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Design, Fabrication, and Initial Operation of HTGR-ORR Capsule OF-2

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K. R. Thoms
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ABSTRACT

The OF-2 irradiation experiment was designed and built to test candidate High-Temperature Gas-Cooled Reactor (HTGR) fuel and fuel-rod matrix designs. The capsule was designed with two separate specimen cells, allowing for independent temperature control as well as independent fission gas release measurements. The OF-2 capsule is presently operating at the Oak Ridge Research Reactor (ORR). Initial fuel rod linear heat rates are between 16.4 and 23.0 kW/m (5 and 7 kW/ft) and fuel centerline temperatures are approximately 1150 and 1350°C. Plans are to operate the capsule for nine ORR cycles to accumulate a maximum damage fluence of 9×10^{21} neutrons/cm^2 ($E > 0.18$ MeV).

1. INTRODUCTION

The High-Temperature Gas-Cooled Reactor (HTGR) fuel irradiation experiments conducted at Oak Ridge National Laboratory (ORNL) in support of the Thorium Utilization and Fueled Graphite Development programs have traditionally been accomplished in two phases. The High-Flux Isotope Reactor (HFIR) target series of experiments (HT) are used to screen potential fuel and fuel-rod matrix designs and identify poor performers. Successful designs are translated into prototype fuels and fuel-rod matrix designs and irradiated in the instrumented facilities in the HFIR removable beryllium (HRB) facilities and the ORR. The OF-2 experiment will supplement information from previously conducted HT and HRB tests. In addition, OF-2 represents the first test of Triso-coated fissile fuel fabricated in the 13-cm-diam coating furnace at ORNL. The objectives of this experiment are listed below.

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*Metals and Ceramics Division.

1. To test the performance of reference weak-acid resin (WAR), Triso-coated fissile particles and reference Biso-coated fertile particles both coated in the 13-cm-diam coating furnace.

2. To investigate the matrix-particle interaction phenomenon. This portion of the experiment will involve a study of the effects of particle strength, matrix type, and particle surface conditions on irradiation performance.

3. To investigate the behavior under irradiation of various coating microstructures arising from variation of the coating process parameters: gas concentration, deposition rate, deposition temperature, and batch size.

4. To investigate the influence of stoichiometry and kernel density on the irradiation performance of WAR-derived fuels.

5. To verify the adequate performance of fissile and fertile fuels that will be irradiated at a later date in early proof-test elements in the Fort St. Vrain Reactor.

6. To compare the performance of coatings deposited in the 13-cm coating furnace using a fritted gas distribution system with coatings deposited using a cone gas distributor. The fritted system is the present reference for the HTGR Recycle Demonstration Facility (HRDF).

7. To test our ability to remove fuel rods from the graphite holder after full-life irradiation, particularly as this applies to in-block carbonization.

This report discusses the design, fabrication, and initial operation of the OF-2 capsule. Another report covering the operation and postirradiation examination will be issued following completion of those tasks.

2. IRRADIATION FACILITY

The OF-2 capsule is being irradiated in the E-7 position of the ORR core. A cross section of the ORR core showing the location of OF-2, as well as other capsules in the HTGR irradiation program, is shown in Fig. 1. Figure 2 shows the installation of the OF-2 capsule in the

