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POSTIRRADIATION EXAMINATION OF CAPSULE P13Q

by
C. A. YOUNG and C. B. SCOTT

**Prepared under
Contract EY-76-C-03-0167
Project Agreement No. 17
for the San Francisco Operations Office
U.S. Energy Research and Development Administration**

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GENERAL ATOMIC COMPANY

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ABSTRACT

Capsule P13Q was the sixth in a series of irradiation tests conducted under the ERDA-sponsored HTGR Fuels and Core Development Program. It was the first accelerated irradiation test of large-diameter graphite-fuel bodies irradiated to peak LHTGR fast fluences. The primary purpose of the test was to evaluate the irradiation performance of the integral bodies and cured-in-place fuel rods. One TRISO UC_2 and two BISO ThO_2 coated particle batches were used in the fuel rods.

The postirradiation examination revealed that the performance of the H-451 graphite bodies and fuel rods irradiated to a peak fluence of $9.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} and to an average peak fuel rod temperature of 1175°C was acceptable. A range of fuel rod variables was tested and none were detrimental to the integrity of the rods. The coated fuel particles behaved in a manner predicted by previous irradiation data.

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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 reactors was directed toward demonstrating the coated fuel particle concept and the multihole graphite fuel element design. Development of fuel for the large commercial HTGRs, termed LHTGRs, draws heavily upon General Atomic's (GA) experience in developing and manufacturing fuel for the early reactors, especially for the 330-MW(e) Fort St. Vrain power station. However, optimization of the LHTGR fuel has led to a number of changes from Fort St. Vrain fuel, which are summarized in Table 1-1.* These differences are principally the result of three major design goals: (1) complete separation of fissile and fertile material, (2) simplification of the fuel fabrication process, and (3) improved fuel performance.

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 consisting of an organic binder and graphite filler, which 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 element. The use of isotropic graphite shim particles and the cure-in-place process for LHTGR rods represents design improvements that are attractive in both fresh fuel manufacturing and in the remote refabrication process. This commonality between fresh and recycle fuel will reduce overall development costs and reduce risks associated with the refabrication plant.

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

Two types of coated fuel particles are used in LHTGRs: fissile and fertile. The fissile particle for fresh fuel has a dense UC_2 fuel kernel consisting of highly enriched (93%) uranium; the fertile particle has a ThO_2 kernel. The design of the coated particles using TRISO coatings on fissile particles and BISO coatings on fertile particles facilitates separation of the bred U-233 from the nuclear poison U-236, generated primarily in the fissile kernel. During reprocessing, a burn-leach step is used to separate 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, it is important to ensure a high degree of coating integrity under all normal operating conditions. This is done in two ways: (1) design and specification of coated particle parameters to ensure a high probability of surviving irradiation-induced stresses, and (2) thermal design of 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. Energy Research and Development Administration (ERDA) has been under way at GA to provide for the evaluation, qualification, and verification of LHTGR fuel (Ref. 1-1). The program includes the irradiation of a series of test vehicles which 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 P13Q was the sixth in one series of irradiation tests. The capsule was the GA portion of the GA - Oak Ridge National Laboratory (ORNL) cooperative experiment OF-1, which was irradiated in the Oak Ridge Research Reactor (ORR). The P13Q capsule was the first accelerated irradiation test of large-diameter graphite bodies and was irradiated to a peak fast fluence of $9.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} and to a peak fuel rod temperature of 1175°C. Eighteen fuel rods were placed in three graphite bodies representing a section of a LHTGR fuel element. Capsule P13Q was also the first

large-scale integrated test of fuel rods made by the cure-in-place (CIP) process.

The results of the postirradiation examination of capsule P13Q and a discussion of these results and their impact on the current LHTGR fuel specifications are presented in this report.

REFERENCE

- 1-1. Harmon, D. P., and C. B. Scott, "Development and Irradiation Performance of LHTGR Fuel," ERDA Report GA-A13173, General Atomic Company, October 31, 1975.

TABLE 1-1
PRINCIPAL DIFFERENCES BETWEEN FORT ST. VRAIN AND LARGE HTGR FUEL

	Fort St. Vrain	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 Length: 50.8	Diameter: 15.7 Length: 62.9	Improve core design and simplify process

2. DESCRIPTION OF EXPERIMENT

2.1. OBJECTIVES

The objectives of capsule P13Q were as follows:

1. Evaluate the performance of fuel bodies representative of the LHTGR fuel element configuration and irradiated to peak LHTGR fluences. This was the first capsule designed to test relatively large bodies of H-451 graphite containing candidate LHTGR fuel rods. The results will be used to support the prismatic block concept.
2. Characterize the irradiation performance of CIP fuel rods made using prototype pilot plant equipment and containing reference UC_2 TRISO/ ThO_2 BISO coated fuel particles and candidate 1099 (H-451 graphite) shim particles. Compare CIP fuel rods fabricated by hot-injection with rods fabricated by the admix-compaction process and/or cured-in-bed (reference Fort St. Vrain process).
3. Provide additional data on the irradiation performance of UC_2 TRISO and ThO_2 BISO coated particles as a function of temperature and fluence as part of the continuing effort to define and support the permissible range of acceptable coating parameters for the LHTGR specifications. These particles were designed to survive irradiation at a peak LHTGR fluence and peak fuel rod temperature of 1150°C or less.
4. Provide support for and update current fuel performance models by measuring in-pile fission gas release, which provides a means for monitoring fuel failure as a function of fluence and temperature.

5. Provide unbonded irradiated particles (secondary samples) for out-of-pile thermal stability tests and for study of the performance of the particles under more severe thermal conditions.

2.2. DESCRIPTION OF FUEL SPECIMENS

The fuel specimens tested in capsule P13Q are described in detail in Ref. 2-1. Capsule P13Q was designed primarily to test fuel rod variables under conditions that were representative of LHTGR steady-state operation. One fissile and two fertile particle batches that were representative of reference fresh LHTGR fuel particles were used in the fuel rods. The capsule also contained unbonded particle samples of several particle batches in the piggyback (secondary) positions of the graphite bodies. These samples were included primarily for postirradiation out-of-pile heating tests, burnup analysis, and density studies.

2.2.1. Coated Particles

One UC_2 TRISO and two ThO_2 BISO coated particle batches were tested in the fuel rods in capsule P13Q. Also, one TRISO coated batch and one BISO coated batch of inert particles were used in the rods. A general description of the particle batches is given in Table 2-1. The properties of the three fuel batches fell, in general, within the preliminary specifications for LHTGR fuel (Ref. 2-2) listed in Table 2-2, which also indicates those properties that did not meet the present specifications. All three fuel batches were fabricated in 127-mm-diameter coaters and the OPyC coating was deposited using propylene gas. The process data for the coated particle batches are presented in Table 2-3.

The primary difference in the two fertile particle batches was the outer PyC (OPyC) coating density (1.80 Mg/m^3 versus 1.88 Mg/m^3). The two fertile batches had high OPyC coating rates, which did not meet the present LHTGR specification range. The fissile particle batch (6151-00-010) had a relatively low mean OPyC coating rate of $1.5 \text{ } \mu\text{m/min}$, which was also outside

the LHTGR fuel specification. Subsequent irradiation tests have indicated that OPyC coatings deposited at this low rate are dimensionally unstable during irradiation to high fast neutron exposures. (It should be noted that the final zero of all the particle batch numbers is not necessary for identification and has been left out of all numbers given in text.)

Unbonded samples containing 30 particles from several particle batches were also tested in the piggyback positions. The samples were density separated in a liquid gradient column from the parent batches. Inert particles from one batch of BISO and one batch of TRISO coated carbon kernels were used in the fuel rods to satisfy fuel rod volume loading requirements. The carbon kernels were processed from cation-exchange resin beads. Particles from sample 6641-00-043 from parent batch 6641-00-040 were included in piggyback spaces to provide data on the dimensional change behavior of BISO inert particles. A general description of the coated particle batches tested in the unbonded particle samples is given in Table 2-1.

2.2.2. Fuel Rods

Fuel rods tested in capsule P13Q were nominally 53.8 mm (2.12 in.) long by 15.7 mm (0.62 in.) in diameter. The rods consisted of TRISO coated fissile and BISO coated fertile fuel particles, shim particles, and matrix. In addition, varying amounts of TRISO and BISO coated inert resin particles were added to the fuel rods in order to achieve close particle packing. A general description of the fuel rods is given in Table 2-4. The LHTGR specifications for fuel rods (Ref. 2-2) were written after the P13Q rods were fabricated. However, most of the significant properties of the P13Q rods met these specifications, as shown in Table 2-5. The only important parameter which the P13Q rods did not meet was the matrix composition, which has been tested in succeeding irradiation test vehicles.

Two processes were used to fabricate the rods. Nine rods were made using a prototype LHTGR hot injection press. The admix-compaction process, which was being considered as an alternate fuel rod fabrication procedure, was used to fabricate the other nine fuel rods that were irradiated.

Three matrix compositions were tested. The principal matrix [40% type 1089 isotropic graphite flour plus 54% type A240 petroleum pitch plus 6% SC011 (octadecanol) additive] was used in 14 rods. The matrix composition of two rods was 40% type 1089 isotropic graphite flour plus 60% type A240 petroleum pitch. The other two rods contained a matrix consisting of 30% type 6353 natural-flake graphite flour filler plus 67% type A240 petroleum pitch plus 3% SC011 additive. These variables were included to compare the performance of matrices having isotropic and natural-flake graphite flour fillers. The octadecanol additive was used to improve fabricability.

Large HTGR fuel rods will contain nonfueled graphite shim particles in order to achieve the required particle packing fractions. The shim material used in all P13Q rods was unimpregnated Great Lakes Carbon Corporation (GLCC) type 1099 isotropic graphite powder. The properties of this material are similar to the reference H-451 graphite shim material selected for the LHTGR. The shim particle packing fraction in all rods was nominally 20 vol %, which is representative of nominal LHTGR shim loading requirements.

Two rods were fired using the reference Fort St. Vrain packed alumina bed technique (cured-in-bed). The remainder of the rods were fired either in H-451 near-isotropic graphite tubes or in the P13Q graphite bodies, which were machined from near-isotropic H-451 graphite, to simulate the cured-in-place firing process which is the reference LHTGR process.

Three firing conditions were used to carbonize and fire the fuel rods. Rods cured and fired in packed alumina beds were cured by heating to 1000°C at 10°C/min in a N₂ atmosphere. After curing, they were removed from the alumina beds, cleaned by brushing, and fired by heating to 1800°C in an argon atmosphere. The cured-in-place rods were cured and fired by heating to the maximum firing temperature at a rate of 10°C/min. The furnace atmosphere was N₂ for temperatures up to 1000°C and argon at temperatures exceeding 1000°C. Fourteen rods were heated to a maximum temperature of 1800°C, which is the reference LHTGR fuel rod firing condition. Two rods were heated to a maximum temperature of 1500°C to evaluate the effect of reducing the firing temperature on the irradiation performance of fuel

rods. Representative photographs of a cured-in-place and cured-in-bed fuel rod are shown in Figs. 2-1 and 2-2.

One purpose of P13Q was to demonstrate the irradiation performance of fuel rods fired using the cure-in-place process and graphite parts that had been used as firing containers. Fuel rods were cured in-place in either H-451 graphite tubes or the P13Q fuel bodies. Before firing, Grafoil disks were placed at the ends of the rods to prevent sticking. The rods fired in P13Q bodies were fired in the same positions to be used for irradiation. The tubes that were used as containers for firing the remaining rods were machined to hold two fuel rods in the same configuration as the rods in a single fuel hole of a P13Q capsule body. Since this was the first large-scale capsule test of rods fired using the cure-in-place process, all rods were removed from their containers for preirradiation examination. To facilitate removal after firing, all firing tubes and capsule fuel holes were dusted with 6353 graphite powder before inserting the green rods. Following firing, rods were removed from firing containers by pushing on the bottom of the rods with a hydraulic press. Push-out shear stresses in the range of 63 to 152 kPa (9.1 to 22.0 psi) were required to loosen the rods from the firing containers. After loosening, the rods were pushed out by hand. Following the preirradiation examination, selected fuel rods were placed back into the P13Q graphite irradiation bodies.

2.3. CAPSULE DESIGN

The P13Q capsule occupied the upper 386-mm length of the 610-mm-long stainless steel primary containment tube, which also contained the ORNL capsule designated OF-1. Capsule P13Q was assembled at GA and the experimental assembly was then shipped to ORNL, where the ORNL section was loaded, the lower portion of the primary containment tube was completed, and the secondary containment and lead tube were assembled. A nickel bulkhead separated the GA and ORNL experiments and allowed each experiment to be monitored and controlled independently during irradiation.

The GA fuel specimens were housed in three large-diameter H-451 graphite bodies designed to simulate the fuel - coolant hole pattern of a LHTGR fuel block. Each graphite body was nominally 62 mm in diameter and 117 mm in length and held six fuel rods, arranged two in each of three holes spaced 120° apart about the axial center of the body. Three secondary fuel sample holes located between the fuel rod holes and a central hole for thermocouples and dosimeters simulated LHTGR fuel element coolant holes. The scheme used to identify fuel rod columns and the secondary fuel sample holes in the graphite bodies is shown in Fig. 2-3. The graphite bodies were arranged vertically in the containment tube and were numbered G1 through G3 from the bottom of the P13Q capsule. The fuel holes were numbered 1, 2, and 3 and the identification was maintained by the presence of 1, 2, or 3 small holes drilled in the graphite web between the fuel holes and the outer surface of the body. Each fuel column consisted of two fuel rods designated A (top) and B (bottom). For example, the rods in hole 1 of body G2 were designated as G2-1A and G2-1B. The fueled and nonfueled secondary (piggyback) specimens located in the three "coolant" holes were identified in a similar manner. The number G2-PB1/2 indicated the piggyback hole was located between fuel holes 1 and 2 in body G2.

Temperature control under changing conditions of reactor power was achieved by varying the gas mixture in the cell from a range of 100% helium to 100% neon. This varied the conductance of the gaps between the fuel rods and the graphite bodies and between the graphite bodies and the primary containment tube. The purge system was designed for a slow gas flow (0.2 to 1.5 ml/s) to allow the gas to diffuse from the bottom of the capsule, through the graphite, and up the gaps to the gas exhaust port in the end cap at the top of the cell.

Thermocouples used for measuring temperatures below 1100°C were Inconel-sheathed Chromel-Alumel insulated with MgO. Tantalum-sheathed, BeO-insulated tungsten-rhenium (W3%Re/W25%Re) thermocouples were used for measuring temperatures higher than 1100°C. Thermocouples penetrated the upper end cap to various points in the graphite bodies. Eight thermocouples were placed in the center of the bodies and six in an outer ring of

the graphite bodies at varying axial locations, and three were inserted through the center of the upper three fuel rods. The outer thermocouple positions contained three W/Re-C/A thermocouple pairs to be used to predict neutron-induced decalibration in the W/Re thermocouples located in the fuel rods and in the center of the bodies.

Dosimetry wires (V-Co, V-Fe) were encapsulated separately in quartz vials. Each set of quartz vials was sealed in a Nb-Zr tube and placed in the dosimetry hole in the graphite spline or in the thermocouple holes below thermocouples W-2 and K-3.

REFERENCES

- 2-1. Smith, C. L., "Preirradiation Report, Fuel Materials for Irradiation P13Q," ERDA Report GA-A13265, General Atomic Company, June 13, 1975.
- 2-2. "HTGR Fuel Product Specification," General Atomic unpublished data, January 1976.

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TABLE 2-1
GENERAL DESCRIPTION OF COATED PARTICLES TESTED IN CAPSULE P13Q

Particle Batch Data Retrieval Number	Kernel ^(a)			Coatings ^(a)															Total Coated Particle ^(a)							Used In	
				Type	Buffer		Inner Isotropic PyC			SiC		Outer Isotropic PyC															
	Type	Thick- ness (μm)	Density (Mg/m^3)		Thick- ness (μm)	Density (Mg/m^3)	BAF ^(b) _o	Thick- ness (μm)	Density (Mg/m^3)	Thick- ness (μm)	Density (Mg/m^3)		BAF ^(b) _o	Coating Rate ($\mu\text{m}/\text{min}$)	Accessible Porosity (ml/kg of OPyC Coating)	Total Coating Thick- ness (μm)	Mean Diameter (μm)	Density ^(c) (Mg/m^3)	Metal Loadings		Fission Gas Release ^(d)	Thorium Contamination ^(e) ($\text{kg Th}/\text{kg Th}$)					
											U (%)	Th (%)															
Type	Density (Mg/m^3)	Mean Diameter (μm)	Type	Thick- ness (μm)	Density (Mg/m^3)	Thick- ness (μm)	Density (Mg/m^3)	BAF ^(b) _o	Thick- ness (μm)	Density (Mg/m^3)	Thick- ness (μm)	Liquid Gradient	Bulk	BAF ^(b) _o	Coating Rate ($\mu\text{m}/\text{min}$)	Accessible Porosity (ml/kg of OPyC Coating)	Total Coating Thick- ness (μm)	Mean Diameter (μm)	Density ^(c) (Mg/m^3)	U (%)	Th (%)	Fission Gas Release ^(d)	Thorium Contamination ^(e) ($\text{kg Th}/\text{kg Th}$)	Fuel Rods	Piggy- Back Samples		
Fissile																											
4163-00-0140 ^(f)	(Th,U)O ₂ ^(g,h)	(10.00)	250	TRISO	63	(1.17)	(32)	(1.79)	(i)	49	(3.20)	74	(1.77)	(i)	(i)	4.2	(i)	218	668	2.40	(9.13)	(9.18)	$<1.0 \times 10^{-7}$	(2.3×10^{-4})		X	
5466-037-132 ^(f)	(Th,U)O ₂ ^(g,h)	(9.94)	248	TRISO	93	(1.12)	(29)	(1.87)	(i)	35	(3.18)	36	(1.79)	(i)	(i)	7.0	(i)	193	625	2.40	(12.65)	(12.25)	1.1×10^{-6}	(6.1×10^{-5})		X	
6151-00-0100	UC ₂ ^(h,j)	10.99	199	TRISO	97	1.18	35	1.94	1.084	31	3.20	44	1.80	1.75	1.039	1.5	8.3	200	595	(2.26)	17.28	0.43	4.0×10^{-7}	0	X		
6151-00-0130 ^(f)	UC ₂ ^(h,j)	(10.99)	193	TRISO	89	(1.18)	(35)	(1.94)	(1.084)	31	(3.20)	44	(1.80)	(1.74)	(1.039)	1.5	(8.3)	191	581	2.27	(17.28)	(0.43)	4.0×10^{-7}	(0)		X	
Fertile																											
6542-01-0100	ThO ₂	10.04	500	BISO	79	1.08	-	-	-	-	-	85	1.80	1.71	1.027	10.0	26.6	164	828	(3.49)	-	56.51	-	$<1.6 \times 10^{-6}$	X		
6542-01-0130 ^(f)	ThO ₂	(10.04)	500	BISO	81	(1.08)	-	-	-	-	-	87	(1.80)	(1.71)	(1.027)	10.2	(26.6)	168	819	3.45	-	(56.51)	-	($<1.6 \times 10^{-6}$)		X	
6542-02-0100	ThO ₂	9.88	504	BISO	77	1.09	-	-	-	-	-	91	1.88	1.80	1.030	8.6	22.0	168	833	(3.39)	-	54.99	-	1.6×10^{-6}	X		
6542-02-0130 ^(f)	ThO ₂	(9.88)	509	BISO	78	(1.09)	-	-	-	-	-	89	(1.88)	(1.80)	(1.030)	8.4	(22.0)	167	841	3.45	-	(54.99)	-	($<1.6 \times 10^{-6}$)		X	
4252-06-0120 ^(f)	ThO ₂	(9.94)	508	BISO	79	(1.10)	-	-	-	-	-	73	(1.82)	(i)	(i)	5.5	(i)	152	820	3.67	-	(58.90)	-	(2.5×10^{-4})		X	
Inert																											
6641-00-0400	C	1.28	$\sim$ 500	BISO	$\sim$ 80	(i)	-	-	-	-	-	62	1.88	(i)	(i)	1.0	(i)	$\sim$ 142	791	(1.48)	-	-	-	-	X		
6641-00-0430 ^(f)	C	(1.28)	($\sim$ 500)	BISO	($\sim$ 80)	(i)	-	-	-	-	-	63	(1.88)	(i)	(i)	1.0	(i)	$\sim$ 143	729	1.50	-	-	-	-		X	
4361-00-0100	C	1.4 ^(k)	370 ^(k)	TRISO	(i)	(i)	(i)	(i)	(i)	16	3.19	28	1.90	1.75	(i)	4.0	39.3	(i)	534	(1.72)	-	-	-	-	X		

(a) Numbers in parentheses are values measured on particle parent batches.
(b) Measured on a Siebersdorf BAF apparatus using oil immersion - step scan, 43- μm spot.
(c) Densities shown in parentheses are actual parent batch densities as measured by Hg porosimetry. All other densities were obtained via a liquid gradient column.
(d) Release rate/birth rate for Kr-85m at 1100°C.
(e) Values given indicate amount of exposed thorium as determined by Th hydrolysis.
(f) Particle test samples were selected from parent batches by density separation.
(g) Th:U ratio = 1.01/1.
(h) U is 93.15% enriched with U-235.
(i) Not determined.
(j) Kernels contain approximately 1 wt % Th.
(k) Data obtained from ORNL.

TABLE 2-2
PRIMARY LHTGR SPECIFICATIONS^(a) AND OUT-OF-SPECIFICATION PROPERTIES OF
COATED PARTICLE BATCHES FOR P13Q CAPSULE FUEL RODS

Attribute	Fertile Particles			Fissile Particles	
	Spec. Value	Out-of-Spec Items		Spec. Value	Out-of-Spec Items
		6542-01-0100	6542-02-0100		6151-00-0100
Kernel diameter, μm	480-520			180-210	
Buffer					
Thickness, μm	80-110	79	77	95-125	
Density, Mg/m^3	0.90-1.20			0.90-1.20	
Diluent and carrier gas	Ar			Ar	
Coating gas	C_2H_2			C_2H_2	
IPyC	(b)	(b)	(b)		
Thickness, μm				25-45	
Density, Mg/m^3				1.85-1.95	
Coating rate ^(d) , $\mu\text{m/min}$					
Minimum				≥ 1.0	0.8
Maximum				≤ 5.0	
Diluent and carrier gas				Ar	
Coating gas				$\text{C}_2\text{H}_2/\text{C}_3\text{H}_6$	
SiC	(b)	(b)	(b)		
Thickness, μm				30-40	
Density, Mg/m^3 ^(c)				≥ 3.18	
Coating rate, $\mu\text{m/min}$				≤ 0.33	
Diluent and carrier gas				H_2	
Coating gas				CH_3SiCl_3	
OPyC					
Thickness, μm	70-90		91	30-50	
Density, Mg/m^3 ^(d)	1.80-1.95			1.75-1.90	
Coating rate ^(d) , $\mu\text{m/min}$					
Minimum	≥ 2.5			≥ 2.0	1.2
Maximum	≤ 8.0	13.0	10.7	≤ 8.0	
Diluent and carrier gas	Ar or N_2			Ar or N_2	
Coating gas	$\text{C}_2\text{H}_2/\text{C}_3\text{H}_6$			$\text{C}_2\text{H}_2/\text{C}_3\text{H}_6$	
Defective Particles					
Excessive fuel dispersion	$\leq 1 \times 10^{-3}$			$\leq 1 \times 10^{-3}$	
Plus missing or incomplete buffer coating	(Total for both)			(Total for both)	
Missing or incomplete SiC coating	(b)			$\leq 1 \times 10^{-3}$	
Missing or incomplete outer isotropic coating	$\leq 1 \times 10^{-3}$			$\leq 1 \times 10^{-3}$	

(a) Specifications from Ref. 2-2. (This table does not contain all specifications.)

(b) Not applicable.

(c) Measured by liquid gradient technique.

(d) Minimum and maximum coating rates determined by dividing the lower and upper 95% percentile limit, respectively, for the coating thickness by the coating time.

TABLE 2-3
COATING PROCESS DATA FOR PARTICLE BATCHES FOR P130 CAPSULE FUEL RODS

Batch Number/ Particle Type	Coatings	Coater Size (mm)	Initial Load Size (kg)	Distributor Type	Coating Parameters						Temperature (°C)
					Coating Rate (μm/min)			Coating Gases			
					Mean	Minimum	Maximum	Inert	Diluent	Deposition	
6151-00-0100 UC ₂ TRISO	Buffer	127	0.400	Frit	4.75	(b)	(b)	Ar	Ar	C ₂ H ₂	1175
	Seal	127	(a)	Frit	(b)	(b)	(b)	Ar	Ar	C ₃ H ₆	1000
	IPyC	127	(b)	Frit	1.17	0.80	1.50	Ar	Ar	C ₃ H ₆	1275
	SiC	127	0.962	Cone	0.19	(b)	(b)	H ₂	H ₂	CH ₃ SiCl ₃	1675
	OPyC	127	1.344	Multi-nozzle frit	1.47	1.15	1.78	Ar	Ar	C ₃ H ₆	1350
6542-01-0100 ThO ₂ BISO	Buffer	127	2.0	Moly-nozzle porous cone	17.95	(b)	(b)	Ar	Ar	C ₂ H ₂	1200
	Seal	127	(a)	" "	(b)	(b)	(b)	Ar	Ar	C ₃ H ₆	1050
	OPyC	127	2.335	" "	10.0	7.04	12.96	Ar	Ar	C ₃ H ₆	1530
6542-02-0100 ThO ₂ BISO	Buffer	127	2.0	Moly-nozzle porous cone	18.33	(b)	(b)	Ar	Ar	C ₂ H ₂	1200
	Seal	127	(a)	" "	(b)	(b)	(b)	Ar	Ar	C ₃ H ₆	1100
	OPyC	127	2.305	" "	8.58	6.50	10.67	Ar	Ar	C ₃ H ₆	1400
6641-00-0400 Inert BISO	Buffer	127	0.28	Multi-nozzle Frit	5.16	(b)	(b)	Ar	Ar	C ₃ H ₆	1250
	OPyC	127	(a)	" "	1.03	0.92	1.14	Ar	Ar	C ₃ H ₆	1320
4361-00-0100 Inert TRISO	Buffer	64	(b)	Cone	10.0	(b)	(b)	(b)	He	C ₂ H ₂	1125
	IPyC	64	(b)	"	2.5	(b)	(b)	(b)	He	C ₃ H ₆	1350
	SiC	44	(b)	"	0.08	(b)	(b)	(b)	He	C ₂ H ₅ SiCl ₃	1550
	OPyC	64	(b)	"	4.0	2.06	6.08	(b)	He	C ₃ H ₆	1350

(a) Continuous from buffer coating run.

(b) Data not available.

