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EXPERIMENTAL TEST PLAN: USDOE/JAERI COLLABORATIVE PROGRAM FOR THE COATED PARTICLE FUEL PERFORMANCE TEST

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EXPERIMENTAL TEST PLAN: USDOE/JAERI COLLABORATIVE PROGRAM FOR THE COATED-PARTICLE FUEL PERFORMANCE TEST

M. J. Kania and K. Fukuda*

ABSTRACT

This document describes the coated-particle fuel performance test agreed to under Annex 2 of the arrangement between the U.S. Department of Energy and the Japan Atomic Energy Research Institute on cooperation in research and development regarding high-temperature gas-cooled reactors (HTGRs). The test will evaluate the behavior of reference fuel compacts containing coated-particle fuels fabricated according to the specifications for the U.S. Modular HTGR and the Japanese High-Temperature Engineering Test Reactor (HTTR) concepts. Two experimental capsules, HRB-21 and HRB-22, are being tested. Capsule HRB-21 contains only U.S. reference fuel, and HRB-22 contains only JAERI reference fuel. Both capsules will be irradiated in the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL). Capsule HRB-21 will be operated at a mean volumetric fuel temperature of 975°C and will achieve a peak fissile burnup of 26% fissions per initial metal atom (FIMA) and a fast fluence of $\leq 4.5 \times 10^{25}$ neutrons/m^2. Capsule HRB-22 will be operated at a mean centerline fuel temperature of 1250 to 1300°C and will achieve a peak fissile burnup of 5.5% FIMA and a fast fluence of 1.7×10^{25} neutrons/m^2. Performance of the fuels during irradiation will be closely monitored using on-line fission gas surveillance. Following irradiation, both capsules will undergo detailed examinations and core heatup simulation testing. Results from in-reactor monitoring and postirradiation testing will be analyzed to comparatively assess U.S. and Japanese coated-particle fuel performance.

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1. SCOPE

Pursuant to Article III-2 of the Implementing Arrangement between the U.S. Department of Energy (USDOE) and the Japan Atomic Energy Research Institute (JAERI) on cooperation in research and development in the area of high-temperature gas-cooled reactors (HTGRs), the parties have agreed

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to establish a collaborative program to conduct a fuel performance test. This program is currently evaluating the performance of reference fuel compacts containing coated-particle fuels that have been fabricated according to the specifications for the U.S. Modular HTGR (MHTGR) concept and the Japanese High-Temperature Engineering Test Reactor (HTTR) concept.

Two irradiation capsules, designated HRB-21 and HRB-22, are used. Capsule HRB-21 contains only USDOE reference fuel compacts, while capsule HRB-22 contains only JAERI reference compacts. The USDOE fuel was fabricated by General Atomics, Inc., (GA) according to MHTGR fuel product specifications, and the JAERI fuel was fabricated in Japan by Nuclear Fuel Industries according to HTTR specifications. Quality assurance (QA) characterization of both the USDOE and the JAERI fuels[1] was performed at GA prior to start of irradiation. The experimental capsules were designed, fabricated, and assembled at the Oak Ridge National Laboratory (ORNL). The irradiation is being performed in the High Flux Isotope Reactor (HFIR) located at ORNL. Postirradiation examinations (PIEs) will be performed both at GA and ORNL, and the core heatup simulation tests (CHSTs) will take place at ORNL. The analysis of test results will be performed jointly by ORNL, GA, and JAERI, with the final documentation being issued by ORNL and JAERI.

This experimental plan describes in detail the capsule design, fuel compact designs and loadings, irradiation and surveillance requirements, PIE and CHST matrices, documentation requirements, and the projected schedule.

2. OBJECTIVES

The objectives of this collaborative program are to determine the following for both the USDOE and JAERI reference HTGR fuel compacts:

1. the capacity of low-enriched uranium (LEU) coated-particle fuels to meet their respective performance goals under normal irradiation conditions, and
2. the capability of irradiated coated-particle fuels to meet specified failure fraction limits under simulated core heatup tests.

Performance goals for the USDOE MHTGR fuel specify that the failure fraction on a core average basis for end-of-life (EOL) conditions be $\leq 5 \times 10^{-5}$ at the 50% confidence level. This value represents the total expected particle-failure level from all sources under normal operating conditions. In the event of a core heatup accident, an additional incremental fraction of $\leq 1.5 \times 10^{-4}$ at the 50% confidence level may be tolerated. At the 95% confidence level, these values are 2×10^{-4} and 6×10^{-4}, respectively.

For the JAERI HTTR design, fuel performance requirements are that the EOL failure fraction, under maximum burnup of 3.8% fissions per initial metal atom (FIMA), be less than the beginning-of-life (BOL) failure fraction plus the BOL SiC defective fraction, for which the maximum value is 1.65×10^{-3} with 95% confidence. Conversely, the failure fraction under the accident conditions is less than 1×10^{-2} with a 95% confidence limit.

3. REFERENCE FUEL CONCEPTS

The reference fuel element for the U.S. 350-MW(t) MHTGR concept with an annular prismatic core is a machined, hexagonal, graphite block (H-451 graphite), approximately 360 mm across the flats and 800 mm long. Separate fuel and coolant holes are drilled into the graphite block in a hexagonal array. In the fuel holes, prefabricated fuel compacts are stacked to a height of approximately 760 mm. The individual fuel compact nominal dimensions are 12.5 mm in diameter by 50 mm long.

A two-particle system, consisting of a TRISO-P-coated LEU UCO fissile particle and a TRISO-P-coated ThO_2 fertile particle, is required for the MHTGR concept. A schematic of the U.S. two-particle system is shown in Fig. 1. Fissile particle enrichment is 19.7%. Nominal specifications for the U.S. coated-particle design are shown in Table 1. The TRISO-P coating design is a modification to the well-known TRISO coating design that is necessary to prevent excessive particle breakage during the GA fuel compact hot-injection fabrication process. The TRISO-P design consists of the standard TRISO coating plus a sacrificial, low-strength overcoating of

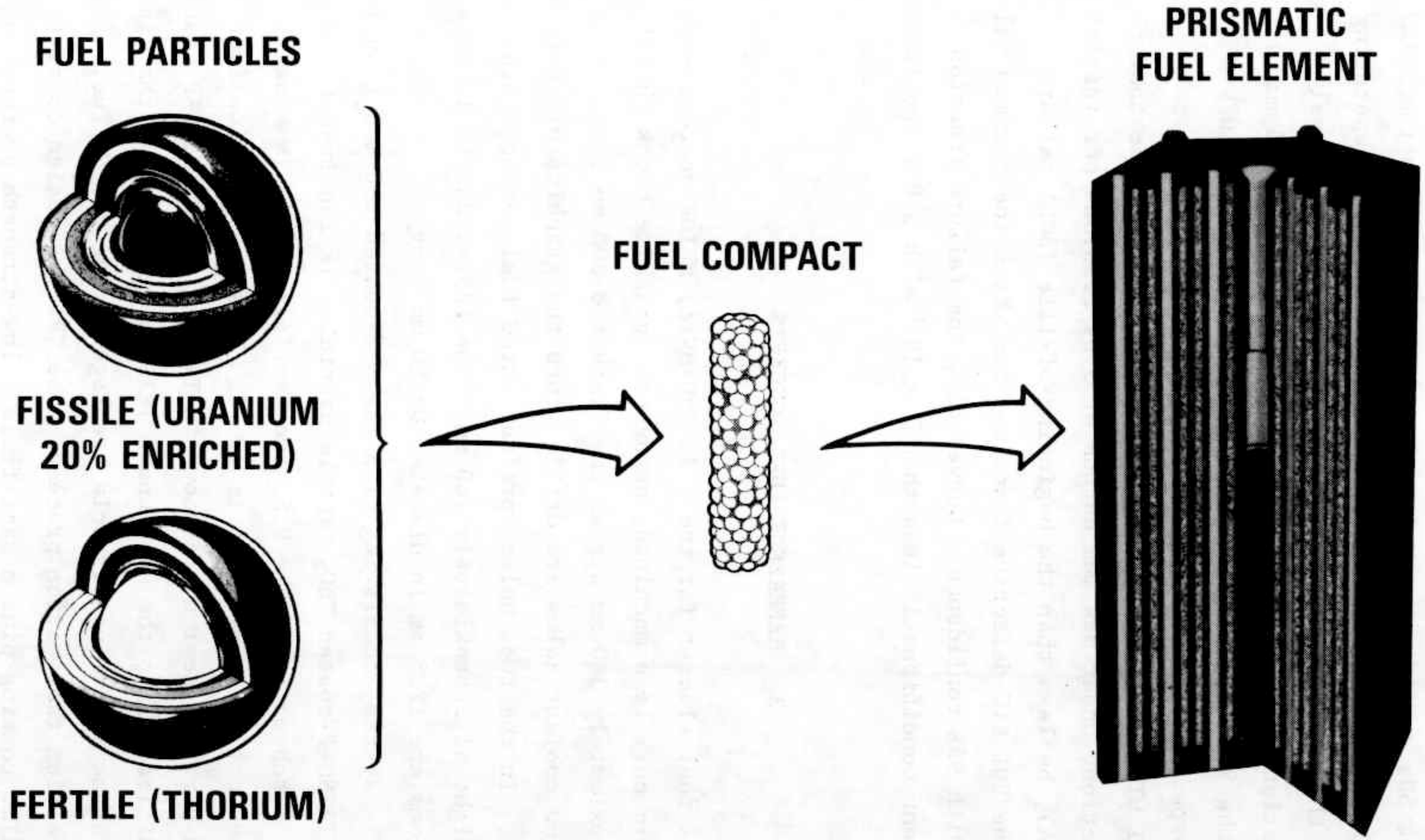

Fig. 1. Schematic of the U.S. two-particle system for HTGR fuel. *Source*: General Atomics, Inc., San Diego, CA.

