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**POSTIRRADIATION EXAMINATION OF
CAPSULE P13T**

by
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ABSTRACT

Capsule Pl3T was the ninth in a series of irradiation tests conducted under the Department of Energy (DOE)-sponsored High-Temperature Gas-Cooled Reactor (HTGR) Fuels and Core Development Program. It was the first accelerated irradiation test of large-diameter graphite-fuel bodies containing cure-in-place fuel rods not removed prior to irradiation and irradiated to peak large high-temperature gas-cooled reactor (LHTGR) fast fluences. The primary purpose of this test was to evaluate the irradiation performance of the integral bodies and cured-in-place fuel rods and to compare the irradiation and thermal performance of dense melted high-enriched uranium (HEU) UC_2 -TRISO and HEU-UCO weak acid resin (WAR) TRISO fissile fuel particles. A secondary purpose of this test was to support the LHTGR fuel product specifications and to provide irradiation data for fuel performance models used in design evaluations. Seven TRISO UC_2 , one TRISO UCO-WAR, and nine BISO- ThO_2 coated-particle batches were used in the 36 fuel rods. The test irradiated two types of near-isotropic graphite fuel bodies. The capsule was irradiated 363.4 equivalent full power days in the Oak Ridge Research Reactor (ORR) at Oak Ridge National Laboratory (ORNL).

The postirradiation examination revealed excellent performance of the H-451 and TS-1240 graphite bodies and fuel rods irradiated to a peak fluence of $8.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} and to a peak volume-average fuel rod temperature of 1215°C . A range of fuel rod variables was tested (e.g., two types of matrix filler graphites, three types of shim particles, three matrix compositions, and five shim volume fractions); no variable was detrimental to the rod integrity.

Particle batches with coating designs representative of the LHTGR design requirements exhibited fair irradiation performance to full fast neutron exposure [$(8.0 \times 10^{25} \text{ n/m}^2)$ ($E > 29 \text{ fJ}$)_{HTGR}] and burnups of 75%

fissions per initial metal atom (FIMA) fissile, 3.8% FIMA fertile. When individual in-service particle failure levels are determined by release/birth rate (R/B) measurements, <0.3% of the fissile particles contained in 32 P13T fuel rods would fail, assuming that all failures occurred in the fissile particles (i.e., no fertile failures). If all in-service failures were caused by fertile rather than fissile particles, the failure would again be <0.3%. Thus, the true in-service particle failures were concluded to be <0.3% for all P13T particles. The observed failure was attributed to the outer pyrolytic carbon (OPyC) layer failing due to coating matrix interaction because of high microporosity in the as-fabricated OPyC layers. The higher the mean OPyC microporosity, the larger the observed OPyC/matrix interaction.

The failure fraction for 32 P13T fuel rods, based on R/B measurements at 95% confidence, are greater than predicted by the pressure vessel models. However, the mean observed value is less than predicted by the models up to fast fluences of $\sim 6.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 50% confidence. Therefore, agreement with the model is fair, but additional work is needed to reduce SiC defective fractions and improve the OPyC layer to achieve the fuel performance assumed in core design pressure vessel models.

Incipient degradation of the SiC coating due to palladium attack was observed in the HEU UC₂-TRISO and the UCO [oxygen/uranium ratio (O/U) = 0.64] fuel rods.

Capsule P13T was considered to be a very successful qualification test of HEU fuel components. These results provided additional support for the LHTGR fuel product specification and the performance models in HTGR generic code design studies.

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1. INTRODUCTION

Development of the high-temperature gas-cooled reactor (HTGR) has been under way in the United States since 1957. The initial fuel development effort for the Peach Bottom and Fort St. Vrain (FSV) reactors was directed toward demonstrating the coated fuel particle concept and the multihole graphite fuel element design, respectively. Development of fuel for the large commercial HTGRs (LHTGRs) draws heavily upon the General Atomic (GA) experience in developing and manufacturing fuel for the early reactors, especially the 330-MW(e) FSV power station. However, optimizing the LHTGR fuel changed the FSV fuel; Table 1-1* summarizes these changes. These differences principally result from three major design goals: (1) completely separate fissile and fertile material, (2) simplify the fuel fabrication process, and (3) improve fuel performance.

In 1977, the U.S. HTGR fuel development effort was diverted away from the high-enriched uranium/thorium (HEU/Th) cycle and toward the low-enriched uranium/thorium (LEU/Th) cycle to provide a more proliferation-resistant nuclear fuel (Ref. 1-1). The capsule Pl3T work was initiated prior to 1977 to support the HEU/Th cycle; however, because most fuel design parameters are generic, the results are applicable to the LEU/Th fuel cycle.

LHTGR fuel consists of small, right-cylinder rods containing an intimate blend of coated fuel particles and isotropic graphite shim particles bonded together in a close-packed array. Fuel rods are formed by injecting the close-packed particle bed with a matrix material. This matrix, consisting of organic binder and graphite filler, when carbonized and heat treated, yields a relatively strong carbonaceous bonding medium. The fuel rods are carbonized and heat treated in situ in the graphite fuel

*Tables, figures, and references appear at the end of each section.

element. The use of isotropic graphite shim particles and the cure-in-place process for LHTGR rods represent attractive design improvements in fresh fuel manufacturing and remote refabrication. This commonality between fresh and recycle fuel will reduce overall development costs and reduce risks associated with the refabrication plant.

Two types of coated fuel particles are used in LHTGRs: fissile and fertile. One fissile particle variant for fresh fuel has a dense UC_2 fuel kernel consisting of high-enriched (93%) uranium (HEU); the fertile particle has a ThO_2 kernel. The coated particle design, which uses TRISO coatings on fissile particles and BISO coatings on fertile particles, facilitates separating the bred U-233 from the nuclear poison U-236, which is generated primarily in the fissile kernel. During reprocessing, a burn-leach step separates thorium and U-233 in the fertile particle from the fissile particle.

Since the coatings also serve as the primary barrier to fission product release, a high degree of coating integrity under all normal operating conditions must be ensured. This is done in two ways: (1) designing and specifying coated particle parameters to ensure a high probability of surviving irradiation-induced stresses and (2) thermally designing the reactor core to eliminate significant failure due to thermochemical interactions between fuel and fission products and the structural coating layers.

An extensive fuel development program sponsored by the U.S. Department of Energy (DOE) has been under way at GA to evaluate, qualify, and verify LHTGR fuel (Ref. 1-2). The program irradiates a series of test vehicles that expose the fuel to expected LHTGR conditions. After irradiation, the fuel of each test vehicle is examined to determine its performance and whether it meets core design requirements.

Capsule P13T is the ninth in a GA series of LHTGR fuel irradiation tests of fully enriched fuel conducted under the DOE-sponsored HTGR Fuels and Core Development Program. This capsule began irradiation in the Oak

Ridge Research Reactor (ORR) in May 1975 and ended in July 1976 for a total exposure of 363.4 equivalent full power days (EFPD). Capsule P13T is a large-diameter capsule containing two cells in which HEU/Th reference* fresh and recycle fuels were irradiated to peak HTGR temperature-fluence conditions. The capsule tested 36 fuel rods. Cell 1 was exposed to a peak fluence of $7.7 \times 10^{21} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} and a peak fuel rod temperature of 1255°C; Cell 2 was exposed to a peak fluence of $8.0 \times 10^{21} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} and a peak fuel rod temperature of 1100°C.

The capsule P13T design was similar in many respects to that of capsule P13Q (Ref. 1-4), and its range of irradiation conditions falls within the design exposures for capsules P13Q, P13R, and P13S (Ref. 1-5). Capsule P13T and these previous capsules have the following primary differences:

1. Cell 1 of P13T contains only reference fuel processed in a manner that closely approximates reference manufacturing conditions. This irradiation was designed to qualify HEU/Th reference LHTGR fuel tested under extreme irradiation conditions.
2. The fuel bodies irradiated in P13T contain fuel rods that were cured-in-place and not removed for preirradiation inspection. This was the first such integral block irradiation test with reference HEU/Th fuel.
3. P13T was the first GA test to irradiate significant quantities of weak acid resin (WAR) TRISO fissile particles.
4. P13T extensively tested a number of evolutionary fuel particle design modifications. These include isotropic pyrocarbon coatings deposited from mixed gases (acetylene-propylene), thicker inner pyrocarbon (IPyC) and SiC coatings, the absence of a buffer seal coating, and Lonza KS-15 graphite for the matrix filler. Capsule

*This report uses the word reference to refer to fuel made to HEU/Th specifications described in Ref. 1-3.

P13T also initially tested fuel rods carbonized in TS-1240 graphite.

This report presents the results of the postirradiation examination (PIE) of capsule P13T and discusses these results and their impact on the current LHTGR fuel specifications.

REFERENCES

- 1-1. "Low-Enrichment and Mid-Enrichment Denatured (Thorium) Fuels for the HTGR: A Feasibility Study," General Atomic Report GA-A14684, October 1977.
- 1-2. Harmon, D. P., and C. B. Scott, "Development and Irradiation Performance of LHTGR Fuel," ERDA Report GA-A13173, General Atomic Company, October 31, 1975.
- 1-3. "HTGR Fuel Production Specification," Issue C, General Atomic unpublished data, August 1979.
- 1-4. Young, C. A., and C. B. Scott, "Postirradiation Examination of Capsule P13Q," General Atomic Report GA-A14174, September 1977.
- 1-5. Scott, C. B., D. P. Harmon, and J. F. Holzgraf, "Postirradiation Examination of Capsules P13R and P13S," General Atomic Report GA-A13827, October 8, 1976.

TABLE 1-1
PRINCIPAL DIFFERENCES BETWEEN FSV AND LHTGR FUEL

	FSV	LHTGR	Purpose of Change
Fuel particles			
Fissile kernel	4:1 (Th,U)C ₂	UC ₂ (melted kernel)	Improve separability
Fertile kernel	ThC ₂	ThO ₂	Simplify process and improve performance
Fissile/fertile coatings	TRISO/TRISO	TRISO/BISO	Improve separability
Fuel rods			
Carbonization technique	In Al ₂ O ₃	In-block	Simplify process
Rod shimming method	Fuel particle blending	Graphite shim particles	Simplify process
Dimensions, mm			
Diameter	12.7	15.7	Improve core design and simplify process
Length	50.8	62.8	

2. DESCRIPTION OF EXPERIMENT

2.1. OBJECTIVES

The P13T test has the following primary objectives:

1. Qualify HEU reference fuel at full exposure in graphite bodies simulating a segment of an HTGR fuel block.
2. Compare the irradiation and thermal performance of dense melted HEU UC_2 at 1000° and 1300°C and HEU WAR-derived UC_xO_y TRISO-coated fissile particles at 1100°C to peak fluence.
3. Test variations in particle coating attributes to help define the permissible range of acceptable coating properties for the HEU LHTGR product specifications.
4. Characterize the irradiation performance of fuel rods in alternate fuel block graphite and fuel rods containing alternate shim and matrix materials.

2.2. DESCRIPTION OF FUEL SPECIMENS

Capsule P13T contained 36 fuel rod specimens designed to test a broad spectrum of property and process variables for LHTGR fuel. Either reference HEU UC_2 dense-melted (called VSM) TRISO or HEU WAR UC_xO_y TRISO fissile particles were combined with ThO_2 BISO fertile particles and used in all fuel samples. The fuel rod specimens were fabricated by hot injection and were cured-in-place in reference graphite fuel bodies. Reference 2-1 details the fuel specimens tested in capsule P13T.

2.2.1. Coated Particles

Tables 2-1 and 2-2 generally describe the coated particles.

The Pl3T irradiation capsule tested a large number of fissile and fertile batches. Specific particle parameters were varied to help determine the optimum range in coating design. One HEU fissile and one fertile batch, made up of four or five single batches, represented LHTGR composite batches from several coating runs. Most attributes of the coated fuel particle batches fell within the specifications of Ref. 2-2. All fissile and fertile batches were TRISO and BISO coated, respectively. All fuel rods also used one TRISO-coated inert batch.

One batch of WAR $UC_{2.92}O_{0.64}$ and seven batches, including one composite, of dense, melted (VSM) UC_2 TRISO-coated fissile batches were tested in the Pl3T fuel rods. The WAR $UC_{2.92}O_{0.64}$ TRISO batch consisted of 315- μ m kernels, while the UC_2 VSM batches were made up of 200- μ m kernels. The irradiation performance of the WAR versus the VSM TRISO fissile particles were compared in cell 2 of this test. The VSM- UC_2 particle is the reference fresh fissile particle, and the UCO-WAR-TRISO particle is the reference recycle particle. Table 2-3 lists the fissile particle variables.

This experiment tested a number of coating variables. The IPyC and outer pyrocarbon (OPyC) coatings were deposited from mixed gas (acetylene-propylene) instead of propylene because of processing advantages. Mixed gas deposited pyrocarbon (PyC) coatings were used on seven fissile batches. Propylene deposited coatings were used on one fissile batch to compare the two processes. The coating thicknesses of the IPyC and the SiC coatings were varied to evaluate performance.

The Pl3T fuel rods tested nine fertile particle batches, including one composite. All batches are the reference BISO-coated particles, containing 500- μ m ThO_2 kernels. The coating variables, listed in Table 2-4, include

PyC deposition gas, OPyC coating rate and density, buffer seal coating, and total coating thickness.

Mixed-gas-deposited OPyC coatings were used on eight batches. Propylene-deposited coatings were used on one batch to compare with previous irradiation test results.

The density and coating rate of the OPyC coating were thought to greatly affect the irradiation performance of BISO fertile particles. The density (measured in a density gradient column) and coating rate for the mixed-gas coatings were therefore varied from 1.84 to 1.96 mg/m³ and 4.3 to 6.4 $\mu\text{m}/\text{min}$ (0.072 to 0.107 mm/s), respectively.

All coating batches except one were designed to have a nominal 160- μm total coating thickness (the mean for the expected LHTGR specification limits) (Ref. 2-2). One batch was designed to a less conservative (140- μm) total coating thickness, but was expected to perform acceptably.

Historically, a seal coating has been deposited on the buffer coating of FSV fertile particles to prevent hydrolysis of the ThC₂ kernels during storage and handling prior to applying the IPyC. The seal coat application was continued during early fabrication of ThO₂-BISO particles. The seal coat has now been eliminated from the reference design, since it appears unnecessary for ThO₂-BISO particles. However, two particle batches with seal coatings were tested to compare to particles without seal coats.

One batch of TRISO inert particles containing carbon kernels served as a filler particle for proper fuel rod metal loading and particle volume. The total diameter of the inert particles is similar to that of the TRISO fissile particle.

2.2.2 Fuel Rods

Thirty-six types of fuel rods (see Fig. 2-1) were fabricated for the four graphite fuel bodies. All fuel rods were carbonized in-place in the

graphite crucibles. Table 2-5 describes the P13T fuel rod variables, including different coated particle, matrix, and shim types. Table 2-6 generally describes the P13T fuel rods.

Section 2.2.1 described the coated particle variables. Cell 1 fuel rods contain three batches each of VSM UC₂-TRISO and ThO₂-BISO particles. All cell 1 rods were made from the same batch of fissile and fertile particles. Cell 2 rods were made from coated particle batches. Holes A and B of the three cell 2 bodies contained VSM UC₂-TRISO particles. Hole C contained the WAR UC₂.92O_{0.64} TRISO batch.

The P13T fuel rods tested three matrix types. All types contained A-240 petroleum pitch. One type contained 6353 graphite flour, while the other two were used in quantities of 5 or 15 wt % in each matrix batch. The fuel rods located in a single hole of each graphite body used only one matrix type. Reference 2-1 describes the matrix raw materials and compositions. The matrix containing 38 wt % KS-15 graphite flour, 47 wt % A-240 pitch, 10% octadecanol, and 5% polystyrene is the prime candidate for LHTGR fuel rods.

The P13T fuel rods used shim types including Great Lakes Carbon Company GLCC-1099 (in 2/3 of the rods), Union Carbide Corporation TS-1240X (in 1/6 of the rods), and POCO Graphite, Inc., X4029A (in 1/6 of the rods). The GLCC-1099 shim was made from H-451 graphite and impregnated at GA with furfuryl alcohol. The TS-1240X and X4029A shims were not impregnated. All three shim materials were being considered for LHTGR fuel rods at the start of this irradiation. The volume fractions of shim were varied from 12.1 to 35 vol % to duplicate the different shim loadings required for a reactor core. Reference 2-1 describes the shims and gives photomicrographs of the shim types.

2.2.3. Piggyback Samples

The four fuel bodies of capsule P13T contain simulated coolant holes designed to accommodate secondary piggyback samples. These piggyback samples are inert, or they contain small amounts of fuel (total uranium and thorium in piggyback samples per cell is $\leq 1\%$ of the total fuel per cell). They are being tested to obtain irradiation data on a variety of materials.

Table 2-7 describes the piggyback positions, and Fig. 2-1 is a schematic layout of the irradiation capsule. Each body contains three 1.27-cm (0.5-in.) diam piggyback holes identified by a letter. Piggyback samples were placed directly in the holes in bodies 1 and 2. A graphite crucible insert containing three 0.356-cm (0.140-in.) diam holes identified by a number were placed in each of the coolant holes in bodies 3 and 4; therefore, nine holes were available for piggyback samples in those bodies. All piggyback sample holders were designed so that the samples can be pushed out from the bottom of each container after completing the irradiation test.

Five research groups [see footnote (a) Table 2-7] at GA were granted space for piggyback samples consisting of either coated fuel particles or inert specimens. The samples were loaded into the holes in the locations listed in Table 2-7. Reference 2-1 further details the piggyback samples for each group.

These samples were not a part of the overall objectives of the P13T irradiation, but are from a diversity of groups within GA that will conduct their own PIEs. Therefore, this report will not include the results of any PIE performed on the piggyback samples.

2.3. CAPSULE DESIGN

Capsule P13T was a 66.5-mm (2.62-in.) diam capsule containing four graphite bodies in two cells. Each body contains 15.7-mm (0.618-in.) diam

fuel rods, piggyback samples, thermocouples, dosimetry, and gas lines. Figures 2-1 and 2-2 show a schematic layout and a pictorial drawing, respectively, of the irradiation capsule. (Reference 2-1 gives a more detailed description of the capsule design.)

Each crucible had three 15.88-mm (0.625-in.) diam holes containing the fuel rods and three 12.7-mm (0.5-in.) diam holes containing secondary piggyback specimens. A 11.96-mm (0.47-in.) diam hole in the center of the crucible contains the graphite spine for thermocouples, dosimetry, and inlet gas line.

Cells 1 and 2 contain one and three graphite fuel bodies, respectively. Each body had a diameter of ~62 mm (2.44 in.). The bottom cell (cell 1) contains body 1, which was made of H-451 graphite. It was loaded with 12 fuel rods; six of these are 61 mm (2.4 in.) long, and six are 30.5 mm (1.2 in.) long. The upper cell (cell 2) houses graphite bodies 2, 3, and 4. Bodies 2 and 4 were machined from TS-1240 graphite, and body 3 was made from H-451 graphite. Bodies 2 and 3 each contain six 50-mm (1.97-in.) long fuel rods. Body 4 contains twelve 30.5-mm (1.2-in.) long rods.

Graphite body 2 was rotated 60 deg with respect to bodies 3 and 4 so that the fuel holes of body 2 were aligned with the simulated coolant holes in the other two bodies. Thermocouples were then pushed through the coolant holes in bodies 3 and 4 and inserted into the three top fuel rods in body 2.

Thermocouples used for measuring temperatures below ~1100°C were chromel-alumel (C/A, also called type K), with an Inconel sheath and MgO insulation. Tungsten-rhenium (tungsten-3% rhenium/tungsten-25% rhenium, also called type W) thermocouples (tantalum sheath and BeO or MgO insulation) were used for higher temperatures. In addition, several tungsten-rhenium (W/Re) thermocouples were selectively placed in lower temperature areas adjacent to C/A thermocouples to indicate the amount of electromotive force (emf) drift in the W/Re thermocouples (thermocouple decalibration due

to neutron exposure). Nine W/Re thermocouples were located in fuel rods to measure the fuel rod centerline temperature during irradiation.

Dosimetry wires (vanadium-0.5% cobalt, vanadium-iron) were separately encapsulated in alumina tubes. Each set of alumina tubes was sealed in a niobium-1% zirconium tube. These tubes were then placed along the axis of the capsule in the dosimetry holes in the center graphite spines and in various thermocouple holes below the thermocouples.

The four bodies were placed in a stainless-steel primary containment can. Cells 1 and 2 were separated by a double bulkhead brazed into the containment. The thermocouples and gas lines were brazed and/or welded into the end caps at the bottom of cell 1 and the top of cell 2. The primary containment was fitted inside a stainless-steel secondary containment. The thermocouples and gas tubes from cell 1 were placed in a tube attached to the outside of the secondary containment.

The gaps between the graphite crucible and the stainless-steel containment were to control temperature within the desired range by varying the gas mixture composition.

Each cell had a separate purge gas control system to control temperature and measure fission gas release. High-purity helium and neon gases were the temperature-controlling gases. Periodic fission gas release samples were taken from each cell to determine the release/birth rate (R/B) values for specified krypton and xenon isotopes.

Pl3T was designed for a range of irradiation conditions. Cell 1 was designed for peak temperature of $1300^{\circ} \pm 50^{\circ}\text{C}$ (estimated volume average design temperature of 1230°C) and for a fluence of 5.4 to $8.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}. These time-average temperature-fluence conditions were more severe than those experienced by ~99% of the fuel in the LHTGR on the HEU/Th fuel cycle. The design average burnups for cell 1 were estimated to be ~73% fissions per initial metal atom (FIMA) for the fissile particles and 3.1%

FIMA for the fertile particles. Cell 2 was designed for a peak fuel temperature of $1100^{\circ} \pm 50^{\circ}\text{C}$ (estimated volume average design temperature of 1020°C) and for a fluence of 4.5 to $8.1 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}. The design peak exposure in cell 2 exceeded that received by ~95% of the fuel in the LHTGR core. The design average fissile and fertile fuel burnups for cell 2 were 66% and 2.3% FIMA, respectively. The beginning-of-life (BOL) fission heat per length of fuel rod was designed to be 20 W/mm for both cells 1 and 2.

REFERENCES

- 2-1. Young, C. A., and D. P. Harmon, "Preirradiation Report of Fuel Materials for P13T Capsule Irradiation," General Atomic Report GA-A13343, April 1976.
- 2-2. "HTGR Fuel Product Specification," Issue C, General Atomic unpublished data, August 1979.
- 2-3. Kovacs, W. J., private communication, November 2, 1977.

*THERMOCOUPLE RODS

**BODY 2 IS ROTATED 60 DEG WITH RESPECT TO BODIES 3 AND 4 SO THERMOCOUPLES CAN BE INSERTED THROUGH COOLANT HOLES INTO FUEL RODS CONTAINED IN BODY 2.

Fig. 2-1. Schematic layout of capsule P13T

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Fig. 2-2. Pictorial drawing of capsule P13T

TABLE 2-1
GENERAL DESCRIPTION OF COATED PARTICLE BATCHES TESTED IN CAPSULE P13T

Particle Batch Data Retrieval No.	Kernel		Coating Type (b)	Buffer			Isotropic IPyC			Coatings SiC		Isotropic OPyC					Total Coating			Metal Loading		Fission Gas Release(h)	Exposed Heavy Metal ⁽¹⁾		
	Type(a)	Diameter (μm)		Thick- ness(c) (μm)	Density(d) (g/cm ³)	Seal Coat	Thick- ness (μm)	Density(e) (g/cm ³)	BAF ₀ (f)	Thick- ness (μm)	Density(e) (g/cm ³)	Thick- ness (μm)	Coating Gas	Density(e) (g/cm ³)	Coating Rate (μm/min)	Microporosity (ml/kg OPyC)	BAF ₀ (f)	Thick- ness (μm)	Diameter (μm)	Density(g) (g/cm ³)	Uranium (wt %)		Thorium (wt %)	Uranium (g U/g heavy metal)	Thorium (g Th/g heavy metal)
Fissile Particles																									
6151-00-035	UC ₂	201	TRISO	87 ^(j)	1.07	None	33	1.92	1.22	27	3.20	37	C ₂ H ₆	1.85	3.85	23.7	1.049	191	577	2.29	18.86	ND ^(k)	2.7 × 10 ⁻⁷	3.9 × 10 ⁻⁷	2.5 × 10 ⁻⁵
6151-10-015	UC ₂	205	TRISO	89 ^(j)	1.05	None	32	1.90	1.14	30	3.22	42	C ₂ H ₆ /C ₃ H ₆	1.85	4.12	53.8	1.033	193	596	2.22	18.88	0.31	1.8 × 10 ⁻⁶	6.0 × 10 ⁻⁵	0
6151-12-015	UC ₂	191	TRISO	100 ^(j)	1.11	Yes	23	1.93	1.15	28	3.21	43	C ₂ H ₆ /C ₃ H ₆	1.78	4.78	48.0	1.038	193	578	2.22	16.57	0.46	4.5 × 10 ⁻⁷	1.3 × 10 ⁻⁶	1.4 × 10 ⁻⁵
6151-17-015	UC ₂	204	TRISO	94 ^(j)	1.08	None	36	1.87	1.15	37	3.21	38	C ₂ H ₆ /C ₃ H ₆	1.81	4.11	49.9	1.033	205	613	2.38	17.67	0.45	2.7 × 10 ⁻⁶	5.3 × 10 ⁻⁶	0
6151-17-025	UC ₂	204	TRISO	100 ^(j)	1.20	None	35	1.87	1.14	30	3.20	33	C ₂ H ₆ /C ₃ H ₆	1.84	3.57	44.9	1.041	198	602	2.29	16.50	0.35	9.5 × 10 ⁻⁷	2.3 × 10 ⁻⁶	0
6151-18-015	UC ₂	209	TRISO	84 ^(j)	1.05	None	27	1.90	1.14	39	3.20	41	C ₂ H ₆ /C ₃ H ₆	1.81	4.44	54.4	1.041	191	594	2.36	19.29	0.36	2.2 × 10 ⁻⁶	2.5 × 10 ⁻⁶	0
6151-19-015 ⁽¹⁾	UC ₂	201	TRISO	104 ^(m)	1.10 ^(m)	None	32 ^(m)	1.89 ^(m)	1.13	33	3.21	37	C ₂ H ₆ /C ₃ H ₆	1.82	4.06	54.1	1.044	191	589	2.34	17.88	0.42	3.5 × 10 ⁻⁶	8.4 × 10 ⁻⁷	1.3 × 10 ⁻⁵
6157-02-015	UC _{2.92} O _{0.64} ⁽ⁿ⁾	297	TRISO	35 ^(j)	1.09	None	32	1.96	1.15	34	3.22	30	C ₂ H ₆ /C ₃ H ₆	1.89	3.57	33.2	1.049	132	572	2.29	16.26	0.07	3.3 × 10 ⁻⁶	8.6 × 10 ⁻⁶	0
Fertile Particles																									
6542-02-025	ThO ₂	484	BISO	73	1.08	Yes	--	--	--	--	--	80	C ₃ H ₆	1.91	9.41	20.2	1.019	159	784	3.59	ND	56.18	ND	1.2 × 10 ⁻⁷	0
6542-27-015	ThO ₂	512	BISO	84	1.09	None	--	--	--	--	--	81	C ₂ H ₆ /C ₃ H ₆	1.86	4.59	19.4	1.027	164	836	3.47	ND	56.70	1.2 × 10 ⁻⁵	1.0 × 10 ⁻⁷	3.7 × 10 ⁻⁶
6542-29-015	ThO ₂	499	BISO	81	1.18	None	--	--	--	--	--	76	C ₂ H ₆ /C ₃ H ₆	1.96	4.31	21.7	1.052	157	797	3.60	ND	59.65	8.5 × 10 ⁻⁶	1.0 × 10 ⁻⁷	3.9 × 10 ⁻⁶
6542-31-015	ThO ₂	501	BISO	83	1.10	None	--	--	--	--	--	75	C ₂ H ₆ /C ₃ H ₆	1.92	6.00	27.3	1.030	158	814	3.61	ND	57.32	6.4 × 10 ⁻⁵	1.0 × 10 ⁻⁷	3.2 × 10 ⁻⁵
6542-32-015	ThO ₂	515	BISO	82	1.12	Yes	--	--	--	--	--	82	C ₂ H ₆ /C ₃ H ₆	1.84	4.65	24.6	1.030	163	840	3.45	ND	57.32	6.1 × 10 ⁻⁶	4.6 × 10 ⁻⁷	2.0 × 10 ⁻⁵
6542-33-025	ThO ₂	505	BISO	81	1.08	None	--	--	--	--	--	66	C ₂ H ₆ /C ₃ H ₆	1.86	4.31	28.9	1.038	147	802	3.66	ND	61.29	7.6 × 10 ⁻⁵	1.1 × 10 ⁻⁵	7.1 × 10 ⁻⁶
6542-34-015	ThO ₂	505	BISO	84	1.09	None	--	--	--	--	--	80	C ₂ H ₆ /C ₃ H ₆	1.86	6.40	34.6	1.035	164	839	3.48	ND	57.80	4.6 × 10 ⁻⁵	3.3 × 10 ⁻⁷	2.8 × 10 ⁻⁶
6542-35-015	ThO ₂	505	BISO	86	1.09	None	--	--	--	--	--	70	C ₂ H ₆ /C ₃ H ₆	1.94	5.60	31.7	1.038	156	824	3.57	ND	58.71	4.6 × 10 ⁻⁵	1.3 × 10 ⁻⁷	1.1 × 10 ⁻⁶
6542-36-015 ^(o)	ThO ₂	509	BISO	82 ^(m)	1.11 ^(m)	None	--	--	--	--	--	76	C ₂ H ₆ /C ₃ H ₆	1.87	5.38	27.1	1.044	158	824	3.54	ND	57.56	ND	5.1 × 10 ⁻⁶	4.7 × 10 ⁻⁶
Inert Particles																									
6351-01-020	C	253	TRISO	ND	ND	None	29	1.76	1.09	29	3.22	36	C ₂ H ₆	1.75	1.05	9.1	1.035	94	573	1.83	ND	ND	ND	ND	ND

(a) Kernels are VSM UC₂ and sol-gel ThO₂, except where noted.

(b) TRISO denotes a coating design with a SiC layer, and BISO denotes a particle with no SiC layer.

(c) Measured after buffer coating was deposited, except where noted.

(d) Determined by a mathematical calculation.

(e) Measured by a density gradient technique.

(f) Bacon anisotropy factor (BAF₀) = 0.27 optical anisotropy factor (OPTAF₀) + 0.733 (Ref. 2-3).

(g) Determined using air pycnometer.

(h) R/B rate for Kr-85m at 1100°C. R/B of fissile particles measured in TRIGA reactor; R/B of fertile particles measured in linear accelerator. The steady-state correction factor for TRIGA runs only is 1.9.

(i) Determined by acid leach test.

(j) Calculated by subtracting the inner isotropic thickness from the measured buffer plus inner isotropic coatings.

(k) ND = Not determined.

(l) Composite of batches 6151-10-015, -17-015, -17-025, and -18-015.

(m) Estimated by averaging individual batches.

(n) WAR kernel.

(o) Composite of batches 6542-27-015, -29-015, -31-015, -34-015, and -35-015.

TABLE 2-2
PROPERTIES OF TOTAL COATED PARTICLE BATCHES FOR CAPSULE P13T

Coated Particle			Particle Fabrication No.	Total Diameter			Particle Density(a) (g/cm ³)	Chemical Composition (wt %)							Fraction Defective		Exposed Heavy Metal			Fission Gas Release(f)	
				95% Confidence Limit of Total Population	Standard Deviation	U							Coated Particle(b)		Silicon Carbide(c) (g U/g U)	Acid Leach Test (d)		Hydrolysis Test(e) (g heavy metal/g heavy metal)			
Mean	Lower	Upper				Si		C	O/U Ratio	Boron Equivalents (ppm)	Fe Impurity (ppm)	(g U/g heavy metal)	(g Th/g heavy metal)								
														U	Th						
Particle Batch Data Retrieval No.	Type	Coating	Mean	Lower	Upper	Standard Deviation	U	Th	Si	C	O/U Ratio	Boron Equivalents (ppm)	Fe Impurity (ppm)	Coated Particle(b)	Silicon Carbide(c) (g U/g U)	(g U/g heavy metal)	(g Th/g heavy metal)	(g heavy metal/g heavy metal)	Gas Release(f)		
Fissile Particles																					
6151-00-035	UC ₂	TRISO	6062-151	577	516	638	29.06	2.29	18.86	0.20 ^(g)	16.87	64.22	ND ^(h)	5.00	80	0	1.8 × 10 ⁻⁶	3.9 × 10 ⁻⁷	2.5 × 10 ⁻⁵	ND	2.7 × 10 ⁻⁷
6151-10-015	UC ₂	TRISO	6216-43-0	596	514	678	38.96	2.22	18.88	0.31	17.92	63.14	ND	2.33	40	0	3.9 × 10 ⁻⁴	6.0 × 10 ⁻⁵	0	ND	1.8 × 10 ⁻⁶
6151-12-015	UC ₂	TRISO	6216-29-0	578	512	644	31.52	2.22	16.57	0.46	18.98	65.27	ND	1.66	40	0	1.7 × 10 ⁻³	1.2 × 10 ⁻⁶	1.4 × 10 ⁻⁵	ND	4.5 × 10 ⁻⁷
6151-17-015	UC ₂	TRISO	6216-57	613	523	703	42.87	2.38	17.67	0.45	22.58	59.76	ND	1.75	22	0	1.8 × 10 ⁻³	5.3 × 10 ⁻⁶	0	ND	2.7 × 10 ⁻⁶
6151-17-025	UC ₂	TRISO	6216-67	602	521	683	38.76	2.29	16.50	0.35	20.72	62.59	ND	1.75	39	0	4.4 × 10 ⁻⁵	2.3 × 10 ⁻⁶	0	ND	9.5 × 10 ⁻⁷
6151-18-015	UC ₂	TRISO	6216-61	594	507	681	41.43	2.36	19.29	0.36	22.21	59.40	ND	1.75	55	0	2.5 × 10 ⁻⁵	2.5 × 10 ⁻⁶	0	ND	2.2 × 10 ⁻⁶
6151-19-015 ⁽¹⁾	UC ₂	TRISO	--	589	495	683	44.74	2.34	17.88	0.42	20.74	63.01	ND	0.77	115	0	4.9 × 10 ⁻⁴	8.4 × 10 ⁻⁷	1.3 × 10 ⁻⁵	ND	3.5 × 10 ⁻⁶
6157-02-015	UC _{2.92} O _{0.64}	TRISO	6202-109	572	478	666	44.71	2.39	16.26	0.07	26.08	57.34	0.64 ^(j)	1.75	46	0	7.3 × 10 ⁻⁴	8.6 × 10 ⁻⁶	0	ND	5.5 × 10 ⁻⁶
Fertile Particles																					
6542-02-025	ThO ₂	BISO	5730-7ABC	784	719	649	30.84	3.59	ND	56.18	ND	36.00	ND	1.38	6	0	ND	2.1 × 10 ⁻⁷	0	7.0 × 10 ⁻⁷	ND
6542-27-015	ThO ₂	BISO	6291-53	836	750	922	41.12	3.47	ND	56.70	ND	34.39	ND	1.27	28	0	ND	0	4.1 × 10 ⁻⁷	7.0 × 10 ⁻⁵ (k)	1.2 × 10 ⁻⁵
6542-29-015	ThO ₂	BISO	6291-71	797	713	881	39.83	3.60	ND	59.65	ND	34.31	ND	1.75	15	0	ND	2.4 × 10 ⁻⁷	3.9 × 10 ⁻⁶	9.0 × 10 ⁻⁶ (k)	8.5 × 10 ⁻⁶
6542-31-015	ThO ₂	BISO	6291-73	814	743	885	33.82	3.61	ND	57.32	ND	34.02	ND	1.75	19	0	ND	6.7 × 10 ⁻⁷	3.2 × 10 ⁻⁵	9.0 × 10 ⁻⁵ (k)	6.4 × 10 ⁻⁵
6542-32-015	ThO ₂	BISO	6291-55	840	768	913	34.55	3.45	ND	57.32	ND	33.76	ND	1.27	10	0	ND	4.6 × 10 ⁻⁷	2.0 × 10 ⁻⁵	1.5 × 10 ⁻⁶	6.1 × 10 ⁻⁶
6542-33-025	ThO ₂	BISO	6291-75	802	719	885	39.75	3.66	ND	61.29	ND	30.18	ND	1.75	25	0	ND	1.1 × 10 ⁻⁵	7.1 × 10 ⁻⁶	1.1 × 10 ⁻⁴ (k)	7.6 × 10 ⁻⁵
6542-34-015	ThO ₂	BISO	6291-77	839	777	901	29.45	3.48	ND	57.80	ND	34.21	ND	1.75	25	0	ND	3.3 × 10 ⁻⁷	2.8 × 10 ⁻⁶	2.3 × 10 ⁻⁴ (k)	4.6 × 10 ⁻⁵
6542-35-015	ThO ₂	BISO	6291-81	824	752	896	34.46	3.57	ND	58.71	ND	32.87	ND	1.75	50	0	ND	0	1.4 × 10 ⁻⁵	1.1 × 10 ⁻⁴ (k)	4.6 × 10 ⁻⁵
6542-36-015 ⁽¹⁾	ThO ₂	BISO	--	824	752	896	34.32	3.54	ND	57.56	ND	33.79	ND	1.75	29	0	ND	5.1 × 10 ⁻⁶	4.7 × 10 ⁻⁶	1.0 × 10 ⁻⁴ (k)	ND
Inert Particles																					
6351-01-020	C	TRISO	6062-35	573	512	634	29.00	1.83	ND	ND	22.39	78.28	ND	<1	20	0	ND	ND	ND	ND	ND

(a) Measured using air pycnometer.

(b) Determined by microscopic examination of particle batch radiograph.

(c) Determined by burn-leach test; 10-g samples leached in ultra-leach for 1 h.

(d) 10-g samples leached in ultra-leach for 1 h for fissile particles and 5 h for fertile particles.

(e) Heated in vacuum at 1800°C for 1 h before hydrolysis (25-g samples).

(f) Release/birth rate of Kr-85m at 1100°C; 5-g fissile samples measured in a TRIGA reactor; 10-g fertile samples measured in a linear accelerator. The steady-state correction for the TRIGA runs only is 1.9.

(g) Estimated value.

(h) ND = Not determined.

(i) Composite of batches 6151-10-015, -17-015, -17-025, and -18-015.

(j) Measured at the BISO stage.

(k) Value given is the measured value multiplied by five to correct for incomplete conversion of ThO₂ to ThC₂; corrected because of possibility of fertile particle failure. The value given is a conservative estimate.

(l) Composite of batches 6542-27-015, -29-015, -34-015, and -35-015.

TABLE 2-3
FISSILE PARTICLE VARIABLES BEING TESTED IN CAPSULE P13T

Particle Batch Data Retrieval No.	Kernel			IPyC				SiC Thick- ness (μm)	OPyC Coating Gas	Particle Variables
	Fabri- cation Process	Diameter (μm)	Density (g/cm^3)	Buffer Seal	Thick- ness (μm)	Density (g/cm^3)	Coating Gas			
6157-02-015	WAR	315	≥ 3.3	No	35	1.90	M-G ^(a)	35	M-G ^(a)	Recycle ^(b)
6151-17-015 -025	VSM	200	≥ 10.3	No	35	1.90	M-G	35	M-G	Thick IPyC, thick SiC
6151-12-015	VSM	200	≥ 10.3	Yes ^(c)	25	1.90	M-G	25	M-G	Reference fuel
6151-10-015	VSM	200	≥ 10.3	No	35	1.90	M-G	25	M-G	Thick IPyC
6151-18-015	VSM	200	≥ 10.3	No	25	1.90	M-G	35	M-G	Thick SiC
6151-19-015	VSM	200	≥ 10.3	No	25-35	1.90	M-G	25-35	M-G	Composite
6151-00-035	VSM	200	≥ 10.3	Yes ^(c)	25	1.95	Propylene	25	Propylene	Previous reference ^(d)

(a) M-G = mixed gases (acetylene/propylene).

(b) The WAR UC_2 kernel has been selected as the reference recycle fissile fuel.

(c) Buffer seal coating is not included in reference design, although this coating has been routinely applied to particles in previous tests.

(d) Particle batch to compare performance of M-G isotropic PyC with that of propylene PyC.

TABLE 2-4
FERTILE PARTICLE VARIABLES BEING TESTED IN CAPSULE P13T

Particle Batch Data Retrieval No.	Particle Type	Buffer Seal	OPyC		Total Coating Thickness (μm)	OPyC Coating Rate	Particle Coating Variables
			Coating Gas	Density (g/cm^3)			
6542-27-015	ThO_2 BISO	No (a)	M-G (b)	1.85 (c)	160	$\geq 3, \leq 5$ (d)	Near reference
6542-29-015	ThO_2 BISO	No (a)	M-G	1.95 (d)	160	$\geq 3, \leq 5$ (d)	High-density OPyC
6542-34-015	ThO_2 BISO	No (a)	M-G	1.85 (c)	160	$\geq 5, \leq 8$ (c)	High coating rate
6542-35-015	ThO_2 BISO	No (a)	M-G	1.95 (d)	160	$\geq 5, \leq 8$ (c)	High coating rate, high-density OPyC
6542-31-015	ThO_2 BISO	No (a)	M-G	1.90 (c)	160	$\geq 5, \leq 8$ (c)	High coating rate, medium-density OPyC
6542-36-015	ThO_2 BISO	No (a)	M-G	1.85-1.95 (c)	160	$\geq 3, \leq 8$	Composite
6542-33-025	ThO_2 BISO	No (a)	M-G	1.85 (c)	140	$\geq 3, \leq 5$ (d)	Thin coating
6542-32-015	ThO_2 BISO	Yes	M-G	1.85 (c)	160	$\geq 3, \leq 5$ (d)	Buffer seal
6542-02-025	ThO_2 BISO	Yes	Propylene	1.90 (c)	160	$\geq 1, \leq 10$	Previous reference

(a) Buffer seal coating is not included in reference design, although this coating has been routinely applied to particles in previous tests.

(b) M-G = mixed gases (acetylene/propylene).

(c) Values within expected specification limits.

(d) Current most probable midrange value; represents a change from previous reference design.

TABLE 2-5
CAPSULE P13T FUEL ROD TEST VARIABLES

	Hole A	Hole B	Hole C
Cell 1			
Body 1 200- μm (VSM) UC_2 TRISO + 500- μm ThO_2 BISO Range of shim volume fractions	Matrix 1, M0380 ^(a) Composite of fertile particle batches	Matrix 2, M0378, and M0386 ^(b) Buffer seal on fissile and fertile particles	Matrix 3, M0379 ^(c) Alternate shims ^(d)
Cell 2			
Body 2 ^(e) Matrix 1 ^(a) High shim volume fraction Body 3 ^(e) Matrix 2 ^(b) Medium shim volume fraction Body 4 ^(e) Matrix 3 ^(c) Low shim volume fraction	(VSM) UC_2 Fissile and fertile particle coating variables Composites of fissile and fertile particle batches	(VSM) UC_2 Alternate shims ^(d) Fissile and fertile particle coating variables Composites of fissile and fertile particle batches	Recycle fissile fuel (WAR $\text{UC}_{x,y}\text{O}_2$) Fertile particle coating variables

(a) Matrix 1 is 30 wt % Asbury 6353 natural-flake graphite flour, 65 wt % A-240 pitch, and 5 wt % octadecanol.

(b) Matrix 2 is 38 wt % Lonza KS-15 graphite flour, 47 wt % A-240 pitch, 5 wt % polystyrene, and 10 wt % octadecanol.

(c) Matrix 3 is 38 wt % Lonza KS-15 graphite flour, 57 wt % A-240 pitch, and 5 wt % octadecanol.

(d) Alternate shims are TS-1240X and X4029A.

(e) All rods in this body contain these items.

