Table 7-2 also shows that the number of palladium atoms per particle was 5.9×10^{15} for the $(\text{Th,U})\text{O}_2$ particles (rod No. 4) irradiated to about the same temperature as the ThO_2 particles in rod No. 1, but the palladium penetration was much less. Another observation was that the palladium concentrated at the IPyC-SiC interface whether or not SiC attack was observed in all the fissile particles but not in the fertile particles. However, the penetration was the highest in the fertile particles. Previous experimental observations on fissile particles have indicated that the palladium must concentrate in local regions near the SiC coating before palladium attack will occur in particles with low concentrations of palladium (Ref. 7-16). The palladium attack in the TRISO ThO_2 irradiated in capsule HRB-14 supports these observations. If the palladium concentration could be prevented, palladium attack of the SiC coating could be minimized (Ref. 7-16).

7.2.2.2. Kernel Migration. Kernel migration was observed in the TRISO UO_2 particles (rod No. 6), but not in the TRISO $(\text{Th,U})\text{O}_2$ and $\text{UC}_{0.7}\text{O}_{0.5}$ particles irradiated under similar conditions (rods No. 4 and 8). This is in good agreement with the predicted migration for UO_2 and $(\text{Th,U})\text{O}_2$ particles given in Ref. 7-17, based upon migration coefficients in Ref. 7-18. The UO_2 migration was predicted to be 24 μm and measured 16 μm . The $(\text{Th,U})\text{O}_2$ migration was predicted to be 7 μm , and none was measured. This still agrees, because 7 μm of kernel migration would not have been easily detected on the metallographic polished section. This is because a reference point could not be established to measure 7 μm of movement of a 350 μm kernel and because the sample size was small (87 particles). Since no kernel migration data existed on dense UC_xO_y kernels, no predictions were made for $\text{UC}_{0.7}\text{O}_{0.5}$ particles.

7.2.2.3. Iron Attack. The outside surface of the SiC coating of one TRISO UO_2 particle was chemically attacked (see Fig. 6-35). The attack was assumed to be caused by a localized iron contaminant in the matrix, because the iron content was very low (31 ppm) in the particle batch. The attack appearance was similar to the iron attack in unirradiated particles in fuel rods made for capsule HRB-15A (Ref. 7-19). Also, iron was found to attack the SiC coating in irradiated particles from the Peach Bottom Reactor recycle test elements (Ref. 7-20). In the 15 HRB-14 rods examined metallographically, only one particle was attacked. This indicates that iron attack was not a significant problem in capsule HRB-14 fuel rods.

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Fig. 7-1. OPyC coating failure versus fast fluence for the TRISO fissile, fertile, and non-doped inert particles. Temperature also increased with fluence. Curves were hand-fitted.

Fig. 7-2. OPyC coating failure versus total particle diameter for the TRISO fissile, fertile, and non-doped inert particles. Curves were hand-fitted.

Fig. 7-3. OPyC coating failure versus microporosity for the TRISO fissile, fertile, and non-doped inert particles

Fig. 7-4. OPyC coating failure versus microporosity for the TRISO fissile and fertile particles having diameters $< 820 \mu\text{m}$

Fig. 7-5. OPyC coating failure versus density for the TRISO ThO_2 particles

Fig. 7-6. OPyC coating failure versus optical anisotropy for the TRISO ThO_2 particles

Fig. 7-7. OPyC coating failure versus OPyC coating gas volume fraction for the TRISO fissile, fertile, and non-doped inert particles

Fig. 7-8. Pressure vessel failure versus total particle diameter of the TRISO ThO_2 particles

Fig. 7-9. Graph of SiC thinning versus temperature. The points given are the penetration distances of the fission products in the SiC coating of all the HRB-14 TRISO particles. The measurements were taken on metallographic polished sections. The points representing more than one number show the number of measurements for those points. The dotted lines are the 90% confidence bounds of the $\sqrt{t}$ model for SiC thinning (Ref. 7-7).