Table 1. Comparison between USDOE and JAERI reference fuel particle system

	USDOE design		JAERI design
	Fissile	Fertile	Fissile
Kernel			
Composition	UCO	ThO_2	UO_2
Diameter (μm)	350	500	600
Enrichment (% ^{235}U)	19.7		4.06
Nominal coating thickness, μm			
Buffer	100	65	60
Inner pyrocarbon	50	50	30
SiC	35	35	25
Outer pyrocarbon	40	40	45

low-density pyrocarbon (PyC), much like the buffer layer. This coating greatly increases the crush strength of the U.S. fabricated coated particles and minimizes particle-to-particle interactions during compact fabrication. The "P" in TRISO-P designation denotes the protective low-density PyC coating.

The reference fuel element for the Japanese 30-MW(t) HTTR concept with a prismatic core is also a machined, hexagonal, graphite block (IG-110 graphite), approximately 360 mm across the flats and 580 mm long (Fig. 2). A number of large-diameter holes are drilled into the graphite block to accommodate the fuel. Annular fuel compacts are then stacked in machined graphite sleeves to form the fuel pins that are inserted into these holes. Cooling is provided by flowing helium along the radial gap between the fuel pin and the graphite block. Nominal dimensions of the HTTR annular fuel compacts included in HRB-22 are 24 mm outer diameter and 8 mm inner diameter by 40 mm long. The size of the reference compact in the updated HTTR design (Fig. 2) is changed slightly to 26 mm outer diameter and 11 mm inner diameter by 39 mm long.

The Japanese very high temperature gas reactor design (VHTGR) design employs a single-particle system that uses a TRISO-coated LEU UO_2 fissile particle with an enrichment of 4.06%. The nominal specifications of the JAERI reference particle is compared with the reference USDOE design in Table 1. Prior to compact fabrication, the JAERI coated particles are overcoated with a 200-μm-thick layer of compact matrix material. A schematic of the JAERI particle design, fuel compact, and graphite block element is shown in Fig. 2.

4. DESCRIPTION OF EXPERIMENT

To accomplish the objectives for testing both the JAERI and USDOE fuel concepts, separate irradiation capsules are being used. Specific test requirements that differ significantly are outlined below for the USDOE capsule, HRB-21, and the JAERI capsule, HRB-22:

Test requirements	USDOE (HRB-21)	JAERI (HRB-22)
1. Operating temperature (time-averaged fuel centerline)	975°C	1250 to 1300°C
2. Fissile fuel burnup (% FIMA)	≤26	≤5
3. Fertile fuel burnup (% FIMA)	≤4	-
4. Irradiation period	6 HFIR cycles	2 HFIR cycles
5. Fuel compact type	MHTGR reference (cylindrical, 12.4 mm diam × 50 mm long)	HTTR reference (annular, 8 mm ID × 24-mm OD × 39 mm long) Updated (11-mm ID × 26-mm OD × 39 mm long)
6. Fuel compacts/capsule	24	12
7. Graphite bodies	8, with 3 fuel compacts each	1, with 12 fuel compacts
8. Graphite type	H-451	IG-110 (represented by POCO, AXF-5Q)

4.1 GENERAL CAPSULE DESIGN

The generic capsule design is a doubly contained, single-purged cell with an available cylindrical test volume of about 660 cm³ and with dimensions 40 mm in diameter by 500 mm long. This test volume is

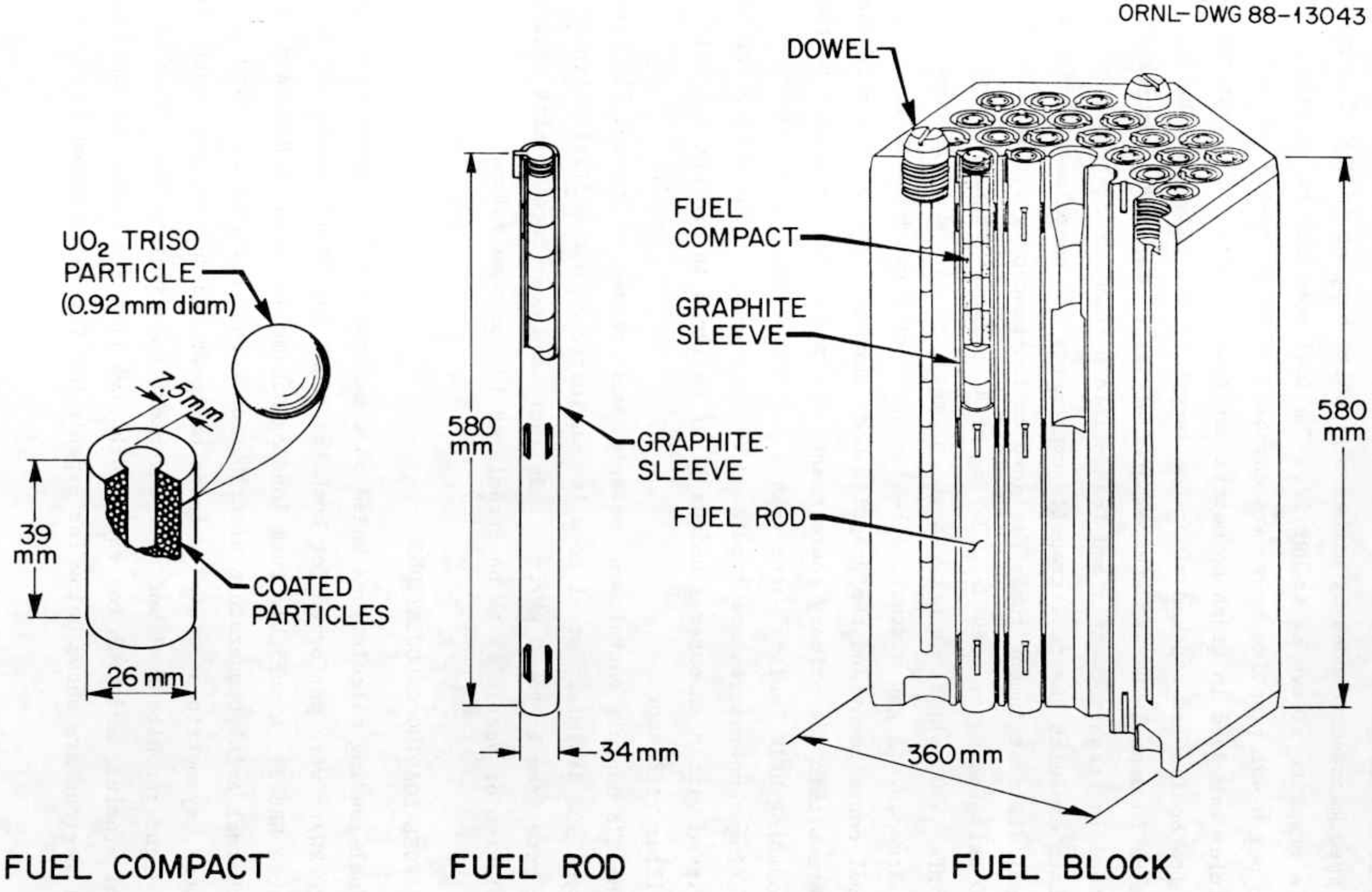

Fig. 2. Schematic of the JAERI particle design, fuel compact, and graphite block element.

sufficiently large to contain either USDOE or JAERI reference fuel compact test specimens surrounded by either a graphite body as in HRB-21, or a single graphite sleeve as in HRB-22. The fuel compacts in capsule HRB-21, three per H-451 graphite body, are composed of TRISO-coated UCO and ThO_2 particles embedded in graphite matrix material. A total of eight fueled graphite bodies are stacked along the length of the capsule. The fuel compacts in capsule HRB-22 are composed of TRISO-coated UO_2 particles embedded in graphite matrix and loaded into a POCO AXF-5Q graphite sleeve. For both capsules the fuel graphite components are contained within two Inconel 718 containment tubes designed to independently withstand 6.9 MPa (1000 psi) inside or outside. During HFIR operation, pure helium at 4.47 MPa (650 psi) flows between the primary and secondary Inconel containments. A gas mixture of helium and neon flows between the primary Inconel containment and the graphite body surface. By varying this gas mixture within the primary containment, the radial heat transfer to the surrounding HFIR cooling water system is controlled. Fuel-compact operating temperatures are regulated by this method. The entire capsule is fitted within an outer aluminum liner designed to protect the HFIR beryllium reflector.

The HRB capsule containment material was changed to Inconel 718 instead of type 304 stainless steel to allow an increase in the fission linear heat rate from 15 to 20 kW/ft. This increased heat rate permits a larger population of particles to be irradiated in the same volume.

4.2 FUEL-LOADING CALCULATIONS

Fuel-loading calculations based on a maximum fission linear heat rate of 20 kW/ft were performed for both the USDOE and JAERI capsules. In capsule HRB-21, a variable fuel-loading scheme was used to maintain an isothermal axial temperature distribution. Four different loading regions, symmetric about the reactor horizontal midplane, were used along the eight graphite fuel bodies. Inventory requirements for ^{235}U, ^{238}U, total uranium, and ^{232}Th for each of the two graphite bodies in the four fuel regions are shown below for capsule HRB-21. Also shown is the estimated population of fissile and fertile particles contained in each fuel region. A total of 145,660 particles are contained in the capsule: 106,480 ThO_2 fertile and 39,180 UCO fissile.