TABLE 2-6
DESCRIPTION OF FUEL RODS BEING TESTED IN CAPSULE P137

Capsule Identification	Fuel Rod Data Retrieval No. (7161-008-)	Coated Particles (a)				Shim Particle Type	Shim Volume Fraction	Green Rod				Matrix										Fired Rod					
		Fissile		Fertile				Length	Diameter	Weight (g)	Packing Fraction(d)	Batch No. (e)	Filler Content(f) (wt %)	Apparent Fired Density (g/cm ³)(g)		Macroporosity (h) (i)		Coke Yield (j)		Fuel Loading Uniformity(k) U-235 Th-232	Diameter (h)	Exposed Heavy Metal (l) (g heavy metal/g heavy metal)		Fission Gas Release (n)			
		Type (b)	Data Retrieval No.	Type (c)	Data Retrieval No. (6542-)									Rods from Tubes (g)	Rods from Bodies (h)	Rods from Tubes (g)	Rods from Bodies (h)	Rods from Tubes (g)	Rods from Bodies (h)			Rods from Tubes (g)	Rods from Bodies (h)	Rods from Tubes (g)	Rods from Bodies (h)	Rods from Tubes (g)	Rods from Bodies (h)
1-1A1 (a)	01-9	UC ₂	6151-17-015	ThO ₂	36-015	1099 (p)	0.20	3.012	1.573	11.499	0.580	70380	34	0.65	0.65	36	42	30.6	28.9	1.03	1.02	1.581	1.2 x 10 ⁻⁴ (a)	<9.0 x 10 ⁻⁷	2.0 x 10 ⁻⁶	2.3 x 10 ⁻⁷	
1-1A2	04-3	UC ₂	6151-17-015	ThO ₂	36-015	1099 (p)	0.25	3.067	1.573	11.470	0.562	70380	33	0.64	0.65	40	--	29.8	29.9	1.01	1.06	1.580	<2.5 x 10 ⁻⁶	--	1.7 x 10 ⁻⁶	--	
1-1A3	07-9	UC ₂	6151-17-015	ThO ₂	36-015	1099 (p)	0.30	6.057	1.575	22.486	0.571	70380	34	0.67	0.67	37	--	29.9	30.9	1.03	1.02	1.581	<1.5 x 10 ⁻⁶	--	5.3 x 10 ⁻⁷	--	
1-1A4	10-6	UC ₂	6151-17-015	ThO ₂	36-015	1099 (p)	0.35	6.098	1.574	22.223	0.560	70380	36	0.67	0.65	37	--	ND	28.5	1.02	1.02	1.578	<1.6 x 10 ⁻⁶	--	9.8 x 10 ⁻⁷	--	
1-1B1 (a)	02-10	UC ₂	6151-12-015	ThO ₂	32-015	1099 (p)	0.20	3.050	1.572	11.610	0.577	70378	43	0.68	0.68	35	--	24.0	22.1	1.01	1.00	1.581	<2.0 x 10 ⁻⁶	--	<1.0 x 10 ⁻⁷	--	
1-1B2	05-20	UC ₂	6151-12-015	ThO ₂	32-015	1099 (p)	0.25	3.040	1.572	11.508	0.576	70386	42	0.70	0.70	37	40	25.6	24.3	1.02	1.02	1.581	2.5 x 10 ⁻⁶	--	3.8 x 10 ⁻⁶	--	
1-1B3	08-11	UC ₂	6151-12-015	ThO ₂	32-015	1099 (p)	0.30	6.115	1.573	22.407	0.571	70386	40	0.71	0.67	43	--	25.4	21.8	1.00	1.03	1.580	<1.5 x 10 ⁻⁶	--	1.4 x 10 ⁻⁶	--	
1-1B4	11-7	UC ₂	6151-12-015	ThO ₂	32-015	1099 (p)	0.35	6.124	1.573	22.327	0.564	70378	41	0.74	0.68	38	--	28.6	21.6	1.02	1.00	1.580	<1.6 x 10 ⁻⁶	--	3.6 x 10 ⁻⁷	--	
1-1C1 (a)	03-12	UC ₂	6151-17-025	ThO ₂	27-015	TS-1240X	0.20	3.038	1.572	11.789	0.577	70379	43	0.78	0.76	26	--	29.9	26.3	1.01	1.00	1.581	<1.9 x 10 ⁻⁶	--	1.8 x 10 ⁻⁷	--	
1-1C2	06-2	UC ₂	6151-17-025	ThO ₂	27-015	X4029A	0.25	3.031	1.573	11.440	0.594	70379	42	0.77	0.78	29	--	31.0	30.8	1.03	1.02	1.581	1.8 x 10 ⁻⁵	--	1.4 x 10 ⁻⁶	--	
1-1C3	09-12	UC ₂	6151-17-025	ThO ₂	27-015	TS-1240X	0.30	6.079	1.573	22.868	0.577	70379	40	0.79	0.79	27	--	31.1	32.0	1.02	1.00	1.581	<1.5 x 10 ⁻⁶	--	1.3 x 10 ⁻⁶	--	
1-1C4	12-1	UC ₂	6151-17-025	ThO ₂	27-015	X4029A	0.35	6.053	1.574	22.009	0.601	70379	42	0.79	0.80	33	31	31.3	32.8	1.03	1.01	1.579	<1.7 x 10 ⁻⁶	--	2.7 x 10 ⁻⁷	--	
2-2A1	13-2	UC ₂	6151-17-025	ThO ₂	27-015	1099 (p)	0.35	4.985	1.574	17.631	0.569	70380	35	0.62	0.66	40	39	25.3	30.3	1.01	1.04	1.579	<2.8 x 10 ⁻⁶	<6.6 x 10 ⁻⁷	4.1 x 10 ⁻⁶	1.7 x 10 ⁻⁵	
2-2A2	16-12	UC ₂	6151-00-035	ThO ₂	02-025	1099 (p)	0.35	5.007	1.573	17.045	0.562	70380	34	0.63	0.63	42	--	26.9	27.3	1.01	1.03	1.578	<2.5 x 10 ⁻⁶	--	7.6 x 10 ⁻⁷	--	
2-2B1	14-5	UC ₂	6151-18-015	ThO ₂	35-015	TS-1240X	0.35	4.976	1.573	17.632	0.565	70380	33	0.69	0.68	38	--	32.4	32.2	1.00	1.05	1.581	<2.8 x 10 ⁻⁶	--	4.8 x 10 ⁻⁷	--	
2-2B2 (a)	17-14	UC ₂	6151-10-015	ThO ₂	34-015	X4029A	0.35	5.023	1.573	16.676	0.595	70380	33	0.68	0.68	43	42	33.6	29.8	1.04	1.05	1.580	1.3 x 10 ⁻⁶	--	5.0 x 10 ⁻⁷	--	
2-2C1	15-3	UC ₂ , 92 ⁰ 0.64	6157-02-015	ThO ₂	27-015	1099 (p)	0.35	4.977	1.573	17.666	0.571	70380	36	0.64	0.63	43	40	27.9	28.6	1.04	1.04	1.580	<2.8 x 10 ⁻⁶	--	2.7 x 10 ⁻⁵	--	
2-2C2 (a)	18-4	UC ₂ , 92 ⁰ 0.64	6157-02-015	ThO ₂	33-025	1099 (p)	0.35	5.030	1.573	17.025	0.552	70380	32	0.62	0.61	34	--	24.8	25.2	1.06	1.07	1.579	<2.5 x 10 ⁻⁶	--	1.9 x 10 ⁻⁶	--	
2-3A1	19-6	UC ₂	6151-17-015	ThO ₂	29-015	1099 (p)	0.30	5.018	1.573	18.000	0.564	70378	41	0.69	0.68	33	34	24.4	21.5	1.02	1.06	1.578	<2.1 x 10 ⁻⁶	6.9 x 10 ⁻⁵	9.1 x 10 ⁻⁷	2.8 x 10 ⁻⁶	
2-3A2	22-6	UC ₂	6151-10-015	ThO ₂	33-025	1099 (p)	0.30	5.035	1.572	18.484	0.563	70378	41	0.71	ND	32	--	24.7	ND	1.04	1.04	1.580	5.5 x 10 ⁻⁶	--	3.9 x 10 ⁻⁷	--	
2-3B1	20-11	UC ₂	6151-18-015	ThO ₂	31-015	TS-1240X	0.30	5.017	1.572	18.117	0.563	70378	41	0.72	0.70	25	--	26.5	25.0	1.02	1.04	1.580	<2.5 x 10 ⁻⁶	--	2.8 x 10 ⁻⁷	--	
2-3B2	23-4	UC ₂	6151-19-015	ThO ₂	36-015	X4029A	0.30	5.020	1.572	18.318	0.591	70386	40	0.70	0.70	30	35	25.6	24.7	1.02	1.06	1.581	<1.8 x 10 ⁻⁶	--	2.3 x 10 ⁻⁷	--	
2-3C1	21-5	UC ₂ , 92 ⁰ 0.64	6157-02-015	ThO ₂	34-015	1099 (p)	0.30	4.969	1.572	17.984	0.563	70386	40	0.71	0.69	35	40	25.3	23.9	1.04	1.04	1.580	4.6 x 10 ⁻⁵	--	2.0 x 10 ⁻⁶	--	
2-3C2	24-10	UC ₂ , 92 ⁰ 0.64	6157-02-015	ThO ₂	34-015	1099 (p)	0.30	4.975	1.572	18.405	0.562	70386	40	0.67	0.64	36	--	22.8	21.6	1.05	1.03	1.579	<1.8 x 10 ⁻⁶	--	1.5 x 10 ⁻⁶	--	
2-4A1	25-6	UC ₂	6151-12-015	ThO ₂	35-015	1099 (p)	0.25	3.063	1.574	11.871	0.563	70379	42	0.74	0.77	29	36	27.6	30.8	1.01	1.02	1.577	<1.9 x 10 ⁻⁶	1.4 x 10 ⁻⁴	2.7 x 10 ⁻⁷	3.5 x 10 ⁻⁷	
2-4A2	28-6	UC ₂	6151-18-015	ThO ₂	34-015	1099 (p)	0.25	3.057	1.574	11.758	0.566	70379	42	0.73	0.77	31	--	30.8	31.9	1.01	1.02	1.578	<2.4 x 10 ⁻⁶	--	3.1 x 10 ⁻⁷	--	
2-4A3	31-7	UC ₂	6151-19-015	ThO ₂	36-015	1099 (p)	0.20	3.061	1.574	12.224	0.570	70379	42	0.73	0.77	30	--	28.9	30.0	1.00	1.04	1.578	<1.9 x 10 ⁻⁶	--	2.9 x 10 ⁻⁷	--	
2-4A4 (a)	34-7	UC ₂	6151-00-035	ThO ₂	02-025	1099 (p)	0.121	3.023	1.573	12.690	0.578	70379	43	0.74	0.74	33	--	27.4	33.7	1.07	1.03	1.578	<1.4 x 10 ⁻⁶	--	4.5 x 10 ⁻⁷	--	
2-4B1	26-12	UC ₂	6151-17-025	ThO ₂	33-025	TS-1240X	0.25	3.006	1.573	11.722	0.571	70379	44	0.73	0.79	28	--	29.1	34.0	1.00	1.02	1.578	<2.2 x 10 ⁻⁶	--	3.9 x 10 ⁻⁷	--	
2-4B2	29-2	UC ₂	6151-10-015	ThO ₂	29-015	X4029A	0.25	3.024	1.574	11.447	0.596	70379	41	0.80	0.80	30	--	32.7	31.1	1.03	1.02	1.579	2.5 x 10 ⁻⁴ (a)	--	2.5 x 10 ⁻⁷	--	
2-4B3	32-15	UC ₂	6151-18-015	ThO ₂	31-015	TS-1240X	0.20	3.068	1.573	12.280	0.562	70379	39	0.77	0.78	24	44	30.4	33.1	1.02	1.00	1.577	<1.6 x 10 ⁻⁶	--	1.1 x 10 ⁻⁶	--	
2-4B4 (a)	35-3	UC ₂	6151-18-015	ThO ₂	27-015	X4029A	0.135	3.021	1.573	12.471	0.603	70379	41	0.78	0.79	26	--	30.1	31.9	1.08	1.04	1.579	<1.4 x 10 ⁻⁶	--	1.3 x 10 ⁻⁷	--	
2-4C1	27-4	UC ₂ , 92 ⁰ 0.64	6157-02-015	ThO ₂	31-015	1099 (p)	0.25	3.070	1.573	12.024	0.564	70379	42	0.75	0.75	32	--	28.3	30.9	1.04	1.03	1.578	<2.2 x 10 ⁻⁶	--	1.4 x 10 ⁻⁶	--	
2-4C2	30-1	UC ₂ , 92 ⁰ 0.64	6157-02-015	ThO ₂	27-015	1099 (p)	0.25	3.043	1.573	11.765	0.569	70379	42	0.75	0.75	33	--	28.5	28.0	1.04	1.04	1.579	<2.4 x 10 ⁻⁶	--	2.2 x 10 ⁻⁶	--	
2-4C3	33-9	UC ₂ , 92 ⁰ 0.64	6157-02-015	ThO ₂	35-015	1099 (p)	0.20	3.046	1.573	12.220	0.573	70379	41	0.76	0.77	38	--	28.1	29.1	1.02	1.04	1.579	<2.1 x 10 ⁻⁶	--	2.2 x 10 ⁻⁶	--	
2-4C4 (a)	36-8	UC ₂ , 92 ⁰ 0.64	6157-02-015	ThO ₂	29-015	1099 (p)	0.134	3.046	1.573	12.793	0.580	70379	41	0.77	0.76	35	27	26.4	30.0	1.01	1.01	1.578	<1.3 x 10 ⁻⁶	--	2.3 x 10 ⁻⁶	--	

(a) All fuel rod types except 2-4B1, 2-4B4, and 2-4C4 contain TRISO inert batch 6351-01-020.

(b) All fissile particles are TRISO coated.

(c) All fertile particles are BISO coated.

(d) Calculated from rod and mean particle data.

(e) Table 2-5 shows matrix compositions.

(f) Measurement made on companion green rods.

(g) Measurements made on companion rods fired in graphite tubes.

(h) Measurement made on companion rods fired in quality control graphite bodies.

(i) Determined from metallographic cross section.

TABLE 2-7
LOADING OF PIGGYBACK SAMPLES^(a) IN CAPSULE P137

Body No.	Piggyback Hole No.	Insert Hole No.	Axial Position ^(c)																							
			1		2		3		4		5		6		7		8		9		10		11		12	
			Sample No.	Branch	Sample No.	Branch	Sample No.	Branch	Sample No.	Branch	Sample No.	Branch	Sample No.	Branch	Sample No.	Branch	Sample No.	Branch	Sample No.	Branch	Sample No.	Branch	Sample No.	Branch	Sample No.	Branch
1	A	--	1	FMB	1H	GDB	R	PCB	Spacer ^(d)	--	4	FMB	Spacer ^(d)	--	(e)	FCB	1/64	PCB	1MM	PCB	1/16	PCB	A	PCB	7	FMB
1	B	--	2	FMB	2H	GDB	RA 572-E, F, G, H	GDB	P	PCB	5	FMB	Spacer ^(d)	--	6486-8-1	GDB	1MM	PCB	1/16	PCB	B	PCB	B	FMB	--	--
1	C	--	3	FMB	3H	GDB	Z	PCB	M3	PChB	6	FMB	1,2,3,4	PCB	1/16	PCB	D	PCB	C	PCB	9	FMB	--	--	--	--
2	A	--	10	FMB	M12	PChB	(e)	PCB	(e)	PCB	6486-8-2	GDB	RA 572-A, B, C, D RA 563-A	GDB	Spacer ^(f)	--	13	FMB	--	--	--	--	--	--	--	--
2	B	--	11	FMB	E	PCB	1/16	PCB	1 mm	PCB	1/64	PCB	RA 563-A M8	PChB	1P	GDB	14	FMB	--	--	--	--	--	--	--	--
2	C	--	12	FMB	F	PCB	1/16	PCB	N/1	PChB	2	PCB	2P	GDB	15	FMB	--	--	--	--	--	--	--	--	--	--
3	A	1	3-A1	FMB	1	PCB	5	PCB	Spacer ^(g)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
3	A	2	3-A2	FMB	2	PCB	6	PCB	Spacer ^(g)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
3	A	3	3-A3	FMB	Z	PCB	Spacer ^(g)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
3	B	1	A	PCB	Spacer ^(g)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
3	B	2	B	PCB	Spacer ^(g)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
3	B	3	C	PCB	Spacer ^(g)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
3	C	1	3-C1	FMB	Spacer ^(g)	--	3-C1 ^(h)	FMB	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
3	C	2	3-C2	FMB	Spacer ^(g)	--	3-C2 ^(h)	FMB	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
3	C	3	3-C3	FMB	Spacer ^(g)	--	3-C3 ^(h)	FMB	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
4	A	1	4-A1 ⁽ⁱ⁾	FMB	3	PCB	Spacer ^(g)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
4	A	2	4-A2 ⁽ⁱ⁾	FMB	4	PCB	Spacer ^(g)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
4	A	3	4-A3 ⁽ⁱ⁾	FMB	X	PCB	Spacer ^(g)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
4	B	1	A	PCB	G	PCB	Spacer ^(g)	--	4-B1 ^(j)	FMB	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
4	B	2	B	PCB	H	PCB	Spacer ^(g)	--	4-B2 ^(j)	FMB	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
4	B	3	C	PCB	Spacer ^(g)	--	4-B3 ^(j)	FMB	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
4	C	1	D	PCB	7	PCB	Spacer ^(g)	--	4-C1 ^(j)	FMB	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
4	C	2	E	PCB	8	PCB	Spacer ^(g)	--	4-C2 ^(j)	FMB	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
4	C	3	F	PCB	Spacer ^(g)	--	4-C3 ^(j)	FMB	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

- (a) The following five branches contributed piggyback samples:
1. Fuel Materials Branch (FMB)
 2. Graphite Development Branch (GDB)
 3. Fuel Chemistry Branch (FCB)
 4. Physical Ceramics Branch (PCB)
 5. Physical Chemistry Branch (PChB)

(b) Graphite inserts used in bodies 3 and 4 only.

(c) Sample No. 1 is located at the bottom of hole, and the other samples are numbered consecutively to the top.

(d) H-451 graphite.

(e) No identification on sample.

(f) TS-1240 graphite.

(g) POCO (DFF-1) graphite.

(h) One dot on sample.

(i) Two dots on sample.

(j) Three dots on sample.

3. CAPSULE OPERATION AND EVALUATION

3.1. OPERATING HISTORY

The irradiation of capsule P13T began on May 10, 1975 in the E-3 position of the 30-MW(t) ORR at Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee. The experiment was irradiated for eight ORR cycles (125 through 132) and was discharged on July 5, 1976 after accumulating 363.4 EFPD of operation. Table 3-1 lists the ORR fuel cycles accumulated during the P13T irradiation.

Only two problems were encountered during capsule life:

1. A leak occurred between the secondary gas system and the cell 1 primary gas system. The small leak [~ 6.89 kPa/day (~ 1 psi/day)] was first discovered on November 3, 1975; however, the leak was believed to be in the gas supply tubing to the secondary system. During the reactor shutdown on December 8, 1975, the gas supply lines were checked, several fittings were tightened, and the system was pressure tested. No leaks were evident during shutdown, but the leak recurred the first day after reactor startup. The leak rate increased in early March 1976 to 41.36 kPa/day (6 psi/day). Subsequent tests revealed that the leak was not in the gas supply piping, but between the secondary gas system and the cell 1 primary gas system. Because of the ingress of secondary gas into the primary gas system, the secondary gas supply was changed so that the same ultrahigh-purity gas used in the primary system was also used in the secondary system. The leak rate continued to increase during subsequent thermal cycles, and the capsule was ultimately discharged from the reactor on July 6, 1976, rather

than July 31, 1976 as originally planned. The capsule PIE revealed that the leak was in two of the cell 1 thermocouple penetrations.

2. All type W (W/Re) thermocouples in cell 1 failed. Thermocouples W3 and W10 failed in August 1975; W12 failed in November 1975; W1 and W11 failed in December 1975; W2 failed in January 1976; and W5, W7, and W9 failed in May 1976. These failures were thought to be related to the gas leakage into cell 1. However, the PIE revealed that the junction between the tantalum-sheathed thermocouple and the Inconel-sheathed, compensated lead wire had failed. This failure was apparently caused by a higher-than-expected operating temperature for the area in which these junctions resided and subsequent failure of the brazes.

The P13T capsule was instrumented with 32 thermocouples. Twelve were in cell 1, and 20 were in cell 2. Three fuel rods in cell 1 and six rods in cell 2 had thermocouples in the center to measure fuel temperatures. Cell 1 had three thermocouples measuring central graphite temperatures and six measuring outer graphite temperatures. Cell 2 had eight thermocouples measuring central graphite temperatures and six measuring outer graphite temperatures. The outer graphite thermocouples in each cell consisted of three type W and three type K (C/A) thermocouples. These thermocouples were paired to help quantify the emf loss in the type W thermocouples due to neutron irradiation. Subsection 3.5.2 discussed decalibration.

An automatic data logger directly measured the emf output of the thermocouples, except the control thermocouples. The emf signal from the control thermocouples was retransmitted to the data logger from the control recorder. The data from the data logger were reduced by computer to operating temperatures, transferred to magnetic tape, and shipped to GA. At GA, the data were further reduced to four temperatures per day per thermocouple and punched on computer cards. These were then used in the postirradiation thermal analysis. Table 3-2 summarizes the P13T thermocouple operation.

At the start of the irradiation, all operating temperatures were within $\pm 75^{\circ}\text{C}$ of the predicted design values. Control thermocouples were then chosen to control the temperature in each cell during subsequent capsule operation. Thermocouple K6 in the graphite fuel body was chosen as the control thermocouple for cell 1, as shown in Table 3-3. The thermal analysis indicated that thermocouple K6 would operate at 1000°C with the fuel at the desired temperature of 1300°C .

Thermocouple W13 was chosen as the initial control thermocouple for cell 2. This was a fuel specimen thermocouple near the center of the core. After startup, the fuel sample that contained thermocouple W14 was shown to be operating at a slightly higher temperature than the one containing W13. Therefore, control was switched to thermocouple W14. Cell 2 was operated in this manner until a relationship between the fuel temperature (indicated by thermocouple W14) and the graphite temperature (indicated by thermocouple K19) could be established. When thermocouple W14 began to show signs of decalibration, control was switched to thermocouple K19. The control temperature for thermocouple K19 was changed to account for graphite and fuel rod dimensional and thermal power changes to maintain an estimated peak temperature of 1100°C . Table 3-3 lists the control temperatures used during the capsule operation. Figure 3-1 plots the temperatures indicated by the control thermocouples during operation.

3.2. IN-PILE FISSION GAS RELEASE MEASUREMENTS

The exhaust gas from both cells was periodically sampled. These samples were analyzed to determine the amount of fission gases released from the fuel versus the fission gases produced.

The samples were taken by placing a bottle on the sampling station and evacuating the sample bottle. A portion of the exhaust gas was then drawn into the sample bottle. A sodium-iodide detector and a multichannel analyzer analyzed for Kr-85m, Kr-87, Kr-88, Xe-133, and Xe-135 by directly counting the bottle. The Kr-89 and Xe-138 were analyzed by allowing the

sample to remain in the bottle for 15 min, then reevacuating. The bottle was then counted for the daughter products Rb-89 and Cs-138.

Fission power for each cell was calculated based on fuel burnup and breeding; the amount of fission products released versus the amount born (R/B) was calculated.

Figure 3-2 plots the Kr-85m R/B versus operating days for cell 1, and Fig. 3-3 plots for cell 2. Tables 3-4 and 3-5 list the R/Bs of all the isotopes analyzed.

3.3. ANALYSIS OF FLUX DOSIMETERS

The P13T capsule contained 28 dosimeters. The dosimeters, consisting of vanadium-0.522% iron (88.25% Fe-54) alloy wires and vanadium-0.216% cobalt alloy wires, were positioned alternately to span the four crucibles. The primary dosimeters were placed in the center of the crucibles, while the secondary dosimeters, comprised of the same alternating vanadium-iron and vanadium-cobalt alloy wires, occupied two partially available thermocouple holes parallel to the primary dosimeters. Individual dosimeters were enclosed within alumina tubes, which were encapsulated in niobium-1% zirconium tubes.

Capsule P13T dosimeters were disassembled in the GA hot cell. After removing niobium-1% zirconium encapsulation, the dosimeters were transferred to radiochemistry for gamma ray analysis with the Sigma 2 computer, and all activities were decayed back to end of irradiation. The activities resulting from these spectral analyses were input to the DOSE-1 computer program, which computed corresponding thermal and fast neutron flux and fluences.

Fast neutron flux and fluences are monitored with the fast neutron reaction $^{54}\text{Fe}(n,p)^{54}\text{Mn}$. The neutron energy threshold for this reaction is ~ 1.5 MeV. While neutrons below the threshold for the reaction do not contribute toward generating activity in the monitor, using an effective cross

section yields fluence values as though lower energy neutrons had entered into the reaction. GA uses 46.5 mB for the ORR, which is consistent with their spectral evaluations for the fractional fluxes above 29 fJ.

Historically, cobalt has monitored thermal flux in capsule irradiation experiments at GA. The standard method measures the reaction rate in a vanadium/cobalt dosimeter, then divides this measurement by the tabulated 2200 m/s cross section at 20°C for the dosimeter to obtain flux. This flux, called conventional flux or 2200 m/s flux, was converted to thermal flux by correcting for temperature.

Burnups predicted using the cobalt thermal fluxes and the FISSIN computer code did not agree. Gamma scan evaluations of the metal secondary containment shelf revealed that the thermal dosimetry was too widely spaced in the area of the stainless-steel bulkhead (see Fig. 3-4). The bulkhead depressed the thermal flux, and no cobalt dosimetry was near enough to the bulkhead to detect this depression (see Fig. 3-5). Since both the thermal and fast dosimetry were essentially pure vanadium wire doped with either iron or cobalt, the vanadium, which forms a stable chromium isotope under thermal neutron irradiation, determined the thermal neutron irradiation, determining the thermal neutron exposure by the following reaction:

Atomic absorption spectrophotometry, rather than gamma-ray spectrometry, then measured the stable chromium. The values determined by this method yielded thermal fluences that were consistent with the burnups obtained through chemical analysis.

Figure 3-5 shows the fast and thermal neutron fluxes, and Fig. 3-6 the fast and thermal fluences. A third-order least-squares fit was performed on

these data to establish the equation for fast fluences. The fast fluence values were fit in an equation of the form:

$$f(x) = a + bx + cx^2 + dx^3 \quad , \quad (3-2)$$

where x is the distance from the bottom of the core in inches. The values for the coefficients are presented below:

$$f(x) = 2.36 + 1.45 x - 0.108x^2 + 1.99 \times 10^{-3} x^3 \quad . \quad (3-3)$$

Table 3-6 lists the neutron exposures for the fuel specimens, and Table 3-7 lists the neutron exposures for the piggyback specimens.

The thermal flux values obtained from the vanadium wires, the initial fuel loadings, and the reactor power history were input into the FISSIN computer code for each fuel rod. The data for the rods in cells 1 and 2 were then combined to give a fission power history for each cell. Figure 3-7 shows the fission power history for cell 1, and Fig. 3-8 shows for cell 2.

3.4. HEAVY METAL BURNUP ANALYSIS

The GA Analytical Chemistry Department analyzed six capsule P13T fuel particle samples for heavy metal burnup.

The fuel particles were first cleaned to remove external contamination, then measured for prominent fission products. The atom ratios of fission products to Zr-95 were calculated for each sample to reveal any abnormal fuel particles.

The American Society for Testing and Materials (ASTM) fission-product-monitor radiochemical method (which uses Cs-137 as the burnup monitor) (Ref. 3-1) analyzed the fissile and fertile fuel particles. A second fission product monitor method (which uses stable zirconium as the burnup monitor)

(Ref. 3-2) also analyzed the fissile fuel particles. This second method cannot effectively analyze fertile fuel particles due to thorium interference. In addition to the fission product monitor methods, a mass spectrometric uranium-isotopic-analysis method analyzed the fissile fuel particles. This method measures burnup through changes in uranium isotopic composition and can be applied only to fuel particles that do not contain thorium and/or U-233 before irradiation; thus, it is not applicable for fertile fuel particles.

Replicate analyses were performed on the particles passing the selection criteria. Initially, the particles were crushed and dissolved in a perchloric acid mixture. These solutions, containing fission products and uranium (plus thorium if fertile fuel particles), were separated by an anion exchange method. The thorium and uranium fractions were spectrophotometrically analyzed by absorbance of their Arsenazo-III complex. Zirconium fractions were recovered from the fissile fuel particle samples; these fractions were also colorimetrically analyzed. A portion of the uranium fraction from each sample was analyzed mass spectrometrically for uranium isotopic composition. Tables 3-8 and 3-9 show the results.

The mass spectrometric data (atom percent) were treated in accordance with ASTM procedure E-244 (Ref. 3-1). The capture-to-fission ratio for U-235 ($\alpha_5 = 0.178$) used in these calculations is the previous value determined for P13Q. Table 3-10 shows burnup by this method under the heading Percent FIMA/ASTM Procedure E-244.

The radiochemical fission product monitor burnup method is essentially performed using the ASTM Procedure E-219 (Ref. 3-2). In principle, the number of fissions that have occurred in the fuel particles is determined by measuring the number of atoms of Cs-137 present and dividing by the fractional fission yield (U-233 yield is 6.80% , and U-235 yield is 6.27%). These numbers of fissions are then divided by the initial heavy metal atoms. Table 3-10 shows the radiochemical burnup results under the headings Percent FIMS/Fiss Cs-137 and Percent FIMA/Fiss Zr.

For long irradiations, decay must be considered for the correct Cs-137 concentrations during and after irradiation. An approximate correction was made using the following ASTM recommended equation:

$$N' = N / \{e^{-\lambda t'} - [(1 - e^{-\lambda t}) / \lambda t]\} \quad , \quad (3-4)$$

where N' = atoms of Cs-137 corrected for decay during and after irradiation,

N = atoms of Cs-137 at time of measurement,

λ = Cs-137 decay constant ($7.3 \times 10^{-10} \text{ s}^{-1}$),

t' = elapsed time from end of irradiation to measurement (s), and

t = irradiation time (s).

In addition to the burnups determined by radiochemistry and mass spectrometric methods, the Sigma 2 FISSIN program gave calculated values. The Sigma 2 FISSIN program calculates burnup (FIMA) for both U-235 and thorium at the beginning of each reactor irradiation cycle. The program calculates weights of uranium and thorium and the final uranium isotopic inventory. Required inputs are reactor power history, thermal fluence, and uranium and thorium loadings. Table 3-10 shows the resulting FISSIN calculated burnup values under the heading Percent FIMA/FISSIN.

Table 3-11 compares mass spectrometric uranium isotopic compositions at end of irradiation with those computed by the FISSIN program.

The GA FISSIN computer program calculated heavy metal burnup values for all fuel specimens in this and the following sections of this report. This program normalized the heavy metal reaction rates to cobalt reaction rates so that burnup on any sample within the capsule could be computed based on its location relative to the cobalt thermal fluence profile.

Burnups determined by the FISSIN code were concluded to be sufficiently close in agreement with those determined by the GA Analytical Chemistry Department. Thus, Tables 3-12 and 3-13 show all heavy metal burnups determined by the FISSIN code for all fuel rod and piggyback samples irradiated in P13T.

3.5. THERMAL ANALYSIS

The fuel thermal environment is one of the most important parameters influencing fuel irradiation behavior. Therefore, evaluation of fuel performance requires a good knowledge of the fuel operating temperature history. For this reason, thermocouples extensively monitored temperature profiles in capsule P13T.

C/A thermocouples measured capsule operating temperatures below 1100°C in unfueled regions. These thermocouples are not affected by the reactor neutron environment (Ref. 3-3). Therefore, the C/A temperature measurements provide the bases for comparison with calculated values. W/Re thermocouples monitored fuel and other high-temperature regions ($T > 1100^{\circ}\text{C}$). These thermocouples undergo irradiation-induced emf changes, resulting from alloy compositional changes caused by transmutations in both metals. Empirical data can account for the reduced emf changes due to irradiation exposure; however, relatively large uncertainties are currently associated with the correction factors. One thermal analysis primary objective was to more accurately predict irradiation-induced emf changes in the W/Re thermocouples.

Determining fuel rod temperature histories for the P13T capsule employed a combination of measured thermocouple temperature and graphite dimensional data, TAC2D* computer modeling, and a calculational procedure. TAC-2D models were constructed for each capsule fuel body, and temperature matching runs were made at five time points of the irradiation history. The

*Thermal Analysis Code - Two Dimensional.

calculational procedure involved curve fitting the TAC-calculated values, then, using the daily measured data as input, calculating peak fuel, surface fuel, and average graphite temperatures, which were plotted as a function of exposure time. TAC-calculated and measured temperatures agreed well; at all times, the TAC-calculated temperatures were within 20°C of the C/A measurements and 40°C of the corrected W/Re temperatures. Thermocouple decalibration was detailed, and corrected temperatures for all W/Re thermocouples were calculated over the irradiation period. Reference 3-3 completely details the thermal analysis for capsule P13T.

3.5.1. Fuel Rod Temperatures

The P13T thermal analysis used both measured data and analytical calculations to determine the capsule temperature history over the entire irradiation. The measured data consisted of daily irradiation temperature readings and control gas flow rates, postirradiation capsule dosimetry, and PIE measurements. The analytical portion included TAC-2D (Ref. 3-4) computer modeling and a calculational technique to determine peak fuel rod temperatures.

Figure 3-9 shows a 60-deg section of symmetry from an axial cross section of P13T. Thermocouples in the four capsule crucibles measured the temperatures at points A and B (TA and TB, respectively). Figure 3-10 shows a typical temperature profile radially outward from the capsule centerline through one of the fuel rods. If the temperature at the outer edge of the fuel rod hole, T_{OF} , is known, then the peak fuel rod temperature is simply

$$T_{PEAK} = T_{OF} + \Delta T_{GAP} + \Delta T_{FUEL} \quad (3-5)$$

ΔT_{GAP} and ΔT_{FUEL} will be shown to be determinable for each day of capsule operation; however, temperature T_{OF} is also needed. Fortunately, previous TAC analyses of this type capsule showed that, outboard of the fuel rod holes, the temperature distribution in the graphite is one of concentric isotherms, as shown in Fig. 3-9. Thus, the temperature measured at point B

in the graphite is nearly identical to the temperature at the edge of the fuel rod hole, and the two can be interchanged in Eq. 3-5 to give

$$T_{\text{PEAK}} = T_B + \Delta T_{\text{GAP}} + \Delta T_{\text{FUEL}} \quad (3-6)$$

Similarly, the fuel rod surface temperature will be

$$T_{\text{SURFACE}} = T_B + \Delta T_{\text{GAP}} \quad (3-7)$$

Figure 3-9 shows the temperature drop between points A and B, ΔT_{AB} . Since no gas gaps occur between these two points, over short periods, ΔT_{AB} will change only as the local reactor power changes (rod bank movement). Thus, a power factor (PF) can be defined as follows:

$$\text{PF} = \Delta T_{\text{AB}} / \Delta T_{\text{AB REF.}} \quad (3-8)$$

where $\Delta T_{\text{AB REF.}}$ = reference value, and

ΔT_{AB} = measurement made at any other time (within a relatively short period).

Computer models were constructed of a 60-deg sector of each of the four graphite crucibles. Temperature matching runs were then made for several irradiation time points for each crucible. These reference TAC runs gave the reference ΔT_{AB} , ΔT_{GAP} , and ΔT_{FUEL} values. Fuel temperatures for each irradiation day are obtained by curve fitting these reference values and expressing them as functions of megawatt days. Since the differential temperature (ΔT) across the fuel is a function of reactor power only and the ΔT across the gap is a function of both reactor power and gas conductivity, the calculation for peak fuel rod temperature becomes

$$T_{\text{FUEL PEAK}} = T_B + \Delta T_{\text{FUEL REF.}} (\text{PF}) + \left(\frac{\Delta T_{\text{GAP}}}{\Delta T_{\text{GAP REF.}}} \right) (\text{PF}) \left(\frac{K_{\text{GAS REF.}}}{K_{\text{GAS MEAS.}}} \right) \quad (3-9)$$

where

T_B = daily measured temperature at point B,

$\Delta T_{\text{FUEL REF.}}$ = temperature drop across fuel rod from reference curve fit,

$\Delta T_{\text{GAP REF.}}$ = temperature drop across fuel-crucible gap from reference curve fit,

PF = power factor, as detailed in Eq. 3-8, which corrects local power variations (i.e., rod bank movement),

$K_{\text{GAS REF.}}$ = gas mix conductivity from reference runs, and

$K_{\text{GAS MEAS.}}$ = daily measured gas mix conductivity, which corrects for sweep gas mixture changes.

The rod surface temperature is

$$T_{\text{SURFACE}} = T_B + \left(\frac{\Delta T_{\text{GAP REF.}}}{\Delta T_{\text{GAP REF.}}} \right) (PF) \left(\frac{K_{\text{GAS REF.}}}{K_{\text{GAS MEAS.}}} \right) . \quad (3-10)$$

While this method is admittedly not as detailed or exhaustive as some, it can quickly and accurately determine daily capsule operating temperatures. Given the uncertainties associated with previous thermal analysis results (Ref. 3-5), the reduced complexity and time were felt to more than justify any slight losses in accuracy. This method replaces complex SHAPE and CAPTEM (Refs. 3-6, 3-7) computer analyses following the temperature matching phase. It therefore greatly reduces overall computer usage. This method also analyzed capsule P13Q (Ref. 3-8) with satisfactory results.

The experiment operation was closely monitored; thermocouple readings and gas flow data were recorded four to five times each day. These data were then sent via magnetic tape to GA, where they were recorded and punched on computer cards. The data were also inspected for errors, which were either eliminated or corrected. Since the four or five daily readings resulted in an unnecessarily large amount of data for thermal analysis, a program averaged the values into one data set for each day of operation.

The 100% helium data were not included in these averaged values, since the capsule operated in this mode only long enough to normalize temperatures and to record data.

Dosimetry wires included in the experiment were recorded during the PIE. These wires (see Subsection 3.3) indicated the flux and fluence at the capsule reactor during the test. The fluxes and fluences then determined heating rates and fluence-dependent property changes.

The PIE capsule component measurements indicated the dimensional changes of graphite and fuel rods. The measured dimensional change rates for graphite and fuel rods calculated gap widths for use in the TAC thermal models.

Any thermal analysis needs simplified assumptions so that the problem complexity remains practical. Several assumptions were made in constructing and using the TAC thermal models for this analysis.

Since a capsule is three-dimensional, a rigorous analysis requires a three-dimensional mathematical model. Such models tend to be very cumbersome and time consuming, especially when they require many computer runs. For this reason, an approximation must reduce the problem to two dimensions. This approximation was made by assuming zero axial heat flow for appropriate model locations (e.g., midplane of fuel stacks); four r, θ TAC-2D computer models were constructed, one for each of the four P13T crucibles.

A second assumption was that the corresponding temperatures on opposite sides of the capsule were the same. Typical cross-capsule ΔT s are estimated to vary from 10° to 40°C . These variances are small compared to the total radial ΔT of $\sim 900^\circ\text{C}$. This assumption allows computer models to use 60-deg sectors, since the same pattern is repeated six times around the capsule axis.

This report earlier assumed concentric isotherms outboard of the fuel rod holes.

With the reference values obtained from the TAC models and the daily data, Eq. 3-6 then calculated the temperature histories. Figures 3-11 through 3-14 show the peak fuel, average fuel, and average graphite temperatures for each crucible. Each case assumed the following:

1. Peak fuel temperature is the highest temperature in a fuel rod; it is not usually the centerline rod temperature because of the asymmetric configuration of this capsule.
2. Average fuel temperature is half the sum of the peak fuel rod and rod surface temperatures. Volume-average rod temperatures are 10° to 20°C higher than these average values. This was determined using the CUSTOM subroutine of the TAC code, which allows the user to make extra calculations. The volumes of the temperature nodes were called out and used to weight the fuel rod node temperatures to obtain the volume average values (Ref. 3-9).
3. Average graphite temperature is half the sum of the inner and outer graphite crucible temperatures.

Because cell 2 contained three crucibles swept by the same gas mixture, temperatures could not be controlled in each crucible. Since the control thermocouples were located in crucible 2 of cell 2, temperatures in crucibles 3 and 4 varied considerably during reactor cycles, explaining the cyclic appearance of the temperature histories of these crucibles.

Figures 3-15 and 3-16 show only the peak fuel rod temperatures in crucibles 1 and 2. Rods within crucible 1 ran within $\pm 50^{\circ}\text{C}$ of the 1300°C design temperature during the first half of the irradiation and from 100° to 150°C below design during the second half. Cell 1 was plagued with thermocouple failures. All the fuel thermocouples failed after 6500 MWd; by the

end of the irradiation, only thermocouples K6 and K8 were still operating. Fortunately, K6 was the control thermocouple for this cell, so temperature control was not sacrificed. The high failure rate of thermocouples in this cell was attributed to failure of the junctions where the thermocouple wires were joined to the compensated lead wires, as indicated in Subsection 3.1.

In crucible 2, the fuel rod temperatures rose steadily from a BOL value of 950° to 1230°C until control was switched from fuel thermocouple W14 to graphite thermocouple K19. This temperature rise was expected, since the set point for W14 remained at the 1100°C design temperature, and as this thermocouple decalibrated, the actual fuel temperature continued to rise. Although this procedure promised to give useful information about the decalibration rate, the unknowns in the decalibration phenomenon prevented this effect from being accurately determined. Therefore, control was switched to thermocouple K19 on December 12, 1975 at the start of reactor cycle 129. Just prior to the change, K19 had been reading $\sim 775^{\circ}\text{C}$. The pre-determined set point for K19 was 750°C , and after the switch, K19 averaged 740°C . This 35°C drop in graphite temperature caused an even larger drop in fuel temperatures, causing the discontinuity in the crucible 2 fuel temperature history at ~ 5500 MWd (December 12, 1975). Of course, for reasons already discussed, crucibles 3 and 4 showed this same abrupt drop in temperature (Figs. 3-13 and 3-14). This actually brought the fuel temperature in crucible 2 down to within 50°C of the design value, where it remained until the end of the irradiation.

Tables 3-14 through 3-17 present the percent temperature distributions. In each case, the values printed for one rod represent three rods. For example, the peak temperatures given for rod 1-1 represent those for rods 1A1, 1B1, and 1C1 (Fig. 2-1), since these were all at the same axial position within the capsule. The same applies for the fuel rod surface and volume-average temperatures.

In studying the temperature history of crucible 1, the design temperature was very apparently not met during the last half of the irradiation. This may at first seem strange, since the control thermocouple K6 operated at its 1000°C set point during the entire experiment. The fuel-crucible gap size seems to have caused the temperature drop. Table 3-18 shows the preirradiation thermal analysis gap sizes versus the actual values determined from the capsule PIE. While they agreed well at BOL, the end-of-life (EOL) values differed considerably. The fuel rods did not shrink as much as expected; as a result, the EOL gaps were small. Thus, in cell 1, the 1000°C graphite-control temperature, which would have meant design-value fuel temperatures with the predicted gap size, produced lower fuel temperatures with the 50%-smaller gap.

If this was the case in crucible 1, crucible 2 fuel rod operation at design temperature was, for a time, thought to be uncertain. Actually, the gap size difference for crucible 2 was only half that for crucible 1. More importantly, the control set point temperature in crucible 2 was adjusted twice during the latter part of the irradiation. Between December 12, 1974 (when the control thermocouple switch was made) and EOL, the set point of K19 was changed from 750° to 790°C to compensate for the then evidently decreasing temperatures. This allowed the fuel temperatures to stay within the design range despite the smaller fuel-crucible gaps.

Fuel temperatures for crucibles 3 and 4 were also below design (1100°C); since the gap size effect was quite large, crucibles 3 and 4 showed 51% and 40% differences, respectively. Evidently, the change in control set point in cell 2 could not compensate for the larger gap size differences in these two crucibles.

3.5.2. Thermocouple Decalibration

The W/Re thermocouples used in capsule experiments are well established as decalibrating or progressively indicating lower-than-actual temperatures as the irradiation proceeds (Ref. 3-10). The alloys comprising the

thermocouple wires are known to transmute to different forms due to neutron capture. Also, the W/Re thermocouple almost always reads slightly higher initially than the true temperature. This is due to gamma heating, since the thermocouple is constructed of fairly dense materials. Figure 3-17 shows a typical emf response curve of a W/Re thermocouple exposed to a neutron flux and held at a constant temperature.

In earlier capsule analysis, a decalibration relationship was desired for use in any experiment to predict the irradiation-induced emf loss of the W/Re thermocouples. However, later data showed that factors other than thermal fluence apparently affected decalibration. The routing of the thermocouple within the capsule, the length of lead wire, and the thermal and flux gradients seen by the thermoelements all affect the thermocouple emf response. This explains why decalibration factors from different irradiation tests seldom correlate with each other; subtle differences in geometry and exposure will affect thermocouple behavior and, thus, decalibration rates. Due to the complexity of this phenomenon, a generalized decalibration equation will probably not be defined. Thus, decalibration factors need to be determined for each test, as was done with the Pl3T capsule.

The preirradiation thermal analysis determined that certain locations in the graphite crucibles of each cell would need to be at specific temperature levels for the fuel to operate at the design temperatures. Control was achieved by placing C/A thermocouples in these graphite locations and adjusting the sweep gas mixtures to always maintain the set point temperature. In Pl3T, cell 2, an alternate method of control was attempted. Since crucible 2 of cell 2 contained W/Re thermocouples in the fuel rods, a fuel thermocouple initially controlled fuel temperature for less uncertainty. This thermocouple was to be decalibrated by identifying the relationship between it and the nearest C/A thermocouple and correcting as needed. This control method was unsuccessful, however, and control was eventually shifted to graphite thermocouple K19, also in crucible 2.

Decalibration factors with a thermocouple pair can be determined in two ways: (1) the temperature readings of the C/A thermocouple (T_K) and the W/Re thermocouple (T_W) can be ratioed or (2) the differences can be determined. This analysis used differences. In either case, the temperatures are always normalized so that the BOL ΔT is zero. This step negates the gamma heating effect in the W/Re thermocouple mentioned above and any geometry effects that exist.

Figure 3-18 plots the ΔT s for each thermocouple pair in P13T for the entire irradiation. The best-fit linear relationship was applied to each curve. Then the total ΔT ($T_W - T_K$) at EOL was divided by the thermal fluence seen at the location of each pair to obtain the decalibration factor. Table 3-19 shows decalibration rates calculated for the six thermocouple pairs in P13T. The corrected readings for any W/Re thermocouple in the capsule are determined by applying the decalibration factor of the nearest thermocouple pair.

Three crucibles contained W/Re thermocouples embedded in the fuel rods. The measured temperatures and the analytically calculated temperatures cannot be compared directly because of the decalibration effect. However, the decalibrated or corrected temperature measurements can be compared to the calculated values; Figs. 3-19 through 3-21 show these. Generally, the differences can be seen as $\pm 100^\circ\text{C}$, averaging $\pm 50^\circ\text{C}$. Known errors and uncertainties in the calculational technique and decalibration estimates prevent good agreement. Therefore, the total uncertainty in the P13T W/Re thermocouples was estimated to be $\pm 100^\circ\text{C}$.

REFERENCES

- 3-1. "Atom Percent Fission in Uranium and Plutonium Fuels (Mass Spectrometric Method)," ASTM Procedure E-224-69 (Reapproved 1974), in 1977 Annual Book of ASTM Standards, Part 45, "Nuclear Standards," American Society for Testing and Materials, Philadelphia, 1977.

- 3-2. "Atom Percent Fission in Uranium Fuel (Radiochemical Method), "ASTM Procedure E-219-69 (Reapproved 1974) in 1977 Annual Book of ASTM Standards, Part 45, "Nuclear Standards," American Society for Testing and Materials, Philadelphia, 1977.
- 3-3. Ketterer, J. W., "Postirradiation Thermal Analysis of Capsule Pl3T," General Atomic Report GA-A14654, December 1978.
- 3-4. Petersen, J. F., "GAC2D, A General Purpose Two-Dimensional Heat Transfer Computer Code, User's Manual," USAEC Report GA-8868, General Atomic Company, September 6, 1969.
- 3-5. Scott, C. B., D. P. Harmon, and J. F. Holzgraf, "Postirradiation Examination of Capsules Pl3R and Pl3S," General Atomic Report GA-A13827, October 8, 1976.
- 3-6. Kearny, D. W., "SHAPE: A Computer Program to Calculate Shape Factors for the CAPTEM Program," General Atomic Report GA-10602, April 16, 1971.
- 3-7. Carosella, D. P., H. W. Chi, and D. W. Kearny, "CAPTEM: A Computer Code for the Thermal Analysis of Fuel Irradiation Capsules," General Atomic Report GA-B10620, September 1971.
- 3-8. Young, C. A., and C. B. Scott, "Postirradiation Examination of Capsule Pl3Q," ERDA Report GA-A14174, General Atomic Company, September 1977.
- 3-9. Ketterer, J., "Volume Average Temperatures of Fuel Specimens, General Atomic unpublished data, August 2, 1977.
- 3-10. Sandefur, N. L., J. S. Steibel, and R. J. Grenda, "EMF Drift of Chromel/Alumel and W-3% Re/W-25% Re Thermocouples," General Atomic Report GA-A12501, May 24, 1973.