TABLE 7-1
SUMMARY OF FAILURE ANALYSIS OF FUEL PARTICLES

Rod (a) Position	Irradiation Conditions					TRISO Fissile Particles					TRISO ThO ₂ Particles			
						Batch No.	Kernel	Total Failure (b) Metallo-graphic Exam (%)	In-Pile Failure (%)		Batch No. (6252-)	Total Failure (b) Metallo-graphic Exam (%)	In-Pile Failure (%)	
	Volume-Averaged	Center-line	Fluence x 10 ²⁵ n/m ² (E > 29 fJ/HTGR)	Burnup (% FIMA)					FGR Test	Predicted (c)			FGR Test	Predicted (c)
				Fissile	Fertile									
1	1130	1190	8.3	—	8.5	—	—	—	—	—	17-010	1.3	2.7	0.1
2	1105	1180	8.2	19.3	—	6155-05-020	(Th,U)O ₂	ND (d)	0.9	<0.1	—	—	—	—
3	1095	1170	8.1	—	8.4	—	—	—	—	—	20-010	0	1.6	<0.1
4	1090	1165	8.1	19.1	—	6155-05-020	(Th,U)O ₂	0	1.7	<0.1	—	—	—	—
5	1080	1155	8.0	—	8.2	—	—	—	—	—	19-010	2.4	1.5	<0.1
6	1070	1145	7.8	29.5	8.0	6152-01-010	UO ₂	0	(e)	0.1	18-010	0	1.2 (e)	<0.1
7	1065	1135	7.6	—	7.8	—	—	—	—	—	18-010	2.0	1.0	<0.1
8	1055	1130	7.5	28.6	7.6	6157-08-010	UCO ₂ 0.5	0	(e)	2.7	18-010	ND	2.3 (e)	<0.1
9	1050	1120	7.3	—	7.3	—	—	—	—	—	18-010	ND	0	<0.1
10	1040	1110	7.1	27.8	7.2	6157-08-020	UCO ₂ 0.6	0	(e)	8.2	18-010	0	0 (e)	<0.1
12	1025	1095	6.6	26.4	6.6	6157-08-010	UCO ₂ 0.5	0	(e)	<2.7	18-010	0	0.4 (e)	<0.1
13	1015	1085	6.4	—	6.3	—	—	—	—	—	12 COMP	ND	0	<0.1
14	1010	1075	6.2	26.1	6.0	6157-08-010	UCO ₂ 0.5	0	ND	<2.7	18-010	0	ND	<0.1
15	1000	1065	5.9	—	5.7	—	—	—	—	—	12 COMP	0	ND	<0.1
16	990	1060	5.6	15.4	—	6155-05-010	(Th,U)O ₂	0	ND	<0.1	—	—	—	—
17	985	1050	5.3	—	5.0	—	—	—	—	—	14-010	0	ND	<0.1
18	975	1040	5.0	14.5	—	6155-05-010	(Th,U)O ₂	ND	<0.1	<0.1	—	—	—	—
19	965	1030	4.8	—	4.4	—	—	—	—	—	16-010	0	ND	<0.1
20	960	1025	4.5	22.9	4.1	6157-08-010	UCO ₂ 0.5	0	(e)	<2.7	18-010	0	2.2 (e)	<0.1

(a) Rod No. 11 not evaluated.

(b) Total failure equals as-fabricated failure and in-pile failure.

(c) Predicted failure fraction of intact particles (with no missing coatings) based on a mean apparent failure stress of 33 MPa (4800 psi).

(d) ND = not determined.

(e) Assumption made that no fissile failure and all failure came from fertile particles.

TABLE 7-2
COMPARISON OF SiC ATTACK AND PALLADIUM PER PARTICLE

Rod No.	Kernel Type	Irradiation Conditions ^(a)		Number of Pd Atoms per Particle	Maximum Pd Penetration in SiC (μm) ^(b)	Pd Concentrated at IPyC-SiC Interface
		Centerline Temperature ($^{\circ}\text{C}$)	Burnup (% FIMA)			
1	ThO ₂	1190	8.5	7.36×10^{14}	14	No
3	↓	1170	8.4	7.26×10^{14}	0	↓
5		1155	8.2	7.08×10^{14}		
7		1135	7.8	6.54×10^{14}	↓	
4	(Th,U)O ₂	1165	19.1	5.91×10^{15}	2	Yes
16	(Th,U)O ₂	1060	15.4	4.04×10^{15}	0	↓
6	UO ₂	1145	29.5	6.43×10^{15}	2	
8	UC _{0.7} O _{0.5}	1130	28.6	1.15×10^{16}	3	
10	UC _{0.7} O _{0.5}	1095	27.8	1.09×10^{16}	9	
12	UC _{0.7} O _{0.6}	1095	26.4	1.03×10^{16}	5	
14	UC _{0.7} O _{0.5}	1075	26.1	9.53×10^{15}	4	
20	UC _{0.7} O _{0.5}	1025	22.9	7.09×10^{15}	0	↓

(a) Total irradiation time was 5124 h.