ORNL-DWG 75-15687

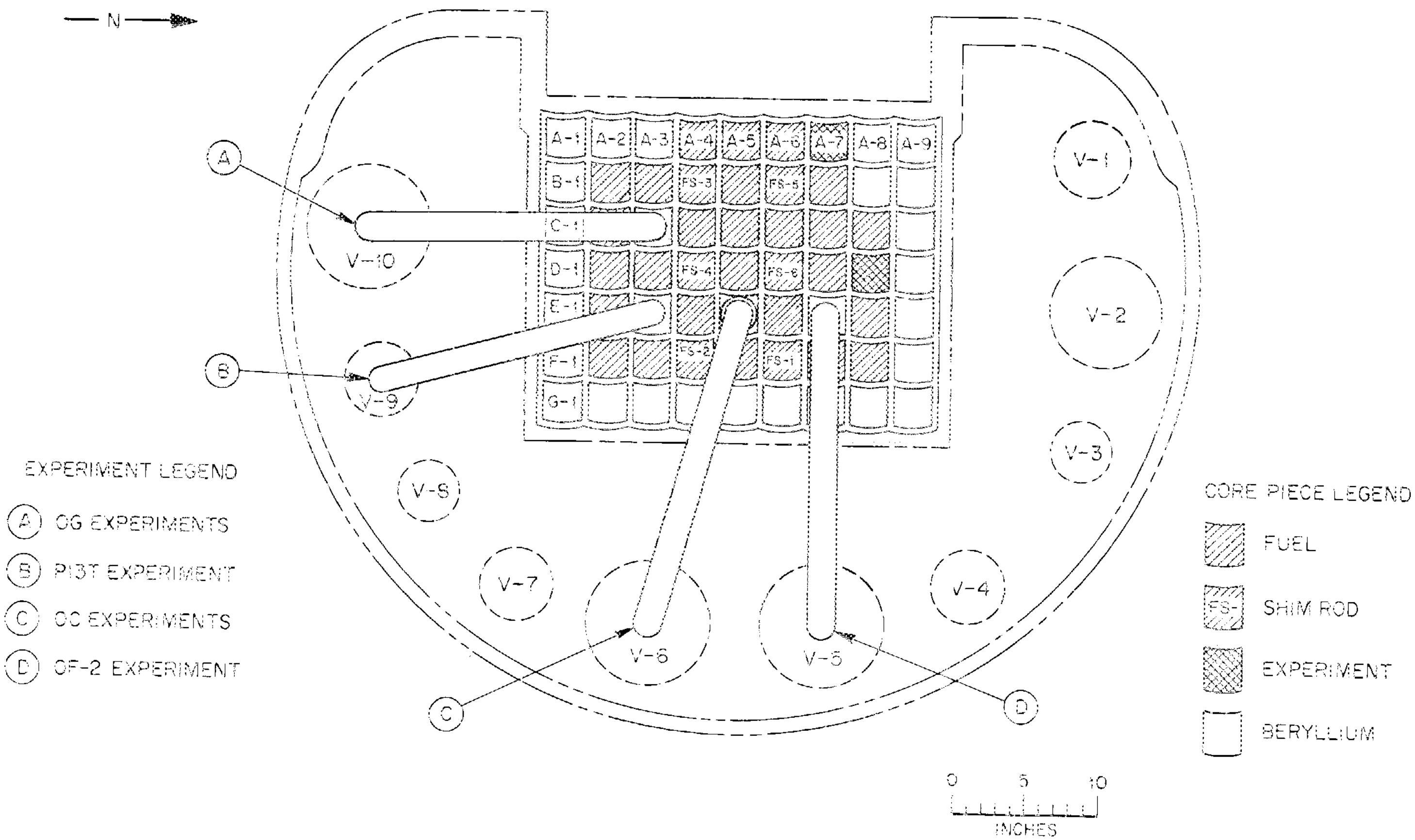


Fig. 1. HTGR irradiation experiment locations in the ORR.