Graphite body number	Total fuel loading (g)				Fissile particles	Fertile particles
	^{235}U	^{238}U	U-total	^{232}Th		
9,8	0.288	1.173	1.466	7.500	6,700	13,310
2,7	0.239	0.975	1.214	7.500	5,540	13,310
3,6	0.176	0.716	0.891	7.500	4,070	13,310
4,5	0.146	0.594	0,740	7.500	3,380	13,310
Total (8 bodies)					39,380	106,480

The fuel loading for capsule HRB-22 was calculated based on a single constant loading scheme along the length of the capsule. The loading was based upon a maximum linear heat generation rate of 20 kW/ft and is the same in all 12 JAERI fuel compacts. Inventory requirements for ^{235}U, ^{238}U, and total uranium are provided below. An estimated 2,575 fissile UO_2 particles are contained in each compact for a total of 30,900 in the entire capsule.

JAERI compact numbers	Total fuel loading (g)			Fissile particles
	^{235}U	^{238}U	U-total	
1 through 12	0.0948	2.2499	2.3447	2,575
Total (12 compacts)				30,900

4.3 DESIGN THERMAL ANALYSES

The design thermal analyses for both capsules were performed with the HEATING6 code,[2] an appropriate mathematical model, and thermal physical properties available for the capsule component materials. For capsule HRB-21, a three-dimensional model (r,ϕ,z) in cylindrical coordinates was used, and for capsule HRB-22 a two dimensional model (r,z) was used. Each model consisted of a symmetric section of a graphite holder, or portion of the graphite sleeve, and the primary and secondary containments with insulated boundary conditions on the top, bottom, and planes of symmetry of the design. Peak operating temperature requirements in HRB-21 were maintained at 975°C along the fuel compact centerline. For capsule HRB-22, the maximum temperature in the annular fuel compact was limited to 1300°C. Based on the results of these analyses, dimensions for the H-451 graphite fuel bodies and the IG-110 graphite sleeve were determined. The diameters of the graphite fuel bodies and the graphite sleeve, along with the radial gaps to the primary containment wall at operating temperature are:

USDOE capsule HRB-21

Graphite fuel body	Diameter (mm)	Radial gap (mm)
9, 8	38.05	0.203
2, 7	38.10	0.178
3, 6	38.20	0.127
4, 5	38.20	0.127

JAERI capsule HRB-22

Graphite sleeve	Diameter (mm)	Radial gap (mm)
1, 12	37.24	0.635
2, 11	38.15	0.178
3, 10	38.15	0.178
4, 9	38.30	0.102
5, 8	38.30	0.102
6, 7	38.30	0.102

A schematic of a horizontal section through capsule HRB-21 is shown in Fig. 3, and a schematic of a vertical section is shown in Fig. 4. Similar schematic diagrams for capsule HRB-22 are shown in Figs. 5 and 6.

4.4 CAPSULE THERMOMETRY

Thermocouples in HRB-21 are placed within the graphite bodies with a total of 24 junctions in 4 separate thermocouple central array tube assemblies (TCAT). Three TCAT assemblies contain seven thermocouple junctions, and the fourth TCAT assembly contains three junctions.

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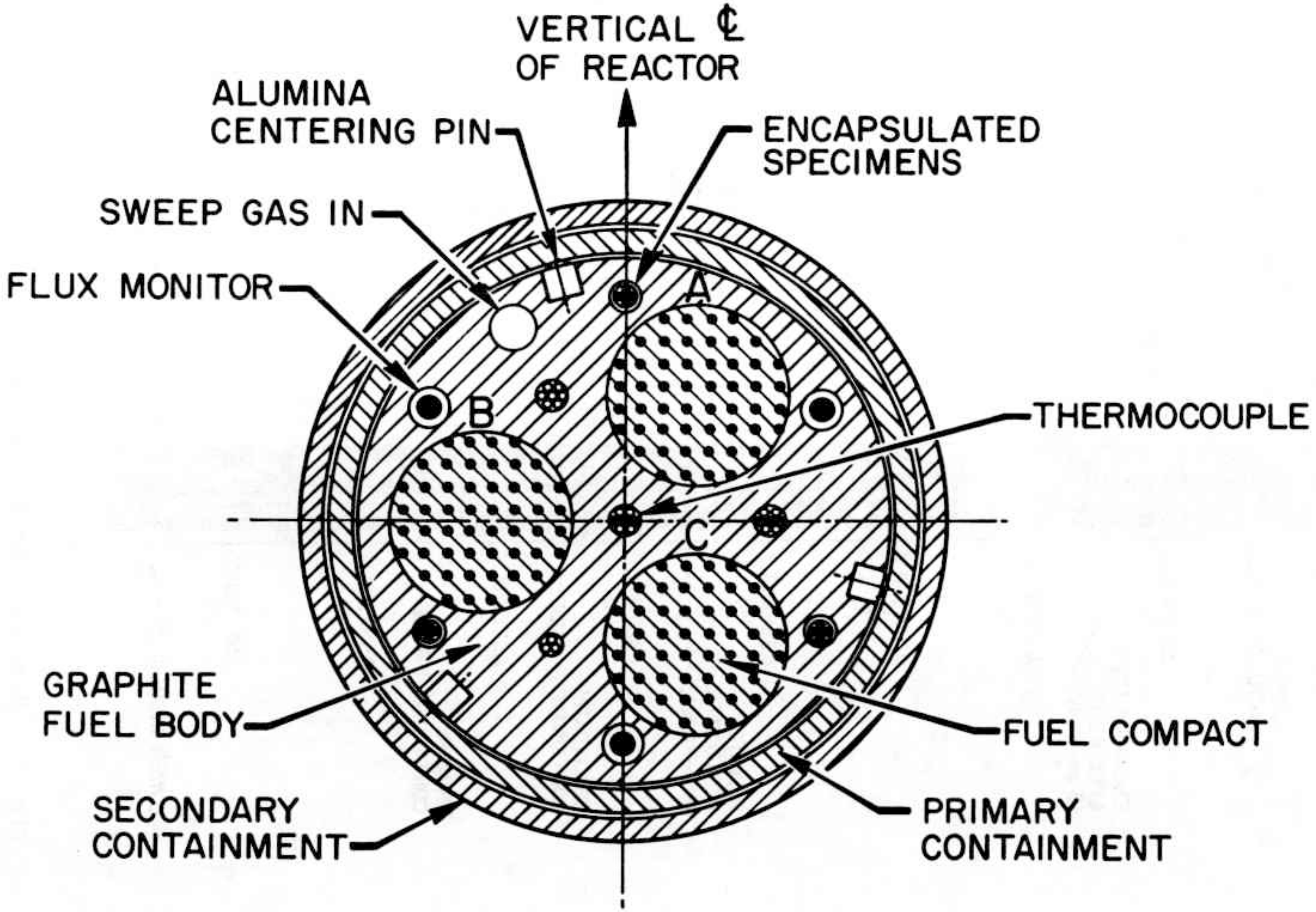

Fig. 3. Horizontal section through capsule HRB-21.

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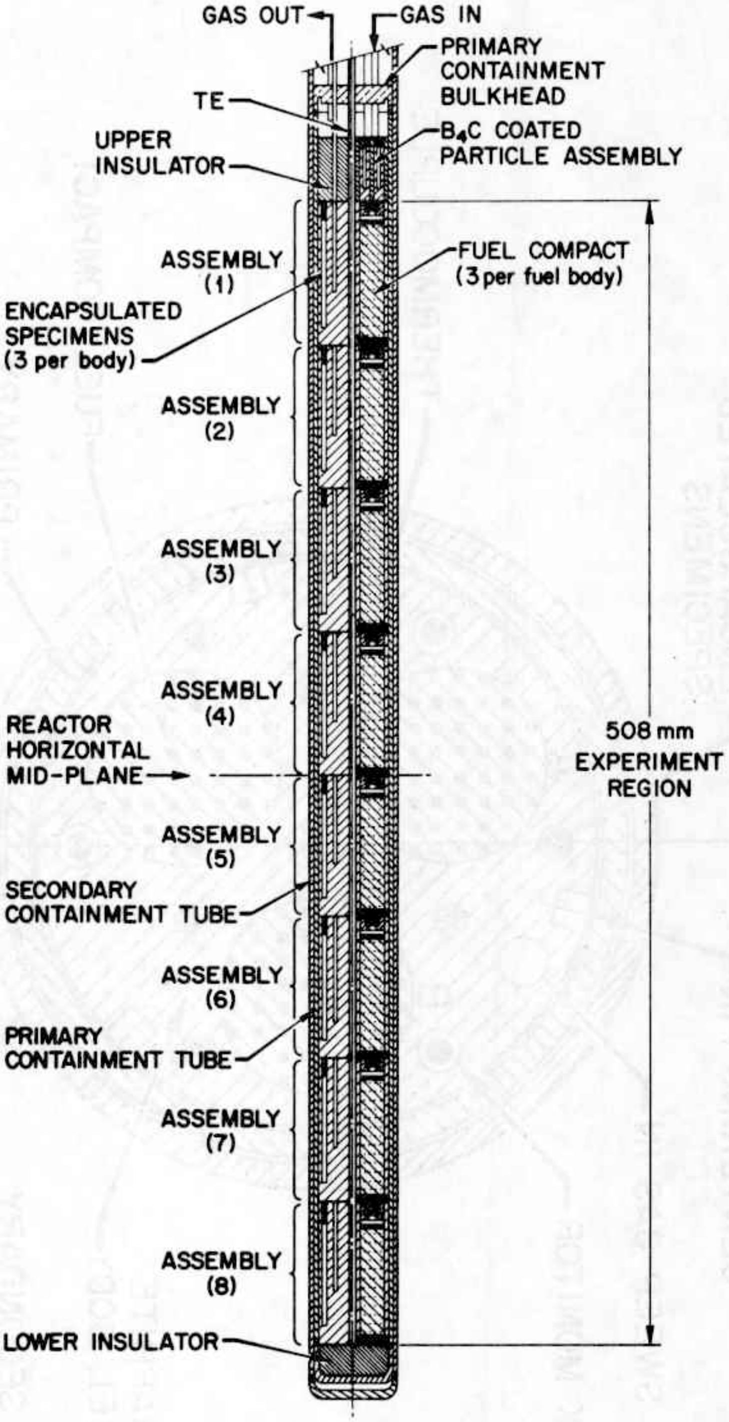

Fig. 4. Vertical section through capsule HRB-21.

