**Irradiation Performance of HTGR Fuel
Rods in HFIR Experiments HT-26 and -27**

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HFIR EXPERIMENTS HT-26 AND -27

T. N. Tiegs, A. J. Caputo, E. L. Long, Jr.,
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CONTENTS

ABSTRACT	1
INTRODUCTION	1
DESCRIPTION OF HT-26 AND -27 CAPSULES AND FUEL SPECIMENS	5
Capsules	5
Fuel	9
Loading Scheme	9
Coated Particles	11
Matrices	13
Preparation of Specimens	13
Chlorine Leach Analysis for Broken Particles	13
DESCRIPTION OF IRRADIATION	19
POSTIRRADIATION EXAMINATION	23
DISCUSSION AND CONCLUSIONS	35
ACKNOWLEDGMENTS	36
APPENDIX — Thermal Analysis	39

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T. N. Tiegs, A. J. Caputo, E. L. Long, Jr.,
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ABSTRACT

Capsules HT-26 and -27 were irradiated in the target region of the High Flux Isotope Reactor. The purpose was to study matrix-particle interaction in High-Temperature Gas-Cooled Reactor fuel rods before and after irradiation. The first objective was to fabricate fuel with a failed fuel fraction $<0.1\%$. This was accomplished for packed Al_2O_3 and in-block carbonization techniques, using annealed Biso-coated fertile particles and either annealed or unannealed Triso-coated fissile particles. The second objective, to irradiate fuel rods and determine the failed fuel fraction ($<1\%$ for acceptable results), was not completely accomplished. In HT-26 the capsule evidently leaked, and the fuel rods suffered attack by steam. In HT-27 the fuel rods only in the high-temperature region suffered attack by zirconium (used as an oxygen getter in the capsule). These problems resulted in failed particles and consequently made it impossible to determine failure fractions due to matrix-particle interaction. Results from the other fuel rods in HT-27 showed that particle failure fractions of $<1\%$ can be obtained from fuel rods carbonized in-tube and irradiated at temperatures up to $\sim 900^\circ\text{C}$ (fuel surface temperature).

INTRODUCTION

Uninstrumented test capsules HT-26 and -27 were irradiated in the target region of the High Flux Isotope Reactor (HFIR). Their purpose was to study matrix-particle interaction in High-Temperature Gas-Cooled Reactor (HTGR) fuel rods. The effect of both matrix and fuel particle properties on matrix-particle interaction was investigated.

¹Reactor Division.

Fuel used in HTGRs consists of coated microspheres (or kernels) containing uranium or thorium (as fissile or fertile material respectively) in the form of oxides or carbides. The coatings consist of both porous and dense pyrolytic carbon and sometimes silicon carbide, but always with the dense pyrolytic carbon as the outermost layer. These coated particles (300 to 850 μm in diameter) are formed into rods by injecting hot pitch and graphite filler into a bed of particles held in a mold. The volatiles from the pitch are removed by heating in a process called carbonization. Because the rods have a tendency to deform during carbonization, they are placed in packed Al_2O_3 powder or in the graphite blocks in which they will be irradiated. Since carbonization in Al_2O_3 involves powder handling operations which would be extremely difficult to perform in a remotely controlled hot-cell facility, for HTGR recycle it is essential to develop the in-block carbonization process.

The primary objective of the HT-26 and -27 experiments was to study the irradiation behavior of fuel rods carbonized in graphite tubes, which simulates the in-block carbonization technique proposed for remote refabrication. Specific objectives include:

1. fabrication of fuel rods with a failed fuel content of $<0.1\%$;
2. irradiation of fuel rods and determination of the failed fuel content following irradiation (this number should be $<1\%$ for acceptable results).

Previous accelerated irradiation tests² of HTGR fuel rods have revealed a potential problem associated with an interaction between the matrix and the fuel particle coatings in rods carbonized by the proposed in-block carbonization technique. The HRB-4 and -5 irradiation tests showed that a rod carbonized in a graphite tube (simulating in-block) with a high pitch-coke yield³ ($\sim 40\%$) and a very dense microstructure contained many broken particles after irradiation. On the other hand, a rod carbonized in packed Al_2O_3 powder with a low pitch-coke yield ($\sim 25\%$) and a very porous matrix microstructure gave acceptable irradiation performance. A comparison of the matrix microstructures is shown in Fig. 1.

It is hypothesized that shrinkage of the matrix during fabrication (in particular, carbonization) produces stresses which initiate tears in the particle coating and could lead to particle failure. An example of particle coating tearing is shown in Fig. 2. Additional shrinkage

²F. J. Homan et al., *Irradiation Performance of HTGR Fuel Rods in HFIR Experiments HRB-4 and -5*, ORNL/TM-5115 (June 1976).

³Weight fraction of pitch plus additives remaining in the rod after carbonization.

Fig. 1. Comparison of Matrix Microstructures From (a) Packed Al_2O_3 Powder and (b) In-Block Carbonization Techniques Before Irradiation.

Fig. 2. Unirradiated Triso Particle Showing Tearing of Outer Isotropic Coating Due to Particle-Matrix Interaction.

of the matrix during irradiation causes additional particle failures as shown in Fig. 3. It is further hypothesized that the extent of matrix-particle interaction leading to particle failure is dependent on the strength of the matrix, the strength of the particles, and the strength of the matrix-particle bond. The strength of the matrix and the matrix-particle bond is related to the pitch-coke yield and the surface texture of the particles.

Recent development work has shown that the broken particle fraction in fired fuel rods is related to the pitch-coke yield of the fuel rod matrix and the mean rupture load of the coated particles. It has also been shown that the pitch-coke yield can be substantially reduced by proper selection of binders and by controlling process parameters.

In addition, the mean rupture load of Biso-coated particles can be increased by annealing. Development coating studies have shown that the surface texture of coated particles can be altered by gaseous impregnation at the end of the coating run.

The objectives of HT-26 and -27 were fulfilled by determining the failed fuel fraction of fuel rods both before and after irradiation. This was the first test in which the failed fuel fraction was determined by means of chlorine leach analysis of fired fuel rods. Exposure of fired rods to gaseous chlorine at elevated temperatures ($>1000^{\circ}\text{C}$) results in the leaching of thorium or uranium because of cracked coatings. In this manner, matrix-particle interaction could be investigated and a meaningful evaluation of in-block carbonization made. It was recognized that because of the very low fuel loading required in the target region of the HFIR, this first experiment might only serve as a survey experiment.

DESCRIPTION OF HT-26 AND -27 CAPSULES AND FUEL SPECIMENS

Capsules

The exterior capsule design and containment for capsules HT-26 and -27 were identical to those of the previous capsules in the HT series, and the internal design was similar to that of capsules HT-24 and -25. Each capsule contained 16 fuel specimens, with 4 specimens in each of the Poco graphite magazines, which were contained inside a standard aluminum irradiation capsule as shown in Fig. 4.

The capsules in the target region of the HFIR have no provision for monitoring the irradiation temperature and are sealed under an inert atmosphere. Thus, temperature control is accomplished by adjusting the initial fuel loading, the gap between the fuel specimens and the graphite sleeve, and the gap between the graphite sleeve and the aluminum capsule, as determined by the thermal analysis of the system.

Fig. 3. Particles Broken Because of Matrix-Particle Interaction During Irradiation.
(a) Biso particle, and (b) Triso particle.

Fig. 4. HFIR Target Capsule Typical for HT-26 and -27.