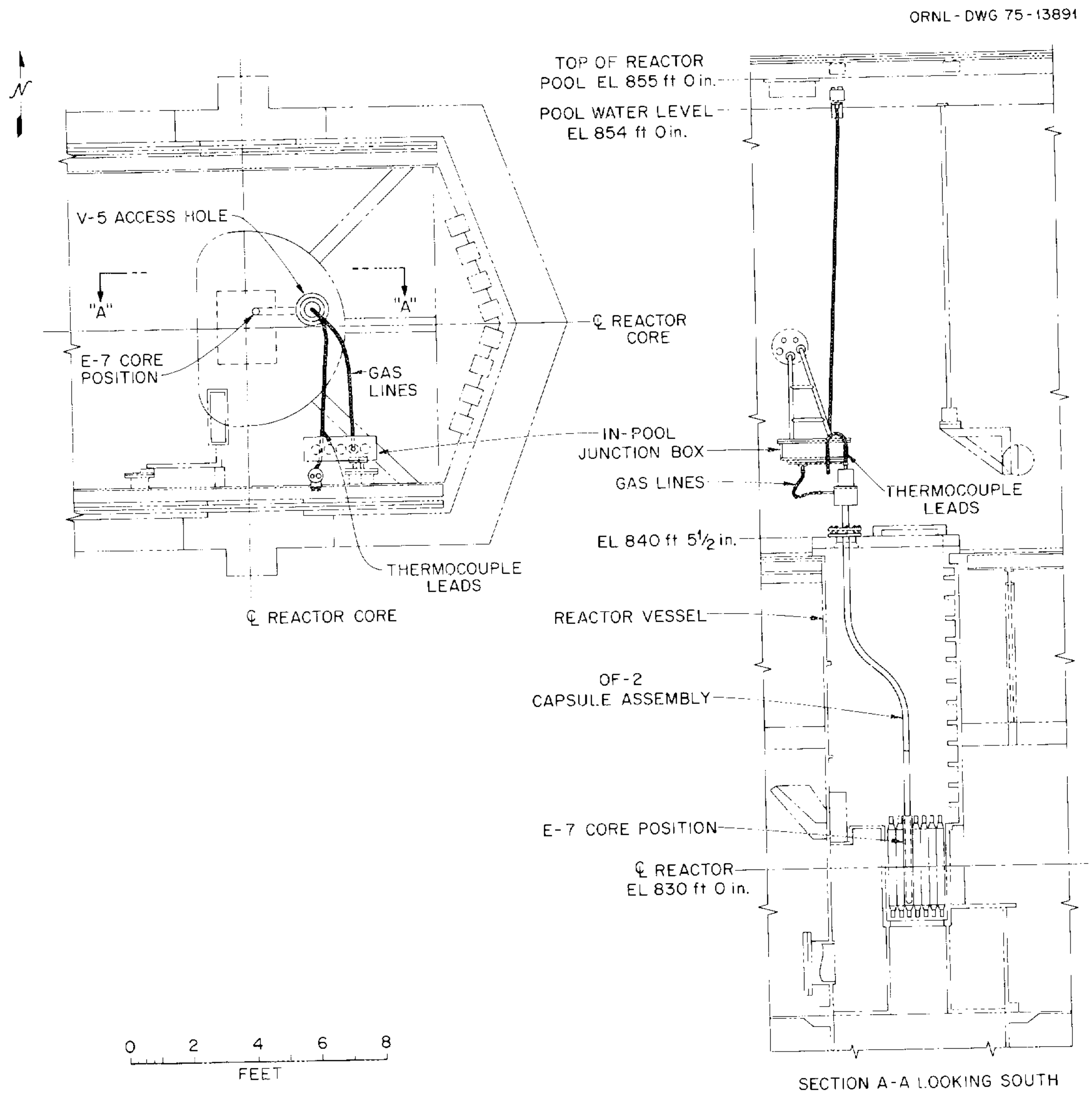


Fig. 2. Installation of OF-2 capsule in ORR (1 ft = 0.3048 m).

ORR pool. The thermocouple leads that run to the top of the pool are connected to the lead wires that feed into recorders and a data-acquisition system. Gas lines coming from the capsule are fed into the in-pool junction box, where they are connected to existing gas supply and vent systems. A schematic flow diagram of the OF-2 capsule is presented in Fig. 3.

3. EXPERIMENTAL ASSEMBLY

The description of the experimental assembly is divided into four parts: the capsule design, the instrumentation used to monitor operation, the dosimetry incorporated to determine neutron fluxes, and the fuel specimens.

3.1 Capsule Design

The general configuration of capsule OF-2 is shown in Fig. 4. The three fuel specimen holders are doubly contained in two type 304 stainless steel containment vessels. The inner or primary containment vessel is 63.19 cm (24.88 in.) long and has a 6.195-cm (2.439-in.) ID and a 6.447-cm (2.539-in.) OD. The outer or secondary containment vessel is 81.92 cm (32.25 in.) long with a 6.464-cm (2.545-in.) ID and a 6.668-cm (2.625-in.) OD. The total active test space is a cylinder 63.50 cm (25.0 in.) long and 6.05 cm (2.38 in.) in diameter. The capsule is divided into two cells by a copper bulkhead brazed into the primary containment vessel at a point 8.573 cm (3.375 in.) below the reactor midplane and approximately 36.8 cm (14.5 in.) below the upper end of the capsule.

The bottom cell (cell 1) contains one H-451 graphite specimen holder (designated specimen holder C), which is 22.23 cm (8.750 in.) long and 6.1054 cm (2.4037 in.) in diameter. The specimen holder has a 0.953-cm-diam (0.375-in.) central spline hole and four 1.595-cm-diam (0.628-in.) peripheral fuel holes. Each fuel hole contains four 5.08-cm-long (2.00-in.) by 1.575-cm-diam (0.620-in.) fuel rods. Nine Chromel-P/Alumel (C/A) thermocouples are incorporated to monitor peripheral graphite temperature