Fig. 3-1. P13T control thermocouple temperature versus EFPD

Fig. 3-2. P13T R/B Kr-85m, cell 1

Fig. 3-3. P13T R/B Kr-85m, cell 2

Fig. 3-4. Axial gamma scan of secondary containment shell from capsule P13T

Fig. 3-5. Pl3T thermal and fast fluxes versus distance from bottom of core

Fig. 3-6. P13T thermal and fast fluences versus distance from bottom of core

Fig. 3-7. P13T fission power versus EFPD, cell 1

Fig. 3-8. P13T fission power versus EFPD, cell 2

Fig. 3-9. Radial 60-deg section of symmetry of P13T capsule

Fig. 3-10. P13T radial temperature profile

*MWD = DAYS AT POWER X REACTOR POWER (30 MW)

Fig. 3-11. P13T temperature history for crucible 1

Fig. 3-12. P13T temperature history for crucible 2

Fig. 3-13. P13T temperature history for crucible 3

Fig. 3-14. P13T temperature history for crucible 4

Fig. 3-15. Crucible 1 peak fuel rod temperatures: rods 1-3A, 1-3B, and 1-3C

Fig. 3-16. Crucible 2 peak fuel rod temperatures: rods 2-1A, 2-1B, and 2-1C

Fig. 3-17. Thermocouple calibration cell contained in irradiation capsule P13M (GA19-2) measured the effect of neutron bombardment on emf output of W3%Re/W25%Re thermocouples by measuring melting point of copper

Fig. 3-18. Decalibration in P13T (all ΔT s normalized to 0°C at BOL)

Fig. 3-19. T (calculated) minus T (measured) for crucible 1 fuel thermocouple.
Note: All fuel thermocouples in this crucible had failed by ~6000 MWd.

Fig. 3-20. T (calculated) minus T (measured) for crucible 2 fuel thermocouple

Fig. 3-21. T (calculated) minus T (measured) for crucible 4 fuel thermocouple

TABLE 3-1
 ORR FUEL CYCLES DURING P13T IRRADIATION

<u>Cycle</u>	<u>Startup</u>	<u>Shutdown</u>	<u>Cumulative EFPD</u>
125-3	5/10/75	5/28/75	17.3
125-4	5/29/75	6/15/75	34.5
126-1	6/21/75	7/7/75	50.8
126-2	7/7/75	7/15/75	58.7
126-3	7/15/75	7/29/75	72.4
126-4	7/29/75	8/10/75	84.1
127-1	8/16/75	8/18/75	86.5
127-2	8/23/75	9/2/75	96.4
127-3	9/2/75	9/10/75	103.9
127-4	9/10/75	9/29/75	122.7
127-5	9/29/75	10/5/75	128.9
128-1	10/75	10/17/75	135.4
128-2	10/17/75	10/20/75	138.0
128-3	10/20/75	11/3/75	151.7
128-4	11/3/75	11/19/75	167.1
128-5	11/19/75	12/5/75	182.9
129-1	12/12/75	12/30/75	200.4
129-2	12/30/75	1/14/76	215.2
129-3	1/14/75	1/25/76	226.3
130-1	1/30/76	2/13/76	240.1
130-2	2/13/76	3/5/76	260.9
130-3	3/5/76	3/21/76	277.0
131-1	4/1/76	4/9/76	284.7
131-2	4/10/76	4/21/76	295.6
131-3	4/21/76	5/4/76	307.4
131-4	5/4/76	5/13/76	315.9
131-5	5/13/76	5/22/76	324.8
132-1	5/27/76	6/8/76	236.5
132-2	6/8/76	6/21/76	349.0
132-3	6/21/76	7/5/76	363.4
			or 8720 h

TABLE 3-2
OPERATION OF P13T THERMOCOUPLES

Thermocouple	Location	Distance From Bottom of Core [cm (in.)]	Thermal Fluence (10^{25} n/m ²)	Fast Fluence [(10^{25} n/m ²) (E > 29 fJ) _{HTGR}]	Normal Temperature (°C)	Operating Time (h)
Cell 1						
W1	Fuel	2.95 (1.16)	1.77	2.17	1300	4390 ^(a)
W2	Fuel	2.95 (1.16)	2.08	2.55	1300	5156 ^(a)
W3	Fuel	2.95 (1.16)	0.82	1.00	1300	2035 ^(a)
K4	Outer graphite	3.51 (1.38)	3.08	3.95	1000	7430 ^(a)
W5	Outer graphite	3.51 (1.38)	3.22	4.15	1000	7790 ^(a)
K6	Outer graphite	9.65 (3.80)	4.67	7.12	1000	8720
W7	Outer graphite	9.65 (3.80)	0.78	1.19	1000	1464 ^(a)
K8	Outer graphite	15.75 (6.20)	5.54	8.51	1000	8720
W9	Outer graphite	15.75 (6.20)	4.95	7.60	1000	7790 ^(a)
W10	Inner graphite	5.99 (2.36)	0.93	1.35	1175	2035 ^(a)
W11	Inner graphite	9.65 (3.80)	2.57	4.69	1175	4805 ^(a)
W12	Inner graphite	15.75 (6.20)	2.55	3.91	1175	4006 ^(a)
Cell 2						
W13	Fuel	28.52 (11.23)	5.97	8.71	1100	8720
W14	Fuel	28.52 (11.23)	5.97	8.71	1100	8720
W15	Fuel	28.52 (11.23)	5.97	8.71	1100	8720
W16	Fuel	56.03 (22.06)	1.91	3.61	1100	8720
W17	Fuel	56.03 (22.06)	1.91	3.61	1100	8720
W18	Fuel	56.03 (22.06)	1.91	3.61	1100	8720

TABLE 3-2 (Continued)

Thermocouple	Location	Distance From Bottom of Core [cm (in.)]	Thermal Fluence (10^{25} n/m ²)	Fast Fluence [(10^{25} n/m ²) (E > fJ) _{HTGR}]	Normal Temperature (°C)	Operating Time (h)
Cell 2 (continued)						
K19	Outer graphite	27.89 (10.98)	5.97	8.76	750	8720
W20	Outer graphite	27.89 (10.98)	5.97	8.76	750	8720
K21	Outer graphite	39.57 (15.58)	4.75	6.97	750	8720
W22	Outer graphite	39.57 (15.58)	4.75	6.97	750	8720
K23	Outer graphite	55.40 (21.81)	1.97	3.70	750	8720
W24	Outer graphite	55.40 (21.81)	1.97	3.70	750	8720
W25	Inner graphite	23.52 (9.26)	5.72	9.00	950	8720
W26	Inner graphite	25.43 (10.01)	2.72	4.12	950	4022 ^(a)
W27	Inner graphite	28.52 (11.23)	5.97	8.71	950	8720
W28	Inner graphite	37.08 (14.60)	5.17	7.46	950	8720
W29	Inner graphite	42.06 (16.56)	4.30	6.47	950	8720
W30	Inner graphite	49.30 (19.41)	2.91	4.91	950	8720
W31	Inner graphite	52.98 (20.86)	2.33	4.15	950	8720
W32	Inner graphite	56.03 (22.06)	1.91	3.61	950	8720

(a) Thermocouple failed during capsule irradiation. Data are given at time of failure.

TABLE 3-3
P13T CONTROL TEMPERATURES

Dates	Thermocouple	Control Temperature (°C)
Cell 1		
5/10/75 to 7/6/76	K6	1000
Cell 2		
5/10/75 to 5/29/75	W13	1100
5/29/75 to 12/12/75	W14	1100
12/12/75 to 3/5/76	K19	750
3/5/76 to 4/26/76	K19	790
4/26/76 to 7/6/76	K19	800

TABLE 3-4
R/B VALUES FOR CELL 1 OF CAPSULE P13T

EFPD	Kr-85m	Kr-87	Kr-88	Xe-133	Xe-135	Kr-89	Xe-138
2	4.17×10^{-7}	3.52×10^{-7}	3.22×10^{-7}	6.49×10^{-7}	1.10×10^{-7}	3.97×10^{-8}	3.54×10^{-8}
3	1.19×10^{-6}	7.93×10^{-7}	8.43×10^{-7}	1.39×10^{-7}	1.30×10^{-7}	--	--
6	1.17×10^{-6}	1.00×10^{-6}	1.37×10^{-6}	3.20×10^{-6}	1.59×10^{-7}	--	--
10	8.25×10^{-7}	1.32×10^{-7}	7.08×10^{-8}	1.07×10^{-5}	1.84×10^{-8}	--	--
13	1.21×10^{-6}	8.36×10^{-7}	5.24×10^{-7}	1.01×10^{-5}	2.74×10^{-7}	--	--
17	1.74×10^{-6}	1.03×10^{-6}	3.62×10^{-7}	1.41×10^{-5}	1.90×10^{-7}	--	--
26	1.74×10^{-6}	1.35×10^{-6}	1.27×10^{-6}	1.26×10^{-5}	2.03×10^{-7}	6.57×10^{-9}	2.54×10^{-8}
33	3.11×10^{-6}	1.50×10^{-6}	1.87×10^{-6}	0.00	4.25×10^{-7}	--	--
39	3.03×10^{-6}	2.13×10^{-6}	1.62×10^{-6}	2.33×10^{-5}	3.66×10^{-7}	--	--
46	2.12×10^{-6}	1.45×10^{-6}	1.12×10^{-6}	2.79×10^{-5}	4.38×10^{-7}	--	--
53	3.00×10^{-6}	1.78×10^{-6}	1.84×10^{-6}	2.70×10^{-5}	3.44×10^{-7}	--	--
61	1.60×10^{-6}	1.27×10^{-6}	1.47×10^{-6}	1.54×10^{-5}	1.65×10^{-7}	--	--
68	1.88×10^{-6}	1.40×10^{-6}	1.03×10^{-6}	1.83×10^{-5}	2.38×10^{-7}	6.60×10^{-9}	5.40×10^{-9}
75	7.64×10^{-6}	2.58×10^{-6}	2.33×10^{-6}	2.72×10^{-6}	1.20×10^{-6}	--	--
80	1.09×10^{-6}	8.03×10^{-7}	6.75×10^{-7}	9.21×10^{-6}	3.83×10^{-7}	--	--
91	5.62×10^{-6}	2.51×10^{-6}	2.01×10^{-6}	8.98×10^{-5}	6.17×10^{-7}	7.63×10^{-8}	1.83×10^{-7}
100	5.09×10^{-6}	1.99×10^{-6}	2.15×10^{-6}	2.33×10^{-5}	7.48×10^{-6}	--	--
112	3.00×10^{-6}	1.84×10^{-6}	1.80×10^{-6}	1.78×10^{-5}	1.07×10^{-6}	1.18×10^{-7}	3.94×10^{-7}
118	3.10×10^{-6}	2.12×10^{-6}	1.99×10^{-6}	3.31×10^{-5}	9.02×10^{-7}	--	--
127	3.98×10^{-6}	3.00×10^{-6}	2.65×10^{-6}	2.89×10^{-5}	1.84×10^{-6}	7.47×10^{-8}	4.82×10^{-7}
134	3.76×10^{-6}	2.32×10^{-6}	2.10×10^{-6}	2.72×10^{-5}	9.66×10^{-7}	0	0

TABLE 3-4 (Continued)

EFPD	Kr-85m	Kr-87	Kr-88	Xe-133	Xe-135	Kr-89	Xe-138
141	3.19×10^{-6}	2.39×10^{-6}	2.14×10^{-6}	1.77×10^{-5}	7.49×10^{-7}	6.31×10^{-9}	1.39×10^{-7}
147	3.30×10^{-6}	2.42×10^{-6}	2.50×10^{-6}	2.03×10^{-5}	4.46×10^{-6}	0	0
156	4.68×10^{-6}	2.34×10^{-6}	2.42×10^{-6}	1.91×10^{-4}	1.54×10^{-6}	0	0
161	3.19×10^{-6}	2.32×10^{-6}	2.08×10^{-6}	3.12×10^{-5}	1.43×10^{-6}	9.18×10^{-8}	4.72×10^{-6}
174	4.14×10^{-6}	2.47×10^{-6}	2.82×10^{-6}	2.49×10^{-5}	1.86×10^{-6}	0	0
182	4.04×10^{-6}	1.78×10^{-6}	1.53×10^{-6}	2.03×10^{-5}	1.52×10^{-6}	5.28×10^{-8}	4.58×10^{-6}
189	1.55×10^{-6}	1.02×10^{-6}	1.14×10^{-6}	9.86×10^{-6}	8.78×10^{-7}	0	0
200	4.43×10^{-6}	2.64×10^{-6}	2.09×10^{-6}	2.89×10^{-5}	2.14×10^{-6}	0	0
209	6.43×10^{-6}	3.64×10^{-6}	3.75×10^{-6}	3.20×10^{-5}	3.15×10^{-6}	4.86×10^{-8}	1.23×10^{-6}
218	6.16×10^{-6}	2.65×10^{-6}	2.78×10^{-6}	3.82×10^{-5}	3.15×10^{-6}	0	0
222	5.56×10^{-6}	2.91×10^{-6}	2.79×10^{-6}	2.11×10^{-5}	3.05×10^{-6}	0	0
234	6.65×10^{-6}	3.75×10^{-6}	3.56×10^{-6}	3.75×10^{-5}	1.41×10^{-6}	1.34×10^{-7}	1.21×10^{-6}
239	5.59×10^{-6}	3.08×10^{-6}	3.12×10^{-6}	3.02×10^{-5}	1.58×10^{-6}	0	0
247	6.14×10^{-6}	3.37×10^{-6}	2.86×10^{-6}	3.51×10^{-5}	1.97×10^{-6}	0	8.93×10^{-7}
253	4.89×10^{-6}	2.60×10^{-6}	2.47×10^{-6}	2.93×10^{-5}	1.73×10^{-6}	0	0
259	5.62×10^{-6}	3.29×10^{-6}	2.60×10^{-6}	3.68×10^{-5}	1.47×10^{-6}	3.07×10^{-7}	1.02×10^{-6}
266	6.66×10^{-6}	5.31×10^{-6}	3.87×10^{-6}	4.34×10^{-5}	9.70×10^{-7}	--	--
275	8.03×10^{-6}	1.14×10^{-6}	3.00×10^{-6}	2.63×10^{-5}	1.14×10^{-6}	--	--
285	7.25×10^{-6}	5.10×10^{-6}	2.47×10^{-6}	2.40×10^{-5}	1.41×10^{-6}	--	--
289	7.84×10^{-6}	4.16×10^{-6}	4.74×10^{-6}	1.83×10^{-5}	1.26×10^{-6}	1.51×10^{-7}	4.35×10^{-7}
300	5.01×10^{-6}	7.30×10^{-6}	6.25×10^{-6}	3.43×10^{-5}	2.84×10^{-6}	--	--

TABLE 3-4 (Continued)

EFPD	Kr-85m	Kr-87	Kr-88	Xe-133	Xe-135	Kr-89	Xe-138
310	1.23×10^{-5}	7.31×10^{-6}	5.98×10^{-6}	1.63×10^{-5}	2.77×10^{-6}	4.61×10^{-7}	1.16×10^{-6}
315	1.17×10^{-5}	8.29×10^{-6}	5.83×10^{-6}	3.17×10^{-5}	2.55×10^{-6}	4.61×10^{-8}	1.28×10^{-7}
323	1.32×10^{-5}	8.58×10^{-6}	1.03×10^{-5}	1.02×10^{-5}	2.51×10^{-6}	--	--
332	1.68×10^{-5}	1.27×10^{-5}	1.09×10^{-5}	5.15×10^{-5}	2.32×10^{-6}	--	--
339	3.03×10^{-5}	2.03×10^{-5}	0	8.39×10^{-5}	5.23×10^{-6}	6.15×10^{-7}	1.33×10^{-6}
345	2.32×10^{-5}	1.47×10^{-5}	9.95×10^{-6}	1.59×10^{-4}	3.19×10^{-6}	--	--
351	1.83×10^{-5}	1.73×10^{-5}	1.36×10^{-5}	5.63×10^{-5}	3.51×10^{-6}	--	--

TABLE 3-5
R/B VALUES FOR CELL 2 OF CAPSULE P13T

EFPD	Kr-85m	Kr-87	Kr-88	Xe-133	Xe-135	Kr-89	Xe-138
2	2.78×10^{-7}	2.38×10^{-7}	2.05×10^{-7}	4.81×10^{-7}	1.62×10^{-7}	1.36×10^{-8}	2.66×10^{-8}
3	1.73×10^{-7}	6.68×10^{-8}	5.98×10^{-7}	0.00	3.12×10^{-8}	--	--
6	2.27×10^{-7}	2.18×10^{-7}	1.21×10^{-7}	3.69×10^{-7}	6.65×10^{-8}	--	--
10	4.84×10^{-7}	2.66×10^{-7}	1.85×10^{-7}	6.32×10^{-7}	9.22×10^{-8}	--	--
13	5.00×10^{-7}	3.19×10^{-8}	2.81×10^{-7}	7.16×10^{-7}	8.56×10^{-8}	--	--
17	5.84×10^{-7}	4.81×10^{-7}	7.51×10^{-8}	9.34×10^{-7}	7.48×10^{-8}	2.70×10^{-9}	1.41×10^{-8}
26	2.97×10^{-7}	2.11×10^{-7}	1.81×10^{-7}	4.88×10^{-7}	6.50×10^{-8}	--	--
33	5.60×10^{-7}	3.45×10^{-7}	3.16×10^{-7}	8.05×10^{-7}	6.88×10^{-8}	--	--
39	3.33×10^{-7}	1.68×10^{-7}	1.15×10^{-7}	3.10×10^{-7}	4.00×10^{-8}	--	--
46	7.23×10^{-7}	2.90×10^{-7}	2.15×10^{-7}	8.68×10^{-7}	4.62×10^{-8}	--	--
53	1.22×10^{-6}	4.20×10^{-7}	4.57×10^{-7}	1.63×10^{-6}	1.27×10^{-7}	--	--
61	5.05×10^{-7}	3.20×10^{-7}	2.46×10^{-6}	1.08×10^{-6}	8.58×10^{-8}	--	--
68	2.53×10^{-7}	5.83×10^{-7}	5.26×10^{-7}	2.18×10^{-6}	1.27×10^{-7}	1.09×10^{-9}	3.69×10^{-9}
75	1.40×10^{-6}	6.49×10^{-7}	2.74×10^{-7}	2.33×10^{-6}	9.59×10^{-8}	--	--
80	3.87×10^{-6}	1.34×10^{-6}	1.41×10^{-6}	6.36×10^{-6}	2.32×10^{-7}	--	--
91	4.36×10^{-6}	1.66×10^{-6}	1.46×10^{-6}	4.07×10^{-6}	1.65×10^{-6}	2.15×10^{-9}	8.74×10^{-8}
100	6.30×10^{-6}	2.39×10^{-6}	2.72×10^{-6}	5.61×10^{-6}	7.48×10^{-8}	--	--
112	7.60×10^{-6}	4.30×10^{-6}	4.62×10^{-6}	9.46×10^{-6}	2.44×10^{-6}	4.50×10^{-8}	1.86×10^{-7}
118	1.14×10^{-5}	4.54×10^{-6}	5.53×10^{-6}	1.75×10^{-5}	3.44×10^{-7}	--	--
127	1.29×10^{-5}	3.97×10^{-6}	4.09×10^{-6}	2.08×10^{-5}	2.79×10^{-7}	6.30×10^{-9}	1.72×10^{-7}
134	1.40×10^{-5}	4.22×10^{-6}	3.69×10^{-6}	8.71×10^{-6}	1.79×10^{-7}		

TABLE 3-5 (Continued)

EFPD	Kr-85m	Kr-87	Kr-88	Xe-133	Xe-135	Kr-89	Xe-138
141	4.79×10^{-6}	2.50×10^{-6}	3.01×10^{-6}	1.09×10^{-5}	1.49×10^{-6}	1.19×10^{-9}	7.05×10^{-8}
147	7.24×10^{-6}	3.59×10^{-6}	2.17×10^{-6}	2.91×10^{-6}	7.73×10^{-7}	--	--
156	5.62×10^{-6}	3.19×10^{-6}	3.23×10^{-6}	1.05×10^{-5}	1.55×10^{-7}	--	--
161	6.48×10^{-6}	3.33×10^{-6}	3.54×10^{-6}	1.06×10^{-5}	1.15×10^{-7}	1.22×10^{-8}	1.16×10^{-7}
174	7.79×10^{-6}	3.09×10^{-6}	3.32×10^{-6}	1.10×10^{-5}	5.20×10^{-8}	--	--
182	6.65×10^{-6}	3.35×10^{-6}	4.24×10^{-6}	2.45×10^{-5}	6.56×10^{-7}	1.92×10^{-8}	2.11×10^{-7}
189	2.77×10^{-6}	1.37×10^{-6}	1.85×10^{-6}	5.84×10^{-6}	--	--	--
200	3.38×10^{-6}	1.74×10^{-6}	1.76×10^{-6}	1.09×10^{-5}	--	--	--
209	1.93×10^{-6}	1.04×10^{-6}	1.01×10^{-6}	4.14×10^{-6}	1.53×10^{-7}	6.50×10^{-9}	3.95×10^{-8}
218	7.27×10^{-7}	4.25×10^{-7}	3.41×10^{-7}	3.29×10^{-6}	7.86×10^{-8}	--	--
222	1.46×10^{-6}	7.89×10^{-7}	6.73×10^{-7}	4.30×10^{-6}	1.16×10^{-7}	--	--
234	9.91×10^{-7}	6.31×10^{-7}	5.88×10^{-7}	2.01×10^{-6}	1.98×10^{-7}	5.83×10^{-9}	8.81×10^{-8}
239	1.03×10^{-6}	6.39×10^{-7}	5.34×10^{-7}	2.56×10^{-6}	2.20×10^{-7}	--	--
247	9.10×10^{-7}	6.06×10^{-7}	5.20×10^{-7}	2.38×10^{-6}	2.29×10^{-7}	1.24×10^{-8}	9.58×10^{-8}
253	8.14×10^{-7}	6.48×10^{-7}	5.48×10^{-7}	3.67×10^{-6}	2.00×10^{-7}	--	--
259	1.08×10^{-6}	7.49×10^{-7}	5.55×10^{-7}	5.91×10^{-6}	2.99×10^{-7}	2.17×10^{-8}	9.49×10^{-8}
266	8.75×10^{-7}	7.74×10^{-7}	7.57×10^{-7}	3.45×10^{-6}	3.52×10^{-7}	--	--
275	1.48×10^{-6}	1.01×10^{-6}	7.80×10^{-7}	7.40×10^{-6}	9.43×10^{-7}	--	--
285	1.22×10^{-6}	8.46×10^{-7}	5.00×10^{-7}	2.89×10^{-6}	1.85×10^{-7}	--	--
289	1.17×10^{-6}	8.51×10^{-7}	3.44×10^{-7}	5.63×10^{-6}	2.44×10^{-7}	--	1.06×10^{-7}
300	9.52×10^{-7}	9.93×10^{-7}	7.56×10^{-7}	3.87×10^{-6}	2.05×10^{-7}	--	--
310	1.28×10^{-6}	1.00×10^{-6}	3.42×10^{-7}	5.68×10^{-6}	2.94×10^{-7}	1.55×10^{-8}	1.07×10^{-7}

TABLE 3-5 (Continued)

EFPD	Kr-85m	Kr-87	Kr-88	Xe-133	Xe-135	Kr-89	Xe-138
315	1.44×10^{-6}	1.21×10^{-7}	7.92×10^{-7}	6.17×10^{-6}	3.82×10^{-7}	5.62×10^{-9}	1.54×10^{-7}
323	9.66×10^{-7}	1.29×10^{-6}	1.40×10^{-6}	3.11×10^{-6}	1.16×10^{-7}	--	--
332	1.54×10^{-6}	1.19×10^{-6}	5.80×10^{-7}	4.59×10^{-6}	2.38×10^{-7}	--	--
339	2.70×10^{-6}	1.31×10^{-6}	1.05×10^{-6}	1.35×10^{-5}	3.48×10^{-7}	--	--
345	2.19×10^{-6}	9.2×10^{-7}	9.63×10^{-7}	4.92×10^{-6}	3.55×10^{-7}	3.32×10^{-8}	1.60×10^{-7}
351	2.99×10^{-6}	2.21×10^{-6}	1.51×10^{-6}	8.28×10^{-7}	4.20×10^{-8}	--	--

TABLE 3-6
NEUTRON EXPOSURES FOR FUEL RODS

Rod No.	Distance from Bottom of Core [cm (in.)]	Thermal (E = 0.004 aJ)		Fast (E > 29 fJ)		
				Flux (10 ¹⁸ n/m ² · s)	Fluence (10 ²⁵ n/m ²)	
		Flux (10 ¹⁸ n/m ² · s)	Fluence (10 ²⁵ n/m ²)		ORR	HTGR
1-1	2.03 (0.8)	1.09	3.42	1.22	3.83	3.45
1-2	5.08 (2.0)	1.22	3.84	1.71	5.38	4.84
1-3	9.65 (3.8)	1.49	4.67	2.27	7.13	6.42
1-4	15.75 (6.2)	1.77	5.56	2.71	8.52	7.67
2-1	25.37 (9.99)	1.88	5.89	2.85	8.93	8.04
2-2	30.38 (11.96)	1.88	5.90	2.71	8.49	7.64
3-1	37.06 (14.59)	1.65	5.17	2.38	7.43	6.69
3-2	42.06 (16.56)	1.36	4.27	2.06	6.41	5.77
4-1	47.75 (18.8)	1.02	3.19	1.67	5.16	4.64
4-2	50.80 (20.0)	0.84	2.64	1.47	4.50	4.05
4-3	53.85 (21.2)	0.69	2.16	1.27	3.88	3.49
4-4	56.90 (22.4)	0.58	1.81	1.10	3.31	2.98

TABLE 3-7
NEUTRON EXPOSURES FOR PIGGYBACK SAMPLES

Sample	Distance from Bottom of Core [cm (in.)]	Thermal (E = 0.004 aJ)		Fast (E > 29 fJ)		
		Flux (10^{18} n/m ² · s)	Fluence (10^{25} n/m ²)	Flux (10^{18} n/m ² · s)	Fluence (10^{25} n/m ²)	
					ORR	HTGR
1A-1	0.84 (0.33)	1.05	3.30	1.00	3.14	2.83
1A-2	3.58 (1.41)	1.15	3.61	1.48	4.65	4.19
1A-3	7.26 (2.86)	1.35	4.25	2.00	6.29	5.66
1A-4	8.71 (3.43)	1.43	4.48	2.17	6.82	6.14
1A-5	9.22 (3.63)	1.46	4.58	2.22	6.99	6.29
1A-6	9.68 (3.81)	1.49	4.67	2.27	7.13	6.42
1A-7	12.34 (4.86)	1.64	5.14	2.50	7.86	7.07
1A-8	15.24 (6.00)	1.75	5.50	2.69	8.44	7.60
1A-9	16.05 (6.32)	1.77	5.56	2.73	8.56	7.70
1A-10	16.99 (6.69)	1.79	5.62	2.76	8.68	7.81
1A-11	17.83 (7.02)	1.80	5.64	2.79	8.77	7.89
1A-12	18.49 (7.28)	1.80	5.64	2.81	8.83	7.95
1B-1	0.84 (0.33)	1.05	3.30	1.00	3.14	2.83
1B-2	3.58 (1.41)	1.15	3.61	1.48	4.65	4.19
1B-3	6.38 (2.51)	1.29	5.06	1.89	5.94	5.35
1B-4	7.82 (3.08)	1.38	4.34	2.07	6.51	5.86
1B-5	9.22 (3.63)	1.46	4.58	2.22	6.99	6.29
1B-6	9.88 (3.89)	1.50	4.71	2.29	7.20	6.48
1B-7	12.90 (5.08)	1.66	5.22	2.54	7.99	7.19
1B-8	16.03 (6.31)	1.61	5.06	2.73	8.56	7.70
1B-9	16.99 (6.69)	1.79	5.62	2.76	8.68	7.81
1B-10	17.83 (7.02)	1.80	5.64	2.79	8.77	7.89
1B-11	18.47 (7.27)	1.80	5.64	2.81	8.83	7.95
1C-1	0.84 (0.33)	1.05	3.30	1.00	3.14	2.83
1C-2	3.58 (1.41)	1.15	3.61	1.48	4.65	4.19
1C-3	7.06 (2.78)	1.34	4.20	1.98	6.22	5.60
1C-4	8.53 (3.36)	1.43	4.48	2.15	6.76	6.08

TABLE 3-7 (Continued)

Sample	Distance from Bottom of Core [cm (in.)]	Thermal (E = 0.004 aJ)		Fast (E > 29 fJ)		
		Flux (10^{18} n/m ² · s)	Fluence (10^{25} n/m ²)	Flux (10^{18} n/m ² · s)	Fluence (10^{25} n/m ²)	
					ORR	HTGR
1C-5	9.22 (3.63)	1.46	4.58	2.22	6.99	6.29
1C-6	12.67 (4.99)	1.65	5.18	2.53	7.94	7.15
1C-7	13.31 (6.42)	1.78	5.58	2.74	8.59	7.73
1C-8	17.15 (6.75)	1.79	5.63	2.77	8.70	7.83
1C-9	15.24 (6.00)	1.80	5.64	2.79	8.77	7.89
1C-10	18.44 (7.26)	1.80	5.64	2.81	8.83	7.94
2A-1	23.19 (9.13)	1.80	5.64	2.87	9.00	8.10
2A-2	23.77 (9.36)	1.84	5.76	2.87	8.99	8.09
2A-3	24.56 (9.67)	1.86	5.83	2.86	8.97	8.07
2A-4	25.53 (10.05)	1.88	5.89	2.85	8.92	8.03
2A-5	28.65 (11.28)	1.90	5.96	2.77	8.69	7.82
2A-6	31.85 (12.54)	1.85	5.81	2.65	8.30	7.47
2A-7	32.26 (12.70)	1.83	5.75	2.62	8.21	7.39
2A-8	32.94 (12.97)	1.81	5.70	2.60	8.14	7.33
2B-1	23.19 (9.13)	1.80	5.64	2.87	9.00	8.10
2B-2	23.85 (9.39)	1.84	5.76	2.87	8.99	8.09
2B-3	24.71 (9.73)	1.86	5.73	2.86	8.96	8.06
2B-4	25.65 (10.10)	1.88	5.90	2.84	8.92	8.03
2B-5	26.47 (10.42)	1.89	5.94	2.83	8.87	7.98
2B-6	27.30 (10.75)	1.90	5.97	2.81	8.81	7.93
2B-7	30.20 (11.89)	1.88	5.91	2.72	8.51	7.66
2B-8	32.94 (12.97)	1.88	5.90	2.60	8.14	7.33
2C-1	23.19 (9.13)	1.80	5.64	2.87	9.00	8.10
2C-2	23.83 (9.38)	1.84	5.76	2.87	8.99	8.09
2C-3	24.69 (9.72)	1.86	5.73	2.86	8.96	8.06
2C-4	25.43 (10.01)	1.88	5.89	2.85	8.93	8.04
2C-5	26.75 (10.53)	1.90	5.95	2.82	8.85	7.97

TABLE 3-7 (Continued)

Sample	Distance from Bottom of Core [cm (in.)]	Thermal (E = 0.004 aJ)		Fast (E > 29 fJ)		
		Flux (10^{18} n/m ² • s)	Fluence (10^{25} n/m ²)	Flux (10^{25} n/m ² • s)	Fluence (10^{25} n/m ²)	
					ORR	HTGR
2C-6	30.20 (11.89)	1.88	5.91	2.72	8.51	7.66
2C-7	32.94 (12.97)	1.88	5.90	2.60	8.14	7.33
3A1-1	35.53 (13.99)	1.72	5.39	2.47	7.71	6.94
3A1-2	39.40 (15.51)	1.53	4.79	2.24	6.97	6.27
3A1-3	42.39 (16.69)	1.35	4.22	2.04	6.34	5.71
3A1-4	43.51 (17.13)	1.28	4.03	1.96	6.10	5.49
3A2-1	35.53 (13.99)	1.72	5.39	2.47	7.71	6.94
3A2-2	39.37 (15.50)	1.53	4.79	2.24	6.97	6.27
3A2-3	42.39 (16.69)	1.35	4.22	2.04	6.34	5.71
3A2-4	43.51 (17.13)	1.28	4.03	1.96	6.10	5.49
3A3-1	35.53 (13.99)	1.72	5.39	2.47	7.71	6.94
3A3-2	37.29 (14.68)	1.63	5.13	2.37	7.39	6.61
3A3-3	41.25 (16.24)	1.42	4.47	2.12	6.58	5.92
3B1-1	35.53 (13.99)	1.72	5.39	2.47	7.71	6.94
3B1-2	40.49 (15.94)	1.47	4.61	2.17	6.74	6.07
3B2-1	35.53 (13.99)	1.72	5.39	2.47	7.71	6.94
3B2-2	40.49 (15.94)	1.47	4.61	2.17	6.74	6.07
3B3-1	35.53 (13.99)	1.72	5.39	2.47	7.71	6.94
3B3-2	40.40 (15.94)	1.47	4.61	2.17	6.74	6.07
3C1-1	35.53 (13.99)	1.72	5.39	2.47	7.71	6.94
3C1-2	30.50 (15.55)	1.51	4.74	2.23	6.95	6.26
3C1-3	43.46 (17.11)	1.28	4.03	1.97	6.11	5.50

TABLE 3-7 (Continued)

Sample	Distance from Bottom of Core [cm (in.)]	Thermal (E = 0.004 aJ)		Fast (E > 29 fJ)		
		Flux (10^{18} n/m ² · s)	Fluence (10^{25} n/m ²)	Flux (10^{18} n/m ² · s)	Fluence (10^{25} n/m ²)	
					ORR	HTGR
3C2-1	35.53 (13.99)	1.72	5.39	2.47	7.71	6.94
3C2-2	39.47 (15.54)	1.51	4.74	2.23	6.96	6.26
3C2-3	43.38 (17.08)	1.28	4.03	1.97	6.12	5.51
3C3-1	35.53 (13.99)	1.72	5.39	2.47	7.71	6.94
3C3-2	39.50 (15.55)	1.51	4.74	2.23	6.95	6.25
3C3-3	43.46 (17.11)	1.28	4.03	1.97	6.11	5.50
4A1-1	48.23 (18.99)	0.99	3.09	1.64	5.06	4.55
4A1-2	53.09 (20.90)	0.72	2.27	1.32	4.03	3.63
4A1-3	57.07 (22.47)	0.57	1.79	1.09	3.28	2.95
4A2-1	48.23 (18.99)	0.99	3.09	1.64	5.06	4.55
4A2-2	53.06 (20.89)	0.72	2.27	1.32	4.03	3.36
4A2-3	57.05 (22.46)	0.57	1.79	1.09	3.29	2.96
4A3-1	48.23 (18.99)	0.99	3.09	1.64	5.06	4.55
4A3-2	51.00 (20.08)	0.83	2.59	1.45	4.46	4.01
4A3-3	54.97 (21.64)	0.65	2.03	1.21	3.66	3.29
4B1-1	47.47 (18.69)	1.03	3.24	1.69	5.22	4.70
4B1-2	49.94 (19.66)	0.88	2.77	1.52	4.68	4.21
4B1-3	52.68 (20.74)	0.65	2.35	1.35	4.11	3.70
4B1-4	56.16 (22.11)	0.60	1.88	1.14	3.44	3.10
4B2-1	47.47 (18.69)	1.03	3.24	1.69	5.22	4.70
4B2-2	49.94 (19.66)	0.88	2.77	1.52	4.68	4.21
4B2-3	52.68 (20.74)	0.75	2.35	1.35	4.11	3.70
4B2-4	56.16 (22.11)	0.60	1.88	1.14	3.44	3.10

TABLE 3-7 (Continued)

Sample	Distance from Bottom of Core [cm (in.)]	Thermal (E = 0.004 aJ)		Fast (E > 29 fJ)		
		Flux (10^{18} n/m ² · s)	Fluence (10^{25} n/m ²)	Flux (10^{18} n/m ² · s)	Fluence (10^{25} n/m ²)	
					ORR	HTGR
4B3-1	47.47 (18.69)	1.03	3.24	1.69	5.22	4.70
4B3-2	51.44 (20.25)	0.81	2.55	1.42	4.37	3.93
4B3-3	56.18 (22.12)	0.60	1.88	1.14	3.44	3.10
4C1-1	47.47 (18.69)	1.03	3.24	1.69	5.22	4.70
4C1-2	48.87 (19.24)	0.96	3.00	1.60	4.92	4.43
4C1-3	51.59 (20.31)	0.80	2.51	1.41	4.34	3.91
4C1-4	56.18 (22.12)	0.60	1.88	1.14	3.44	3.10
4C2-1	47.47 (18.69)	1.03	3.24	1.69	5.22	4.70
4C2-2	48.87 (19.24)	0.96	3.00	1.60	4.92	4.43
4C2-3	51.87 (20.31)	0.80	2.51	1.41	4.34	3.91
4C2-4	56.13 (22.10)	0.60	1.88	1.14	3.44	3.10
4C3-1	47.47 (18.69)	1.03	3.24	1.69	5.22	4.70
4C3-2	51.44 (20.25)	0.81	2.55	1.42	4.37	3.93
4C3-3	56.16 (22.11)	0.60	1.88	1.14	3.44	3.10

TABLE 3-8
FISSILE PARTICLE URANIUM ISOTOPIC COMPOSITION DETERMINED BY MASS SPECTROMETRY

Sample	Capsule Position	Atom Percent at Atomic No.					Weight Percent at Atomic No.				
		233	234	235	236	238	233	234	235	236	238
Irradiated Particles											
6157-02-0260-004	PB3C1-3	ND ^(a)	1.189	43.23	39.03	16.55	ND ^(a)	1.180	43.07	39.05	16.70
6157-02-0260-004	PB3C1-3	ND	1.212	42.41	39.59	16.78	ND	1.202	42.25	39.61	16.43
6157-02-0260-004	PB3C1-3	ND	1.192	43.23	39.06	16.53	ND	1.182	43.07	39.08	16.67
6157-02-0260-003	PB4B3-3	ND	0.960	68.23	19.64	11.17	ND	0.954	68.08	19.68	11.29
6157-02-0260-003	PB4B3-3	ND	0.983	67.88	19.96	11.17	ND	0.977	67.73	20.00	11.29
6157-02-0260-003	PB4B3-3	ND	0.981	67.54	20.20	11.28	ND	0.974	67.39	20.24	11.40
6157-02-0170-001	PB2A-1	ND	1.221	21.54	55.75	21.48	ND	1.210	21.44	55.71	21.65
6157-02-0170-001	PB2A-1	ND	1.224	22.37	55.18	21.22	ND	1.213	22.26	55.14	21.38
6157-02-0170-001	PB2A-1	ND	1.234	21.65	55.52	21.60	ND	1.223	21.54	55.47	21.76
Reference Archive Particles											
6157-02-015	--	ND	0.629 ±0.003	93.084 ±0.016	0.337 ±0.002	5.951 ±0.016	ND	0.626 ±0.003	93.014 ±0.016	0.338 ±0.002	6.022 ±0.016
6157-02-025	--	ND	0.623 ±0.005	93.098 ±0.015	0.333 ±0.004	5.946 ±0.014	ND	0.620 ±0.005	93.029 ±0.025	0.334 ±0.004	6.018 ±0.014

(a) ND = not determined.

TABLE 3-9
FERTILE PARTICLE URANIUM ISOTOPIC COMPOSITION DETERMINED BY MASS SPECTROMETRY

Sample	Capsule Position	Atom Percent at Atomic No.					Weight Percent at Atomic No.				
		233	234	235	236	238	233	234	235	236	238
6542-27-0160-015	PB4C3-3	91.895	7.282	0.721	0.037	0.065	91.859	7.310	0.727	0.038	0.066
6542-27-0160-015	PB4C3-3	92.261	6.981	0.657	0.032	0.070	92.226	7.009	0.662	0.032	0.071
6542-27-0160-010	PB2A-8	78.01	18.041	3.355	0.548	0.046	77.92	18.097	3.380	0.555	0.047
6542-27-0160-010	PB2A-8	78.11	17.96	3.332	0.542	0.052	78.02	18.02	3.356	0.548	0.054
6542-27-0160-006	PB1A-1	86.69	11.59	1.491	0.144	0.087	86.63	11.63	1.503	0.146	0.089

TABLE 3-10
COMPARISON OF P13T BURNUP DETERMINATIONS BY VARIOUS METHODS

Capsule Position	Batch No.	Type	% FIMA by Various Methods			
			Average of Case I, II, and III of ASTM Procedure E244 ^(a)	FISSIN Code ^(b)	ASTM Procedure E219	
					FISS Cs-137 ^(c)	FISS Zr ^(d)
PB3C1-3	6157-02-0260-004	TRISO WAR	67.77	67.95	67.5	68.7
PB4B3-3	6157-02-0260-003	TRISO WAR	51.38	52.04	51.4	49.6
PB2A-1	6157-02-0170-001	TRISO WAR	74.97	74.63	76.2	76.1
PB4C3-3	6542-27-0160-015	ThO ₂ BISO	NA ^(e)	0.85	0.75	ND ^(f)
PB2A-8	6542-27-0160-010	ThO ₂ BISO	NA	4.03	4.08	ND
PB1A-1	6542-27-0160-006	ThO ₂ BISO	NA	1.93	1.89	ND

(a) ASTM E-244 = atom percent fissions per initial heavy metal atom based on the average of Case I, II, and III of ASTM Procedure E-244 (Ref. 3-1).

(b) FISSIN = atom percent fissions per initial heavy metal atom, Sigma 2 calculation, based on input thermal nvt, reactor power history, and macroscopic cross sections.

(c) FISS Cs = atom percent fissions per initial heavy metal atom based on fission product cesium determined by ASTM Procedure E-219 (Ref. 3-2).

(d) FISS Zr = atom percent fissions per initial heavy metal atom based on fission product zirconium determined by ASTM Procedure E-219 (Ref. 3-2).

(e) ND = not determined.

(f) NA = not applicable.

TABLE 3-11
COMPARISON OF FISSILE AND FERTILE PARTICLE URANIUM ISOTOPIC COMPOSITION
DETERMINED BY MASS SPECTROMETRY AND THE SIGMA 2 FISSIN COMPUTER PROGRAM

Sample	Capsule Position	U-234	U-235	U-236	U-238	Method
Fissile (wt %)						
6157-02-0170-001	PB2A-1	1.22	21.75	55.44	21.60	Mass spec
		1.27	21.75	54.96	22.02	Sigma 2
6157-02-0260-003	PB4B3-3	0.97	67.73	19.97	11.32	Mass spec
		0.98	67.64	19.64	11.24	Sigma 2
6157-02-0260-004	PB3C1-3	1.19	42.80	39.25	16.77	Mass spec
		1.21	43.10	38.44	12.25	Sigma 2
Sample	Capsule Position	U-233	U-234	U-235	U-236	Method
Fissile (wt %)						
6542-27-0160-006	PB1A-1	86.63	11.69	1.53	0.15	Mass spec ^(a)
		86.78	11.42	1.64	0.16	Sigma 2
6542-27-0160-010	PB2A-8	78.01	18.07	3.37	0.55	Mass spec ^(a)
		77.89	17.92	3.55	0.63	Sigma 2
6542-27-0160-015	PB4C3-3	92.29	7.01	0.66	0.03	Mass spec ^(a)
		92.53	6.78	0.65	0.03	Sigma 2

(a) Normalized to eliminate U-238.