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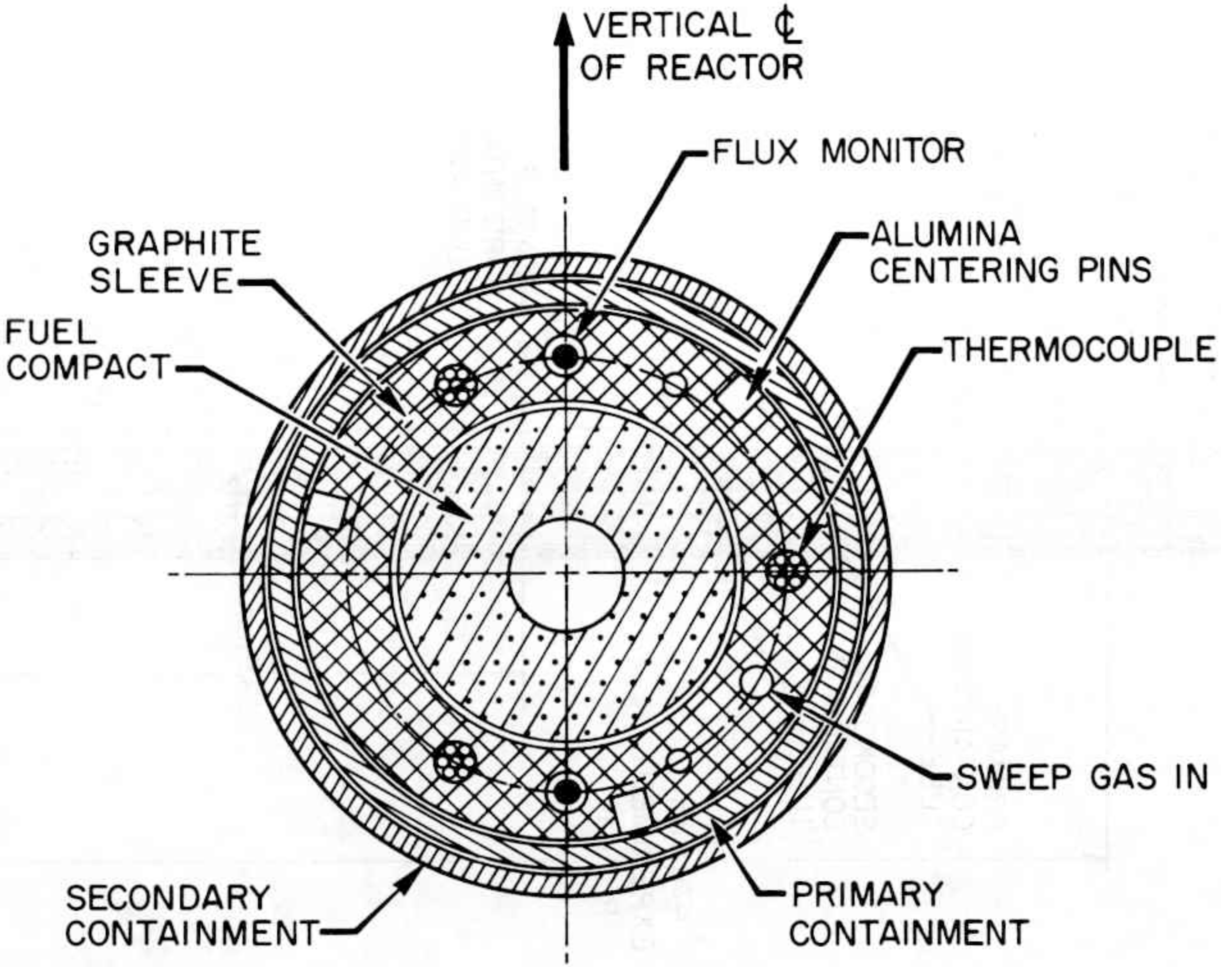

Fig. 5. Horizontal section through capsule HRB-22.

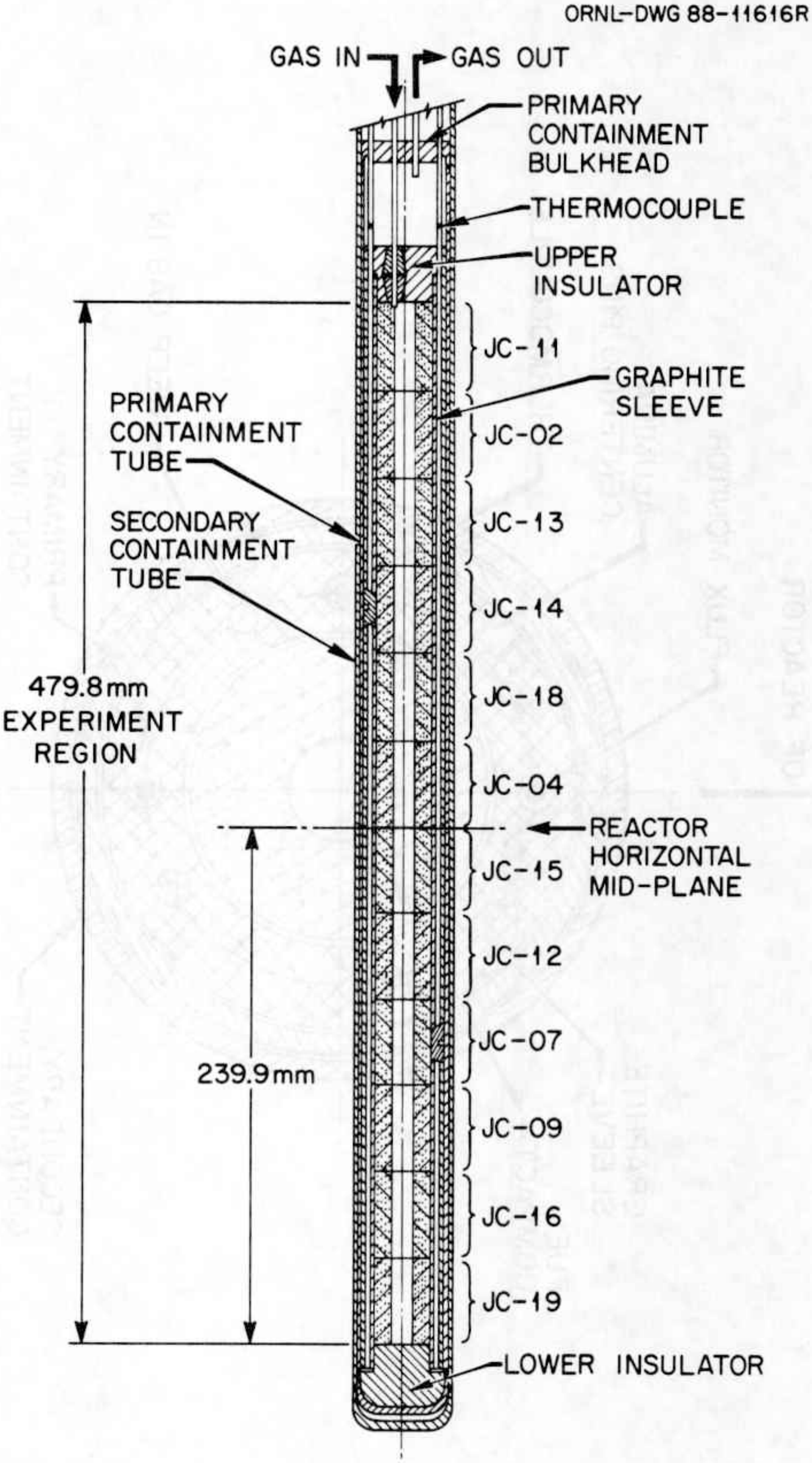

Fig. 6. Vertical section through capsule HRB-22.

Twenty-three of the thermocouples for HRB-21 are Chromel/Alumel (Type K), and one is a Nicrosil-Nisil (Type N) thermocouple. Placement as shown in Fig. 7 is such that three junctions are available at the axial midpoint of each fuel graphite body to monitor temperature continuously. For capsule HRB-22, 24 thermocouples are also used and configured in 3 TCAT assemblies, each containing 7 junctions, together with 1 TCAT containing 2 thermocouple junctions, and 1 single-junction thermocouple. All four of the TCAT assemblies in HRB-22 are placed within the graphite sleeve and contain Chromel/Alumel thermo- couples. The single-junction thermocouple of HRB-22 is a Nicrosil/Nisil (Type N). Placement of the thermocouple junctions in capsule HRB-22 is shown in Fig. 8.