TABLE 2-4
GENERAL DESCRIPTION OF UNIRRADIATED FUEL RODS TESTED IN CAPSULE P13Q

Data Retrieval Number	Position in Capsule	Particles ^(a)		Matrix					Fabrication			Push-Out Shear Stress ^(f) (kPa)	Particle Packing ^(b,c) (%)	Fission Gas Release ^(g,h)	Thorium Contamination ^(i,e) (kg Th/kg Th)
		Fissile TRISO Batch Number (6151-)	Fertile BISO Batch Number (6542-)	Average Filler Content (wt %)	Apparent Density ^(b,c) (Mg/m ³)	Macro-porosity ^(d,e) (%)	Coke Yield ^(e) (%)	Composition	Green Rod Fabrication Process	Firing Medium	Firing Temp. (°C)				
7161-002-19-3	G3-1A ^(j)	00-0100	01-0100	44.07	(k)	(k)	(k)	(l)	Hot injection	H-451 ^(m)	1800	90	60 ⁽ⁿ⁾	<1 x 10 ⁻⁷	7.3 x 10 ⁻⁵
7161-002-20-3	G3-2A ^(j)	↓	01-0100	45.07	(k)	21.4	(k)	(l)	Hot injection	H-451 ^(m)	1500	70	60 ⁽ⁿ⁾	1.5 x 10 ⁻⁷	<6.0 x 10 ⁻⁷
7161-002-21-3	G3-3A ^(j)	↓	02-0100	43.93	(k)	27.4	(k)	(l)	Hot injection	H-451 ^(m)	1800	63	60 ⁽ⁿ⁾	2.4 x 10 ⁻⁷	<6.0 x 10 ⁻⁷
7261-002-10-3	G3-1B	↓	01-0100	44.32	0.843	22.8	34.5	(l)	Admix compaction	H-451 ^(m)	1800	90	55.9	1.3 x 10 ⁻⁶	1.6 x 10 ⁻⁶
7261-002-11-3	G3-2B	↓	01-0100	44.48	0.840	25.6	35.5	(l)	Admix compaction	H-451 ^(o)	1500	70	55.6	<1 x 10 ⁻⁷	6.6 x 10 ⁻⁵
7261-002-12-8	G3-3B	00-0100	02-0100	44.65	0.851	21.2	35.3	(l)	Admix compaction	H-451 ^(o)	1800	63	55.6	5.1 x 10 ⁻⁷	<9.0 x 10 ⁻⁷
7261-002-13-3	G2-1A	00-0100	01-0100	42.74	0.844	22.9	34.0	(l)	Admix compaction	H-451 ^(m)	1800	152	56.1	1.8 x 10 ⁻⁶	5.5 x 10 ⁻⁶
7261-002-14-3	G2-2A	↓	↓	40.92	0.913	21.0	31.5	(p)	Admix compaction	H-451 ^(m)	↓	66	57.1	1.8 x 10 ⁻⁶	<1.3 x 10 ⁻⁶
7261-002-15-3	G2-3A	↓	↓	32.48	0.744	31.2	33.4	(q)	Admix compaction	H-451 ^(m)	↓	73	56.7	5.6 x 10 ⁻⁶	5.3 x 10 ⁻⁵
7161-002-13-3	G2-1B	↓	↓	45.06	0.871	18.8	36.2	(l)	Hot injection	H-451 ^(m)	↓	152	60.3	4.2 x 10 ⁻⁷	<1.8 x 10 ⁻⁶
7161-002-14-3	G2-2B	↓	↓	44.62	0.912	24.2	39.4	(p)	Hot injection	H-451 ^(m)	↓	66	60.3	4.6 x 10 ⁻⁶	1.5 x 10 ⁻⁵
7161-002-15-3	G2-3B	00-0100	01-0100	35.54	0.743	34.8	35.2	(q)	Hot injection	H-451 ^(o)	1800	73	60.0	3.4 x 10 ⁻⁷	4.7 x 10 ⁻⁴
7261-002-16-3	G1-1A	00-0100	01-0100	41.80	0.822	26.2	32.1	(l)	Admix compaction	H-451 ^(o)	1800	73	55.9	1.1 x 10 ⁻⁶	<2.0 x 10 ⁻⁶
7261-002-17-3	G1-2A	↓	01-0100	45.46	0.789	24.0	24.5	(l)	Admix compaction	PB ^(r)	↓	(k)	56.6	7.9 x 10 ⁻⁶	<2.0 x 10 ⁻⁶
7261-002-18-5	G1-3A	↓	02-0100	39.94	0.847	25.9	33.5	(l)	Admix compaction	H-451 ^(m)	↓	121	56.3	3 x 10 ⁻⁵	<4.1 x 10 ⁻⁶
7161-002-16-3	G1-1B	↓	01-0100	44.12	0.855	20.1	34.5	(l)	Hot injection	H-451 ^(o)	↓	73	60.0	1.6 x 10 ⁻⁶	4.1 x 10 ⁻⁵
7161-002-17-3	G1-2B	↓	01-0100	43.62	0.794	22.6	25.9	(l)	Hot injection	PB ^(r)	↓	(k)	61.0	9.8 x 10 ⁻⁶	<2.2 x 10 ⁻⁶
7161-002-18-3	G1-3B	00-0100	02-0100	45.84	0.875	20.4	37.0	(l)	Hot injection	H-451 ^(o)	1800	121	60.5	<1 x 10 ⁻⁷	9.1 x 10 ⁻⁶

(a) All rods contained TRISO coated inert particles (4361-00-0100), BISO coated inert particles (6641-00-0400), and GLCC type 1099 isotropic graphite shim particles

(b) Calculated from green/fired fuel rod dimensions and nominal fuel and shim particle parameters.

(c) Data obtained by using batch average values.

(d) Determined by taking average value from two metallographic cross-section composite photographs of a rod from each batch.

(e) Data obtained on companion fuel rod from same batch.

(f) Shear forces measured on rods cured in fuel bodies.

(g) Data obtained on fuel rod actually used in capsule.

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

(i) Determined by thorium hydrolysis test. Value indicates amount of exposed thorium.

(j) Fuel rods tested in positions G3-1A, G3-2A, and G3-3A have a central thermocouple.

(k) Not determined.

(l) Forty percent type 1089 isotropic graphite filler, 54% type A240 petroleum pitch, 6% SC011 (octadecanol) additive.

(m) Type H-451 isotropic graphite firing tube.

(n) Design values.

(o) P13Q graphite bodies made of type H-451 isotropic graphite.

(p) Forty percent type 1089 isotropic graphite filler, 60% type A240 petroleum pitch

(q) Thirty percent 6353 natural-flake graphite filler, 67% type A240 petroleum pitch, 3% SC011 (octadecanol) additive.

(r) PB - packed Al₂O₃ powder bed Reference FSV fuel rod firing procedure.

TABLE 2-5
REFERENCE LHTGR PILOT PLANT SPECIFICATIONS FOR FUEL RODS

Parameter	Specification	Number of Rods In Specification	Number of Rods Out of Specification
Matrix composition	(a)	0	18
Shim Type	H-451 graphite	18	0
Green Rod			
Fabrication process	Hot injection	9	9
Properties ^(b)			
Dimensions, mm			
Length	62.89 ± 1.02	0	18
Diameter	15.67 ± 0.038 $- 0.013$	0	18
Matrix filler content, %	≥ 32 for each rod half	18	0
Fired Rod			
Firing method ^(b)	Cure-in-place	16	2
Firing conditions ^(b)			
Final temperature, °C	1800 ± 50	16	2
Time at temperature	(c)	(d)	(d)
Properties ^(b)			
Coke yield, %	≥ 25 , ≤ 35 gm coke/initial gm pitch + additive	14	4
Macroporosity, %	≤ 35	18	0
Heavy metal contamination			
U, kg U/kg U	$\leq 1 \times 10^{-4}$	18	0
Th, kg Th/kg Th	$\leq 1 \times 10^{-4}$	17	1
Graphite in which rods are cured	H-451	18 (3 bodies)	0

(a) Composition by weight: 47% A240 petroleum pitch, 38% Lonza KS-15HTR graphite filler, 5% polystyrene, and 10% octadecanol.

(b) Specified in Ref. 2-2.

(c) The combined total time at temperature greater than 1750°C in the fuel rods shall be greater than 15 minutes but shall not exceed 90 minutes.

(d) Not determined.

M39297-1,2

(a)

M39297-6 (b)

M39297-5 (c)

M39297-3,4

(d)

Fig. 2-1. Macro photographs of a representative fuel rod which was made by hot injection and cured-in-place for capsule P13Q: (a) side at 45°, (b) bottom, (c) top, (d) side at 135°

M39299-1,2

(a)

M39299-6 (b)

M39299-5 (c)

M39299-3,4

(d)

Fig. 2-2. Macrophotographs of a representative fuel rod which was made by hot injection and cured in a packed bed for capsule P13Q: (a) side at 0°, (b) bottom, (c) top, (d) side at 180°

Fig. 2-3. Identification scheme to be used to identify fuel and piggyback "coolant" holes in graphite bodies of P13Q. Graphite body G2 is used as an example.

3. CAPSULE OPERATION AND EVALUATION

3.1. OPERATING HISTORY

Capsule P13Q was inserted into the E-3 position of the ORR at ORNL on August 22, 1973. Irradiation was completed on February 23, 1975 after 391.7 effective full power days of operation. A peak fast neutron fluence of $9.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} was reached by the capsule.

After insertion the capsule operated normally until February 1974. It was discovered at that time that the nickel bulkhead separating the GA portion (cell 2) of the test from the ORNL portion (cell 1) of the test had failed. Gas flows in the ORNL portion of the test were reduced to assure no contamination of the cell 2 fission gas samples with sweep gas from cell 1.

The experiment continued operation until May 24, 1974 when a leak from one of the sweep gas lines to the lead tube necessitated capsule discharge. The capsule lead tube was opened and the leak was repaired. The capsule was reinserted into the reactor on June 18, 1974. However, another leak in the sweep gas lines was found after reinsertion and the capsule was again discharged for repair. The capsule was reinserted on July 19, 1974 after being out of the reactor for about 2 months. The irradiation test vehicle then operated satisfactorily until completion of its irradiation. Approximately 1 month after the second reinsertion, the ORR was shut down for about 2 months due to a reactor problem.

During the capsule irradiation the ORR was normally shut down and refueled for a new fuel cycle approximately once every 2 weeks. Each cycle was characterized by a gradual shift in the axial neutron flux profile resulting from reactor control rod withdrawal. These flux perturbations

caused the temperatures in two of the three crucibles to fluctuate while the remaining crucible, which had the control thermocouple, was maintained at design temperature.

Temperature control during the first two-thirds of the capsule operation was based on the Chromel-Alumel thermocouples. Control during the last one-third of the operation was switched to a tungsten-rhenium thermocouple because erratic output from some of the Chromel-Alumel thermocouples made control by these thermocouples questionable. A decalibration factor derived from the Chromel-Alumel/tungsten-rhenium pairs was used to compensate for the emf drift in the tungsten-rhenium thermocouples. For a further discussion of the temperature control see Section 3.5, Thermal Analysis.

3.2. IN-PILE FISSION GAS RELEASE MEASUREMENTS

The inert sweep gas used to control fuel temperatures in the capsule was periodically sampled to monitor the fission gas release from the fuel specimens during irradiation. Seven short-lived gaseous fission product isotopes (Kr-85m, Kr-87, Kr-88, Kr-89, Xe-133, Xe-135, and Xe-138) were measured. These isotopes were of primary interest because they constitute the main source of gaseous activity released from failed fuel and thereby can be a direct means of determining fuel performance during irradiation. Approximately 50 measurements were made during operation. Samples were collected three times a week for the first 2 weeks of the test and were monitored biweekly for the remainder of the test.

The procedure for taking gas samples was developed at the ORR. A known volume of gas was withdrawn from the exhaust gas stream into an evacuated glass vial. This sample was then counted using a Na-I detector to determine the concentrations of Kr-85m, Kr-87, Kr-88, Xe-133, and Xe-135. To analyze for Kr-89 and Xe-138, the sample was allowed to decay for 15 minutes and then re-evacuated. The vial was then counted for the daughter products Rb-89 and Cs-138. Absolute quantities of all isotopes were calculated to determine the amount of gas released at the surface of

the samples. This was accomplished by knowing the flow rates of the sweep gas through the capsule. Calibrated Hastings flowmeters were used to monitor the flow rates of the sweep gas entering the capsule.

The R/B data for each of the seven isotopes monitored throughout the irradiation period are presented in Figs. 3-1 and 3-2. The broad scatter in some of the data results from variations in reactor operating parameters and the inherent experimental error in making the fission gas release measurements. The pronounced dip and rise in the R/B values at a fluence of about $5 \times 10^{25} \text{ n/m}^2$ occurred after the 2-month outage to repair the capsule gas line leak and the 2-month shutdown due to reactor problems. The gaseous releases showed an upward trend during irradiation. However, the end-of-life in-pile R/B value was nine times lower than the out-of-pile R/B value measured in the TRIGA reactor and, therefore, the in-pile R/B values are only qualitative (see Section 4.5.5 for discussion).

3.3. ANALYSIS OF FLUX DOSIMETERS

Dosimetry wires of V - 0.216% Co and V - 0.522% Fe were employed in capsule P13Q to monitor long-term thermal (2200 m/s) and fast ($E > 29 \text{ fJ}$) neutron fluences, respectively. All wires were individually encapsulated in quartz ampoules. The ampoules, when placed in the same radial position of a body, were sealed together in a Nb-Zr tube. Two pairs of the V-Co and V-Fe wires (primary dosimeters) were placed in the central hole of the three graphite bodies. Also, pairs (secondary dosimeters) of dosimetry wires were located in two thermocouple holes below thermocouples K-3 and W-2, which were approximately 180° apart.

During disassembly of capsule P13Q, the dosimetry wires were removed from the graphite bodies. The irradiated wires ranged from completely intact to a powder form. All primary dosimeters of body 1 were destroyed (only a powder remained) by a reaction between the vanadium and quartz ampoules. The other primary wires and all of the secondary wires except one (one of the two V-Fe dosimeters in the K-3 hole of crucible 2 was never found) were recovered.

After removal from the capsule, each wire was cleaned and weighed. The gamma-ray spectrum of each wire was analyzed with a lithium-drifted germanium detector and a Sigma II 4096-channel computer analyzer. Due to the high radiation levels of the V-Fe and V-Co dosimetry wires, it was necessary to dissolve and aliquot them prior to gamma-ray spectrometry analysis. Thermal and fast neutron fluxes and fluences were calculated for each axial position with the DOSE-1 computer program using the gamma-ray spectrometry analyses of the dosimeter wires. A cobalt cross section of 36.8 barns (2200 m/s) was used to calculate the thermal fluences and an iron cross section of 0.0465 barns ($E > 29$ fJ) was used for the fast fluences. A plot of the thermal flux values indicated that the remaining primary flux wires did not agree with either the secondary wires or some earlier ORNL data for the E-3 irradiation position. Also, the primary fast flux values were inconsistent. The reasons for these differences were not determined, but because of the differences no primary flux values were reported. A third-order polynomial fit was made through the secondary dosimetry data points to obtain the final axial thermal and fast neutron flux and fluence profiles shown in Figs. 3-3 and 3-4.

Average values of the ORR fast and thermal neutron flux and fluence for each fuel specimen are given in Tables 3-1 and 3-2. These data were obtained from the flux and fluence profiles. The neutron spectra of the E-3 position of the ORR experimental reactor and a typical LHTGR are different, especially in the 50- to 180-keV range. To be consistent with HTGR design studies, the fast fluence data were converted to equivalent fast fluences in an HTGR environment [$(E > 29 \text{ fJ})_{\text{HTGR}}$] using the following relationship:

$$\Phi (E > 29 \text{ fJ})_{\text{HTGR}} = 0.90 \Phi (E > 29 \text{ fJ})_{\text{ORR}} \quad . \quad (\text{Ref. 3-1}) \quad (3-1)$$

The equivalent average fast neutron fluence in a LHTGR environment for each fuel specimen is given in Tables 3-1 and 3-2 and the fluence is plotted in Fig. 3-5. These values will be reported exclusively in the following sections of this document.

ORNL performed a dosimetry analysis on their half of the OF-1 capsule and agreement of the fluences was good. ORNL and GA reported peak fast fluences of 11.0 and $10.7 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{ORR}, respectively. The ORNL thermal fluence (2200 m/s) of $7.4 \times 10^{25} \text{ n/m}^2$ was approximately 10% lower than the GA value of $8.4 \times 10^{25} \text{ n/m}^2$.

3.4. HEAVY METAL BURNUP ANALYSIS

Heavy metal burnup is a measure of the total fissions which have occurred in a fuel sample during irradiation and is proportional to the amount of fission products generated. Heavy metal burnup analysis of capsule P13Q was conducted by two techniques: (1) wet chemical analysis and mass spectroscopy and (2) calculations based on gamma-emitting fission product inventory and capsule irradiation history.

Determination of heavy metal burnups by chemical analysis was conducted in accordance with ASTM Procedure E-495-73T, "Spectrophotometric Determination of Fission Zirconium in Irradiated Nuclear Fuels;" ASTM Procedure E-244-69, "Atom Percent Fission in Uranium and Plutonium Fuel (Mass Spectrometric Method);" and General Atomic Procedure ACD-RC-001, "Atom Percent Fission in Fissile and Fertile Fuel Particles." TRISO UC_2 and BISO ThO_2 particles from the piggyback samples were selected to be measured. Prior to chemical analysis all fuel particles were cleaned to remove external contamination. The gamma-ray spectrum of the individual fuel particles was analyzed to ensure that the fuel particles had not failed during irradiation, thus releasing a portion of their fission product inventory. The fuel particles were then crushed and dissolved in a perchloric - nitric acid solution. These solutions, which contained zirconium, uranium, and thorium in a strongly acidic chloride medium, were separated from plutonium and fission products by an anion exchange separation. Each fraction (Th, Zr, and U) was determined spectrophotometrically by the absorbance of its respective Arsenazo-III complex.

Total heavy metal atom percent fissions (% FIMA) were calculated from the results of the chemical analysis using the following equations:

$$\% \text{ FIMA (U-235)} = \frac{F}{U_o} \times 100 = \frac{F}{U_R + F} \times 100 \quad , \quad (3-2)$$

$$\% \text{ FIMA (U-233)} = \frac{F}{Th_o} \times 100 = \frac{F}{Th_R + U_R + F} \times 100 \quad , \quad (3-3)$$

where F = fissions per total sample = N'/Y ,

N' = atoms of Zr or Cs-137 (corrected for decay during and after irradiation),

Y = fractional fission yields of Zr and Cs-137 (Table 3-3),

U_o = initial atoms of uranium,

Th_o = initial atoms of thorium,

U_R = remaining atoms of uranium,

Th_R = remaining atoms of thorium.

The heavy metal burnup values determined from the wet chemical analysis using Eqs. 3-2 and 3-3 are shown in Table 3-4.

In addition to using cesium and zirconium as fission product monitors, fissile particle burnups were also determined by a mass spectrometric uranium isotopic analysis method. This method measures burnup through changes in uranium isotopic composition and can only be applied to fuel particles that do not contain thorium before irradiation. The uranium isotopic compositions of the irradiated fissile, fertile, and reference archive fissile particle samples determined by mass spectrometry are given in Tables 3-5 and 3-6. The fissile particle burnups were calculated from the data given in Table 3-5 in accordance with ASTM Procedure E244-69, and the results are presented in Table 3-4. A capture-to-fission cross-section ratio for U-235 of 0.178 was used in the mass spectrometric calculations.

The heavy metal burnup of each sample irradiated in capsule P13Q was then calculated using the Sigma II FISSIN computer code. This program calculated the burnup for both U-235 and thorium (U-233) and the weight of uranium and thorium at the beginning of each reactor cycle, as well as the uranium isotopic inventory at the end of irradiation. Required inputs were

reactor power history, average thermal fluences, initial uranium and thorium loadings, macroscopic cross sections, and fission yields. The cross sections used in the program were adjusted relative to the thermal fluence measured by the cobalt dosimetry in the ORR (see Section 3.3). This was accomplished by adjusting the cross sections inputted into the FISSIN computer code until the calculated uranium inventory was equal to the uranium inventory measured by mass spectroscopy at different fluence levels. The uranium isotopic inventory at the fissile and fertile samples determined by mass spectroscopy and the FISSIN computer code using the adjusted cross sections is compared in Table 3-7. The burnups calculated for the five particle samples using the FISSIN computer program are given in Table 3-4. The heavy metal burnup values (see Tables 3-1 and 3-2) reported for all fuel specimens in the following sections of this report were calculated using the FISSIN computer program.

Wet chemistry burnup measurements of high burnup fissile particles overestimated the burnup by approximately 5% based on the results from the mass spectrographic analysis (see Table 3-4). At lower burnups the error would be less. This overestimation occurred because small amounts of U-236 and U-238 were transmuted to neptunium and plutonium and therefore were not recovered during the anion exchange separation. Modification of the chemistry procedure is planned to permit recovery and analysis of these transuranic species.

3.5. THERMAL ANALYSIS

One of the most important requirements to maximize the information to be gained from a capsule experiment is that a detailed temperature history of each sample be available during both the operational and postirradiation examination/data analysis phases of the experiment. For this reason the temperature profiles in capsule P13Q were extensively monitored by thermocouples as shown in Table 3-8. However, because only three fuel rods were instrumented with thermocouples and because the high-temperature thermocouples (tungsten-rhenium) decalibrate as a function of neutron fluence, it was difficult to determine the maximum sample temperature solely from the

thermocouples. Therefore a method was devised whereby both thermocouple data and detailed numerical analyses were used to better estimate the daily sample temperatures.

The TAC3D (Ref. 3-2) computer code was used for the analysis to account for axial and radial heat transfer and the asymmetry of the P13Q capsule configuration. Four cylindrical R-Z- θ computer models were initially used for the design phase computer analysis as shown in Fig. 3-6. A model was used for each end of the capsule and two similar models for the middle section. The division between models was placed at one-sixth the fuel rod length rather than between fuel rods because the axial temperature gradients were thought to be minimal at those locations. This simplified the modeling by allowing the specification of adiabatic boundaries at the ends of each model. A 60° cylindrical R- θ segment extending from the middle of a fuel hole to the middle of a piggyback hole was modeled as shown in Fig. 3-7.

Conventional capsule design practice was employed; i.e., such effects as the variation of the thermal properties with temperature, the axial variation of gamma and fission heat, the changing of gap dimensions due to thermal expansion, irradiation-induced property changes, reactor operating parameters, and the operational mode of the capsule were incorporated into the computer model.

Capsule operating temperatures below 1100°C in unfueled regions were measured with Chromel-Alumel thermocouples. Since these thermocouples are not affected by the reactor's neutron environment (Ref. 3-3), these measurements provide a basis for comparison with calculated values. Fuel and other high-temperature regions ($T > 1100^\circ\text{C}$) were monitored with tungsten/rhenium (W3%Re/W25%Re) thermocouples. These thermocouples undergo irradiation-induced drift (decalibration) resulting from alloy composition changes caused by transmutations in both metals. Empirical data are available to account for this emf drift; however, relatively large uncertainties are currently associated with the correction factors.

Upon the startup of the capsule it was determined that the fission heats used in the original design thermal analysis models were incorrect by a significant amount. The fission heats for models 4 and 2 were reduced to 40 and 65% of the original, respectively, so that the calculated and experimental temperatures showed good agreement at beginning-of-life. In addition, the actual as-built dimensions were incorporated into the models, and it was determined from both thermocouple and calculated data that temperatures obtained from model 1 (rods 3B and 2A - see Fig. 3-6) could be inferred by linear interpolation from models 2 and 4 (rods 2B and 3A). Therefore, work on model 1 was terminated. Also further work on model 3 was stopped because it was determined that temperatures within the 1B rods were approximately 105% of the temperatures obtained for the 1A rods within model 2. Gamma heating for both models 2 and 4 remained unchanged from design calculations.

The reason for the large difference between the temperatures derived from the design thermal analysis and the actual initial operating temperature was later traced to a misunderstanding over the definition of thermal flux as used by General Atomic and Oak Ridge capsule designers. This discrepancy led to an inadvertent one-third reduction in fuel loadings in the capsule and the subsequent difficulties in operating all of the crucibles at the desired 1150°C operating temperature.

3.5.1. Fuel Rod Temperatures

TAC3D runs for models 2 and 4 were taken at beginning-of-life, end-of-life, and at three evenly spaced intermediate steps. Each run yielded a temperature distribution which was then compared with specific thermocouple temperature points, on the same day, from the experimental P13Q data file. When good agreement was reached on each run, three reference values described below were computed. After all five runs were made, a curve was fit to each of these reference values as a function of megawatt days (MWD). Interpolation of these curves enables the calculation of peak fuel temperature for every day in the life of the P13Q capsule. The maximum, minimum,

average, and end-of-life peak,* surface, and volume-average fuel temperatures for each fuel rod sample are shown in Table 3-9. The distribution of peak, surface, and volume-average temperatures is shown in Table 3-10. The peak fuel temperature history for each of the six fuel samples is shown in Figs. 3-8 through 3-10. A detailed description of the temperature calculations is given below.

The fuel temperatures were calculated using both actual thermocouple and TAC3D calculated data. The radial temperature profile of the P13Q capsule had the general shape shown in Fig. 3-11. The temperatures along this profile were calculated using the TAC3D computer model. (Note that the peak temperature is not at the fuel rod centerline.) In addition, the temperatures at points A and B were measured using thermocouples during the entire operation. There were two temperature drops between the measured temperature at point B and the centerline fuel temperature: (1) the temperature drop across the fuel-graphite gap (called ΔT_G gap) and (2) the temperature drop across the fuel rod (called ΔT_F fuel). There were no gas gaps between the thermocouples measuring the temperatures at points A and B.

If operation during a short period of time (i.e., several weeks) is considered so that there were no power changes caused by fuel burnup or breeding, the ΔT between the thermocouples at A and B was a function of local reactor power only (i.e., rod bank travel).

The TAC3D models were then made to match the operational temperatures at five points during the entire operation and the temperature drops ΔT_G and ΔT_F were determined. The fuel surface temperature, T_s , was then:

$$T_s = T_B + \Delta T_G \quad (3-4)$$

*Peak temperature is the highest temperature in the fuel rod at any time; it is not exactly at the rod centerline.

and the peak fuel temperature, T_C , for operation over short periods of time was:

$$T_C = T_B + \Delta T_G + \Delta T_F \quad . \quad (3-5)$$

The ΔT across the fuel, ΔT_F , was a function of only local rod bank travel.

The ΔT between thermocouples A and B calculated by the TAC3D model was defined as a reference temperature, ΔT_{AB} (Ref.), and a power factor (PF) at any time relative to the reference case was then defined as:

$$PF = \frac{\Delta T_{AB}}{\Delta T_{AB} \text{ (Ref.)}} \quad . \quad (3-6)$$

The ΔT across the fuel then became:

$$\Delta T_F = \Delta T_F \text{ (Ref.)} \times PF \quad , \quad (3-7)$$

where ΔT_F (Ref.) was the ΔT across the fuel from the TAC3D model.

The ΔT across the gap, ΔT_G , was a function of both local power and gas conductivity. This ΔT can then be defined as:

$$\Delta T_G = \frac{C}{C \text{ (Ref.)}} \times PF \times \Delta T_G \text{ (Ref.)} \quad , \quad (3-8)$$

where C = gas conductivity,

C (Ref.) = gas conductivity used in TAC3D model,

ΔT_G (Ref.) = ΔT across the fuel-graphite gap computed by the TAC3D model.

To use this calculated model over long periods of time, five TAC3D runs were made at various points during the capsule operating history to account for changes in gap size, fuel and graphite conductivity, and capsule power variations as a result of burnup and breeding effects. Time

points were selected at beginning-of-life (590 MWD), end-of-life (11,682 MWD), and at three intermediate steps (3043, 6015, and 9424 MWD). A curve was then fit to the ΔT_{AB} (Ref.), ΔT_F (Ref.), and ΔT_G (Ref.) values from each of the five runs so that these values were now able to be defined as a function of time (MWD) and, therefore, to account for the gap size changes, conductivity changes, etc.