(b) Measured on metallographic polished section.

8. CONCLUSIONS

Twenty fuel rods containing TRISO ThO_2 , $\text{UC}_{0.7}\text{O}_{0.5}$, UO_2 , and $(\text{Th},\text{U})\text{O}_2$ particles were irradiated at 960° to 1130°C . The fluence was 4.5 to $8.3 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}. The fertile burnup was 4.1% to 8.5% FIMA; the mixed oxide burnup was 14.5% to 19.3% FIMA; and the uranium fissile burnup was 27.9% to 29.5% FIMA. The conclusions follow:

1. All fuel rods were intact at the end of the irradiation. Eighteen rods completely or partially debonded during removal from the graphite sleeve. The rods were friable, because the matrix-coating bond apparently was weak.
2. No matrix-OPyC-coating interaction was observed in the cured-in-place fuel rods.
3. OPyC coating failure of the fissile, fertile, and inert particles increased with particle diameter. The OPyC coatings of particles $< 820 \mu\text{m}$ in diameter performed the best and had failure levels (average of 0.8%) consistent with the fuel design requirements.
4. The irradiation performance of the fissile particles was good. The pressure vessel failure measured in the UO_2 sample, all the $\text{UC}_{0.7}\text{O}_{0.5}$ samples, and the $(\text{Th},\text{U})\text{O}_2$ particles irradiated to a burnup of 15% FIMA was much less than the design goal of 0.5%. A failure up to 1.7% was measured in the $(\text{Th},\text{U})\text{O}_2$ particles exposed to 19% FIMA; this was higher than the failure predicted by the pressure vessel model.
5. The irradiation performance of the fertile particles depended upon particle diameter. The $800\text{-}\mu\text{m}$ -diam particles had zero pressure vessel failure; the $875\text{-}\mu\text{m}$ particles had zero to 2.7% in-pile

failure. If the 875- μm particles had retained their OPyC coatings, they would have probably performed better.

6. Capsule HRB-14 tested the TRISO $(\text{Th,U})\text{O}_2$ and ThO_2 particles presently being irradiated in the FSV FTE-1 through FTE-8. The HRB-14 particles exposed to the design peak irradiation conditions of the test elements had $<0.1\%$ in-pile failure.
7. The OPyC coating failure of the 1050- μm -diam inert particles was high apparently because of the large particle diameter. The OPyC coating failure of the non-doped particles was 29% to 73%, compared to 28% to 50% for the silicon-doped batch with a similar OPyC thickness. The other silicon-doped batch had a 23- μm -thick OPyC coating, and its OPyC failure was 60% to 100%.
8. Chemical attack of the SiC coating was detected in the TRISO ThO_2 , UO_2 , $(\text{Th,U})\text{O}_2$, and $\text{UC}_{0.7}\text{O}_{0.5}$ particles. Palladium was detected in the reaction zone of the SiC in the oxide particles. Palladium and rare earths were measured in the reaction zone of the $\text{UC}_{0.7}\text{O}_{0.5}$ particles. The observed penetration distance was higher than predicted for the $\text{UC}_{0.7}\text{O}_{0.5}$ and ThO_2 particles.
9. The measured kernel migration of the UO_2 and $(\text{Th,U})\text{O}_2$ particles agreed well with the predicted migration.

9. ACKNOWLEDGMENTS

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9-2

APPENDIX A
DISCUSSION OF BURNUP ANALYSIS

by
T. B. Crockett

Burnup analysis of the HRB-14 fuel particle batches represents the first GA effort to measure the FIMA and heavy metal reaction rates for fuel particles irradiated in an RB position of the HFIR facility. For these measurements, fuel particles were selected from high and low flux positions to establish a consistent set of reaction rates. This was not an exhaustive evaluation, but it did produce fuel irradiation characterization on the basis of average flux during each 21-day power cycle.