Typical dimensions of the fuel specimens and the graphite sleeves are shown in Fig. 5. As noted, the nominal fuel specimen diameter was 0.381 in. and the nominal length was 0.93 in. This resulted in a stacked fuel length of 3.73 in. per magazine, or 14.92 in. per capsule.

The capsules were designed to have a nominal specimen surface temperature of 1250°C in the magazine nearest the reactor horizontal midplane (magazines B and C) and a nominal 900°C in the magazine on each end (magazines A and D). To obtain these temperatures, the specimens in the middle magazines (B and C) had higher loadings than the specimens in the end magazines (A and D). However, since flux varies with distance from the reactor midplane, especially in the end magazines, identical temperatures for all specimens are not possible.

Capsule HT-26 operated at low fluence (two cycles) and HT-27 at high fluence (four cycles). The flux levels and heavy-metal loading for the capsules are shown in Table 1.

Fig. 5. Typical Magazine Configuration for HT-26 and -27.

Table 1. Fast-Neutron Flux and Heavy-Metal Loading
for Capsules HT-26 and -27

Position in Capsule	Heavy-Metal Loading, g/cm ³						Fast-Neutron Flux, $E > 0.18$ MeV (n cm ⁻² sec ⁻¹)
	HT-26			HT-27			
	²³⁵ U	²³⁸ U	²³² Th	²³⁵ U	²³⁸ U	²³² Th	
(1)	0.00084	0.01318	0.0275	0.00084	0.01321	0.0276	0.60×10^{15}
(2)	0.00084	0.01319	0.0276	0.00084	0.01319	0.0276	0.71
(3)	0.00083	0.01306	0.0273	0.00083	0.01302	0.0272	0.82
(4)	0.00084	0.01315	0.0275	0.00083	0.01300	0.0272	0.91
(5)	0.00115	0.01814	0.0381	0.00118	0.01852	0.0389	1.07
(6)	0.00117	0.01843	0.0388	0.00116	0.01830	0.0385	1.11
(7)	0.00115	0.01804	0.0379	0.00116	0.01828	0.0384	1.15
(8)	0.00117	0.01838	0.0386	0.00117	0.01841	0.0387	1.17
Reactor Midplane							
(9)	0.00116	0.01820	0.0383	0.00117	0.01842	0.0387	1.17
(10)	0.00118	0.01862	0.0392	0.00118	0.01852	0.0389	1.15
(11)	0.00117	0.01839	0.0387	0.00114	0.01797	0.0378	1.11
(12)	0.00116	0.01820	0.0383	0.00117	0.01843	0.0388	1.07
(13)	0.00082	0.01281	0.0268	0.00082	0.01293	0.0270	0.91
(14)	0.00083	0.01305	0.0273	0.00082	0.02190	0.0269	0.82
(15)	0.00084	0.01317	0.0275	0.00083	0.01304	0.0272	0.71
(16)	0.00084	0.01319	0.0276	0.00085	0.01329	0.0278	0.60

Fuel

Loading Scheme

Each capsule contained 16 specimens, with all specimens made by the slug-injection process at ORNL. General Atomic Company (GAC) supplied one of the four matrix types tested. All the specimens were separated by a Grafoil-zirconium-Grafoil sandwich as shown in Fig. 5. The zirconium foil was to act as an oxygen "getter," and the Grafoil was to prevent reaction of the zirconium with the specimens. However, this was the major disappointment of the test, as discussed later in this report.

Since the main purpose of the experiment was to study the matrix-particle interaction phenomenon, combinations of four matrix types and two particle types were tested. The 16 specimens per capsule permitted at least one sample of each of the eight specimen types (four matrix and two particle types) to be tested at each of the two capsule

temperatures (900 and 1250°C). However, since the first priority was to evaluate the matrix-particle interaction, using in-block carbonization of the candidate reference matrix, these specimens were duplicated in each capsule in order to bring the total number of fuel particles subjected to postirradiation chlorine leaching into a statistically significant range. To accommodate these duplications, four other specimens were eliminated from each capsule.

The second priority was given to the GAC matrix; thus, none of these specimens were removed. Therefore, two of the four specimens of the remaining two matrix types were removed from HT-26, and the other two specimen types were removed from HT-27. Due to the variable flux in the end magazines, specimens were positioned to optimize comparison between particle types, both within and among matrix types. The loading plan for both capsules is shown in Table 2. This identifies the specimen type in relation to the matrix, carbonization mode, pitch-coke yield, particle type, surface temperature, and specimen location in each capsule.

Table 2. Loading Plan for HT-26 and -27 Irradiation Test^a to Study Matrix-Particle Interaction

Position in Capsule		Specimen Type	Approximate Surface Temperature (°C)	Particle ^b Type	Approximate Coke Yield (wt %)	Carbonization Mode	Matrix ^c Type
HT-26	HT-27						
13	13	1	900	I	24-27	In-tube	D
1,2	1,15	2	900	I	38-43	In-tube	B
	14	3	900	I	27-29	In-tube	C
14		4	900	I	18-20	In Al ₂ O ₃	A
7	11	5	1250	I	24-27	In-tube	D
6,9	6,7	6	1250	I	38-43	In-tube	B
11		7	1250	I	27-29	In-tube	C
	9	8	1250	I	18-20	In Al ₂ O ₃	A
Reactor Midplane							
	8	9	1250	II	18-20	In Al ₂ O ₃	A
5		10	1250	II	27-29	In-tube	C
8,12	10,12	11	1250	II	38-43	In-tube	B
10	5	12	1250	II	24-27	In-tube	D
3		13	900	II	18-20	In Al ₂ O ₃	A
	3	14	900	II	27-29	In-tube	C
16,15	2,16	15	900	II	38-43	In-tube	B
4	4	16	900	II	24-27	In-tube	D

^aHT-26 operated two cycles; HT-27 operated four cycles.

^bParticle type I consists of Triso fissile with outer LTI deposited at 1275°C from 100% MAPP gas, surface treated and annealed (batch OR2248H), and Biso-coated fertiles with unannealed LTI deposited at 1350°C from 100% propylene (batch J-461). Particle type II consists of Triso fissiles with outer LTI deposited at 1325°C from 50% MAPP gas without surface treating or annealing (batch OR2249), and Biso-coated fertiles with annealed LTI deposited at 1350°C from 100% propylene (batch J-465). MAPP is an Airco, Inc., trade name for stabilized methylacetylene propadiene.

^cMatrix types are as follows: type A contains high coke yield Ashland A-240 pitch carbonized in Al₂O₃; type B contains Ashland A-240 pitch carbonized in a graphite tube; type C contains low coke yield Ashland A-170 pitch carbonized in a graphite tube; type D is current GAC matrix carbonized in a graphite tube.

Coated Particles

All specimens in the test contained fertile, fissile (6.5% enrichment), and carbon inert particles. Since a primary objective of the test was to evaluate fuel particles, two types of both fertile and fissile were used. The characteristics of all particles are given in Table 3.

The primary objective of the two types of Biso-coated fertile particles was to evaluate particle strength of essentially reference design particles. The fertile kernels (ThO_2) were prepared by the sol-gel process, and the particles were identical through deposition of the low-temperature isotropic (LTI) coating. The type I fertile particles were used in the unannealed (as-coated) condition, but the type II fertile particles were used in the annealed (an additional heat treatment at 1800°C) condition (see Table 2). Under these conditions the unannealed particles were relatively "weak," with an average crush load of 5.09 lb, whereas the annealed particles were relatively "strong," with an average crush load of 6.48 lb.