TABLE 3-12
CALCULATED EOL HEAVY METAL BURNUPS FOR P13T FUEL RODS

Sample	Distance from Bottom of Core [cm (in.)]	Fissile Burnup (% FIMA)	Fertile Burnup (% FIMA)
1-1	2.03 (0.8)	67.7	1.86
1-2	5.08 (2.0)	69.1	2.05
1-3	9.65 (3.8)	72.2	2.66
1-4	15.75 (6.2)	74.7	3.45
2-1	25.37 (9.99)	75.3	3.74
2-2	30.38 (11.96)	75.5	3.83
3-1	37.06 (14.59)	74.0	3.20
3-2	42.06 (16.56)	70.3	2.25
4-1	47.75 (18.8)	62.7	1.33
4-2	50.80 (20.0)	57.8	0.99
4-3	53.85 (21.2)	54.1	0.79
4-4	56.90 (22.4)	53.4	0.76

TABLE 3-13
CALCULATED EOL HEAVY METAL BURNUPS FOR P13T PIGGYBACK SAMPLES

Sample	Distance from Bottom of Core [cm (in.)]	Fissile Burnup (% FIMA)	Fertile Burnup (% FIMA)
1A1	0.84 (0.33)	--	1.90
1A5	9.22 (3.63)	72.0	--
1A12	18.49 (7.28)	75.1	--
1B1	0.84 (0.33)	--	1.90
1B5	9.22 (3.63)	72.0	--
1B11	18.47 (7.27)	--	3.59
1C1	0.84 (0.33)	68.1	--
1C5	9.22 (3.63)	72.0	--
1C7	13.31 (6.42)	--	3.66
1C10	18.44 (8.26)	--	3.59
2A-1	23.19 (9.13)	74.8	--
2A-8	32.94 (12.97)	--	3.66
2B-1	23.19 (9.13)	74.8	--
2B-8	32.94 (12.97)	--	3.66
2C-1	23.19 (9.13)	74.8	--
3A1-1	35.53 (13.99)	74.5	--
3A2-1	35.53 (13.99)	74.5	--
3A3-1	35.53 (13.99)	74.5	--
3C1-1	35.53 (13.99)	--	3.35
3C1-3	43.46 (17.11)	69.2	--
3C2-1	35.53 (13.99)	--	3.35
3C2-3	43.38 (17.08)	69.2	--
3C3-1	35.53 (13.99)	--	3.35
3C3-3	43.46 (17.11)	69.2	--
4A1-1	48.23 (18.99)	62.6	--
4A2-1	48.23 (18.99)	62.6	--
4A3-1	48.23 (18.99)	62.6	--
4B1-4	56.16 (22.11)	54.8	--
4B2-4	56.16 (22.11)	54.8	--

TABLE 3-13 (Continued)

Sample	Distance from Bottom of Core [cm (in.)]	Fissile Burnup (% FIMA)	Fertile Burnup (% FIMA)
4B3-3	56.18 (22.12)	54.8	--
4C1-4	56.18 (22.12)	--	0.82
4C2-4	56.13 (22.10)	--	0.82
4C3-3	56.16 (22.11)	--	0.82

TABLE 3-14
TEMPERATURE DISTRIBUTION BY PERCENTAGES, CRUCIBLE 1 of CELL 1

	Temperature (°C)											
	Peak Fuel Rod				Fuel Rod Surface				Volume Average Fuel			
	Rod 1-1	Rod 1-2	Rod 1-3	Rod 1-4	Rod 1-1	Rod 1-2	Rod 1-3	Rod 1-4	Rod 1-1	Rod 1-2	Rod 1-3	Rod 1-4
Minimum value	967	967	987	1005	970	970	990	1008	989	989	1009	1027
1% are less or equal	1105	1105	1125	1143	1003	1003	1023	1041	1074	1074	1094	1112
5% are less or equal	1128	1128	1148	1166	1034	1034	1054	1072	1102	1102	1122	1140
10% are less or equal	1144	1144	1164	1182	1046	1046	1066	1084	1115	1115	1135	1153
20% are less or equal	1153	1153	1173	1191	1058	1058	1078	1096	1126	1126	1146	1164
30% are less or equal	1164	1164	1184	1202	1067	1067	1087	1105	1135	1135	1155	1173
40% are less or equal	1182	1182	1202	1220	1076	1076	1096	1114	1150	1150	1170	1188
50% are less or equal	1213	1213	1233	1251	1097	1097	1117	1135	1174	1174	1194	1212
60% are less or equal	1245	1245	1265	1283	1119	1119	1139	1157	1205	1205	1225	1243
70% are less or equal	1264	1264	1284	1302	1137	1137	1157	1175	1218	1218	1238	1256
80% are less or equal	1277	1277	1297	1315	1146	1146	1166	1184	1232	1232	1252	1270
90% are less or equal	1290	1290	1310	1328	1157	1157	1177	1195	1241	1241	1261	1279
95% are less or equal	1297	1297	1317	1335	1166	1166	1186	1204	1248	1248	1268	1286
99% are less or equal	1332	1332	1352	1370	1193	1193	1213	1231	1280	1280	1300	1318
Maximum value	1409	1409	1429	1447	1216	1216	1236	1254	1332	1332	1352	1370
Average value	1215	1215	1235	1253	1100	1100	1120	1138	1177	1177	1197	1215

TABLE 3-15
TEMPERATURE DISTRIBUTION BY PERCENTAGES, CRUCIBLE 2 of CELL 2

	Temperature (°C)					
	Peak Fuel Rod		Fuel Rod Surface		Volume Average Fuel	
	Rod 2-1	Rod 2-2	Rod 2-1	Rod 2-2	Rod 2-1	Rod 2-2
Minimum value	881	875	731	725	826	820
1% are less or equal	949	943	793	787	891	885
5% are less or equal	978	972	823	817	920	914
10% are less or equal	997	991	840	834	938	932
20% are less or equal	1047	1041	893	887	989	983
30% are less or equal	1090	1084	939	933	1034	1028
40% are less or equal	1103	1097	949	943	1047	1041
50% are less or equal	1110	1104	961	955	1056	1050
60% are less or equal	1118	1112	971	965	1064	1058
70% are less or equal	1126	1120	976	970	1069	1063
80% are less or equal	1144	1138	991	985	1085	1079
90% are less or equal	1199	1193	1066	1060	1152	1146
95% are less or equal	1216	1210	1081	1075	1168	1162
99% are less or equal	1224	1218	1086	1080	1174	1168
Maximum value	1229	1223	1091	1085	1179	1173
Average value	1101	1095	952	946	1047	1041

TABLE 3-16
TEMPERATURE DISTRIBUTION BY PERCENTAGES, CRUCIBLE 2 of CELL 2

	Temperature (°C)					
	Peak Fuel Rod		Fuel Rod Surface		Volume Average Fuel	
	Rod 3-1	Rod 3-2	Rod 3-1	Rod 3-2	Rod 3-1	Rod 3-2
Minimum value	870	866	713	709	811	807
1% are less or equal	948	944	803	799	907	903
5% are less or equal	965	961	837	833	919	915
10% are less or equal	979	975	847	843	936	932
20% are less or equal	996	992	865	861	952	948
30% are less or equal	1013	1009	878	874	965	961
40% are less or equal	1030	1026	889	885	980	976
50% are less or equal	1051	1047	901	897	996	992
60% are less or equal	1069	1065	916	912	1014	1010
70% are less or equal	1090	1086	934	930	1030	1026
80% are less or equal	1110	1106	949	945	1051	1047
90% are less or equal	1141	1137	999	995	1088	1084
95% are less or equal	1163	1159	1027	1023	1113	1109
99% are less or equal	1186	1182	1044	1040	1135	1131
Maximum value	1195	1191	1054	1050	1143	1139
Average value	1054	1050	910	906	1002	998

TABLE 3-17
TEMPERATURE DISTRIBUTION BY PERCENTAGES, CRUCIBLE 4 OF CELL 2

	Temperature (°C)											
	Peak Fuel Rod				Fuel Rod Surface				Volume Average Fuel			
	Rod 4-1	Rod 4-2	Rod 4-3	Rod 4-4	Rod 4-1	Rod 4-2	Rod 4-3	Rod 4-4	Rod 4-1	Rod 4-2	Rod 4-3	Rod 4-4
Minimum value	859	854	837	840	733	728	711	714	816	811	794	797
1% are less or equal	945	940	923	926	805	800	783	786	894	889	872	875
5% are less or equal	963	958	941	944	815	810	793	796	911	906	889	892
10% are less or equal	980	975	958	961	830	825	808	811	926	921	904	907
20% are less or equal	1000	995	978	981	848	843	826	829	945	940	923	926
30% are less or equal	1016	1011	994	997	862	857	840	843	959	954	937	940
40% are less or equal	1030	1025	1008	1011	875	870	853	856	970	965	948	951
50% are less or equal	1048	1043	1026	1029	888	883	866	869	988	983	966	969
60% are less or equal	1062	1057	1040	1043	903	898	881	884	1003	998	981	984
70% are less or equal	1081	1076	1059	1062	921	916	899	902	1019	1014	997	1000
80% are less or equal	1102	1097	1080	1083	941	936	919	922	1042	1037	1020	1023
90% are less or equal	1151	1146	1129	1132	974	969	952	955	1080	1075	1058	1061
95% are less or equal	1186	1181	1164	1167	1005	1000	983	986	1114	1109	1092	1095
99% are less or equal	1239	1234	1217	1220	1048	1043	1026	1029	1172	1167	1150	1153
Maximum value	1277	1272	1255	1258	1089	1084	1067	1070	1196	1191	1174	1177
Average value	1055	1050	1033	1036	896	891	874	877	995	990	973	976

TABLE 3-18
PREDICTED VERSUS ACTUAL FUEL ROD-CRUCIBLE GAP SIZES

Crucible No.	BOL [cm (in.)]		EOL [cm (in.)]		Difference at EOL (%)
	Predicted	Actual	Predicted	Actual	
1	0.0064 (0.0025)	0.0058 (0.0023)	0.0286 (0.009)	0.0107 (0.0042)	53
2	0.0064 (0.0025)	0.0058 (0.0023)	0.0165 (0.0065)	0.0122 (0.0048)	26
3	0.0064 (0.0025)	0.0053 (0.0021)	0.0224 (0.0088)	0.0109 (0.0043)	51
4	0.0064 (0.0025)	0.0051 (0.0020)	0.0330 (0.013)	0.0201 (0.0079)	40

TABLE 3-19
W/Re THERMOCOUPLE DECALIBRATION RATES IN P13T

Thermocouple Pair	Cell No.	Distance from Bottom of Core [cm (in.)]	$\Delta T^{(a)} / \psi_{th}^{(b)} = \text{Decal. Factor } (^{\circ}\text{C/unit } \psi_{th})$
K4/W5	1	3.51 (1.38)	-112/3.80 = -29.5
K6/W7	1	9.65 (3.80)	-30.9 ^(c)
K8/W9	1	15.75 (6.20)	-181/5.60 = -32.3
K19/W20	2	27.89 (10.98)	-29.3 ^(d)
K21/W22	2	39.57 (15.58)	-162/4.80 = -33.8
K23/W24	2	55.40 (21.81)	-52/2.10 = -24.8

(a) ΔT is $(T_{W/Re} - T_K)$ after normalization at BOL.

(b) ψ_{th} is thermal fluence $\times 10^{-25} \text{ n/m}^2$.

(c) This pair failed early in life (W7 failed on July 17, 1975), so this decalibration factor is the average of K4/W5 and K8/W9 pairs.

(d) The calculated decalibration factor for this pair was $-8.2^{\circ}\text{C}/\psi_{th}$. This value does not correlate with the analytical results obtained for crucible 2 nor with any of the other thermocouple pairs. Therefore, the average of the other two pairs in crucible 2 was used for the K19/W20 pair.

4. POSTIRRADIATION EXAMINATION

After removal from the graphite crucibles, the unbonded particle samples and fuel rods were examined visually, and dimensional measurements were made on all fuel rods. Neutron activation in the TRIGA reactor facility evaluated fission gas retention of all fuel specimens. Metallographic examination was performed on selected fuel rods to evaluate irradiation-induced changes in the fuel components. Thermal expansivity measurements were performed on six irradiated P13T fuel rods. Subsections 4.1 through 4.7 present the results from these examinations.

4.1. CAPSULE DISASSEMBLY

On July 6, 1976, after shutdown of the ORR, the gas lines to P13T were cut and seal welded shut. After the welds were dye penetrant inspected, the capsule was removed from the E-3 core position and moved to the ORR storage pool. On August 24, 1976, the P13T lead tube was removed from the main body of the experiment. All cuts were made above water; the first was performed in the ORR canal. Later cuts were performed in the ORR hot cell, which reduced the experiment to 83.82 cm (33 in.) in length. The hot cell was then placed in an ORNL 2R cask liner, purged with argon, and shipped to the GA hot cells in a Pratt and Whitney cask.

The PIE of P13T was started in the GA hot cells on September 10, 1976. The secondary (outer) containment was initially removed. At this point, the gas supply lines to cell 1 were reconnected to a regulated helium supply and pressurized to 34.47 kPa (5 psi). The cell 1 containment, which during capsule operation had been suspected of having a primary-to-secondary containment leak (see Subsection 3.1), was then checked for leaks with a liquid-bubble check solution. Leaks were detected at the thermocouple (TC)-10 and TC-11 penetrations into cell 1, as shown in Fig. 4-1.

The primary (inner) containment was cut, and the thermocouples were extracted from the graphite fuel bodies. All four graphite crucibles were removed from the primary metal containment without difficulty.

The four crucibles were marked for capsule orientation in the ORR, then photographed. Figures 4-2 through 4-5 show all four crucibles as removed from the primary containment.

The 28 dosimeters were then removed. They were located in a spine in the center hole of each crucible or in the remaining portion of thermocouple holes beyond the hot-junction end of the thermocouples. Removing dosimeters from crucible 1 was difficult for the following reasons:

1. Graphite crucible 1 was later shown to have experienced the most bow of the four crucibles.
2. Impure secondary containment gas was used for a short period after the secondary-to-primary-containment leak in cell 1 was discovered during capsule operation. This may have caused a chemical reaction or deposit to occur between the niobium-1% zirconium dosimeter containments and the graphite.

Also, adjacent niobium dosimeter containments showed evidence of diffusion bonding in crucibles 1 and 2, as shown in Fig. 4-6. The dosimeters were broken apart at the diffusion joint without difficulty. The new concept, of placing dosimeters in alumina vials within sealed niobium tubes, first tried in Pl3T, was quite successful and improved the dosimetry containment over previous capsules (e.g., Pl3Q, Ref. 4-1).

Next, the four fuel crucibles were transferred to the TRIGA reactor facility, and fission gas release measurements were made on each of the four fuel-containing crucibles. Subsection 4.4 shows results from these tests.

The crucibles were then measured for postirradiation diameter and length. Table 4-1 shows these measurements. Bowing measurements were also taken on each crucible at 0, 90, 180, and 270 deg. Special fixtures, using a dial indicator that was able to detect dimensional changes of ± 0.013 mm (± 0.0005 in.), performed these measurements. The measurements on the graphite crucibles compared the dial indicator readings to readings made on quality assurance (QA) certified length and diameter standards. Subsection 4.3 shows the results from these measurements.

All fuel rods were pushed out of crucibles 1, 2, and 4, and two fuel rods were removed from crucible 3 without difficulty using the unloading mechanism shown in Fig. 4-7. Table 4-2 shows the force necessary to begin the fuel stack movement in each fuel hole. The higher forces are apparently associated with Great Lakes Carbon Company H-451 graphite.

The pre- and postirradiation shear stress were compared as a function of graphite, fuel rod/fuel hole gap, and matrix. Table 4-2 shows the results. Since the bond results from the cure-in-place processing, different matrix types might be expected to affect the bond. However, the data for the three matrix types used in Pl3T do not generally support this theory. Instead, these data indicate that a stronger bond or a smaller gap exists between the fuel rods and the surrounding H-451 (Great Lakes Carbon Company) than between the fuel rods and the TS-1240 graphite (Union Carbide Corporation). This effect holds true for both the pre- and postirradiation data, as shown in Table 4-3.

The piggyback samples were removed from simulated coolant (piggyback) holes. Figure 2-1 and Subsection 2.2.3 describe these samples. The samples were placed in numbered hot cell bottles and stored. The research group that had requested irradiation of the sample was then notified. This report will not discuss these results.

Tables 4-4 through 4-7 give the fuel hole diameters on all crucibles. A direct-reading inside-diameter micrometer made these measurements to

determine the average postirradiation fuel rod/fuel hole gap. Figure 4-8 shows the heat of this micrometer.

Finally, the metal secondary containment shell was gamma scanned. The thermal flux dosimeter evaluations used this gamma scan, as indicated in Subsection 3.3. The gamma scan revealed the thermal flux depression caused by the stainless-steel bulkhead, which separated cell 1 from cell 2 in the P13T capsule (see Fig. 3-4). Because of the wide spacing of the thermal dosimeters in the bulkhead area, only the gamma scan showed this depression.

4.2. VISUAL EXAMINATION

Visual examination assessed general irradiation performance and integrity of fuel rod samples after irradiation. The examination used an in-cell Bausch and Lomb stereomicroscope with a 4X to 30X magnification range and a camera attachment.

The visual examination judged fuel rod integrity by whether the fuel rods remained intact and experienced negligible debonding. In addition, the visual examination characterized the following:

1. Surface striations and fuel particle damage attributed to unloading cured-in-place irradiated fuel rods.
2. Fuel particle damage attributed to irradiation.

All P13T fuel rods gave excellent general irradiation performance. Figures 4-9 through 4-18 are macrophotographs of all fuel rods unloaded from P13T as ejected. The general surface appearance of all rods was excellent. Two rods (2B1 and 2B2) exhibited slight surface striations, which were attributed to unloading damage. Figures 4-19a and 4-20 show these rods in greater detail.

A significant percent of failed OPyC layers was observed in fuel rods tested in body 1 (i.e., values ranging from 1.1% to 27.7%). Generally, at ~20X, failures could not be discriminated as fissile, fertile, or inert particles. Table 4-8 summarizes the results of the visual examination. Figures 4-19 through 4-26 show representative macrophotographs of typical rods from each cell taken during the visual examination. Figures 4-19, 4-25, and 4-26 show pre- and postirradiation comparative microphotographs for representative fuel rods with better-than-average, average, and worse-than-average surface conditions, respectively.

Nine of the 36 P13T fuel rods contained fuel thermocouples in their center. These thermocouples were separated from the fuel particles by a 0.056-cm (0.022-in.) wall Great Lakes Carbon Copany H-451 graphite tube. The PIE gave no evidence of particle or fuel rod matrix-graphite tube interaction, and the graphite tube apparently did not contract axially as much as the surrounding fuel rod. Figures 4-9, 4-12, 4-14, 4-16, 4-17, and 4-18 show the graphite thermocouple tube extending from the end of the fuel rods. The PIE gave no evidence of particle failures caused by the presence of the graphite thermocouple tube.

4.3. DIMENSIONAL CHANGE ANALYSIS

4.3.1. Fuel Rods

As indicated in Subsection 2.2.2, all P13T fuel rods were carbonized in-place in the graphite fuel bodies. The rods were fired with Grafoil discs ~0.13 mm (0.005 in.) thick by 15.8 mm (0.622 in.) in diameter separating all axial fuel-rod/graphite and fuel-rod/fuel-rod interfaces. The Grafoil spacers prevented intimate bonding carbonization; however, portions of the disks and, in some instances, intact disks remained adhered to the rod during pre- and postirradiation length measurements (see Fig. 4-25).

Unirradiated fuel rod dimensional measurements were made on historical quality control rods, which were carbonized in graphite bodies and removed.

These rods were comparable to the actual irradiated rods and provided a statistical base for defining the dimensional limits of rods carbonized in-place. Calibrated micrometers were used to make one axial and one diametral measurement on each rod. The tolerance on any individual measurement was ± 0.013 mm (0.0005 in.). Table 4-9 presents statistical limits on the diametral and axial measurements for unirradiated fuel rods.

Postirradiation fuel rod dimensional measurements were performed using a calibrated dial gauge micrometer that could be interpreted to ± 0.013 mm (0.0005 in.). Two axial measurements, rotated 90 deg to one another, were taken on each fuel rod. Six diametral measurements were made at randomly selected 0- and 90-deg orientations. Grafoil wafers located between the fuel rods hindered accurate postirradiation axial fuel rod measurements. The Grafoil created two obstacles in accurately measuring the axial dimensional change: (1) the Grafoil dimensional change was different than that of the fuel rod, and (2) the Grafoil appeared to flake off some rods, especially at higher fluences. The Grafoil would be expected to expand perpendicular to the plane of the wafer so that axial fuel rod measurements would tend to increase, resulting in a smaller negative axial dimensional change than actually existed. Table 4-10 summarizes axial and diametral irradiation-induced strains in P13T fuel rods. Table 4-10 defines statistical bounds at 95% confidence for mean axial and radial strains. The bounds establish limits based on the uncertainty of the pre-irradiated dimensional measurements.

Figures 4-27 through 4-29 plot the mean irradiation-induced diametral, axial, and volumetric changes. The scatter in the axial plots was caused by the problem in obtaining accurate PIE fuel rod axial length because of the Grafoil wafers located between fuel rods. These plots also show the range for the predicted dimensional and volumetric changes and represent the effect of different fuel rod TRISO fissile and inert, BISO fertile, and shim particle compositions and the operating temperature effect of the four cells.

Dimensional changes were predicted using the RODON computer code and the equations below (Ref. 4-2).

The predicted strain in the axial and radial directions in HTGR fuel rods may be expressed in terms of the predicted fuel rod volume change ($V_{\text{fuel rod}}$) and the strain anisotropy ($\Delta\epsilon$):

$$\frac{\Delta l}{l} = \epsilon'_{zz} = 1/3 \left(\hat{V}_{\text{fuel rod}} + 2 \cdot \Delta\epsilon \right), \quad (4-1)$$

$$\frac{\Delta d}{d} = \epsilon'_{rr} = 1/3 \left(\hat{V}_{\text{fuel rod}} - \Delta\epsilon \right), \quad (4-2)$$

where $\Delta\epsilon = \epsilon'_{zz} - \epsilon'_{rr}$, the difference between axial and radial strains.

Figures 14 and 15 of Ref. 4-2 define $\Delta\epsilon$ for rods with and without shim particles, respectively.

$$\hat{V}_{\text{fuel rod}} = \frac{1}{1 - \bar{V}_{\text{porosity}}} \left(\bar{V}_{\text{matrix}} \hat{V}_{\text{matrix}} + 1 - 2 \bar{V}_{\text{porosity}} + \sum_{k=1}^{N-2} \hat{V}_k \bar{V}_k \right), \quad (4-3)$$

where $\hat{V}_{\text{porosity}}$ = volumetric change of porosity,

$\bar{V}_{\text{matrix}}$ = volume fraction of matrix,

$\hat{V}_{\text{matrix}}$ = volumetric change of matrix,

$\hat{V}_k$ = volumetric change of k^{th} component for a given irradiation exposure,

$\bar{V}_k$ = volume fraction of k^{th} component for a given irradiation exposure, and

$N-2$ = total number of fuel rod components, excluding the matrix and porosity.

Two general trends are evident from Figs. 4-27 through 4-29:

1. Irradiation-induced strain in fuel rods is anisotropic (axial and diametral strains are unequal).
2. Observed bulk volume changes are more than the RODON computer code predicts.

In general, the Pl3T fuel rod contracts less axially than radially for 1100°C exposure. This trend is consistent with the observations in capsules HT-24 and HT-25 (Ref. 4-3) and capsule Pl3Q (Ref. 4-4).

The mean irradiation-induced diametral, axial, and volumetric fuel rod dimensional changes were also calculated using the models presented in the Fuel Design Data Manual (FDDM) (Ref. 4-5). Figures 4-27 through 4-29 show the results and compare them against the Pl3T fuel rod dimensional changes. When FDDM and RODON results were compared, the following was found:

1. The FDDM predictions are about twice as large as the RODON predictions of axial, diametral, and volumetric changes.
2. The observed Pl3T fuel rod dimensional changes generally fall between the two predictions (i.e., the FDDM model overpredicts dimensional changes, and the RODON model underpredicts the actual changes for capsule Pl3T).

Figure 4-30 correlates fuel rod irradiation-induced dimensional changes with the Pl3T fuel rod BISO content. Figure 4-30 clearly shows the strong dependence of fuel rod dimensional changes on BISO content. Figure 4-30 also shows the dependence of shim content on dimensional change; however, BISO content is thought to control fuel rod dimensional change more than does shim content. This occurs because dimensional change caused by shim particles is roughly comparable to that of TRISO particles, while BISO particles cause significantly more fuel rod dimensional change. In Pl3T, the

overall volume fraction of TRISO, BISO, and shim particles was held constant for all fuel rods at nominally 58%. Therefore, as shim content increased in Pl3T rods, the BISO content decreased, as shown in Fig. 4-30.

4.3.2. Graphite Crucibles

Extensive measurements were made on the graphite fuel bodies from Pl3T. Table 4-11 presents the dimensional change data for Pl3T graphite crucibles for axes both parallel and perpendicular to the extrusion axis. Greater dimensional change per unit fast fluence was noted for H-451 graphite than for TS-1240 graphite, as had been expected.

Table 4-12 presents bowing measurements taken on all four Pl3T fuel crucibles. The H-451 graphite crucibles exhibited more bowing per unit fast fluence than the TS-1240 crucibles. This correlates well with predictions, since in the presence of flux gradients, the material with the greatest dimensional change per unit of fast fluence will exhibit the most bowing. The most bowing was indicated in crucibles 1 and 3, both made of H-451 graphite. This may explain why the dosimeters and thermocouples from this crucible were difficult to remove. A comparative analysis was performed on the graphite dimensional change data to determine if the observed changes were of the same order as had been previously determined (Refs. 4-5 and 4-6) for these graphites. Figures 4-31 through 4-33 show the results for the H-451 and TS-1240 graphites used in Pl3T. The curves shown in these figures represent the established values based on graphite irradiation capsule results. The data points shown are from Pl3T crucibles. Comparing the Pl3T data points with the established curves gives fair to good agreement for H-451 graphite radially (Fig. 4-31) and excellent agreement for H-451 graphite axially (Fig. 4-32). The TS-1240 graphite (Fig. 4-33) showed better agreement radially.

Although these data will not add substantially to the H-451 and TS-1240 data base, the Pl3T data reasonably agreed with the already established data for graphites H-451 (Ref. 4-5) and TS-1240 (Ref. 4-6).

4.4. FISSION GAS RELEASE

4.4.1. Postirradiation Fission Gas Release Measurements

Fission gas release measurements conducted in the GA TRIGA reactor evaluated fission gas retention characteristics of the loaded fuel crucibles and the fuel rod samples. The quality control evaluation made preirradiation measurements to determine the amount of heavy metal contamination in the fuel specimens prior to irradiation. The postirradiation measurements had the following primary objectives:

1. Cross-check the in-pile R/B measurements made at the ORR during capsule irradiation.
2. Obtain R/B values for each fuel sample to better define fuel failure as a function of irradiation conditions.
3. Compare the more statistically significant particle failure fractions predicted from R/B data with those determined by other PIE techniques.

The TRIGA irradiation facility at GA determined fission gas release characteristics on each of the four crucibles. Table 4-13 shows the results of the PIE fission gas release analysis for each of the loaded crucibles and the EOL in-pile R/B for each P13T cell. Because of a heater tube failure, crucible 1 was irradiated in TRIGA at room temperature and corrected to 1100°C. Because this results in a large correction, the R/B for four fuel rods from crucible 1 were run in TRIGA at both room temperature and 1100°C to establish the R/B relationship between these temperatures for capsule P13T.

The fuel rod fission gas release was measured by irradiating the rods at 1100°C in a graphite tube furnace designed to fit into a fuel element position of the TRIGA reactor core (Ref. 4-7). 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, helium swept the released fission gases into a liquid-nitrogen-cooled charcoal trap. Gamma-ray spectroscopy assayed the trapped gases for fission product isotopes (Ref. 4-8) 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 EOL fissionable material loadings. The remaining Sigma 2 FISSIN computer code calculated the amount of fissionable material remaining in each fuel rod. This code takes into account initial fuel loadings, capsule irradiation conditions, and the ORR power history and cross sections.

Table 4-14 lists the irradiated fuel rods tested in TRIGA and the resulting Kr-85m R/B at 1100°C. Only two of six rods from body 3 were submitted for fission gas release measurements. The equivalent U-235 loading given in Table 4-14 takes into account the contribution from U-233 and U-235 remaining in the fuel rods at EOL. The Kr-85m isotope was selected as the reference isotope, because it has a short half-life (4.4 h) and because its gamma-ray energy peak can easily be resolved. Fuel failure levels were analyzed at a reference temperature of 1100°C; however, fission gas release measurements were also made at room temperature on fuel body 1 due to failure of the heating element in the TRIGA King furnace. This resulted in a temperature-dependence study on fuel rods from body 1 to obtain a correction factor to be applied to the room-temperature data. Table 4-15 shows the results of the temperature dependence study on all 1B rods in body 1. Fission gas release was measured from all four rods at room temperature and 1100°C on the same day. A report of the 1100°C measurement was made 24 h later to determine the effect of consecutive TRIGA irradiations on the apparent steady-state birth rate. As can be seen in Table 4-15, this effect was small, and therefore, the 1100°C R/B values were averaged. Rod 1-1B1 was an exception in that the repeat 1100°C measurement was a factor of 20 lower, possibly indicating a problem in collecting released fission gases.

Rod 1-1B4 was the only rod showing significant release at room temperature. The R/B was found to increase by a factor of 11 between room temperature and 1100°C. This correction factor, while lower than would be calculated based on the FDDM (i.e., 13.7, Ref. 4-5), corrected the room temperature R/B value obtained from body 1.

One objective of the postirradiation fission gas release measurements was to verify the Pl3T in-pile data. To accomplish this, an EOL in-pile fission gas release value was determined for each crucible from the TRIGA postirradiation fission gas release data. The contribution from each fuel rod to the total cell R/B was calculated using the equation

$$R/B_i = (R/B_{EOL})(T_{corr})(X_i) \quad , \quad (4-5)$$

where R/B_i = contribution to the cell R/B from the i^{th} fuel rod,

R/B_{EOL} = postirradiation TRIGA fission gas release value (R/B Kr-85 at 1100°C) for the i^{th} fuel rod,

T_{corr} = temperature correction factor for Kr-85m determined from the FDDM (Ref. 4-5), and

X_i = fraction of fission cells occurring in the i^{th} fuel rod.

The TRIGA fission gas release data (R/B_{EOL}) were corrected to the volume-average irradiation temperature at which the fuel rods operated when the in-pile fission gas release measurements were made. The contribution from each fuel rod was then added to obtain the calculated TRIGA EOL R/B for each cell. Table 4-16 gives the results of these calculations.

The cell EOL R/B values calculated from the TRIGA postirradiation data and the EOL cell R/B values monitored in-pile agreed well for cell 2 (i.e., 6.9×10^{-6} R/B for Kr-85m was obtained from apportioned TRIGA crucible R/Bs, and 2.8×10^{-6} was measured from cell 2 in-pile at EOL). However, a derived value of 2.2×10^{-5} for Kr-85m for cell 2 was also obtained from individual

rod TRIGA R/Bs, which is about a factor of eight higher than that monitored in-pile at EOL. The crucible EOL R/Bs derived from individual fuel rod TRIGA R/B and the measured TRIGA crucible Kr-85m R/B agreed relatively well.

For cell 1, the calculated Kr-85m value of 4.7×10^{-5} was derived from individual fuel rod TRIGA R/Bs. This compares well with an EOL measured in-pile R/B of 1.6×10^{-5} . In this case, however, a TRIGA measured crucible Kr-85m R/B of 1.3×10^{-4} was also obtained. This is also about a factor of eight too high when compared to the EOL in-pile measured cell 1 Kr-85m R/B.

The discrepancy between the calculated and measured EOL R/B values for the two cells has several possible reasons. The TRIGA R/B data are believed to be the most valid measure of fission gas release from the fuel specimens, based on previous experience (Refs. 4-9 and 4-10). Possibly, the EOL volume-average fuel temperatures used in the calculations were lower than the actual operating temperatures of the fuel specimens at the time the in-pile measurements were made. However, even a temperature difference of 100°C would only increase the calculated TRIGA cell R/B values by a factor of two. When the R/B values were normalized to the fraction of fissions occurring in each fuel rod, a constant neutron flux across the cell was assumed. Although a steep flux gradient existed across bodies 1 and 4, the effect could not account for such a large discrepancy between the calculated and measured R/B values.

Based on these results, fission gas release data obtained from in-pile measurements at the ORR qualitatively indicate fuel performance throughout irradiation. However, to quantitatively evaluate levels of irradiation-induced fuel failure, this report required postirradiation TRIGA fission gas release measurements. If another P13T-type experiment is run in the ORR, consideration should be given before the start of the irradiation to verifying the ORR R/B procedures and techniques.

4.4.2. Determination of Fuel Failure Levels

The fission gas release data determined fuel particle failure levels for each specimen. The fission gas released during TRIGA activation comes from two sources: (1) heavy metal contamination outside the particle coatings and (2) failed fuel particles, as shown by the following equation:

$$R/B_{EOL} = R/B_{\text{failed fuel}} + R/B_c(U) + R/B_c(Th) \quad , \quad (4-6)$$

where R/B_{EOL} = measured postirradiation fission gas release,
 $R/B_{\text{failed fuel}}$ = fission gas release from failed fuel particles,
 $R/B_c(U)$ = fission gas release from uranium contamination, and
 $R/B_c(Th)$ = fission gas release from thorium (U-233) contamination.

A certain amount of uranium and thorium contamination in the fuel rods and on the surface of the coated particles is unavoidable during fabrication. Uranium and thorium contamination levels were determined for each fuel specimen prior to irradiation using fission gas release, thorium hydrolysis, or acid-leach tests (Ref. 4-11). The difference between the fission gas release resulting from contamination and the measured postirradiation fission gas release (R/B_{EOL}) is the fission gas released from fuel particles that failed during irradiation.

The gaseous fission product release resulting from in-service fuel particle failure was calculated for each fuel rod specimen using the following equation:

$$R/B_{\text{failed fuel}} = R/B_{EOL} - [R/B_c(U) + R/B_c(Th)] \quad . \quad (4-7)$$

Table 4-17 gives the results. The fission gas release from heavy metal contamination was calculated using the following equations:

$$R/B_c(U) = (R/B_{BOL})(X_{U-235}) \quad , \quad (4-8)$$

$$R/B_c(Th) = (Th_c)(r/b_c)(X_{U-233}) \quad , \quad (4-9)$$

where R/B_{BOL} = measured pre-irradiation fission gas release,

Th_c = level of thorium contamination (g Th/g Th),

r/b_c = fractional gaseous release from heavy metal contamination,

X_{U-235} = fraction of fissions that occurred in U-235 at EOL, and

X_{U-233} = fraction of fissions that occurred in U-233 at EOL.

These calculations used 0.30 (i.e., 30%) as a value for the fractional gaseous release from heavy metal contamination (Ref. 4-9). The fraction of fissions occurring in each isotope at EOL was determined by summing the weights of all remaining fissionable material (U-233 and U-235), normalized to the thermal fission yields of Kr-85m.

When the postirradiation fission gas release (R/B_{EOL}) of 16 of the fuel rods was corrected for heavy metal contamination, the irradiation-induced change in the R/B value became negative. This indicates that no fuel failure occurred during irradiation and that the level of thorium contamination measured on a companion unirradiated fuel rod was slightly higher than in the fuel rod actually tested.

An equivalent level of in-service fuel failure (F), which would release the amount of fission gas attributed to failed fuel, was calculated for each fuel rod using the following equation:

$$F = \frac{R/B_{\text{failed fuel}}}{r/b_f} \quad . \quad (4-10)$$

Table 4-16 gives the results as percent in-service particle failures. All available data (Refs. 4-9 and 4-5) indicate that the mean fractional release of Kr-85m at 1100°C from failed UC₂ fuel particles (r/b_f) constrained in a fuel rod is 5.0×10^{-3} . These calculations used this value. A value of 3.4×10^{-2} was used for Kr-85m at 1100°C for fuel rods containing UCO-WAR fissile fuel particles (Ref. 4-12). However, for conservatism, LHTGR inventory calculations use a value of 0.02 (Ref. 4-13). The calculated in-service particle failure levels ranged from 0 to 2.0%. Thirty of the 32 rods tested exhibited particle failure levels of less than 1.0%.

Extremely low levels of particle failure can be detected by fission gas release measurements. P13T fuel rods contained from ~6,500 to 14,000 coated fissile and fertile particles. Assuming a fractional release from failed fuel of 5.0×10^{-3} , an R/B of 7.7×10^{-7} to 3.6×10^{-7} corresponds to one failed particle (a failure level of 0.015% to 0.007%) in P13T rods.

Although low levels of particle failure in fuel rods can be detected, fissile and fertile particle failure cannot be accurately differentiated using postirradiation R/B data alone. The maximum possible fissile and fertile particle failure levels were calculated for each fuel rod by assuming that all the fission gas recovered was released from either the fissile or the fertile particles. The fraction of fissions occurring in each particle type (i.e., x_{fissile} or x_{fertile}) calculated the particle failure fractions. Dividing the gaseous release from failed fuel by x_{fissile} in one case and x_{fertile} in the other gave the maximum R/B for each particle type. For this reason, the particle failure fractions calculated from the R/B data using Eqs. 4-11 and 4-12 are termed maximum failure fractions:

$$F_{\text{fissile}} = \frac{R/B_{\text{failed fuel}}}{(x_{\text{fissile}})(r/b_f)} \quad , \quad (4-11)$$

$$F_{\text{fertile}} = \frac{R/B_{\text{failed fuel}}}{(x_{\text{fertile}})(r/b_f)} \quad . \quad (4-12)$$

The maximum in-service fertile particle failure levels calculated using Eq. 4-12 ranged from 0 to 5.0% (Table 4-17). Since the failure levels calculated from the R/B data represent the maximum possible in-service failure, these failure levels are considered to be an upper limit for particle failure in the fuel rods rather than the upper 95% confidence limit obtained during the metallographic examination (see Subsection 4.6).

Assuming that no fertile particle failure occurred, the maximum possible fissile particle failure levels calculated for the fuel rods using Eq. 4-11 ranged from 0 to 15.8%. When the amount of fissionable material in the fissile particles is low relative to the fertile particles, a much smaller fraction of fissions occurs in the fissile particles than in the fertile particles at EOL, as shown in Table 4-17. When this is the case, a low level of fertile particle failure gives an R/B equivalent to a much higher fissile particle failure fraction.

Using the equation

$$R/B_T = \left\{ \frac{(U_C \cdot F_{U-235} \cdot Y_{U-235}) + (T_C \cdot F_{U-233} \cdot Y_{U-233})}{(F_{U-235} \cdot Y_{U-235}) + (F_{U-233} \cdot Y_{U-233})} \right\} \text{ contamination} \quad (4-13)$$

$$+ \left\{ \frac{(X_{fissile} \cdot R_{fissile} \cdot F_{U-235} \cdot Y_{U-235}) + (X_{fertile} \cdot R_{fertile} \cdot F_{U-233} \cdot Y_{U-233})}{(F_{U-235} \cdot Y_{U-235}) + (F_{U-233} \cdot Y_{U-233})} \right\} \text{ fuel failure,}$$

where R/B_T = total release per birth,

U_C = BOL uranium contamination measured by TRIGA,

T_C = BOL thorium contamination measured on companion rods using LINAC or thorium hydrolysis test,

F_{U-235} = fraction of fissions from U-235,

F_{U-233} = fraction of fissions from U-233,

Y_{U-235} = yield of a particular isotope per U-235 fission (Y_{U-235} or Kr-85m = 0.013),

Y_{U-233} = yield of a particular isotope per U-233 fission (Y_{U-233} for Kr-85m = 0.022),

X_{fissile} = TRISO failure fraction for burnup and temperature of the fuel rod as given in the FDDM (Ref. 4-5),

X_{fertile} = BISO failure fraction for burnup and temperature of the fuel rod as given in the FDDM (Ref. 4-5),

R_{fissile} = release of a certain isotope per failed TRISO particle (FDDM, Ref. 4-5),

R_{fertile} = release of a certain isotope per failed BISO particle (FDDM, Ref. 4-5),

and the temperature correction given in the FDDM (Ref. 4-5), a theoretical R/B for Kr-85m was calculated to compare with the measured in-pile R/B throughout the P13T in-pile lifetime. Table 4-18 gives these values and the irradiation conditions. Concerning Eq. 4-13 and R/B measurements, at the BOL and in the absence of fuel failure, the contamination term dominates R/B measurements. Also at BOL, the fraction of fissions in fissile fuel is much greater than in fertile fuel ($F_{\text{U-235}} > F_{\text{U-233}}$) and reverses at EOL ($F_{\text{U-233}} > F_{\text{U-235}}$). This implies that either fertile contamination and/or failure dominates R/B near EOL. Also, short-lived isotopes, such as Kr-85m, measure instantaneous fission gas release and do not account for time-dependent diffusive release. However, long-lived isotopes, such as Kr-85, account for the cumulative time-dependent diffusive release of gases occurring in surface contamination or in failed fuel. In Table 4-18, the average observed/predicted Kr-85m ratio is near 1.00 (i.e., 0.93), and the standard deviation of 1.13 measures the model uncertainty. Thus, on the average, the predicted and observed failure fractions were about equal, indicating that, at 50% confidence, good agreement was achieved between the pressure vessel models (Ref. 4-5) and the observations.

Figure 4-34 plots the resulting Kr-85m R/B ratio shown in Table 4-18 versus fast fluence. The failure fraction for 32 P13T fuel rods, based on R/B measurements at 95% confidence, are greater than predicted by the pressure vessel models, as shown in Fig. 4-34. However, the mean observed value is less than predicted by the models up to fast fluences of $\sim 6.0 \times 10^{25} \text{ n/m}^2$

($E > 29$ fJ)_{HTGR} at 50% confidence (see Fig. 4-34). Therefore, agreement with the model is fair, but additional work is needed to reduce SiC defective fractions and to improve the OPyC layer to achieve the fuel performance assumed in core-design pressure-vessel models.

4.5. THERMAL EXPANSIVITY OF P13T FUEL RODS

The thermal expansion between 300 and 1173 K was measured on six fuel rods irradiated in capsule P13T. Four fuel rods containing VSM UC₂-TRISO fissile kernels and two rods containing WAR-UCO-TRISO fissile kernels were tested for thermal expansivity. All six fuel rods contained ThO₂-BISO fertile particles. The four VSM UC₂-TRISO kernel rods, located in cell 1 positions 1B1, 1B2, 1B3, and 1B4, contained shim ranging from 20 to 35 vol %. The two UCO-WAR kernel rods, located in cell 2 capsule locations 2-4C2 and 2-4C3, contained 25 and 20 vol % shim.

The coefficient of thermal expansion (CTE) between 300 and 1073 K [$\bar{\alpha}(300-1073)$] measured axially and radially ranged from 3.71 to 4.32 x 10⁻⁶ K⁻¹ for the four VSM-UC₂ rods. The two UCO-WAR-based rods (2-4C2 and 2-4C3) exhibited lower thermal expansion with $\bar{\alpha}(300-1073)$ values of 2.6 to 3.4 x 10⁻⁶ K⁻¹ axially. No straightforward relationships between fuel rod CTE and shim loading were observed.

Table 4-19 describes the six fuel rods tested. Shim content and fast neutron fluence were the primary variables in the four-rod VSM-UC₂ fissile-kernel group (1-1B1, 1-1B2, 1-1B3, and 1-1B4) (Ref. 4-11). Shim content increased in 5 vol % increments from 20 vol % in rod 1-1B1 to 35 vol % in 1-1B4. Similarly, fast neutron fluence increased from 3.4 x 10²⁵ n/m² in rod 1-1B1 to 7.7 x 10²⁵ n/m² ($E > 29$ fJ)_{HTGR} in rod 1-1B4. The two fuel rods that were made with UCO-WAR fissile kernels (2-4C2, 2-4C3) contained 25 and 20 vol % shim and were irradiated to ~3.5 to 4.0 x 10²⁵ n/m² ($E > 29$ fJ)_{HTGR} at ~1250 K (Table 4-19). Fuel rods 1-1B3 and 1-1B4 were ~6 cm (2.36 in.) long by 1.56 cm (0.61 in.) in diameter. Rods 1-1B1, 1-1B2, 2-4C2, and 2-4C3 were ~3 cm (1.18 in.) in length and 1.56 cm (0.61 in.) in diameter.

The thermal expansion apparatus (Refs. 4-14 and 4-15) was rechecked to calibrate for 6-cm (2.36-in.) specimens using a 3-cm (1.18-in.) graphite standard, so that calibrations were established for 3- and 6-cm (1.18- and 2.36-in.) long samples.

Table 4-20 lists the thermal expansion test results for the six P13T rods axially. Two rods (1-1B3 and 1-1B4) were also tested radially. The four VSM-UC₂-based rods (1-1B1 through 1-1B4) displayed similar CTEs, but no systematic variation with either shim content or fast fluence (Table 4-19) was found. The CTE radially on rod 1-1B4 was about the same as axially. The CTE radially on rod 1-1B3 was about equal to that of 1-1B4, but the axial CTEs differed considerably. Rod 1-1B3 was retested axially three weeks after the first axial test, and the two tests agreed within 2%.

Rods 2-4C2 and 2-4C3 expanded less than the four VSM-UC₂ rods (Table 4-20). Rod 2-4C2 was tested twice to 1173 K, and the thermal expansion at 1173 K agreed within 2% for the tests.

The mean CTE between 300 and 1073 K [$\bar{\alpha}(300-1073 \text{ K})$] was averaged as follows:

<u>Rod No.</u>	<u>Axial</u>	<u>Radial</u>
1-1B1	$4.0 \times 10^{-6} \text{ K}^{-1(a)}$	
1-1B2	$4.0 \times 10^{-6} \text{ K}^{-1(a)}$	
1-1B3	$4.0 \times 10^{-6} \text{ K}^{-1(a)}$	$4.3 \times 10^{-6} \text{ K}^{-1}$
1-1B4	$4.0 \times 10^{-6} \text{ K}^{-1(a)}$	$4.3 \times 10^{-6} \text{ K}^{-1}$
2-4C2	$3.0 \times 10^{-6} \text{ K}^{-1}$	
2-4C3	$3.0 \times 10^{-6} \text{ K}^{-1}$	

(a) Standard deviation of $0.3 \times 10^{-6} \text{ K}^{-1}$.

Table 4-20 shows the mean CTEs for all six rods for the three temperature ranges and compares them to the mean FDDM (Ref. 4-5) values for the same temperature ranges. The agreement was within 10%, with the P13T values

slightly higher than the previously established FDDM values. Figure 4-35 shows the thermal expansion of the P13T fuel rods as a function of measurement temperature compared to the predicted FDDM values. The experimental data displayed no dependence of $\bar{\alpha}$ on irradiation temperature or neutron fluence over the range of 990° to 1215°C and fast fluences of 3.5 to 7.7 x 10²⁵ n/m² (E > 29 fJ)_{HTGR}.

4.6. METALLOGRAPHIC EXAMINATION OF FUEL RODS

Twelve fuel rods were metallographically examined to evaluate the irradiation-induced changes in the fuel particle coatings and fuel kernel microstructure and to observe the condition of the carbonaceous fuel rod matrix. Metallographic specimens were prepared in the metallographic hot cell using special high-radiation metallography techniques. After grinding, most specimens were reimpregnated with mounting compound to reduce kernel pullout during polishing. A second polished section of some fuel rods was taken to increase the population of the fuel particles examined. Prior to examination, all polished specimens were passivated with a solution of 50/50 HNO₃-H₂O to impede hydrolysis of the UC₂ fuel kernels. All specimens were examined under bright-field illumination and polarized light with a Lietz metallograph. Table 4-21 summarizes the results of the TRISO-coated fissile and inert particle evaluation. Table 4-22 summarizes the results of the BISO-coated fertile particle evaluation. Figures 4-36 through 4-39 are photographs of representative particles from some of the fuel rods examined metallographically.

4.6.1. Fuel Rod Matrix

The carbonaceous matrix of all 12 fuel rods examined was judged to be in good condition after irradiation. No significant matrix cracking or other deleterious irradiation effects were observed. Figures 4-40 through 4-43 show representative photomicrographs of the matrix graphite and composite radial cross sections of the fuel rods.

Matrix macroporosity is made up of the large voids in the injected matrix of a fired rod. The voids are characterized by an absence of continuous matrix and a physical dimension in excess of 50 μm . Macroporosity, or the lack of matrix, influences the amount of surface area available for bonding between the particles and matrix and, thus, is related to the strength and thermal conductivity of the fuel rod. Table 4-23 gives fuel rod matrix macroporosities, determined by the point-count method (Ref. 4-16) from the diametral composite metallographic cross sections.

The postirradiation fuel rod macroporosities ranged from 31 to 54 vol % of the matrix phase. Densification of the carbonaceous matrix during irradiation is reflected by an increase in the fuel rod macroporosity. Irradiation-induced change in the fuel rod macroporosities ranged from 3% to 58%. The mean was found to be 20.2% with a standard deviation of 15.6%. The precision of the measurements was estimated to be $\pm 2.5\%$ (absolute) at 95% confidence, based on the results obtained in capsules P13R and P13S (Ref. 4-17) for six measurements made on the same polished section of two different fuel rods. The uncertainty in the fuel rod macroporosity is probably greater than this, however, since macroporosity varies with location in a rod.

4.6.2. Fissile Particles

The overall condition of the TRISO-coated fissile particles was considered to be excellent after irradiation to the severe P13T fast neutron exposures. Figures 4-36 through 4-39 show photomicrographs of representative fissile particles after irradiation. No SiC coating failure was observed that could be attributed to thermochemical effects, such as fuel kernel migration or fission product attack. A large amount (up to 70%) of OPyC failure occurred in the VSM-UC₂-TRISO fissile and TRISO inert particles, and a significant amount (up to 60%) of cracked or consumed buffer coating occurred in the UCO-WAR-TRISO fissile particles. SiC-fission product reactions (up to 5 μm of penetration) were observed in a considerable number (up to 48%) of TRISO-UC₂ fissile particles.

Figure 4-44 shows an example of UC₂-TRISO fissile particle OPyC coating failure and incipient SiC attack. Most attack occurred in high-temperature cell 1, which contained UC₂-TRISO fissile fuel, as shown in Table 4-21. Previous evidence, based on the HRB-4, -5, and -6 PIEs (Ref. 4-18), indicates that, in some instances, premature OPyC failure can result from excessive matrix/coating interactions. An increase in particle-matrix bond strength is equivalent to potentially subjecting the OPyC layer to a greater tensile component. The tensile component exerted on the OPyC layer results from the differential volume contraction between the TRISO-coated particle and the surrounding matrix phase. In previous work, failure of particles in fuel rods was correlated with irradiation conditions (temperature and fluence) and matrix structural properties (ratio of binder coke weight to matrix surface area) (Ref. 4-18). However, the most significant property variation capable of explaining differences in OPyC failure between P13T and other capsule tests was microporosity in the OPyC layer. TRISO-coated fissile particles tested in capsules P13R and P13S (Ref. 4-17) had OPyC microporosity [measured by mercury intrusion at 69 MPa (10,000 psi) values of <30 ml/kg OPyC], and these batches gave no evidence of matrix/OPyC interactions. However, eight of the twelve fuel rods examined in the P13T PIE evidenced matrix/OPyC coating interactions.