There are three primary sources of error in the method used in the P13Q thermal analysis. One is the error in the measurement of the graphite temperature which includes the error in the decalibration function and error in the thermocouple reading. The second is error in calculating the temperature drop across the fuel rod - graphite gap (ΔT_G) which consists of the thickness and gas mixture of the gap. The last source of error is the calculation of the temperature drop across the fuel (ΔT_F). The errors in power generation and thermal conductivity of the fuel rod make up this last source of error. The uncertainty of the fuel rod temperature is the root mean square of the above errors and was calculated to be approximately $\pm 100^\circ\text{C}$.

3.5.2. Thermocouple Decalibration

In addition to providing fuel thermal histories, the temperature analysis has provided information on the degree of irradiation-induced decalibration of tungsten-rhenium thermocouples. During most of the operation, the P13Q cell temperature was controlled using Chromel-Alumel thermocouples. However, as shown below, during approximately the last one-third of the P13Q irradiation, a tungsten-rhenium thermocouple was used to control the cell temperature.

<u>Control Thermocouple</u>	<u>Start Date</u>	<u>End Date</u>
K1 (crucible 1)	8/29/73	8/8/74
K2 (crucible 2)	9/9/74	9/10/74
W4 (crucible 1)	9/11/74	2/23/75 (end of irradiation)

During the period in which the tungsten-rhenium thermocouple was used to control the cell temperature, a decalibration factor was used which had been calculated from the adjacent W1/K1 pair of thermocouples and the design fluence values over the first two-thirds of the irradiation. The decalibration formula that was used was:

$$t_c = \frac{t_m}{1 - m\phi_{th}},$$

where t_c = temperature decalibrated, °C,
 t_m = temperature measured, °C,
 m = decalibration factor, $(n/cm^2)^{-1}$,
 ϕ_{th} = thermal fluence $\times 10^{-25}$, n/m^2 .

During the irradiation a decalibration factor of $m = 0.02 (n/cm^2)^{-1}$ was used to adjust the W4 thermocouple reading.

Because the fuel loading in P13Q was lower than necessary and because all three crucibles were contained within a single cell, it was not possible during the operation of the capsule to control the cell so that all three crucibles were at the desired operating temperature. Usually only crucible 1 was operated at the desired temperature of 1150°C, while crucibles 2 and 3 operated at lower temperatures (900° to 1000°C). Since the W4 thermocouple was contained in crucible 1, during the last one-third of the irradiation, it was controlled at a decalibrated temperature of approximately 1150°C using the decalibration formula shown above.

After the irradiation was completed and the actual dosimetry established, a new analysis was performed on the W/K pairs of thermocouples contained within P13Q. This analysis resulted in the following decalibration equations:

Equation used to decalibrate thermocouples W1, W2, W4, W5, W6, W7, W8, and W9:

$$t_c = \frac{t_m}{1 - 0.0179 \phi_{th}} \quad (3-9)$$

Equation used to decalibrate thermocouples W3, W10, W11, W12, W13, and W14:

$$t_c = \frac{t_m}{0.929 + (0.071)e^{-0.805 \phi_{th}}} \quad , \quad (3-10)$$

(equivalent to $m = 0.023$ at end-of-life)

where t_c = temperature decalibrated, °C,
 t_m = temperature measured, °C,
 ϕ_{th} = thermal fluence $\times 10^{-25}$, n/m².

These equations were used in the final thermal analysis of P13Q.

As shown in Fig. 3-12, good agreement was obtained between the calculated and measured peak fuel temperature for fuel rods in the 3A position during the first half of the irradiation. Over the second half of the irradiation, this difference gradually increased until approximately a 70°C difference was evident at the end-of-life. This difference may have resulted from a decalibration factor that was too low or may have been a result of an increased axial heat flux at the ends of the capsule that was not accounted for in the thermal analysis. A decalibration factor of $m = 0.047$ would account for the 70°C difference at the end-of-life and would more nearly agree with the reported decalibration factors ($m = 0.06$ to 0.09) from capsule P13R and P13S (Ref. 3-4). It should be noted, however, that had an increased decalibration been utilized during the irradiation, the capsule would have been operated at an even lower operating temperature.

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TABLE 3-1
IRRADIATION PARAMETERS FOR CAPSULE P13Q FUEL RODS

Capsule Position	Fuel Rod Data Retrieval Number	Location ^(a) (mm)	Heavy Metal Burnup ^(b) (% FIMA)		ORR Neutron Exposure ^(c)				Equivalent ^(d) HTGR Fast Neutron Fluence (10 ²⁵ n/m ²) (E > 29 fJ) HTGR
					Thermal (2200 m/sec)		Fast (E > 29 fJ) ORR		
			Fissile	Fertile	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)	
G3-1A	7161-002-19-3	559	62.8	1.4	0.9	3.0	1.4	4.7	4.3
G3-2A	7161-002-20-3	559	62.8	1.4	0.9	3.0	1.4	4.7	4.3
G3-3A	7161-002-21-3	559	62.8	1.4	0.9	3.0	1.4	4.7	4.3
G3-1B	7261-002-10-3	505	68.9	2.1	1.1	3.9	1.9	6.3	5.7
G3-2B	7261-002-11-8	505	68.9	2.1	1.1	3.9	1.9	6.3	5.7
G3-3B	7261-002-12-8	505	68.9	2.1	1.1	3.9	1.9	6.3	5.7
G2-1A	7261-002-13-3	434	74.1	3.3	1.6	5.3	2.4	8.0	7.2
G2-2A	7261-002-14-3	434	74.1	3.3	1.6	5.3	2.4	8.0	7.2
G2-3A	7261-002-15-3	434	74.1	3.3	1.6	5.3	2.4	8.0	7.2
G2-1B	7161-002-13-3	380	76.0	4.3	1.9	6.4	2.7	9.1	8.1
G2-2B	7161-002-14-3	380	76.0	4.3	1.9	6.4	2.7	9.1	8.1
G2-3B	7161-002-15-3	380	76.0	4.3	1.9	6.4	2.7	9.1	8.1
G1-1A	7261-002-16-8	310	77.1	5.4	2.3	7.7	3.0	10.1	9.0
G1-2A	7261-002-17-3	310	77.1	5.4	2.3	7.7	3.0	10.1	9.0
G1-3A	7261-002-18-5	310	77.1	5.4	2.3	7.7	3.0	10.1	9.0
G1-1B	7161-002-16-8	256	77.3	5.9	2.4	8.2	3.1	10.5	9.5
G1-2B	7161-002-17-3	256	77.3	5.9	2.4	8.2	3.1	10.5	9.5
G1-3B	7161-002-18-8	256	77.3	5.9	2.4	8.2	3.1	10.5	9.5

(a) Location is the distance from the bottom of the core to the fuel rod centerline.

(b) Burnup calculated with FISSIN computer program.

(c) Given values are the average of the top, middle, and bottom values of each rod.

(d) Equivalent fast fluence in an HTGR environment (E > 29 fJ)_{HTGR} equals 0.9 times the ORR fluence.

TABLE 3-2
IRRADIATION PARAMETERS FOR CAPSULE P13Q SECONDARY SAMPLES

Sample Position	Particle Batch Data Retrieval Number	Location ^(a) (mm)	Heavy Metal Burnup ^(b) (% FIMA)	ORR Neutron Exposure ^(c)				Equivalent ^(d) HTGR Fast Neutron (10 ²⁵ n/m ²) (E > 29 fJ) HTGR
				Thermal (2200 m/s)		Fast (E > 29 fJ) ORR		
				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)	
G1-PB1/2-D	6542-01-0130	232	6.0	2.5	8.4	3.2	10.7	9.6
G1-PB1/2-A	6151-00-0130	333	76.0	2.2	7.3	2.9	9.8	8.8
G1-PB2/3-E	6542-01-0130	232	6.0	2.5	8.4	3.2	10.7	9.6
G1-PB2/3-A	6151-00-0130	333	76.0	2.2	7.3	2.9	9.8	8.8
G1-PB3/1-F	6641-00-0430	235	0	2.5	8.4	3.2	10.7	9.6
G1-PB3/1-A	6542-02-0130	298	5.5	2.3	7.8	3.0	10.2	9.2
G2-PB1/2-D	4163-00-0140	356	40.2	2.0	6.8	2.8	9.5	8.6
G2-PB1/2-A	6542-01-0130	458	2.9	1.4	4.8	2.2	7.5	6.8
G2-PB2/3-E	5466-037-132	356	40.9	2.0	6.8	2.8	9.5	8.6
G2-PB2/3-A	4252-06-0120	458	2.9	1.4	4.8	2.2	7.5	6.8
G2-PB3/1-A	6641-00-0430	356	0	2.0	6.8	2.8	9.5	8.6
G2-PB3/1-E	4163-00-0140	458	40.2	1.4	4.8	2.2	7.5	6.8
G3-PB1/2-D	6151-00-0130	481	70.2	1.3	4.3	2.1	7.0	6.3
G3-PB1/2-A	6542-01-0130	582	1.2	0.8	2.7	1.2	4.0	3.6
G3-PB2/3-D	6151-00-0130	481	70.2	1.3	4.3	2.1	7.0	6.3
G3-PB2/3-A	6542-01-0130	582	1.2	0.8	2.7	1.2	4.0	3.6
G3-PB3/1-E	6641-00-0430	481	0	1.3	4.3	2.1	7.0	6.3
G3-PB3/1-A	6542-02-0130	582	1.2	0.8	2.7	1.2	4.0	3.6

(a) Location is the distance from the bottom of the core to the centerline of the secondary sample.

(b) Burnup calculated with FISSIN computer code.

(c) The exposure is that received at the centerline of the secondary sample.

(d) Equivalent fast fluence in an HTGR environment ($E > 29$ fJ)_{HTGR} equals 0.9 times the ORR fluence.

TABLE 3-3
THERMAL FISSION YIELDS^(a) OF CESIUM AND ZIRCONIUM ISOTOPES

Isotope	U-233 Yield (%)	U-235 Yield (%)
Zr-91	6.52	5.92
Zr-92	6.59	5.96
Zr-93	7.01	6.37
Zr-94	6.81	6.42
Zr-96	5.68	6.26
Cs-137	6.80	6.27

^(a) Used in heavy metal burnup calculations using the wet chemical technique.

TABLE 3-4
RESULTS OF HEAVY METAL BURNUP DETERMINATIONS

Capsule Position	Particle Batch Data Retrieval Number	Particle Type	Heavy Metal Burnup (% FIMA)					Thermal Fluence ^(f) (10 ²⁵ n/m ²) (2200 m/s)
			Wet Chemistry		Mass Spectroscopy		FISSIN Calculation ^(e)	
			Fiss Zr ^(a)	Fiss Cs ^(b)	N 6/5 ^(c)	N 5/8 ^(d)		
G1-PB1/2-A	6151-00-0130	UC ₂ -TRISO	80.1	79.9	76.73	76.47	76.58	7.0
G1-PB3/1-A	6542-02-0130	ThO ₂ -BISO		5.06	NA ^(g)	NA	4.87	7.1
G2-PB2/3-A	4252-06-0120	ThO ₂ -BISO		2.87	NA	NA	2.87	4.8
G3-PB2/3-D	6151-00-0130	UC ₂ -TRISO	72.3	69.9	67.92	66.26	68.58	3.8
G3-PB2/3-A	6542-02-0130	ThO ₂ -BISO		1.06	NA	NA	0.98	2.4

- (a) FIMA Fiss Zr = atom percent fissions per initial heavy metal atom based on fission product zirconium.
- (b) FIMA Fiss Cs = atom percent fissions per initial heavy metal atom based on fission product cesium.
- (c) FIMA N 6/5 = atom percent fissions per initial heavy metal atom based on U-236/U-235 ratio.
- (d) FIMA N 5/8 = atom percent fissions per initial heavy metal atom based on U-238/U-235 ratio.
- (e) FIMA FISSIN = atom percent fissions per initial heavy metal atom, Sigma II calculation, based on input thermal fluence, reactor power history, and macroscopic cross sections.
- (f) Thermal fluence value used in FISSIN program calculations.
- (g) NA = not applicable.

TABLE 3-5
FISSILE PARTICLE URANIUM ISOTOPIC COMPOSITION
DETERMINED BY MASS SPECTROMETRY

Attribute	Irradiated Particles		Reference Archive Particles
Particle batch data retrieval number	6151-00-0130	6151-00-0130	6151-00-0130
Capsule position	G1-PB1/2-A	G3-PB2/3-D	--
Atom Percent			
233	0.150	0.099	Not detectable
234	1.286	1.221	0.651 ± 0.005
235	12.21	42.18	93.15 ± 0.008
236	62.97	40.25	0.397 ± 0.0023
238	23.39	16.25	5.81 ± 0.006
Weight Percent			
233	0.148	0.098	Not detectable
234	1.247	1.211	0.648 ± 0.005
235	12.14	42.02	93.08 ± 0.008
236	62.88	40.82	0.399 ± 0.0023
238	23.56	16.40	5.875 ± 0.006

TABLE 3-6
FERTILE PARTICLE URANIUM ISOTOPIC COMPOSITION
DETERMINED BY MASS SPECTROMETRY

Attribute	Irradiated Particles		
Particle batch data retrieval number	6542-02-0130	4252-06-0120	6542-01-0130
Capsule Position	G1-PB3/1-A	G2-PB2/3-A	G3-PB2/3-A
Atom percent			
233	75.66	83.14	91.62
234	19.65	14.14	7.406
235	3.820	2.293	0.727
236	0.789	0.286	0.043
238	0.087	0.142	0.208
Weight Percent			
233	75.56	83.07	91.58
234	19.70	14.19	7.435
235	3.848	2.311	0.733
236	0.798	0.290	0.043
238	0.089	0.145	0.212

TABLE 3-7
COMPARISON OF FISSILE AND FERTILE PARTICLE URANIUM ISOTOPIC COMPOSITION
DETERMINED BY MASS SPECTROMETRY AND THE SIGMA II FISSIN COMPUTER PROGRAM

Particle Batch Data Retrieval Number	Capsule Position	Uranium Isotopic Composition				Method Used
Fissile Weight Percent						
		U-234	U-235	U-236	U-238	
6151-00-0130	G1-PB1/2-A	1.24	12.16	62.98	23.60	Mass Spec ^(a) Sigma II
		1.25	12.18	62.95	23.62	
6151-00-0130	G3-PB2/3-D	1.20	42.06	40.32	16.42	Mass Spec ^(a) Sigma II
		1.27	41.85	39.73	17.15	
Fertile Weight Percent						
		U-233	U-234	U-235	U-236	
6542-02-0130	G1-PB3/1-A	75.63	19.72	3.85	0.799	Mass Spec ^(b) Sigma II
		75.93	19.26	3.99	0.82	
4252-06-0120	G2-PB2/3-A	83.19	14.21	2.314	0.29	Mass Spec ^(b) Sigma II
		83.17	14.16	2.37	0.30	
6542-01-0130	G3-PB2/3-A	91.77	7.45	0.733	0.0434	Mass Spec ^(b) Sigma II
		91.78	7.42	0.76	0.04	

(a) U-233 normalized out.

(b) U-238 normalized out.

TABLE 3-8
THERMOCOUPLE ARRANGEMENT WITHIN CAPSULE P13Q

Crucible Number	Thermocouples			Distance from Center of Core ^(a) (mm)	Comments
	Fuel	Graphite Body	Center Spine		
3 ↓	W12			+231.3	Fuel rod thermocouple in rod 3-1A
	W13			+231.3	Fuel rod thermocouple in rod 3-3A
	W14			+231.3	Fuel rod thermocouple in rod 3-2A
			W11	+231.3	Adjacent to fuel rod thermocouple
		W3		+225.2	Adjacent to interface between
		K3		+225.2	fuel rods 3A and 3B
			W10	+198.2	Adjacent to midlength of fuel rod 3B
2 ↓			W9	+127.6	Adjacent to midlength of fuel rod 2A
		W2		+100.7	Adjacent to interface between
		K2		+100.7	fuel rods 2A and 2B
			W7	+73.79	Adjacent to midlength of fuel
			W8	+73.79	rod 2B
1 ↓			W6	+3.18	Adjacent to midlength of fuel rod 1A
		K1		-23.75	Adjacent to interface between
		W1		-23.75	fuel rods 1A and 1B
			W4	-50.67	Adjacent to midlength of fuel
			W5	-50.67	rod 1B

(a) + = above core centerline; - = below core centerline.

TABLE 3-9
LIFETIME IRRADIATION TEMPERATURES OF CAPSULE P13Q FUEL RODS

Capsule Position	Peak Fuel Temperature ^(a) (°C)				Fuel Surface Temperature ^(c) (°C)				Volume Average Temperature (°C)				Average Surface Temperature Gradient ^(d) (°C/mm)
	Maximum	Minimum	Average	EOL ^(b)	Maximum	Minimum	Average	EOL ^(b)	Maximum	Minimum	Average	EOL ^(b)	
3-1A, 2A, 3A	1106	751	917	1002	989	639	793	840	1047	696	855	921	26
3-1B, 2B, 3B	1071	783	930	966	998	681	831	862	1034	732	881	914	20
2-1A, 2A, 3A	1051	814	943	930	1007	723	869	884	1022	768	906	907	16
2-1B, 2B, 3B	1035	846	956	892	1016	766	908	908	1020	806	932	900	10
1-1A, 2A, 3A	1259	962	1121	1124	1197	907	1089	1079	1200	934	1105	1102	6
1-1B, 2B, 3B	1321	1010	1177	1181	1257	952	1144	1133	1260	981	1161	1157	6

(a) Note that the peak fuel temperature is not the exact centerline fuel temperature as indicated in Fig. 3-11.

(b) EOL = end of life.

(c) Calculated at the outermost surface of rod relative to graphite body as indicated in Fig. 3-11.

(d) Calculated by equation: $\frac{2(\text{average peak-surface temperature})}{\text{Radial distance between peak and surface temperature}}$

TABLE 3-10
DISTRIBUTION OF TEMPERATURES WITHIN CAPSULE P13Q FUEL RODS

Percent of Time that Fuel Rod Operated at ≤ Indicated Temperature	Capsule Fuel Rod Position																	
	Peak ^(a) Fuel Temperature (°C)						Fuel Surface ^(b) Temperature (°C)						Volume-Average Temperature (°C)					
	3A	3B	2A	2B	1A	1B	3A	3B	2A	2B	1A	1B	3A	3B	2A	2B	1A	1B
1	757	788	819	851	979	1028	644	686	729	733	926	973	700	737	744	812	953	1000
5	816	846	874	873	1042	1094	696	736	777	817	999	1049	757	792	826	860	1024	1075
10	850	878	894	892	1064	1117	735	773	811	848	1034	1086	793	824	855	877	1049	1101
20	876	895	909	920	1091	1145	756	796	836	876	1054	1106	814	846	875	897	1075	1129
30	889	907	921	940	1107	1163	768	808	848	889	1064	1117	829	856	884	910	1088	1143
40	901	918	932	953	1118	1174	775	817	858	898	1076	1130	840	868	894	924	1100	1155
50	913	927	944	962	1126	1182	789	828	869	908	1091	1146	848	878	906	935	1109	1164
60	925	938	954	971	1134	1191	799	842	881	920	1106	1162	861	889	917	947	1119	1175
70	939	952	967	979	1143	1200	815	853	894	935	1117	1172	877	902	931	956	1130	1186
80	964	967	980	990	1155	1213	835	869	906	945	1130	1187	900	916	942	970	1142	1199
90	999	995	995	1009	1171	1229	864	898	928	964	1153	1210	929	944	962	986	1156	1213
95	1022	1021	1014	1019	1182	1241	894	923	952	985	1174	1233	955	969	985	1001	1170	1229
99	1078	1053	1037	1033	1214	1274	952	968	990	1012	1190	1250	1008	1009	1010	1013	1191	1250

(a) Note that the peak fuel temperature is not the exact centerline temperature of rod as indicated in Fig. 3-11.

(b) Calculated at the outermost surface of the rod relative to the graphite body as indicated in Fig. 3-11.

Fig. 3-1. Measured in-pile fission gas release (krypton isotopes) values versus fast fluence for capsule P13Q. The EOL R/B value measured in the TRIGA reactor is also plotted.

Fig. 3-2. Measured in-pile fission gas release (xenon isotopes) values versus fast fluence for capsule P13Q

Fig. 3-3. Neutron flux as a function of axial position for capsule P130

Fig. 3-4. Neutron fluence as a function of axial position for capsule P13Q

Fig. 3-5. Fast fluence versus axial position for capsule P13Q

Fig. 3-6. Axial locations of four computer models

Fig. 3-7. Section through capsule P13Q indicating 60° sector used in TAC3D analysis

Fig. 3-8. Peak temperature history for fuel rods irradiated in graphite body 1 of capsule P13Q

Fig. 3-9. Peak temperature history for fuel rods irradiated in graphite body 2 in capsule P13Q

Fig. 3-10. Peak temperature history for fuel rods irradiated in graphite body 3 of capsule P13Q

Fig. 3-11. Radial temperature profile for $\theta = 0^{\circ}$ as shown in Fig. 3-7 except point B was rotated 30°

Fig. 3-12. Comparison between measured (thermocouple W14) and calculated peak fuel temperatures versus time for rod 3A of capsule P13Q

4. POSTIRRADIATION EXAMINATIONS

After capsule P13Q was disassembled, dimensional measurements were made on the fuel bodies. Postirradiation fission gas release measurements were then made by reirradiating each body in the TRIGA facility, prior to removal of the fuel specimens. The fuel specimens were then removed from the graphite bodies. Visual examination, dimensional measurements, and additional fission gas release measurements were made on all the fuel rods. Gamma-ray spectrometry analysis was performed on all fuel rods and capsule components to evaluate the extent of metallic fission product release and transport that occurred during irradiation. Metallography was performed on selected fuel rods to evaluate irradiation-induced changes in the fuel particles and matrix components. The linear coefficient of thermal expansion was measured on selected fuel rods and the results were published in another document (Ref. 4-1). Contact microradiography and density measurements were performed on certain unbonded particle piggyback samples. The results obtained from the above examinations are presented in Sections 4.1 through 4.8.

4.1. CAPSULE DISASSEMBLY

The end caps of the stainless steel primary containment tube were girdle cut and the tube was slit at 0° and 180° orientations to expose the three graphite fuel bodies. The bulkhead at the bottom end of the capsule was cracked in a radial pattern with five cracks propagating from the center to the circumference as shown in Fig. 4-1. The bulkhead was returned to ORNL for metallographic examination. The inner surface of the bottom third of the containment tube was discolored, which indicated body G1 operated hotter than bodies G2 and G3. The purge gas inlet tube at the top of the capsule was severed near the end cap as shown in Fig. 4-2. Degradation of the niobium purge tube was attributed to corrosion resulting from impurities in the purge gas. All of the dosimeter vials were recovered from

the niobium tube containers with the exception of the primary dosimeters from body G1, which were completely disintegrated as a result of a reaction between the vanadium wires and the quartz ampoules, and one secondary dosimeter in body G2, which was never found.

The PALORITE-C carbon insulation disk at the bottom end of the capsule (highest fluence region) exhibited considerable irradiation-induced dimensional change. The bottom end of the disk shrank to form a frustrum of a cone as shown in Fig. 4-3. The PALORITE-C disk at the top end of the capsule (lowest fluence region) did not exhibit any significant dimensional change; however, the disk split circumferentially when the end cap of the containment tube was girdle cut.

The three graphite fuel bodies were removed from the primary containment tube in good condition as shown in Fig. 4-4. No cracks or signs of oxidation of the bodies were observed. A residue resulting from the bleed-off of resin during the cure-in-place process was visible on the exterior of body G1.

4.2. FUEL REMOVAL

The secondary (piggyback) specimens were removed from the simulated "coolant" holes of each graphite body with the body in a vertical position as shown in Fig. 4-5. The specimens were exposed by pushing in an upward direction on the bottom of the sample column with a push rod. Each sample was then lifted off the top of the column with the master-slave manipulators.

The fuel rods were removed in a horizontal fixture using a 9.5-mm-diameter push rod driven by an electric screw jack, as shown in Fig. 4-6. The breakaway force required to start each fuel column moving was recorded by a Dillon force gage placed between the screw jack and push rod. A maximum shear stress of 27 kPa (3.9 psi) was required to start the G1-2 fuel column moving (see Table 4-1). Breakaway shear stresses ranging from <2 to 9 kPa were required to remove the other eight fuel columns. The

postirradiation shear stresses cannot be compared to the preirradiation values because the rods were inserted in the capsule bodies after being fired in the graphite crucibles. Representative photographs showing the removal of one fuel column from a graphite body are shown in Fig. 4-7. All 18 fuel rods were removed in good condition. No evidence of surface damage resulting from mechanical interaction between the fuel rods and walls of the graphite bodies was observed on any of the fuel rods.

No significant cracking or particle debonding was observed in any of the fuel rods. Ten of the eighteen fuel rods exhibited very slight circumferential cracking on the bottom end. This may have been an artifact of the technique used to remove the fuel rods from the graphite bodies. As the rods were pushed out of each fuel hole, they tipped slightly into a V-block. Since there was very little clearance between the fuel rods and the wall of the graphite body, the last few millimeters of each rod could have been damaged by the high moment placed on the bottom end of the rod.

4.3. VISUAL EXAMINATION

After removal from the graphite bodies, the fuel rods were examined visually using an in-cell stereomicroscope. The criteria for evaluating fuel rod integrity after irradiation were that the fuel rods remain intact and exhibit negligible cracking or particle debonding. Representative postirradiation photographs taken of each fuel rod during the visual examination are shown in Figs. 4-8 through 4-25. It should be noted that Grafoil remained on the ends of most of the cured-in-place rods as seen in the photographs. The visual appearance of each fuel rod after irradiation is summarized in Table 4-1.

All fuel rods were judged to be in excellent condition. No significant matrix cracking or particle debonding was observed. Slight circumferential cracking was noted on the bottom of ten rods, which was accompanied by slight (0 to 29 particles) particle debonding. Although some of the cracking occurred at the matrix end cap of the hot-injected rods, which is usual, some of the rods may have been damaged slightly during unloading.

The fuel rod fabrication variables tested (admix-compaction versus hot-injection, fired in block versus packed bed, and fired at 1500° versus 1800°C) did not have any effect on fuel rod integrity.

Eighteen particle batches were tested in the secondary "coolant" hole positions of the graphite fuel bodies. Thirty particles from each batch were contained in individual holes of disk-shaped graphite crucibles with sliding lids. Each sample was photographed and examined with the crucible lid removed prior to unloading. All 30 fuel particles in each sample were present; however, one particle was lost from three different samples when the particles were removed from the graphite crucibles. Representative photographs taken during the visual examination of each particle type tested are shown in Figs. 4-26 through 4-29. Results of the visual examination are reported in Table 4-2. After examination the particles were placed in storage for subsequent testing and out-of-pile thermal stability tests.

Coating failure was only observed in one of the 18 samples tested. A UC₂ TRISO particle batch (6151-00-013) irradiated to a fast fluence of $8.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} in position G1-PB2/3-A exhibited 16.6% OPyC coating failure and 3.3% total coating failure. A companion sample of the same particle batch, also tested in body G1, did not experience any coating failure. The OPyC coating anisotropy of this batch was high and failure would be expected.