The objective in regard to the fissile particles was to evaluate not only particle strength but also the surface condition of the outer LTI coating. Among other factors, the extent to which matrix-particle interaction can lead to particle failure is dependent upon the strength of the matrix-to-particle bond. Coating studies had shown that the porosity and texture of the surface of the outer LTI coating could be altered by gaseous impregnation at the end of the coating run. Thus the fissile particles [Triso-coated weak-acid resin (WAR) UC_{xO_y}] were processed (in the 2 1/2-in.-diam coater of the HTGR base program) as a single lot through the deposition of the SiC coating. For type I fissile particles, the deposition of the outer LTI included a surface treatment at the end of the coating run followed by annealing at 1800°C . The type II fissile particles had neither a surface treatment nor annealing (see Table 2). It was anticipated that the unannealed and annealed fissile particles would have different crush strengths, similar to the fertile particles. However, both types of particles had rather high crush strength: unannealed and not surface treated, 8.2 lb; annealed and surface treated, 7.6 lb. The SiC and the outer LTI (40 and 45 μm respectively) were thicker than the present reference design (30 and 35 μm respectively), and it appears this was a significant contribution to the high strength of both types of particles. Thus the weaker of the two types was used in fuel rods containing the "weak" fertile particles. Since evaluation (both metallographic and chlorine leach) discriminates between fissile and fertile particles, separate evaluation of the fertile and fissile particles can be made.

All specimens in the experiment contained Biso-coated inert particles. The inert carbon kernels were made from desulfurized strong-acid resin and were coated in the 2 1/2-in.-diam coater of the HTGR base program.

Table 3. Characterization of Coated Particles for HT-26 and -27^a

	Batch Number ^b					
	OR-2249	OR-2248H	J-461	J-465	OR-2239H	OR-2240H
Coated particle						
Annealed	No	Yes	No	Yes	Yes	Yes
Crush strength, lb	8.22 ± 0.89	7.57 ± 0.97	5.09 ± 0.99	6.48 ± 0.80	ND	ND
Kernel material	WAR·UC _x O _y	WAR·UC _x O _y	ThO ₂	ThO ₂	SAR carbon	SAR carbon
Uranium content, wt %	16.79	15.76	NA	NA	NA	NA
²³⁵ U enrichment, at. %	6.53	6.53	NA	NA	NA	NA
Thorium content, wt %	NA	NA	56.43	56.52	NA	NA
Kernel						
Diameter, μm	422.6 ± 33.9	422.6 ± 33.9	497.8 ± 3.8	497.1 ± 3.2	478.0 ± 33.4	478.0 ± 33.4
Density, g/cm ³	2.87 ^c	2.87 ^c	9.91	9.91	1.34 ^c	1.34 ^c
Buffer						
Thickness, μm	55.1 ± 11.1	55.1 ± 11.1	81.0 ± 9.6	83.9 ± 12.1	73.5 ± ND	73.5 ± ND
Density, g/cm ³	1.12 ^c	1.12 ^c	1.106/1.263 ^d	1.106/1.257 ^d	1.03 ^c	1.03 ^c
Inner carbon						
Thickness, μm	40.7 ± 4.8	40.7 ± 4.8	NA	NA	NA	NA
Density, g/cm ³	1.934 ± 0.008	1.934 ± 0.008	NA	NA	NA	NA
SiC						
Thickness, μm	38.9 ± 1.7	38.9 ± 1.7	NA	NA	NA	NA
Density, g/cm ³	ND	ND	NA	NA	NA	NA
Outer carbon						
Thickness, μm	43.4 ± 3.5	46.8 ± 3.3	80.5 ± 8.1	77.7 ± 8.0	95.4 ± 5.7	97.7 ± 6.6
Density, g/cm ³	1.820 ± 0.008	2.020 ± 0.005	1.934/1.833 ^e	1.979/1.882 ^e	1.970 ± 0.006	1.958 ± 0.005
Surface treated	No	Yes	No	No	No	No

^aWhere applicable, values are mean ± standard deviation.^bNA = not applicable; ND = not determined.^cFrom tapped volume.^dBefore and after depositing LTI, calculated from burn-off and mercury density.^eObserved gradient/corrected gradient.

Matrices

In addition to other factors, the extent of matrix-particle interaction is related to the pitch-coke yield of the matrix. Pitch shrinks during carbonization, and at the higher pitch-coke yields there is more carbonization and thus more shrinkage, which increases the possibility of the shrinkage on the surface of the particles and thus the possibility of breaking the coating. The experiment used four matrices to investigate pitch-coke yields ranging from approximately 18 to 43%. High coke yields (~43%) were obtained by using a matrix containing Ashland A-240 pitch carbonized in graphite tubes. Low coke yields were obtained from the other three matrices by:

1. in-powder (Al_2O_3) carbonization using Ashland A-240 pitch,
2. in-tube carbonization using a low-coke-yield pitch (Ashland A-170),
3. in-tube carbonization of a matrix developed by GAC (MO-357).

The composition of the various matrices is shown in Table 4.

Preparation of Specimens

All of the specimens were prepared by the slug-injection process and had nominal dimensions of 0.381 in. in diameter and 0.93 in. long. All of the specimens were injected at 1000 psi, but since the various matrices contained different pitches and had different compositions, the injection temperatures (actually mold heater temperature) of the matrices were different. As shown in Table 4, the temperatures were 130°C for the Ashland A-170 pitch, 140°C for the GAC matrix, and 180°C for the Ashland A-240 pitch.

Although all the specimens were carbonized at 800°C, different heating rates were used for the different matrices, since both the desired coke yield and carbonization mode were different. As shown in Table 4, the specimens were either packed vertically in Al_2O_3 powder or horizontally in a graphite tube and heated at rates from 3 to 10°C/min.

All of the specimens were heat treated at 1800°C for 30 min to stabilize the matrix. Specimens were characterized by coke yield, dimensions, visual inspection, radiography, and metallography. A summary of this characterization data is shown in Tables 5 and 6.

Chlorine Leach Analysis for Broken Particles

Because of the small number of fuel particles (80 to 400) contained in the test specimens, the failure of a single particle would result in a failure fraction much higher than the desired 1×10^{-3} . Therefore, chlorine leach tests for broken particles were conducted on rods containing either all fissile or all fertile particles that were fabricated along with the irradiation test specimens. As mentioned previously, both types of fissile particles (unannealed and not surface treated, and annealed and surface treated) had comparable and rather high crush strength,

Table 4. Fabrication History of Specimens for HT-26 and -27

Matrix Type	Matrix Batch Number	Matrix Description				Slug Injection		Carbonization		Approximate Coke Yield ^b (wt %)	Matrix Density (g/cm ³)
		Filler		Pitch		Pressure (psi)	Temperature ^a (°C)	Mode	Heating Rate (°C/min)		
		(wt %)	Type	(wt %)	Type						
A	M-105	29	6353 N.F. ^c	71	A-240 ^d	1000	180	In Al ₂ O ₃	4	18–20	0.53
B	M-105	29	6353 N.F. ^c	71	A-240 ^d	1000	180	In-tube	3	38–43	0.70
C	M-138	29	6353 N.F. ^c	71	A-170 ^d	1000	130	In-tube	7	27–29	0.58
D	M-136	GA batch MO-357 composition proprietary				1000	140	In-tube	10	24–27	0.66

^aActually mold heater temperature.^bCoke yield = $\frac{\text{fired rod weight} - (\text{coated particle weight} + \text{filler weight})}{\text{green rod pitch weight} + \text{additives}} \times 100$.^cAsbury Mills.^dAshland Oil.