Figures 4-45 through 4-48 are metallographic cross sections of typical interactions. Tearing in Figs. 4-45, 4-46, and 4-47 is described in terms of the OPyC fracture morphology (i.e., the crack opens at the OPyC surface and propagates inward). Figure 4-48 is a more descriptive photomicrograph; it depicts a BISO particle (partially torn) with a TRISO-coated OPyC fragment adhered. An interface phase evidences that the matrix partially impregnated the OPyC layers of both particle types. However, all the OPyC failure evidently did not occur from tearing. Figure 4-49 shows an example of OPyC failure by mechanisms other than tearing. Because of the high microporosity in the OPyC layer, binder is believed to have been introduced into the outer surface (~5 to 10 μ m) of the OPyC in rod manufacturing. This could occur especially if the rods were pressed under high pressure (see Table 4-24 for the fuel rod matrix injection pressure). Reference 4-19

indicated that injection pressures of ~ 8.6 MPa (1250 psi) will fill the outer portion of the OPyC with matrix binder if sufficient OPyC microporosity is present. Ten of the twelve rods shown in Table 4-24 exceed this pressure. In this case, the outer portion of the OPyC coating would be filled by almost pure binder, because the larger graphite filler particles would be filtered out. Figure 4-50 is a series of metallographic cross sections depicting the microporosity present in preirradiated OPyC layers of TRISO-coated fissile particles tested in capsule P13T. If the outer portion of the OPyC porosity in this figure and that observed in Figs. 4-45 through 4-49 is carefully examined, the outer OPyC can generally be concluded to be indeed partly filled with binder during rod manufacturing. Binder shrinks in volume under irradiation at roughly twice the rate of PyC when unrestrained (Ref. 4-20). This effect could therefore have also led to a portion of the OPyC failure observed in P13T fuel rods. Subsection 4.7 gives additional details of OPyC coating permeability studies done on P13T fertile fuel particles.

Most SiC coating failure appeared mechanical and occurred as fine radial cracks, as shown in Fig. 4-51. Previous examinations showed that the brittle SiC coatings are subject to finite damage during the metallographic specimen preparation (Refs. 4-17, 4-18, 4-21). The metallographic examination indicated that three rods (1-1C1, 1-1C4, and 2-4C4) had low levels of SiC failure (see Table 4-21).

The in-service particle failure levels determined by fission gas release measurements for these samples were 0 to 0.7% (see Table 4-17 and Subsection 4.4.2). These low particle failure levels indicate that the SiC coatings in most of the particles were intact and that a large fraction of the cracked SiC coatings observed was an artifact of sample preparation.

SiC coating attack was evident (up to 48%) in the UC_2 -TRISO particles irradiated at the high temperatures in cell 1, as shown in Figs. 4-52 and 4-53. The maximum fission product attack observed in the SiC layers in VSM- UC_2 -TRISO particles tested at fuel-rod-volume average-temperatures of

1177° to 1215°C was 4 to 5 μm . This observation is consistent with the kinetics of fission product attack developed from out-of-pile tests.

Very slight ($<1 \mu\text{m}$) SiC attack was observed in UC_2 -TRISO particles irradiated at lower temperatures than that of cell 1 (see Fig. 4-53). The UCO-WAR particles evidenced some incipient SiC fission product attack, as shown in Fig. 4-55.

Significant diffusion of metallic fission products into the IPyC coating of the UC_2 -TRISO particles was observed, as shown in Figs. 4-36, 4-37, and 4-44; localized concentrations of metallic fission products were observed in the IPyC coatings of UC_2 -TRISO particles tested; and slight SiC degradation ($<5 \mu\text{m}$) by metallic fission products was observed in particles irradiated in fuel rods at average temperatures above 1050°C. The localized concentration of fission products was observed in the IPyC coating on the cool side, away from the fuel rod centerline, of most UC_2 -TRISO fuel particles. If the buildup of fission products at the IPyC/SiC coating interface was large enough, the IPyC coating was forced away from the SiC coating, as shown in Fig. 4-53. Table 4-21 summarizes the metallic fission product interactions observed in the UC_2 -TRISO particles during the metallographic examination.

Table 4-21 reports the levels of IPyC coating debonded and failure observed in the fissile particles. The UC_2 -TRISO fissile particles showed relatively high levels of IPyC debonding (see Figs. 4-36 and 4-37). However, actual failure of the IPyC coating was observed in only a few particle batches (see Fig. 4-56).

In UC_2 -TRISO particles where the IPyC coating remained bonded to the SiC (see Fig. 4-57), the buffer coating decoupled from the IPyC coating and densified onto the fuel kernel. In most particles, the buffer remained attached to the IPyC coating only in a small localized area, creating a gap at the buffer-IPyC interface on predominantly one side of the particle. Although gap formation at the buffer-IPyC interface can affect the particle

temperature profile (Ref. 4-22), the gap location was random with respect to the hot or cold side of the particle.

Only a small fraction (<6.5%) of the buffer coatings of the UC₂-TRISO particles was cracked. This occurred only in particles where the fuel kernel had segregated into what appeared to be a fuel phase and regions of rejected carbon, as shown in Fig. 4-58. When the buffer coating cracked, the fuel kernel did not extrude into the resulting gap. In particles where the fuel kernels appeared to have segregated into a fuel phase and regions of rejected carbon, the fission product recoil zone at the buffer-kernel interface was often perforated with holes up to 30 μm in diameter. The holes in the recoil zone may have resulted from a combination of fission recoil damage and interaction with fragments of the fuel kernel.

Two distinct microstructures were observed in the UC₂ fuel kernels. The kernels that operated in the high-temperature positions (average temperature above $\sim 1150^{\circ}\text{C}$) had mostly homogeneous-appearing kernels and had smooth surfaces, as shown in Fig. 4-59. The fuel kernels that operated at average temperatures of less than 1050°C had much rougher kernel surfaces and contained large fission-gas bubbles, as shown in Fig. 4-60. In many cases, a substance filled the smaller fission gas voids or coated the inner surface of the larger voids. This material was probably carbon, and it appeared optically active under polarized light. The 1 % wt thorium in most UC₂ fuel kernels did not noticeably affect the kernel microstructure.

No kernel migration was observed in the UC₂-TRISO particles irradiated in the fuel rods contained in high-temperature cell 1. This is consistent with the UC₂ amoeba migration model (Ref. 4-5), which predicts only 2 to 3 μm of migration for the maximum Pl3T time, temperature, and temperature gradient.

Small lenticular inclusions in the SiC coating, of the type shown in Fig. 4-61, were observed in 1% to 2% of the UC₂-TRISO particles examined metallographically. Since only one polished cross section of a particle was

examined, the actual population of the inclusions would be greater. This inclusion in the SiC coating is observed in most batches of TRISO-coated fuel particles. Previous electron microprobe analysis of TRISO particles revealed that these inclusions consist almost entirely of carbon (Ref. 4-21). No SiC coating failure was observed to be directly attributable to these inclusions.

WAR particles ($\text{UC}_{2.92}\text{O}_{0.64}$) tested at volume-average-fuel-rod temperatures of 976° to 1047°C did not show an optically active IPyC layer under polarized light. This evidences that the concentration of fission products beyond the kernel phase is markedly reduced when compared to VSM- UC_2 particles tested under comparable conditions. However, a fine dispersed (~ 2 to $3\text{ }\mu\text{m}$ near the SiC interface) was present in some UCO-WAR particles. When observed, the position of this phase bore no consistent relation to the thermal gradient and is apparently randomly distributed about the inner SiC interface. Figures 4-38, 4-39, and 4-62 are representative metallographic cross sections of WAR $\text{UC}_{2.92}\text{O}_{0.64}$ fissile particles tested at 1041°C to a fluence of $7.6 \times 10^{25}\text{ n/m}^2$ ($E > 29\text{ fJ}$)_{HTGR}.

Up to 60% of the buffer coatings were consumed or cracked in the UCO-WAR-TRISO particles (batch 6157-02-015), as shown in Figs. 4-62 and 4-63; however, interaction between the kernel and IPyC coating was not observed.

Only one type of UCO-WAR kernel morphology was observed, as shown in Figs. 4-62 and 4-63. The WAR kernel had generally dispersed in the densified buffer and looked much like irradiated UO_2 , in which fission gas bubbles and inclusions are visible. Two kernel phases were dispersed in the densified buffer with no visible metallic inclusion. Localized fission product accumulations, probably rare earths and palladium, were observed at the SiC coating, as shown in Fig. 4-55. These fission products primarily accumulated in the areas adjacent to where the UCO-WAR kernels had shrunk and adhered to the IPyC coating.

As shown in Table 4-21, only one rod containing UCO-WAR particles exhibited any SiC failure, 2.6% (or three failures) in rod 2-4C4. Of the three particles with observed SiC failure, two were faceted particles, and the remaining one particle was probably damaged during preparation of the metallographic specimen, so that this failure was an artifact of sample preparation.

The OPyC failures in the UCO-WAR particles were also limited to rod 2-4C4, as indicated in Table 4-21. The single UCO-WAR particle batch (6151-02-015) had a microporosity of 33.2 ml/kg OPyC, and this value (lower than that of the UC₂ batches) is taken as the reason for the reduced OPyC failure in the UCO-WAR batch.

Fissile particles with severely faceted coatings (Fig. 4-64 and Table 4-21) exhibited generally low failure levels. However, two of eight faceted particles in rod 2-4C4 were failed, and Fig. 4-65 shows one.

4.6.3. Fertile Particles

Figures 4-66 through 4-68 show photomicrographs of representative fertile particles irradiated in fuel rods. A number of particle batches with coating parameters representative of LHTGR design requirements did not exhibit any failure. Table 4-22 summarizes the coating failure analysis obtained during the metallographic examination.

No OPyC failure was observed in near-reference BISO-coated particles (batch 6542-27-015) exposed to volume-average-fuel-rod temperatures of 1177° to 1215°C and a fluence of $7.7 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} (see Fig. 4-40).

The maximum OPyC failure of 0.8% occurred in fuel rod 2-2C2 containing batch 6542-33-025 (see Fig. 4-67). This batch had a mean OPyC thickness of 66 μm with a standard deviation of 7 μm . If all failure is assumed to have occurred in the thin coating portion of the thickness distribution, the failure implies a critical limit of 49 μm . These data support a critical

limit in fuel product specifications of OPyC thickness. As a point of comparison, the mean, reference, BISO-coated OPyC thickness currently specified is 80 μm , and the critical limit is 46 μm .

The BISO OPyC coatings of all particle batches appeared relatively isotropic under polarized light.

The buffer coatings densified during irradiation and appeared slightly optically active under polarized light. Some buffer cracks were noted in most particle batches (see Table 4-22); however, this did not appear to be detrimental to the stability of the BISO coatings during irradiation. In particles where the buffer coatings cracked and densified, the OPyC coating remained intact, as shown in Fig. 4-69. Propagation of buffer coating cracks into the adjacent OPyC coating was not observed.

In all but one ThO_2 -BISO particle batch (6542-32-015), a thin high-density seal coat was omitted between the buffer and OPyC coating. Figure 4-70 shows fertile particles from this batch. These can be compared to Figs. 4-66 through 4-68, which show fertile particle batches that contain no seal on the buffer coat. During the metallographic examination, no significant difference could be determined between the one batch of fertile particles that contained a seal coat and those with no seal coat. The absence of the thin seal coat, therefore, apparently did not affect the BISO-coating irradiation performance.

In some particles, the buffer coating delaminated and shrank away from the OPyC coating or debonded from the OPyC (see Table 4-22). In either case, no deleterious effect was noted, and no particular importance is assigned to these phenomena.

Irradiation-induced changes in the ThO_2 fuel kernel microstructure were not very apparent. At the low P13T burnup ($<4\%$ FIMA), the kernel grain structure was generally still visible under polarized light. In a few particles, the ThO_2 grain structure was obliterated, although large variations

were observed in the microstructures of fertile particles within a given sample. Intergranular failure of the ThO₂ kernel was observed in 0.5% to 1% of the fertile particles examined metallographically, as shown in Fig. 4-68. This failure is limited to P13T high fluence [$(>7.6 \times 10^{25} \text{ n/m}^2)$ ($E > 29 \text{ fJ}_{\text{HTGR}}$) and high burnup ($>3.7\%$ FIMA).

Figure 4-64 shows fertile faceted particles (see also Table 4-22). No BISO fertile failures were observed in any of the severely faceted BISO particles examined metallographically.

4.6.4. Inert Particles

All but three of the 36 P13T fuel rods contained TRISO carbon inert particles to achieve close particle packing and the desired fuel particle and shim loadings. Figure 4-71 shows photomicrographs of a representative inert particle. The OPyC coating of the TRISO inert particles was deposited at a low coating rate of 1.05 $\mu\text{m}/\text{min}$. Consequently, significant levels of irradiation-induced OPyC coating failure occurred in the particles, as shown in Table 4-21. The large amount of OPyC failure (up to 59%) observed was attributed to the very low microporosity (9.1 ml/kg OPyC) and active coating gas ratio (0.17). Also, OPyC failure was likely enhanced by the OPyC anisotropy associated with low microporosity and coating gas ratio in spite of the BAF₀ value (1.035) shown in Table 2-1 from pre-irradiation work on the inerts. The most severe OPyC failure on the inert particles occurred in high-temperature cell 1.

4.7. OPyC MICROSTRUCTURE CHARACTERISTICS

Because of the large amount of OPyC failure that was evident from both the visual and metallographic examination of the P13T fuel rods, several tests were performed on the OPyC of selected fissile and fertile particles

to determine the cause of these failures. These tests included the following:

1. Determine the OPyC microporosity.
2. Determine the OPyC neon/helium ratio.
3. Determine the normalized amount of fiber (NAF) component in the OPyC microstructure by small angle x-ray scattering (SAXS).
4. Determine the OPyC active coating gas ratio.
5. Determine the amount of heavy metal released through the permeable OPyC by long-term chlorine leach and x-ray microradiography.

Each test is briefly described below, and the results are given for the P13T fuel particle batches. Table 4-24 summarizes all these results.

4.7.1. OPyC Microporosity

As already mentioned in Subsection 4.7.3, the OPyC microporosity is a critical property affecting the irradiation stability of OPyC layers on TRISO-coated particles. In fact, a microporosity specification has already been established for FSV and LHTGR fuel (95% confidence that the mean OPyC microporosity for fissile and fertile fuel composites is ≥ 13 and ≤ 32 ml/kg OPyC) (Ref. 4-23). This specification was required to improve the OPyC performance margin, since the OPyC layers on TRISO-coated fuel particles are structural and must withstand internal fission gas pressure. The OPyC layer provides an adequate compressive stress on the SiC substrate and also acts as a backup barrier to fission gas release in the event of SiC failure. Consequently, the integrity of the OPyC layer impacts the pressure vessel survival probability and the risk associated with fission product release.

The OPyC microporosity upper limit is defined to limit OPyC/matrix coating interactions. Previous empirical evidence based on the HRB-4, HRB-5, and HRB-6 PIEs (Ref. 4-18) indicates that, in some instances, premature OPyC failure can result from excessive matrix/coating interactions. An increase in particle-matrix bond strength in this case is equivalent to potentially subjecting the OPyC layer to a greater tensile component. The tensile component exerted on the OPyC layer then results from differential volume contraction between the OPyC coating layer and the surrounding matrix phase.

The most significant property variation capable of explaining differences in OPyC failure between results observed in capsule P13T and other capsule tests is the relatively high microporosity in the OPyC layer. TRISO-coated fissile particles tested in capsules P13R and P13S (Ref. 4-17) had OPyC microporosity values of <30 ml/kg OPyC, and these batches gave no evidence of matrix/OPyC interactions. However, eight of the twelve fuel rods examined in the P13T PIE evidenced matrix/OPyC coating interactions; OPyC tearing was observed with the crack opening at the matrix/OPyC interface and propagating inward (see Figs. 4-41 and 4-42). In addition, Fig. 4-72 presents supporting evidence, showing matrix impregnation into the outer region of a porous OPyC layer from P13T fissile batch 6151-17-025. This batch has a mean microporosity value of 44.9 ml/kg OPyC. The batch exhibited up to 70% OPyC failure, as shown in Table 4-24.

The lower microporosity specification (13 ml/kg OPyC) does not apply to the BISO fertile particles, because preliminary data indicate that BISO particles compress under mercury intrusion pressures of 69 MPa (10,000 psi) and because the data base is insufficient to support a specification.

4.7.2. Inert Gas Permeability by Neon/Helium Ratio Determinations

All P13T fertile particles were BISO coated. The OPyC coating of the BISO particles is permeable to some metallic fission products, but is expected to be quite impermeable to gaseous fission products. This coating

thus functions as a pressure vessel and is designed to retain fission gases and other gases, such as CO. Therefore, retaining the volatile fission products in the BISO-coated fuel particles is important to minimize radioactive contamination of the HTGR primary coolant system.

ORNL workers determined the permeability of PyC coatings of BISO fuel particles by directly measuring the movement of inert gases through the PyC coating (Ref. 4-21). The BISO fuel particles are annealed at high temperature in an inert gas atmosphere. The amount of gas diffusing through the coating into the buffer layer is then determined by breaking the PyC coating in a mass spectrometer and measuring the quantity of the gas released.

Neon-helium intrusion is performed at 1375°C for 1 h with a 50% neon/helium mixture at 98 kPa (14.2 psi). Because of the smaller atomic size of helium, PyC is more permeable to helium than to neon. The amount of neon that penetrates the OPyC layer is influenced by the permeability of the PyC. Permeable PyCs allow relatively large amounts of neon to penetrate the OPyC to fill the particle void volume (buffer and kernel). When these particles are broken and analyzed for their noble gas inventory, the neon/helium ratio approaches one, while gas-tight particles have neon/helium ratios that approach zero.

The neon/helium ratios of fuel particle batches with different geometry can be compared by using normalization factors proportional to the buffer void volume and inversely proportional to the particle surface area. Since this adjusted permeability still cannot be compared with other material properties, a third normalization factor is used proportional to the coating thickness.

ORNL workers used a normalization procedure based on a normal particle having the following parameters:

1. Particle diameter of 814 μm .
2. PyC thickness of 75 μm .

3. Void volume corresponding to 90 pmol helium in equilibrium with 50.7 kPa (0.50 atm) helium at 1375°C.

Since surface area is proportional to diameter squared and void volume is proportional to helium intrusion, the normalization equation is

$$\frac{Ne}{He_{Norm}} = \frac{Ne}{He_{Exp}} \times \frac{L}{75} \times \frac{814^2}{D^2} \times \frac{V}{90} \quad , \quad (4-14)$$

where L = PyC coating thickness (μm),

D = particle diameter (μm),

V = helium content of particle (pmol).

This equation reduces to

$$\frac{Ne}{He_{Norm}} = 9.82 \frac{Ne}{He_{Exp}} \frac{LV}{D^2} \quad . \quad (4-15)$$

Table 4-24 gives the normalized neon/helium ratios for five of the OPyCs of the Pl3T fertile fuel particle batches. ORNL workers established the following OPyC on BISO coatings:

1. Gas-tight if the neon/helium ratio is <0.3 .
2. Marginally gas permeable if the neon/helium ratio is ≥ 0.3 and ≤ 0.4 .
3. Gas permeable if the neon/helium ratio is >0.4 .

The permeability of the Pl3T fertile particle batches depends primarily on the status of the PyC structure. The permeability increases with increasing disorder in the PyC and departure from an ideal graphite lattice. The PyC structure and, hence, its permeability depend strongly on deposition. The structure depends on the hydrocarbon gas used, diluent gas concentration, temperature, and deposition rate. Of these variables, the PyC deposition rate is thought to dominate (Ref. 4-24). Figure 4-73 shows the

neon/helium ratio as a function of deposition rate for Pl3T fertile fuel particles. Figure 4-73 shows fair agreement with the ORNL correlation (Ref. 4-24) of the same item.

4.7.3. Normalized Amount of Fiber Measurements

The NAF content, as determined by SAXS, was measured by workers at KFA* on the OPyC of six Pl3T BISO-coated fertile particle batches.

SAX can detect pores in the form of voids, cracks, gaps, and misfitting layers from ~1 to 100 nm (Ref. 4-25). For scattering angles up to 3 deg from the beam axis, the scattered x-ray intensity depends on the number, size, and shape of the pores. The x-ray measurements were performed on fractured pieces of OPyC coatings that had been separated from the buffer layer. Each SAXS measurement requires the coatings from more than 50 particles. The pore-size distribution of a single coating cannot be determined. Using a minimum of 50 coatings provides more representative average values for a particle batch. A Kratky camera with a stepscanning device, a proportional counter in connection with a discriminator, and a teletype measured and registered the SAXS intensity.

Instead of measuring the entire scattering curve, the SAXS is recorded at only seven positions. The angles chosen were such that the intensities were proportional to the concentration of pores with diameters of 1.0, 2.5, 5.0, 10, 25, 50, and 100 nm. These diameters correspond to pores with the average volume of pore-size intervals listed in Table 4-25. To eliminate the effects of x-ray beam geometry and camera alignment and to facilitate the comparison of different PyC coatings, the measured pore concentrations of the different pore-size intervals are compared to a reference sample. The reference sample is arbitrarily assigned the value of 100% for each pore-size interval. This allows a relatively accurate comparison for different samples with a reproducibility of better than 1%.

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Transmission electron microscopy (TEM) and SAXS measurements revealed that the microstructural variations observed in low-temperature isotropic (LTI) coatings could be described in terms of two microstructural constituents with very different pore-size distributions. Coatings deposited in the temperature range between 1260° and 1400°C (LTI) may consist of a mosaic component and a fiber component, or an intermediate microstructural state. The crystallites in the mosaic component derived at ~1250°C are closely packed and well aligned in regions that extend up to 1 μm. The fiber component deposited at 1400°C consists of an interwoven network of tangled fibers containing a varying amount of fine porosity (Ref. 4-26).

Comparison of TEM micrographs and pore-size distributions showed that the ratio of the mosaic component to the fiber material, or an intermediate microstructure state, can be correlated with the relative concentration of pores ranging from 6 to 25 nm in diameter. Therefore, the NAF component is derived from this pore concentration, as shown below:

$$NAF = \frac{2 C_{10} - C_{20}}{3} , \quad (4-16)$$

where C_{10} and C_{20} are the relative pore concentrations of the pore size intervals ranging from 6 to 12 nm and from 12.1 to 25 nm, respectively (Ref. 4-25).

The NAF values for the Pl3T BISO fertile batches were done on unannealed particles. During heat treatment of PyC coatings, a sintering effect agglomerates small pores and increases pore size concentration of pores ranging from 6 to 25 nm. As the NAF is derived from this pore size interval, the NAF increases. Therefore, criteria for the NAF value must be established for annealed and unannealed coatings separately. The KFA laboratories have recommended (Ref. 4-25) the following criteria for annealed particles based on limited data:

1. $NAF < 1.08$ is not gas permeable.

2. $\text{NAF} \geq 1.08$ and < 1.18 gas tightness is marginal.
3. $\text{NAF} > 1.18$ is gas permeable.

Figure 4-74 correlates the NAF values derived from KFA SAXS measurements with the ORNL-normalized neon/helium ratios. The limited number of data points gave a fair correlation. The KFA laboratories found better agreement between the neon/helium ratio and the NAF values for annealed particles, so that the poor correlation found in Fig. 4-74 on P13T particles may be due to using unannealed samples.

The NAF values could not be related to overall irradiation performance because of the very limited amount of OPyC tearing or failure on the P13T BISO fertile particles and because most OPyC damage occurred on the fissile particles, as shown in Table 4-24. The NAF value did not correlate well with the BISO microporosity values, as shown in Fig. 4-74. All but one of the BISO particle batches are within the current microporosity specification of ≤ 32 ml/kg OPyC.

4.7.4. OPyC Active Coating Gas Ratio

The active coating gas ratio (ACGR) is defined as the following:

$$\text{ACGR} = \frac{C}{C + L + D} \quad , \quad (4-17)$$

where C = active coating as (C_2H_2 and C_3H_6) flow rate,
 L = levitation gas (Ar, He, or N_2) flow rate, and
 D = diluent gas (Ar, He, N_2 , or H_2) flow rate.

This ratio was determined for all of the P13T fuel particle batches. Table 4-24 shows ratios for the metallographically examined batches. Previous work (Fig. 3-11 in Ref. 4-23) established a strong positive correlation between OPyC microporosity and the volume fraction of active coating gases and defined a critical structural region based on properties that are out of specification (i.e., microporosity < 13 ml/kg OPyC and < 0.25 active

gas concentration). When considering the deposition process, the volume fraction of hydrocarbon gases (C_2H_2 and C_3H_6) in the total coating gas and the coating temperature determine the relative amounts of PyC crystallite nucleation and growth in the vapor phase and on the levitated particle bed substrate. This, in turn, controls the structure of the PyC layers. Oriented PyC crystallites within conical growth features usually orient with the carbon layer planes parallel to the substrate surface as the deposition coating rate or hydrocarbon concentration is reduced (Ref. 4-27). No intergrowth feature pores are present, because the cones impinge uniformly on each other, and the crystallites tend to lie with the layer planes perpendicular to the axis of the conical growth feature. Consequently, the interconnecting microporosity for these types of structures is expected to be low. As the deposition coating rate and hydrocarbon gas concentration are increased, the growth features progress from conical to spherical, and intragrowth-feature pores develop, resulting in higher measured microporosities. In effect, this is a transition from substrate to gas-phase nucleation. In addition, the preferred orientation of the PyC crystallites between different spherical growth features is randomly disposed, resulting in a more isotropic structure.

Figure 4-75 correlates the microporosity of P13T fuel particle batches and the active coating gas ratio. The location of one inert and two fertile particle batches in the out-of-specification region and the P13T particle batches tend to correlate well with the previous data fit, as shown in Ref. 4-23. Inert particle batch (6351-01-020) was out of specification in both the active coating gas ratio and the microporosity and performed very poorly with regard to OPyC failure. This batch had up to 58% OPyC failure, as shown in Table 4-24. The two fertile batches (6542-29-015 and 6542-31-015), however, which were out of the allowable coating gas ratio specification range, had no OPyC failure, as shown in Table 4-24. The lower microporosity specification does not apply to the BISO fertile particles, because preliminary data indicate that BISO particles compress under mercury intrusion pressures of 69 MPa (10,008 psi) and because the data base is insufficient. The inferior irradiation performance of PyC structures deposited under low

hydrocarbon gas concentrations (≤ 0.25) and with low microporosities (≤ 13 ml/kg OPyC) (e.g., P13T inert particle batch) is attributed to excessive orientation of PyC crystallites. This anisotropy leads to a differential between irradiation-induced strains parallel and perpendicular to the substrate surface, which in turn, results in higher irradiation-induced stresses. Failure of up to 58.7% of the OPyC coating for the inert particle batch was observed (Table 4-21) and is attributed to this effect.

4.7.5. Long-Term Chlorine Leach

The ORNL workers performed a long-term chlorine leach on all P13T fertile particle batches and on three P13T fuel rods. Chlorine leach was applied to the fuel particles at 1500°C for 18 h. The heavy metal release was analyzed after 3, 6, 12, and 18 h, as shown in Fig. 4-76 for selected particle batches. After the 18 h chlorination, the batches were x-ray microradiographed. Permeable PyC coatings allow chlorine to migrate through the OPyC. In this case, chlorine reacts with the kernel to form volatile heavy metal chlorides, which diffuse in severe cases of PyC permeability through the PyC and can be analyzed in the reaction tube. For particles with less permeable coatings, the heavy metal chlorides are trapped within the buffer layer and at the OPyC-buffer interface. The heavy metal chlorides can be readily detected by x-ray microradiography, and ORNL designated the results in the following manner:

<u>ORNL Chlorine Leach No.</u>	<u>Amount of Heavy Metal in Buffer</u>
1	Large
2	Light
3	None

Table 4-24 and Fig. 4-76 show the results. Of the six fertile batches measured, five fall within the GA-established OPyC microporosity specification.

None of the particle batches had such severe gas-permeable OPyC coatings that large amounts of heavy metal chlorides were released during chlorination. Only low thorium values were analyzed at the 3, 6, 12, and 18 h chlorination times (see Fig. 4-77), and the x-ray microradiographs showed three out of the six batches to be permeable for chlorine, as indicated by the large amount of heavy metal trapped in the buffer layer and at the buffer-OPyC interface. The batches determined as being permeable to chlorine are the following:

6542-27-015
6542-34-015
6542-35-015

Extensive studies at ORNL determined that OPyC coatings are permeable to Cl_2 if the neon/helium ratio is greater than 0.4 and that batches with neon/helium ratios greater than 0.3 are marginally gas-tight to chlorine (see Subsection 4.7.2).

Figure 4-76 shows the normalized neon/helium ratios next to the particle batch numbers. It shows the batch with a neon/helium ratio <0.3 to contain no heavy metal in the buffer after the 18-h chlorination test, which is consistent with the neon/helium criteria. Also, Fig. 4-76 shows neon/helium values >0.3 to have light to large amounts of heavy metals in the buffer about in proportion to their neon/helium ratio (except batch 6542-27-015).

Samples of irradiated BISO-coated P13T fertile fuel particles were also obtained by electrochemical deconsolidation of irradiated fuel rods 1-1B3, 1-1C3, and 2-4C3. These samples were analyzed for thorium fractional release by long-term low-temperature chlorine leach at ORNL. Radioactivity dictated that the samples be chlorine leached remotely in the ORNL hot cell facilities. Each sample was leached with gaseous chlorine at 1000°C for 48 h in three successive 16-h periods; the thorium released was measured after each 16 h. Figure 4-78 gives the thorium release data. When Fig.

4-78 is compared with Fig. 4-77, batch 6542-32-015 from fuel rod 1-1B3 at 18 h is shown to have increased its leachable thorium ~1.5 times. This is consistent with the R/B results for fuel rod 1-1B4, which also contained batch 6542-32-015 and which showed the highest capsule in-service particle failure. However, fuel rod 1-1B2, which also contained this fertile batch, did not have high R/B in-service particle failure (0.1%). Figure 4-77 indicates that batch 6542-32-015 was permeable to Cl₂ and Cl₄, yet Fig. 4-76 indicates that this batch had only a minor amount of heavy metal in the buffer, as shown in an x-ray microradiograph after an 18-h chlorination run. Also, Fig. 4-77 shows that batch 6542-35-015 had 11.9% of its pre-irradiation thorium leached, yet Fig. 4-78 indicates that only 0.05% thorium was leached from fuel particles contained in fuel rod 2-4C3. These results seemingly indicate large uncertainties in classifying particle batches by chlorination-leach.

REFERENCES

- 4-1. Young, C. A., and C. B. Scott, "Postirradiation Examination of Capsule P13Q," General Atomic Report GA-A14174, September 1974.
- 4-2. Kovacs, W. J., and D. P. Harmon, "Irradiation-Induced Dimensional Changes in HTGR Fuel Rods," General Atomic unpublished data, October 1979.
- 4-3. Johnson, W. R., et al., "Postirradiation Examination of Capsules HT-24 and -25," ERDA Report GA-A13486, General Atomic Company, September 15, 1975, pp. 44-48.
- 4-4. Young, C. A., and C. B. Scott, "Postirradiation Examination of Capsule P13Q," ERDA Report GA-A14174, General Atomic Company, September 1977, pp. 4-4 and 4-5.
- 4-5. "Fuel Design Data Manual," Issue C, General Atomic unpublished data, September 1979.
- 4-6. Price, R. J., and L. A. Beavan, "Final Report on Graphite Irradiation Test OG-3," ERDA Report GA-A14211, General Atomic Company, January 1977.

- 4-7. Anderson, E. E., et al., "An In-Core Furnace for the High-Temperature Irradiation Testing of Reactor Fuels," Nucl. Technol. 11, 259 (1971).
- 4-8. Lofting, D. R., E. E. Anderson, and L. R. Zumwalt, "The Use of Gamma-Ray Spectroscopy in the Study of Fission Product Release from Nuclear Fuels," General Atomic Report GA-4615, October 8, 1963.
- 4-9. Myers, B. F., et al., "The Behavior of Fission Product Gases in HTGR Fuel Material," General Atomic Report GA-A13723, October 1977.
- 4-10. Harmon, D. P., and C. B. Scott, "Development and Irradiation Performance of LHTGR Fuel," DOE Report GA-A13173, General Atomic Company, October 31, 1975.
- 4-11. Young, C. A., and D. P. Harmon, "Preirradiation Report of Fuel Materials for P13T Capsule Experiment," General Atomic Report GA-A13343, April 1976.
- 4-12. "HTGR Fuels and Core Development Program Quarterly Progress Report for the Period Ending February 28, 1975," DOE Report GA-A13353, General Atomic Company, March 31, 1975.
- 4-13. Haire, M. J., and D. W. McEachern, "Gaseous Radioactivity Levels in the Primary Coolant of an HTGR," General Atomic Report GA-A12942 (GA-LTR-14), October 1, 1974.
- 4-14. "HTGR Fuels and Core Development Program Quarterly Program Report for the Period Ending May 31, 1976," ERDA Report GA-A13941, General Atomic Company, June 30, 1976.
- 4-15. "HTGR Fuels and Core Development Program Quarterly Program Report for the Period Ending November 30, 1976," ERDA Report GA-A14180, General Atomic Company, December 27, 1976.
- 4-16. Rostoker, W., and J. R. Dvorak, Interpretation of Metallographic Structures, Academic Press, New York, 1965, pp. 195-200.
- 4-17. Scott, C. B., D. P. Harmon, and J. F. Holzgraf, "Postirradiation Examination of Capsules P13R and P13S," General Atomic Report GA-A13827, October 8, 1976.
- 4-18. Scott, C. B., and D. P. Harmon, "Postirradiation Examination of Capsules HRB-4, HRB-5, and HRB-6," ERDA Report GA-A13267, General Atomic Company, November 28, 1975, pp. 113-118.

- 4-19. Bullock, R. E., "Full-Fluence Tests of Experimental Thermosetting Fuel Rods for the HTGR," General Atomic Report GA-A15815, March 1980.
- 4-20. Bullock, R. E., "Irradiation-Induced Dimensional Changes of Poorly Crystalline Carbons," Carbon 17, 447 (1977).
- 4-21. Scott, C. B., and D. P. Harmon, "Postirradiation Examination of Capsule F-30," General Atomic Report GA-A13208, April 1, 1975.
- 4-22. McElmury, S. S., and O. M. Stansfield, "An Analysis of the Effect of Buffer-IPyC Coating Separation on the Temperature Distribution in TRISO UC₂ Fuel Particles," General Atomic Report GA-A13500, December 1, 1975.
- 4-23. Kovacs, W. J., and D. P. Harmon, "Technical Support Document for Issue C of the HTGR Fuel Product Specification," General Atomic unpublished data, August 1979.
- 4-24. Morgan, C. S., "Characterization of Pyrocarbon Coatings of HTGR Fuel Particles by Inert Gas Intrusion," Oak Ridge National Laboratory Report ORNL/TM-6819, September 1979.
- 4-25. Krautwasser, P., M. J. Kania, and E. Wallura, "SAXS Characterization Study on GAC BISO-Coated Fertile Particles Irradiated in Capsule HT-12 Through -19, HT-33, and P13R/S/T," Kernforschungsanlage Report KFA-IRW, IB-20/29, June 1970.
- 4-26. Yust, C. S., and P. Krautwasser, Carbon 13, 125 (1977).
- 4-27. Kaae, J. L., "Implications of the Structure of Pyrolytic Carbons on the Deposition Mechanism," General Atomic Report GA-A14673, January 1978.
- 4-28. Tiegs, T. N., and K. R. Thomas, "Operation and Postirradiation Examination of ORR Capsule OF-2: Accelerated Testing of HTGR Fuel," Oak Ridge National Laboratory Report ORNL-5428, March 1979.

K2-12

Fig. 4-1. View of cell 1 thermocouple bulkhead. Note small (white) leak detection fluid bubbles around TC-10 and TC-11 penetrations. This is thought to be the cause of the in-pile observed primary-to-secondary leak.

K7630258 to 263

(a)

Fig. 4-2. Postirradiation condition of body 1, cell 1 of P13T
(sheet 1 of 2)

K7630-240-1

(b)

K7630-236

(c)

Fig. 4-2. Postirradiation condition of body 1, cell 1 of P13T: (b) top end view, (c) bottom end view (sheet 2 of 2)

4-47

K7630-241 to 243

(a)

Fig. 4-3. Postirradiation condition of body 2, cell 2 of P13T (sheet 1 of 2)

K7630-244

(b)

K7630-245

(c)

Fig. 4-3. Postirradiation condition of body 2, cell 2 of P13T: (b) top end view, (c) bottom end view (sheet 2 of 2)

K7630-246 to 249

(a)

Fig. 4-4. Postirradiation condition of body 3, cell 2 of P13T (sheet 1 of 2)

K7630-257

(b)

K7630-256

(c)

Fig. 4-4. Postirradiation condition of body 3, cell 2 of P13T: (b) top end view, (c) bottom end view (sheet 2 of 2).

K7630-253 to 255

(a)

Fig. 4-5. Postirradiation condition of body 4, cell 2 of P13T (sheet 1 of 2)

K7630-250

(b)

K7630-251

(c)

Fig. 4-5. Postirradiation condition of body 4, cell 2 of PL3T: (b) top end view, (c) bottom end view (sheet 2 of 2)

K2-21

Fig. 4-6. Example of two dosimeters (dosimeters 16 and 17) fused together

K7630-264 to 266

Fig. 4-7. Mechanism used to push fuel rod stacks from P13T fuel bodies. Note extracted rod in receiving tray.

Fig. 4-8. Direct reading inside diameter micrometer head used to measure fuel hole inside diameters in P13T crucibles. Note that the inside diameter is averaged because the three measuring surfaces are placed 120 deg apart and because of the rather large pad [~ 0.3175 cm ($\sim 1/8$ in.) diam] on each of the measuring surfaces.

K7630-2105 to 2108

Fig. 4-9. Macro photograph of as-ejected P13T fuel rod stack from column A, body 1: Fuel rods shown were exposed to fast neutron fluences from 3.5 to 7.7×10^{25} n/m² ($E > 29$ fJ)_{HTGR} at 1177° to 1215°C. Shim volume fluences ranged from 20% to 35%.

K7630-2109 to 2112

Fig. 4-10. Macrophotograph of as-ejected P13T fuel rod stack from column B, body 1: **Fuel rods** shown were exposed to fast neutron fluences from 3.5 to $7.7 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1177° to 1215°C . Shim volume fractions ranged from 20% to 35%.

K7630-2114 to 2117

Fig. 4-11. Macrophotograph of as-ejected P13T fuel rod stack from column C, body 1: Fuel rods shown were exposed to fast neutron fluences from 3.5 to $7.7 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1177° to 1215°C . Shim volume fractions ranged from 20% to 35%.

K7630-289 to 291

Fig. 4-12. Macro photograph of as-ejected P13T fuel rod stack from column A, body 2: Fuel rods shown were exposed to fast neutron fluences from 7.6 to $8.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1041° to 1047°C . Shim volume fraction was 35%. Note the graphite pushout-spacer disk at the left end of the stack and the central graphite thermocouple tube at the right end of the stack.

K7630-292 to 294

Fig. 4-13. Macrophotograph of as-ejected P13T fuel rod stack from column B, body 2: Fuel rods shown were exposed to fast neutron fluences from 7.6 to $8.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1041° to 1047°C . Shim volume fraction was 35%. Rod 2-2B2 on the right represents the worst fuel rod physical condition of all rods examined from P13T. Note the graphite pushout-spacer disk at the left end of the stack and the matrix-end-cap which debonded from the remainder of rod 2-2B2 at the right end.

K7630-295 to 297

Fig. 4-14. Macro photograph of as-ejected P13T fuel rod stack from column C, body 2: Fuel rods shown were exposed to fast neutron fluences from 7.6 to $8.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$) HTGR at 1041° to 1047°C . Shim volume fraction was 35%. Note the graphite pushout-spacer disk at the left end of the stack and the graphite central thermocouple tube at the right end of the stack.

K7630-2100 to 2102

Fig. 4-15. Macrophotograph of as-ejected P13T fuel rod stack from column B, body 3: Fuel rods shown were exposed to fast neutron fluences from 5.8 to 6.7×10^{25} n/m^2 ($E > 29$ fJ)_{HTGR} at 998° to 1002°C . Shim volume fraction was 30%. Note the graphite pushout-spacer disk at the left end of the stack.

K7630-269 to 271

Fig. 4-16. Macro photograph of as-ejected P13T fuel rod stack from column A, body 4: Fuel rods shown were exposed to fast neutron fluences from 3.0 to $4.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 976° to 995°C . Shim volume fraction ranged from 12.1% to 25%. Note the central graphite thermocouple tube at the right end of the stack.

K7630-272 to 275

Fig. 4-17. Macro photograph of as-ejected P13T fuel rod stack from column B, body 4: Fuel rods shown were exposed to fast neutron fluences from 3.0 to $4.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$) HTGR at 976° to 995°C . Shim volume fraction ranged from 13.5% to 25%. Note the graphite pushout-spacer disk at the left end of the stack and the graphite thermocouple tube at the right end of the stack.

K7630-277 to 279

Fig. 4-18. Macro photograph of as-ejected P13T fuel rod stack from column C, body 4: Fuel rods shown were exposed to fast neutron fluences from 3.0 to $4.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$) HTGR at 976° to 995°C . Shim volume fraction ranged from 13.4% to 25%. Note the graphite pushout-spacer disk at the left end of the stack and the graphite thermocouple tube at the right end of the stack.

S7630-27 & 28

(a)

S7630-25

(b)

S7630-26

(c)

Fig. 4-19. Typical macrophotographs of a 5.08-cm (2-in.) long fuel rod: (a), (b), (c) postirradiation capsule rod 2-2B1 from body 2. (b) top end, (c) bottom end. The fuel rod was exposed to a fast neutron fluence of $8.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1047°C. Shim volume fraction was 35%. (sheet 1 of 2)

SR75004-1 & 2

(d)

SR75004-5

(e)

SR75004-6

(f)

Fig. 4-19. Typical macrophotographs of a 5.08-cm (2-in.) long fuel rod: (d), (e), (f) preirradiation sister rod to capsule rod 2-2B1. (e) end 1, (f) end 2. This rod had better than average surface condition. (sheet 2 of 2)

Fig. 4-20. Postirradiation macrophotographs of a 5.08-cm (2-in.) long fuel rod (2-2B2) from body 2: (b) top end, (c) magnified view, (d) bottom end. The fuel rod was exposed to a fast neutron fluence of $7.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$) HTGR at 1041°C . Shim volume fraction was 35%. This rod represents the worst postirradiation condition of all P13T fuel rods examined. The separation of particles shown at the left end of the rod was attributed to a matrix end cap effect. Note the failed coating in (c) which may have been caused by unloading damage.

S7630-13 to 15

(a)

S7630-12

(b)

S7630-16

(c)

S7630-11

(d)

Fig. 4-21. Typical postirradiation macrophotographs of a 5.08-cm (2-in.) long fuel rod (1-1A4) from body 1: (b) bottom end, (c) magnified view, (d) top end. The fuel rod was exposed to a fast neutron fluence of $7.7 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1215°C. Shim volume fraction was 35%. Note the typical OPyC coating failures in (c). These are seen in most body 1 P13T fuel rods. The visual examination indicated 6.1% failed OPyC coating for this rod.

S7630-109 & 110

(a)

S7630-107

(b)

S7630-108

(c)

Fig. 4-22. Typical postirradiation macrophotographs of a 3.05-cm (1.2-in.) long fuel rod (1-1A1) from body 1: (b) top end, (c) bottom end. The fuel rod was exposed to a fast neutron fluence of $3.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1177°C. Shim volume fraction was 20%. The hole and graphite tube in the center of the rod was for a fuel thermocouple.

Fig. 4-23. Typical postirradiation macrophotographs of a 3.05-cm (1.2-in.) long fuel rod (1-1B2) from body 1: (b) top end, (c) magnified view, (d) bottom end. The fuel rod was exposed to a fast neutron fluence of $4.8 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1177°C. Shim volume fraction was 25%. Note the typical cell 1 OPyC coating failures in (c). The visual examination indicated that this rod had 18% failed OPyC coatings.

S7630-135 & 136

(a)

S7630-132

(b)

S7630-134

(c)

S7630-133

Fig. 4-24. Typical postirradiation macrophotographs of a 5.08-cm (2-in.) long fuel rod (2-3B2) from body 3: (b) top end, (c) magnified view, (d) bottom end. The fuel rod was exposed to a fast neutron fluence of $5.8 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$) HTGR at 998°C . Shim volume fraction was 30%. Note the typical OPyC coating failure in (c). The visual examination for this rod indicated 9.3% OPyC coating failure.

S7630-182 & 183

(a)

S7630-181

(b)

S7630-182

(c)

Fig. 4-25. Typical macrophotographs of a 3.05-cm (1.2-in.) long fuel rod with an average surface condition: (a), (b), (c) postirradiation capsule rod 2-4B4 from body 4. (b) top end, (c) bottom end. The fuel rod was exposed to a fast neutron fluence of $3.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$) HTGR at 976°C . Shim volume fraction was 13.5%. Note the Graphoil fuel rod separator still retained in (b). The hole and graphite tube in the center of the rod was for a fuel thermocouple. (sheet 1 of 2).

SR75001-1 & 2

(d)

SR75001-5

(e)

SR75001-6

(f)

Fig. 4-25. Typical macrophotographs of a 3.05-cm (1.2-in.) long fuel rod with an average surface condition: (d), (e), (f) preirradiation sister rod to capsule rod 2-4B4. (e) end 1, (f) end 2. (sheet 2 of 2).

S7630-147 & 148

(a)

S7630-145

(b)

S7630-146

(c)

Fig. 4-26. Typical macrophotographs of a 3.05-cm (1.2-in.) long fuel rod with a worse than average surface condition: (a), (b), (c) postirradiation capsule rod 2-4B1 from body 4. (b) top end, (c) bottom end. The fuel rod was exposed to a fast neutron fluence of $4.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 995°C. Shim volume fraction was 25%. (sheet 1 of 2).

SR75002-1 & 2

(d)

SR75002-5

(e)

SR75002-6

(f)

Fig. 4-26. Typical macrophotographs of a 3.05-cm (1.2-in.) long fuel rod with a worse than average surface condition: (d), (e), (f) preirradiation sister rod to capsule rod 2-4B1. (e) end 1, (f) end 2. (sheet 2 of 2).