4.5 CAPSULE DOSIMETRY

Both capsules contain 24 separate dosimeters to record the total, thermal, and fast neutron fluences at the axial midpoint of each fuel compact. Each compact consists of a stainless steel tube 1.59 mm in diameter (0.063 in.) by 9.53 mm long (0.375 in.) and containing Fe, Nb, Ni, Ti, and 80.2% Mn-Cu dosimetry wires. After irradiation, the dosimetry specimens will be analyzed to determine fluence exposures for each compact.

5. REFERENCE FUEL COMPACTS

5.1 USDOE MHTGR FUEL COMPACTS

The reference fuel compacts for the MHTGR are formed by a hot-injection process whereby a viscous mixture of binder, binder additives, and graphite filler at a temperature of 150 to 200°C is injected into a closely packed array of coated fuel particles and inert H-451 shim particles contained in a cylindrical mold. The nominal injection pressure of 6.9 MPa (1000 psi) was decreased for HRB-21 compact manufacture to reduce particle-to-particle interactions. Petroleum-derived pitch is used as the binder phase, and graphite powder is used as filler. The volume fraction of particles in a compact is maintained at less than 58%. The formed "green" fuel compacts are then heat-treated up to 1850°C to carbonize the binder material, drive off volatiles, and stabilize compact

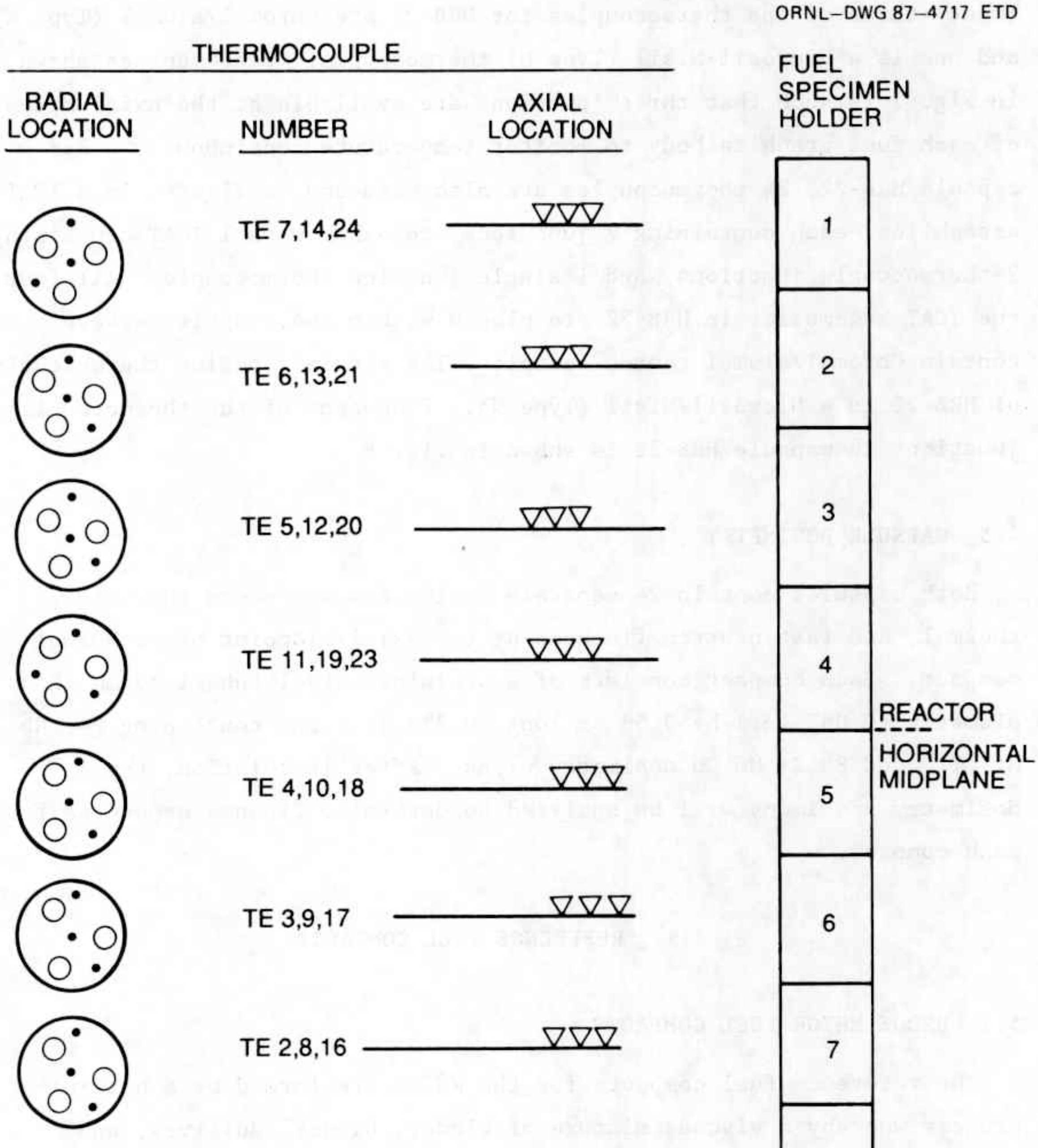

Fig. 7. HRB-21 TE locations.

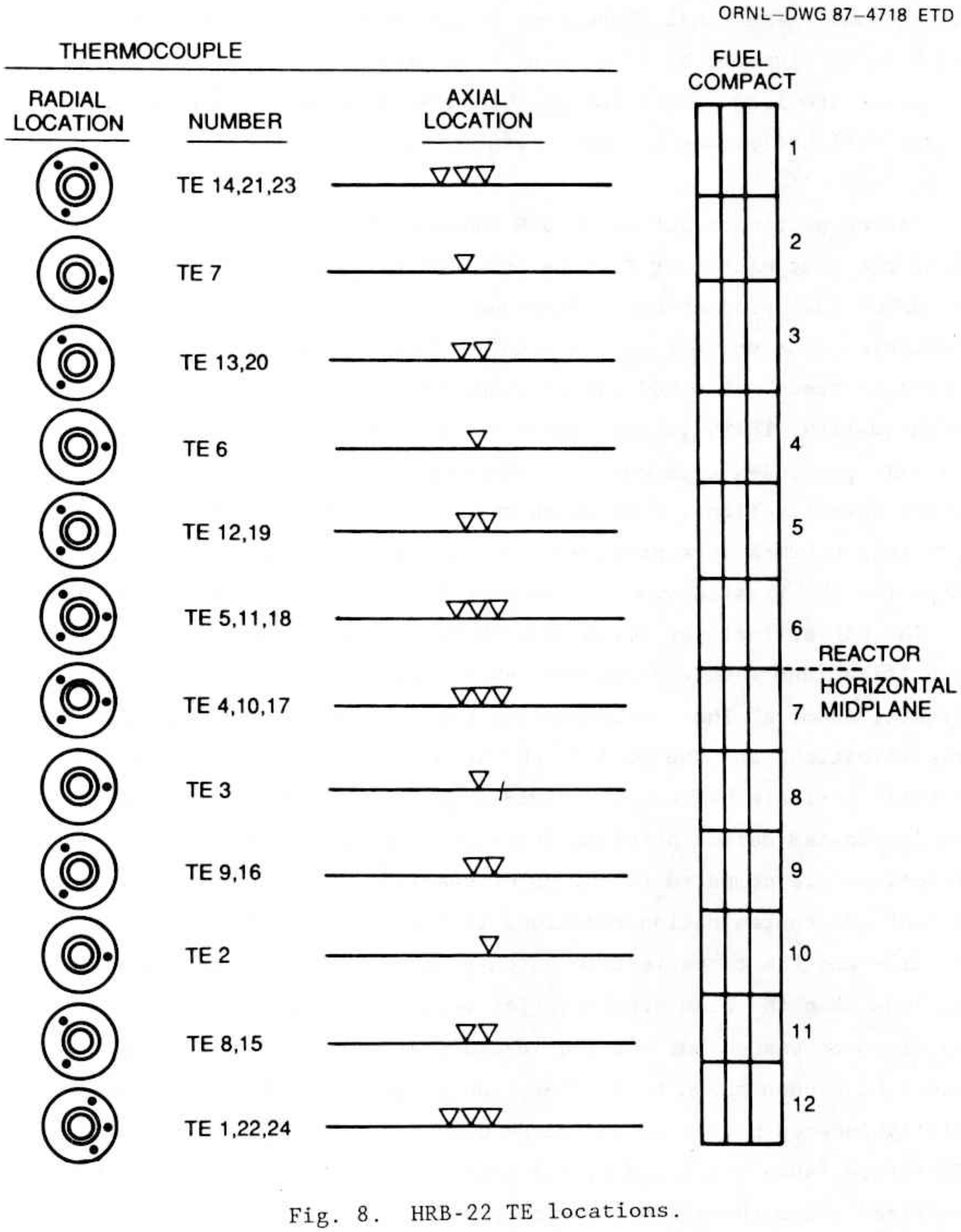

Fig. 8. HRB-22 TE locations.

dimensions. The final dimensions of the MHTGR fuel compact are nominally 12.4 mm in diameter by 50 mm long. In capsule HRB-21, three fuel compacts are loaded into each machined H-451 graphite fuel body (Fig. 9). Eight fuel bodies are loaded in tandem along the length of the capsule (Fig. 4).