Capsule irradiation experiment HRB-14 is the first of a series of irradiations on LEU fuels. Part of the postirradiation experiment (PIE) studies and characterization involves fission products and/or fission by-products bred during irradiation, as well as end-of-bombardment (EOB) heavy metal composition. Gamma-ray spectrometry provided some information regarding EOB composition via prominent radionuclides present in the fuel particles; however, chemical separations were performed to apportion the source of fission. This will be detailed later.

A.1. IRRADIATION HISTORY

HRB-14 was irradiated in an RB position of the ORNL HFIR reactor beginning at cycle 162 and terminating at the end of cycle 171. The capsule began its irradiation on May 20, 1978 and was removed on January 4, 1979 for a total residence time in the reactor of 229.6 days. The cumulative power of the capsule was 21,350 MWd for 213.5 days at power, yielding an average power level of 100 MW.

A.2. BURNUP DETERMINATIONS, GENERAL

Six batches of fuel particles from high and low neutron flux regions were analyzed in accordance with standard GA procedures for determining burnup.

The fuel particle batches were cleaned to remove external contamination; after cleaning, each particle was measured for prominent fission products (plus Pa-233 in the fertile fuel particles). Fission products and Pa-233/Zr-95 atom ratios were then calculated for each sample to reveal any abnormal fuel particles (i.e., either damaged or particles foreign to the set being analyzed).

Replicate analyses were performed on the particles passing the selection criteria. Initially, the particles were crushed and dissolved. Following dissolution, these solutions were separated by an anion exchange method into thorium, plutonium, and uranium fractions. The thorium (fertile particles) and uranium fractions were spectrophotometrically analyzed by absorbance of their Arsenazo-III complex. A portion of the uranium fractions from each sample was analyzed mass spectrometrically for uranium isotopic composition. Portions of the plutonium fractions from the fissile particles were also analyzed mass spectrometrically for plutonium isotopic compositions. The plutonium fractions were assayed by measuring their alpha activity and converting this assay into weight via the isotopic composition.

A.3. URANIUM BURNUP (U-235, PU-2390, AND PU-241 FIMA)

The radiochemical fission product monitor burnup technique analyzed these fissile fuel particles. This method is essentially that of the American Society for Testing Materials (ASTM) E-129, "Atom Percent Fission in Uranium Fuel (Radiochemical Method)." In principle, the number of fissions that have occurred in the fuel particle is determined by measuring

the number of atoms of Cs-137 present and dividing by the fraction fission yield.

While it is recognized that the Cs-137 originated from bred Pu-239/Pu-241 and the initial U-235, only a small error is introduced by assuming all were from U-235. This is true because of the small difference in fractional fission yield for Cs-137 in U-235 and Pu-239/Pu-241. Such is not true for fission products not on or near the peaks of the fission yield curves. Table A-1 presents burnup values determined for these fissile particles.

A.4. THORIUM BURNUP (U-233 FIMA)

The ASTM radiochemical fission product monitor burnup technique also analyzed the fertile fuel particles. Again, the Cs-137 present at EOB had two sources of origin (U-233 and U-235). The error introduced by assuming all fissions were from U-233 is small (1% to 2%). Table A-2 presents the burnup values determined for these fertile fuel particles.

A.5. CALCULATIONAL METHOD DEVELOPMENT

In addition to the burnups determined by radiochemical methods, the CURIE computer program calculated values. The CURIE computer program calculates burnup and heavy metal depletion for fertile (Th-232) and fissile [(U-235) (U-238)] fuel particles at the beginning of each reactor irradiation cycle. The program computes the uranium and plutonium isotopic inventories and the fission product inventories. Whether the fission product is stable or radioactive doesn't matter. The program will also compute fission by-products [i.e., radioactive species bred from stable fission products, such as Cs-134 (Cs-133) and Ag-110m (Ag-109)]. To develop the reaction rates, each heavy metal cross section was adjusted to yield consistent data with that obtained by radiochemistry, gamma-ray spectrometry, and mass spectrometry for the flux position of the sample that had been irradiated. Tables

A-1 and A-2 present these data under the heading comparing isotopic compositions and atom ratios.