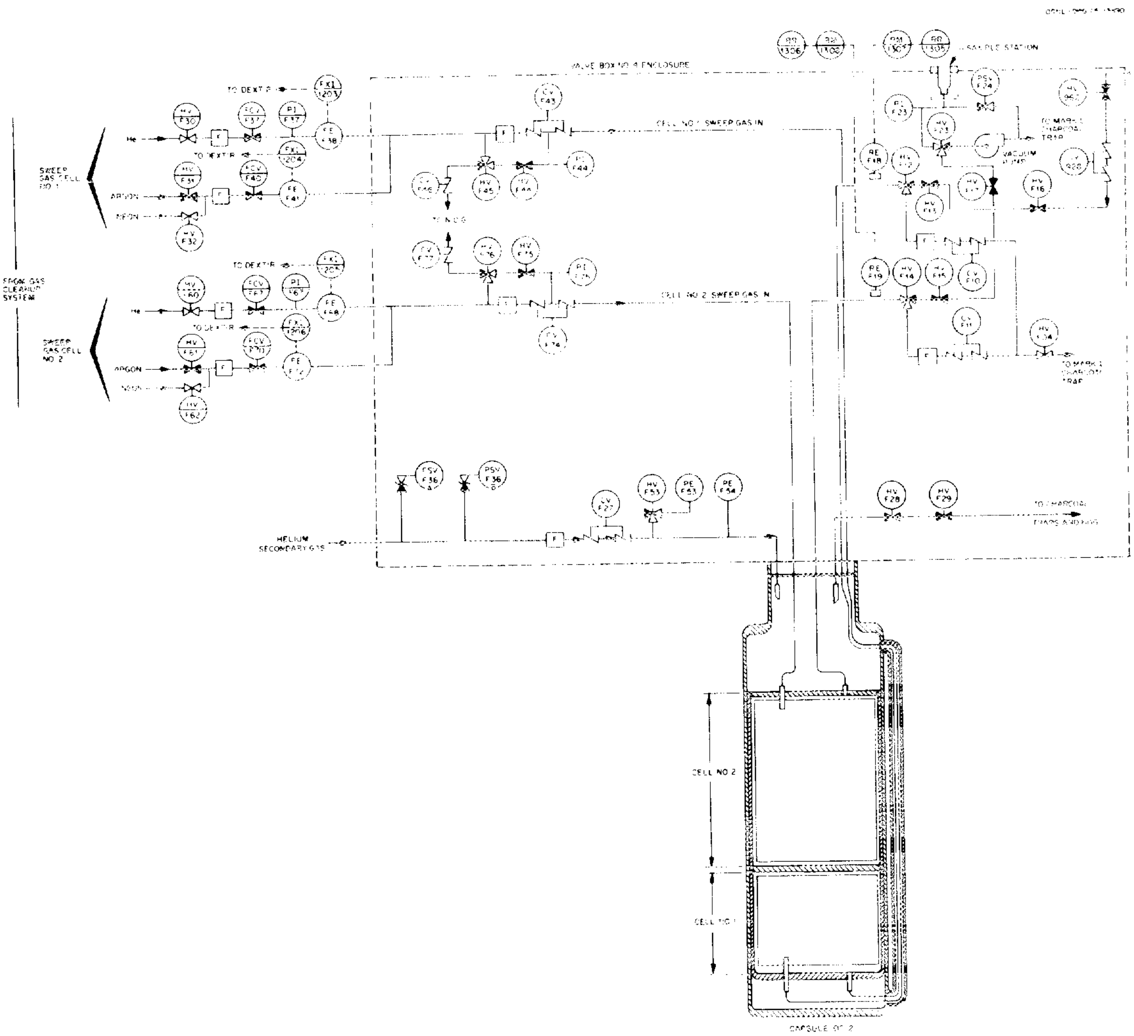


Fig. 3. Schematic flow diagram for capsule OF-2.