4.4. DIMENSIONAL CHANGE ANALYSES

4.4.1. Fuel Rods

Preirradiation dimensional measurements of the fired fuel rods were made using calibrated micrometers. One length and six diametral measurements were made on each fuel rod to tolerances of $\pm 0.013 \text{ mm}$. The diametral measurements were made at 0° and 90° points at the top, middle, and bottom of the rod. The 0° orientation was selected in reference to a characteristic marking on the surface of each rod (Ref. 4-3). The average values are given in Table 4-3.

Postirradiation fuel rod dimensional measurements were performed using a calibrated dial gauge micrometer. Six diametral measurements were made to tolerances of ± 0.013 mm at the preirradiation 0° and 90° orientations for all rods except one. One length measurement was made to tolerances of ± 0.025 mm. The average values and standard deviations of the diametral measurements are presented in Table 4-3.

The majority of the fuel rods were cured in graphite; to prevent the rods from sticking to one another, pieces of Grafoil were placed on their ends. In most cases, these disks remained attached after firing, and therefore preirradiation and postirradiation length measurements included these disks. The nominal preirradiation thickness of a disk was 0.13 mm (0.005 in.).

Irradiation-induced fuel rod dimensional changes were calculated to show the percent difference between the unirradiated and irradiated states. This was done for diametral, length, and volume changes. These data are summarized in Table 4-3. The fuel rods exhibited diametral shrinkage from -1.09 to -2.02%, axial shrinkage from -0.17 to -1.67%, and volume shrinkage from -2.33 to -5.59%. The three types of dimensional change are plotted as a function of fast neutron fluence in Figs. 4-30 through 4-32. The dimensional changes exhibited a turnaround in the average fast fluence range of about 5 to 7×10^{25} n/m² ($E > 29$ fJ)_{HTGR}. Figures 4-30 through 4-32 also indicate the firing and matrix variables and the average volume temperature of the fuel rods. The linear dimensional changes were anisotropic in all rods since the axial shrinkages were always less than the diametral shrinkages.

The model for predicting the dimensional change behavior of fuel rods during irradiation is presently being revised. A comparison of measured and predicted dimensional changes of the P13Q capsule rods will be included in a separate report (Ref. 4-4).

4.4.2. Graphite Bodies

Diametral measurements were made on the fuel bodies prior to removal of the fuel specimens. Axial measurements were not made because of the presence of the threaded graphite caps on the ends of the fuel bodies. Diametral measurements were made to a tolerance of ± 0.13 mm at 0° and 90° orientations at the top, center, and bottom of each body. Irradiation-induced dimensional changes were calculated using preirradiation dimensions that were obtained in a similar manner; the results are given in Table 4-4.

The measured diametral dimensional changes are compared to the predicted changes for H-451 graphite in the radial direction for irradiation at 650° and 850°C (Ref. 4-5) as a function of fast fluence in Fig. 4-33. Almost all the measured values fall close to the 650°C design curve.

4.5. FISSION GAS RELEASE MEASUREMENTS

Fission gas retention characteristics of the fuel rods before and after irradiation were evaluated by neutron activation in the General Atomic Company TRIGA reactor facility. Preirradiation measurements of the fissile fuel were made as part of the quality control evaluation to determine the amount of heavy metal contamination in the fuel specimens prior to irradiation. The primary objectives of the postirradiation measurements were (1) to cross check the in-pile R/B measurements made at the ORR during capsule irradiation, and (2) to obtain an accurate measure of the average fuel failure in each fuel rod.

4.5.1. Technique

Fission gas release measurements were made by irradiating fuel specimens in a graphite tube furnace designed to fit into a fuel element position of the TRIGA reactor core (Ref. 4-6). 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 hour to produce approximately 10^{14} fissions in each fuel specimen. During

irradiation, the released fission gases were swept with helium into a liquid-nitrogen-cooled charcoal trap. The trapped gases were assayed for fission product isotopes by gamma-ray spectroscopy (Ref. 4-7) using a Ge(Li) detector and a 4096-channel analyzer. The fission product isotope birth fractions were calculated using the neutron flux in the TRIGA core and the end-of-life (EOL) fissionable material loadings. The amount of fissionable material remaining in each fuel rod was calculated using the Sigma II FISSIN computer code, which takes into account initial fuel loadings, capsule irradiation conditions, and the ORR power history and cross sections. The adjusted EOL fissile fuel loading for each specimen was determined by expressing the sum of the weights of all remaining fissionable material (U-233 and U-235) in terms of U-235, producing the equivalent Kr-85m yield (Ref. 4-8). The Kr-85m isotope was selected as the reference isotope because it has a short half-life (4.4 hours) and its gamma-ray energy peak can easily be resolved. A reference temperature of 1100°C was used for analysis of fuel failure levels; however, a fission gas release measurement was also made at 950°C on one fuel body. The preirradiation R/B data obtained under non-steady-state conditions were corrected to steady-state production rates (multiplied by a factor of 1.9). However, the postirradiation R/B values were not corrected to steady-state production rates because a study showed that the R/B values obtained for irradiated fuel in the 0.5-hour TRIGA irradiation were essentially steady-state values (Ref. 4-9).

4.5.2. Fuel Bodies

Fission gas release measurements were made on each of the three graphite fuel bodies prior to removal of the fuel specimens. This was done in case any of the cured-in-place fuel rods were subsequently damaged during removal from the graphite bodies. If this had occurred, an assessment of the fuel failure levels could still have been made since this measurement yielded an average fission gas release value for all six fuel rods contained in a body.

The postirradiation fission gas release levels obtained for the fuel bodies are given in Table 4-5. The Kr-85m R/B values measured at 1100°C ranged from 9.7×10^{-6} to 7.8×10^{-5} . Measurements were made on body G2 at 950° and 1100°C. When the R/B value measured at 950°C was corrected to 1100°C using the equation for the temperature dependence of steady-state fission gas release given in Ref. 4-9, a value of 5.8×10^{-5} was obtained. This is in good agreement with the actual value of 6.4×10^{-5} measured at 1100°C.

4.5.3. Fuel Rods

After removal of the fuel rods from the graphite bodies, fission gas release measurements were made at 1100°C on each individual rod to evaluate the in-service fuel performance. The results of these measurements are given in Table 4-6.

To compare the R/B values measured for the individual fuel rods to the R/B values obtained for each graphite fuel body, the contribution to the fuel body R/B level from each rod was calculated. This was done by multiplying each fuel rod R/B value by the fraction of fissions that occurred in each fuel rod at EOL relative to the total number of fissions that occurred in the fuel body. The total fuel body R/B was then obtained by summing the contribution from each fuel rod. The results of these calculations are given in Table 4-7. The calculated and measured fission gas releases for each fuel body are summarized in Table 4-8. The differences between the measured fuel body R/B value and the value calculated from the individual fuel rod measurements were 3.1, 7.8, and 17.9% for bodies G3, G2, and G1, respectively. The values for bodies G3 and G2 are within the absolute uncertainty of the TRIGA fission gas release measurements of $\pm 10.0\%$. The larger difference for body G1 might have resulted from a number of factors including external contamination or the added uncertainty associated with calculating the contribution to the R/B level from the individual fuel rods.

4.5.4. Calculation of In-Service Fuel Failure Levels

The fission gas released during the 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:

$$R/B_{EOL} = R/B_{\text{failed fuel}} + R/B_{C(U)} + R/B_{C(Th)} \quad , \quad (4-1)$$

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,
 $R/B_{C(Th)}$ = 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. 4-3). 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 Eq. 4-1. These results are given in Table 4-9. The fission gas release arising from heavy metal contamination was calculated using the following equations:

$$R/B_{C(U)} = (R/B_{BOL}) (X_{U-235}) \quad (4-2)$$

$$R/B_{C(Th)} = (Th_C) (r/b_C) (X_{U-233}) \quad , \quad (4-3)$$

where R/B_{BOL} = measured preirradiation fission gas release,
 Th_C = level of thorium contamination,
 r/b_C = fractional gaseous release from heavy metal contamination,
 $X_{\text{U-235}}$ = fraction of fissions that occurred in U-235 at EOL,
 $X_{\text{U-233}}$ = fraction of fissions that occurred in U-233 at EOL.

A value for the fractional gaseous release from heavy metal contamination of 0.30 was used in these calculations (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. An R/B for failed fuel of zero was calculated for three fuel rods. This indicates that no fuel failure occurred in these rods during irradiation and that the level of thorium contamination measured on a companion unirradiated fuel rod was slightly higher than that 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:

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

The results are given in Table 4-9. The failure level (F) actually represents the fraction of fissions occurring in failed fuel at EOL. A value for the fractional release of Kr-85m from failed fuel particles (r/b_f) constrained in a fuel rod of 5.0×10^{-3} was used in these calculations. However, it should be noted that for conservatism in LHTGR inventory calculations, a value of 2.0×10^{-2} has been used (Ref. 4-10).

It is not possible to accurately differentiate between fissile and fertile particle failure in fuel rods using postirradiation TRIGA R/B data alone since failed fuel of both types contributes to the gaseous release. A maximum fertile particle failure can be calculated from the R/B data by

assuming that all the fissions in failed fuel occur in the fertile particles. This is a good approximation since from 79 to 93% of the fissions in the rods at EOL occurred in the fertile fuel as shown in Table 4-9. The maximum gaseous release for fertile fuel was obtained by dividing the R/B from failed fuel by the fraction of fissions occurring in the fertile particles (X_{fertile}). A maximum fertile particle failure level in each rod was then calculated using the following equation:

$$F_{\text{fertile}} = \frac{R/B_{\text{failed fuel}}}{(X_{\text{fertile}})(r/b_f)} \quad (4-5)$$

The results are given in Table 4-9. The calculated maximum fertile particle failure levels ranged from 0 to 2.6%.

A similar analysis was not performed for the fissile particles. The fraction of fissions that occurred in the fissile particles at EOL only ranged from 7 to 21%. An assumption that all the fissions in failed fuel occurred in the fissile particles would result in a gross overestimation of the fissile particle failure levels. However, failure of several percent of fissile particles could make a significant contribution to the total gaseous release.

4.5.5. Comparison of In-Pile and Postirradiation Fission Gas Release Measurements

In-pile fission gas release measurements (see Section 3.2) were used to evaluate fuel performance during irradiation. One of the objectives of the postirradiation fission gas release measurements was to verify the in-pile data. To accomplish this, an EOL in-pile fission gas release value for the capsule was determined from the TRIGA postirradiation fission gas release data. The contribution from each fuel rod to the total capsule R/B was calculated using the equation

$$R/B_i = (R/B_{\text{EOL}}) (T_{\text{corr}}) (X_i) \quad (4-6)$$

where R/B_i = contribution to the capsule R/B from the i^{th} fuel rod,
 R/B_{EOL} = postirradiation TRIGA fission gas release value (R/B Kr-85m at 1100°C) for the i^{th} rod,
 T_{corr} = temperature correction factor for Kr-85m (Ref. 4-9),
 X_i = fraction of fissions in cell 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 results of these calculations are given in Table 4-10. An EOL R/B (Kr-85m) value for the capsule of 2.3×10^{-5} was obtained by summing the contribution from each fuel rod. This value was a factor of nine higher than the EOL R/B (Kr-85m) level of 2.7×10^{-6} monitored in-pile. Since the postirradiation TRIGA R/B measurements on the fuel bodies and fuel rods were in good agreement (see Section 4.5.3), and the TRIGA measurement is believed to be the most valid measure of R/B, it appears that the in-pile R/B values gave only a qualitative indication of fuel performance throughout irradiation.

There are several possible reasons for the large discrepancy between the in-pile and TRIGA R/B values, and probably all of them contributed to the difference. The purge gas inlet tube was severed near the end cap (see Section 4.1), which may have caused the fuel zone to be partially bypassed by the purge gas. The EOL volume-average temperatures used in the R/B calculations may have been higher than the actual operating temperatures of the fuel at the time the final in-pile R/B measurement was made. It is possible that a systematic or calibration error in the in-pile fission gas release measurements occurred. Another source of error was the estimation of the number of fissions which occurred during the in-pile fission gas release measurement. Although a large discrepancy between the two R/B values is undesirable, it was also observed for capsules P13R and P13S (Ref. 4-2) and apparently for capsule P13T (Ref. 4-11).

4.6. GAMMA-RAY SPECTROMETRY ANALYSES

Gamma-ray spectrometry was utilized to study fuel rods, fuel rod graphite crucibles, and the primary containment. The analyses were conducted to provide information on fuel rod homogeneity, fuel specimen fission product inventories, and fission product transport.

Gamma counting was performed using a lithium-drifted germanium (Ge-Li) gamma spectrometer coupled to a Sigma II 4096-channel computer analyzer. Single channel analyzers were used to print out relative profiles of individual isotopes. All specimens were counted in the low-level hot cell at a distance of 0.651 m from the end of a 1.07-m-long collimator. The spectrometer was placed next to the other end of the collimator. Each type of specimen required a different size collimator cross section because of the different sample activities and geometries. Fuel rods and graphite crucibles were scanned axially using a special traversing unit that allowed a slow and continuous movement of the sample past the collimator.

4.6.1. Fuel Rods

Fuel rods were gamma counted using a 0.58 mm by 22.2 mm collimator that was positioned with the long axis perpendicular to the long axis of the fuel rod. A column of rods was moved past the collimator continuously at a speed of 1.27 mm/min. Single-channel scans for Cs-137, Zr-95, and Pa-233 using their prominent energy peaks were plotted as a function of rod position. These scans, which indicate the fuel homogeneity, are shown in Figs. 4-34 through 4-36 for all fuel rods irradiated in the three bodies. Also, multichannel scans which were each 7 minutes in duration and included the 0 to 380 fJ energy range were made on all fuel rods. Therefore, a complete scan was averaged over every 8.9 mm (1.27 mm x 7 minutes) of fuel rod axis. All the complete scans (end scans excluded) were averaged together for each rod. The major fission product isotope inventory using the average multichannel scans, the internal standards, and the FISS-PROD computer program are given in Table 4-11. The isotope concentrations are similar

for all rods. The counting error of each fission product isotope is also presented in Table 4-11. A detailed description of the calculations is given below. A Cs/Zr ratio gives an indication of the amount of metallic fission product release since cesium is more mobile than zirconium. Theoretical and measured Cs-137/Zr-95 ratios were compared and the results showed that all the fuel rods had apparently retained the cesium.

The quantitative isotope inventory of the fuel rods given in Table 4-11 was calculated in the following manner. The spectrometer detected the counts per minute (CPM) of each isotope based on the gamma-ray energy spectrum. A calibration factor or counting efficiency (CE) had to be determined in order to calculate the disintegrations per minute (DPM) of each isotope for the total rod from the CPM measured on a small volume of the rod through the collimator. The CE is a function of counting geometry.

The following equation was used to determine the CE for the various isotopes;

$$CE = \frac{CPM}{(DPM)(AI)} \quad , \quad (4-7)$$

where DPM = disintegrations per minute of each isotope,

CPM = counts per minute of each isotope, measured by the detector,

CE = counting efficiency of each isotope,

AI = absolute intensity of each isotope.

The CPM was measured and the AI was a known value for each isotope. The theoretical DPM was selected for the other input. Fuel rods 7161-002-16-3 (G1-1A), 7261-002-13-3 (G2-1A), and 7161-002-19-3 (G3-1A) were chosen as internal standards. The theoretical DPM of each isotope of these three rods was determined using the FISS-PROD computer program. A CE was then calculated for each isotope and a calibration curve was established by plotting the CE values as a function of peak gamma energy (each isotope has a unique energy spectrum) using Eq. 4-7. The DPM values of the isotopes of the P13Q rods, excluding the standards, were subsequently calculated using

Eq. 4-7 (solving for DPM), the CE values from the calibration curve, and the measured CPM values. The DPM values were converted to Curies. It should be emphasized that the values are based on a theoretical calculation and not on an absolute measurement.

The P13Q fuel rods selected as internal standards were the first fuel rods of reference LHTGR diameter (15.87 mm) to be used to calibrate the gamma counting of rods of this diameter. They were selected because the irradiation history of the rods was well known and the fuel rod temperature and coated particle failure were low. This calibration will be useful in determining the fission product inventory of fuel rods from future uninstrumented irradiation tests or HTGR cores.

4.6.2. Graphite Crucibles

The empty graphite crucibles were gamma counted to aid in the evaluation of metallic fission product release and transport from the fuel rods. The three graphite fuel bodies were aligned in a row with fuel holes 1, 2, and 3 of each body lined up. The center of each fuel rod hole was aligned with the center of the collimator and multichannel scans were measured in a similar manner to that for the fuel rods except a 2.54 by 22.2 mm collimator was used. The three holes were scanned identically; the results are given in Table 4-12.

The only isotope activities detected were Ta-182 and Cs-137. The concentration of the cesium isotope was calculated in the same manner as described in the previous section using the calibration curve for fuel rods. The relative activity of Ta-182 (190 fJ) was reported instead of the concentration because the calibration curve was only valid over the energy range 48 to 120 fJ. The amount of Cs-137 detected in the graphite was negligible since it was approximately the same as the background counts. Ta-182, which originated from the tungsten thermocouple sheath, was detected in or near body 1 only because this body operated at a higher temperature.

4.6.3. Primary Containment

A 15-minute multichannel scan was taken on one selected area of the inner surface of the stainless steel primary containment to analyze for fission product plateout. The only isotopes detected were Co-60, Cr-51, Mn-54, and Fe-59, which were constituents of the stainless steel. Therefore, no metallic fission product plateout occurred in the primary containment.

4.7. METALLOGRAPHIC EXAMINATION

Metallographic examination was performed on nine fuel rods 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 of the fuel rods were prepared in the metallographic hot cell using special techniques developed for high-radiation metallography. The rods were mounted and ground to obtain a longitudinal section near the center. After grinding, most specimens were reimpregnated with mounting compound to reduce kernel pullout during polishing. A second polished section of the majority of the fuel rods was taken to increase the population size of the fuel particles examined. Prior to examination, all polished specimens were passivated with a solution of 50/50 $\text{HNO}_3\text{-H}_2\text{O}$ to retard hydrolysis of the UC_2 fuel kernels. All specimens were examined under bright-field illumination and polarized light with a Lietz metallograph. Photographs of representative fissile and fertile particles from the fuel rods examined metallographically are shown in Figs. 4-37 through 4-45.

An evaluation of the fissile, fertile, and inert particle coating failure observed in the fuel rods and unbonded particle samples was made during the metallographic examination; the results are summarized in Tables 4-13 through 4-17. The corresponding 95% confidence intervals for the failure levels, determined using a binomial distribution (Ref. 4-12), are also reported. The 95% confidence statement, which was based on the number of particles examined, means that an infinite population of particles with

attributes of the particle batch tested to these conditions will at the 95% confidence level have a failure level bounded by this interval.

4.7.1. Fuel Rod Matrix

The carbonaceous matrix of all 9 fuel rods examined was judged to be in good condition after irradiation. No significant matrix cracking or other deleterious irradiation effects were observed. Representative photomicrographs of the matrix graphite and composite radial cross sections of the fuel rods are shown in Figs. 4-46 through 4-54.

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 about 100 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. Fuel rod matrix macroporosities, determined by the point-count method (Ref. 4-13) from the photographs of the metallographic cross sections, are reported in Table 4-13. The two rods with the 57.0% pitch and 3% additive matrix had the highest values.

The postirradiation fuel rod macroporosities ranged from 29 to 48 vol % of the matrix phase. Densification of the carbonaceous matrix during irradiation was reflected by an increase in the fuel rod macroporosity. Irradiation-induced change in the fuel rod macroporosities, listed in Table 4-13, ranged from 36 to 97%. The results indicate that the matrix densification usually increased with fast fluence. The precision of the measurements was estimated to be $\pm 2.5\%$ (absolute) at the 95% confidence level based on six measurements made on the same polished section of two different fuel rods of previous capsules (Ref. 4-2). The uncertainty in the fuel rod macroporosity is probably greater than this, however, since macroporosity varies with location in a rod.

4.7.2. Fissile Particles

TRISO coated UC₂ batch 6151-00-010 was used in all fuel rods for the P13Q capsule. Photomicrographs of representative fissile particles of each metallographic rod after irradiation are shown in Figs. 4-37 through 4-45. The results of the metallographic examination indicated a significant amount of OPyC failure and a small pressure vessel failure fraction in some fuel rods (see Table 4-14). A slight chemical reaction of the SiC coating was observed in the rods irradiated at an average peak temperature of >955°C.

Pressure vessel failure, which included all particles with at least the OPyC and SiC coatings broken, ranged from 0 to 4.2% for the fissile particles in the rods. Sometimes the amount of fragmentation was severe as shown in Fig. 4-55. Other times, there were fine cracks in at least the SiC coating and the IPyC was usually intact, as indicated in Fig. 4-56. The fine cracks in the SiC coating may have been a result of metallographic polishing and not irradiation, as noted in Table 4-14. Almost all particles exhibiting pressure vessel failure had relatively faceted coatings.

The observed OPyC failure of batch 6151-00-010 ranged from 0 to 20.8%. No failure was observed in the body 3 rods, which were irradiated at the lowest temperatures and neutron fluences. An example of this type of failure is shown in Fig. 4-57. This example shows gaps in the OPyC coating and the optical anisotropy of the OPyC coating (polarized light photomicrograph). The failed coatings of some particles had fine cracks. Most of the failure was attributed to the high anisotropy caused by low coating rate.

IPyC coating failure ranged from 0.6 to 22.7% and debonding from the SiC coating ranged from 29 to 52% in the nine fuel rods examined. An example of failure and debonding is shown in Fig. 4-58. The amount of cracking and debonding of the IPyC coating did not appear to have any detrimental effects on particle performance. The cracking of the coating was probably due to the dimensional change during irradiation. The polarized light photomicrograph of the preirradiated particles indicated high anisotropy of the IPyC coating (Fig. 4-59).

The buffer coatings densified and a small fraction of cracking occurred in some fuel rods (0 to 9%). Also, the buffer debonded from the IPyC coating in many of the fissile particles. Figure 4-60 shows a particle with a cracked buffer coating which had debonded from the IPyC coating. Cracking and debonding did not affect the other particle components except in one particle where the buffer crack extended through the IPyC coating. The kernels did not extrude into the cracks of the buffer. The interface between the buffer and kernel (only for kernels with segregated microstructure) was perforated with small holes as shown in Fig. 4-56. The holes in the recoil zone may have resulted from a combination of fission recoil damage and interaction with fragments of the fuel kernel.

The UC_2 kernels exhibited acceptable irradiation behavior. No kernel migration or extrusion was observed. Two distinct types of kernel microstructure were observed in the kernels. The kernels in all the fissile particles of rod G3-2A and most of the particles in G3-3A were spherical and contained many fission gas bubbles (see Fig. 4-61). These rods were irradiated in body 3 at average peak temperatures of 915° and 930°C. A few of the kernels in G3-3B and all of the kernels in the other higher temperature rods appeared to be segregated into two main solid phases. Typical kernels are presented in Figs. 5-57 and 4-60. The primary phase, which was white, was probably the high fuel phase. The other phase, which was a light gray, was most likely a high carbon phase. Some of the UC_2 kernels also contained voids. The periphery of these kernels was irregular. Nodules of the white phase sometimes were located in the reaction zone between the buffer and kernel.

Tearing of the OPyC coating of the fissile particles was observed occasionally in the fuel rods examined by metallography and the results are given in Table 4-15. The majority of the OPyC tearing occurred near where two particles were in contact and was caused by a mechanical interaction as shown in Fig. 4-62. There were some torn OPyC coatings which were not where particles were in contact. These tears did not appear to be due to a matrix-coating interaction as observed in Ref. 4-14. Figure 4-63 shows two examples of this type of torn coating on TRISO particles and indicates

the matrix did not cause the fractured OPyC coating. The tearing was probably due to the anisotropy of the coating.

Fission product buildup was detected in the IPyC coatings of 36% to 97% of the fissile particles examined in the fuel rods tested in bodies 2 and 3, which were irradiated at higher temperatures than body 1. A representative example is shown in Fig. 4-64. The optically active areas in the IPyC coating in the polarized light photomicrograph result from the graphitization of the pyrocarbon due to the high concentration of fission products. A significant observation was that the fission products were located randomly around the circumference of the IPyC coating and not predominantly on one side of the particle. This indicates that the thermal gradient was low.

A slight degradation of some of the SiC coatings due to a chemical reaction at the IPyC interface in four of the rods was noted. Photomicrographs of some of the reaction zones are presented in Figs. 4-65 and 4-66. The photographs show small localized reaction zones which did not appear to be dependent on a thermal gradient. Most of the particles had only one or two reaction zones around the circumference of the interface. The depth of the reaction ranged from 2 to 15 μm and the average was 6 μm for the 14 particles with SiC degradation. Each zone of reaction had a small white phase in the IPyC coating adjacent to the SiC coating. No microprobe work was done on the samples; however, the white phase was probably a concentration of fission products. Previous experiments have shown that the chemical reaction of the SiC coating in highly enriched UC_2 TRISO particles was associated with the rare earth elements cerium, neodymium, lanthanum, praseodymium, and samarium (Refs. 4-15 and 4-16). The white phase of the reaction zone was always located in the optically active areas of the IPyC coating (see above). This observation would also support the conclusion that the white phase was fission products. The postirradiation examination of capsules P13R and P13S (Ref. 4-2) also showed slight attack of the SiC coating in the temperature range of 1010° to 1055°C. A comparison of the two examinations revealed fissile particles with similar microstructures except that the reaction zone in P13R and P13S fuel rods was much more

spread out along the SiC - IPyC coating interface than in the P13Q rods where the reaction was more localized. The reaction zones in the TRISO UC_2 particles in the P13Q rods did not cause the SiC coating to fracture. There was one instance where there was a crack in the SiC coating next to the reaction region, but this was apparently an artifact of metallographic polishing.

4.7.3. Fertile Particles

Two BISO coated ThO_2 batches were tested in the P13Q capsule. Batch 6542-01-010, which had a low OPyC coating density (1.80 Mg/m^3), was examined in six of the fuel rods prepared for metallography. The other batch (6542-02-010), which had a medium high OPyC coating density (1.88 Mg/m^3), was analyzed in three rods. Photomicrographs of representative fertile particles from each fuel rod after irradiation are shown in Figs. 4-37 through 4-45.

The results of the metallographic examination given in Table 4-16 indicated that the condition of the fertile particles was good and no OPyC coating failure was observed.

Both the high- and low-density OPyC coatings performed well during irradiation. This is in agreement with the observation that the fertile particles appeared relatively isotropic under polarized light even at the highest fluences. A comparison of the OPyC coatings of the fissile and fertile particles in Figs. 4-37 through 4-45 shows that fissile particle coatings were much more anisotropic than the fertile particle coatings. Comparison of the preirradiation and postirradiation photomicrographs of the fertile particles indicated a decrease in the porosity in the irradiated OPyC coatings. A small amount of tearing of the OPyC coating was observed in fertile batch 6542-01-010 and the results are given in Table 4-15. All tearing occurred near two particles in contact, as shown in Fig. 4-67.