Coated particles for the USDOE compacts for HRB-21 have been selected from the test matrix of fissile and fertile particles that was fabricated to MHTGR fuel product specifications.[3] The UCO fissile (19.7% enriched) particles used nominal 350-μm-diam UCO kernels prepared to MHTGR specifications. Two UCO kernel composites were used to produce four high-quality, TRISO-coated, fissile fuel particle batches. The ThO_2 fertile particles used nominal 500-μm-diam ThO_2 kernels, prepared to MHTGR specifications, from which three high-quality, TRISO-coated fertile particle batches were prepared. A summary of the quality control (QC) data for the fissile and fertile kernel material is provided in Table 2.

The HRB-21 fuel particles were TRISO coated to MHTGR reference specifications (Sect. 3) in the 240-mm-diam development coater at General Atomics, Inc. A comparison between the reference coating specifications and the QC data obtained on the four fissile and three fertile particle batches is provided in Table 3. Measured mean, as-fabricated defect particle fractions and heavy-metal contamination fractions are compared to the MHTGR specifications for mean particle defect and contamination fractions in Table 4. In all cases, the four fissile and the three fertile batches, the QC measurements were found to be less than the mean specification value. The data in Table 4 were obtained on washed but not liquid-elutriated and screened material. These steps have been shown to further reduce the defect fractions by removing highly faceted particles and large-diameter, coated, doublet materials. Therefore, some small additional improvement in particle quality may be realized after these steps are completed. All the coated particle QC data presented in Tables 2 through 4 were obtained from ref. 3.

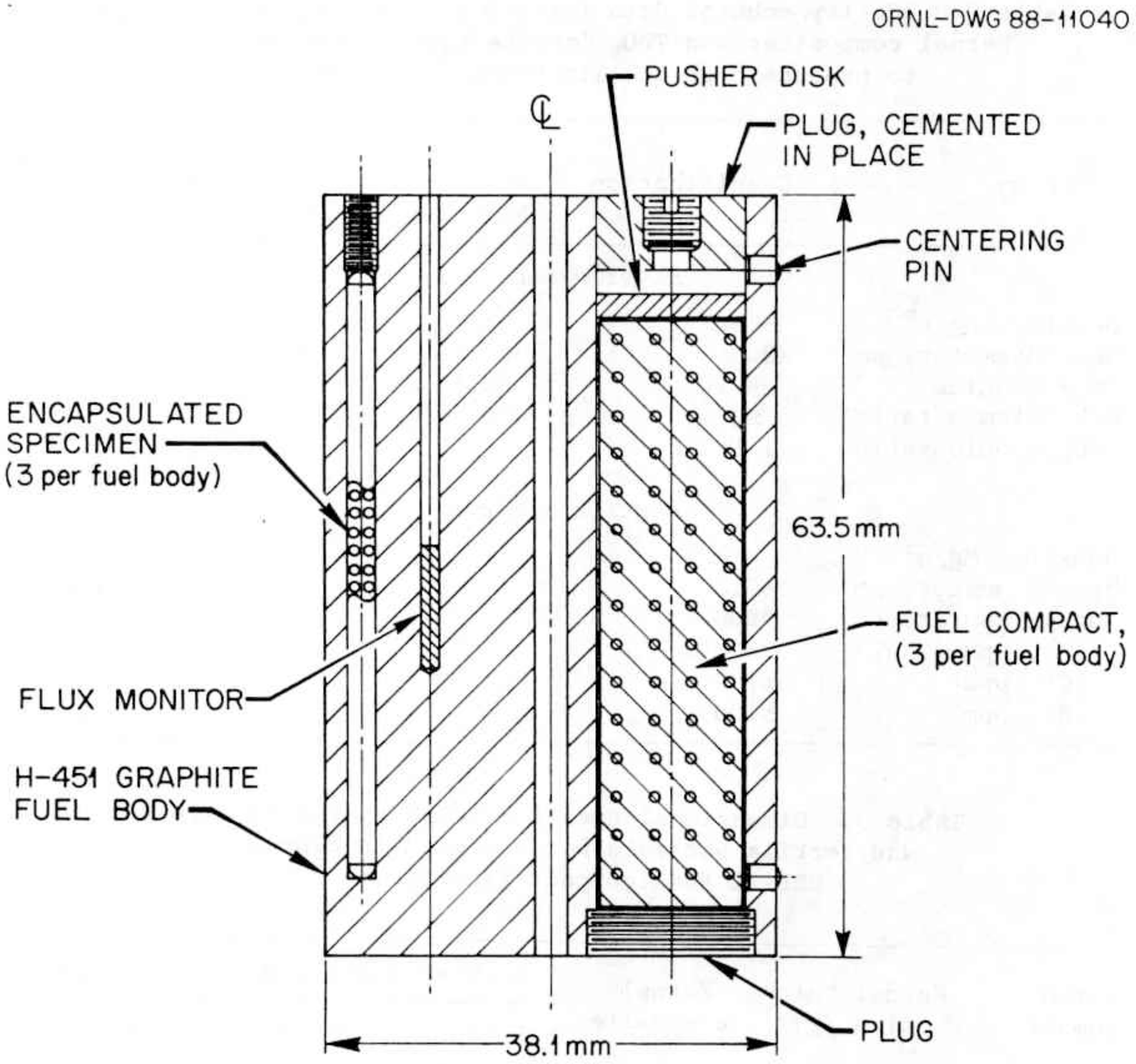

Fig. 9. Graphite fuel body for capsule HRB-21.

Table 2. Quality control data for UCO (19.7% enriched) fissile kernel composites and ThO_2 fertile kernel material used to produce high-quality USDOE fuel compacts

Property	Specification	Fissile kernels NU38-10001	Fissile kernels NU38-10003	Fertile ThO_2 kernels
		Fissile material		
Density, Mg/m^3	≥10.5	10.67	10.65	
Mean diameter, μm	≤360	345	351	
Wt % uranium	≥87.0	88.6	88.6	
C/U, atomic ratio	≤0.4	0.3	0.2	
O/U, atomic ratio	1.8–1.6	1.64	1.65	
		Fertile material		
Density, Mg/m^3	≥9.5			9.94
Mean diameter, μm	≤510			512
Total impurities	≤5000			≤287
Fe, ppm	≤100			≤50
Cr, ppm	≤100			≤5
Ni, ppm	≤100			≤1

Table 3. Dimensional data for TRISO-coated fissile and fertile particle batches used in capsule HRB-21 fuel compact fabrication

Batch number	Kernel batch size (g)	Kernel composite	Mean coating dimensions (μm) Buffer	IPyC/Seal	SiC	OPyC
		Fissile particle batches				
MHTGR specification	5,000[a]		90–100	40–60	30–40	30–50
8876-65	2,215	NU38-10001	102.8	50.6	35.0	34.1
8876-66	2,215	NU38-10001	105.5	50.0	35.2	41.8
8876-68	2,215	NU38-10001	104.7	48.6	35.2	41.8
8876-70	2,215	NU38-10003	105.0	52.8	32.6	42.8
		Fertile particle batches				
MHTGR specification	10,000[a]		55–75	40–60	30–40	30–50
8876-52	10,000		63.1	54.6	33.0	39.0
8876-56	9,810		68.2	55.5	35.1	40.4
8876-58	9,810		67.1	56.4	36.0	41.1

[a]Long-range development goal.

Table 4. **As-fabricated quality control data on coated particle heavy-metal contamination level and defect particle fractions[a]**

Coating batch	Surface contamination	Missing buffer	Missing permeable IPyC	Defective SiC	Missing permeable OPyC
		Fissile particle batches			
MHTGR specification	≤1E-5	≤5E-5	≤4E-5	≤5E-5	≤1E-4
8876-64	7.4E-7	1.7E-5	*b*	8.9E-6	≤6.7E-5
8876-66	6.6E-7	3.2E-5	*b*	5.0E-6	≤7.1E-5
8876-68	8.0E-6	2.0E-5	*b*	1.5E-5	≤7.4E-5
8876-70	7.4E-8	4.1E-5	*b*	2.5E-5	≤7.5E-5
		Fertile particle batches			
MHTGR specification	≤1E-5	≤5E-5	≤4E-5	≤5E-5	≤1E-4
8876-52	3.7E-7	1.8E-5	*b*	3.3E-5	≤7.0E-5
8876-56	<2.0E-7	7.6E-6	*b*	1.6E-6	≤7.3E-5
8876-58	<1.5E-7	1.7E-5	*b*	3.2E-5	≤6.5E-5

[a]Defect and contamination fractions obtained after washing but before liquid elutriation and screening.

[b]Measurement obtained at fuel compact stage by fuel dispersion.

One fissile particle batch, 8876-70, and one fertile particle batch, 8876-58, were selected from the batches listed in Tables 3 and 4 and overcoated in the GA Development Coater to form the TRISO-P-coated-particle feed materials for fuel compact manufacture. From these fissile and fertile particle batches a total of 160 fuel compacts were fabricated for each of the four uranium and thorium material loadings specified in Sect. 4.2 for the HRB-21 design. From this number, a total of six were selected for irradiation from each loading zone, and the rest were used for QC and archival purposes. The characteristics of the 24 fuel compacts selected for irradiation in HRB-21 are provided in Table 5. For each fuel loading zone the total particle volume fraction was maintained as close as possible to 58 vol %. The exact particle volume fractions are:

Graphite fuel body	Particle volume fraction (%)			
	Fissile	Fertile	Shim	Total
9, 8	15.99	35.14	7.35	58.48
2, 7	12.60	37.58	7.78	57.96
3, 6	9.25	37.58	10.80	57.63
4, 5	7.68	37.58	12.18	57.44

The QC results performed on a large number of fuel compacts from each fuel loading zone are shown below. From 60 to 64 fuel compacts were consumed in making the heavy-metal contamination determinations using a hot HCl gaseous leach process, and from 15 to 20 were used for the defective SiC determinations based on a burn/leach procedure. The data are provided in terms of the fraction of heavy metal removed by the destructive QC process to the total heavy-metal content of all the samples tested from each loading zone. Fuel loading zone 4 is located closest to the reactor horizontal midplane and represents the lowest uranium content fuel compacts, whereas 1 is at the top of the capsule and represents the highest uranium content.