Table 5. Characterization of Specimens for HT-26^a

Capsule Position	Specimen Number	Specimen Type ^b	Average Diameter (in.)	Average Length (in.)	Volume (cm ³)	Weight (g)	Density, g/cm ³		Particle Volume Loading (%)	Coke Yield (%)	Metallo- graphic Mount Number
							Matrix	Total			
1	M-105-656	2	0.3795	0.9283	1.7206	2.220	0.71	1.290	58.6	40.8	79119
2	M-105-660	2	0.3797	0.9273	1.7206	2.209	0.70	1.284	58.2	42.0	79119
3	M-105-649	13	0.3823	0.9238	1.7377	2.122	0.54	1.221	58.5	19.4	79130
4	M-136-56	16	0.3835	0.9113	1.7249	2.187	0.67	1.268	57.7	26.4	79133
5	M-138-96	10	0.3816	0.9360	1.7542	2.168	0.96	1.263	57.8	28.0	79127
6	M-105-668	6	0.3810	0.9241	1.7264	2.241	0.69	1.298	58.0	41.0	79123
7	M-136-42	5	0.3830	0.9345	1.7642	2.262	0.65	1.282	57.8	24.1	79122
8	M-105-678	11	0.3797	0.9329	1.7310	2.247	0.71	1.298	57.7	42.5	79128
9	M-105-664	6	0.3804	0.9388	1.7484	2.272	0.70	1.299	58.1	39.7	79123
10	M-136-52	12	0.3812	0.9137	1.7088	2.220	0.68	1.299	58.3	27.1	79129
11	M-138-92	7	0.3813	0.9248	1.7305	2.169	0.58	1.254	58.2	28.4	79124
12	M-105-679	11	0.3802	0.9399	1.7486	2.241	0.68	1.282	57.1	41.5	79128
13	M-136-38	1	0.3826	0.9401	1.7711	2.230	0.65	1.259	57.3	24.9	79118
14	M-105-618	4	0.3825	0.9230	1.7380	2.110	0.54	1.214	57.7	20.2	79121
15	M-105-685	15	0.3807	0.9236	1.7228	2.178	0.71	1.264	56.2	41.5	79132
16	M-105-684	15	0.3807	0.9223	1.7203	2.155	0.68	1.253	56.2	41.7	79132

^aPhotographs 2786-74 and 2793-74 apply to all specimens.^bSee Table 2 for description.

Table 6. Characterization of Specimens for HT-27^a

Capsule Position	Specimen Number	Specimen Type ^b	Average Diameter (in.)	Average Length (in.)	Volume (cm ³)	Weight (g)	Density, g/cm ³		Particle Volume Loading (%)	Coke Yield (%)	Metallographic Mount Number
							Matrix	Total			
1	M-105-662	2	0.3791	0.9287	1.7177	2.205	0.69	1.284	58.7	40.7	79119
2	M-105-687	15	0.3802	0.9243	1.7195	2.168	0.70	1.261	56.3	43.1	79132
3	M-138-109	14	0.3821	0.9273	1.7425	2.123	0.58	1.219	57.3	28.9	79131
4	M-136-57	16	0.3835	0.9221	1.7454	2.197	0.66	1.259	57.1	27.0	79133
5	M-136-53	12	0.3817	0.9165	1.7185	2.220	0.68	1.292	58.0	24.6	79129
6	M-105-669	6	0.3806	0.9329	1.7392	2.227	0.66	1.280	57.5	38.4	79123
7	M-105-670	6	0.3808	0.9329	1.7410	2.245	0.69	1.289	57.5	39.9	79123
8	M-105-645	9	0.3830	0.9158	1.7289	2.141	0.52	1.238	59.1	18.8	79126
9	M-105-640	8	0.3832	0.9143	1.7279	2.139	0.53	1.238	58.3	18.7	79125
10	M-105-680	11	0.3793	0.9280	1.7183	2.239	0.71	1.303	58.1	41.5	79128
11	M-136-44	5	0.3834	0.9360	1.7708	2.273	0.66	1.284	57.6	25.1	79122
12	M-105-681	11	0.3786	0.9358	1.7263	2.235	0.70	1.265	57.9	39.4	79128
13	M-136-39	1	0.3828	0.9304	1.7546	2.235	0.68	1.274	57.8	26.2	79118
14	M-138-87	3	0.3825	0.9342	1.7591	2.124	0.55	1.207	57.1	27.4	79120
15	M-105-663	2	0.3802	0.9353	1.7400	2.212	0.69	1.271	57.6	41.0	79119
16	M-105-689	15	0.3795	0.9211	1.7073	2.158	0.69	1.264	56.7	39.7	79132

^aPhotographs 2791-74 and 2972-74 apply to all specimens.^bSee Table 2 for description.

8.2 and 7.6 lb respectively. As shown in Table 7, this resulted in very low particle failure fractions, regardless of the matrix or pitch-coke yield. Although fuel specifications call for a failure fraction of 1×10^{-3} , it was desired to fabricate fuel with failure fractions of $<1 \times 10^{-4}$.

Table 7. Broken-Particle Analysis of Fuel Rods^a Containing Triso-Coated WAR $^{235}\text{UC}_{4.86}\text{O}_{1.22}$ Particles by Chlorine Leach

Matrix Type	Specimen Number	Carbonization Mode	Pitch-Coke Yield (wt %)	Particle Failure Fraction ^b	
				Annealed and Surface Treated Rupture Load, 7.57 lb	Unannealed and Not Surface Treated Rupture Load, 8.22 lb
A ^c	M-105-622	Al ₂ O ₃	18.7	0.06×10^{-4}	
	M-105-625	Al ₂ O ₃	19.5		2.19×10^{-4}
B ^c	M-105-696	In-tube	42.5	0.33	
	M-105-691	In-tube	42.1		0.12
C ^d	M-138-116	In-tube	20.7	0.04	
	M-138-112	In-tube	29.7		0.03
D ^e	M-136-64	In-tube	25.4	0.06	
	M-136-68	In-tube	26.7		0.05

^aFuel rods contain only WAR $^{235}\text{UC}_{4.86}\text{O}_{1.22}$ particles and rods leached with gaseous chlorine for 2 hr at 1500°C.

^bGrams of uranium recovered by chlorine leach per gram of uranium in rod. Desired failure fraction was 1×10^{-4} .

^c29 wt % Asbury 6353 natural flake and 71 wt % Ashland A-240 pitch.

^d29 wt % Asbury 6353 natural flake and 71 wt % Ashland A-240 pitch.

^eGeneral Atomic matrix batch MO-357, composition proprietary.

The unannealed and annealed fertile particles had a wider range of crush strength, 5.1 and 6.5 lb respectively. As shown in Table 8, the annealed fertile particles had a very low particle failure fraction, regardless of the matrix or pitch-coke yield. However, Table 8 shows that the unannealed fertile particles with low crush strength had the highest failure fraction ($\sim 50 \times 10^{-4}$) when carbonized in-tube, using matrix type B (A-240 pitch) at a coke yield of approximately 42%. The failure fraction of these particles when used with the other three matrices at lower coke yields ranged from 20 to 0.5×10^{-4} , as shown in Table 8. These data reinforce the view that fuel rods containing sufficiently strong particles can be fabricated with very low failure fractions with various matrices or level of coke yield, but with weaker particles the failure fraction can be dependent upon the fabrication process.