Fig. 4-27. Diametral dimensional change in Pl3T fuel rods versus fast fluence (sheet 1 of 2)

Fig. 4-27. Diametral dimensional change in P13T fuel rods versus fast fluence (sheet 2 of 2)

Fig. 4-28. Axial dimensional change in Pl3T fuel rods versus fast fluence
 (sheet 1 of 2)

Fig. 4-28. Axial dimensional change in P13T fuel rods versus fast fluence
(sheet 2 of 2)

Fig. 4-29. Bulk volume change in P13T fuel rods versus fast fluence
 (sheet 1 of 2)

Fig. 4-29. Bulk volume change in P13T fuel rods versus fast fluence
(sheet 2 of 2)

Fig. 4-30. Fuel rod dimensional change as a function of fuel rod BISO content

Fig. 4-31. Dimensional change of H-451 graphite in the radial direction as a function of fast fluence, capsule P13T

Fig. 4-32. Dimensional change of H-451 graphite in the axial direction as a function of fast fluence, capsule P13T

Fig. 4-33. Dimensional change of TS-1240 graphite as a function of fast neutron fluence, P13T capsule

Fig. 4-34. Ratio of observed/predicted Kr-85m R/B versus fast fluence

Fig. 4-35. Comparison of the thermal expansion of HTGR irradiated fuel rods, axial orientation

L7630-232

(a)

L7630-233

(b)

Fig. 4-36. Representative photomicrographs of TRISO-UC₂ fissile (batch 6151-17-025) and ThO₂-BISO fertile (batch 6542-27-015) particles irradiated in fuel rod 1-1C1 to a fast neutron fluence of $3.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1177°C: (a) bright field, (b) polarized light.

L7630-331

(a)

L7630-332

(b)

Fig. 4-37. Representative photomicrographs of TRISO-UC₂ fissile (batch 6151-12-015) and ThO₂-BISO fertile (batch 6542-32-015) particles irradiated in fuel rod 1-1B4 to a fast neutron fluence of $7.7 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1215°C: (a) bright field, (b) polarized light.

L7630-80

(a)

L7630-81

(b)

Fig. 4-38. Representative photomicrographs of TRISO UCO-WAR fissile (batch 6157-02-015) and ThO_2 -BISO fertile (batch 6542-33-025) particles irradiated in fuel rod 2-2C2 to a fast neutron fluence of $7.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1041°C : (a) bright field, (b) polarized light.

L7630-295

(a)

L7630-296

(b)

Fig. 4-39. Representative photomicrographs of TRISO UCO-WAR fissile (batch 6157-02-015) and ThO_2 -BISO fertile (batch 6542-29-015) particles irradiated in fuel rod 2-4C4 to a fast neutron fluence of $3.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 976°C: (a) bright field, (b) polarized light.

L7630-218

(a)

L7630-203 to 208

(b)

Fig. 4-40. Representative photomicrographs of fuel rod 1-1C1 irradiated to a fast neutron fluence of $3.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1177°C. After irradiation, this rod was heated to 1100°C for TRIGA fission gas release measurements: (a) typical appearance of matrix, (b) composite showing radial cross section.

L7630-329 (a)

L7630-348 to 355

(b)

Fig. 4-41. Representative photomicrographs of fuel rod 1-1B4 irradiated to a fast neutron fluence of $7.7 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1215°C. After irradiation, this rod was heated to 1100°C in TRIGA for fission gas release measurements: (a) typical appearance of matrix, (b) composite showing radial cross section.

L7630-97

(a)

L7630-82 to 88

(b)

Fig. 4-42. Representative photomicrographs of fuel rod 2-2C2 irradiated to a fast neutron fluence of $7.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1041°C. After irradiation, this rod was heated to 1100°C in TRIGA for fission gas release measurements: (a) typical appearance of matrix, (b) composite showing radial cross section.

L7630-289

(a)

L7630-283 to 288

(b)

Fig. 4-43. Representative photomicrographs of fuel rod 2-4C4 irradiated to a fast neutron fluence of $3.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$) HTGR at 976°C . After irradiation, this rod was heated to 1100°C in TRIGA for fission gas release measurements: (a) typical appearance of matrix, (b) composite showing radial cross section.

L7630-228

(a)

L7630-229

(b)

Fig. 4-44. Metallographic cross section of VSM TRISO-UC₂ fissile particle (batch 6151-17-025) irradiated in fuel rod 1-1C1 to a fast neutron fluence of $3.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1177°C: (a) bright field, (b) polarized light. Photo depicts OPyC failure and fission product concentration at the SiC interface.

L7630-423

(a)

L7630-424

(b)

L7630-425

(c)

Fig. 4-45. Metallographic cross section of TRISO-UC₂ fissile particle (batch 6151-17-025) irradiated in fuel rod 1-1C4 to a fast neutron fluence of $7.7 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1215°C: (a) and (c) bright field, (b) polarized light. Photos depict localized tearing and OPyC failure.

L7630-311

(a)

L7630-313

(b)

Fig. 4-46. Metallographic cross section of TRISO-coated WAR $UC_{2.94}O_{0.64}$ particle (batch 6157-02-015) irradiated in fuel rod 2-4C4 to a fast neutron fluence of $3.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$) HTGR at 976°C : Photo depicts torn OPyC layer.

L7630-428

(a)

L7630-291

(b)

L7630-601

(c)

Fig. 4-47. Representative photomicrographs of TRISO-UC₂ fissile particles:
 (a) fuel rod 1-1C4, 3.5×10^{25} n/m² ($E > 29$ fJ)_{HTGR} at 1215°C;
 (b) fuel rod 2-4C4, 3.0×10^{25} n/m² ($E > 29$ fJ)_{HTGR} at 976°C;
 (c) fuel rod 1-1A4, 3.5×10^{25} n/m² ($E > 29$ fJ)_{HTGR} at 1215°C.
 Photos depict OPyC localized failure by tearing. **Note the**
 apparent strong attachment of the matrix to the OPyC, especially
 at (b).

L7630-420

(a)

L7630-421

(b)

L7630-422

(c)

Fig. 4-48. Metallographic cross section of ThO_2 -BISO (batch 6540-27-051) and TRISO inert (batch 6351-01-020) particles irradiated in fuel rod 1-1C4 to a fast fluence of $7.7 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1215°C : (a) and (c) bright field, (b) polarized light. Photos depict interaction between particles.

L7630-505

(a)

L7630-507

(b)

L7630-490

(c)

L7630-493

(d)

Fig. 4-49. Photomicrographs of TRISO-UC₂ fissile particles (batch 6151-17-015) irradiated in fuel rod 1-1A1 to a fast neutron fluence of $3.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1177°C: Photos depict OPyC localized failure by mechanisms other than tearing.

MP74024-6

(a)

MP7406

(b)

MP7403-10

(c)

MP74068-10

(d)

Fig. 4-50. Metallographic cross sections depicting microporosity in preirradiated OPyC layers on TRISO-coated fissile particles: (a) UC_2 batch 6151-12-015 (48 $\mu\text{l/g}$ OPyC), (b) UC_2 batch 6151-17-015 (50 $\mu\text{l/g}$ OPyC), (c) UC_2 batch 6151-17-025 (45 $\mu\text{l/g}$ OPyC), and (d) UCO-WAR batch 6157-02-015 (33 $\mu\text{l/g}$ OPyC).

L7630-240

(a)

L7630-242

(b)

Fig. 4-51. Photomicrographs of TRISO-UC₂ particle (batch 6151-17-025) irradiated in fuel rod 1-1C1 to a fast fluence of $3.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1177°C: Photos depict appearance of a typical cracked SiC coating. A significant fraction of the cracked SiC coatings observed was an artifact of sample preparation.

L7630-230

Fig. 4-52. Metallographic cross section depicting fission product attack ($\leq 2 \mu\text{m}$ into SiC) in a TRISO-UC₂ fissile particle (batch 6151-17-025) irradiated in fuel rod 1-1C1 to a fast neutron fluence of $3.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1177°C

Fig. 4-53. Representative photomicrographs showing metallic fission product attack ($\leq 5 \mu\text{m}$ into SiC) of the SiC in a TRISO-UC₂ particle (batch 6151-12-015) irradiated in fuel rod 1-1B4 to a fast neutron fluence of $7.7 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$) HTGR at 1215°C : (a) and (c) bright field, (b) polarized light.

L7630-179

(a)

L7630-180

(b)

L7630-181

(c)

Fig. 4-54. Representative photomicrographs showing metallic fission product attack ($\leq 2 \mu\text{m}$ into SiC) of the SiC in a TRISO-UC₂ particle (batch 6151-12-015) irradiated in fuel rod 2-4A1 to a fast neutron fluence of $4.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 995°C: (a) and (c) bright field, (b) polarized light.

L7630-73

(a)

L7630-74

(b)

L7630-109

(c)

Fig. 4-55. Metallographic cross section depicting fission product distribution in UCO-WAR fissile particle ($\text{UC}_{2.90.6}$) (batch 6157-02-015 irradiated in fuel rod 2-2C2 to a fast neutron fluence of $7.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1041°C : (a) and (c) bright field, (b) polarized light. Photos depict incipient fission-product attack of the SiC.

L7630-567

(a)

L7630-568

(b)

L7630-569

(c)

Fig. 4-56. Photomicrographs of a TRISO-UC₂ particle (batch 6151-17-015) irradiated in fuel rod 1-1A4 to a fast fluence of 7.7×10^{25} n/m² ($E > 29$ fJ)_{HTGR} at 1215°C: (a) and (c) bright field, (b) polarized light. Photos depict appearance of a typical particle with a failed IPyC coating.

L7630-223

(a)

L7630-224

(b)

Fig. 4-57. Photomicrographs of a TRISO-UC₂ particle (batch 6151-17-025) irradiated in fuel rod 1-1C1 to a fast fluence of 3.5×10^{25} n/m² ($E > 29$ fJ)_{HTGR} at 1177°C: (a) bright field, (b) polarized light. Photos depict appearance of a typical particle with the IPyC still apparently attached to the SiC but with the buffer decoupled from the IPyC.

L7630-266

(a)

L7630-267

(b)

Fig. 4-58. Photomicrographs of a TRISO-UC₂ particle (batch 6151-17-025) irradiated in fuel rod 2-2A1 to a fast fluence of 8.0×10^{25} n/m² ($E > 29$ fJ)_{HTGR} at 1047°C: (a) bright field, (b) polarized light. Photos depict appearance of a typical cracked buffer coating. Note also the lenticular flaws in the SiC.

L7630-462

(a)

L7630-466

(b)

L7630-464

(c)

Fig. 4-59. Representative photomicrographs depicting morphology of UC_2 -TRISO kernel irradiated at high temperature. Particle (batch 6157-17-015) was irradiated in fuel rod 1-1A1 to a fast neutron fluence of $3.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1177°C : (a) and (c) bright field, (b) polarized light.

L7630-196

L7630-197

(b)

L7630-198

(c)

Fig. 4-60. Representative photomicrographs depicting morphology of UC₂-TRISO kernel irradiated at low temperature. Particle (batch 6151-12-015) was irradiated in fuel rod 2-4A1 to a fast neutron fluence of $4.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$) HTGR at 995°C: (a) and (c) bright field, (b) polarized light.

L7630-266

(a)

L7630-46

(b)

L7630-272

(c)

L7630-249

(d)

Fig. 4-61. Representative photomicrographs showing TRISO-coated fuel particles (batch 6151-17-025) with lenticular flaws within the SiC that survived irradiation: (a), (b), and (c) fuel rod 2-2A1, $8.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1047°C, (d) fuel rod 1-1C1, $3.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1177°C.

L7630-73

(a)

L7630-74

(b)

Fig. 4-62. Metallographic cross section depicting morphology of UCO-WAR kernel ($\text{UC}_{2.9}\text{O}_{0.6}$) (batch 6157-02-015) irradiated in fuel rod 2-2C2 to a fast neutron fluence of $7.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1041°C : (a) bright field, (b) polarized light.

L7630-279

(a)

L7630-280

(b)

L7630-281

(c)

Fig. 4-63. Photomicrographs of a UCO-WAR-TRISO particle (batch 6157-02-015) irradiated in fuel rod 2-2C2 to a fast neutron fluence of $7.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1041°C: (a) and (c) bright field, (b) polarized light. Photos depict appearance of typical UCO-WAR particle with a consumed buffer.

L7630-263

(a)

L7630-437

(b)

L7630-277

(c)

L7630-556

(d)

Fig. 4-64. Representative photomicrographs of severely faceted UC_2 -TRISO fissile particles: (a) and (b) ThO_2 -BISO fertile particle, (c) and (d) doublet ThO_2 -BISO fertile particle. (a) fuel rod 2-2A1 (batch 6151-17-015), $8.0 \times 10^{25} \text{ n/m}^2$ ($E > 20 \text{ fJ}$)_{HTGR} at 1047°C ; (b) fuel rod 1-1C4 (batch 6151-17-025), $7.7 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1215°C ; (c) fuel rod 2-2C2 (batch 6542-33-025, $7.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1041°C ; (d) fuel rod 1-1B2 (batch 6542-32-015), $4.8 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1177°C .

L7630-318

(a)

L7630-319

(b)

L7630-320

(c)

Fig. 4-65. Photomicrographs of UCO-WAR TRISO particle (batch 6157-02-015) irradiated in fuel rod 2-4C4 to a fast neutron fluence of $3.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 976°C: (a) and (c) bright field, (b) polarized light. Photos depict appearance of a typical failed, faceted particle.

L7630-216

(a)

L7630-217

(b)

Fig. 4-66. Metallographic cross section of ThO_2 -BISO fertile particle (batch 6542-27-015) irradiated in fuel rod 1-1C4 to a fast neutron fluence of $7.7 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1215°C : (a) bright field, (b) polarized light.

L7630-92

(a)

L7630-93

(b)

Fig. 4-67. Metallographic cross section of ThO_2 -BISO fertile particle (batch 6542-33-025) with failed OPyC layer. Particle was irradiated in fuel rod 2-2C2 to a fast neutron fluence of $7.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1041°C : (a) bright field, (b) polarized light.

L7630-54

(a)

L7630-95

(b)

Fig. 4-68. Representative photomicrographs of ThO_2 -BISO particles: (a) (batch 6542-27-015) irradiated in fuel rod 2-2C1 to a fast neutron fluence of $8.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}, (b) (batch 6542-33-025) irradiated in fuel rod 2-2C2 to a fast neutron fluence of $7.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}. Photos depict intergranular failure of the ThO_2 kernel.

L7630-29

(a)

L7630-30

(b)

Fig. 4-69. Photomicrographs of ThO₂-BISO particle (batch 6542-27-015) irradiated in fuel rod 2-2C1 to a fast neutron fluence of $8.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$) HTGR at 1047°C: (a) bright field, (b) polarized light. Photos depict appearance of a typical particle where the buffer coating cracked and densified while the OPyC coating remained intact.

L7630-327

(a)

L7630-328

(b)

Fig. 4-70. Photomicrographs of ThO_2 -BISO particle (batch 6542-32-015) irradiated in fuel rod 1-1B4 to a fast neutron fluence of $7.7 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1215°C : (a) bright field, (b) polarized light. Photos depict appearance of a typical ThO_2 -BISO particle which had a seal coat placed on the buffer coating.

L7630-391

(a)

L7630-374

(b)

Fig. 4-71. Representative photomicrographs of TRISO inert particles (batch 6351-01-020) irradiated to a fast neutron fluence of $7.7 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1215°C : (a) fuel rod 1-1C4, (b) fuel rod 1-1B4. The OPyC failure was typical for the higher temperature conditions of cell 1.

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Fig. 4-72. Matrix/OPyC observations and interactions. Preirradiation scanning electron micrograph of OPyC layer on UC₂-TRISO particle (batch 6151-17-025) in a polished fuel rod. Photograph focuses on the matrix phase which has impregnated the interconnecting OPyC microporosity (mean value = 44.9 ml/kg OPyC layer) during fuel rod fabrication. The dark spots are voids (i.e., where the matrix has not impregnated the OPyC). This particle batch exhibited up to 70% OPyC failure in capsule P13T.

Fig. 4-73. Normalized neon/helium ratios for P13T BISO fertile particle batches as a function of OPyC coating rate

Fig. 4-74. Correlation of NAF values with neon/helium ratios for Pl3T BISO fertile particle batches

Fig. 4-75. Correlation of Pl3T fuel particle batch microporosity to active coating gas ratio

Fig. 4-76. Correlation of Pl3T fertile particle microporosity values to long-term chlorine leach results

Fig. 4-77. Release of thorium by chlorination from unirradiated P13T fertile particle batches as a function of chlorination time

Fig. 4-78. Release of thorium by chlorination from postirradiation P13T fuel rods as a function of chlorination time

TABLE 4-1
PRE- AND POSTIRRADIATION DIMENSIONS OF P13T
GRAPHITE CRUCIBLES

Crucible	Average Pre-irradiation Diameter [cm (in.)]	Postirradiation Diameter [cm (in.)]					
		Top		Middle		Bottom	
		0-deg	90-deg ^(a)	0-deg	90-deg	0-deg	90-deg
1	6.040 (2.378)	--	--	--	--	5.997 (2.361)	5.997 (2.361)
1	6.114 (2.407)	6.066 (2.388)	6.068 (2.389)	6.068 (2.389)	6.053 (2.383)	--	--
2	6.129 (2.413)	6.124 (2.411)	6.129 (2.413)	6.126 (2.412)	6.129 (2.413)	6.116 (2.408)	6.129 (2.413)
3	6.147 (2.420)	6.093 (2.399)	6.096 (2.400)	6.078 (2.393)	6.081 (2.394)	6.068 (2.389)	6.071 (2.390)
4	6.139 (2.417)	--	--	6.126 (2.412)	6.124 (2.411)	6.126 (2.412)	6.119 (2.409)
4	6.093 (2.399)	6.088 (2.397)	6.068 (2.398)	--	--	--	--

Crucible	Average Pre-irradiation Diameter [cm (in.)]	Postirradiation Length [cm (in.)]			
		0-deg	90-deg ^(a)	180-deg	270-deg
1	20.071 (7.902)	19.512 (7.682)	19.586 (7.711)	19.685 (7.750)	19.616 (7.723)
2	11.697 (4.605)	11.582 (4.560)	11.587 (4.561)	1.427 (0.562)	11.577 (4.558)
3	11.697 (4.605)	11.534 (4.541)	11.529 (4.539)	11.519 (4.535)	11.532 (4.540)
4	13.721 (5.402)	13.690 (5.390)	13.688 (5.389)	13.686 (5.388)	13.688 (5.389)

(a) Viewed from top of each crucible relative to white dot at 0-deg.

TABLE 4-2
FORCE NECESSARY TO BEGIN FUEL STACK MOVEMENT
IN EACH FUEL HOLE OF CAPSULE P13T

Crucible No.	Hole	Nominal Fuel Rod Diameter [cm (in.)]	Nominal Fuel Stack Length [cm (in.)]	Graphite Type	Force Necessary to Begin Fuel Stack Movement
					[N (lbf)]
1	A	1.58 (0.622)	18.28 (7.20)	H-451	667 (149)
1	B	1.58 (0.622)	18.28 (7.20)	H-451	534 (120)
1	C	1.58 (0.622)	18.28 (7.20)	H-451	489 (110)
2	A	1.58 (0.622)	10.01 (3.94)	TS-1240	44 (10)
2	B	1.58 (0.622)	10.01 (3.94)	TS-1240	22 (5)
2	C	1.58 (0.622)	10.01 (3.94)	TS-1240	22 (5)
3	B ^(a)	1.58 (0.622)	10.01 (3.94)	H-451	356 (80)
4	A	1.58 (0.622)	12.19 (4.80)	TS-1240	<22 (<5)
4	B	1.58 (0.622)	12.19 (4.80)	TS-1240	53 (17)
4	C	1.58 (0.622)	12.19 (4.80)	TS-1240	22 (5)

(a) The remaining two fuel holes in crucible 3 were not unloaded as this body is planned to be used for postirradiation annealing thermal stability experiments under another DOE program.

TABLE 4-3
COMPARISON OF P13T PREIRRADIATION AND POSTIRRADIATION FUEL
ROD SHEAR STRESS AS A FUNCTION OF GRAPHITE TYPE,
FUEL HOLE GAP, AND MATRIX TYPE

Fuel Rod Column No.	Graphite Type	Matrix Type ^(a)	Pre- Irradiation Fired Radial Gap [mm (in.)]	Pre- Irradiation Shear Stress [kPa (psi)]	Post- Irradiation Radial Gap [mm (in.)]	Post- Irradiation Shear Stress [kPa (psi)]
1A	H-451	1	0.043 (0.0017)	122.7 (17.80)	0.099 (0.0039)	76.5 (11.10)
1B	H-451	2	0.039 (0.0015)	108.2 (15.69)	0.104 (0.0041)	60.7 (8.80)
1C	H-451	3	0.036 (0.0014)	34.5 (5.00)	0.102 (0.0040)	55.2 (8.01)
2A	TS-1240	1	0.042 (0.0017)	90.1 (13.07)	0.137 (0.0054)	9.0 (1.31)
2B	TS-1240	1	0.046 (0.0018)	45.5 (6.50)	0.097 (0.0038)	4.8 (0.70)
2C	TS-1240	1	0.051 (0.0020)	81.4 (11.81)	0.137 (0.0054)	4.8 (0.70)
3B	H-451	2	0.042 (0.0017)	90.3 (13.10)	0.097 (0.0038)	73.8 (10.70)
4A	TS-1240	3	0.045 (0.0018)	29.6 (4.29)	0.218 (0.0086)	2.8 (0.41)
4B	TS-1240	3	0.061 (0.0024)	29.6 (4.29)	0.241 (0.0095)	9.0 (1.31)
4C	TS-1240	3	0.043 (0.0017)	29.6 (4.29)	0.211 (0.0083)	4.2 (0.61)

(a) Matrix 1 is 30 wt % Asbury 6353 natural-flake graphite flour, 65 wt % A-240 pitch, and 5 wt % octadecanol. Matrix 2 is 38 wt % Lonza KS-15 graphite flour, 47 wt % A-240 pitch, 5 wt % polystyrene, and 10 wt % octadecanol. Matrix 3 is 38 wt % Lonza KS-15 graphite flour, 57 wt % A-240 pitch, and 5 wt % octadecanol.

TABLE 4-4
CRUCIBLE 1
POSTIRRADIATION FUEL HOLE INSIDE DIAMETER MEASUREMENTS

Hole Letter	Fuel Hole I.D. at X cm (in.) from Top Surface [cm (in.)]				
	X = 1.27 (0.5)	2.54 (1)	5.08 (2)	7.62 (3)	
A	1.5753 (0.6202)	1.5740 (0.6197)	1.5733 (0.6194)	1.5705 (0.6183)	
A repeat	1.5753 (0.6202)	1.5761 (0.6205)	1.5745 (0.6199)	1.5710 (0.6185)	
B	1.5730 (0.6193)	1.5745 (0.6199)	1.5745 (0.6199)	1.5743 (0.6198)	
B repeat	1.5753 (0.6202)	1.5753 (0.6202)	1.5725 (0.6191)	1.5756 (0.6203)	
C	1.5748 (0.6200)	1.5735 (0.6195)	1.5748 (0.6200)	1.5728 (0.6192)	
C repeat	1.5725 (0.6191)	1.5753 (0.6202)	1.5761 (0.6205)	1.5723 (0.6190)	
	10.16 (4)	12.7 (5)	15.24 (6)	17.78 (7)	Overall Average
A	1.5725 (0.6191)	1.5740 (0.6197)	1.5748 (0.6200)	1.5761 (0.6205)	} 1.5740 (0.6197)
A repeat	1.5720 (0.6189)	1.5748 (0.6200)	1.5748 (0.6200)	1.5761 (0.6205)	
B	1.5748 (0.6200)	1.5715 (0.6187)	1.5705 (0.6183)	1.5718 (0.6188)	} 1.5735 (0.6195)
B repeat	1.5763 (0.6206)	1.5730 (0.6193)	1.5702 (0.6182)	1.5738 (0.6196)	
C	1.5710 (0.6185)	1.5715 (0.6187)	1.5758 (0.6204)	1.5799 (0.6220)	} 1.5745 (0.6199)
C repeat	1.5710 (0.6185)	1.5720 (0.6189)	1.5758 (0.6204)	1.5809 (0.6224)	

TABLE 4-5
CRUCIBLE 2
POSTIRRADIATION FUEL HOLE INSIDE DIAMETER MEASUREMENTS

Hole Letter	Fuel Hole I.D. at X cm (in.) from Top Surface [cm (in.)]						Overall Average [cm (in.)]
	X = 1.27 (0.5)	2.54 (1)	5.08 (2)	7.62 (3)	10.16 (4)	11.1125 (4-3/8)	
A	1.5829 (0.6232)	1.5822 (0.6229)	1.5837 (0.6235)	1.5852 (0.6241)	1.5791 (0.6217)	1.5799 (0.6220)	1.5822 (0.6229)
A repeat	1.5829 (0.6232)	1.5832 (0.6233)	1.5832 (0.6233)	1.5842 (0.6237)	1.5809 (0.6224)	1.5799 (0.6220)	
B	1.5804 (0.6222)	1.5806 (0.6223)	1.5845 (0.6238)	1.5837 (0.6235)	1.5809 (0.6224)	1.5796 (0.6219)	1.5822 (0.6229)
B repeat	1.5819 (0.6228)	1.5832 (0.6233)	1.5842 (0.6237)	1.5850 (0.6240)	1.5801 (0.6221)	1.5804 (0.6222)	
C	1.5806 (0.6223)	1.5827 (0.6231)	1.5842 (0.6237)	1.5832 (0.6233)	1.5804 (0.6222)	1.5801 (0.6221)	1.5817 (0.6227)
C repeat	1.5824 (0.6230)	1.5824 (0.6230)	1.5829 (0.6232)	1.5819 (0.6228)	1.5789 (0.6216)	1.5801 (0.6221)	

TABLE 4-6
CRUCIBLE 3
POSTIRRADIATION FUEL HOLE INSIDE DIAMETER MEASUREMENTS

Hole Letter (a)	Fuel Hole I.D. at X cm (in.) from Top Surface [cm (in.)]						Overall Average [cm (in.)]
	X = 1.27 (0.5)	2.54 (1)	5.08 (2)	7.62 (3)	10.16 (4)	11.1125 (4-3/8)	
B	1.5756 (0.6203)	1.5763 (0.6206)	1.5748 (0.6200)	1.5725 (0.6191)	1.5669 (0.6169)	1.5634 (0.6155)	1.5715 (0.6187)
B repeat	1.5758 (0.6204)	1.5761 (0.6205)	1.5748 (0.6200)	1.5720 (0.6189)	1.5672 (0.6170)	1.5636 (0.6156)	

(a) Fuel holes A and C were not unloaded so that postirradiation heating test can be performed on in-situ fuel rod at a later date.

TABLE 4-7
CRUCIBLE 4
POSTIRRADIATION FUEL HOLE INSIDE DIAMETER MEASUREMENTS

Hole Letter	Fuel Hole I.D. at X cm (in.) from Top Surface [cm (in.)]						Overall Average [cm (in.)]
	X = 1.27 (0.5)	2.54 (1)	5.08 (2)	7.62 (3)	10.16 (4)	12.7 (5)	
A	1.5913 (0.6265)	1.5903 (0.6261)	1.5878 (0.6251)	1.5872 (0.6249)	1.5829 (0.6232)	1.5852 (0.6241)	1.5878 (0.6251)
A repeat	1.5901 (0.6263)	1.5916 (0.6266)	1.5875 (0.6250)	1.5867 (0.6247)	1.5842 (0.6237)	1.5850 (0.6240)	
B	1.5903 (0.6261)	1.5903 (0.6261)	1.5880 (0.6252)	1.5875 (0.6250)	1.5855 (0.6242)	1.5837 (0.6235)	1.5875 (0.6250)
B repeat	1.5901 (0.6263)	1.5905 (0.6262)	1.5872 (0.6249)	1.5878 (0.6251)	1.5852 (0.6241)	1.5832 (0.6233)	
C	1.5901 (0.6263)	1.5913 (0.6265)	1.5888 (0.6255)	1.5875 (0.6250)	1.5860 (0.6244)	1.5855 (0.6242)	1.5878 (0.6251)
C repeat	1.5913 (0.6265)	1.5900 (0.6260)	1.5895 (0.6258)	1.5875 (0.6250)	1.5865 (0.6246)	1.5850 (0.6240)	

TABLE 4-8
STEREO VISUAL EXAMINATION OF P13T FUEL RODS

Fuel Rod Capsule Position (a)	Fuel Rod Designation 7161-008-	Capsule Irradiation Conditions		Maximum Force Required To Remove Fuel Column From Graphite Body [N (lbf)]	Macroscopic Visual Examination at 20X Magnification				
		Vol. Av Temp (°C)	Fast Fluence [(10 ²⁵ n/m ²) _{HTGR}] (E > 29 fJ)		Observed Surface Striations Attributed to Unloading	Failed OPyC Layers Within Surface Striations	Failed OPyC Layers Attributed to Performance		Upper 95% Confidence Bound on Failure (%)
							Total No. of Particles Observed on Surface	Failed OPyC Layers (%)	
1-1A1	01-9	1177	3.45	667 (150)	None ↓	NA ^(b)	350	10.3	14.0
1-1A2	04-3	1177	4.84	667 (150)		175	1.1	4.0	
1-1A3	07-9	1197	6.42	667 (150)		168	6.0	11.5	
1-1A4	10-6	1215	7.67	667 (150)		700	6.1	8.0	
1-1B1	02-10	1177	3.45	534 (120)		350	10.6	15.0	
1-1B2	05-20	1177	4.84	534 (120)		350	18.0	23.0	
1-1B3	08-11	1197	6.42	534 (120)		700	14.7	16.0	
1-1B4	11-7	1215	7.67	534 (120)		350	3.7	5.5	
1-1C1	03-12	1177	3.45	890 (200)		350	27.7	30.0	
1-1C2	06-2	1177	4.84	890 (200)		350	12.6	17.0	
1-1C3	09-12	1197	6.42	890 (200)		700	9.6	12.0	
1-1C4	12-1	1215	7.67	890 (200)		700	18.0	19.0	
2-2A1	13-2	1047	8.04	44 (10)	Yes Yes None ↓		290	0	2.0
2-2A2	16-12	1041	7.64	44 (10)				0	2.0
2-2B1	14-5	1047	8.04	22 (5)		19		0	2.0
2-2B2	17-14	1041	7.64	22 (5)		21		2.7	5.5
2-2C1	15-3	1047	8.04	22 (5)		NA		0	2.0
2-2C2	18-4	1041	7.64	22 (5)				0	2.0
2-3B1	20-11	1002	6.69	356 (80)	↓		290	0.3	2.0
2-3B2	23-4	998	5.77	356 (80)			583	9.3	11.0
2-4A1	25-6	995	4.64	<22 (<5)			175	0	4.0
2-4A2	28-6	990	4.05	<22 (<5)				0	4.0
2-4A3	31-7	973	3.49	<22 (<5)				0.6	3.5
2-4A4	34-7	976	2.98	<22 (<5)				0	4.0
2-4B1	26-12	995	4.64	53 (12)				0	4.0
2-4B2	29-2	990	4.05	53 (12)				2.8	7.5
2-4B3	32-15	973	3.49	53 (12)				0	4.0
2-4B4	35-3	976	2.98	53 (12)				0	4.0
2-4C1	27-4	995	4.64	22 (5)				0	4.0
2-4C2	30-1	990	4.05	22 (5)				0	4.0
2-4C3	33-9	973	3.49	22 (5)				0	4.0
2-4C4	37-8	976	2.98	22 (5)				0	4.0

(a) The first digit is the cell number, the second digit is the graphite body number, the letter refers to the axial hole, and the last digit refers to the axial stacking sequence in the hole.

(b) NA = not applicable.

TABLE 4-9
PREIRRADIATED DIMENSIONS OF P13T
FUEL RODS CARBONIZED IN GRAPHITE BODIES

Mean Diametral Measurement, μ_o [mm (in.)]	Mean Axial Measurement, μ_A [mm (in.)]	Standard Deviation [mm (in.)]	Number of Measurements	Statistical Bounds ^(a) on Measurements [mm (in.)]
15.80 (0.622)	--	0.02 (0.0008)	36	$15.74 (0.619) \leq \mu_o \leq 15.86 (0.624)$
--	30.52 (1.202)	0.24 (0.0095)	18	$29.77 (1.172) \leq \mu_A \leq 30.78 (1.212)$
--	50.07 (1.971)	0.26 (0.0102)	12	$49.22 (1.938) \leq \mu_A \leq 50.92 (2.005)$
--	61.13 (2.406)	0.16 (0.0063)	6	$60.48 (2.381) \leq \mu_A \leq 61.78 (2.432)$

(a) Statistical bounds defined such that no more than 1% of the measurements will be beyond limits at the 95% confidence level.

TABLE 4-10
IRRADIATION-INDUCED DIMENSIONAL CHANGE IN P13T FUEL RODS

Capsule Ident. (a)	Fuel Rod Designation 7161-008-	Capsule Irradiation Conditions (b)		Irradiation-Induced Strain							
		Temp (°C)	Fast Fluence [(10 ²⁵ n/m ²) (E > 29 fJ) _{HTGR}]	Diametral Strain, $\Delta D/D \times 100$					Axial Strain, $\Delta L/L \times 100$ (f)		
				Top of Rod	Middle of Rod	Bottom of Rod	Mean μ_D (c)	Upper Lower Bounds on Mean (d)	Mean μ_A (e)	Upper and Lower Bounds on Mean (d)	
1-1A1	01-9	1177	3.45	-2.22	-2.03	-1.90	-2.02	-1.65 < μ_D < -2.40	-3.41	-0.97 < μ_A < -4.22	
1-1A2	04-3	1177	4.84	-1.71	-1.90	-1.52	-1.71	-1.33 < μ_D < -2.08	-3.41	-0.97 < μ_A < -4.22	
1-1A3	07-9	1197	6.42	-1.14	-1.52	-1.52	-1.71	-1.02 < μ_D < -1.77	-2.03	-0.98 < μ_A < -3.06	
1-1A4	10-6	1215	7.67	-1.58	-1.46	-1.14	-1.71	-1.02 < μ_D < -1.77	-1.36	-0.31 < μ_A < -2.64	
1-1B1	02-10	1177	3.45	-2.09	-2.22	-2.53	-2.28	-1.91 < μ_D < -2.65	-0.56	-1.07 < μ_A < 1.95	
1-1B2	05-20	1177	4.84	-1.65	-1.71	-1.77	-1.71	-1.33 < μ_D < -2.08	-4.46	-5.06 < μ_A < -2.05	
1-1B3	08-11	1197	6.42	-1.33	-1.46	-1.65	-1.46	-1.08 < μ_D < -1.83	-1.95	-2.98 < μ_A < -0.90	
1-1B4	11-7	1215	7.67	-1.71	-1.33	-1.14	-1.39	-1.02 < μ_D < -1.77	-0.57	-1.62 < μ_A < 0.50	
1-1C1	03-12	1177	3.45	-2.22	-2.22	-2.41	-2.28	-1.91 < μ_D < -2.65	-1.97	-2.79 < μ_A < 0.49	
1-1C2	06-2	1177	4.84	-2.15	-2.09	-1.90	-2.03	-1.65 < μ_D < -2.40	-1.87	-2.69 < μ_A < 0.59	
1-1C3	09-12	1197	6.42	-0.95	-1.14	-1.46	-1.20	-0.83 < μ_D < -1.58	-0.95	-1.99 < μ_A < 0.11	
1-1C4	12-1	1215	7.67	-0.70	-0.95	-1.20	-0.95	-0.57 < μ_D < -1.32	-1.44	-2.48 < μ_A < -0.39	
2-2A1	13-2	1047	8.04	-1.52	-1.46	-1.33	-1.46	-1.08 < μ_D < -1.83	-0.62	-2.27 < μ_A < 1.09	
2-2A2	16-12	1041	7.64	-1.90	-1.65	-1.52	-1.71	-1.33 < μ_D < -2.08	-0.68	-2.33 < μ_A < 1.03	
2-2B1	14-5	1047	8.04	-0.82	-0.89	-1.14	-0.95	-0.57 < μ_D < -1.32	-0.88	-2.53 < μ_A < 0.83	
2-2B2	17-14	1041	7.64	-1.20	-1.27	-1.14	-1.20	-0.83 < μ_D < -1.58	-0.68	-2.33 < μ_A < 1.03	
2-2C1	15-3	1047	8.04	-1.77	-1.65	-1.39	-1.58	-1.21 < μ_D < -1.95	-0.78	-2.43 < μ_A < 0.93	
2-2C2	18-4	1041	7.64	-1.65	-1.71	-1.58	-1.65	-1.27 < μ_D < -2.02	-0.26	-1.94 < μ_A < 1.46	
2-3B1	20-11	1002	6.69	-1.20	-1.46	-1.27	-1.33	-0.95 < μ_D < -1.70	-0.62	-2.27 < μ_A < 1.09	
2-3B2	23-4	998	5.77	-2.53	-2.22	-1.90	-2.22	-1.84 < μ_D < -2.59	-1.38	-3.02 < μ_A < 0.32	
2-4A1	25-6	995	4.64	-2.28	-2.22	-2.09	-2.22	-1.84 < μ_D < -2.59	-0.46	-1.30 < μ_A < 2.04	
2-4A2	28-6	990	4.05	-1.96	-1.84	-2.03	-1.96	-1.59 < μ_D < -2.33	-0.79	-1.62 < μ_A < 1.70	
2-4A3	31-7	973	3.49	-2.41	-2.28	-2.28	-2.34	-1.97 < μ_D < -2.71	-2.20	-3.02 < μ_A < 0.25	
2-4A4	34-7	976	2.98	-2.34	-2.72	-2.53	-2.53	-2.16 < μ_D < -2.90	-1.97	-2.79 < μ_A < 0.49	
2-4B1	26-12	995	4.64	-2.28	-2.15	-2.09	-2.15	-1.78 < μ_D < -2.52	-1.21	-2.04 < μ_A < 1.26	
2-4B2	29-2	990	4.05	-2.66	-2.53	-2.34	-2.53	-2.16 < μ_D < -2.90	-3.87	-4.68 < μ_A < -1.46	
2-4B3	32-15	973	3.49	-2.47	-2.47	-2.28	-2.41	-2.03 < μ_D < -2.77	-0.39	-1.23 < μ_A < 2.10	
2-4B4	35-3	976	2.98	-2.97	-3.29	-3.29	-3.16	-2.79 < μ_D < -3.53	-4.19	-5.00 < μ_A < 2.77	
2-4C1	27-4	995	4.64	-2.28	-2.34	-2.15	-2.28	-1.91 < μ_D < -2.65	-0.46	-1.30 < μ_A < 2.04	
2-4C2	30-1	990	4.05	-2.15	-2.22	-2.03	-2.15	-1.78 < μ_D < -2.52	-0.72	-1.56 < μ_A < 1.75	
2-4C3	33-9	973	3.49	-1.96	-1.90	-2.09	-1.96	-1.59 < μ_D < -2.33	-1.80	-2.63 < μ_A < 0.66	
2-4C4	36-8	976	2.98	-2.47	-2.28	-2.09	-2.28	-1.91 < μ_D < -2.65	-2.13	-2.95 < μ_A < 0.66	

(a) The first digit is the cell number, the second digit is the graphite body number, the letter refers to the axial hole, and the last digit refers to the axial stacking sequence in the hole.

(b) Final thermal and dosimetry analysis not completed.

(c) Mean of top, middle, and bottom diametral strains.

(d) Based on a 95% confidence statement that no more than 1% of the measurements will be outside stated bounds.

(e) Based on two axial measurements taken at right angles.

(f) Axial dimensional changes are subject to uncertainties caused by Grafoil wafers placed between fuel rods.

TABLE 4-11
GRAPHITE DIMENSIONAL CHANGE DATA FOR P13T CRUCIBLES

Crucible No.	Graphite Type	Av Original Dimension [cm (in.)]	Av Lifetime Irrad. Temp (°C)	Actual Fast Fluence [(10 ²⁵ n/m ²) (E > 29 fJ)HTGR]			ΔD/D (% Change)					
				Top	Middle	Bottom	Top		Middle		Bottom	
							0-deg	90-deg	0-deg	90-deg	0-deg	90-deg
Diametral Change (Perpendicular to Extrusion Axis)												
1	H-451	6.040 (2.378)	1070	--	--	3.2	--	--	--	--	-0.70	-0.71
	H-451	6.114 (2.407)	1070	7.9	6.4	--	-0.78	-0.74	-0.88	-0.98	--	--
2	TS-1240	6.153 (2.422)	850	7.4	7.9	8.1	-0.48	-0.40	-0.44	-0.41	-0.61	-0.38
3	H-451	6.147 (2.420)	840	5.3	6.3	7.1	-0.87	-0.84	-1.12	-1.10	-1.29	-1.25
4	TS-1240	6.138 (2.417)	800	--	3.8	4.8	--	--	-0.20	-0.24	-0.19	-0.32
	TS-1240	6.094 (2.399)	800	2.8	--	--	-0.08	-0.05	--	--	--	--
Length Change (Parallel to Extrusion Axis)												
							ΔL/L (% Change)					
							0-deg	90-deg	180-deg	270-deg		
1	H-451	20.070 (7.902)	1070	7.9	6.4	3.2	-2.78	-2.41	-1.92		-2.26	
2	TS-1240	11.697 (4.605)	850	7.4	7.9	8.1	-0.99	-0.93	-0.94		-1.02	
3	H-451	11.697 (4.605)	840	5.3	6.3	7.1	-1.40	-1.44	-1.53		-1.41	
4	TS-1240	13.721 (5.402)	800	2.8	3.8	4.8	-0.22	-0.25	-0.26		-0.24	

TABLE 4-12
BOWING MEASUREMENTS TAKEN ON P13T GRAPHITE CRUCIBLES
DURING THE POSTIRRADIATION EXAMINATION

Crucible No.	Cell No.	Graphite Type	Av Original Length [cm (in.)]	Body Midlength Design Fast Fluence [(10 ²⁵ n/m ²) (E > 29 fJ) _{HTGR}]	Av Lifetime Irrad. Temp ^(a) (°C)	Peripheral Angle (deg)	Maximum Observed Bow ^(b) [mm (in.)]
1	1	H-451	20.069 (7.901)	7.2	1070	0	0.65 (0.0256)
						90	0.39 (0.0154)
						180	0.70 (0.0276)
						270	0.40 (0.0157)
2	2	TS-1240	11.697 (4.605)	8.8	850	0	0.06 (0.0024)
						90	0.10 (0.0039)
						180	0.08 (0.0031)
						270	0.03 (0.0012)
3	2	H-451	11.697 (4.605)	7.4	840	0	0.24 (0.0094)
						90	0.21 (0.0083)
						180	0.22 (0.0087)
						270	0.22 (0.0087)
4	2	TS-1240	13.721 (5.402)	4.3	800	0	0.02 (0.0008)
						90	0.09 (0.0035)
						180	0.14 (0.0055)
						270	0.11 (0.0043)

(a) The fluence and temperature values shown have been estimated and are subject to revision following completion of the P13T dosimetry and thermal analyses.

(b) Defined as the absolute magnitude of the maximum difference between the high and low points along the length of the crucible.

TABLE 4-13
TRIGA RELEASE RESULTS FOR P13T CRUCIBLES

Crucible No.	Cell No.	TRIGA Kr-85m R/B	EOL In-Pile Kr-85m R/B
1	1	1.3×10^{-4} ^(a)	1.6×10^{-5}
2	2	1.3×10^{-5}	} Cell 2: 2.8×10^{-6}
3	2	8.0×10^{-6}	
4	2	2.6×10^{-6}	

(a) Crucible irradiated in TRIGA at room temperature;
R/B value shown corrected to 1100°C.