A thin, high-density anisotropic seal coat ($<7\text{ }\mu\text{m}$) was applied between the buffer and OPyC coating in the two fertile batches. The coating, visible under polarized light, was intact in all particles examined from the two rods irradiated in body 3 at fast fluences of $5.7 \times 10^{25}\text{ n/m}^2$ ($E > 29\text{ fJ}$)_{HTGR}. The seal coatings were apparently cracked in the fertile particles tested at higher fluences as would be expected. The cracking of the seal coat did not have any detrimental effect on the buffer and OPyC coatings.

The buffer coating of the two batches performed acceptably during irradiation. A comparison of the preirradiation and postirradiation photomicrographs indicated that the coating had densified considerably and had become optically active (anisotropic) under polarized light. Levels of buffer cracking were low and ranged from 0 to 3.0%. The cracking did not initiate fracture in the OPyC coating. An example of buffer cracking is shown in Fig. 4-68.

The ThO_2 kernels exhibited acceptable irradiation behavior. No kernel migration was observed in any of the fuel rods. The kernels did not crack or deform in shape. The ThO_2 kernels in rod G3-2A, which had a burnup of 1.4%, had a uniform microstructure. Minute pores were evenly dispersed in the kernel structure as shown in Fig. 4-69. All the other rods had a large variation in microstructure. The general trend was that the fine pores in the middle and sometimes in the periphery disappeared, large scattered pores formed, and some grain boundaries became visible in the higher burnup kernels. An example of this structure is shown in Fig. 4-70.

4.7.4. Inert Particles

Two inert particle batches were used in the fuel rods to achieve close particle packing and the desired fuel and shim particle loadings. Both batches contained a carbon kernel; one batch (4361-00-010) had a TRISO coating and the other batch (6641-00-040) had a BISO coating applied to the kernels. Photomicrographs of a representative TRISO and BISO particle after irradiation are shown in Figs. 4-71 and 4-72, respectively.

The results of the metallographic examination which are given in Table 4-17 show that the OPyC coating failure was low for the TRISO and BISO inert particles. The irradiation-induced failure of the TRISO particles was 0 to 2.9%. Two rods examined had BISO OPyC coating failure of 0.5% and 1.0%, which could be attributed to metallographic polishing. OPyC tearing was observed occasionally in both particle types and was similar to the tearing discussed previously for the TRISO UC_2 and BISO ThO_2 . Of all the particle types, the TRISO inert particles exhibited the highest frequency of torn OPyC coatings in the fuel rods.

4.8. X-RAY MICRORADIOGRAPHY

X-ray microradiographs of all of the unbonded (secondary) particle samples were obtained by exposing high-resolution photographic plates to an x-ray pulse from a Picker 110-kV x-ray unit. The particle images on the radiograph plates were then examined to determine the particle dimensions. Preirradiation and postirradiation dimensions obtained for the particle samples are given in Tables 4-18 and 4-19, respectively.

As Table 4-19 indicates, the number of particles measured did not always agree with the number of particles observed during the visual examination (see Section 4.3). Particle sample 6542-01-0130-6 contained 33 particles instead of 30. During removal of the particles from the graphite holders, the extra particles were accidentally transferred from sample 6542-02-013-3. All the other samples with the incorrect number of particles were a result of particles being lost during handling.

Calculated irradiation-induced changes in the particle and coating dimensions are given in Table 4-20. Diametral changes ranged from -2.0 to -3.5% for the BISO coated ThO_2 particles and from -5.1 to -6.7% for the BISO coated inert particles. The BISO inert shrank more than the BISO ThO_2 because of the difference in kernel dimensional change. These data will be used in subsequent fuel rod dimensional change and coated particle design studies.

4.9. DENSITY MEASUREMENTS

Total particle density measurements were made on six BISO coated ThO_2 and three TRISO inert samples irradiated in the P13Q capsule. Sample preparation and density measurements were conducted in the hot cell facility. Small samples were split from the irradiated particle batches and examined using an in-cell stereomicroscope to ensure that all the particles were intact. The samples were cleaned in an ultrasonic bath to remove any surface contamination. A liquid density column technique similar to the one described in Ref. 4-17 was employed to measure the density of the coated particles. Two concentrations of aqueous thallium malonate were blended to provide a uniform density gradient column medium, and a density gradient curve for the liquid column was established with calibrated glass density floats.

The results of the density measurements are given in Table 4-21. The irradiation-induced densification of the BISO ThO_2 particle samples ranged from 11.9% to 13.3%. The results indicated that the degree of densification was similar for the low and high fluences. The data will be used in BISO particle model and design studies. The densification of the BISO inert samples was 20.7% to 22.0%.

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TABLE 4-1
RESULTS OF VISUAL EXAMINATION AND PUSH-OUT SHEAR STRESSES OF FUEL RODS

Fuel Rod Description ^(a)					Irradiation Parameters		Postirradiation Condition		Push-Out Shear Stress (kPa)
Position	Data Retrieval Number	Matrix Composition ^(b)	Fuel Rod Fabrication Process	Firing Medium	Average Peak Temperature (°C)	Average Fast Fluence, 10^{25} n/m^2 (E > 29 fJ) _{HTGR}	Appearance	Number of Particles Debonded	
G3-1A ^(c)	7161-002-19-2	(d)	Hot injection	H-451 ^(e)	915	4.3	Excellent	2	< 2
G3-2A ^(c)	7161-002-20-3	(d)	Hot injection	H-451 ^(e)	915	4.3	Excellent	6	< 2
G3-3A ^(c)	7161-002-21-3	(d)	Hot injection	H-451 ^(e)	915	4.3	Excellent	0	4
G3-1B	7261-002-10-3	(d)	Admix-compaction	H-451 ^(e)	930	5.7	Excellent	0	< 2
G3-2B	7261-002-11-8	(d)	Admix-compaction	H-451 ^(f)	930	5.7	Excellent	0	< 2
G3-3B	7261-002-12-8	(d)	Admix-compaction	H-451 ^(f)	930	5.7	Excellent	0	4
G2-1A	7261-002-13-3	(d)	Admix-compaction	H-451 ^(e)	945	7.2	Excellent	2	< 2
G2-2A	7261-002-14-3	(g)	Admix-compaction	H-451 ^(e)	945	7.2	Excellent	10	< 2
G2-3A	7261-002-15-3	(h)	Admix-compaction	H-451 ^(e)	945	7.2	Excellent	2	6
G2-1B	7161-002-13-3	(d)	Hot injection	H-451 ^(e)	955	8.1	Excellent	15	< 2
G2-2B	7161-002-14-3	(g)	Hot injection	H-451 ^(e)	955	8.1	Excellent	0	< 2
G2-3B	7161-002-15-8	(h)	Hot injection	H-451 ^(f)	955	8.1	Excellent	14	6
G1-1A	7261-002-16-8	(d)	Admix-compaction	H-451 ^(f)	1120	9.0	Excellent	7	9
G1-2A	7261-002-17-3	(d)	Admix-compaction	PB ^(h)	1120	9.0	Excellent	0	27
G1-3A	7261-002-18-5	(d)	Admix-compaction	H-451 ^(e)	1120	9.0	Excellent	1	6
G1-1B	7161-002-16-8	(d)	Hot injection	H-451 ^(f)	1175	9.5	Excellent	0	9
G1-2B	7161-002-17-3	(d)	Hot injection	PB ⁽ⁱ⁾	1175	9.5	Excellent	29	27
G1-3B	7161-002-18-8	(d)	Hot injection	H-451 ^(f)	1175	9.5	Excellent	4	6

(a) All fuel rods also contain TRISO UC₂ particles (6151-00-0100), BISO ThO₂ particles (6542-01-0100 or 6542-02-0100), TRISO inert particles (4361-00-0100), and BISO inert particles (6641-00-0400).

(b) All fuel rods contain Great Lakes Carbon Corporation type 1099 near-isotropic graphite shim particles.

(c) Thermocouple fuel rod.

(d) 40% type 1089 isotropic graphite filler, 54% type A240 petroleum pitch, and 6% SC011 (octadecanol) additive.

(e) Fired in H-451 near-isotropic graphite tube to simulate LHTGR cured-in-block process.

(f) Fired in P13Q graphite bodies made of type H-451 near-isotropic graphite.

(g) 40% type 1089 isotropic graphite filler and 60% type A240 petroleum pitch.

(h) 30% type 6353 natural-flake graphite filler, 67% type A240 petroleum pitch, and 3% SC011 (octadecanol) additive.

(i) Fired in packed bed of alumina (reference Fort St. Vrain process).

TABLE 4-2
RESULTS OF VISUAL EXAMINATION OF UNBONDED PARTICLE PIGGYBACK SAMPLES

Batch Number	Sample Position	Hole Number	Particle Type	Average Centerline Temperature (°C)	Fast Fluence (10^{25} n/m ²) (E > 29 fJ) _{HTGR}	Heavy Metal Burnup (% FIMA)	Number of Particles Examined	Coating Failure (%)	
								OPyC	Total
6542-01-0130	G1-PB1/2-D	17	ThO ₂ BISO	795	9.6	6.0	30	0	0
6151-00-0130	G1-PB1/2-A	14	UC ₂ BISO	795	8.8	76.0	29	0	0
6542-01-0130	G1-PB2/3-E	18	ThO ₂ BISO	795	9.6	6.0	30	0	0
6151-00-0130	G1-PB2/3-A	15	UC ₂ TRISO	795	8.8	76.0	30	16.6	3.3
6641-00-0430	G1-PB3/1-F	16	Inert BISO	795	9.6	0	29	0	0
6542-02-0130	G1-PB3/1-A	13	ThO ₂ BISO	795	9.2	5.5	30	0	0
4163-00-0140	G2-PB1/2-D	11	(Th,U)O ₂ TRISO	755	8.6	40.2	30	0	0
6542-01-0130	G2-PB1/2-A	8	ThO ₂ BISO	740	6.8	2.9	30	0	0
5466-037-132	G2-PB2/3-E	12	(Th,U)O ₂ TRISO	755	8.6	40.9	30	0	0
4252-06-0120	G2-PB2/3-A	9	ThO ₂ BISO	740	6.8	2.9	30	0	0
6641-00-0430	G2-PB3/1-A	7	Inert BISO	740	8.6	0	30	0	0
4163-00-0140	G2-PB3/1-E	10	(Th,U)O ₂ TRISO	755	6.8	40.2	30	0	0
6151-00-0130	G3-PB1/2-D	5	UC ₂ TRISO	695	6.3	70.2	30	0	0
6542-01-0130	G3-PB1/2-A	2	ThO ₂ BISO	660	3.6	1.2	30	0	0
6151-00-0130	G3-PB2/3-D	6	UC ₂ TRISO	695	6.3	70.2	30	0	0
6542-01-0130	G3-PB2/3-A	3	ThO ₂ BISO	660	3.6	1.2	30	0	0
6641-00-0430	G3-PB3/1-E	4	Inert BISO	695	6.3	0	30	0	0
6542-02-0130	G3-PB3/1-A	1	ThO ₂ BISO	660	3.6	1.2	29	0	0

TABLE 4-3
FUEL ROD DIMENSIONAL CHANGE DATA OBTAINED FROM CAPSULE P13Q

Capsule Position	Fuel Rod Data Retrieval Number	Irradiation Conditions		Measured Dimensions (mm)						Dimensional Change ^(d)			
				Average Diameter ^(a)				Length					
		Average Volume Temperature (°C)	Average Fast Fluence (10 ²⁵ n/m ²) (E > 29 fJ) HTGR	Preirradiation ^(b)		Postirradiation ^(c)				ΔD/D ₀ (%)		ΔL/L (%) ^o	ΔV/V (%) ^o
				Mean	Standard Deviation	Mean	Standard Deviation						
G3 1A	7161-002-019-3	855	4 3	15 76	1 7 x 10 ⁻²	15 57	1 9 x 10 ⁻²	55 00	54 41	-1 24	0 07	-1 06	-3 50
G3-2A	7161-002-20-3	855	4 3	15 77	2 5 x 10 ⁻²	15 57	2 7 x 10 ⁻²	55 77	55 25	-1 25	0 07	-0 93	-3 41
G3 3A	7161-002-21-3	855	4 3	15 78	3 9 x 10 ⁻³	15 50	2 5 x 10 ⁻²	55 89	55 10	-1 55	0 15	-1 41	-4 84
G3-1B	7261-002-10-3	880	5 7	15 75	3 0 x 10 ⁻²	15 49	1 7 x 10 ⁻²	54 44	53 82	-1 64	0 14	-1 18	-4 36
G3-2B	7261-002-11-8	880	5 7	15 79	2 2 x 10 ⁻²	15 54	2 0 x 10 ⁻²	54 58	53 70	-1 85	0 14	-1 45	-5 07
G3-3B	7261-002-12-8	880	5 7	15 78	1 8 x 10 ⁻²	15 47	2 4 x 10 ⁻²	54 55	53 64	-2 02	0 14	-1 67	-5 59
G2 1A	7261-002-13-3	905	7 2	15 74	3 6 x 10 ⁻²	15 46	3 0 x 10 ⁻²	54 49	53 88	-1 83	0 27	-1 10	-4 68
G2 2A	7261-002-14-3	905	7 2	15 76	2 8 x 10 ⁻²	15 46	2 1 x 10 ⁻²	54 03	53 30	-1 88	0 14	-1 34	-5 03
G2 3A	7261-002-15-3	905	7 2	15 76	4 7 x 10 ⁻²	15 45	2 3 x 10 ⁻²	53 76	53 40	-1 96	0 17	-0 67	-4 54
G2-1B	7161-002-13-3	930	8 1	15 77	1 4 x 10 ⁻²	15 48	2 6 x 10 ⁻²	54 03	53 74	-1 84	0 16	-0 54	-4 16
G2 2B	7161-002-14-3	930	8 1	15 77	1 3 x 10 ⁻²	15 49	1 9 x 10 ⁻²	54 04	53 48	-1 81	0 10	-1 05	-4 59
G2 3B	7161-002-15-8	930	8 1	15 80	6 1 x 10 ⁻³	15 49	2 3 x 10 ⁻²	54 19	53 65	-1 98	0 18	-0 99	-4 86
G1 1A	7261-002-16-8	1105	9 0	15 77	1 3 x 10 ⁻²	15 54	2 5 x 10 ⁻²	54 46	54 37	-1 49	0 18	-0 17	-3 11
G1-2A	7261-002-17-3	1105	9 0	15 73	4 4 x 10 ⁻²	15 56 ^(e)	4 9 x 10 ⁻²	54 03	53 93	-1 09 ^(e)	0 20	-0 18	-2 33
G1-3A	7261-002-18-5	1105	9 0	15 76	1 7 x 10 ⁻²	15 51	2 3 x 10 ⁻²	54 26	54 04	-1 57	0 24	-0 42	-3 51
G1 1B	7161-002-16-8	1160	9 5	15 80	1 7 x 10 ⁻²	15 59	1 9 x 10 ⁻²	54 17	53 88	-1 36	0 13	-0 52	-3 22
G1-2B	7161-002-17-3	1160	9 5	15 76	4 0 x 10 ⁻²	15 57	3 6 x 10 ⁻²	53 46	53 25	1 22	0 10	-0 40	-2 82
G1-3B	7161-002-18-8	1160	9 5	15 79	1 6 x 10 ⁻²	15 54	2 3 x 10 ⁻²	53 75	53 27	-1 57	0 16	-0 88	-3 98

(a) The average of six measurements taken at the same 0° and 90° positions for the top, middle and bottom of the rods before and after irradiation except where noted

(b) Measured with a ratchet barrel micrometer

(c) Measured with a dial gauge micrometer

(d) Δ signifies final minus initial dimension and the subscript o means initial dimension

(e) The postirradiation 0° and 90° orientations were different from the preirradiation 0° and 90° orientation

TABLE 4-4
MEASURED DIAMETRAL DIMENSIONAL CHANGES OF H-451 GRAPHITE FUEL BODIES FOR P13Q CAPSULE

Body	Position	Diameter (mm)				Diametral Dimensional Change ΔD/D _o (%)			Fast Fluence (10 ²⁵ n/m ²) (E > 29 fJ) _{HTGR}	Average Temp. ^(a) (°C)	Distance From Bottom of Core (mm)
		Pre-Irrad.	Avg.	Postirrad.		Avg.	0°	90°			
				0°	90°						
G3	Top	61.01	60.81	60.80	60.81	-0.33	-0.34	-0.32	3.6	730	584
	Center	61.26	60.93	60.93	60.93	-0.55	-0.55	-0.55	5.0	745	533
	Bottom	61.26	60.81	60.82	60.81	-0.74	-0.73	-0.75	6.2	755	483
G2	Top	61.47	60.89	60.89	60.90	-0.93	-0.94	-0.93	6.8	810	457
	Center	61.47	60.82	60.82	60.82	-1.05	-1.05	-1.05	7.7	825	406
	Bottom	61.47	60.72	60.75	60.69	-1.21	-1.17	-1.26	8.5	835	356
G1	Top	61.54	60.72	60.66	60.79	-1.34	-1.44	-1.23	8.8	870	330
	Center	61.54	60.78	60.73	60.83	-1.24	-1.32	-1.16	9.3	870	279
	Bottom	61.54	60.62	60.58	60.67	-1.49	-1.56	-1.42	9.6	870	229

(a) Calculated by time averaging the temperatures measured by the thermocouples in the graphite. The temperature given are an approximation of the actual temperature.

TABLE 4-5
FUEL BODY TRIGA FISSION GAS RELEASE DATA

Fuel Body Number	EOL Fissile Loading ^(a) (mg U-235)	Measurement Temperature (°C)	TRIGA Fission Gas Release (R/B Kr-85m)
G1	307.2	1100	7.8×10^{-5}
G2	437.6	950	3.0×10^{-5}
G2	437.6	1100	6.4×10^{-5}
G3	837.7	1100	9.7×10^{-6}

(a) EOL fissile loading is the weight of U-235 which would produce the equivalent Kr-85m yield of all fissionable material calculated to be in the sample.

TABLE 4-6
FUEL ROD TRIGA FISSION GAS RELEASE DATA

Data Retrieval Number	Capsule Position	EOL Fissile Loading ^(a) (mg U-235)	TRIGA Fission Gas Release Data (R/B Kr-85m at 1100°C)	
			BOL ^(b)	EOL
7161-002-19-3	G3-1A	156.7	$<1.0 \times 10^{-7}$	6.8×10^{-7}
7161-002-20-3	G3-2A	162.6	1.5×10^{-7}	2.9×10^{-7}
7161-002-21-3	G3-3A	154.8	2.4×10^{-7}	0
7261-002-10-3	G3-1B	120.7	1.3×10^{-6}	2.8×10^{-6}
7261-002-11-8	G3-2B	121.2	$<1.0 \times 10^{-7}$	6.1×10^{-6}
7261-002-12-8	G3-3B	121.7	5.1×10^{-7}	5.9×10^{-5}
7261-002-13-3	G2-1A	84.9	1.8×10^{-6}	2.5×10^{-5}
7261-002-14-3	G2-2A	83.8	1.8×10^{-6}	1.2×10^{-4}
7261-002-15-3	G2-3A	78.6	5.6×10^{-6}	4.8×10^{-5}
7161-002-13-3	G2-1B	62.5	4.2×10^{-7}	5.1×10^{-5}
7161-002-14-3	G2-2B	63.6	4.6×10^{-6}	8.8×10^{-5}
7161-002-15-8	G2-3B	64.2	3.4×10^{-7}	8.5×10^{-5}
7261-002-16-8	G1-1A	53.9	1.1×10^{-6}	4.8×10^{-5}
7261-002-17-3	G1-2A	54.1	7.9×10^{-6}	6.1×10^{-5}
7261-002-18-5	G1-3A	52.2	3.0×10^{-5}	7.9×10^{-5}
7161-002-16-8	G1-1B	48.9	1.6×10^{-6}	5.9×10^{-5}
7161-002-17-3	G1-2B	49.3	9.8×10^{-6}	7.2×10^{-5}
7161-002-18-8	G1-3B	48.8	$<1.0 \times 10^{-7}$	6.5×10^{-5}

(a) EOL fissile loading is the weight of U-235 which would produce the equivalent Kr-85m yield of all fissionable material calculated to be in the sample.

(b) Beginning-of-life (BOL) measurements were made during quality control evaluation to determine the amount of heavy metal contamination in the fuel specimens prior to irradiation.

TABLE 4-7
CONTRIBUTION OF FUEL ROD FISSION GAS RELEASE
TO GRAPHITE FUEL BODY FISSION GAS RELEASE

Data Retrieval Number	Capsule Position	Measured TRIGA EOL R/B ^(a)	Fraction of Fissions in Sample ^(b)	Contribution to Fuel Body R/B ^(a)
7161-002-19-3	G3-1A	6.8×10^{-7}	0.187	1.3×10^{-7}
7161-002-20-3	G3-2A	2.9×10^{-7}	0.194	5.6×10^{-8}
7161-002-21-3	G3-3A	0	0.185	0
7261-002-10-3	G3-1B	2.8×10^{-6}	0.144	4.0×10^{-7}
7261-002-11-8	G3-2B	6.1×10^{-6}	0.145	8.8×10^{-7}
7261-002-12-8	G3-3B	5.9×10^{-5}	0.145	8.6×10^{-6}
7261-002-13-3	G2-1A	2.5×10^{-5}	0.194	4.9×10^{-6}
7261-002-14-3	G2-2A	1.2×10^{-4}	0.191	2.3×10^{-5}
7261-002-15-3	G2-3A	4.8×10^{-5}	0.180	8.6×10^{-6}
7161-002-13-3	G2-1B	5.1×10^{-5}	0.143	7.3×10^{-6}
7161-002-14-3	G2-2B	8.8×10^{-5}	0.145	1.3×10^{-5}
7161-002-15-8	G2-3B	8.5×10^{-5}	0.147	1.2×10^{-5}
7261-002-16-8	G1-1A	4.8×10^{-5}	0.175	8.4×10^{-6}
7261-002-17-3	G1-2A	6.1×10^{-5}	0.176	1.1×10^{-5}
7261-002-18-5	G1-3A	7.9×10^{-5}	0.170	1.3×10^{-5}
7161-002-16-8	G1-1B	5.9×10^{-5}	0.159	9.4×10^{-6}
7161-002-17-3	G1-2B	7.2×10^{-5}	0.160	1.2×10^{-5}
7161-002-18-8	G1-3B	6.5×10^{-5}	0.159	1.0×10^{-5}

(a) R/B of Kr-85m at 1100°C.

(b) 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 fuel body at EOL.

TABLE 4-8
COMPARISON BETWEEN MEASURED AND CALCULATED
FUEL BODY TRIGA FISSION GAS RELEASE

Body	Fuel Body R/B ^(a)		Difference (%)
	Measured	Calculated ^(b)	
G3	9.7×10^{-6}	1.0×10^{-5}	-3.1
G2	6.4×10^{-5}	6.9×10^{-5}	-7.8
G1	7.8×10^{-5}	6.4×10^{-5}	+17.9

(a) R/B of Kr-85m at 1100°C.

(b) Calculated by adding the contribution from each fuel rod in the body (see Table 4-6).

TABLE 4-9
GASEOUS FISSION PRODUCT RELEASE (R/B Kr-85m) RESULTING FROM IN-SERVICE FUEL PARTICLE FAILURE IN CAPSULE P13Q FUEL RODS

Data Retrieval Number	Capsule Position	Th _c ^(a) (kg Th/kg Th)	R/B _{EOL}	Fraction Fissions at EOL ^(b)		R/B _c (Th) ^(c)	R/B _c (U)	R/B _{EOL}	R/B Failed Fuel	In Service Particle Failure ^(d) (%)	Maximum Fertile Particle Failure ^(d,e) (%)
				Fissile	Fertile						
7161-002-19-3	G3-1A	7.3×10^{-5}	$<1 \times 10^{-7}$	0.207	0.793	1.7×10^{-5}	2.1×10^{-8}	6.8×10^{-7}	0	0	0
7161-002-20-3	G3-2A	$<6.0 \times 10^{-7}$	1.5×10^{-7}	0.202	0.798	1.4×10^{-7}	3.0×10^{-8}	2.9×10^{-7}	1.2×10^{-7}	0	0
7161-002-21-3	G3-3A	$<6.0 \times 10^{-7}$	2.4×10^{-7}	0.201	0.799	1.4×10^{-7}	4.8×10^{-8}	0	0	0	0
7261-002-10-3	G3-1B	1.6×10^{-6}	1.3×10^{-6}	0.141	0.859	4.1×10^{-7}	1.8×10^{-7}	2.8×10^{-6}	2.2×10^{-6}	0.04	0.05
7261-002-11-8	G3-2B	6.6×10^{-5}	$<1 \times 10^{-7}$	0.140	0.860	1.7×10^{-5}	1.4×10^{-8}	5.1×10^{-6}	0	0	0
7261-002-12-8	G3-3B	$<9.0 \times 10^{-7}$	5.1×10^{-7}	0.140	0.860	2.3×10^{-7}	7.1×10^{-8}	5.9×10^{-5}	5.9×10^{-5}	1.2	1.4
7261-002-13-3	G2-1A	5.5×10^{-6}	1.8×10^{-6}	0.092	0.908	1.5×10^{-6}	1.7×10^{-7}	2.5×10^{-5}	2.3×10^{-5}	0.46	0.5
7261-002-14-3	G2-2A	$<1.3 \times 10^{-6}$	1.8×10^{-6}	0.093	0.907	3.5×10^{-7}	1.7×10^{-7}	1.2×10^{-4}	1.2×10^{-4}	2.4	2.6
7261-002-15-3	G2-3A	5.3×10^{-5}	5.6×10^{-6}	0.100	0.900	1.4×10^{-5}	5.6×10^{-7}	4.8×10^{-5}	3.3×10^{-5}	0.67	0.7
7161-002-13-3	G2-1B	$<1.8 \times 10^{-6}$	4.2×10^{-7}	0.081	0.919	5.0×10^{-7}	3.4×10^{-8}	5.1×10^{-5}	5.0×10^{-5}	1.0	1.1
7161-002-14-3	G2-2B	1.5×10^{-5}	4.6×10^{-6}	0.081	0.919	4.1×10^{-6}	3.7×10^{-7}	8.8×10^{-5}	8.4×10^{-5}	1.7	1.8
7161-002-15-8	G2-3B	4.7×10^{-4}	3.4×10^{-7}	0.081	0.919	$2.7 \times 10^{-6(f)}$	2.8×10^{-8}	8.5×10^{-5}	8.3×10^{-5}	1.7	1.8
7261-002-16-8	G1-1A	$<2.0 \times 10^{-6}$	1.1×10^{-6}	0.071	0.929	5.6×10^{-7}	7.8×10^{-8}	4.8×10^{-5}	4.7×10^{-5}	0.94	1.0
7261-002-17-3	G1-2A	$<2.0 \times 10^{-6}$	7.9×10^{-6}	0.069	0.931	5.6×10^{-7}	5.5×10^{-7}	6.1×10^{-5}	6.0×10^{-5}	1.2	1.3
7261-002-18-5	G1-3A	$<4.1 \times 10^{-6}$	3.0×10^{-5}	0.071	0.929	1.1×10^{-6}	2.1×10^{-6}	7.9×10^{-5}	7.6×10^{-5}	1.5	1.6
7161-002-16-8	G1-1B	4.1×10^{-5}	1.6×10^{-6}	0.070	0.930	1.1×10^{-5}	1.1×10^{-7}	5.9×10^{-5}	4.8×10^{-5}	1.0	1.0
7161-002-17-3	G1-2B	$<2.2 \times 10^{-6}$	9.8×10^{-6}	0.070	0.930	6.1×10^{-7}	6.9×10^{-7}	7.2×10^{-5}	7.1×10^{-5}	1.4	1.5
7161-002-18-8	G1-3B	9.1×10^{-6}	$<1 \times 10^{-7}$	0.071	0.929	2.5×10^{-6}	7.1×10^{-9}	6.5×10^{-5}	6.2×10^{-5}	1.2	1.3

(a) Thorium contamination level was measured on an unirradiated companion rod by the thorium hydrolysis test

(b) Calculated using FISSPROD computer program. Values were normalized to Kr-85m thermal fission yields

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

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

(e) Calculated assuming all fission gas release came from failed fertile particles

(f) A fractional release of 5×10^{-3} was used to calculate R/B_c(Th) because the high thorium contamination level measured for this fuel rod probably resulted from a broken particle rather than surface contamination

TABLE 4-10
CONTRIBUTION OF INDIVIDUAL FUEL ROD R/B VALUES TO THE TOTAL CAPSULE R/B LEVEL

Data Retrieval Number	Capsule Position	Volume Average Temperature ^(a) (°C)	Measured TRIGA EOL R/B at 1100°C	Temperature Correction Factor	TRIGA R/B at Vol. Avg. Temp. ^(b)	Fraction of Fissions ^(c) in Sample	Contribution to Total Capsule R/B
7161-002-19-3	G3-1A	892	6.8×10^{-7}	0.390	2.6×10^{-7}	0.099	2.6×10^{-8}
7161-002-20-3	G3-2A	892	2.9×10^{-7}	0.390	1.1×10^{-7}	0.103	1.1×10^{-8}
7161-002-21-3	G3-3A	892	0	0.390	0	0.098	0
7261-002-10-3	G3-1B	892	2.8×10^{-6}	0.390	1.1×10^{-6}	0.076	8.4×10^{-8}
7261-002-11-8	G3-2B	892	6.1×10^{-6}	0.390	2.4×10^{-6}	0.076	1.8×10^{-7}
7261-002-12-8	G3-3B	892	5.9×10^{-5}	0.390	2.3×10^{-5}	0.077	1.8×10^{-6}
7261-002-13-3	G2-1A	893	2.5×10^{-5}	0.390	9.8×10^{-6}	0.054	5.3×10^{-7}
7261-002-14-3	G2-2A	893	1.2×10^{-4}	0.390	4.7×10^{-5}	0.053	2.5×10^{-6}
7261-002-15-3	G2-3A	893	4.8×10^{-5}	0.390	1.9×10^{-5}	0.050	9.5×10^{-7}
7161-002-13-3	G2-1B	894	5.1×10^{-5}	0.390	2.0×10^{-5}	0.040	8.0×10^{-7}
7161-002-14-3	G2-2B	894	8.8×10^{-5}	0.390	3.4×10^{-5}	0.040	1.4×10^{-6}
7161-002-15-8	G2-3B	894	8.5×10^{-5}	0.390	3.3×10^{-5}	0.040	1.3×10^{-6}
7261-002-16-8	G1-1A	1089	4.8×10^{-5}	0.948	4.6×10^{-5}	0.034	1.6×10^{-6}
7261-002-17-3	G1-2A	1089	6.1×10^{-5}	0.948	5.8×10^{-5}	0.034	2.0×10^{-6}
7261-002-18-5	G1-3A	1089	7.9×10^{-5}	0.948	7.5×10^{-5}	0.033	2.5×10^{-6}
7161-002-16-8	G1-1B	1144	5.9×10^{-5}	1.182	7.0×10^{-5}	0.031	2.2×10^{-6}
7161-002-17-3	G1-2B	1144	7.2×10^{-5}	1.182	8.5×10^{-5}	0.031	2.6×10^{-6}
7161-002-18-8	G1-3B	1144	6.5×10^{-5}	1.182	7.7×10^{-5}	0.031	2.4×10^{-6}

(a) Volume average irradiation temperature at the time the EOL in-pile fission gas release measurements were made.