Table 8. Broken-Particle Analysis of Fuel Rods^a Containing Biso-Coated ThO₂ Particles by Chlorine Leach

Matrix Type	Specimen Number	Carbonization Mode	Pitch-Coke Yield (wt %)	Particle Failure Fraction ^b	
				J-461 Unannealed Crush Strength, 5.09 lb	J-465 Annealed Crush Strength, 6.47 lb
A ^c	M-105-632	Al ₂ O ₃	16.6	12.2×10^{-4}	
	M-105-633	Al ₂ O ₃	16.7	21.3	
	M-105-628	Al ₂ O ₃	19.2		0.158×10^{-4}
	M-105-629	Al ₂ O ₃	17.1		0.554
B ^c	M-105-701	In tube	42.2	49.6	
	M-105-702	In-tube	42.2	18.8	
	M-105-699	In-tube	42.1		0.185
	M-105-700	In-tube	41.4		0.167
C ^d	M-138-123	In-tube	29.7	5.59	
	M-138-124	In-tube	26.3	0.22	
	M-138-118	In-tube	28.2		0.116
	M-138-119	In-tube	28.0		0.086
D ^e	M-136-70	In-tube	27.0	0.47	
	M-136-71	In-tube	25.8	1.82	
	M-136-74	In-tube	26.6		1.43
	M-136-75	In-tube	24.4		0.86

^aFuel rods contain only ThO₂ particles and rods leached with gaseous chlorine for 2 hr at 1500°C.

^bGrams of thorium recovered by chlorine leach per gram of thorium in rod. Desired failure fraction was 1×10^{-4} .

^c29 wt % Asbury 6353 natural flake and 71 wt % Ashland A-240 pitch.

^d29 wt % Asbury 6353 natural flake and 71 wt % Ashland A-170 pitch.

^eGeneral Atomic matrix batch MO-357, composition proprietary.

DESCRIPTION OF IRRADIATION

Both of the capsules were irradiated in the target region of the HFIR. The location of this facility is shown in Fig. 6. A detailed description of the neutron fluxes and gamma heating characteristics was previously reported⁴ and will not be repeated here.

⁴R. D. Cheverton and T. M. Sims, *HFIR Core Nuclear Design*, ORNL-TM-4621 (July 1971).

Fig. 6. Cross Section of HFIR, Showing Location of Target Facility.

Table 9 gives an operating history of HT-26 and -27. As can be seen from the table, HT-26 was a two-cycle experiment inserted in target position A-3 at the beginning of HFIR cycle 113 on Nov. 1, 1974, and was removed at the end of cycle 114 on Dec. 18, 1974. During the two cycles it accumulated a total of 1100.4 hr of irradiation time with the reactor at 100 MW.

Table 9. Target Capsules HT-26 and -27 Reactor Power History

Target Capsule	Target Facility	HFIR Fuel Cycle	Begin		End		Irradiation Time, hr	
			Time	Date	Time	Date	During Cycle	Accumulated
HT-26	A-3	113	0818	11-1-74	1028	11-24-74	558.72	558.72
	A-3	114	1332	11-25-74	0400	12-18-74	541.68	1100.40
HT-27	F-7	113	0818	11-1-74	1028	11-24-74	558.72	558.72
	F-7	114	1332	11-25-74	0400	12-18-74	541.68	1100.40
	F-7	115	1435	12-20-74	1716	1-11-75	529.68	1630.08
	F-7	116	1700	1-12-75	2000	2-3-75	530.16	2160.24

Capsule HT-27 was a four-cycle experiment inserted in target position F-7 at the beginning of cycle 113 on Nov. 1, 1974, and was removed at the end of cycle 116 on Feb. 3, 1975. During the four cycles it accumulated a total of 2160.24 hr of irradiation time with the reactor at 100 MW.

Both thermal ($E < 0.414$ eV) and fast ($E > 0.18$ MeV) neutron fluxes were obtained from information that gives the fluxes as a function of axial position. These fluxes were assumed to be constant as a function of time. Neutron fluences were calculated and are summarized in Table 10.

In both HT-26 and -27, fuel rods 8 and 9 (which were located nearest the horizontal midplane) received the highest fluences. In HT-26 the largest fast fluence ($E > 0.18$ MeV) was 4.63×10^{21} n/cm², and in HT-27 it was 9.10×10^{21} n/cm².

Fuel burnups for HT-26 and -27 are given in Tables 11 and 12 respectively. Burnups are reported as fissions per initial heavy-metal atom (FIMA) in percent.

Table 10. Calculated Thermal and Fast Fluences for Target Capsules HT-26 and -27

Specimen Number	Preirradiation Distance From HMP ^a to Specimen (in.)	Thermal Flux, $E < 0.414 \text{ eV}$ ($\text{n cm}^{-2} \text{ sec}^{-1}$)	Fast Flux, $E > 0.18 \text{ MeV}$ ($\text{n cm}^{-2} \text{ sec}^{-1}$)	HT-26 Fluence		HT-27 Fluence	
				Thermal, $E < 0.414 \text{ eV}$ (n/cm^2)	Fast, $E > 0.18 \text{ MeV}$ (n/cm^2)	Thermal, $E < 0.414 \text{ eV}$ (n/cm^2)	Fast, $E > 0.18 \text{ MeV}$ (n/cm^2)
3,9	1.07	2.78×10^{15}	1.17×10^{15}	1.101×10^{22}	4.63×10^{21}	2.16×10^{22}	9.10×10^{21}
7,10	2.00	2.68	1.15	1.062	4.56	2.08	8.94
6,11	2.94	2.56	1.11	1.014	4.39	1.99	8.63
5,12	3.88	2.42	1.07	0.959	4.24	1.88	8.32
4,13	6.07	2.06	0.91	0.816	3.61	1.60	7.08
3,14	7.00	1.89	0.815	0.749	3.23	1.47	6.34
2,15	7.94	1.70	0.710	0.673	2.81	1.32	5.52
1,16	8.88	1.52	0.602	0.602	2.38	1.18	4.68

^aHorizontal midplane.

Table 11. Fuel Particle Burnup for HT-26

Specimen Number	Distance From Horizontal Midplane (in.)	Burnup, % FIMA		
		^{235}U	^{238}U	^{233}Th
1,16	8.88	81.71	5.10	1.35
2,15	7.94	82.55	5.92	1.62
3,14	7.00	83.26	6.65	1.88
4,13	6.07	83.83	7.25	2.09
5,12	3.88	84.50	8.25	2.52
6,11	2.94	84.65	8.55	2.65
7,10	2.00	84.70	8.70	2.72
8,9	1.07	84.75	8.89	2.80

Table 12. Fuel Particle Burnup for HT-27

Specimen Number	Distance From Horizontal Midplane (in.)	Burnup, % FIMA		
		^{235}U	^{238}U	^{233}Th
1,16	8.88	84.25	11.40	5.02
2,15	7.94	84.35	13.05	5.80
3,14	7.00	84.45	14.37	6.60
4,13	6.07	84.55	15.49	7.20
5,12	3.88	84.75	17.25	8.40
6,11	2.94	84.80	17.80	8.70
7,10	2.00	84.85	18.20	8.90
8,9	1.07	84.86	18.50	9.05

POSTIRRADIATION EXAMINATION

When HT-26 was disassembled, all fuel rods in the high-temperature and -fluence regions of the capsule (i.e., rods 5 through 12) were badly debonded, while those in the low-temperature and -fluence regions (i.e., rods 1 through 4 and 13 through 16) were in excellent condition. Representative photomacrographs of the rods after irradiation are shown in Fig. 7. A summary of the visual examination is given in Table 13.