Table 5. **Capsule HRB-21 fuel compact dimensions and the total heavy-metal loading of 24 compacts to be irradiated in HRB-21**

Position from top of capsule	Hole	Outer diameter (mm)			Length (mm)	Weight (g)	U-total (g)	Th-total (g)
		Top	Mid	Bottom				
9	A	12.45	12.46	12.30	49.13	10.651	0.516	2.355
	B	12.45	12.43	12.27	49.19	10.666	0.516	2.355
	C	12.46	12.45	12.30	49.22	10.667	0.516	2.355
2	A	12.48	12.47	12.37	49.28	10.655	0.402	2.540
	B	12.44	12.47	12.35	49.30	10.676	0.402	2.540
	C	12.45	12.45	12.35	49.26	10.691	0.402	2.540
3	A	12.48	12.46	12.38	49.28	10.581	0.298	2.540
	B	12.46	12.44	12.39	49.29	10.597	0.298	2.540
	C	12.46	12.43	12.33	49.30	10.591	0.298	2.540
4	A	12.46	12.47	12.31	49.32	10.527	0.248	2.500
	B	12.51	12.46	12.32	49.32	10.482	0.248	2.500
	C	12.48	12.46	12.32	49.32	10.505	0.248	2.500
5	A	12.50	12.46	12.33	49.33	10.522	0.248	2.500
	B	12.49	12.45	12.35	49.33	10.511	0.248	2.500
	C	12.49	12.50	12.34	49.32	10.517	0.258	2.500
6	A	12.44	12.46	12.35	49.35	10.589	0.298	2.540
	B	12.46	12.43	12.37	49.32	10.583	0.298	2.540
	C	12.46	12.45	12.35	49.28	10.574	0.298	2.540
7	A	12.46	12.41	12.37	49.33	10.660	0.402	2.540
	B	12.47	12.43	12.35	49.33	10.676	0.402	2.540
	C	12.46	12.43	12.38	49.26	10.703	0.402	2.540
8	A	12.45	12.44	12.32	49.22	10.655	0.516	2.355
	B	12.45	12.45	12.33	49.22	10.646	0.516	2.355
	C	12.45	12.44	12.31	49.16	10.636	0.516	2.355

Fuel Loading zone	Contamination (g/g)		Defective SiC (g/g)	
	Fissile	Fertile	Fissile	Fertile
1	1.2E-5	1.2E-6	9.8E-7	4.1E-5
2	7.5E-6	6.7E-7	1.0E-6	2.8E-6
3	7.6E-6	7.5E-6	3.1E-5	2.3E-6
4	1.2E-5	8.0E-7	1.2E-6	4.1E-5
<Mean>	1.0E-5	2.6E-6	0.7E-5	2.1E-5

5.2 JAERI HTGR FUEL COMPACTS

The reference fuel compact for the JAERI HTGR is a molded compact fabricated using only overcoated particles under high pressure. Prior to the compact fabrication step, JAERI TRISO-coated UO_2 particles are overcoated with a 200-μm-thick layer of matrix material made up of natural graphite and petroleum graphite powders with the addition of a phenol resin binder. The overcoated particles are then placed into a steel mold at about 100°C and formed into a green annular compact under a pressure of 10 MPa (1450 psi). The particle volume fraction in each compact is maintained at 30 vol % by the addition of inert coated particles when needed. After the green compacts are removed from the molds, they are heated in a two-step process to carbonize the binder, remove volatiles, and stabilize compact dimensions. Final dimensions of the JAERI compacts for HRB-22 are 24-mm outer diameter and 8-mm inner diameter by 40 mm long. In HRB-22, a total of 12 compacts are loaded in tandem inside a POCO AXF-5Q graphite sleeve as shown in Fig. 6.

The JAERI fuel compacts were fabricated from a single batch of TRISO-coated UO_2 particles. Characteristics of this particle batch are provided in Table 6. From this particle batch 20 fuel compacts were fabricated, from which 12 were selected for irradiation in capsule HRB-22. The characteristics of these 12 compacts are provided in Table 7. The total particle volume fraction was maintained at 29.8 vol %; with 23.9 vol % made up from an inert SiC TRISO-coated inert particle batch, and 5.9 vol % of the UO_2 particle batch. The total uranium content per compact was 0.098 g, of which 4.046% was enriched. The density of each compact was

Table 6. Characteristics of TRISO-coated UO_2 particles used to fabricate JAERI fuel compacts for capsule HRB-22

Kernel material

	Specifications	HRB-22
Density (Mg/m^3)	10.41 ± 0.22	10.21
Mean diameter (μm)	600 ± 60	578 ± 27.9
Weight % uranium		
O/U (atomic ratio)	2.00 + 0.01 - 0.00	2.006 - 2.009

TRISO coating

	Thickness (μm)		Density (Mg/m^3)	
Layer	Specifications	HRB-22	Specifications	HRB-22
Buffer	60 ± 15	63.0	1.10 ± 0.10	1.19
IPyC	30 ± 5	28.5	1.85 ± 0.05	1.87
SiC	25 ± 5	23.0	≥ 3.20	3.20
OPyC	45 ± 5	45.5	1.85 ± 0.05	1.88

Total particle

	Specification	HRB-22
Diameter (μm)	920 ± 90	898 ± 37.6
Density (Mg/m^3)		4.13
Weight % uranium		59.224

Quality control

Free U fraction	9.2E-7 to 1.9E-5
Defective SiC fraction	5.0E-5 to 5.4E-4

Table 7. Characteristics of JAERI compacts in capsule HRB-22

Position	JAERI compact No.	Outer diameter (mm)	Inner diameter (mm)	Length (mm)	Weight (g)	U-total (g)
(top)						
1	JC-11	24.03	8.06	39.96	31.308	0.097
2	JC-02	24.04	8.06	39.98	31.316	0.098
3	JC-13	24.04	8.06	39.99	31.334	0.097
4	JC-14	24.04	8.07	39.96	31.324	0.099
5	JC-18	24.05	8.04	39.96	31.294	0.099
6	JC-04	24.05	8.06	40.04	31.337	0.098
7	JC-15	24.05	8.04	39.93	31.271	0.098
8	JC-12	24.04	8.06	39.98	31.328	0.097
9	JC-07	24.04	8.06	39.98	31.324	0.098
10	JC-09	24.04	8.07	40.01	31.328	0.097
11	JC-16	24.03	8.06	39.98	31.285	0.097
12	JC-19	24.02	8.06	39.95	31.279	0.098
(bottom)						

1.94 Mg/m^3 with a matrix density of 1.69 Mg/m^3. Quality control performedon five compacts indicated a free uranium fraction that ranged from 5.6E-5 to 1.4E-4. The SiC defect fraction obtained by a burn/leach procedure yielded values ranging from 2.2E-4 to 1.3E-3.

6. IRRADIATION

Irradiation of capsules HRB-21 and HRB-22 is being performed in the High Flux Isotope Reactor (HFIR) located at ORNL. The capsules will be inserted into two recently updated, removable beryllium (RB) positions; capsule HRB-21 will be irradiated for six HFIR cycles (about 126 days) and capsule HRB-22 will be irradiated for two HFIR cycles (about 42 days). Peak burnup for the JAERI UO_2 fuel will not exceed 5% FIMA, while for the U.S. UCO and ThO_2 fuels, the maximum burnups will be about 24% and 3% FIMA, respectively. Tables 8 and 9 provide estimates of the fissile and fertile material burnups and fast fluence expected for each fuel compact of capsules HRB-21 and HRB-22, respectively.

The target fuel centerline mean temperature for capsule HRB-21 is 975°C and for capsule HRB-22 the peak fuel temperature is 1300°C. In both capsules, the graphite fuel body or graphite sleeve radial gaps were specified to maintain this temperature as uniformly as possible over the length of the capsule. Fuel compact temperatures will be inferred from the graphite thermocouple temperature data and the preirradiation design thermal analysis. In-reactor temperature control will be maintained by adjusting the neon and helium concentrations in the sweep gas. After irradiation and completion of the fuel/graphite metrology, a detailed thermal analysis will be performed to obtain in-reactor fuel compact temperatures.

No thermocouples have been placed within the fuel compacts themselves. The fuel operating temperature uncertainty during irradiation may be as much as ±125°C. This uncertainty may be reduced after postirradiation metrology. The average value for the graphite operating temperature is expected to be approximately 650°C.