(b) Measured TRIGA fission gas release data corrected to the 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 capsule at EOL.

TABLE 4-11
FISSION PRODUCT INVENTORY^(a) OF FUEL RODS IRRADIATED IN CAPSULE P13Q

Fission Product Isotope ^(a)	Average Isotope Counting Error ^(b) 2σ (%)	Fission Product Isotope Inventory ^(c) (C1)																	
		G1-1A ^(d,e)	G1-1B	G1-2A	G1-2B	G1-3A	G1-3B	G2-1A ^(e)	G2-1B	G2-2A	G2-2B	G2-3A	G2-3B	G3-1A ^(e)	G3-1B	G3-2A	G3-2B	G3-3A	G3-3B
Pu-233	0.5	250	230	257	227	226	214	240	234	247	233	235	214	257	261	263	265	249	250
Ru-103	3.0	4.62	4.51	4.80	4.33	4.35	4.12	4.76	4.28	4.84	4.35	4.72	4.21	5.94	5.70	6.26	5.65	5.60	5.46
Ru-106	13.5	0.59	0.59	0.63	0.58	0.59	0.51	0.53	0.66	0.53	0.48	0.47	0.35	0.65	0.55	0.69	0.66	0.72	0.58
Cs-134	1.9	1.13	1.16	1.17	1.10	1.01	1.05	0.87	1.00	0.95	1.07	0.86	0.95	0.54	0.84	0.57	0.82	0.57	0.74
Cs-137	2.1	0.63	0.63	0.64	0.58	0.57	0.56	0.56	0.60	0.59	0.60	0.55	0.56	0.64	0.66	0.62	0.64	0.61	0.60
Ce-144	7.1	9.79	8.87	9.94	10.00	9.49	8.42	8.87	7.91	9.07	8.88	9.92	9.38	11.10	10.60	9.80	11.00	9.85	10.80
Zr-95	0.9	16.40	15.30	16.50	14.50	14.60	13.90	15.20	15.30	16.10	15.10	15.40	13.90	18.00	18.20	18.30	18.00	17.40	17.20

(a) Gamma counted using a lithium-drifted gamma ray spectrometer coupled to a 4096-channel Sigma 2 computer analyzer.

(b) Calculated as follows:

$$2\sigma = \frac{2 \left\{ \text{CNT} + \left(1 - \frac{\text{CH}}{2}\right)^2 \left[\frac{(\text{LC} + \text{RC})}{\text{PTS}} \right] \right\}^{1/2}}{\text{Peak} \times 100}$$

where CNT = total counts in peak (peak and background)

CH = number of channels in peak

LC = counts in lowest energy channel

RC = counts in highest energy channel

PTS = number of smoothing points

Peak = counts in peak

(c) Fission product inventory decayed back to end-of-life. The values for all the rods except the internal standard rods were calculated using a calibration curve which was derived from selected internal standards. Therefore, the values are relative to the internal standards.

(d) G1-1A = fuel rod identification (position in fuel body).

(e) This rod was used as one of the internal standards. The values for this rod was obtained from the measured cpm and the theoretical inventory calculated by using the FISSPROD program for each isotope.

TABLE 4-12
GAMMA SPECTROSCOPY RESULTS OF P13Q FUEL GRAPHITE BODIES

Fuel Hole 1					Fuel Hole 2					Fuel Hole 3				
Body Number	Spectrum Number	Axial Position (mm)	Isotopes Detected		Body Number	Spectrum Number	Axial Position (mm)	Isotopes Detected		Body Number	Spectrum Number	Axial Position (mm)	Isotopes Detected	
			Cu-137 ^(c) (696 KeV) (uCi)	Ta-182 ^(d) (1121 KeV) (cpm/A I)				Cu-137 ^(c) (696 KeV) (uCi)	Ta-182 ^(d) (1121 KeV) (cpm/A I)				Cu-137 ^(c) (661 KeV) (uCi)	Ta-182 ^(d) (1121 KeV) (cpm/A I)
(Position)					(Position)					(Position)				
1 (top)	3452	5 6	111	426	1 (top)	3554	0 3	119	220	1 (top)	3640	6 7	127	1014
		to					to					to		
	3453	13 9	0	401		3555	9 6	175	480		3641	15 4	0	993
		to					to					to		
	3454	22 2	185	430		3556	18 8	119	458		3642	24 0	0	800
		to					to					to		
	3455	30 5	71	448		3557	28 0	0	458		3643	32 7	127	913
		to					to					to		
	3456	38 8	71	520		3558	37 3	0	422		3644	41 4	135	858
		to					to					to		
	3457	47 1	0	491		3559	46 5	135	426		3645	50 0	0	753
		to					to					to		
	3458	55 4	0	477		3560	55 8	0	350		3646	58 7	0	702
		to					to					to		
	3459	63 8	63	426		3561	65 0	0	249		3647	67 3	0	702
		to					to					to		
	3460	72 1	0	412		3562	74 3	0	437		3648	76 0	63	804
		to					to					to		
	3461	80 4	0	491		3563	83 5	0	516		3649	84 7	127	782
		to					to					to		
	3462	88 7	0	516		3564	92 8	0	419		3650	93 3	0	662
		to					to					to		
(bottom)	3463	97 0	63	563		3565	102 0	0	404	(bottom)	3651	102 0	0	589
		to					to					to		
2 (top)	3464	105 3	0	631	(bottom)	3566	111 3	103	285	2 (top)	3652	110 6	0	407
		to					to					to		
	3465	114 1	175	462	2 (top)	3567	120 5	151	0		3653	119 3	135	0
		to					to					to		
	3466	121 9	159	0		3568	129 7	111	0		3654	128 0	167	0
		to					to					to		
	3467	130 2	0	0		3569	139 0	143	0		3655	136 6	0	0
		to					to					to		
	3468	138 5	167	0		3570	148 1	135	0		3656	145 3	175	0
		to					to					to		
	3469	146 8	0	0		3571	157 5	0	0		3657	154 0	159	0
		to					to					to		
	3470	155 1	184	0		3572	166 7	135	0		3658	162 6	127	0
		to					to					to		
	3471	163 4	175	0		3573	176 0	48	0		3659	171 3	159	0
		to					to					to		
	3472	171 7	56	6		3574	185 3	0	0		3660	179 9	135	0
		to					to					to		
	3473	180 0	111	4		3575	194 5	24	0		3661	188 6	127	0
		to					to					to		
	3474	188 3	143	9		3576	203 7	16	0		3662	197 3	87	0
		to					to					to		
(bottom)	3475	196 6	95	6	3 (bottom)	3577	213 0	111	0	3 (bottom)	3663	205 9	0	10
3 (top)		to			3 (top)		to			3 (top)		to		
	3476	205 0	135	0		3578	222 2	0	0		3664	214 6	135	11
		to					to					to		
	3477	213 3	95	0		3579	231 4	103	0		3665	223 2	71	13
		to					to					to		
	3478	221 6	135	18		3580	240 7	175	0		3666	231 9	151	0
		to					to					to		
	3479	229 9	0	0		3581	249 9	175	0		3667	240 6	111	0
		to					to					to		
	3480	238 2	143	0		3582	259 2	190	0		3668	249 5	151	0
		to					to					to		
	3481	246 5	190	0		3583	268 4	0	0		3669	257 9	167	0
		to					to					to		
	3482	254 8	159	0		3584	277 7	167	0		3670	266 5	0	0
		to					to					to		
	3483	263 1	0	0		3585	286 8	127	0		3671	275 2	95	0
		to					to					to		
	3484	271 4	13	0		3586	296 2	206	0		3672	283 9	103	0
		to					to					to		
	3485	279 7	0	0		3587	305 4	151	0		3673	292 5	103	0
		to					to					to		
	3486	288 0	103	0		3588	314 7	159	0		3674	301 2	151	0
		to					to					to		
	3487	296 3	79	0		3589	323 9	135	0		3675	309 9	103	0
		to					to					to		
	3488	304 6	151	0	(bottom)	3590	333 1	0	0	(bottom)	3676	318 5	167	0
		to			Background		to			Background		to		
	3489	312 9	111	0		3591	342 4	56	0		3677	327 2	151	0
		to					to					to		
	3490	321 2	0	0		3592	351 6	0	0		3678	335 8	63	0
		to					to					to		
(bottom)	3491	329 5	0	0		3593	360 9	0	0		3679	344 5	135	0
Background		to					to					to		
	3492	337 8	151	0		3594	370 1	95	0		3680	353 2	111	0
		to					to					to		
	3493	346 2	135	0		3595	379 4	95	0		3681	361 8	0	0
		to					to					to		
	3494	354 5	103	0		3596	388 6	119	0		3682	370 5	95	0
		to					to					to		
	3495	362 8	95	0			397 9				3683	379 1	111	0
		to										to		
	3496	371 1	0	0								to		
		to										to		
	3497	379 4	63	0								to		
		to										to		
		387 7										387 8		

- (a) All spectrum decayed to end-of-life, background was not subtracted out from the measured values
(b) All three graphite bodies and the fuel holes were aligned and the column was moved slowly past the collimator. The centers of the collimator and each fuel hole were lined up for the measurements
(c) The counting efficiency calibration curve for fuel rods was used to calculate these values. These are relative values.
(d) The units are counts per minute/absolute intensity. These are relative values.

TABLE 4-13
RESULTS OF MATRIX MACROPOROSITY MEASUREMENTS OF CAPSULE P13Q FUEL RODS

Capsule Position	Fuel Rod Data Retrieval Number	Irradiation Conditions		Macroporosity ^(a) (%)			Fuel Rod Variables						
		Average Peak Temperature (°C)	Average Fast Fluence (10 ²⁵ n/m ²) (E > 29 fJ) _{HTGR}	Measured		Change ^(b)	Matrix Composition				Fuel Rod Fabrication Process	Medium	Final Firing Temp (°C)
				Pre- irrad	Post- irrad		Filler		A240 Pitch	Octadecanol Additive (SC011)			
							1089	6353					
G3-2A	7161-002-20-3	915	4.3	21	29	+36	40	0	54	6	Hot Injection ^(c)	H-451	1500
G3-3B	7261-002-12-8	930	5.7	21	29	+37	40	0	54	6	Admix Compaction	H-451	1800
G2-3A	7261-002-15-3	945	7.2	31	44	+41	0	30	57	3	Admix Compaction	H-451	1800
G2-1B	7161-002-13-3	955	8.1	19	37	+97	40	0	54	6	Hot Injection	H-451	1800
G2-2B	7161-002-14-3	955	8.1	24	36	+49	40	0	60	0	Hot Injection	H-451	1800
G2-3B	7161-002-15-8	955	8.1	35	38	+38	0	30	57	3	Hot Injection	H-451	1800
G1-3A	7261-002-18-5	1120	9.0	26	43	+66	40	0	54	6	Admix Compaction	H-451	1800
G1-2B	7161-002-17-3	1175	9.5	23	38	+68	40	0	54	6	Hot Injection	PB ^(d)	1800
G1-3B	7161-002-18-8	1175	9.5	20	38	+86	40	0	54	6	Hot Injection	H-451	1800

(a) Determined by point-count method on metallographic cross-section (radial) composite of fuel rod. $\text{Macroporosity} = \frac{\text{Area}_{\text{void}}}{\text{Area}_{\text{void}} + \text{Area}_{\text{matrix}}}$

(b) Equation used: $\text{postirradiation} - \text{preirradiation macroporosity}$

(c) Rod has a central thermocouple hole.

(d) Fired in packed bed of alumina (reference FSV process).

TABLE 4-14
RESULTS OF METALLOGRAPHIC EXAMINATION OF FISSILE^(a) PARTICLES IRRADIATED IN CAPSULE P13Q FUEL RODS

Fuel Rod Data Retrieval Number	Capsule Position	Average Peak Temp ^(b) (°C)	Average Fast Fluence (10 ²⁵ n/m ²) (E > 29 fJ) HTGR	Burnup (% FIMA)	Number of Particles Examined	OPyC Coating Failure ^(c)		SiC Coating Reaction ^(e) (%)	IPyC Coating			Pressure Vessel Failure ^(g)	
						Measured (%)	95% Confidence Interval P ^(d) (%)		Reaction ^(f) (%)	Failure (%)	Debonding from SiC Coating (%)	Measured (%)	95% Confidence Interval P ^(d) (%)
7161-002-20-3	G3-2A	915	4.3	62.8	158	0	0 ≤ P ≤ 2.4	0	0	0.6	52.5	0	0 ≤ P ≤ 2.4
7261-002-12-8	G3-3B	930	5.7	68.9	73	0	0 ≤ P ≤ 5.0	0	0	9.6	45.2	0	0 ≤ P ≤ 5.0
7261-002-15-3	G2-3A	945	7.2	74.1	111	15.3	9.8 ≤ P ≤ 23.2	0	55.0	8.1	48.6	3.6 ^(h)	1.4 ≤ P ≤ 8.9
7161-002-13-3	G2-1B	955	8.1	76.0	75	5.3	1.5 ≤ P ≤ 12.0	2.7	36.0	22.7	40.0	0	0 ≤ P ≤ 4.9
7161-002-14-3	G2-2B	955	8.1	76.0	77	6.5	2.2 ≤ P ≤ 14.8	0	53.2	9.1	28.6	2.6	0 ≤ P ≤ 9.4
7161-002-15-8	G2-3B	955	8.1	76.0	72	20.8	10.8 ≤ P ≤ 31.6	0	81.9	8.3	33.3	4.2 ^(h)	1.0 ≤ P ≤ 11.5
7261-002-13-5	G1-3A	1120	9.0	77.1	104	15.4	9.7 ≤ P ≤ 23.5	8.7	97.2	5.8	46.2	2.9 ⁽ⁱ⁾	0.9 ≤ P ≤ 8.1
7161-002-17-3	G1-2B	1175	9.5	77.3	55	3.6	0 ≤ P ≤ 12.8	3.6	41.7	1.8	41.8	0	0 ≤ P ≤ 6.4
7161-002-18-8	G1-3B	1175	9.5	77.3	62	6.5	1.8 ≤ P ≤ 15.0	1.6	66.1	17.7	46.8	1.6	0 ≤ P ≤ 9.0

(a) All fuel rods contained fissile particle batch 6151-00-0100 (UC₂ TRISO).

(b) Time-averaged.

(c) Includes particles having pressure vessel failure.

(d) The 95% confidence statement means that an infinite population of particles with attributes of the particle batch tested to these conditions will have a failure level at the 95% confidence level bounded by this interval.

(e) Fraction of particles that exhibited apparent metallic fission product attack of the SiC coating.

(f) Fraction of particles with large concentrations of metallic fission products in the IPyC coating.

(g) Pressure vessel failure includes particles which had at least the OPyC and SiC coatings cracked.

(h) SiC coatings had fine cracks which could have been a result of polishing and not irradiation.

(i) Three particles failed; one particle had fine cracks in SiC [see footnote (h)].

TABLE 4-1
RESULTS OF TEARING OF OPyC COATINGS FROM METALLOGRAPHIC EXAMINATION

Fuel Rod Data Retrieval Number	Capsule Position	Observations of Tearing of OPyC Coatings (%)				Fertile Particle Batch 6542-	Particle Packing (%)	Matrix Composition	Fuel Rod Fabrication Process ^(d)	Firing Process ^(e)	Final Firing Temp. (°C)	Pitch Coke Yield (%)	Coke Weight/ Surface Area ^(f) (mg/m ²)
		TRISO Fissile ^(a)	BISO Fertile	TRISO Inert ^(b)	BISO Inert ^(c)								
7161-002-20-3	G3-2A	0.6	0.1	0.9	(g)	01-0100	60	(h)	HI	CIP	1500	(1)	(1)
7261-002-12-8	G3-3B	0	0	0	0	02-0100	55.6	(h)	AC	CIP	1800	35.3	22.5
7261-002-15-3	G2-3A	0	0	0.2	0	01-0100	56.7	(j)	AC	CIP	1800	33.4	66.4
7161-002-13-3	G2-1B	1.3 to 2.7(k)	0	0.2 to 0.4(k)	0	01-0100	60.3	(h)	HI	CIP	1800	36.2	22.7
7161-002-14-3	G2-2B	0	1.6	3.6	0.4	01-0100	60.3	(l)	HI	CIP	1800	39.4	25.1
7161-002-15-3	G2-3B	4.2 to 5.5(k)	0 to 0.5(k)	0 to 0.5(k)	0 to 0.5(k)	01-0100	60.0	(j)	HI	CIP	1800	35.2	67.8
7261-002-16-5	G1-3A	0	0	0	0	02-0100	56.3	(h)	AC	CIP	1800	33.5	21.4
7161-002-17-3	G1-2B	0	0	0.6	0	01-0100	61.0	(h)	HI	PB	1800	25.9	16.3
7161-002-19-3	G1-3B	1.6	0	0.4	0	02-0100	60.5	(h)	HI	CIP	1800	37.0	23.3

(a) All fuel rods contain fissile batch 6151-00-0100.

(b) All fuel rods contain TRISO inert batch 4361-00-0100.

(c) All fuel rods contain BISO inert batch 6641-00-0400.

(d) HI = hot injection and AC = admix compaction.

(e) CIP = cure-in-place and PB = cured in packed bed.

(f) The surface area is the total surface area of all particles and the filler.

The following BET values (m²/g) were used: all coated particles - 0.3; shim particles - 1; 1089 filler - 21; 6353 filler - 8.

(g) No BISO inerts in rod.

(h) 40% 1089 graphite filler, 54% A240 pitch and 6% SC011 additive.

(i) Not determined.

(j) 30% 6353 graphite filler, 67% A240 pitch and 3% SC011 additive.

(k) The type of particle could not be identified for one torn coating.

(l) 40% 1089 graphite filler and 60% A240 pitch.

TABLE 4-16
RESULTS OF METALLOGRAPHIC EXAMINATION OF FERTILE PARTICLES

Batch Data Retrieval Number	Fuel Rod Data Retrieval Number	Capsule Position	Average Peak Temp. (°C)	Average Fast Fluence (10^{25} n/m ²) ($E > 29$ fJ) _{HTGR}	Burnup (% FIMA)	Number of Particles Examined	OPyC Coating Failure		Buffer Coating Cracked (%)
							Measured (%)	95% Confidence Interval, P ^(a) (%)	
6542-01-0100	7161-002-20-3	G3-2A	915	4.3	1.4	708	0	$0 \leq P \leq 0.5$	0
6542-01-0100	7261-002-15-3	G2-3A	945	7.2	3.3	200	0	$0 \leq P \leq 1.9$	3.0
6542-01-0100	7161-002-13-3	G2-1B	955	8.1	4.3	151	0	$0 \leq P \leq 2.5$	2.0
6542-01-0100	7161-002-14-3	G2-2B	955	8.1	4.3	117	0	$0 \leq P \leq 3.2$	0.9
6542-01-0100	7161-002-15-8	G2-3B	955	8.1	4.3	132	0	$0 \leq P \leq 2.8$	0.8
6542-01-0100	7161-002-17-3	G1-2B	1175	9.5	5.9	97	0	$0 \leq P \leq 4.1$	3.1
6542-02-0100	7261-02-12-8	G3-3B	930	5.7	2.1	137	0	$0 \leq P \leq 2.7$	2.2
6542-02-0100	7261-002-18-5	G1-3A	1120	9.0	5.4	122	0	$0 \leq P \leq 3.1$	2.5
6542-02-0100	7161-002-18-8	G1-3B	1175	9.5	5.9	143	0	$0 \leq P \leq 2.6$	1.4

(a) The 95% confidence statement means that an infinite population of particles with attributes of the particle batch tested to these conditions will have a failure level at the 95% confidence level bounded by this interval.

TABLE 4-17
RESULTS OF METALLOGRAPHIC EXAMINATION OF INERT PARTICLES IRRADIATED IN CAPSULE P13Q FUEL RODS

Fuel Rod Data Retrieval Number	Capsule Position	Average Peak Temp. (a) (°C)	Average Fast Fluence (10^{25} n/m ²) (E > 29 fJ) _{HTGR}	TRISO Batch 4361-00-0100		BISO Batch 6641-00-0400	
				Number of Particles Examined	OPyC Coating Failure (%)	Number of Particles Examined	OPyC Coating Failure (%)
7161-002-20-3	G3-2A	915	4.3	627	1.3	(b)	(b)
7261-002-12-8	G3-3B	930	5.7	79	0	111	0
7261-002-15-3	G2-3A	945	7.2	415	1.4	311	0
7161-002-13-3	G2-1B	955	8.1	545	1.3	360	0
7161-002-14-3	G2-2B	955	8.1	497	1.2	359	0
7161-002-15-8	G2-3B	955	8.1	206	2.9	400	0.5 ^(c)
7261-002-18-5	G1-3A	1120	9.0	436	0.5	381	0
7161-002-17-3	G1-2B	1175	9.5	661	1.1	411	0
7161-002-18-8	G1-3B	1175	9.5	512	2.1	411	1.0 ^(c)

(a) Time-averaged.

(b) No BISO particles used in this batch.

(c) Very fine cracks which could be a result of polishing and not irradiation.

TABLE 4-18
PREIRRADIATION DIMENSIONS^(a) OF CAPSULE P13Q UNBONDED PARTICLE SAMPLES^(b)

Data Retrieval Number	Piggyback Hole Position	Holder Number	Radio- graph Plate Number	Kernel Diameter			Buffer Thickness			SiC Thickness			OPyC Thickness			Total Particle Diameter		
				Mean	Standard Deviation	Range	Mean Thick- ness	Standard Deviation	Range	Mean	Standard Deviation	Range	Mean	Standard Deviation	Range	Mean	Standard Deviation	Range
6151-00-0130-5	G1-PB2/3-A	15	V-74	195	6.56	183-213	90 ^(c)	7.20 ^(c)	72-110 ^(c)	28	2.74	24-35	42	3.20	34-46	593	18.44	552-646
4252-06-0120-9	G2-PB2/3-A	9	V-77	508	19.25	427-547	79	9.69	34-119	(d)	(d)	(d)	73	7.03	52-90	820	19.04	721-865
6452-01-0130-2	G3-PB2/3-A	3	V-63	509	4.45	499-518	79	5.12	71-90	(d)	(d)	(d)	82	5.84	65-92	836	15.47	795-856
6542-01-0130-3	G3-PB1/2-A	2	V-64	508	7.93	480-522	85	7.20	71-98	(d)	(d)	(d)	81	6.65	67-97	840	14.00	797-863
6542-01-0130-4	G2-PB1/2-A	8	V-65	506	4.35	493-512	81	5.81	72-95	(d)	(d)	(d)	83	4.61	70-91	838	11.82	817-860
6542-01-0130-5	G1-PB1/2-D	17	V-66	508	5.32	498-521	82	7.36	67-96	(d)	(d)	(d)	84	5.65	75-97	844	14.83	806-873
6542-01-0130-6	G1-PB2/3-E	18	V-67	506	5.14	493-516	81	5.46	71-93	(d)	(d)	(d)	84	4.93	71-91	835	17.76	790-870
6542-02-0130-2	G3-PB3/1-A	1	V-61	512	4.46	501-518	77	6.13	62-90	(d)	(d)	(d)	91	6.86	80-104	848	18.37	802-879
6542-02-0130-3	G1-PB3/1-A	13	V-62	509	5.13	494-520	80	5.28	69-93	(d)	(d)	(d)	88	6.05	73-98	849	9.57	829-870
6641-00-0430-2	G3-PB3/1-E	4	V-68	(e)	(e)	(e)	(e)	(e)	(e)	(d)	(d)	(d)	62	5.22	54-74	727	28.84	659-789
6641-00-0430-3	G2-PB3/1-A	7	V-69	(e)	(e)	(e)	(e)	(e)	(e)	(d)	(d)	(d)	58	4.98	48-68	733	21.15	682-780
6641-00-0430-4	G1-PB3/1-F	16	V-70	(e)	(e)	(e)	(e)	(e)	(e)	(d)	(d)	(d)	60	6.97	48-73	729	22.36	691-765

(a) Measured by contact x-radiography. All values are in microns

(b) Each sample contained 30 particles.