A.6. SUMMARY

As a secondary requirement in the burnup analysis of these fissile and fertile fuel particles, a computational method was developed to calculate burnup at all capsule positions and for other capsule irradiations in the RB positions (see Tables A-1 and A-2). If time had permitted, sample C-1708 would have been reanalyzed chemically to determine the disagreement in the atom ratios. The uranium remaining (U^R) at EOL has an apparent error. An 8% reduction in the measured uranium at EOL would bring the atom ratio and percent FIMA for this sample into agreement with the computational values.

TABLE A-1
FISSILE FUEL PARTICLE ANALYSIS SUMMARY

Sample No.	Method of Analysis	Uranium Isotopic Analysis (wt %)				Plutonium Isotopic Analysis (wt %)					FIMA (%)	Atom Ratio		
		U-234	U-235	U-236	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242		Cs-137/ Ru-106	U ^R / Pu-2	U ^R / Ru-106
C-1700	Mass spectrometry	0.0944	0.393	3.38	96.13	4.81	40.76	16.70	10.57	27.15	--	--	--	--
	CURIE computer program	0.057	0.057	3.37	96.52	5.20	41.02	16.30	10.46	27.04	29.5	3.50	29.2	129
	γ-ray spectrometry	--	--	--	--	--	--	--	--	--	--	3.21	--	--
	Radiochemistry	--	--	--	--	--	--	--	--	--	29.5	--	28.8	117
C-1708	Mass spectrometry	0.073	0.302	3.44	96.18	4.82	42.54	17.97	11.54	23.12	--	--	--	--
	CURIE computer program	0.074	0.172	3.42	96.33	4.81	42.94	17.83	11.42	22.99	26.1	3.88	32.9	168
	γ-ray spectrometry	--	--	--	--	--	--	--	--	--	--	3.81	--	--
	Radiochemistry	--	--	--	--	--	--	--	--	--	24.0	--	37.7	183
C-1710	Mass spectrometry	0.099	0.601	3.48	95.82	3.95	46.28	19.92	12.34	17.51	--	--	--	--
	CURIE computer program	0.100	0.601	3.54	95.75	3.97	45.79	19.86	12.67	17.70	22.9	4.59	37.5	238
	γ-ray spectrometry	--	--	--	--	--	--	--	--	--	--	4.49	--	--
	Radiochemistry	--	--	--	--	--	--	--	--	--	23.0	--	36.9	234

TABLE A-2
FERTILE FUEL PARTICLE ANALYSIS SUMMARY

Sample No.	Method of Analysis	Uranium Isotopic Analysis (wt %)				FIMA (%)	Atom Ratios		
		U-233	U-234	U-235	U-236		U ^R /Th ^R	Pa-233/ Cs-137	Pa-233/Th
C-1706	Mass spectrometry	59.08	30.74	6.38	3.36	--	--	--	--
	CURIE computer program	59.30	30.61	5.88	3.21	8.5	0.0633	3.22	0.0214
	γ-ray spectrometry	--	--	--	--	--	--	--	--
	Radiochemistry	--	--	--	--	8.5	0.0643	3.17	0.0204
C-1698	Mass spectrometry	62.14	29.13	5.89	2.61	--	--	--	--
	CURIE computer program	61.98	29.15	6.34	2.52	7.4	0.0576	3.42	0.0192
	γ-ray spectrometry	--	--	--	--	--	--	--	--
	Radiochemistry	--	--	--	--	7.6	0.0604	3.19	0.0192
C-1709	Mass spectrometry	71.22	23.21	4.19	1.10	--	--	--	--
	CURIE computer program	71.22	23.36	4.38	1.04	4.4	0.0426	4.13	0.0133
	γ-ray spectrometry	--	--	--	--	--	--	--	--
	Radiochemistry	--	--	--	--	4.6	0.0418	3.80	0.0128

ERRATA

GA-A15969, PRE- AND POSTIRRADIATION EVALUATION OF FUEL IN CAPSULE HRB-14

by

C. A. Young

September 1980

The following erratum should be noted in General Atomic Report
GA-A15969:

Page 5-9, Table 5-2, footnote (a)--

Change The 1 σ uncertainty to read The 2 σ uncertainty