Fig. 7. Representative Photomacrographs of Fuel Rods After Irradiation from: (a) The Low-Temperature Region (Rod 13), and (b) The High-Temperature Region (Rod 7) in HT-26. Note the debonding in the high-temperature rod, while the low-temperature rod was intact.

Table 13. Summary of Visual Examination of HT-26

Rod Position in Capsule	Approximate Surface Temperature (°C)	Matrix Type ^a	Carbonization Mode	Coke Yield (wt %)	General Condition of Rod	Stereoscopic Examination
1	900	B	In-tube	40.8	Good, no debonding	No failed particles on surface
2	900	B	In-tube	42.0	Good, no debonding	No failed particles on surface
3	900	A	In Al ₂ O ₃	19.4	Good, no debonding	No failed particles on surface
4	900	D	In-tube	26.4	Good, no debonding	No failed particles on surface
5	1250	C	In-tube	28.0	Very extensive debonding (2 large sections remain)	A number of failed particles observed with outer coatings removed
6	1250	B	In-tube	41.0	Complete debonding	No failed particles observed
7	1250	D	In-tube	24.1	Extensive debonding (2 large sections remain)	One failed particle observed (type unknown)
8	1250	B	In-tube	42.5	Complete debonding	No failed particles observed
9	1250	B	In-tube	39.7	Very extensive debonding	A number of failed particles observed (types unknown)
10	1250	D	In-tube	27.1	Intact, but very fragile	No observation made
11	1250	C	In-tube	28.4	Intact, but very fragile	No observation made
12	1250	B	In-tube	41.5	Complete debonding	A number of failed particles observed (types unknown)
13	900	D	In-tube	24.9	Good, no debonding	No failed particles on surface
14	900	A	In Al ₂ O ₃	20.2	Good, no debonding	No failed particles on surface
15	900	B	In-tube	41.5	Good, no debonding	No failed particles on surface
16	900	B	In-tube	41.7	Good, no debonding	No failed particles on surface

^aMatrix types are as follows: Type A contains high-coke-yield Ashland A-240 pitch carbonized in Al₂O₃. Type B contains Ashland A-240 pitch carbonized in a graphite tube. Type C contains low-coke-yield A-170 pitch carbonized in a graphite tube. Type D is current GAC matrix carbonized in a graphite tube.

Additional visual examination revealed a large number of small holes (<0.05 cm in diameter) associated with the graphite magazines from the high-temperature region. The holes are shown in Fig. 8, which is a photomacrograph of a magazine outer surface. Examination of the inner surface of the magazines (from the high-temperature region) showed that the holes extended through the graphite. No direct path could be seen; that is, the holes did not appear to be straight.

The holes were isolated metallographically, and microprobe analysis revealed concentrations of iron and vanadium surrounding the holes. These results are shown in Fig. 9. The holes evidently followed agglomerates (areas of high density formed by fines and a high proportion of pitch), where the iron and vanadium appear as impurities from the pitch.

This type of phenomenon has been observed before and is due to attack of the graphite by steam. As a result, the indications are that the HT-26 capsule developed a leak during or prior to irradiation. This would explain the appearance of holes in the graphite magazines and debonding of the fuel rods due to formation and attack of steam. In light of these results, further examination of the HT-26 capsule was stopped. (The visual and dimensional examinations had been completed and chlorine leaching of rods 1, 2, and 3 finished. Chlorine leaching of rods 5 through 12 was not scheduled because of the debonding.)

Fig. 8. Photomacrograph of Holes Present on Outer Surface of Graphite Magazine in High-Temperature Region of HT-26. 27 $\times$.

Fig. 9. Microprobe Results Showing Concentrations of Iron and Vanadium Surrounding the Holes From High-Temperature Graphite Magazines in HT-26. 500 $\times$. (a) Optical, (b) specimen current, (c) Fe L_{α} , (d) V L_{α} .

It should be pointed out that as a consequence of the possible leakage, gas samples from HT capsules are now taken which prove definitely whether they had a leak during operation (H_2O would be detected if a leak was present). Gas sampling also aids in postirradiation thermal analyses.

When the HT-27 capsule was disassembled, no problems were encountered, and all fuel rods were removed intact and in excellent condition. Visual examination of the fuel rods revealed no failed particles on the outer surfaces and no debonding of the rods. However, the zirconium foils, used as oxygen getters and placed between the fuel rods, had adhered to the ends of the rods from the high-temperature region (i.e., rods 5 through 12). The zirconium foils had been separated from the fuel rods by Grafoil wafers; but apparently a reaction had occurred that extended through the Grafoil into the fuel rods. Representative rods are shown in Figs. 10 and 11. No evidence of the zirconium adhering to the rods from the low-temperature regions was observed.

Fig. 10. Representative Fuel Rod (No. 3) From Low-Temperature Region After Irradiation in HT-27. (a) Side view, (b) top view, (c) bottom view. 6 $\times$.

Fig. 11. Representative Fuel Rod (No. 8) From High-Temperature Region After Irradiation in HT-27. (a) Side view, (b) top view, (c) bottom view. Note appearance of large amounts of zirconium on bottom of rod and very little on the top. 6×.

Dimensional analyses on HT-26 and -27 were made, but both were incomplete. In HT-26 the rods from the high-temperature region (rods 5 to 12) had no measurements taken because of the debonding encountered. In HT-27 the lengths of the rods in the high-temperature region (rods 5 to 12) could not be taken because of the zirconium adhering to the ends. Diameters of the fuel rods were measured at the top, midlength, and bottom at 0 and 90°. Tables 14 and 15 give summaries of the dimensional changes for HT-26 and -27 respectively. The fuel rods experienced shrinkages, with the greater changes at the higher temperatures and fluences. In every case the lengths of the rods shrank more than the diameters. This anisotropic shrinkage is in part a characteristic of the slug-injection method, where the graphite filler particles are preferentially oriented, leading to differential shrinkage.

A thermal analysis was performed using the postirradiation examination (PIE) dimensions, which took into account the radial shrinkages of the fuel rods. The preirradiation thermal analysis did not incorporate changes in fuel rod dimensions. A detailed description of the thermal analyses is given in the appendix. It was calculated that the operating fuel surface temperatures increased from 89 to 121°C above the design surface temperatures of 900 and 1250°C. It was also calculated that the fuel centerline temperatures were 89 to 151°C above the anticipated temperatures.

Chlorine leach tests to determine particle failure fractions were performed on rods 1, 2, and 3 from HT-26 and on all rods from HT-27. The tests are carried out by heating a rod to 1000°C and passing hot chlorine gas over it. Volatile heavy-metal chlorides are formed which can be collected (by condensation) and measured. A chlorination cycle of approximately 20 hr was used after a time study was done to determine evolution rate. In addition to the spectrophotometric measurement of thorium and the fluorometric measurement of uranium, the volatiles collected were examined by gamma spectrometry and spark source mass spectrometry to determine the presence of fission and activation products and impurities. The results are given in Table 16. As shown, high failure fractions were found in the rods from the high-fluence and -temperature regions.