Table 8. Estimated fuel burnup and fast neutron fluences for USDOE fuel compacts irradiated in capsule HRB-21

Compact location	Burnup (FIMA)				Fast neutron fluence, n/m^2 (× 10^{25})
	^{235}U	^{238}U	U-total	^{232}Th	
9, 8	6.60E-01	2.90E-02	1.55E-01	6.60E-03	2.2
2, 7	7.80E-01	5.70E-02	2.02E-01	1.50E-02	3.4
3, 6	8.20E-01	8.30E-02	2.30E-01	2.30E-02	4.4
4, 5	8.30E-01	9.70E-02	2.44E-01	2.70E-02	4.9

Table 9. Estimated fuel burnup and fast neutron fluences for JAERI fuel compacts irradiated in capsule HRB-22 (two cycles)

Compact location	Burnup (FIMA)			Fast neutron fluence, n/m^2 (× 10^{25})
	^{235}U	^{238}U	U-total	
1, 12	0.43	0.80E-02	2.5E-02	0.76
2, 11	0.50	0.12E-01	3.2E-02	1.0
3, 10	0.58	0.18E-01	4.1E-02	1.24
4, 9	0.63	0.23E-01	4.8E-02	1.44
5, 8	0.66	0.26E-01	5.3E-02	1.58
6, 7	0.67	0.28E-01	5.5E-02	1.66

6.1 IN-REACTOR SURVEILLANCE

Fission gas isotopes being monitored in the sweep gas system of each capsule are ^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{89}Kr, ^{90}Kr, ^{131m}Xe, ^{133}Xe, ^{135}Xe, ^{135m}Xe, ^{137}Xe, and ^{138}Xe. The frequency of monitoring will be once per weekday or as specified by the task leader. In addition to fission gas release data, thermocouple temperatures, sweep gas flow rates and mixtures, and capsule inlet and outlet pressure will be monitored continuously with data stored at four-hour intervals for routine operation. In the case of unexpected events, this frequency will be increased as directed by the task leader.

The operating data for each capsule will be reported on a monthly basis. The data will include fission gas R/B values, operating temperatures, and general capsule operation.

7. POSTIRRADIATION EXAMINATION

After completion of their scheduled two- and six-cycle irradiation in HFIR, capsules HRB-22 and HRB-21 will be removed from the reactor and allowed to cool in the pool-side facility for 1 to 3 weeks. Each capsule will then be loaded into a special transportation cask and moved to the High Radiation Level Examination Laboratory (HRLEL) for disassembly and (PIE).

The capsule disassembly and PIE will be performed according to a well-defined plan that will be available to the HRLEL staff before initiation of PIE. This plan will provide detailed disassembly procedures for each capsule, a PIE test matrix, and PIE procedures for examining the irradiated fuel compact and graphite components in each capsule. A tentative PIE test matrix has been prepared for the fuel compact specimens in each of capsules HRB-21 and HRB-22. This test matrix is provided in Table 10 and will be updated as needed in the PIE plan.

7.1 DISASSEMBLY AND METROLOGY

The irradiated specimens will be removed from the capsule containments by making circumferential cuts at the top and bottom of the fueled portion of the capsule. (Engineering drawings with indicated cuts will be supplied in the PIE plan.) At this point, the thermocouple arrays will be removed and stored for further analysis if necessary. The circumferential cut surfaces will be deburred and the carbon insulators and graphite fuel bodies removed by pushing them out onto a clean positioning tray. The insulators and graphite bodies will be visually examined and photographed, and any unusual areas will be noted and photographed. Each fuel body will then be stored in a properly identified, individual container for further disassembly and PIE. The primary and secondary containments will also be stored in properly identified containers for further analysis.

All of the fuel compacts and H-451 fuel bodies and the POCO AXF-5Q graphite sleeve will be visually examined and photographed. Dimensional measurements will be performed on each fuel compact and graphite body and at selected locations along the graphite sleeve. These will include

Table 10. Tentative postirradiation test matrix for JAERI annular fuel and USDOE cylindrical fuel compacts irradiated in capsules HRB-22 and HRB-21, respectively

Compact[a] number	CHST[b]	TRIGA activation	Leach[c]	Ceramography/ microprobe	Deconsolidation/ IMGA[d]
		JAERI annular compacts, HRB-22			
1	X	X			
2		X			
3	X	X			
4		X			
5			X	X	X
6		X			
7			X	X	X
8		X			
9	X	X			
10			X	X	X
11	X	X			
12			X	X	X
		USDOE cylindrical compacts, HRB-21			
1	X	X			
2	X	X			
3	X	X			
4	X	X			
5		X	X	X	X
6		X	X	X	X
7		X	X	X	X
8		X	X	X	X

[a]In capsule HRB-22, number refers to compact location in graphite sleeve from the top of the capsule. In capsule HRB-21, number refers to the position of the graphite fuel body.

[b]Core heatup simulation testing.

[c]JAERI fuel compacts must be deconsolidated prior to leaching step.

[d]Irradiated microsphere gamma analyzer.

measurements of the diameters and lengths of the compacts, fuel bodies, and sleeve, along with additional measurements to characterize fuel-hole diameters in the H-451 graphite bodies and wall thickness of the POCO AXF-5Q graphite sleeve. For a selected number of JAERI annular fuel compacts and USDOE cylindrical fuel compacts, weight will also be measured.

7.2 TRIGA ACTIVATION

Following the fuel and graphite component metrology, a number of JAERI and USDOE fuel compacts will be selected for TRIGA activation measurements. The selected compacts will be shipped to GA for the activation and analysis. JAERI has requested that isothermal and isochronal heating be performed during the TRIGA irradiation. (Specific compacts have not been identified.)

7.3 LEACH

Because JAERI fuel particles are overcoated with a 200-μm-thick layer, acid leaching of the annular fuel compacts will not provide useful information. Therefore, the JAERI compacts must first be deconsolidated, and the remaining unbonded particles and graphitic material must then be subjected to the acid leach.

7.4 CERAMOGRAPHY AND ELECTRON MICROPROBE ANALYSIS

Ceramographic examinations will be performed on sections of the JAERI annular and USDOE cylindrical fuel compacts. Unbonded particles obtained by deconsolidation will also be used. The ceramographic mounts will also be available for electron microprobe analysis. The microprobe analysis will be directed toward determining fission product distributions within the fuel kernel and interaction with the coatings. Particular attention will be given to the Pd-SiC chemical interaction.

7.5 DECONSOLIDATION AND IRRADIATED MICROSPHERE GAMMA ANALYSES

Deconsolidation procedures developed at ORNL have been used for the relatively low-density reference design U.S. fuel compacts and not the high-density reference JAERI compacts. Thus, the electrolytic procedures must be optimized for the dense JAERI annular compacts. USDOE and JAERI compacts will first be subjected to a deconsolidation, and the recovered unbonded particles will then be individually analyzed with the irradiated microsphere gamma analyzer (IMGA). Failed-nonfailed decisions are based on the relative inventory of a volatile fission product to the inventory of a chemically stable fission product, such as Cs:Ru.

7.6 CORE HEATUP SIMULATION TESTING

Four core heatup simulation tests (CHST) have tentatively been chosen for both the USDOE and JAERI irradiated fuel compacts, including:

JAERI compacts:

Test 1: 2000°C; ramp to temperature in 50 h;

Test 2: 1800°C; ramp to 1800°C in 3 h, hold at temperature for 200 h;

Test 3: 1600°C; ramp to 1600°C in 3 h, hold at temperature for 997 h; and

Test 4: 1600°C; ramp to 1600°C in 50 h, hold at temperature for 100 h, ramp down in 850 h.

USDOE compacts:

Test 1: 1400°C; ramp to 1400°C in 10 h, isothermal test at 1400°C for 1000 h;

Test 2: 1600°C; ramp to 1600°C in 10 h, isothermal test at 1600°C for 1000 h;

Test 3: 1600°C; ramp to 1600°C in 10 h, isothermal test at 1600°C for 1000 h; and

Test 4: 1800°C; ramp to 1800°C in 10 h, isothermal test at 1800°C for 500 h.

All of the CHSTs will be conducted in the Conduction Cooldown Test Facility (CCTF) now being constructed at ORNL. This facility will provide simulation of the conditions of a high-temperature HTGR core heat-up and provide for the on-line measurement of fuel failure and fission product release. A minimum of four USDOE graphite fuel bodies and four JAERI annular fuel compacts will be subjected to heating tests in the CCTF. The CHSTs will emphasize temperatures ranging from 1400 to 2000°C.

The key fission product releases to be measured are Cs, Ag, Sr, I, Xe, and Kr. The irradiated fuel compacts from HRB-21 and HRB-22 will have the capability to undergo a short reactivation in a facility available in the

Bulk Shielding Reactor (BSR) at ORNL. This facility will permit the generation of sufficient quantities of radioactive iodine and xenon isotopes in the fuel particles such that their release can be monitored during the CHSTs. During these tests, only the total release for each isotope will be measured; no attempt to identify chemical species will be made.

8. TENTATIVE SCHEDULE

A tentative schedule for testing capsules HRB-21 and HRB-22 has been developed. This schedule is subject to HFIR startup and shutdown requirements and interference from other experiments in the HRLEL.

Item		Completion date	
		HRB-21 (USDOE)	HRB-22 (JAERI)
1	Capsule HRB-21/HRB-22 planning	Sept. 1987	Sept. 1987
2	Issue experimental plan	Nov. 1987	Nov. 1987
3	Complete fuel/graphite fabrication	Dec. 1987	Aug. 1987
4	Complete capsule assembly	Nov. 1988	Dec. 1988
5	Insertion in HFIR	Dec. 1989	Dec. 1989
6	Complete HFIR irradiation	May 1990	Feb. 1990
7	Transfer to HRLEL	June 1990	Mar. 1990
8	Complete disassembly/metrology	Sept. 1990	June 1990
9	Initiate postirradiation examination	Oct. 1990	July 1990
10	Initiate CHST	Oct. 1990	July 1990
11	Complete postirradiation examination	Nov. 1991	Aug. 1991
12	Complete CHST	Feb. 1992	Nov. 1991
13	Complete topical report	July 1992	Apr. 1992

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