TABLE 4-14
POSTIRRADIATION TRIGA R/B VALUES FOR INDIVIDUAL FUEL RODS IRRADIATED
IN CAPSULE P13T

Fuel Rod Position No.	Fuels Chemistry Branch Identification No.	Equivalent U-235 Loading (mg)	EOL Kr-85m R/B at 1100°C in TRIGA
1-1A1	7298-138	123.1	2.44×10^{-5}
1-1B1	7299-12	121.9	6.25×10^{-6}
1-1C1	7299-37	123.1	1.01×10^{-5}
1-1A2	7298-139	94.5	5.70×10^{-5}
1-1B2	7299-13	95.2	6.29×10^{-6}
1-1C2	7299-38	95.2	5.24×10^{-5}
1-1A3	7298-140	159.0	1.46×10^{-5}
1-1B3	7299-10	159.7	1.90×10^{-5}
1-1C3	7299-16	158.9	5.79×10^{-6}
1-1A4	7298-141	146.1	3.99×10^{-5}
1-1B4	7299-11	146.5	1.05×10^{-4}
1-1C4	7299-17	146.6	5.21×10^{-5}
2-2A1	7298-143	87.1	9.68×10^{-5}
2-2B1	7299-35	85.7	5.08×10^{-5}
2-2C1	7298-149	86.9	2.22×10^{-5}
2-2A2	7298-144	97.2	1.58×10^{-5}
2-2B2	7299-36	95.5	2.33×10^{-5}
2-2C2	7298-150	93.1	3.66×10^{-6}
2-3B1	7299-39	106.9	7.11×10^{-5}
2-3B2	7299-40	133.5	4.02×10^{-5}
2-4A1	7298-145	112.6	6.03×10^{-6}
2-4B1	7299-31	112.1	4.99×10^{-6}
2-4C1	7298-151	112.7	8.42×10^{-6}
2-4A2	7298-146	113.6	3.55×10^{-6}
2-4B2	7299-32	112.4	3.65×10^{-8}
2-4C2	7298-152	114.5	8.91×10^{-7}
2-4A3	7299-23	147.2	5.57×10^{-5}

TABLE 4-14 (Continued)

Fuel Rod Position No.	Fuels Chemistry Branch Identification No.	Equivalent U-235 Loading (mg)	EOL Kr-85m R/B at 1100°C in TRIGA
2-4B3	7299-25	145.8	1.44×10^{-6}
2-4C3	7299-33	145.9	1.85×10^{-6}
2-4A4	7299-24	196.9	6.37×10^{-8}
2-4B4	7299-26	196.8	4.08×10^{-7}
2-4C4	7299-34	192.7	5.15×10^{-7}

TABLE 4-15
R/B TEMPERATURE DEPENDENCE FOR P13T CELL 1 FUEL RODS

Rod No.	Fuel Chem. Branch Ident. No.	Date	Time	Temp (°C)	Equiv. U-235 Loading (mg)	Kr-85m R/B
1-1B1	7299-2	10/28/76	0918	RT	121.9	$<10^{-7}$
1-1B1	7299-4	10/28/76	1109	1100		6.25×10^{-6}
1-1B1	7299-12	10/29/76	1101	1100		3.33×10^{-7}
1-1B2	7299-3	10/28/76	0918	RT	95.2	$<10^{-7}$
1-1B2	7299-5	10/28/76	1109	1100		6.99×10^{-6}
1-1B2	7299-13	10/29/76	1101	1100		5.58×10^{-6}
				1100 av		6.29×10^{-6}
1-1B3	7299-6	10/28/76	1317	1100	159.7	2.32×10^{-5}
1-1B3	7299-8	10/28/76	1507	RT		$<10^{-7}$
1-1B3	7299-10	10/29/76	0923	1100		1.47×10^{-5}
				1100 av		1.90×10^{-5}
1-1B4	7299-7	10/28/76	1317	1100	146.5	1.19×10^{-4}
1-1B4	7299-9	10/28/76	1507	RT		9.18×10^{-6}
1-1B4	7299-11	10/29/76	0923	1100		9.05×10^{-5}
				1100 av		1.05×10^{-4}

TABLE 4-16
COMPARISON OF CAPSULE P13T IN-PILE AND TRIGA FISSION GAS RELEASE DATA (R/B Kr-85m)

Fuel Rod Data Retrieval No. (7161-008-)	Fuel Rod No. Position	EOL Kr-85m R/B by TRIGA	Vol Av Temperature (°C)	Temperature Correction Factor(a)	TRIGA R/B(a) Vol Av Temperature(b)	Fraction of Fission Sample(c)	Contribution to Total Cell R/B	Calculated TRIGA EOL Crucible R/B from Fuel Rod R/B	Crucible R/B Measured at EOL in TRIGA	Calculated TRIGA EOL Cell R/B(d) from Fuel Rod R/B	Apportioned Crucible R/B to Cell R/B at EOL(d)	Measured Cell R/B at EOL in-Pile
01-9	1-1A1	2.4×10^{-5}	1177	1.26	3.1×10^{-5}	0.066	2.0×10^{-6}	4.7×10^{-5}	$1.3 \times 10^{-4}(f)$	--	--	1.6×10^{-5}
02-10	1-1B1	6.3×10^{-6}	1177	1.26	7.9×10^{-6}	0.065	5.1×10^{-7}					
03-12	1-1C1	1.0×10^{-5}	1177	1.26	1.3×10^{-5}	0.065	8.3×10^{-7}					
04-3	1-1A2	5.7×10^{-5}	1177	1.26	7.2×10^{-5}	0.055	4.0×10^{-6}					
05-20	1-1B2	6.3×10^{-6}	1177	1.26	7.9×10^{-6}	0.055	4.4×10^{-7}					
06-2	1-1C2	5.2×10^{-5}	1177	1.26	6.6×10^{-5}	0.055	3.6×10^{-6}					
07-9	1-1A3	1.5×10^{-5}	1197	1.34	2.0×10^{-5}	0.104	2.0×10^{-6}					
08-11	1-1B3	1.9×10^{-5}	1197	1.34	2.6×10^{-5}	0.104	2.7×10^{-6}					
09-12	1-1C3	5.8×10^{-6}	1197	1.34	7.8×10^{-6}	0.104	8.1×10^{-7}					
10-6	1-1A4	4.0×10^{-5}	1215	1.41	5.6×10^{-5}	0.108	6.1×10^{-6}					
11-7	1-1B4	1.1×10^{-4}	1215	1.41	1.5×10^{-4}	0.108	1.6×10^{-5}					
12-1	1-1C4	5.2×10^{-5}	1215	1.41	7.4×10^{-5}	0.109	8.0×10^{-6}					
13-2	2-2A1	9.7×10^{-5}	1047	0.85	8.2×10^{-5}	0.159	1.3×10^{-5}	3.4×10^{-5}	1.3×10^{-5}			
14-5	2-2B1	5.1×10^{-5}	1047	0.85	4.3×10^{-5}	0.156	6.7×10^{-6}					
15-3	2-2C1	2.2×10^{-5}	1047	0.85	1.9×10^{-5}	0.158	3.0×10^{-6}					
16-12	2-2A2	1.6×10^{-5}	1041	0.83	1.3×10^{-5}	0.179	3.3×10^{-6}					
17-14	2-2B2	2.3×10^{-5}	1041	0.83	1.9×10^{-5}	0.176	3.4×10^{-6}					
18-4	2-2C2	3.7×10^{-6}	1041	0.83	3.0×10^{-5}	0.172	5.2×10^{-6}	4.5×10^{-6}	2.6×10^{-6}	2.2×10^{-5}	6.9×10^{-6}	2.8×10^{-6}
20-11	2-3B1	7.1×10^{-5}	1002	0.72	5.1×10^{-5}	0.481(e)	2.5×10^{-5}					
23-4	2-3B2	4.0×10^{-5}	998	0.71	2.9×10^{-5}	0.519(e)	1.5×10^{-5}					
25-6	2-4A1	6.0×10^{-6}	995	0.71	4.3×10^{-6}	0.077	3.3×10^{-7}					
26-12	2-4B1	5.0×10^{-6}	995	0.71	3.5×10^{-6}	0.077	2.7×10^{-7}					
27-4	2-4C1	8.4×10^{-6}	995	0.71	6.0×10^{-6}	0.077	4.6×10^{-7}					
28-6	2-4A2	3.6×10^{-6}	990	0.69	2.5×10^{-6}	0.071	1.7×10^{-7}					
29-2	2-4B2	3.7×10^{-8}	990	0.69	2.5×10^{-8}	0.071	1.8×10^{-9}					
30-1	2-4C2	8.9×10^{-7}	990	0.09	6.2×10^{-7}	0.072	4.4×10^{-8}					
31-7	2-4A3	5.6×10^{-5}	973	0.65	3.6×10^{-5}	0.083	3.0×10^{-6}					
32-15	2-4B3	1.4×10^{-6}	973	0.65	9.4×10^{-7}	0.082	7.7×10^{-8}					
33-9	2-4C3	1.9×10^{-6}	973	0.65	1.2×10^{-6}	0.083	1.0×10^{-7}					
34-7	2-4A4	6.4×10^{-8}	976	0.66	4.2×10^{-8}	0.103	4.3×10^{-9}					
35-3	2-4B4	4.1×10^{-7}	976	0.66	2.7×10^{-7}	0.103	2.8×10^{-8}					
36-8	2-4C4	5.2×10^{-7}	976	0.66	3.4×10^{-7}	0.101	3.4×10^{-8}					

(a) Temperature correction was calculated using Eq. 10.1-2 of Ref. 4-5.

(b) Measured TRIGA fission gas release data corrected to volume average irradiation temperature.

(c) Fraction of fissions in individual fuel rods equals the amount of fissionable material in the fuel rod divided by the total amount of fissionable material in the cell at EOL.

(d) Calculated on the basis that 26.3%, 28.8%, and 44.9% of the fissionable material in cell 2 is contained in crucibles 2, 3, and 4, respectively.

(e) Assuming 2-3A1 and 2-3C1 are loaded at EOL identical to 2-3B1 and 2-3A2 and 2-3C2 are identical to 2-3B2.

(f) Crucible irradiated in TRIGA at room temperature; R/B value shown corrected to 1100°C.

TABLE 4-17
GASEOUS FISSION PRODUCT RELEASE (R/B Kr-85m) RESULTING FROM IN-SERVICE PARTICLE FAILURE IN CAPSULE P13T FUEL RODS

Fuel Rod Data Retrieval No. (7161-008-)	Fuel Rod Position No.	Fissile Data Retrieval No.	Fertile Data Retrieval No. (6542-)	EOL Kr-85m R/B by TRIGA	BOL Thorium Contamination (a) (gTh/gTh)	BOL (b) Kr-85m R/B by TRIGA	Fraction of Fission Occurring at EOL (c)		R/B (d) c(Th)	R/B (e) c(U)	R/B (e) Failed Fuel	In-Service Particle Failure (f) (%)	Maximum Particle Failure (g) (%)	Maximum Fissile Particle Failure (h) (%)
							Fertile	Fissile						
01-9	1-1A1	6151-17-015	36-015	2.4×10^{-5}	1.0×10^{-4}	2.0×10^{-6}	0.809	0.191	2.4×10^{-5}	3.8×10^{-7}	2.0×10^{-8}	0	0	0
02-10	1-1B1	6151-12-015	32-015	6.3×10^{-6}	1.5×10^{-6}	1.0×10^{-7}	0.811	0.189	3.6×10^{-7}	1.9×10^{-8}	5.9×10^{-4}	0.1	0.1	0.5
03-12	1-1C1	6151-17-025	27-015	1.0×10^{-5}	7.9×10^{-5}	1.8×10^{-7}	0.802	0.198	1.7×10^{-5}	3.6×10^{-8}	0	0	0	0
04-3	1-1A2	6151-17-015	36-015	5.7×10^{-5}	1.0×10^{-4}	1.7×10^{-6}	0.794	0.206	2.4×10^{-5}	3.5×10^{-7}	3.3×10^{-5}	0.7	0.7	2.5
05-20	1-1B2	6151-12-015	32-015	6.3×10^{-6}	1.5×10^{-6}	3.8×10^{-6}	0.794	0.206	3.6×10^{-7}	7.8×10^{-7}	5.2×10^{-6}	0.1	0.1	0.4
06-2	1-1C2	6151-17-025	27-015	5.2×10^{-5}	7.0×10^{-5}	1.4×10^{-6}	0.793	0.207	1.7×10^{-5}	2.9×10^{-5}	3.5×10^{-5}	0.7	0.7	2.7
07-9	1-1A3	6151-17-015	36-015	1.5×10^{-5}	1.0×10^{-4}	5.3×10^{-7}	0.842	0.158	2.5×10^{-5}	8.4×10^{-8}	0	0	0	0
08-11	1-1B3	6151-12-015	32-015	1.9×10^{-5}	1.5×10^{-6}	1.4×10^{-6}	0.843	0.157	3.8×10^{-7}	2.2×10^{-7}	1.8×10^{-5}	0.4	0.3	1.7
09-12	1-1C3	6151-17-025	27-015	5.8×10^{-6}	7.0×10^{-5}	1.3×10^{-6}	0.836	0.164	1.8×10^{-5}	2.1×10^{-7}	0	0	0	0
10-6	1-1A4	6151-17-015	36-015	4.0×10^{-5}	1.0×10^{-4}	9.8×10^{-7}	0.892	0.108	2.7×10^{-5}	1.1×10^{-7}	1.3×10^{-5}	0.3	0.1	1.7
11-7	1-1B4	6151-12-015	32-015	1.1×10^{-4}	1.5×10^{-6}	3.6×10^{-7}	0.892	0.108	4.0×10^{-7}	3.9×10^{-8}	1.0×10^{-4}	2.0	1.1	13.1
12-1	1-1C4	6151-17-025	27-015	5.2×10^{-5}	7.0×10^{-5}	2.7×10^{-7}	0.892	0.108	1.9×10^{-5}	2.9×10^{-8}	3.3×10^{-5}	0.7	0.4	4.3
13-2	2-2A1	6151-17-025	27-015	9.7×10^{-5}	7.0×10^{-5}	4.1×10^{-6}	0.885	0.115	1.9×10^{-5}	4.7×10^{-7}	7.7×10^{-5}	1.5	1.4	15.8
14-5	2-2B1	6151-18-015	35-015	5.1×10^{-5}	1.1×10^{-4}	4.8×10^{-7}	0.882	0.118	2.9×10^{-5}	5.7×10^{-8}	2.2×10^{-5}	0.4	0.4	4.4
15-3	2-2C1	6157-02-015 (1)	27-015	2.2×10^{-5}	7.0×10^{-5}	2.7×10^{-5}	0.886	0.114	1.9×10^{-5}	3.1×10^{-6}	1.0×10^{-7}	0	0	0
16-12	2-2A2	6151-00-035	02-025	1.6×10^{-5}	7.9×10^{-7}	7.6×10^{-7}	0.889	0.111	1.9×10^{-7}	8.4×10^{-8}	1.6×10^{-5}	0.3	0.3	3.5
17-14	2-2B2	6151-10-015	34-015	2.3×10^{-5}	2.3×10^{-4}	5.0×10^{-7}	0.886	0.114	6.1×10^{-5}	5.7×10^{-8}	0	0	0	0
18-4	2-2C2	6157-02-015 (1)	33-025	3.7×10^{-6}	1.1×10^{-4}	1.9×10^{-6}	0.888	0.112	2.9×10^{-5}	2.1×10^{-7}	0	0	0	0
20-11	2-3B1	6151-18-015	31-015	7.1×10^{-5}	9.0×10^{-5}	2.8×10^{-7}	0.852	0.148	2.3×10^{-5}	4.1×10^{-8}	4.8×10^{-5}	1.0	1.2	9.0
23-4	2-3B2	6151-19-015	36-015	4.0×10^{-5}	1.0×10^{-4}	2.3×10^{-7}	0.768	0.232	2.3×10^{-5}	5.3×10^{-8}	1.7×10^{-5}	0.3	0.6	2.1
25-6	2-4A1	6151-12-015	35-015	6.9×10^{-6}	1.1×10^{-4}	2.7×10^{-7}	0.656	0.344	2.2×10^{-5}	9.3×10^{-8}	0	0	0	0
26-12	2-4B1	6151-17-025	33-025	5.9×10^{-6}	1.1×10^{-4}	3.9×10^{-7}	0.650	0.350	2.1×10^{-5}	1.4×10^{-7}	0	0	0	0
27-4	2-4C1	6157-02-015 (1)	31-015	8.4×10^{-6}	9.0×10^{-5}	1.4×10^{-6}	0.652	0.348	1.8×10^{-5}	4.9×10^{-7}	0	0	0	0
38-6	2-4A2	6151-18-015	34-015	3.6×10^{-6}	2.3×10^{-4}	3.1×10^{-6}	0.517	0.483	3.6×10^{-5}	1.5×10^{-7}	0	0	0	0
29-2	2-4B2	6151-10-015	29-015	3.7×10^{-8}	7.5×10^{-5}	2.5×10^{-7}	0.501	0.499	1.1×10^{-5}	1.2×10^{-7}	0	0	0	0
30-1	2-4C2	6157-02-015 (1)	27-015	8.9×10^{-7}	7.0×10^{-5}	2.2×10^{-6}	0.513	0.487	1.1×10^{-5}	1.1×10^{-6}	0	0	0	0
31-7	2-4A3	6151-19-015	36-015	5.6×10^{-5}	1.0×10^{-4}	2.9×10^{-7}	0.469	0.531	1.4×10^{-5}	1.5×10^{-7}	4.2×10^{-5}	0.8	5.0	2.4
32-15	2-4B3	6151-17-015	31-015	1.4×10^{-6}	9.0×10^{-5}	1.1×10^{-6}	0.473	0.527	9.5×10^{-6}	5.8×10^{-7}	0	0	0	0
33-9	2-4C3	6157-02-015 (1)	35-015	1.9×10^{-6}	1.1×10^{-4}	2.2×10^{-6}	0.465	0.535	1.5×10^{-5}	1.2×10^{-6}	0	0	0	0
34-7	2-4A4	6151-00-035	02-025	6.4×10^{-8}	7.9×10^{-7}	4.5×10^{-8}	0.520	0.480	1.1×10^{-7}	2.2×10^{-7}	0	0	0	0
35-3	2-4B4	6151-18-015	27-015	4.1×10^{-7}	7.0×10^{-5}	1.3×10^{-7}	0.520	0.480	1.1×10^{-5}	6.2×10^{-8}	0	0	0	0
36-8	2-4C4	6157-02-015 (1)	29-015	5.2×10^{-7}	7.5×10^{-5}	2.3×10^{-6}	0.512	0.488	1.2×10^{-5}	1.1×10^{-6}	0	0	0	0

(a) Determined by hydrolysis test on unirradiated fertile particle batch used in these rods (Ref. 4-11).

(b) Determined on companion rods that were cured-in-place, then removed.

(c) Normalized to Kr-85m thermal fission yields.

(d) Calculated assuming a fractional release for contamination of 0.30 (Ref. 4-9).

(e) $R/B_{\text{failed fuel}} = R/B_{\text{EOL}} - [R/B_{\text{c(Th)}} + R/B_{\text{c(U)}}]$

(f) Calculated assuming a fractional release of 5×10^{-3} for failed fuel in a constrained geometry (Ref. 4-9), see Section 4.4.2.

(g) Calculated assuming a fractional release of 5×10^{-3} for failed fuel and corrected for temperature and burnup as per equations in Fuel Design Data Manual (Ref. 4-5).

(h) Calculated assuming 5×10^{-3} for UC_2 and 3.4×10^{-2} for WAR fuel, corrected for temperature as per Fuel Design Data Manual (Ref. 4-5).

(1) WAR/ThO₂ fuel rods.

TABLE 4-18
COMPARISON OF CALCULATED AND MEASURED Kr-85m R/B DETERMINATIONS FOR CAPSULE P13T

Fuel Rod Data Retrieval No. (7161-008-)	Fuel Rod Position No.	Fissile Fuel Type	Fertile Fuel Type	Fissile Burnup (% FIMA)	Fertile Burnup (% FIMA)	Fuel Rod Vol Av Temp (°C)	Fast Fluence [(10 ²⁵ n/m ²) (E > 29 fJ) _{HTGR}]	Kr-85m R/B at EOL		Ratio (a) Observed/ Predicted
								Predicted	Observed	
01-9	1-1A1	UC ₂ -TRISO	ThO ₂ -BISO	67.7	1.86	1177	3.45	3.1 x 10 ⁻⁵	2.4 x 10 ⁻⁵	0.77
02-10	1-1B1	UC ₂ -TRISO	ThO ₂ -BISO	67.7	1.86	1177	3.45	6.6 x 10 ⁻⁶	6.3 x 10 ⁻⁶	0.95
03-12	1-1C1	UC ₂ -TRISO	ThO ₂ -BISO	67.7	1.86	1177	3.45	2.3 x 10 ⁻⁵	1.0 x 10 ⁻⁵	0.43
04-3	1-1A2	UC ₂ -TRISO	ThO ₂ -BISO	69.1	2.05	1177	4.84	3.2 x 10 ⁻⁵	5.7 x 10 ⁻⁵	1.78
05-20	1-1B2	UC ₂ -TRISO	ThO ₂ -BISO	69.1	2.05	1177	4.84	1.5 x 10 ⁻⁵	6.3 x 10 ⁻⁶	0.43
06-2	1-1C2	UC ₂ -TRISO	ThO ₂ -BISO	69.1	2.05	1177	4.84	2.5 x 10 ⁻⁵	5.2 x 10 ⁻⁵	2.10
07-9	1-1A3	UC ₂ -TRISO	ThO ₂ -BISO	72.2	2.66	1197	6.42	3.9 x 10 ⁻⁵	1.5 x 10 ⁻⁵	0.38
08-11	1-1B3	UC ₂ -TRISO	ThO ₂ -BISO	72.2	2.66	1197	6.42	1.5 x 10 ⁻⁵	1.9 x 10 ⁻⁵	1.27
09-12	1-1C3	UC ₂ -TRISO	ThO ₂ -BISO	72.2	2.66	1197	6.42	3.3 x 10 ⁻⁵	5.8 x 10 ⁻⁶	0.18
10-6	1-1A4	UC ₂ -TRISO	ThO ₂ -BISO	74.7	3.45	1215	7.67	4.9 x 10 ⁻⁵	4.0 x 10 ⁻⁵	0.82
11-7	1-1B4	UC ₂ -TRISO	ThO ₂ -BISO	74.7	3.45	1215	7.67	2.3 x 10 ⁻⁵	1.1 x 10 ⁻⁴	4.78
12-1	1-1C4	UC ₂ -TRISO	ThO ₂ -BISO	74.7	3.45	1215	7.67	4.1 x 10 ⁻⁵	5.2 x 10 ⁻⁵	1.27
13-2	2-2A1	UC ₂ -TRISO	ThO ₂ -BISO	75.3	3.74	1047	8.04	3.5 x 10 ⁻⁵	9.7 x 10 ⁻⁵	2.77
14-5	2-2B1	UC ₂ -TRISO	ThO ₂ -BISO	75.3	3.74	1047	8.04	4.5 x 10 ⁻⁵	5.1 x 10 ⁻⁵	1.13
15-3	2-2C1	WAR-TRISO	ThO ₂ -BISO	75.3	3.74	1047	8.04	3.8 x 10 ⁻⁵	2.2 x 10 ⁻⁵	0.46
16-12	2-2A2	UC ₂ -TRISO	ThO ₂ -BISO	75.5	3.83	1041	7.64	1.6 x 10 ⁻⁵	1.6 x 10 ⁻⁵	1.00
17-14	2-2B2	UC ₂ -TRISO	ThO ₂ -BISO	75.5	3.83	1041	7.64	7.7 x 10 ⁻⁵	2.3 x 10 ⁻⁵	0.30
18-14	2-2C2	WAR-TRISO	ThO ₂ -BISO	75.5	3.83	1041	7.64	5.4 x 10 ⁻⁵	3.7 x 10 ⁻⁶	0.07
20-11	2-3B1	UC ₂ -TRISO	ThO ₂ -BISO	74.0	3.20	1002	6.69	3.3 x 10 ⁻⁵	7.1 x 10 ⁻⁵	2.15
23-4	2-3B2	UC ₂ -TRISO	ThO ₂ -BISO	70.3	2.25	998	5.77	2.8 x 10 ⁻⁵	4.0 x 10 ⁻⁵	1.43
25-6	2-4A1	UC ₂ -TRISO	ThO ₂ -BISO	62.7	1.33	995	4.64	2.4 x 10 ⁻⁵	6.0 x 10 ⁻⁶	0.25
26-12	2-4B1	UC ₂ -TRISO	ThO ₂ -BISO	62.7	1.33	995	4.64	2.3 x 10 ⁻⁵	5.0 x 10 ⁻⁶	0.22
27-4	2-4C1	WAR-TRISO	ThO ₂ -BISO	62.7	1.33	995	4.64	1.8 x 10 ⁻⁵	8.4 x 10 ⁻⁶	0.45
28-6	2-4A3	UC ₂ -TRISO	ThO ₂ -BISO	57.8	0.99	990	4.05	3.7 x 10 ⁻⁵	3.6 x 10 ⁻⁶	0.10
29-2	2-4B2	UC ₂ -TRISO	ThO ₂ -BISO	57.8	0.99	990	4.05	1.2 x 10 ⁻⁵	3.7 x 10 ⁻⁸	0.003
30-1	2-4C2	WAR-TRISO	ThO ₂ -BISO	57.8	0.99	990	4.05	1.3 x 10 ⁻⁵	8.9 x 10 ⁻⁷	0.07
31-7	2-4A3	UC ₂ -TRISO	ThO ₂ -BISO	54.1	0.79	973	3.49	1.5 x 10 ⁻⁵	5.6 x 10 ⁻⁵	3.73
32-15	2-4B3	UC ₂ -TRISO	ThO ₂ -BISO	54.1	0.79	973	3.49	1.1 x 10 ⁻⁵	1.4 x 10 ⁻⁶	0.13
33-9	2-4C3	WAR-TRISO	ThO ₂ -BISO	54.1	0.79	973	3.49	1.7 x 10 ⁻⁵	1.9 x 10 ⁻⁶	0.11
34-7	2-4A4	UC ₂ -TRISO	ThO ₂ -BISO	53.4	0.76	976	2.98	8.1 x 10 ⁻⁷	6.4 x 10 ⁻⁸	0.08
35-3	2-4B4	UC ₂ -TRISO	ThO ₂ -BISO	53.4	0.76	976	2.98	1.2 x 10 ⁻⁵	4.1 x 10 ⁻⁷	0.03
36-8	2-4C4	WAR-TRISO	ThO ₂ -BISO	53.4	0.76	976	2.98	1.4 x 10 ⁻⁵	5.2 x 10 ⁻⁶	0.04

(a) Mean = 0.93. Standard deviation = 1.13.

TABLE 4-19
P13T FUEL RODS TESTED FOR THERMAL EXPANSION

Rod Location	Average Irradiation Temperature (K)	Total Fast Neutron Fluence [(10 ²⁵ n/m ²) (E > 29 fJ) _{HTGR}]	Fissile Kernel Type	Volume Fraction Particle Loading (vol %)				Matrix
				Fissile	Fertile	Inert	Shim	
1-1B1	1450	3.45	VSM	7.0	24.5	6.5	20	MO378
1-1B1	1450	4.84	VSM	6.1	16.9	9.6	25	MO386
1-1B3	1470	6.42	VSM	5.5	14.0	7.9	30	MO386
1-1B4	1488	7.67	VSM	4.7	12.9	4.2	35	MO378
2-4C2	1263	4.05	WAR	9.0	17.4	5.6	25	MO379
2-4C3	1246	3.49	WAR	10.5	20.7	6.3	20	MO379

TABLE 4-20
THERMAL EXPANSIVITY OF HTGR FUEL RODS - P13T

Rod	Orientation	$\bar{\alpha}_{(300-773K)}$ (10^{-6} K^{-1})	$\bar{\alpha}_{(300-1073K)}$ (10^{-6} K^{-1})	$\bar{\alpha}_{(300-1173K)}$ (10^{-6} K^{-1})
1B1	Axial	3.13	3.85	3.96
1B2	Axial	3.78	4.29	4.38
1B3	Axial	3.23	3.71	3.88
1B3	Radial	3.61	4.24	--
1B4	Axial	3.71	4.32	4.54
1B4	Radial	3.68	4.30	--
4C2	Axial	1.80	2.58	2.71
4C3	Axial	2.94	3.37	3.56
PBT Mean	Radial	3.65 ± 0.05	4.27 ± 0.04	--
PBT Mean	Axial	3.10 ± 0.7	3.69 ± 0.7	3.84 ± 0.7
FDDM Mean	Axial	2.86 ± 0.9	3.44 ± 0.6	--

TABLE 4-21
SUMMARY OF P13T METALLOGRAPHIC RESULTS OF TRISO-COATED FISSILE AND INERT PARTICLES

Particle Batch Data Retrieval No.	Capsule Position	Irradiation Conditions			No. of Particles Examined	Results of Metallographic Examination (%)										Severely Faceted Particle(e)	
		Fuel Rod Vol Av Temp (°C)	Burnup (% FIMA)	Fast Fluence [(10 ²⁵ n/m ²) _{HTR}]		Cracked or Consumed Buffer(a)	IPyC Debonded from SiC	IPyC Failed	IPyC Coating Reaction(b)	SiC Coating Reaction(c)	SiC Failure	SiC + OPyC Failure	OPyC Tear(d)	OPyC Failure	OPyC Tear And Failure		
TRISO-Coated VSM UC ₂ Particles																	
6151-17-015	1-1A1	1177	67.7	3.5	66	1.5	0	0	0	30.3	0	0	6.1	47.0	6.1	0	
6151-12-015	1-1B2	1177	69.1	4.8	102	0	11.8	0	1.0	48.0	0	0	1.0	24.5	0	0	
6151-12-015	1-1B4	1215	74.7	7.7	102	1.0	14.7	1.0	100	46.1	0	0	0	3.9	0	0	
6151-12-015	2-4A1	995	62.7	4.6	96	1.0	2.0	0	86.5	4.2	0	0	0	2.1	0	ND ^(f)	
6151-17-025	1-1C1	1177	67.7	3.5	98	0	38.8	1.0	100	23.5	3.1	3.1	3.1	70.4	3.1	1.0/0 ^(e)	
6151-17-025	1-1C4	1215	74.7	7.7	91	0	14.3	1.1	97.8	40.7	1.1	1.1	19.8	54.9	18.7	4.4/0 ^(e)	
6151-17-025	2-2A1	1047	75.3	8.0	170	6.5	21.2	0	48.8	0	0	0	0	0	0	ND	
6151-17-015	1-1A4	1215	74.7	7.7	62	3.2	1.6	4.8	1.6	17.7	0	0	6.5	35.5	3.2	0	
					787 TOTAL												
TRISO-Coated WAR UC _{2.92} ⁰ _{0.64} Particles																	
6157-02-015	2-2C1	1047	75.3	8.0	106	60.4	0	0	0	1.9	0	0	0.9	0	0	ND	
6157-02-015	2-2C2	1041	75.5	7.6	150	56.7	0	0	0	3.1	0	0	0	0	0	ND	
6157-02-015	2-4C1	995	62.7	4.6	77	29.9	0	0	0	3.9	0	0	0	0	0	0	
6157-02-015	2-4C4	976	53.4	3.0	116	53.4	1.7	0	0	1.7	2.6	0	2.6	2.6	0.9	6.9/1.7 ^(e)	
					449 TOTAL												
TRISO-Coated Inert Particles																	
6351-01-020	1-1A1	1177	0	3.5	75	ND	ND	ND	ND	ND	ND	ND	0	33.3	0	ND	
6351-01-020	1-1B2	1177	0	4.8	96	ND	ND	ND	ND	ND	ND	ND	0	33.3	0	ND	
6351-01-020	1-1B4	1215	0	7.7	69	ND	ND	ND	ND	ND	ND	ND	0	30.4	0	ND	
6351-01-020	1-1C1	1177	0	3.5	63	ND	ND	ND	ND	ND	ND	ND	0	58.7	0	ND	
6351-01-020	1-1C4	1215	0	7.7	132	ND	ND	ND	ND	ND	ND	ND	3.0	47.0	0.8	ND	
6351-01-020	2-2A1	1047	0	8.0	157	ND	ND	ND	ND	ND	ND	ND	ND	0.6	ND	ND	
6351-01-020	2-2C1	1047	0	8.0	143	ND	ND	ND	ND	ND	ND	ND	ND	0	ND	ND	
6351-01-020	2-2C2	1041	0	7.6	128	ND	ND	ND	ND	ND	ND	ND	ND	0	ND	ND	
6351-01-020	2-4A1	995	0	4.6	58	ND	ND	ND	ND	ND	ND	ND	ND	0	ND	ND	
6351-01-020	2-4C1	995	0	4.6	56	ND	ND	ND	ND	ND	ND	ND	ND	0	ND	ND	
6351-01-020	1-1A4	1215	0	7.7	55	ND	ND	ND	ND	ND	ND	ND	ND	0	ND	ND	
					1032 TOTAL												

(a) Buffer layers in VSM UC₂ particles are characterized as either cracked or not; however, buffer layers in WAR UC_{2.92}^{0.64} particles are characterized as consumed when >50% of the buffer layer reacts with the kernel.

(b) Particles which exhibited large concentrations of metallic fission products in the IPyC layer.

(c) Particles which exhibited metallic fission product attack of the SiC layer up to 5 μ m penetration; attack of ≤ 1 μ m was not observable.

(d) Classed as any degradation of OPyC layer other than failure.

(e) Generally defined as particles with an aspect ratio $\geq 2:1$; second value indicates the percent of faceted particles failures for the total number of particles observed.

(f) ND = not determined.

TABLE 4-22
SUMMARY OF P13T METALLOGRAPHIC RESULTS ON BISO-COATED FERTILE PARTICLES

Particle Batch Data Retrieval No. (6542-)	Capsule Position	Irradiation Conditions				Results of Metallographic Examination (%)						Severely Faceted Particle(b)
		Volume Average Fuel Rod Temp (°C)	Fast Fluence [(10 ²⁵ n/m ²) (E > 29 fJ) _{HTGR}]	Burnup (% FIMA)	No. of Particles Examined	Cracked Kernel	Cracked Buffer	Buffer Debonded from OPyC	OPyC Tear(a)	OPyC Failure	OPyC Tear and Failure	
27-015	1-1C1	1177	3.5	1.86	156	1.3	0	5.8	0	0	0	1.9/0(b)
27-015	1-1C4	1215	7.7	3.45	156	0.6	0	2.6	0.6	0	0	0.6/0
27-015	2-2A1	1047	8.0	3.74	268	8.5	0.7	27.6	0	0	0	ND(c)
27-015	2-2C1	1047	8.0	3.74	116	6.0	0.9	15.5	0.9	0	0	ND
29-015	2-4C4	976	3.0	0.76	144	0	1.4	22.2	0	0	0	0.7/0
31-015	2-4C1	995	4.6	1.33	266	0.8	0	26.7	0	0	0	1.9/0
32-015	1-1B4	1215	7.7	3.45	167	0	0	0	0.6	0.6	0.6	0
33-025	2-2C2	1041	7.6	3.83	371	3.2	1.1	22.6	0	0.8	0	0.3/0
35-015	2-4A1	995	4.6	1.33	265	1.5	0.4	16.2	0	0	0	1.9/0
36-015	1-1A1	1177	3.5	1.86	162	0	0	7.4	0	0	0	0
32-015	1-1B2	1177	4.8	2.05	174	0.6	0	0.6	0	0	0	0.6/0
36-015	1-1A4	1215	7.7	3.45	198	2.0	0	35.9	0	0	0	2.0/0
					2443 TOTAL							

(a) Classed as any degradation of OPyC layer other than complete failure.

(b) Generally defined as particles with an aspect ratio $\geq 2:1$; second value indicates the number of faceted particle failures for the total number of particles observed.

(c) ND = not determined.

TABLE 4-23
IRRADIATION-INDUCED CHANGE IN MACROPOROSITY OF P13T FUEL RODS

IRRADIATION-INDUCED CHANGE IN MACROPOROSITY OF PDS FUEL RODS																		
Data Retrieval No. (7161-008-)	Fuel Rod Position No.	Fuel Rod Volume Average Temperature (°C)	Fast Fluence [(10^{25} n/m^2)] (E > 29 fJ)HTGR]	Macroporosity ^(a) (%)			Matrix Composition ^(b)							Shim Content (vol %)	Shim Type ^(d)	Fissile Content ^(e) (vol %)	Fertile Content ^(e) (vol %)	Inert Content ^(e) (vol %)
				Preirradiation	Postirradiation	Change in Macroporosity ^(c)	Batch No.	Filler		Binder		Octadecanoic (wt %)	Polystyrene (wt %)					
								(Type)	(wt %)	(Type)	(wt %)							
03-12	1-1C1	1177	3.45	26 ^(f)	35	33	MO379	KS-15	38	A240	57	5	0	20	TS-1240X	6.8	24.6	6.2
11-7	1-1B4	1215	7.67	38 ^(f)	45	18	MO378	KS-15	38	A240	47	10	5	35	1099	4.7	12.9	4.2
18-4	2-2C2	1041	7.64	34 ^(f)	54	58	MO380	6353	30	A240	65	5	0	35	1099	4.8	9.6	7.1
36-8	2-4C4	976	2.98	27 ^(g)	31	14	MO379	KS-15	38	A240	57	5	0	13.4	1099	13.2	31.3	0
01-9	1-1A1	1177	3.45	42 ^(g)	44	5	MO380	6353	30	A240	65	5	0	20	1099	6.2	23.7	7.6
05-20	1-1B2	1177	4.84	40 ^(g)	45	13	MO386	KS-15	38	A240	47	10	5	25	1099	6.1	16.9	9.6
10-6	1-1A4	1215	7.67	37 ^(f)	43	16	MO380	6353	30	A240	65	5	0	35	1099	4.1	12.5	4.7
12-1	1-1C4	1215	7.67	31 ^(g)	42	35	MO379	KS-15	38	A240	57	5	0	35	X4029A	4.6	12.9	7.5
13-2	2-2A1	1047	8.04	39 ^(g)	40	3	MO380	6353	30	A240	65	5	0	35	1099	4.3	9.2	8.3
15-3	2-2C1	1047	8.04	40 ^(g)	43	8	MO380	6353	30	A240	65	5	0	35	1099	4.2	9.2	8.4
25-6	2-4A1	995	4.64	29 ^(f)	33	14	MO379	KS-15	38	A240	57	5	0	25	1099	8.3	18.3	5.2
27-4	2-4C1	995	4.64	32 ^(f)	40	25	MO379	KS-15	38	A240	57	5	0	25	1099	7.8	18.5	5.6

(a) Determined by point-count method (Ref. 4-16) on 75x radial composite cross section of fuel rods (see Figs. 4-40 through 4-43) macroporosity = $V_{\text{void}} / (V_{\text{void}} + V_{\text{matrix}})$.

(b) All rods cured-in-place (H-451 graphite bodies or tubes) in nitrogen to 1000°C and argon to 1800°C.

(c) Mean = 20.2%. Standard deviation = 15.6%.

(d) Shim types:

- a) Impregnated 1099 near-isotropic graphite powder, Great Lakes Carbon Company
- b) Non-impregnated TS-1240X near-isotropic graphite powder, Union Carbide Corporation
- c) Non-impregnated X4029A near-isotropic graphite powder, POCO Graphite, Inc.

(e) Based on nominal fuel rod dimensions.

(f) Measured on companion rods fired in quality control graphite tubes.

(g) Measurement made on companion rod fired in quality control graphite body.

TABLE 4-24
COMPARISON OF FIRST OPYC MICROSTRUCTURE CHARACTERIZATION RESULTS WITH METALLOGRAPHIC PIE RESULTS

Fuel Rod Data Retrieval No. (7161-008-)	Fuel Rod Position No.	Fast Fluence [10 ²² n/m ²] (E > 29 eV/atom)	Fuel Rod Volume Average Temp (°C)	Maximum Fuel Rod Injection Pressure (kPa (psia))	Fuel Rod In-Service Particle Failure(s) (Z)	Fertile Fuel										Fertile Fuel										Inert Fuel			
						Data Retrieval No.	Type	Burnup (% FIMA)	Microporosity (ml/kg OPYC)	Active Coating Gas Ratio(s)	PIE Results			Data Retrieval(s) No. (6542-)	Burnup (% FIMA)	Microporosity (ml/kg OPYC)	Active Coating Gas Ratio(s)	Normalized He/He Ratio(s)	NAF No. (f)	CI Leach No. (g)	PIE Results			Data Retrieval No.	Microporosity (ml/kg OPYC)	Active Coating Gas Ratio	PIE Results OPYC Failure (Z)		
											Failure(c) (Z)	OPYC Tearing(c) (Z)	OPYC Failure(c) (Z)								OPYC Tearing(h) (Z)	OPYC Failure(h) (Z)							
01-9	1-1A1	3.45	1177	992.7 (1440)	0	6151-17-015	UC ₂ -TRISO	67.7	49.9	0.53	0	6.1	47.0	36-015	1.86	27.1	0.27	ND ⁽¹⁾	ND	ND	0	0	6357-01-020	9.1	0.17	33.3			
03-12	1-1C1	3.45	1177	972.1 (1410)	0.7	6151-17-025	UC ₂ -TRISO	67.7	44.9	0.53	3.1	3.1	70.4	27-015	1.86	19.4	0.29	0.34	1.10	1	0	0	6357-01-020	9.1	0.17	58.7			
05-20	1-1B2	4.48	1177	820.3 (1190)	0.1	6151-12-015	UC ₂ -TRISO	69.1	48.0	0.60	0	1.0 ⁽²⁾	24.5	32-015	2.05	24.6	0.27	0.31	1.17	3-2	0	0	6357-01-020	9.1	0.17	33.3			
10-6	1-1A4	7.67	1215	1027.2 (1490)	0.3	6151-17-015	UC ₂ -TRISO	74.7	49.9	0.53	0	6.5	35.5	36-015	3.45	27.1	0.27	ND	ND	0	0	6357-01-020	9.1	0.17	58.2				
11-7	1-1B4	7.67	1215	775.6 (1125)	2.0	6151-12-015	UC ₂ -TRISO	74.7	48.0	0.60	0	0	3.9	32-015	3.45	24.6	0.27	0.31	1.17	3-2	0.6	0.6	6357-01-020	9.1	0.17	30.4			
12-1	1-1C4	7.67	1215	961.7 (1395)	0.7	6151-17-025	UC ₂ -TRISO	74.7	44.9	0.53	1.1	19.8	54.9	27-015	3.45	19.4	0.29	0.34	1.10	1	0.6	0	6357-01-020	9.1	0.17	42.0			
13-2	2-2A1	8.04	1047	996.2 (1445)	1.5 ⁽³⁾	6151-17-025	UC ₂ -TRISO	75.3	44.9	0.53	0	0	0	27-015	3.74	19.4	0.29	0.34	1.10	1	0	0	6357-01-020	9.1	0.17	0.6			
15-3	2-2C1	8.04	1047	989.3 (1435)	0	6157-02-015	VAR-TRISO	75.3	33.2	0.35	0	0.9	0	27-015	3.74	19.4	0.29	0.34	1.10	1	0.9	0	6357-01-020	9.1	0.17	0			
18-4	2-2C2	7.64	1041	992.7 (1440)	0	6157-02-015	VAR-TRISO	75.5	33.2	0.35	0	0	0	33-025	3.83	28.9	0.26	ND	ND	ND	0	0.8	6357-01-020	9.1	0.17	0			
23-6	2-4A1	4.64	995	882.4 (1280)	0	6151-02-015	UC ₂ -TRISO	62.7	48.0	0.60	0	0	2.1	35-015	1.33	31.7	0.33	0.49	1.24	1	0	0	6357-01-020	9.1	0.17	0			
27-4	2-4C1	4.64	995	978.9 (1420)	0	6157-02-015	VAR-TRISO	62.7	33.2	0.35	0	0	0	31-015	1.33	27.3	0.21	0.41	1.18	2	0	0	6357-01-020	9.1	0.17	0			
36-8	2-4C4	2.98	976	982.4 (1425)	0	6157-02-015	VAR-TRISO	53.4	33.2	0.35	2.6	2.6	2.6	29-015	0.76	21.7	0.17	0.25	1.08	3	0	0	6357-01-020	9.1	0.17	(j)			

(a) PIE result from Kr-85m R/S analysis, see Table 4-17.

(b) Active coating gas ratio = $C/(C + I + D)$

where C = active coating gas flow rate,
I = levitation gas flow rate, and
D = diluent gas flow rate.

(c) PIE result from metallographic analysis, see Table 4-21.

(d) All fertile particles are ThO₂-BISO.

(e) Measured at ORNL.

He/He ratio < 0.3 is gas tight.
He/He ratio ≥ 0.3 and ≤ 0.5 gas tightness is marginal.
He/He ratio > 0.5 is gas permeable.

(f) Normalized amount of fiber (NAF) determined by SAXS and measured at KFA (Ref. 4-25).

NAF < 1.08 is not gas permeable.
NAF ≥ 1.08 and < 1.18 gas tightness is marginal.
NAF > 1.18 is gas permeable.

(g) Measured at ORNL.

1 = Large amount of heavy metal in buffer.
2 = Light amount of heavy metal in buffer.
3 = No heavy metal in buffer.

(h) PIE result from metallographic analysis, see Table 4-22.

(i) ND = not determined.

(j) Not applicable; no inerts were used in rod 2-4C4.

TABLE 4-25
UPPER AND LOWER DIAMETER LIMITS OF THE DIFFERENT PORE-SIZE INTERVALS

Pore Diameters (nm)		Total Volume of Each Pore-Size Interval (nm ³)	Average Pore Diameter ^(a) (nm)
Lower Limit	Upper Limit		
0.7	1.1	8.0×10^{-1}	1.0
1.1	3.0	1.4×10^1	2.5
3.0	6.0	1.0×10^4	5.0
6.0	12.1	8.1×10^4	10.0
12.1	30.8	1.4×10^6	25.0
30.8	60.5	1.0×10^7	50.0
60.5	121.1	8.1×10^7	100.0

(a) Pore diameters were calculated for the average pore volume for each pore-size interval.

5. DISCUSSION

Capsule P13T was primarily an integral test of cured-in-place fuel rods made from ThO_2 -BISO fertile particles (nine batches) and either UC_2 -TRISO (seven batches) or UCO-WAR-TRISO (one batch) fissile particles (see objectives, Subsection 2.1). The performance of these fuel particle batches and fuel rods is discussed below in reference to the LHTGR fuel specification (Refs. 5-1, 5-2) and previous irradiation capsules.

5.1. COATED PARTICLE IRRADIATION PERFORMANCE

5.1.1. Fissile Particles

The present fuel performance requirement states that fuel which meets 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 fissile particles and/or 7.5% FIMA for fertile particles (Ref. 5-3).

Based on the R/B results shown in Table 4-17, 7 out of 28 rods in P13T containing UC_2 -TRISO fuel (i.e., 25%) exceeded the 0.5% requirement for fluences ranging from 3 to $8 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} and volume-average temperatures of 975° to 1220°C . The poor performance of the OPyC layer caused the 25% failure, including $>0.5\%$ pressure vessel failure. The coating failure was attributed to coating-matrix interaction because of high microporosity in the as-fabricated OPyC layer. Fission gas measurements revealed pressure vessel failure levels of up to 2% for these fuel rods. However, when individual in-service particle failure levels are determined

*Defined as joint failure of the OPyC and SiC layers for TRISO particles.

by R/B measurements, <0.3% of the total fissile particles contained in 32 P13T fuel rods would be failed, assuming that all failures occurred in the fissile particles (i.e., no fertile failures). If all in-service failures were caused by fertile rather than fissile particles, the failure level would again be <0.3%. Thus, the true in-service particle failure levels are concluded to be <0.3% for all P13T particles.

The pressure vessel failures in UCO-WAR-TRISO fuel were zero, based on R/B results (refer to Table 4-12) for six P13T rods for fluences ranging from 3 to 8×10^{25} n/m² ($E > 29$ fJ)_{HTGR} and volume-average temperatures of 975° to 1050°C. These results are supported by the metallographic results that show SiC and OPyC failures exceeding 0.5% in two of eight (i.e., 25%) of the rods examined. However, when the total metallographically-examined UC₂ particles are considered, 6 of 787 particles, or 0.76%, indicated SiC failures. Since failure levels were determined on a much larger sample by R/B measurements, this report will use the failure levels measured by that method (i.e., <0.3%).

No UCO-WAR-TRISO fissile particles showed both SiC and OPyC failure in the metallographic results (Table 4-21). Only one rod out of four examined indicated any SiC failure, and these failures were attributed to faceted particles and metallographic polishing damage, as indicated in Subsection 4.6.2. Therefore, pressure vessel failures in the UCO-WAR-TRISO fissile particles in P13T were concluded not to exist.

Since this irradiation, however, development work has stopped on UCO-WAR fuel, because WAR kernel release is greater than dense kernel release (by an average factor of six per Ref. 5-4). Since this would lead to much higher fission gas release from failed WAR fuel, its development was reduced.

Based on R/B measurements, the failure fraction for 32 P13T fuel rods at 95% confidence is greater than predicted by the pressure vessel models

(see Fig. 4-34). However, the mean observed value is less than predicted by the models up to fast fluences of $\sim 6.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 50% confidence (see Fig. 4-34). Therefore, agreement with the model is fair, but additional work is needed to reduce SiC defective fractions and to improve the OPyC layer to achieve the fuel performance assumed in core design pressure vessel models.

As discussed in Subsection 4.6.2, the high (up to 70%) OPyC failure on the TRISO-UC₂ and inert particles was attributed primarily to the OPyC microporosity. Subsection 5.1.3 will discuss additional fissile and fertile microporosity details.

No fissile coating failure was observed that could be attributed to thermochemical effects, such as kernel migration (amoeba attack) or fission product attack.

During high-temperature operation, carbide fuel kernels migrate into the surrounding PyC coatings under the influence of a temperature gradient. Kernel migration up the temperature gradient results from carbon transport in the fuel phase and is characterized by a rejected graphite layer on the cool side of the kernel. Reference 5-5 discusses the temperature and thermal gradient dependence of fuel kernel migration. Specifically, the kernel migration distance is calculated as follows:

$$X = \int_0^t KMC(T) \frac{dT(\tau)/dx}{T(\tau)^2} d\tau, \quad (5-1)$$

where X = total migration distance (m),

$dT(\tau)/dx$ = temperature gradient (K/m) across a particle at time τ ,

$T(\tau)$ = average particle temperature (K) at time τ ,

τ = total time(s) particles have been in core, and

$KMC(T)$ = kernel migration coefficient ($\text{m}^2 - \text{K/s}$) as a function of temperature.