(c) Buffer thickness was calculated by subtracting parent batch IPyC thickness (35 μ m) from measured buffer plus IPyC thickness.

(d) Not applicable.

(e) Not determined.

TABLE 4-19
POSTIRRADIATION DIMENSIONS^(a) OF CAPSULE P13Q UNBONDED PARTICLE SAMPLES

Data Retrieval Number	Piggyback Hole Position	Holder Number	Radio-graphy Plate Number	Number of Particles Measured	Kernel Diameter			Buffer Thickness			IPyC Thickness			SiC Thickness			OPyC Thickness			Total Particle Diameter		
					Mean	Standard Deviation	Range	Mean	Standard Deviation	Range	Mean	Standard Deviation	Range	Mean	Standard Deviation	Range	Mean	Standard Deviation	Range	Mean	Standard Deviation	Range
6151-00-0130-5	G1-PB2/3-A	15	HA338,342	27	227	10 06	206-250	82	10 94	57 108	27	4 90	20-37	28	3 39	22-36	40	3 68	34-50	590	14 11	565-627
4252-06-0120-9	G2-PB2/3-A	9	HA331,332	27	525	6 56	511-539	63	6 72	47-80	(b)	(b)	(b)	(b)	(b)	(b)	72	5 79	60-80	800	11 99	772-820
6542-01-0130-2	G3-PB2/3-A	3	HA334	28	515	2 54	508-520	67	6 77	52-80							76	7 01	65-94	807	12 70	774-839
6542-01-0130-3	G3-PB1/2-A	2	HA346	28	515	2 96	508-523	70	10 65	45-94							77	7 05	62-90	817	10 90	787-842
6542-01-0130-4	G2-PB1/2-A	8	HA337,341	30	518	2 38	515-523	69	5 85	59-82							79	6 21	66-89	819	10 40	794-839
6542-01-0130-5	G1-PB1/2-D	17	HA339,343,348	28	524	2 78	518-530	70	3 93	63-79							76	7 86	58-89	819	13 31	795-850
6542-01-0130 6	G1-PB2/3-E	18	HA340,344,347	33	521	4 17	503-527	70	6 27	58-83							78	7 00	66-94	816	9 89	792-831
6542-02-0130-2	G3-PB3/1-A	1	HA345	29	516	4 03	507-523	67	7 51	53-85							88	7 18	74-100	831	10 89	802-847
6542-02-0130-3	G1-PB3/1-A	13	HA335,336	25	521	3 20	516-528	68	5 80	59-83							84	4 28	76-97	828	10 57	804-849
6641-00-0430-2	G3-PB3/1-E	4	HA328	30	(c)	(c)	(c)	(c)	(c)	(c)							65	3 53	56-71	690	21 41	648-725
6641-00-0430-3	G2-PB3/1-A	7	HA329	30	(c)	(c)	(c)	(c)	(c)	(c)							64	5 71	54-80	693	15 77	666-727
6641-00-0430-4	G1-PB3/1-F	16	HA330	29	(c)	(c)	(c)	(c)	(c)	(c)							66	5 60	50-78	680	18 35	645-706

(a) Measured by contact X-radiography All values are in microns

(b) Not applicable

(c) Not determined

TABLE 4-20
IRRADIATION-INDUCED DIMENSIONAL CHANGE OF CAPSULE P13Q UNBONDED PARTICLE SAMPLES

Data Retrieval Number	Irradiation Conditions					Particle Type ^(a)	Dimensional Change ^(b)							
	Piggyback Hole Position	Holder Number	Average Centerline Temp. (°C)	Fast Fluence (10 ²⁵ n/m ²) (E > 29 fJ) HTGR	Burnup (% FIMA)		Kernel Diameter		Buffer Thickness		OPyC Thickness		Total Particle Diameter	
							ΔD ^(c) (μ m)	$\Delta D/D_o$ ^(c) (%)	ΔT (μ m)	$\Delta T/T_o$ (%)	ΔT (μ m)	$\Delta T/T_o$ (%)	Δ (μ m)	$\Delta D/D_o$ (%)
6151-00-0130-5	G1-PB2/3-A	15	795	8.8	76	UC ₂ -T	+32	+16.4	-8	-8.6	-2	-4.8	-3	-0.5
4252-06-0120-9	G2-PB2/3-A	9	740	6.8	2.9	ThO ₂ -B	+17	+3.3	-16	-20.3	-1	-1.4	-20	-2.4
6542-01-0130-2	G3-PB2/3-A	3	660	3.6	1.2	ThO ₂ -B	+6	+1.2	-12	-15.2	-6	-7.3	-29	-3.5
6542-01-0130-3	G3-PB1/2-A	2	660	3.6	1.2	ThO ₂ -B	+7	+1.4	-15	-17.6	-4	-4.9	-23	-2.7
6542-01-0130-4	G2-PB1/2-A	8	740	6.8	2.9	ThO ₂ -B	+12	+2.4	-12	-14.8	-4	-4.8	-19	-2.3
6542-01-0130-5	G1-PB1/2-D	17	795	9.6	6.0	ThO ₂ -B	+16	+3.1	-12	-14.6	-8	-9.5	-25	-3.0
6542-01-0130-6	G1-PB2/3-E	18	795	9.6	6.0	ThO ₂ -B	+15	+3.0	-11	-13.6	-6	-7.1	-19	-2.3
6542-02-0130-2	G3-PB3/1-A	1	660	3.6	1.2	ThO ₂ -B	+4	+0.8	-10	-13.0	-3	-3.3	-17	-2.0
6542-02-0130-3	G1-PB3/1-A	13	795	9.2	5.5	ThO ₂ -B	+12	+2.4	-12	-15.0	-3	-3.4	-21	-2.5
6641-00-0430-2	G3-PB3/1-E	4	675	6.3	0	Inert-B	(d)	(d)	(d)	(d)	+3	+4.8	-37	-5.1
6641-00-0430-3	G2-PB3/1-A	7	740	6.8	0	Inert-B	(d)	(d)	(d)	(d)	+6	+10.3	-40	-5.5
6641-00-0430-4	G1-PB3/1-F	16	795	9.6	0	Inert-B	(d)	(d)	(d)	(d)	+6	+10.0	-49	-6.7

(a) T means TRISO coated and B means BISO coated.

(b) Preirradiation and postirradiation particle dimensional data given in Tables 4-18 and 4-19.

(c) Δ signifies the final dimension minus the initial dimension, and subscript o signifies the initial dimension.

(d) Not determined.

TABLE 4-21
RESULTS OF PARTICLE DENSITY MEASUREMENTS OF UNBONDED PARTICLE SAMPLES^(a) OF CAPSULE P13Q

Sample Data Retrieval No.	Particle Type ^(b)	Capsule Identification		Irradiation Conditions			Particle Density (Mg/m ³)				Particle Densification(e) (%)
				Average Centerline Temp. (°C)	Fast Fluence (10 ²⁵ n/m ²) HTGR	Burnup (% FIMA)	Preirradiation(c)		Postirradiation(d)		
		Hole Position	Holder Number				Mean	Standard Deviation	Mean	Standard Deviation	
6542-01-0130-2	ThO ₂ -B	G3-PB2/3-A	3	660	3.6	1.2	3.44	0.031	3.85	0.027	11.9
6542-01-0130-3	ThO ₂ -B	G3-PB1/2-A	2	660	3.6	1.2	3.44	0.031	3.87	0.026	12.5
6542-01-0130-4	ThO ₂ -B	G2-PB1/2-A	8	740	6.8	2.9	3.44	0.031	3.90	0.014	13.3
6542-01-0130-5	ThO ₂ -B	G1-PB1/2-D	17	795	9.6	6.0	3.44	0.031	3.87	0.011	12.5
6542-01-0130-6	ThO ₂ -B	G1-PB2/3-E	18	795	9.6	6.0	3.44	0.031	3.89	0.009	13.1
6542-02-0130-2	ThO ₂ -B	G3-PB3/1-A	1	660	3.6	1.2	3.45	(f)	3.88	0.005	12.5
6641-00-0430-2	Inert-T	G3-PB3/1-E	4	675	6.3	0	1.50	(f)	1.81	0.032	20.7
6641-00-0430-3	Inert-T	G2-PB3/1-A	7	740	6.8	0	1.50	(f)	1.81	0.022	20.7
6641-00-0430-4	Inert-T	G1-PB3/1-F	16	795	9.6	0	1.50	(f)	1.83	0.026	22.0

(a) All samples were density separated in liquid gradient column.

(b) "T" signifies TRISO coated and "B" signifies BISO coated.

(c) Measured on approximately 30 particles representative of the capsule samples.

(d) Measured on all the particles (~30) of each capsule sample.

(e) Calculation: (final ρ - initial ρ) ÷ (initial ρ).

(f) Not determined.

K7507-5

Fig. 4-1. Crack pattern in the bulkhead of capsule P13Q (view from bottom end)

K7507-28

(a)

K7507-27

(b)

Fig. 4-2. Severed gas inlet tube, which was corroded at the top of the capsule: (a) PALORITE-C insulation disk and primary containment still in place, and (b) after PALORITE-C disk and containment had been removed from graphite fuel body

K7507-8

K7507-7

Fig. 4-3. Irradiation-induced dimensional change of PALORITE-C insulation disk at the bottom end (high-fluence region) of the capsule

K7515-32

G1

K7515-18

G2

K7515-4

G3

Fig. 4-4. Graphite fuel bodies after removal from the primary containment tube. The bodies were in good condition and no signs of cracking or oxidation were observed.

K7515-20

Fig. 4-5. Removal of secondary specimens from graphite body G2

K7515-88, 89

Fig. 4-6. Horizontal fixture used to remove fuel rods from the graphite bodies. The breakaway force of each fuel column was recorded by a force gage placed between the electric screw jack and the push rod.

K7515-43

K7515-77

Fig. 4-7. Removal of fuel rods from the graphite bodies. No evidence of surface damage resulting from mechanical interaction between the fuel rods and walls of the graphite bodies was observed on any of the fuel rods.

S7515-53

S7515-54

S7515 (57,58)

0.5 cm

Fig. 4-8. Fuel rod 7161-002-19-3 after irradiation to a fast fluence of $4.2 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} in position G3-1A of capsule P13Q

S7515-51

S7515-52

S7515 (49.50)

0.5 cm

Fig. 4-9. Fuel rod 7161-002-20-3 after irradiation to a fast fluence of $4.2 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} in position G3-2A of capsule P13Q

S7515-30

S7515-29

S7515 (33,34)

0.5 cm

Fig. 4-10. Fuel rod 7161-002-21-3 after irradiation to a fast fluence of $4.2 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} in position G3-3A of capsule P13Q

S7515-39

S7515-40

S7515 (37,38)

0.5 cm

Fig. 4-11. Fuel rod 7261-002-10-3 after irradiation to a fast fluence of $5.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} in position G3-1B of capsule P13Q

S7515-59

S7515-41

S7515-42

S7515 (63,64)

S7515 (43,44)

0.5 cm

Fig. 4-14. Fuel rod 7261-002-1
($E > 29$ fJ)_{HTGR} in

Fig. 4-12. Fuel rod 7161-002-11-8 after irradiation to a fast fluence of 5.6×10^{25} n/m²
($E > 29$ fJ)_{HTGR} in position G3-2B of capsule P13Q

S7515-71

S7515-72

S7515-27

S7515 (73,74)

0.5 cm

0.5 cm

Fig. 4-15. Fuel rod 7261-002-14-3 after irradiation to a fast fluence of $7.2 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} in position G2-2A of capsule P13Q

fast fluence of $5.6 \times 10^{25} \text{ n/m}^2$ P13Q

S7515-83

S7515-84

S7515 (87,88)

0.5 cm

Fig. 4-16. Fuel rod 7261-002-15-3 after irradiation to a fast fluence of $7.2 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} in position G2-3A of capsule P13Q

S7515-70

S7515-69

S7515 (65,66)

0.5 cm

Fig. 4-17. Fuel rod 7161-002-13-3 after irradiation to a fast fluence of $8.1 \times 10^{25} \text{ n/m}^2$
 $(E > 29 \text{ fJ})_{\text{HTGR}}$ in position G2-1B of capsule P13Q

S7515-82

S7515-81

S7515 (77,78)

0.5 cm

Fig. 4-18. Fuel rod 7161-002-14-3 after irradiation to a fast fluence of $8.1 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} in position G2-2B of capsule P13Q

S7515-94

S7515-93

S7515 (91,92)

0.5 cm

Fig. 4-19. Fuel rod 7261-002-15-8 after irradiation to a fast fluence of $8.1 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} in position G2-3B of capsule P13Q

S7515-96

S7515-95

S7515 (97,98)

0.5 cm

Fig. 4-20. Fuel rod 7261-002-16-8 after irradiation to a fast fluence of $9.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} in position G1-1A of capsule P13Q

S7515-105

S7515-106

S7515 (103,104)

0.5 cm

Fig. 4-21. Fuel rod 7261-002-17-3 after irradiation to a fast fluence of $9.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} in position G1-2A of capsule P13Q

S7515-117

S7515-118

S7515 (123, 124)

0.5 cm

Fig. 4-22. Fuel rod 7261-002-18-5 after irradiation to a fast fluence of $9.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} in position G1-3A of capsule P13Q

S7515-107

S7515-108

S7515 (109,110)

0.5 cm

Fig. 4-23. Fuel rod 7161-002-16-8 after irradiation to a fast fluence of $9.4 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} in position G1-1B of capsule P13Q

S7515-119

S7515-120

S7515 (115, 116)

0.5 cm

Fig. 4-24. Fuel rod 7161-002-17-3 after irradiation to a fast fluence of $9.4 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} in position G1-2B of capsule P13Q

S7515-126

S7515-125

S7515 (129,130)

0.5 cm

Fig. 4-25. Fuel rod 7161-002-18-8 after irradiation to a fast fluence of $9.4 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} in position G1-3B of capsule P13Q

S7515-154

S7515-156

Fig. 4-26. Photographs taken during visual examination of ThO_2 BISO particles (6542-02-0130-3) irradiated to a fast neutron fluence of $8.6 \times 10^{25} \text{ n/m}^3$ ($E > 29 \text{ fJ}$)_{HTGR} in holder No. 13, position G1-PB3/1-A, of capsule P13Q

S7515-145

S7515-147

Fig. 4-27. Photographs taken during visual examination of ThO_2 BISO particles (6542-01-0130-5) irradiated to a fast neutron fluence of $9.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} in holder No. 17, position G1-PB1/2-D, of capsule P13Q

S7515-134

S7515-136

Fig. 4-28. Photographs taken during visual examination of UC_2 TRISO particles (6151-00-0130-4) irradiated to a fast neutron fluence of $8.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} in holder No. 14, position G1-PB1/2-A, of capsule P13Q

S7515-131

S7515-133

Fig. 4-29. Photographs taken during visual examination of $(\text{Th,U})\text{O}_2$ TRISO particles (4163-00-0140-3) irradiated to a fast neutron fluence of $8.4 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} in holder No. 11, position G2-PB1/2-D, of capsule P13Q

Fig. 4-30. Linear diametral dimensional change as a function of fast neutron fluence for fuel rods irradiated in capsule P13Q. The numbers in parentheses are the volume average temperatures (°C) for the three rods below each temperature.

Fig. 4-31. Linear axial dimensional change as a function of fast neutron fluence for fuel rods irradiated in capsule P13Q. The numbers in parentheses are the volume average temperatures (°C) for the three rods below each temperature.

Fig. 4-32. Volume dimensional change as a function of fast neutron fluence for fuel rods irradiated in capsule P13Q. The numbers in parentheses are the volume average temperatures (°C) for the three rods below each temperature.

Fig. 4-33. Diametral dimensional change of H-451 graphite bodies as a function of fast neutron exposure. Also shown are design curves for irradiation-induced radial dimensional change in H-451 graphite (Ref. 4-5).

Fig. 4-34. Single channel Zr-95, Cs-137, and Pa-233 gamma-ray scans as a function of position of fuel rods irradiated in body G1 of P13Q. The identification below each curve is the fuel rod position in the body. The Pa-233 scans were not recorded for positions 2B, 3A, and 3B. The following energy peaks were plotted: Zr-95 - 116 fJ (724 keV), Cs-137 = 106 fJ (661 keV), and Pu-233 - 50.0 fJ (312 keV).

Fig. 4-35. Single channel Zr-95, Cs-137, and Pa-233 gamma-ray scans as a function of position of fuel rods irradiated in body G2 of P13Q. The identification below each curve is the fuel rod position in the body. The following energy peaks were plotted: Zr-95 = 116 fJ (724 keV), Cs-137 = 106 fJ (661 keV), and Pa-233 = 50.0 fJ (312 keV).

Fig. 4-36. Single channel Zr-95, Cs-137, and Pa-233 gamma-ray scans as a function of position of fuel rods irradiated in body G3 of P13Q. The identification below each curve is the fuel rod position in the body. The following energy peaks were plotted: Zr-95 = 116 fJ (724 keV), Cs-137 = 106 fJ (661 keV), and Pa-233 = 50.0 fJ (312 keV).

L7515-322

(a)

L7515-323

(b)

Fig. 4-37. Photomicrographs of representative particles from fuel rod 7161-002-20-3 irradiated in capsule P13Q (position G3-2A) to a neutron fast fluence of $4.3 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 915°C; (a) bright field, (b) polarized light

L7515-338

(a)

L7515-339

(b)

Fig. 4-38. Photomicrographs of representative particles from fuel rod 7261-002-12-8 irradiated in capsule P13Q (position G3-3B) to a neutron fast fluence of $5.4 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 930°C: (a) bright field, (b) polarized light

L7515-40

(a)

L7515-41

(b)

Fig. 4-39. Photomicrographs of representative particles from fuel rod 7261-002-15-3 irradiated in capsule P13Q (position G2-3A) to a neutron fast fluence of $7.2 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 945°C: (a) bright field, (b) polarized light

L7515-181

(a)

L7515-182

(b)

Fig. 4-40. Photomicrographs of representative particles from fuel rod 7161-002-13-3 irradiated in capsule P13Q (position G2-1B) to a neutron fast fluence of $8.1 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 955°C; (a) bright field, (b) polarized light

L7515-1

(a)

L7515-2

(b)

Fig. 4-41. Photomicrographs of representative particles from fuel rod 7161-002-15-3 irradiated in capsule P13Q (position G2-3B) to a neutron fast fluence of $8.1 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 955°C; (a) bright field, (b) polarized light

L7515-224

(a)

L7515-225

(b)

Fig. 4-42. Photomicrographs of representative particles from fuel rod 7161-002-14-3 irradiated in capsule P13Q (position G2-2B) to a neutron fast fluence of $8.1 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$) HTGR at 955°C : (a) bright field, (b) polarized light

L7515-288

(a)

L7515-289

(b)

Fig. 4-43. Photomicrographs of representative particles from fuel rod 7261-002-18-5 irradiated in capsule P13Q (position G1-3A) to a neutron fast fluence of $9.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1120°C; (a) bright field, (b) polarized light

L7515-215

(a)

L7515-216

(b)

Fig. 4-44. Photomicrographs of representative particles from fuel rod 7161-002-17-3 irradiated in capsule P13Q (position G1-2B) to a neutron fast fluence of $9.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1175°C; (a) bright field, (b) polarized light

L7515-105

(a)

L7515-106

(b)

Fig. 4-45. Photomicrographs of representative particles from fuel rod 7161-002-18-3 irradiated in capsule P13Q (position G1-3B) to a neutron fast fluence of $9.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1175°C: (a) bright field, (b) polarized light

L7515-317

(a)

FUEL ROD
SURFACE

FUEL ROD
CENTERLINE

L7515 (308-315)

(b)

Fig. 4-46. Representative photomicrographs of fuel rod 7161-002-20-3 after irradiation in capsule P13Q (position G3-2A) to a fast neutron fluence of $4.3 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$) HTGR at 915°C : (a) typical appearance of matrix and (b) composite showing radial cross section

L7515-343

(a)

FUEL ROD
SURFACE

FUEL ROD
CENTERLINE

L7515 (344-351)

(b)

Fig. 4-47. Representative photomicrographs of fuel rod 7261-002-12-8 after irradiation in capsule P13Q (position G3-3B) to a fast neutron fluence of $5.7 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 930°C: (a) typical appearance of matrix and (b) composite showing radial cross section

L7515-49

(a)

FUEL ROD
SURFACE

FUEL ROD
CENTERLINE

L7515 (50-58)

(b)

Fig. 4-48. Representative photomicrographs of fuel rod 7261-002-15-3 after irradiation in capsule P13Q (position G2-3A) to a fast neutron fluence of $7.2 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 945°C: (a) typical appearance of matrix and (b) composite showing radial cross section

L7515-184

(a)

FUEL ROD
SURFACE

FUEL ROD
CENTERLINE

L7515 (164-171)

(b)

Fig. 4-49. Representative photomicrographs of fuel rod 7161-002-13-3 after irradiation in capsule P13Q (position G2-1B) to a fast neutron fluence of $8.1 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 955°C: (a) typical appearance of matrix and (b) composite showing radial cross section

L7515-235

(a)

FUEL ROD
SURFACE

FUEL ROD
CENTERLINE

L7515 (236-243)

(b)

Fig. 4-50. Representative photomicrographs of fuel rod 7161-002-14-3 after irradiation in capsule P13Q (position G2-2B) to a fast neutron fluence of $8.1 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 955°C: (a) typical appearance of matrix and (b) composite showing radial cross section

L7515-14

(a)

FUEL ROD
SURFACE

FUEL ROD
CENTERLINE

L7515 (15-23)

(b)

Fig. 4-51. Representative photomicrographs of fuel rod 7161-002-15-3 after irradiation in capsule P13Q (position G2-3B) to a fast neutron fluence of $8.1 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 955°C: (a) typical appearance of matrix and (b) composite showing radial cross section

L7515-265

(a)

FUEL ROD
SURFACE

FUEL ROD
CENTERLINE

L7515 (268-275)

(b)

Fig. 4-52. Representative photomicrographs of fuel rod 7261-002-18-5 after irradiation in capsule PL3Q (position G1-3A) to a fast neutron fluence of $9.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1120°C: (a) typical appearance of matrix and (b) composite showing radial cross section

L7515-200

(a)

FUEL ROD
SURFACE

FUEL ROD
CENTERLINE

L7515 (203-210)

(b)

Fig. 4-53. Representative photomicrographs of fuel rod 7161-002-17-3 after irradiation in capsule P13Q (position G1-2B) to a fast neutron fluence of $9.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1175°C: (a) typical appearance of matrix and (b) composite showing radial cross section

L7515-112

(a)

FUEL ROD
SURFACE

FUEL ROD
CENTERLINE

L7515 (115-123)

(b)

Fig. 4-54. Representative photomicrographs of fuel rod 7161-002-18-3 after irradiation in capsule P13Q (position G1-3B) to a fast neutron fluence of $9.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1175°C: (a) typical appearance of matrix and (b) composite showing radial cross section

L7515-222

(a)

L7515-223

(b)

Fig. 4-55. Photomicrographs of an example of pressure vessel failure of a TRISO UC_2 particle (6151-00-010) in which severe cracking occurred in a P13Q capsule fuel rod: (a) bright field, (b) polarized light

L7515-26

(a)

L7515-27

(b)

Fig. 4-56. Photomicrographs of an example of pressure vessel failure in a TRISO UC_2 particle (6151-00-010) in which fine cracks were observed in a P13Q capsule fuel rod: (a) bright field, (b) polarized light

L7515-81

(a)

L7515-82

(b)

Fig. 4-57. Photomicrographs of an example of failure of the OPyC coating in a TRISO UC₂ particle (6151-00-010) in a P13Q fuel rod. The polarized light photograph shows the anisotropy of the OPyC coating. (a) Bright field, (b) polarized light.

L7515-332

(a)

L7515-333

(b)

Fig. 4-58. Photomicrographs of an example of cracking and debonding of the IPyC coating in a TRISO UC_2 particle (6151-00-010) in a P13Q capsule fuel rod: (a) bright field, (b) polarized light

M-38959-3

Fig. 4-59. Polarized light photomicrograph of the preirradiated TRISO UC₂ particles (6151-00-010) showing the relatively high anisotropy of the IPyC coating

L7515-246

(a)

L7515-247

(b)

Fig. 4-60. Photomicrographs of an example of cracking and debonding of the buffer coating in a TRISO UC_2 particle (6151-00-010) in a P13Q capsule fuel rod: (a) bright field, (b) polarized light

L7515-296

(a)

L7515-297

(b)

Fig. 4-61. Photomicrographs of an example of the kernel microstructure of a TRISO UC_2 particle (6151-00-010) in the lowest temperature fuel rod 7161-002-20-3 (G3-2A) of capsule P13Q. This type of microstructure was observed in the two rods which operated at average peak temperatures of $\leq 930^\circ C$. (a) Bright field, (b) polarized light.

L7515-30

(a)

L7515-32

(b)

Fig. 4-62. Photomicrographs of an example of tearing of the OPyC coating in a TRISO UC₂ particle (6151-00-010) which is in contact with another particle in a P13Q capsule fuel rod

L7515-128

(a)

L7515-202

(b)

Fig. 4-63. Examples of torn OPyC coatings in a TRISO UC_2 and TRISO inert particle

L7515-75

(a)

L7515-76

(b)

Fig. 4-64. Photomicrographs of an example of fission products concentrated in the IPyC coating in a TRISO UC₂ particle (6151-00-010) in a P13Q capsule fuel rod: (a) bright field, (b) polarized light

L7515-280

(a)

L7515-281

(b)

Fig. 4-65. Photomicrographs of an example of SiC reaction in a TRISO UC_2 particle (6151-00-010) in a P13Q capsule rod: (a) bright field, (b) polarized light

L7515-255

(a)

L7515-149

(b)

Fig. 4-66. Photomicrographs of the examples of an SiC reaction in TRISO UC₂ particles in P13Q capsule fuel rods

L7515-252

(a)

L7515-29

(b)

Fig. 4-67. Photomicrographs of two examples of tearing of the OPyC coating in BISO coated particles in P13Q fuel rods: (a) fertile batch 6542-01-010, (b) fertile batch 6542-01-010 or inert batch 6641-00-040 (identity was not apparent)

L7515-290

(a)

L7515-291

(b)

Fig. 4-68. Photomicrographs of an example of buffer cracking in a BISO ThO_2 particle (6542-02-010) in a P13Q capsule fuel rod: (a) bright field, (b) polarized light

L7515-304

(a)

L7515-305

(b)

Fig. 4-69. Photomicrographs of an example of a kernel microstructure in which there is a uniform distribution of fine porosity in a BISO ThO_2 particle (6542-01-010) in a P13Q capsule fuel rod: (a) bright field, (b) polarized light

L7515-158

(a)

L7515-159

(b)

Fig. 4-70. Photomicrographs of an example of a kernel microstructure in which large pores have formed in a BISO ThO_2 particle (6542-01-010) in a P13Q fuel rod: (a) bright field, (b) polarized light

L7515-266

(a)

L7515-267

(b)

Fig. 4-71. Photomicrographs of an example of a TRISO inert particle (4361-00-010) in a P13Q capsule fuel rod: (a) bright field, (b) polarized light

L7515-139

(a)

L7515-140

(b)

Fig. 4-72. Photomicrographs of an example of a BISO inert particle (6641-00-040) in a P13Q capsule fuel rod: (a) bright field, (b) polarized light

5. DISCUSSION

5.1. COATED PARTICLE IRRADIATION PERFORMANCE

Capsule P13Q was primarily an integral test of fuel rods. One fissile batch and two fertile batches were used in the fuel rods to keep the coated particle variables to a minimum. The performance of these three fuel batches in P13Q rods is discussed below in reference to the LHTGR fuel specifications (Ref. 5-1) and previous irradiation capsules, in particular capsules P13R and P13S (Ref. 5-2). The properties of each batch which did not meet the fuel specifications are listed in Table 2-2.