In addition to the uranium, thorium, fission products, and ^{233}Pa that are expected to be recovered from failed irradiated particles, iron activation products ^{59}Fe , ^{51}Cr , and ^{54}Mn were also observed. The fission products and activation products included: ^{95}Zr , ^{95}Nb , ^{103}Ru , ^{134}Cs , ^{140}Ba , ^{141}Ce , ^{156}Eu , ^{46}Sc , ^{60}Co , ^{110m}Ag , ^{181}Hf , and ^{233}Pa . A subsequent investigation found that the iron contamination was from the graphite magazines (made of Poco AXF-5Q), from where it had evidently migrated into the rods during irradiation.

Table 14. Summary of Dimensional Changes for HT-26

Rod Number	Approximate Surface Temperature (°C)	Postirradiation Dimensional Change and Diameter-to-Length Change Ratio					Fast Fluence, $E > 0.18$ MeV (n/cm ²)
		ΔD (in.)	% Change	ΔL (in.)	% Change	$\frac{\Delta D}{D} / \frac{\Delta L}{L}$	
1	900	0.0106	-2.80	0.0341	-3.67	0.76	2.2×10^{21}
2	900	0.0132	-3.48	0.0337	-3.63	0.96	2.8
3	900	0.0129	-3.36	0.0315	-3.41	0.99	3.2
4	900	0.0131	-3.41	0.0353	-3.87	0.88	3.6
13	900	0.0133	-3.48	0.0072	-4.60	0.76	3.6
14	900	0.0116	-3.04	0.0311	-3.37	0.90	3.2
15	900	0.0123	-3.24	0.0327	-3.54	0.92	2.8
16	900	0.0121	-3.19	0.0393	-4.26	0.75	2.2

Table 15. Summary of Dimensional Changes for HT-27

Rod Number	Approximate Surface Temperature (°C)	Postirradiation Dimensional Change and Diameter-to-Length Change Ratio					Fast Fluence, $E > 0.18$ MeV (n/cm ²)
		ΔD (in.)	% Change	ΔL (in.)	% Change	$\frac{\Delta D}{D} / \frac{\Delta L}{L}$	
1	900	0.0129	-3.40	0.0387	-4.17	0.82	4.6×10^{21}
2	900	0.0105	-2.76	0.0410	-4.44	0.62	5.6
3	900	0.0144	-3.77	0.0428	-4.62	0.82	6.4
4	900	0.0136	-3.55	0.0435	-4.72	0.75	7.1
5	1250	0.0141	-3.69	0.0364	-3.97	0.93	8.1
6	1250	0.0144	-3.78	0.0456	-4.89	0.77	8.4
7	1250	0.0142	-3.73				8.8
8	1250	0.0172	-4.49				9.0
9	1250	0.0157	-4.10				9.0
10	1250	0.0139	-3.66				8.8
11	1250	0.0145	-3.78				8.4
12	1250	0.0137	-3.62				8.1
13	900	0.0139	-3.63	0.0417	-4.48	0.81	7.1
14	900	0.0138	-3.61	0.0427	-4.57	0.79	6.4
15	900	0.0129	-3.24	0.0476	-5.09	0.64	5.6
16	900	0.0126	-3.32	0.0419	-4.55	0.73	4.6

Table 16. Summary of Results from Chlorine Leach Tests

Rod Number	Approximate Fuel Surface Temperature (°C)	Average Fast Fluence, $E > 0.18$ MeV (r/cm ²)	Pitch-Coke Yield (%)	Total Metal Recovered, µg			Percent Failed ^a	
				U	Th	Fe	U	Th
HT-26-1	900	2.38×10^{21}	40.8 ^b	20	<10	200		
-2	900	2.81	42.0 ^b	100	1,380	d		
-3	900	3.23	19.4 ^c	30	<10	d		
HT-27-1	900	4.68	40.7 ^b	27	38	d	0.15	0.08
-2	900	5.52	43.1 ^b	10	28	d	0.05	0.06
-3	900	6.34	28.9 ^b	95	20	d	0.54	0.05
-4	900	7.08	27.0 ^b	<10	24	d	0.06	0.06
-5	1250	8.32	24.6 ^b	2000	1,870	d	8.26	3.05
-6	1250	8.63	38.4 ^b	4100	6,440	d	17.04	10.54
-7	1250	8.94	39.9 ^b	5540	10,700	10,000	23.14	17.56
-8	1250	9.10	18.8 ^c	3350	7,290	d	14.05	11.98
-9	1250	9.10	18.7 ^c	3420	8,430	21,000	14.34	13.86
-10	1250	8.94	41.5 ^b	6100	8,390	d	25.48	13.77
-11	1250	8.63	25.1 ^b	1620	2,660	20,000	6.73	4.36
-12	1250	8.32	39.4 ^b	4900	12,500	d	20.23	20.40
-13	900	7.08	26.2 ^b	60	<10	300	0.34	0.02
-14	900	6.34	27.4 ^b	29	50	d	0.16	0.11
-15	900	5.52	41.0 ^b	<10	<25	300	0.06	0.06
-16	900	4.68	39.7 ^b	23	38	d	0.13	0.08

^aBurnup corrections made.^bCarbonized in graphite tube.^cCarbonized in packed Al₂O₃ powder.^dNot determined.

After the chlorine leach, metallography was performed on selected fuel rods from the high-temperature region of HT-27. Results, as shown in Figs. 12 and 13, indicate an extensive reaction of the zirconium foil with the carbon in the fuel rods and destruction of many particles. Because the reaction took place mainly at the rod centerlines (extending into the rod as shown in Fig. 13) and did not necessarily attack both ends, it is believed to be governed by how much contact the rods had with the zirconium (i.e., the closer the contact, the greater the reaction) and by the temperature. It was also observed that the fueled particles had been attacked to a greater extent than had the inert particles (probably because they were generating heat).

The zirconium reaction with the fuel rods causes the chlorine leach results to be at best compromised, because an attacked fuel particle would show up as a failed particle. Thus the chlorine leach results from the fuel rods in the high-temperature region of HT-27 cannot be interpreted, since the zirconium reaction caused many fueled particles to fail. The failure fractions depended on the extent of the reaction and the number of fueled particles in close proximity to the zirconium, not matrix-particle interaction, as had been expected.

Since no zirconium reaction was observed to be associated with the low-temperature fuel rods, those results are believed to be accurate. In each case, very low failure fractions were recorded.

Metallography also revealed a problem associated with the chlorine leach analysis. In addition to leaching of exposed thorium and uranium, the chlorine gas attacks SiC by the following equation:⁵

The SiCl_4 is very volatile. The particle shown in Fig. 14 had the outer LTI cracked, and attack of the SiC coating is evident. The color of the SiC coating has darkened, and it is believed that the coating no longer contains any silicon. Subsequent tests on unirradiated particles have shown that the coating loses all of the silicon and is essentially carbon.⁶ It should be noted that although the particle in Fig. 14 no longer has an SiC coating, none of the kernel appears to have been leached.

⁵J. Nickl and K. Braunnühl, *Z. Anal. Chem.* 221: 223-28 (1966).

⁶Personal communication with D. Costanzo.

Fig. 12. Transverse Section Through Fuel Rod 10 From the High-Temperature Region of HT-27, Showing Result of Reaction With Zirconium Getter.

Fig. 13. Longitudinal Section Through Fuel Rod 8 From High-Temperature Region of HT-27, Showing Result of Reaction with Zirconium Getter. Note bottom of rod is on the right.

Fig. 14. Example of SiC Coating Attack by Gaseous Chlorine. Note that the SiC has darkened.