Reference 5-5 defines the variation in KMC as follows:

$$\text{KMC} = 0.62 \exp (-3.11 \times 10^5 / RT), (\text{carbide fuel}) \quad (5-2)$$

where R = natural gas constant (8.313 J/K/mol), and
 T = temperature (K).

Using these equations, the kernel migration model (Ref. 5-5) for UC_2 predicts only 2 to 3 μm of migration for the maximum P13T time, temperature, and temperature gradient. Since no migration was observed, the observations and the UC_2 kernel migration model are concluded to be consistent. Also, no kernel migration was observed for the UCO-WAR kernels; this result is consistent with prior observations in ORNL capsules (Refs. 5-6, 5-7).

Metallic fission products diffuse from UC_2 kernels during high-temperature irradiation. In TRISO particles, concentrations of metallic fission products build up in the IPyC coating on the cooler side of the fuel particles and subsequently react with the SiC coating at the SiC/IPyC coating interface. These reactions have been observed in UC_2 -TRISO particles irradiated in capsules P13L, P13M, P13N, P13P, P13R, P13S, GF-1, GF-2, and GF-3 (Refs. 5-8, 5-9). Electron microprobe analysis revealed that certain metals preferentially diffuse out of the fuel kernel to the SiC coating, where the rare earth fission products [cerium, neodymium, lanthanum, samarium, praseodymium, and europium (Ref. 5-10)] and palladium (Ref. 5-11) attack the SiC.

The UC_2 -TRISO particles irradiated in capsule P13T fuel rods at average temperatures above 995°C showed slight degradation of the SiC coating by metallic fission products. The extent of attack increased with increasing temperature. Figure 4-53 is a photomicrograph of fission product attack in a UC_2 -TRISO particle irradiated in fuel rod 1-1B4 at an average centerline temperature of 1215°C . In this particle, the buildup of metallic fission products at the SiC/IPyC coating interface was large enough to mechanically force the IPyC coating away from the SiC coating. Table 4-21 summarizes the

metallic fission product interactions observed in UC₂-TRISO particles during the metallographic examination (see Subsection 4.6.2). In particles where metallic fission products reacted with the SiC coating, maximum depths of penetration into the SiC coating ranged from 2 to 5 μm . No coating failure was observed to result from metallic fission product interaction. This result is consistent with the latest SiC thinning model (Ref. 5-12), which would predict SiC thinning of 3 to 4 μm for the full-term irradiation conditions of cell 1 in P13T. A similar SiC attack, but with less severe penetration, was observed in the fuel rods irradiated in capsules P13R and P13S (Ref. 5-8) and GF-1, -2, and -3 (Ref. 5-9).

No direct SiC attack was observed in UCO-WAR-TRISO (nominal 80% converted) fissile particles; however, incipient attack was observed in a few particles (see Fig. 4-55). This attack agrees with ORNL findings for 75% converted UCO-WAR fuels (Ref. 5-7). The fission products primarily accumulated in areas adjacent to shrunk WAR kernels that were adhered to the IPyC coating (see Fig. 4-55), indicating that the rare earth or palladium migration very probably follows solid diffusion.

The SiC coating is the primary load bearer of the TRISO coating and an absolute barrier to certain metallic fission products. Low-density ($<3.18 \text{ g/cm}^3$) SiC is undesirable as a coating material, because it can contain free silicon, which has a high vapor pressure and forms low-melting-temperature eutectic compounds. The SiC must be avoided at the grain boundaries to enhance diffusion. Also, low-density SiC decreases in strength at temperatures above 1000°C , whereas higher-density ($>3.18 \text{ g/cm}^3$) SiC increases in strength at these temperatures (Ref. 5-13). Thus, SiC coatings with densities $\geq 3.18 \text{ g/cm}^3$ (99% theoretical density) are specified for TRISO particles.

The SiC coating density of fissile particles tested in capsule P13T was $\geq 3.18 \text{ g/cm}^3$. The irradiation performance of these coatings was good. The SiC coating failure in particles that suffered pressure vessel failure was attributed to variables (such as faceted coatings, defective particles, and

loss of the compressive component for SiC stress due to OPyC failure) other than the SiC coating.

The IPyC layer of the UC₂ TRISO particle protects the SiC layer from detrimental chemical reactions during manufacturing and irradiation. For manufacturing, a dense, impermeable coating is most desirable to prevent infiltration of gaseous by-products into the buffer during SiC deposition. Process studies have shown that chlorine compounds in the buffer can extensively disperse the fuel. Although quantitative data relating fuel dispersion to particle performance are not available, such dispersion is limited by the specification during fuel production (Ref. 5-1).

The IPyC layer in the UC₂-TRISO fuel particle also appears to act as a sink for some of the more mobile fission products during irradiation (see Subsection 4.6.2). However, under the more severe irradiation conditions, these fission products alter the structure of the IPyC layer (see Figs. 4-55 and 4-54). Often these products cause the IPyC layer to fail [see Figs. 4-56 and 4-61(d)].

A metallographic examination of a large number of fissile particles tested in capsule P13T revealed that most IPyC layers survived. All three metallographically examined UC₂-TRISO batches exhibited a small fraction (<5%) of cracked IPyC coatings (see Table 4-21).

A low-density buffer coating immediately adjacent to the fuel kernel attenuates fission recoils and provides a void volume to accommodate fission gases and fuel kernel swelling. The thickness and density of TRISO-particle buffer coatings irradiated to peak conditions are interrelated and are a function of the fuel density in the particle and the coating design.

Capsule P13T tested UC₂-TRISO particles with buffer-coating thicknesses ranging from 84 to 104 μm and densities ranging from 1.05 to 1.20 g/cm^3 . During irradiation, the buffer coatings decoupled from the IPyC coatings and densified around the fuel kernels. Zero to 6.5% of the buffer coatings were

cracked in the metallographically examined particles. The cracking was not a function of the buffer-coating thickness or density. Cracking occurred only in particles where the fuel kernel had segregated into a two-phase structure (see Fig. 4-58).

UC₂-TRISO batch 6151-12-015 had a 5- μ m-thick seal coat on the buffer coating, but no evidence was given that this allowed the buffer coating to decouple from the IPyC coating any more than batches without a buffer seal coating. Buffer cracking occurred only in the particles that debonded from the IPyC coating and shrank onto the fuel kernel. Buffer-coating density may also have affected the observed levels of cracking. Batch 6151-17-025 had the highest buffer density (1.20 g/cm³) and the largest amount of buffer cracking (6.5%). Higher-density buffer coatings may be more susceptible to irradiation-induced densification and cracking.

Batch 6151-12-015 of UC₂-TRISO fissile particles contained 120 ppm-wt of iron in the kernel, exceeding the specification limit of <100 ppm-wt (Ref. 5-1). The specification support document (Ref. 5-2) set this 100-ppm-wt limit, because 100-ppm-wt particles did not show rapid iron migration to the cold side of the SiC layer when heated in a thermal gradient. Since these 120-ppm-wt particles showed no evidence of iron migration, these Pl3T data could support extending the iron impurity in UC₂ kernels to 120 ppm.

Two batches of UC₂-TRISO particles (6151-17-015 and 6151-18-015) had kernels with less than the specified carbon content (8.94 wt % versus 9.3 to 10.1 wt %). Only batch 6151-17-015 was examined metallographically, and no detrimental effects were observed that were attributable to the low carbon content. The specification support document (Ref. 5-2) indicated that these batches justified lowering the lower carbon limit to 8.5 wt % for Issue C of the product specification (Ref. 5-1). Free carbon in the kernel was shown not to impede carbon diffusion through the UC₂ phase and, therefore, not to affect the kernel migration rate. The PIE results from Pl3T therefore support the 8.5 wt % specification limit.

Severely faceted particles would be expected to have a higher failure probability than more spherical particles, because the smaller curvature radius would enhance coating stresses. The P13T metallographic examination observed 1236 fissile particles; of these, 13 (~1%) were severely faceted (aspect ratio ≥ 1.18) and two were failed. However, 8 of the 13 observed particles were from UCO-WAR batch 6157-02-015; since both failures were from this batch, severely faceted particles may be expected to have a high failure rate.

5.1.2. Fertile Particles

P13T irradiated nine batches of nominally 500- μ m-kernel, BISO ThO₂ fertile particles, and all performed well. Metallography and fission gas release data determined failure levels of fertile particles tested in fuel rods. Tables 4-17 and 4-22 present the results of the analyses. Only two of the seven metallographically examined batches indicated any OPyC failure (same as the pressure vessel for the BISO particle). The metallography failure data have a large uncertainty, because only a small sample population was examined.

When both the fission gas release data (Table 4-17) and the metallographic data (Table 4-22) are considered, three batches of ThO₂-BISO fuel had no observed or calculated failure. These batches are shown below with the maximum exposure level for each batch.

<u>Batch No.</u>	<u>Maximum Fast Fluence [(10²⁵ n/m²) (E > 29 fJ)_{HTGR}]</u>	<u>Maximum Burnup (% FIMA)</u>	<u>Maximum-Volume- Average Temperature (°C)</u>
6542-33-025	7.6	3.8	1041
6542-34-015	7.6	3.8	1041
6542-29-015	4.0	1.0	990

Fission gas release data were used to calculate maximum fertile particle failure levels by assuming that all the fission gas released during the TRIGA measurement came from failed fertile particles. This is a fair approximation, since more than 80% of the total fission occurred in the fertile particles during the TRIGA measurement (except fuel specimens from body 4) and since metallographic examination revealed low levels of fissile particle failure (Table 4-17). However, the failure levels observed during the metallographic examination and the levels calculated from the fission gas release data agreed. The visually and metallographically determined failure levels for batches 6542-32-015 and 6542-33-025 are generally consistent with the calculated maximum fertile particle failures, based on EOL in-pile Kr-85m R/B measurements. Table 4-17 shows calculated fertile particle failure percentages for GA-fabricated rods. These percentages ranged from 0 to 5%. These values assume that all fissions in failed fuel occur in the fertile fuel (refer to Subsection 4.4.1). Thus, some uncertainty (estimated at a factor of two) exists in calculated fertile particle failure levels, based on EOL Kr-85m R/B. The pressure vessel failure in batch 6542-33-025 is partially attributed to low OPyC thicknesses (66 μm). Currently, BISO-coated ThO₂ has a reference OPyC coating thickness of 70 to 90 μm (Ref. 5-2).

Based on these results, the fission gas release measurements fairly accurately measured pressure vessel failure in the fertile particles tested in the bonded fuel rods. This is substantiated by in-pile Kr-85m R/B measurements on the two cells in capsule P13T. Figures 3-2 and 3-3 show very moderate increases in Kr-85m R/B over the length of the irradiation. This behavior is characteristic of release from heavy metal contamination or perhaps a small amount of fissile failure early in life, followed by a decreasing fraction and leveling off of fissions in the fissile fuel with a few additional fertile particle failures later in life.

The combined metallographic and R/B data show that the failure observed by metallography was lower than the calculated maximum fertile particle failure. The difference in values was attributed to a degree of permeability of fission product gases in the OPyC coating in the P13T

fertile batches, because the R/B measurements indicated some fertile particle failure; yet, the metallographic examination observed very few failed OPyC coatings. A similar phenomenon was seen in the PIE of capsules Pl3R and Pl3S (Ref. 5-8). Subsection 5.1.3 will discuss additional data on both the fissile and fertile OPyC permeability.

No thermochemical effects, including kernel migration, in the fertile particles batches were detected. Using Eq. 5-1 and the KMC shown in Ref. 5-5 for oxide fuel:

$$\text{KMC} = 0.39 \exp(-2.96 \times 10^5 / \text{RT}) \quad , \quad (5-3)$$

the total expected kernel migration for ThO₂ was calculated to be 5 to 6 μm at the maximum time, temperature, and gradient of Pl3T. The absence of ThO₂ kernel migration in the Pl3T fuel specimens can be explained by a delay in the onset of kernel migration. This migration has been calculated at 676 days at 1215°C using data supplied in Ref. 5-5:

$$\text{KMC} = 0 \text{ if kernel burnup} < 2\% \text{ FIMA, and } t_i / \theta_i < 1 \quad , \quad (5-4)$$

where t_i = total time (s) particles have been in reactor,

$$\theta_i = 4.7 \times 10^{-4} \exp\left(\frac{3.16 \times 10^5}{8.313T}\right) \quad , \quad (5-5)$$

where T = temperature (K)

The total irradiation time for Pl3T was 363.4 EFPD. Therefore, no ThO₂ kernel migration in Pl3T agrees with the current ThO₂ kernel migration models.

BISO-coated fertile particles are not as susceptible to degradation by metallic fission products as BISO- and TRISO-coated fissile particles

(Ref. 5-2). The P13T ThO₂-BISO particles had no localized concentrations of fission products in the PyC coatings. No evidence of metallic fission product degradation of ThO₂-BISO particles was observed in the fuel rod specimens irradiated at temperatures up to 1215°C. Although the fertile particle BISO coatings allow a controlled diffusive release of volatile metallic fission products, such as cesium and strontium, the quantities are not sufficient to degrade the PyC coatings.

Because of the excellent irradiation results on the P13T ThO₂-BISO fertile batches, no significant conclusions could be drawn relating solely to the variations in OPyC coating rate or density for the nine P13T fertile batches.

The OPyC coatings of FSV TRISO fuel particles and ThO₂-BISO particles irradiated in previous evaluation tests were deposited from propylene. However, to fabricate coated particles in a 240-mm (9.45-in.) diam coater, mixed gas (acetylene and propylene mixed in the proper proportions) must be used to deposit OPyC coatings to avoid severe thermal transients during coating. Capsule P13T tested eight of nine BISO-coated fertile particle batches with OPyC coatings deposited from mixed gas to evaluate the performance of these coatings upon irradiation to peak LHTGR fast neutron fluences. Propylene was used to deposit the OPyC coatings of the remaining BISO fertile particle batch. Within the range of coating parameters tested, the irradiation performance of BISO OPyC coatings deposited from mixed gas was comparable to that of coatings deposited from propylene.

A low-density buffer coating immediately adjacent to the fuel kernel attenuates fission recoils and provides a void volume to accommodate fission gases and fuel kernel swelling. The thickness and density of buffer coatings required for BISO particles irradiated to peak conditions are inter-related and are a function of kernel diameter and OPyC coating design. Capsule P13T tested ThO₂-BISO particles with buffer coating thicknesses from 73 to 86 μm and densities from 1.08 to 1.18 g/cm³.

The buffer coatings densified during irradiation and appeared slightly anisotropic under polarized light. Densification resulted from a combination of irradiation-induced PyC shrinkage and fuel kernel swelling. Cracked buffer coatings were observed in four of the seven particle batches examined metallographically, as indicated in Table 4-22. Cracking of the buffer coating is not considered detrimental to the performance of BISO coatings unless the cracks propagate into the OPyC coating. This phenomenon was not observed in P13T fertile particles. In cases where the buffer coating cracked, the OPyC coating remained intact, as shown in Fig. 4-69.

ThO₂-BISO batch 6542-32-015 had a 5- μ m-thick seal coat applied on the buffer coating (see Fig. 4-70), but this showed no visible effect on the irradiation behavior of the BISO coatings.

Of the seven batches and 2443 particles of ThO₂-BISO fertile fuel examined metallographically during the PIE, only 21 (~1%) were found to be severely faceted (aspect ratio ≥ 1.18), and none appeared to have failed (see Fig. 4-64). This is about the same percentage as faceted fissile particles in which up to 25% failure per batch was observed (see Subsection 5.1.1). In addition, up to 25% failure per batch of faceted ThO₂-BISO particles was also observed in capsules P13R and P13S (Ref. 5-8); thus, although no failures were observed in P13T faceted ThO₂-BISO particles, failure is still considered likely for a significant fraction of any faceted particles.

5.1.3. OPyC Performance on TRISO and BISO Particles

Reference 5-2 gave mean optical anisotropies of 1.058 and mean coating rates between 2.5 and 8.0 μ m/min as sufficient controls on TRISO OPyC coatings to assure acceptable OPyC performance during irradiation. The OPyC layers were deposited on the P13T TRISO fissile and inert particles using coating rates between 1.05 and 4.78 μ m/min. This produced coatings having a range of anisotropy values ($BAF_0 = 1.033$ to 1.049). This series also included particles having different coating densities (1.75 to 1.89 g/cm³)

(see Table 2-1). When the P13T TRISO particle samples were fabricated, the coating rate was considered to be the primary process variable controlling coating anisotropy. Since previous irradiation results showed a good correlation between coating performance and coating rate (Refs. 5-10 and 5-14), this parameter was a key factor in selecting test samples.

Figures 5-1 and 5-2 plot the OPyC TRISO failure from P13T metallographic results as function of OPyC mean coating rate and mean optical anisotropy, respectively. Except for the TRISO inert batch, all P13T TRISO particles met the 2.5 to 8.0 $\mu\text{m}/\text{min}$ coating specification, and all batches had a mean BAF_0 of <1.058 . Yet, as shown in Figs. 5-1 and 5-2, coating performance and either mean optical anisotropy or mean coating rate have no apparent correlation.

Results from P13T and previous evidence based on the HRB-4, -5, and -6 PIEs (Ref. 5-15) indicate that premature OPyC failure can sometimes result from excessive matrix/coating interactions. An increase in particle-matrix bond strength or in the amount of matrix pitch binder contained in the outer OPyC is equivalent to potentially subjecting the OPyC layer to a greater tensile component. The tensile component exerted on the OPyC layer results from either the differential volume contraction between the TRISO-coated particle and the surrounding matrix phase or from subjecting the OPyC to increased stresses because of different irradiation shrinkage rates between the binder and the OPyC. Reference 5-15 correlated fuel rod particle failure with irradiation conditions (temperature and fluence) and matrix structural properties (ratio of binder coke weight to matrix surface area). However, the PIE results indicate that microporosity in the OPyC layer is the most significant variable to explain differences in the OPyC failure between P13T and other capsule tests. Reference 5-2 established mean microporosity limits of ≥ 13 and ≤ 32 $\text{ml}/\text{kg-OPyC}$, based on previous capsule results. Figure 5-3 plots these limits and the mean microporosity for the P13T TRISO-particle batches as a function of OPyC failure. As Fig. 5-3 shows, the P13T results and the microporosity specification limits, based on previous capsule results, correlated very well. As discussed in Subsection

4.7.1, the microporosity upper limit is defined to limit the OPyC/matrix coating interactions. The lower limit is defined to limit the peak irradiation-induced stresses which develop in the PyC layer at low fluence levels [$(\sim 2.5 \times 10^{25} \text{ n/m}^2)$ ($E > 29 \text{ fJ}_{\text{HTGR}}$)] due to rapid densification and crystallite anisotropy. A further evaluation of coating conditions for Pl3T TRISO-coated inert fuel shows that the OPyC layers were deposited under relatively dilute concentrations of active coating gases (i.e., the volume of C_2H_2 plus C_3H_6 over the total volume of coating gases was 0.17). Currently, process specifications for TRISO-coated OPyC layers require that the actual coating gas ratio be ≥ 0.25 (Ref. 5-2). This is a consequence of the strong positive correlation between the OPyC microporosity and the volume fraction of active coating gases (see Subsection 4.7.2) shown in Fig. 4-75. The inert particle batch (6351-01-020), which fell in both the microporosity and active gas out-of-specification regions (shaded) of Fig. 4-75, exhibited premature irradiation-induced OPyC failure.

When considering deposition, the volume fraction of hydrocarbon gases (C_2H_2 and C_3H_6) in the total coating gas and the coating temperature determine the relative amounts of PyC crystallite nucleation and growth in the vapor phase and on the levitated particle bed substrate. This, in turn, controls the structure of the PyC layers. Reference 5-16 details structural variations in PyCs in terms of different deposition conditions and presents supporting data (transmission electron microscopy) consistent with the empirical observations presented in Fig. 4-75. Specifically, PyC crystallites within conical growth features usually orient with the carbon layer planes parallel to the substrate surface as the deposition coating rate or hydrocarbon concentration is reduced. No intergrowth feature pores are present, because the cones impinge uniformly on each other, and the crystallites tend to lie with the layer planes perpendicular to the axis of the conical growth feature. Consequently, the interconnecting microporosity for these structures is expected to be low. As the deposition coating rate and hydrocarbon gas concentration are increased, the growth features progress from conical to spherical, and intergrowth pores develop, resulting in higher measured microporosities. In addition, the preferred orientation of the PyC

crystallites between different spherical growth features is randomly disposed, resulting in a more isotropic structure. The inferior irradiation performance of PyC structures deposited under low hydrocarbon gas concentrations (≤ 0.25) and with low microporosities (≤ 13 ml/kg OPyC) is attributed to excessive orientation of PyC crystallites. This anisotropy leads to a differential between irradiation-induced strains parallel and perpendicular to the substrate surface, which in turn, results in higher irradiation-induced OPyC stresses (Ref. 5-9).

Unirradiated P13Q samples (Ref. 5-17) and ORNL HRB-4 and HRB-5 samples (Ref. 5-18) evidenced some OPyC tearing. All particle batches in these samples and the P13T TRISO fissile batches, which had high OPyC failures, also had either very high coating rates (> 8 $\mu\text{m}/\text{min}$) and/or very high microporosities (> 39 ml/kg OPyC). High coating rates lead to very high microporosities (Ref. 5-2). For example, a coating rate of 10 $\mu\text{m}/\text{min}$ leads to a mean OPyC microporosity of > 70 ml/kg OPyC. Therefore, some degree of coating/matrix interaction could have occurred in the P13T TRISO fissile batches during rod fabrication and irradiation because of the high OPyC microporosity.

Subsection 4.7.2 showed a fair correlation between the normalized neon/helium ratio and the OPyC coating rate (see Fig. 4-73). The Fig. 4-73 P13T data indicate that some BISO particles would be permeable if the coating rate was greater than ~ 4.5 $\mu\text{m}/\text{min}$. Since the current specification (Ref. 5-1) for the OPyC coating rate on BISO particles is set at ≥ 2.5 and ≤ 8.0 $\mu\text{m}/\text{min}$, some permeable BISO fertile particles would be manufactured.

A fair correlation was shown to exist between mean microporosity and the amount of heavy metal observed in the ThO_2 -BISO buffer coatings after long-term chlorination (see Fig. 4-76). However, the P13T ThO_2 -BISO microporosities correlated very poorly with the KFA development NAF value (see Subsection 4.7.3). The NAF value also correlated poorly with the neon/helium ratio (see Fig. 4-74).

The correlation between BOL Kr-85m R/B and OPyC permeability is very weak, as shown in Fig. 5-4. This is important, since R/B measurements have previously determined the ability of coatings to retain fission gas. However, the fission gas release measurements may not be measuring the permeability of PyC structures to long half-life gaseous isotopes. Steady-state fission gas release (R/B) from a spherical fuel particle may be approximated by the following diffusion equation (Ref. 5-19):

$$R/B = 3/a(D/\lambda)^{1/2} \quad \text{for } R/B < 0.3, \quad (5-6)$$

where D = the diffusion coefficient of the species (cm^2/s),

a = the radius of the particle (cm), and

λ = the decay constant ($1/\text{s}$).

This equation shows that low R/B values for short half-life isotopes could be attributed to large decay constants of the diffusing species through the coatings (i.e., λ is large with respect to D). Consequently, measurement of a low Kr-85m R/B (half-life 4.4 h) may not sufficiently assure impermeable coatings (Ref. 5-2).

In addition, ORNL workers reported (Refs. 5-20 and 5-21) that in their HRB-7 through HRB-10 capsules they had used a BISO-coated driver particle, which was later determined to have had a permeable OPyC coating (using chlorine leach and neon/helium measurements). The fission gas release values were so high in these capsules that Kr-85m R/B values could not be measured. Further evidence, based on long-term chlorination (up to 36 h), showed a high degree of permeability. Reference 5-2 indicates that an ORNL ThO_2 -BISO particle batch (OR2275) had a steady release of ThO_2 by long-term chlorination of ~ 10 mg. This batch also had a neon/helium ratio of 0.41. The ORNL workers showed that the gaseous krypton plus xenon inventory for this batch was substantially lower than the calculated inventory, indicating that a considerable amount of krypton and xenon had leaked out of these particles. The BOL TRIGA Kr-85m value for this batch was 2.2×10^{-6} .

Therefore, measurement of a low BOL Kr-85m R/B may not be sufficient to assure impermeable coatings.

As shown in Fig. 4-77, the ThO₂ release after 18 h of chlorination on P13T ThO₂-BISO batch 6542-35-015 was 108 mg. The neon/helium ratio for this batch was 0.49, and the NAF was 1.24, yet the BOL Kr-85m was 4.6×10^{-5} .

These P13T and ORNL results warrant developing additional quality control techniques to measure OPyC permeability to long-life fission gases. Preliminary work with long-term chlorination suggests that this technique may be adaptable to characterizing different degrees of OPyC permeability. Consequently, the technique should be developed further and correlated with other property measurements, such as Kr-85m R/B and xenon plus krypton particle inventories.

5.1.4. Fuel Rod and Graphite Body Irradiation Performance

The P13T capsule was the first test of cured-in-place fuel rods that were not removed for pre-irradiation inspection. The irradiation was conducted in relatively large graphite bodies, which were representative of the LHTGR fuel element configuration. Curing in the fuel block represented a simpler process than curing in Al₂O₃ powder beds (FSV method). All green rods were fabricated by hot injection, the reference LHTGR process. All rods were carbonized in nitrogen to ~1100°C and fired in argon at 1800°C.

The P13T capsule rods were fabricated with the three matrix compositions being considered for the DESMA fuel rod press. All matrix types included A240 petroleum pitch. The reference HTGR binder was originally a coal tar pitch (FSV fuel rods), but petroleum pitch was found to be more uniform. The P13T matrix batches contained either natural-flake 6353 filler (FSV rods) or synthetic KS-15 filler. The additive content (polystyrene and octadecanol) made up 5 or 15 wt % of the matrix batches (see Tables 12, 13, and 15 of Ref. 5-22).

The shims tested in the P13T fuel rods are impregnated 1099 graphite powder (Great Lakes Carbon Company H-451 graphite impregnated with a 95% furfuryl alcohol-based material at GA), nonimpregnated TS-1240X (Union Carbide Corporation) graphite powder, or nonimpregnated X4029A (POCO Graphite, Inc.) graphite powder (see Tables 12 and 14 of Ref. 5-22).

The following criteria evaluated the capsule P13T fuel rod performance (Ref. 5-3):

1. Maintain integrity to full HTGR lifetime exposure.
2. Exhibit dimensional change compatible with the graphite fuel block so that no detrimental fuel-graphite mechanical interaction occurs.
3. Have bonding characteristics that do not cause fuel failure as a result of matrix-coating interaction.

All fuel rods and graphite bodies were judged to be in excellent condition to irradiation exposures beyond peak LHTGR fluences. The rods showed no significant matrix cracking or particle debonding. Most importantly, the integrity was good for fuel rods that were fired in the P13T bodies using the reference LHTGR cure-in-place process. These results are consistent with other capsule tests, which also demonstrated the excellent irradiation stability of cured-in-place fuel rods (Refs. 5-15, 5-17). The other rod variables, including matrix composition and shim type, apparently did not affect rod integrity. Also, fuel rod temperature and fluence did not affect the surface condition of the P13T rods. The coke yield for P13T rods ranged from 22% to 34% (one rod below the lower LHTGR specification limit of 23, Ref. 5-2), and the matrix pre-irradiation macroporosity ranged from 26% to 44% (three rods greater than the upper LHTGR specification of 40%, Ref. 5-2). The visual examination revealed that rods with these ranges of coke yield and macroporosity values were in excellent condition. These data therefore support the revised LHTGR specification (Ref. 5-1) and

provide additional support for the specification support document (Ref. 5-2). In fact, the P13T data were already used in Ref. 5-2 to support the changed coke yield specification.

Proper thermal and mechanical design of LHTGR fuel elements requires irradiation-induced fuel rod and graphite dimensional change to be characterized. Core thermal analyses need the radial clearance between the fuel rods and the fuel holes to be evaluated. Also, irradiation-induced fuel rod dimensional changes must be compatible with the dimensional change behavior of the graphite fuel elements to ensure that excessive stresses are not built up from dimensional interferences between the fuel rod columns and the graphite fuel element during reactor operation.

The dimensional change of the P13T capsule fuel rods was examined and evaluated in reference to the fuel rod variables. The shim volume fraction was varied, and the total TRISO- and BISO-coated particle volume fractions were significantly different (see Table 14 in Ref. 5-22) throughout the capsule, just as they would be in an LHTGR. The total particle volume fraction was held to ~58%, as it would be in a LHTGR, and TRISO inert particles made up the difference to simulate a fissile volume fraction, as would be expected in an LHTGR.

Figures 4-27 through 4-29 plot the rod linear and volumetric dimensional changes as a function of fluence. A turnaround in the rods occurred at fluences in the range of $3 \text{ to } 5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}, which agrees well with the fuel rod dimensional turnaround predicted by the RODON computer program (Ref. 5-23). However, when the predicted fuel rod dimensional changes calculated by both the RODON computer program and the dimensional change models presented in the FDDM (Ref. 5-5) are considered, the observed P13T fuel rod dimensional changes generally fall between the two predictions (see Figs. 4-27 through 4-29). However, 13 other capsule or fuel test element experiments, containing 253 fuel rods, supported the RODON program (Ref. 5-10); thus, although the observed P13T fuel rod dimensional changes are not exactly predicted by the RODON program, sufficient data

exist (including the P13T data) to consider adopting the RODON program into issue D of the FDDM.

Considerable scatter in the P13T axial fuel rod dimensional change data resulted from the Graphoil spacers placed between each rod, complicating accurately measuring the axial fuel rods. This effect may lend some inaccuracies in both the axial (Fig. 4-28) and bulk volume (Fig. 4-29) dimensional change. In addition, more variability has been shown for the volumetric change model for BISO than for TRISO particles (Ref. 5-23). Therefore, since all P13T fertile particles were BISO coated, this effect probably detrimentally affected the RODON-predicted dimensional change for P13T.

The dimensional change results showed that no rod had net expansion even at peak fluences. The matrix composition, including fillers and additives, apparently did not affect the fuel rod dimensional change. The strong dependence on fuel rod dimensional change of the varying shim- and BISO-particle content fraction was, however, clearly demonstrated (see Fig. 4-30). Within the very limited samples irradiated, fuel rod dimensional change apparently did not differ between the Union Carbide Corporation TS-1240X, POCO Graphic, Inc. X-4029A, and Great Lakes Carbon Company 1099 shims.

Another P13T experiment result was that the fuel rod dimensional change was compatible with that of both the H-451 and TS-1240 graphite bodies, as shown in Figs. 4-27, 4-28, 4-32, and 4-33. The diametral fuel rod strain was greater than the radial strain of the graphite to a fast fluence of $6.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}. These data were supported by the ease in which the fuel rods were pushed out of the graphite bodies. At fast fluences greater than $\sim 6.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}, the rod strain was less than the graphite strain. Since the peak fast fluence for the LHTGR is now $\sim 6.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}, no significant fuel rod/graphite accommodation problems are expected. In any event, these undesirable strain differences would not be detrimental in an LHTGR fuel element, because an axial gap in

each fuel rod hole could be designed to prevent axial mechanical interference.

As shown in Subsection 4.1, all Pl3T rods pushed out of the graphite bodies with relative ease [≤ 667 N (149 lb)]. However, the force (see Table 4-2) to remove rods from the H-451 graphite bodies [mean = 52 kg (115 lb)] clearly differed from the force to remove rods from the TS-1240 bodies [mean = 3 kg (7 lb)]. Figure 5-2 shows analysis of this data and of both pre- and postirradiation fuel rod shear stress. Figure 5-2 indicates that the gap is smaller between the fuel rods and the surrounding H-451 graphite than between the fuel rods and TS-1240 graphite. The most plausible explanation for the bonding difference is that reduced radial shrinkage in TS-1240 graphite (see Fig. 4-33) resulted in a larger postirradiation gap for fuel rods contained in TS-1240 graphite.

The good irradiation stability of the Pl3T fuel rods indicates that the matrix combinations tested are suitable for LHTGR fuel rods. For these matrix combinations, pitch coke yields of 22% to 34% and levels of pre-irradiation matrix macroporosity from 26 to 44 vol % are adequate to ensure good fuel rod integrity during irradiation to peak LHTGR fast neutron exposures.

Another result of the Pl3T fuel rod PIE was that, although nine rods contained 270 ppm iron in the matrix, no SiC attack was apparent in the metallographic examination of five of these rods. These data support a recent determination (Ref. 5-24) to permit 20 μ g iron outside the SiC per gram of burned-back particles. This determination was adopted (Ref. 5-25) for FSV fuel production (the Pl3T rods containing 270 ppm iron in the matrix had 16.7 μ g iron outside the SiC per gram of burned-back particles).

The CTE determined on irradiated Pl3T rods agrees within 10% of the previously established values published in the FDDM (Ref. 5-5).

This experiment detected no systematic influence of either shim content or fast neutron fluence on fuel rod CTE. The difference observed in axial CTE of rods 1-1B1 through 1-1B4 could not be correlated with any other fuel rod attributes.

The lower CTE of rods 2-4C2 and 2-4C3 may have been due to the slight difference in matrix, the lower irradiation temperature, or the fissile kernel type (WAR) from the 1-1B1 rods (VSM kernels).

The P13T rod data presented above, combined with data from P13Q (Ref. 5-17), indicate the thermal expansivity of irradiated LHTGR fuel rods. However, neither experiment tested enough rods to strongly correlate fuel rod CTE with other fuel rod attributes.

REFERENCES

- 5-1. "HTGR Fuel Product Specification," Issue C, General Atomic unpublished data, August 1979.
- 5-2. Kovacs, W. J., and D. P. Harmon, "Technical Support Data for Issue C of the HTGR Fuel Product Specification," General Atomic unpublished data, August 1979.
- 5-3. Smith, C. L., "Fuel Particle Behavior Under Normal and Transient Conditions," ERDA Report GA-A12971, General Atomic Company, October 1, 1974.
- 5-4. "HTGR Fuels and Core Development Program, Quarterly Progress Report for the Period Ending February 20, 1975," General Atomic Report GA-A13353, March 31, 1975.
- 5-5. "Fuel Design Data Manual," Issue C, General Atomic unpublished data, September 1979.
- 5-6. Homan, F. J., et al., "Stoichiometric Effects on Performance of High-Temperature Gas-Cooled Reactor Fuels from the UCO System," Nucl. Technol. 35, 428 (1977).

- 5-7. Tiegs, T. N., and K. R. Thoms, "Operation and Postirradiation Examination of ORR Capsule OF-2: Accelerated Testing of HTGR Fuel," Oak Ridge National Laboratory Report ORNL-5428, March 1979.
- 5-8. Scott, C. B., D. P. Harmon, and J. F. Holzgraf, "Postirradiation Examination of Capsules P13R and P13S," General Atomic Report GA-A13827, October 8, 1976.
- 5-9. Blanchard, R., M. L. Pointud, and W. J. Kovacs, "Postirradiation Examination of Capsules GF-1, 2, and 3," DOE Report GA-A15859, General Atomic Company, September 1980.
- 5-10. Harmon, D. P., and C. B. Scott, "Development and Irradiation Performance of LHTGR Fuel," General Atomic Report GA-A13173, October 31, 1975.
- 5-11. Tiegs, T. N., "Fission Product Pd-SiC Interactions in Irradiated Coated Particle Fuels," Oak Ridge National Laboratory Report ORNL/TM-7203, April 1980.
- 5-12. "HTGR Fuel Development Department Technical Status Report for the Quarter Ending March 31, 1980," General Atomic unpublished data, April 1980.
- 5-13. Gulden, T. D., "Mechanical Properties of Polycrystalline β -SiC," J. Am. Ceramic Soc. 52, 587 (1969).
- 5-14. Scott, C. B., and D. P. Harmon, "Postirradiation Examination of Capsule F-30," General Atomic Report GA-A13208, April 1, 1975.
- 5-15. Scott, C. B., and D. P. Harmon, "Postirradiation Examination of Capsules HRB-4, HRB-5, and HRB-6," General Atomic Report GA-A13267, November 28, 1975.
- 5-16. Kaae, J. L., "Implications of the Structure of Pyrolytic Carbons on the Deposition Mechanism," General Atomic Report GA-A14673, January 1978.
- 5-17. Young, C. A., and C. B. Scott, "Postirradiation Examination of Capsule P13Q," General Atomic Report GA-A14174, September 1977.
- 5-18. Homan, F. J., et al., "Irradiation Performance of HTGR Fuel Rods in HFIR Experiments HRB-4 and -5," Oak Ridge National Laboratory Report ORNL-5115, June 1976.

- 5-19. Bauman, C. D., and P. E. Reagan, "Models for Fission-Gas Release from Pyrocarbon Coated Particles," Nucl. Appl. Tech. 7, 537 (1969).
- 5-20. Valentine, K. H., et al., "Irradiation Performance of HTGR Fuel Rods in HFIR Experiments HRB-7 and -8," Oak Ridge National Laboratory Report ORNL-5228, April 1978.
- 5-21. Homan, F. J., et al., "Irradiation Performance of HTGR Fuel Rods in HFIR Experiments HRB-9 and -10," Oak Ridge National Laboratory Report ORNL-5254, April 1978.
- 5-22. Young, C. A., and D. P. Harmon, "Preirradiation Report of Fuel Materials for Pl3T Capsule Irradiation," General Atomic Report GA-A13343, April 1976.
- 5-23. Kovacs, W. J., and D. P. Harmon, "Irradiation Induced Dimensional Changes in HTGR Fuel Rods," General Atomic unpublished data, October 1979.
- 5-24. Scheffel, W. J., "Fuel Irradiation Section Summary Report on Work Related to Fe in FSV Fuel Rods," General Atomic unpublished data, August 7, 1979.
- 5-25. "FSV Fuel Specification," General Atomic unpublished data, December 13, 1979.

Fig. 5-1. OPyC failure versus mean coating rate for P13T TRISO-coated particles

Fig. 5-2. OPyC failure versus mean optical anisotropy for P13T TRISO-coated particles

Fig. 5-3. OPyC failure versus mean microporosity for P13T coated fuel particles irradiated in fuel rods

Fig. 5-4. BOL Kr-85m as a function of normalized neon/helium ratio for P13T ThO₂-BISO particle batches

Fig. 5-5. Pre- and postirradiation fuel rod shear stress versus pre- and postirradiation fuel rod/graphite hole radial gap

6. SUMMARY AND CONCLUSIONS

Capsule P13T provided a large body of empirical data that support a generic data base for HTGR fuel systems. Evaluation of these results with respect to specific fuel properties provided a substantial data base for the LHTGR fuel product specification and performance models used in core design studies. A brief summary of the irradiation results is presented below.

1. Cured-in-place fuel rods were successfully irradiated in graphite bodies that were representative of an LHTGR fuel element configuration to a fast neutron exposure of $8.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}.
2. The integrity of all fuel rods was excellent after irradiation over a wide range of fuel rod matrix and shim variables (i.e., two types of matrix filler graphites, three types of shim particles, three matrix compositions, and five shim volume fractions). No significant fuel rod property differences were noted for the three matrix formulations nor for the three shim graphites. The irradiation-induced mean increase in macroporosity was 20.2%.
3. The irradiation-induced dimensional change of the fuel rods was anisotropic and compatible with strain of the H-451 and TS-1240 graphite bodies at temperatures $< 1215^\circ\text{C}$ and fluences $< 6.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}. The observed dimensional changes are in fair agreement up to fast fluences of $8.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} with either of two dimensional-change models.
4. High OPyC failure observed for both TRISO fissile and inert particles was caused by matrix coating interaction because of high microporosity specification, $< 32 \text{ ml/kg OPyC}$). The P13T results

support the application of this specification to both TRISO and BISO coating to ensure OPyC coating survival.

5. Based on EOL R/B measurements, fair performance was observed for fuel rods containing HEU UC₂-TRISO fissile and ThO₂-BISO fertile fuel particles over a fast fluence range of 3 to 8 x 10²⁵ n/m² (E > 29 fJ)_{HTGR} and fissile and fertile burnup ranges of 53% to 75% and 0.8% to 3.7% FIMA, respectively. Seventy-five percent of the fuel rods exhibited SiC failure levels of <0.5%. The failure of 25% of the fuel rods, which had >0.5% pressure vessel failure, was caused by the poor performance of the OPyC layer, caused by high microporosity in the as-fabricated OPyC layers. When the average particle failure for the 32 P13T fuel rods is considered, the in-service particle failure levels, determined by R/B measurements, indicated that <0.3% of the total particles were failed.
6. HEU-UCO-WAR fissile fuel performed well to full exposure [(0.8 x 10²⁵ n/m²) (E > 29 fJ)_{HTGR}] and burnup (75% FIMA) with no evidence of in-service pressure vessel failure. Development work has been halted on this fuel, however, because of high kernel fission gas release.
7. The failure fraction for 32 P13T fuel rods, based on R/B measurements, is greater than predicted by the pressure vessel models (Fig. 4-34) at 95% confidence. However, the mean observed value is less than predicted by the models up to fast fluences of ~6 x 10²⁵ n/m² (E > 29 fJ)_{HTGR} at 50% confidence (see Fig. 4-34). Therefore, agreement with the model is fair, but additional work is needed to reduce SiC defective fractions and improve the OPyC layer to achieve the fuel performance assumed in pressure vessel models used in core design.
8. No UC₂ or ThO₂ fuel kernel migration was observed, which is consistent with the migration distances predicted in the FDDM

(Ref. 6-1) for the maximum P13T capsule conditions (1215°C, 11.9 months full-power irradiation time, 250°C/cm thermal gradient). Also, no kernel migration was observed in the UCO-WAR fuel kernels, which is consistent with ORNL observations (Ref. 6-2).

9. Three of the nine BISO fertile particle batches were irradiated in fuel rods to fast neutron fluences up to $7.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} and burnups up to 3.83% FIMA without any apparent coating failure. However, these batches exhibited varying levels of OPyC permeability, as measured by the neon/helium ratio and OPyC microporosity values. The OPyC permeability was attributed to high surface-connected porosity after deposition, which resulted in high OPyC microporosity.
10. The OPyC microporosity on ThO₂-BISO fuel particles correlated fairly well with the OPyC coating rate. Only poor correlations could be found with long-term chlorine leach values, and the KFA NAF values. The higher the mean OPyC microporosity value, the larger the observed OPyC matrix interaction.
11. Limited P13T data on BISO coatings indicate that the OPyC layer would be permeable if the coating rate was greater than $\sim 4.5 \text{ } \mu\text{m/min}$. Reducing the BISO OPyC coating rate specification from the current 8 to $\sim 4.5 \text{ } \mu\text{m/min}$ should be considered.
12. Incipient degradation of the SiC coating probably due to rare earth fission products and palladium at the SiC/IPyC interface was observed in TRISO UC₂ particles in seven of eight UC₂ rods at temperatures as low as 995°C and in all of the UCO-WAR (O/U = 0.64) rods at temperatures as low as 976°C. Rod exposure was at $3 \text{ to } 8 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} and 53% to 75% FIMA fissile burnup.

13. Slight degradation ($\leq 5 \mu\text{m}$) of the SiC coating by metallic fission products was observed in UC_2 -TRISO particles in the P13T fuel rod at average temperatures above 996°C . The attack increased with increasing temperature (maximum was $5 \mu\text{m}$ at 1215°C). This result agrees well with recent SiC thinning models (Ref. 6-3). No SiC thinning was observed in UCO-WAR fissile particles.
14. TS-1240 graphite performed as well as H-451 graphite and exhibited less dimensional change and weaker mechanical bonding between the fuel rods and the graphite bodies because of reduced TS-1240 radial contraction, resulting in larger fuel rod/fuel hole radial gaps.
15. The observed P13T H-451 and TS-1240 graphite irradiation-induced dimensional changes agreed well with predicted dimensional changes for H-451 (Ref. 6-1) and TS-1240 (Ref. 6-4) graphites.
16. Between 300 and 1073 K, the P13T fuel rod CTE measured axially and radially on four UC_2 -TRISO/ ThO_2 -BISO fuel rods ranged from 3.71 to $4.32 \times 10^{-6} \text{ K}^{-1}$. The two UCO-WAR-TRISO/ ThO_2 -BISO fuel rods exhibited lower thermal expansion of 2.6 to $3.4 \times 10^{-6} \text{ K}^{-1}$ axially. These values are consistent with predicted values (Ref. 6-1). No straight-forward relationship between fuel rod CTE and shim loading was observed.
17. Deleting the seal coat on either fissile or fertile particle buffer coatings did not affect coating irradiation performance.
18. Fuel particles with severely faceted coatings (aspect ratio ≥ 1.18) generally survived the P13T irradiation exposure levels [$(7.7 \times 10^{25} \text{ n/m}^2)$ ($E > 29 \text{ fJ}_{\text{HTGR}}$) at $\leq 1215^\circ\text{C}$], but because of the small statistical sample, additional irradiation testing is needed to determine faceted particle irradiation failure levels.

19. All TRISO fuel particles with lenticular inclusions in the SiC survived the P13T irradiation conditions [$(8 \times 10^{25} \text{ n/m}^2)$ ($E > 29 \text{ fJ}_{\text{HTGR}}$) at $\leq 1175^\circ\text{C}$].
20. UC_2 fuel kernels with up to 120 ppm iron and fuel rods with up to 270 ppm iron in matrix performed to a fast fluence exposure of $8.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}_{\text{HTGR}}$) at 1215°C without any apparent damage to the SiC. These data support recent work limiting the iron contained in FSV fuel particles and rods (Ref. 6-5).
21. UC_2 kernels with less than the required carbon in the kernel (8.94 versus 9.3 wt % required at the time P13T particles were manufactured) showed no additional kernel migration and can therefore be used to support a lower kernel carbon content of 8.5 wt % (Ref. 6-6).

REFERENCES

- 6-1. "Fuel Design Data Manual," Issue C, General Atomic unpublished data, September 1979.
- 6-2. Homan, F. J., et al., "Stoichiometric Effects on Performance of High-Temperature Gas-Cooled Reactor Fuels from the UCO System," Nucl. Technol. 35, 428 (1977).
- 6-3. "HTGR Fuel Development Department Technical Status Report for the Quarter Ending March 31, 1980," General Atomic unpublished data, April 1980.
- 6-4. Price, R. J., and L. A. Beavan, "Final Report on Graphite Irradiation Test OG-3," ERDA Report GA-A14211, General Atomic Company, January 1977.
- 6-5. "FSV Fuel Specification," General Atomic unpublished data, December 13, 1979.
- 6-6. Kovacs, W. J., and D. P. Harmon, "Technical Support Document for Issue C of the HTGR Fuel Product Specification," General Atomic unpublished data, August 1979.

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