5.1.1. Fissile Particles

TRISO coated particle batch 6151-00-010 containing 200- μm UC_2 kernels was used in all the P13Q capsule fuel rods. The OPyC coating failure and pressure vessel failure (failure at both the OPyC and SiC coatings) based on the metallography of nine rods were 0 to 20.8% and 0 to 4.2%, respectively, for fluences of 4.3 to $9.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} and average peak temperatures of 915° to 1175°C. (The uncertainty of these data is much higher than for an unbonded particle sample for which a visual examination and fission gas release measurement can be performed on the entire sample.) The fissile batch did not meet the present fuel performance requirement which states that fuel meeting all requirements of particle design and missing and defective coating specifications shall have no more than 0.5% pressure vessel failure after irradiation at 1250°C to $8 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} and/or a burnup of 78% FIMA for fissile particles and/or 7.5% FIMA for fertile particles (Ref. 5-3). The high OPyC failure was primarily attributed to the high anisotropy caused by the low coating deposition rate of 1.5 $\mu\text{m}/\text{min}$ (Refs. 5-2, 5-4). Batch 6151-00-010 had a mean BAF_0 value of 1.04, which was higher than the mean value recommended

in the report of capsules P13R and P13S (Ref. 5-2). The results of capsule P13R and P13S (Ref. 5-2) indicated that significant OPyC failure of TRISO fissile particles occurred for coating rates of less than 2 $\mu\text{m}/\text{min}$. The high pressure vessel failure was affected by two factors. Tensile stresses in the OPyC coating generated by irradiation-induced densification help maintain the SiC coating in compression. Failure of the OPyC coating during irradiation would cause higher stresses in the SiC coating and thus higher SiC coating failure would be expected. Table 4-15 indicates that pressure vessel failure was higher in the samples with higher OPyC coating failure. The other factor was the observation that almost all of the particles that suffered pressure vessel failure exhibited a higher degree of faceted coatings compared to the majority of particles based on the metallographic examination. Faceted particles would have higher coating stresses than round particles of similar design. This observation is consistent with the results of capsules P13R and P13S (Ref. 5-2).

The observed OPyC coating failures of batch 6151-00-010 irradiated in P13Q fuel rods are plotted as a function of fluence in Fig. 5-1. The failure increased at the higher fluences and was not affected by the fuel rod temperature, which was less than or equal to 1175°C. This is consistent with the results of capsules P13R and P13S (Ref. 5-2). A considerable amount of scatter in the data points is a result of statistically small sample sizes (55 to 158 particles) and probably the effects of the fuel rod discussed in Section 5.2.3.

The OPyC and pressure vessel failure levels of batch 6151-00-010 tested in P13Q were consistent with the unbonded particle samples tested in capsule P13R (Ref. 5-2). The samples tested in P13R were irradiated at 1010°C to a peak fluence of $12.1 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}. The OPyC coating failure levels (average of 32.8%) are plotted in Fig. 5-1, which shows that the failure levels observed in both capsules were in relatively good agreement. In addition, the 4.0% pressure vessel failure based on postirradiation fission gas release measurements for capsule P13R was consistent with the P13Q values, which ranged from 0 to 4.2% determined by metallographic examination (Table 4-14).

Cracking of the fissile particle IPyC coating was attributed to the low coating deposition rate and the high optical anisotropy (mean BAF_0 was 1.084) of the IPyC coating. These results were consistent with the results of capsules P13R and P13S indicating that IPyC coating cracking occurred in batches in which the mean IPyC BAF_0 was greater than 1.08. The more important observation was that failure of the IPyC coating was not detrimental to the irradiation performance of the particles.

The thermochemical stability of the fissile particles was generally good. No kernel migration was observed in any of the fuel rods examined because of the relatively low irradiation temperatures and low thermal gradients. Fission products were concentrated in the IPyC coatings of rods which were irradiated in bodies 1 and 2 to average peak temperatures of $\geq 945^\circ\text{C}$. The fission products were not concentrated on one side, which indicated a low thermal gradient. Degradation of a small fraction of SiC coatings due to a chemical reaction at the IPyC interface was detected in four of the rods. However, no apparent SiC coating failure resulted from the degradation. As discussed in Section 4.7.2, the reaction was attributed to the lanthanide rare earth elements. A similar type of SiC attack, except the penetration was not as severe, was observed in the fuel rods irradiated in the temperature range of 1010° to 1055°C in capsules P13R and P13S (Ref. 5-2). A reaction in the SiC coatings of dense, melted UC_2 TRISO particles has not been observed previously in fuel rods irradiated at these relatively low temperatures. Metallic fission product attack of the SiC layer is dependent upon time as well as the concentration of fission products in the particle and temperature. This may explain why the attack had not been observed at these low temperatures in capsules P13L, P13M, P13N, and P13P which only operated 40% to 66% as long as capsule P13Q (Ref. 5-3). The present empirical design model for the degradation of the SiC coating by fission product reactions does not predict detectable degradation at the temperatures of the P13Q capsule fuel. A closer examination of SiC attack at low temperatures is in progress. In summary, one result of capsule P13Q was that degradation of the SiC coating in dense, melted UC_2 TRISO particles was detected at relatively low temperatures (less than 1200°C) and that further analysis and characterization of this phenomenon is required.

5.1.2. Fertile Particles

Two BISO coated particle batches containing 500- μm ThO_2 kernels were used in all fuel rods for capsule P13Q. Batch 6542-01-010 had a relatively low density (1.80 Mg/m^3) and batch 6542-02-020 had a medium-high density (1.88 Mg/m^3). A summary of the properties and failure analysis is presented in Table 5-2. Neither batch exhibited OPyC coating failure (same as pressure vessel failure for BISO particle) due to low anisotropy of the coating based on metallography of nine fuel rods. The BAF_0 values (anisotropy) fell within the recommended specification in the P13R and P13S report (Ref. 5-2). No failure was observed in the visual examination of the secondary unbonded particle samples of these batches. However, the postirradiation fission gas release measurements contradicted these examinations because the fission gas release results indicated a maximum particle failure of up to 1.8% in the rods examined metallographically. No thermochemical effects, including kernel migration, in the fertile particle batches were detected as was expected in BISO ThO_2 irradiated at these low temperatures.

A comparison of the observed pressure vessel failure based on the metallographic examination and the calculated maximum fertile particle failure based on the end-of-life TRIGA R/B (see Section 4.5.4) of batches 6542-01-010 and 6542-02-010 is given in Table 5-1. The calculated maximum fertile particle failure was always equal to or greater than the observed pressure vessel failure but was less than the upper 95% confidence limit for each sample. However, since all fertile particles in both fuel rods and secondary unbonded particle samples had zero observed failure, the combined 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 slight degree of permeability of fission product gases in the OPyC coating in both batches because the R/B measurements indicated fertile particle failure and yet no cracked OPyC coatings were observed in the metallographic examination. A similar phenomenon was seen in the post-irradiation examination of the P13R and P13S capsules (Ref. 5-2). Batch 6542-01-010 was tested in both the unbonded particle samples and the fuel

rods of these two capsules. The visual examination and the fission gas release measurement of the unbonded particle samples showed 0.2% to 6.0% OPyC coating failures, respectively. The same trend was observed in the fuel rods. The permeability in the P13R and P13S samples was attributed to surface-connected porosity which was observed by Kaae (Ref. 5-5) to form during coating deposition. Kaae also noted that the surface-connected porosity increased with increasing coating rate. The OPyC coating of both P13Q batches was deposited at relatively high coating rates, which were above the present LHTGR fuel product specification (see Table 2-2) and, therefore, the surface-connected porosity was high.

The maximum fertile particle failure based on the TRIGA R/B values of fuel rods containing batches 6542-01-010 and 6542-02-010 from capsules P13Q, P13R, and P13S are plotted as a function of fluence in Fig. 5-2. The results indicate that for the irradiation temperatures tested, temperature did not affect the permeability of the fertile particles. The fission gas release was low (zero particle failure) primarily at the lower fluences for some of the P13Q, P13R, and P13S fuel rods. As stated above, the OPyC coatings of both fertile batches had surface-connected porosity formed during fabrication, which implies that the fission gas release should have indicated a slight degree of permeability of the fertile particles for all fuel rods. However, preirradiation characterization studies of fertile coated particles have shown that the dense, thin seal coating can prevent fission gases from being released from the particles even though the OPyC coating is permeable when measured by activation analysis. It is concluded that the seal coat remained intact at low neutron exposures and prevented the fission gases from escaping. At fluences of approximately 5.7×10^{25} n/m² ($E > 29$ fJ)_{HTGR}, the seal coating appeared to have cracked. This conclusion is supported by metallography. Figure 5-2 also shows that the R/B values for the P13R and P13S fuel rods were generally lower than those for the P13Q rods, which can be explained by the fact that the total fission gas release from both fissile and fertile particles was measured as discussed in Section 4.5.4. A maximum fertile particle failure was calculated for each rod based on the assumption that all the fissions in failed fuel occur

in the fertile particles. This is normally a good assumption because the amount of fissioning in the fissile particles is relatively low, and usually the failure fraction of fissile particles is low. In the P13R and P13S rods, the fissile failure fraction was negligible, but in the P13Q rods the fissile failure was significant. Therefore, fissile failure may have contributed significantly (estimated to be as high as 25%) to the measured fission gas release in the P13Q rods. This, in turn, would lower the P13Q fertile failure fractions and would bring them closer to the P13R and P13S results.

5.2. FUEL ROD AND FUEL ELEMENT IRRADIATION PERFORMANCE

The P13Q capsule was primarily a test of fuel rod variables and was the first test of cured-in-place fuel rods in relatively large graphite bodies which were representative of the LHTGR fuel element configuration. Curing in the fuel block represented a process simplification relative to curing in Al_2O_3 powder beds as was done in production for the Fort St. Vrain rods. The green rods were fabricated by two processes. Half the rods were fabricated by hot injection, which was the Fort St. Vrain process. At the time of rod manufacturing for the P13Q capsule, admix compaction was also being considered for the LHTGR fuel, and therefore, the other half of the rods was made with this process. Since then hot injection has been selected for the generic LHTGR process. The final firing temperature of the fuel rod heat treatment was 1800°C for 16 rods and 1500°C for two rods. A reduction in the temperature would decrease the fabrication cost.

The P13Q capsule rods were fabricated with three experimental matrix compositions, which are compared below to the generic fuel rod matrix. All matrix types included A240 petroleum pitch. The reference HTGR binder was originally a coal tar pitch (Fort St. Vrain fuel rods), but petroleum pitch was found to be a more uniform product. The P13Q matrix batches contained either natural-flake 6353 filler, which was used in the Fort St. Vrain rods, or 1089 filler. The 1089 filler, consisting of comminuted H-451 graphite, was once considered a candidate material for the LHTGR matrix

because it was isotropic and could be made from the scraps from fabrication of the graphite elements. Subsequent development work indicated that the matrix with 1089 filler did not inject as well and that the cost of making this filler was not lower. Therefore, 6353 filler was selected for the majority of fuel rods for the succeeding P13R and P13S capsules. Further process development has recently shown that synthetic KS-15 filler (manufactured by Lonza, Ltd.) is cheaper and is a more uniform product, and it has been selected for the generic fuel rod matrix. The octadecanol additive was added to one matrix type for P13Q because it was found to facilitate the injection of the matrix. The generic matrix contains this additive plus a polystyrene additive. These additives reduce the amount of binder pitch, which helps to reduce matrix-coating interactions. The generic matrix for the LHTGR is presently being tested in other irradiation test vehicles.

The criteria used for evaluating the performance of the fuel rods of P13Q capsule are as follows (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.

5.2.1. Integrity

All fuel rods and graphite bodies were judged to be in excellent condition to irradiation exposures beyond peak LHTGR fluences. No significant matrix cracking or particle debonding of the rods was observed. The most important result was that the integrity of fuel rods which were fired using the reference LHTGR cure-in-place process was good. There was no difference between these rods and the rods fired in packed alumina beds (Fort St. Vrain

reference process). The other rod variables, including matrix composition, green fuel rod fabrication process (hot injection and admix compaction), and firing temperature, had no apparent effect on rod integrity. Also, fuel rod temperature and fluence did not affect the surface condition of the P13Q rods. The coke yield for P13Q rods ranged from 25 to 39% (four rods above the upper LHTGR specification limit of 35%) and the matrix macroporosity ranged from 19 to 35%. The visual examination revealed that rods with these ranges of coke yield and macroporosity values were acceptable.

5.2.2. Dimensional Change Behavior

Characterization of irradiation-induced fuel rod and graphite dimensional change is required for the proper thermal and mechanical design of LHTGR fuel elements. An evaluation of the radial clearance between the fuel rods and the fuel holes is necessary for core thermal analyses. 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 as a result of dimensional interferences between the fuel rod columns and graphite fuel element during reactor operation.

The dimensional change of the fuel rods of the P13Q capsule was examined and evaluated in reference to the fuel rod variables. It should be noted that the shim volume fraction was constant and that the total TRISO and BISO coated particle volume fractions were approximately the same for all rods. These rods deviated from LHTGR rods in one important aspect, which was that the P13Q rods contained 8 to 20 vol % of BISO coated inert particles. These particles shrank much more than BISO fertile particles as discussed in Section 4.8 and, therefore, the P13Q rods shrank more than LHTGR rods would. The linear and volumetric dimensional changes of the rods are plotted as a function of fluence in Figs. 4-30, 4-31, and 4-32. A turnaround in the rods occurred at fluences in the range of 5 to 7×10^{25} n/m^2 ($E > 29 \text{ fJ}$)_{HTGR}. The turnaround was at a lower fluence in the axial direction; however, this may not be real because of the large uncertainty

in the axial values caused by two factors. One was that part of a 0.13-mm-thick disk of Grafoil was located at each end of the rods. The difference between the preirradiation and postirradiation lengths ranged from 0.09 to 0.91 mm and, therefore, the Grafoil thickness was large relative to the measured axial difference. The Grafoil created two obstacles in obtaining an accurate measurement of the axial dimensional change. First, the Grafoil dimensional change was different than that of the fuel rod. Secondly, the Grafoil appeared to flake off some of the rods, especially at the higher fluences. The other factor which affected the uncertainty of the axial measurements was that the circumferential cracking appeared to increase the length of the rod because rods with obvious circumferential cracking usually had lower axial strains than the other rods. Other dimensional change results were that no net expansion of any of the rods occurred even at peak fluences. The matrix composition, green rod fabrication process, fuel rod heat treatment process, and maximum firing temperature did not have any apparent effect on the dimensional change of the fuel rods.

The linear dimensional change data revealed the anisotropic behavior of the fuel rods. The diameter shrank more than the length for the P13Q fuel rods, including the packed bed rods which had no Grafoil on the ends, as shown in Fig. 5-3. This phenomenon was observed in P13R and P13S capsules (Ref. 5-2) and HT-24 and HT-25 capsules (Ref. 5-6). Figure 5-3 also shows that the anisotropy increased as a function of fluence, which was observed in some shim rod types of the HT-24 and HT-25 capsules (Ref. 5-6). The anisotropic behavior of the P13Q fuel rods may be attributed to the preferential alignment of the shim particles (Ref. 5-7).

Another result of the P13Q experiment was that the fuel rod dimensional change was compatible with that of the H-451 graphite body, as shown in Fig. 5-4. The diametral fuel rod strain was greater than the radial strain of the graphite to a fast fluence of $8.1 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}. These data were supported by the ease in which the fuel rods were pushed out of the graphite bodies. However, it should again be noted that these rods shrank more than representative LHTGR rods would have shrunk because of the presence of BISO inert particles. The axial fuel rod dimensional

change was compatible at the lower fluences, but at the higher fluences the rod strain was less than the graphite strain. This undesirable strain difference will not be detrimental in an LHTGR fuel element, because an axial gap in each fuel rod hole can be designed to prevent axial mechanical interference.

5.2.3. Effect of Fuel Rods on OPyC Coating of Particles

Tearing or cracking of the OPyC coating was observed in all particle types. Tearing was the most frequent in the TRISO inert batch and was higher in the TRISO coated particles than in the BISO particles. The results of the metallographic examination were presented in Table 4-15 and were analyzed to determine the cause of the tearing. The tearing of the OPyC coating occurred almost entirely in the hot-injected rods rather than the admix-compacted rods for the cured-in-place rods. The apparent difference between these two methods was that the maximum rod formation pressures were 4.83 MPa (700 psi) for the admix-compacted rods and 8.27 to 9.07 MPa (1200 to 1315 psi) for the hot-injected rods. After this observation two unirradiated rods were examined by metallography and tearing of the OPyC coating of all particle types was found to be similar in appearance to that of irradiated rods. It was concluded that OPyC tearing occurred during green rod fabrication apparently due to a mechanical interaction of the particles. ORNL reported the same problem occurred in HRB-4 and HRB-5 fuel rods (Ref. 5-8). This was the first time at GA that tearing of the OPyC was observed in unirradiated fuel rods fabricated for irradiation test vehicles. It had been detected in irradiated fuel rods and was attributed to matrix-coating interaction (Ref. 5-9) which occurred because a strong bond developed between the matrix phase and the OPyC coating. The differential shrinkage between the two phases apparently increased the tangential tensile stresses of the OPyC coatings and, therefore, enhanced failure. It was also reported in Ref. 5-9 that the higher the ratio of weight of pitch coke (residue binder) after firing to total surface area of the fuel rod particle constituents, the higher the probability of matrix-coating interaction. P13Q fuel rods G2-3A and G2-3B had ratios calculated to be about three times higher than the other rods examined by metallography.

These two rods also exhibited the highest OPyC coating failure of the TRISO UC₂ particles at their respective fluences. This result indicates that matrix-coating interaction increased the OPyC coating failure of the TRISO UC₂ particles; however, this conclusion is clouded by the fact that OPyC tearing also occurred during rod fabrication and there was probably a failure contribution due to high anisotropy of the fissile OPyC coating.

The problems of tearing of the OPyC caused by green rod fabrication and increased OPyC coating failure due to matrix-coating interaction will be reduced in LHTGR fuel rods by control of coking yield and injection pressure. The OPyC tearing described above was not observed in all succeeding capsules, including P13R and P13S (Ref. 5-2), which shows that the fuel rod fabrication process can be controlled to prevent OPyC tearing. The strength of the matrix-coating bond has been reduced by decreasing the amount of pitch binder content in the generic LHTGR matrix. It is 13% to 30% less than pitch content in the P13Q rod matrix compositions.

5.2.4. Metallic Fission Product Behavior

5.2.4.1. Fuel Rod Homogeneity. Fuel loadings in the rods were fairly homogeneous, as evidenced by the relatively uniform Cs-137 and Zr-95 fission product profiles measured by gamma-counting, as shown in Figs. 4-34 through 4-36. There was evidence, however, of small localized regions of fuel inhomogeneity in some fuel rods. Regions of high fuel concentrations, the majority of which occurred near the ends of the fuel rods, were indicated by peaks in the fission product profiles. No correlation was obtained between these regions of slightly higher fuel concentration and fuel performance as assessed by metallographic examination, fission gas release measurements, or visual examination.

5.2.4.2. Release From Failed Fuel. The amount of metallic fission product release from the fuel rods was low based on the gamma scanning results. A comparison of the measured and theoretical Cs-137/Zr-95 ratios showed that all fuel rods apparently had retained the cesium. The only fission product from the fuel measured in the graphite bodies was Cs-137, and the amount

was negligible. These data indicate that no significant amount of fission products was released from the fuel during irradiation and are in agreement with those of the P13R and P13S capsules where no diffusive release of metallic fission products was observed from fuel rods irradiated at similar conditions (Ref. 5-2).

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TABLE 5-1
SUMMARY DESCRIPTION AND FAILURE ANALYSIS OF FERTILE PARTICLES IN P13Q CAPSULE FUEL RODS

Sample Description					Irradiation Conditions					Metallographic Examination			Maximum Fertile Particle Failure (%) ^(b)
Fertile Particle Batch Data Retrieval Number	Fuel Rod Data Retrieval Number	OPyC Coating Density (Mg/m ³)	OPyC Coating Rate (µm/min)	OPyC Coating Anisotropy (BAF ₀)	Capsule Position	Average Volume Temperature (°C)	Average Peak Temperature (°C)	Fast Fluence (10 ²⁵ n/m ²) (E > 29 fJ) _{HTCR}	Burnup (% FIMA)	Number of Particles Examined	Pressure Vessel Failure Observed	95% Confidence Interval, (a) P (%)	
6542-01-0100	7161-002-19-3	1.80	10.0	1.027	G3-1A	855	915	4.3	1.4	-	-	-	0
6542-01-0100	7161-002-20-3	1.80	10.0	1.027	G3-2A	855	915	4.3	1.4	708	0	0 ≤ P ≤ 0.5	0
6542-02-0100	7161-002-21-3	1.88	8.6	1.030	G3-3A	855	915	4.3	1.4	-	-	-	0
6542-01-0100	7261-002-10-3	1.80	10.0	1.027	G3-1B	880	930	5.7	2.1	-	-	-	0.05
6542-01-0100	7261-002-11-8	1.80	10.0	1.027	G3-2B	880	930	5.7	2.1	-	-	-	0
6542-02-0100	7261-002-12-8	1.88	8.6	1.030	G3-3B	880	930	5.7	2.1	137	0	0 ≤ P ≤ 2.7	1.4
6542-01-0100	7261-002-13-3	1.80	10.0	1.027	G2-1A	905	945	7.2	3.3	-	-	-	0.5
6542-01-0100	7261-002-14-3	1.80	10.0	1.027	G2-2A	905	945	7.2	3.3	-	-	-	2.6
6542-01-0100	7261-002-15-3	1.80	10.0	1.027	G2-3A	905	945	7.2	3.3	200	0	0 ≤ P ≤ 1.9	0.7
6542-01-0100	7161-002-13-3	1.80	10.0	1.027	G2-1B	930	955	8.1	4.3	151	0	0 ≤ P ≤ 2.5	1.1
6542-01-0100	7161-002-14-3	1.80	10.0	1.027	G2-2B	930	955	8.1	4.3	117	0	0 ≤ P ≤ 3.2	1.8
6542-01-0100	7161-002-15-8	1.80	10.0	1.027	G2-3B	930	955	8.1	4.3	132	0	0 ≤ P ≤ 2.8	1.8
6542-01-0100	7261-002-16-8	1.80	10.0	1.027	G1-1A	1105	1120	9.0	5.4	-	-	-	1.0
6542-01-0100	7261-002-17-3	1.80	10.0	1.027	G1-2A	1105	1120	9.0	5.4	-	-	-	1.3
6542-02-0100	7261-002-18-5	1.88	8.6	1.030	G1-3A	1105	1120	9.0	5.4	122	0	0 ≤ P ≤ 3.1	1.6
6542-01-0100	7161-002-16-8	1.80	10.0	1.027	G1-1B	1160	1175	9.5	5.9	-	-	-	1.0
6542-01-0100	7161-002-17-3	1.80	10.0	1.027	G1-2B	1160	1175	9.5	5.9	97	0	0 ≤ P ≤ 4.1	1.5
6542-02-0100	7161-002-18-8	1.88	8.6	1.030	G1-3B	1160	1175	9.5	5.9	143	0	0 ≤ P ≤ 2.6	1.3

(a) The 95% confidence statement means that an infinite population of the particle batch tested will have a failure level at the 95% confidence level bounded by this interval.

(b) Calculated assuming: (1) a fractional release of 5×10^{-3} for failed fuel in a constrained geometry, and (2) all fission gas release came from failed fertile particles.

Fig. 5-1. Observed OPyC coating failure of the UC₂ TRISO batch 6151-00-010 irradiated in P13Q capsule fuel rods and P13R unbonded particle samples (Ref. 5-1) as a function of fluence. Average peak temperatures ranged from 699° to 1175°C.

Fig. 5-2. Maximum fertile particle failure of batches 6542-01-010 and 6542-01-020 in fuel rods of capsules P13Q, P13R, and P13S based on the postirradiation fission gas release measurements

Fig. 5-3. Least-squares fit of diametral and axial data points of P13Q fuel rods showing the anisotropic dimensional change as a function of fluence. Rods G2-3A and G2-3B, which had a different matrix, were not plotted.

Fig. 5-4. Comparison of diametral (radial) and axial dimensional change of H-451 graphite and P13Q fuel rods as a function of fluence. The average temperature of the graphite bodies ranged from 730° to 870°C.

6. SUMMARY

The results of the postirradiation examination of capsule P13Q can be summarized as follows:

1. Cured-in-place fuel rods were successfully irradiated in graphite bodies which were representative of a LHTGR fuel element configuration to a fast neutron exposure of $9.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}.
2. The integrity of all fuel rods was excellent after irradiation over a wide range of fuel rod variables.
3. The irradiation performance of the rods fired to a maximum temperature of 1500°C was comparable to that of rods fired at 1800°C.
4. The irradiation-induced dimensional change of the fuel rods was anisotropic and compatible with strain of the H-451 graphite bodies at temperatures <900°C and fluences < $7 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}. However, fuel rod shrinkage was enhanced by the presence of BISO inert particles.
5. The metallic fission product release from the fuel rods was low which would be predicted at these low fuel temperatures.
6. Tearing of the OPyC coating of all particle types occurred during green fuel rod fabrication. Almost all of the tearing was observed in the hot-injection rods which were formed at much higher pressures than the admix-compacted rods. The bond between matrix and particle may be enhanced by high injection pressures

to the detriment of fuel coating performance. A limit on injection pressure may be necessary.

7. The TRISO UC_2 particle batch exhibited up to 20.8% OPyC coating failure but less than 4.2% total pressure vessel failure in the fuel rods. The OPyC failure, which permitted the total pressure vessel failure, was attributed to the high anisotropy caused by the low coating deposition rate.
8. The two BISO ThO_2 particle batches irradiated in the fuel rods exhibited completely intact OPyC coatings but the release of fission gas from the fuel rods suggested that the BISO coatings were slightly permeable to the fission product gases. The permeability was attributed to the high surface-connected porosity which was caused by the high OPyC coating deposition rates. Specification of maximum coating rate will be required for OPyC coating.
9. Incipient degradation of the SiC coating due to rare earth fission products at the IPyC interface was observed in TRISO UC_2 particles in some of the rods at temperatures as low as 950°C .
10. The monitoring of in-pile fission gas release was not useful in verifying the fuel performance models because of large uncertainties in the measurements.

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