DISCUSSION AND CONCLUSIONS

The first objective of the HT-26 and -27 tests was to fabricate fuel with a failed fuel fraction less than 0.1% (1×10^{-3}). This objective was accomplished for both Triso-coated fissile particles and Biso-coated fertile particles. With the Triso-coated particles, the failed fuel specification was met by both unannealed and not surface treated, and annealed and surface treated particles. This may be due in part to the stability of the SiC coating, but it is not definite at this time.⁷ In any event, it was demonstrated that fuel rods could be fabricated with a failure fraction of Triso-coated particles $<0.1\%$. On the other hand, the Biso-coated particles showed a significant difference between those annealed and unannealed. As shown in Table 8, high failure fractions

⁷W. J. Lackey, D. P. Stinton, L. E. Davis, and R. L. Beatty, *Crushing Strength of HTGR Fuel Particles*, ORNL/TM-5132 (January 1976).

(up to 0.49%) were observed with the unannealed particles for both carbonization modes (packed Al_2O_3 and in-tube) and high and low pitch-coke yields. The annealed particles showed very low failed fuel fractions ($\leq 0.0143\%$) regardless of the carbonization mode or pitch-coke yield. This indicates the desirability to anneal Biso-coated particles prior to irradiation.

Objective 2, which was to determine the effect of matrix-particle interaction on the particle failure fraction of irradiated fuel ($<1\%$ for acceptable results), was not completely accomplished due to unexpected problems. In the case of HT-26, the capsule had evidently leaked, and the graphite components were attacked by steam. This attack led to fuel rod debonding and is believed to have caused particle failure. As a result, no significant information could be obtained on matrix-particle interaction from HT-26.

In HT-27, half of the fuel rods (those from the high-temperature region) experienced attack by zirconium. Metallography showed that the zirconium caused failure of many fuel particles and consequently exposed the kernels. These failed fuel particles were detected in the chlorine leach analysis. Thus the particle failure fractions depended not on matrix-particle interaction, but the extent of zirconium reaction. As a consequence, no results were interpretable as to the effect of matrix-particle interaction.

The other half of the fuel rods in HT-26 (those from the low-temperature regions) had no zirconium attack. The results of the chlorine leach showed acceptable particle failure fractions ($<1\%$) in all these rods for both the Triso and Biso particles. Because such few results were available and all were very low fractions (with greater chance for error), no difference between the annealed and unannealed particles or matrix types was evident. Among the low-temperature rods, all were carbonized in graphite tubes (simulating in-block), indicating that particle failure fractions of less than 1% can be obtained from fuel rods carbonized in-tube and irradiated at temperatures up to $\sim 1090^\circ\text{C}$ (calculated fuel centerline temperature).

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APPENDIX

Thermal Analysis

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Thermal Analysis

Design considerations called for the magazines closest to the horizontal midplane (HMP) of the reactor to operate at 1250°C (fuel surface temperature) and the magazines farthest from the HMP to operate at 900°C (fuel surface temperature). These two temperatures were to be maintained concurrently and the axial temperature profile kept as isothermal as possible in the two regions. Because of the variations of the thermal flux as a function of time and as a function of axial position, precise design conditions could not be obtained. Therefore, the design was tailored to give the desired conditions at the conclusion of 97 days or four cycles of irradiation (HT-26 and -27 ran two and four cycles respectively). That decision was due to ^{235}U burnup early in operation and the subsequent buildup of ^{233}U and ^{240}Pu from ^{232}Th and ^{238}U respectively (see Table A-1).

Table A-1. Heat Generation for Various Isotopes in HT-26 and -27

Time (days)	Power/Mass at HMP, W/g		
	^{232}Th Chain	^{238}U Chain	^{235}U Chain
0	5.96681	2.3213×10^1	1.04876×10^5
97	1.51648×10^3	1.90349×10^3	5.14125×10^{-1}

A one-dimensional cylindrical heat transfer computer code, GENGTC,¹ was performed with the neon gas gap between the graphite magazines and the containment as the only variable (desired temperatures and maximum fuel loadings were known). Consequently, the outside radius of the magazines decreases toward the center of the reactor. It should be noted that the computer code did not incorporate shrinkage of the fuel rods during irradiation. As a result, the temperatures of the fuel specimens were considerably higher than originally calculated near the termination of the irradiations.

¹H. C. Roland, *GENGTC, A One-Dimensional CEIR Computer Program for Capsule Temperature Calculations in Cylindrical Geometry*, ORNL-TM-1942 (December 1967).

The linear fission heat generation rates (LFHGR) of each of the top eight fuel rods in HT-26 and -27 are shown in Table A-2. Only the first eight rods are presented, because both capsules were considered symmetric about the HMP. The loadings in each fuel rod in all low-temperature magazines were 0.0474 g ^{232}Th , 0.0015 g ^{235}U , and 0.0206 g ^{238}U . The fuel rods in all high-temperature magazines contained 0.0662 g ^{232}Th , 0.0020 g ^{235}U , and 0.0289 g ^{238}U . Note that 47 days corresponds to the end of two HFIR cycles, and 97 days to the end of four HFIR cycles.

Table A-2. Linear Fission Heat Generation Rates
vs Irradiation Time^a

Fuel Rod Number	LFHGR (kW/ft) at Various Irradiation Times (days)			
	0	18.8	47 ^b	97 ^c
1	1.201	0.720	0.800	0.915
2	1.395	0.800	0.923	1.050
3	1.560	0.873	1.03	1.170
4	1.680	0.935	1.12	1.270
5	2.53	1.400	1.71	1.930
6	2.615	1.438	1.77	1.988
7	2.691	1.473	1.825	2.040
8	2.745	1.501	1.870	2.080

^aUsing as-fabricated information.

^bCorresponds to the conclusion of two HFIR cycles,
HT-26.

^cCorresponds to the conclusion of four HFIR cycles,
HT-27.

Table A-3 reports the temperatures at the centerline and surface of the fuel rods at various times throughout irradiation. The temperatures reported under days 0, 19, 47, and 97 (as-built) assume no shrinkage of the fuel rods. The temperatures reported under day 97 (PIE) take into account radial shrinkages of the fuel rods. In particular, the shrinkages are from rods 1 to 8 in HT-27. All of the temperature calculations do not take into account axial shrinkage, which affects the LFHGR, nor do they include the increase in the bulk fuel rod density. As shown in Table A-3, the radial shrinkage of the rods greatly affects the calculated operating temperatures, increasing them in many cases over 100°C.

Table A-3. Calculated Operating Temperatures at Various Times for HT-27

Fuel Rod Number	Fuel Rod Surface Temperature, °C					Fuel Rod Centerline Temperature, °C				
	Day 0	Day 18.8	Day 47	Day 97 (as-built) ^a	Day 97 (PIE) ^b	Day 0	Day 18.8	Day 47	Day 97 (as-built) ^a	Day 97 (PIE) ^b
1	973	852	872	904	995	1051	908	932	969	1058
2	985	943	872	904	995	1070	905	939	976	1066
3	961	818	851	883	1021	1058	885	924	962	1098
4	921	777	815	844	1008	1025	849	895	931	1092
5	1330	1131	1190	1232	1339	1476	1229	1302	1352	1457
6	1346	1145	1207	1245	1350	1498	1246	1322	1370	1472
7	1344	1139	1204	1239	1350	1500	1243	1323	1367	1475
8	1290	1087	1152	1185	1340	1448	1198	1273	1315	1466

^aUsing as-fabricated fuel rod dimensions.

^bUsing postirradiation fuel rod radial dimensions.

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