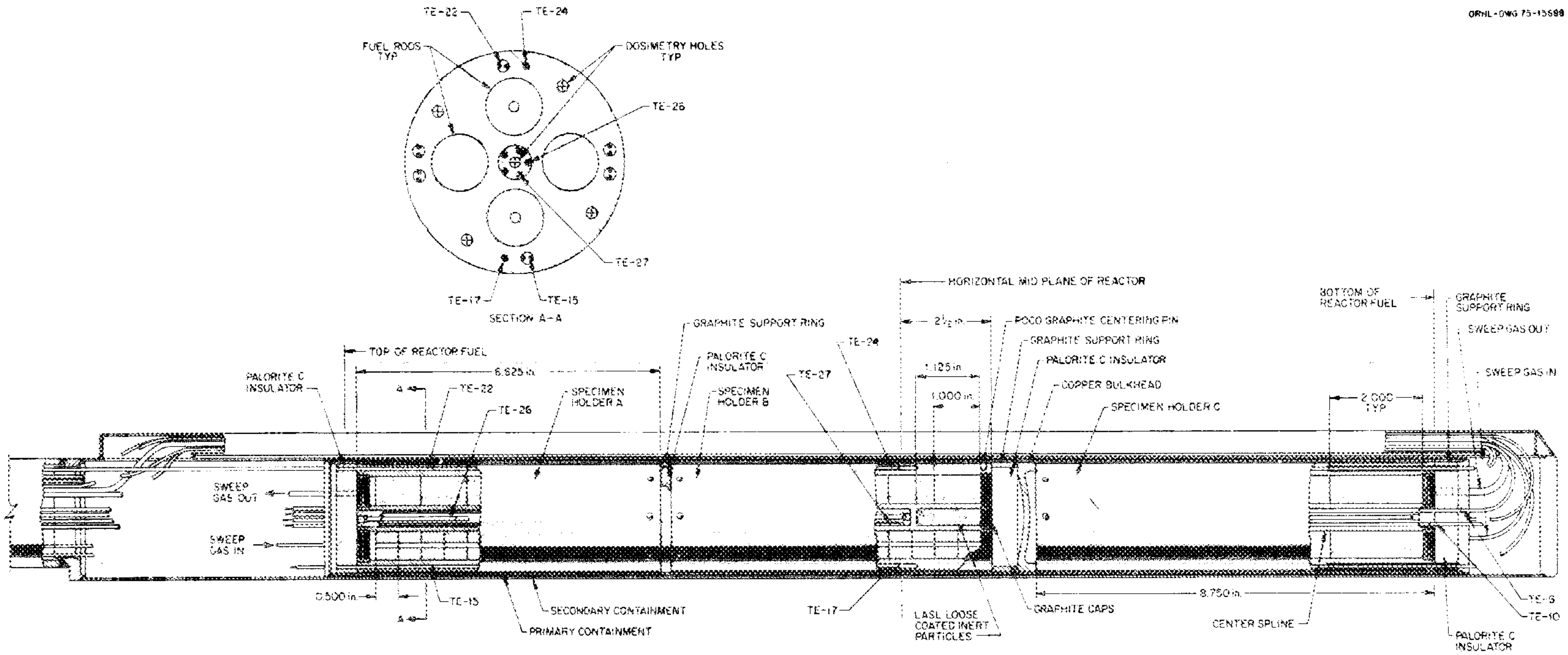


Fig. 4. General configuration of capsule OF-2 (1 in. = 2.54 cm).

and one C/A thermocouple monitors the primary containment bulkhead temperature. The design operating condition for this specimen holder is a maximum fuel centerline temperature of 1350°C.

The top cell (cell 2) contains two H-451 graphite specimen holders, each of which has a 0.953-cm-diam (0.375-in.) central spline hole and four 1.595-cm-diam (0.628-in.) peripheral fuel holes. The upper holder, specimen holder A, is 16.828 cm (6.625 in.) long and 6.134 cm (2.415 in.) in diameter and is designed to operate at a maximum fuel centerline temperature of 1150°C. The lower holder, specimen holder B, is 16.828 cm (6.625 in.) long and 6.116 cm (2.408 in.) in diameter and is designed to operate at a maximum fuel centerline temperature of 1350°C. Each specimen holder contains 36 fuel rods. Two fuel holes in each specimen holder contain six 2.54-cm-long (1.00-in.) by 1.575-cm-diam (0.620-in.) fuel specimens, while the remaining two holes each contain twelve 1.27-cm-long (0.50-in.) fuel specimens having an OD of 1.575 cm (0.620 in.) and an ID of 0.340 cm (0.134 in.). In addition, specimen holder B contains approximately 2 cm^3 of loose coated inert particles fabricated by Los Alamos Scientific Laboratory (LASL). These loose particles are located in a 3.175-cm-long (1.250-in.) by 0.953-cm-diam (0.375-in.) hole at the bottom of specimen holder B.

Specimen holder A is instrumented with a total of 12 thermocouples — 11 C/A and one Pt—0.1% Mo/Pt—5% Mo (Pt-Mo). Eight of the C/A thermocouples monitor the peripheral graphite temperature, while three C/A thermocouples and the Pt-Mo thermocouple monitor the graphite centerline temperature. Specimen holder B contains six C/A thermocouples to monitor graphite peripheral temperatures and one Pt-Mo thermocouple to monitor the graphite centerline temperature.

Flux monitors are also incorporated in each specimen holder and are described in more detail in Sect. 3.3.

3.2 Instrumentation

Operating temperatures in capsule OF-2 are measured by 29 thermocouples — 27 C/A and two Pt-Mo. The location of the thermocouples is shown in Fig. 5.

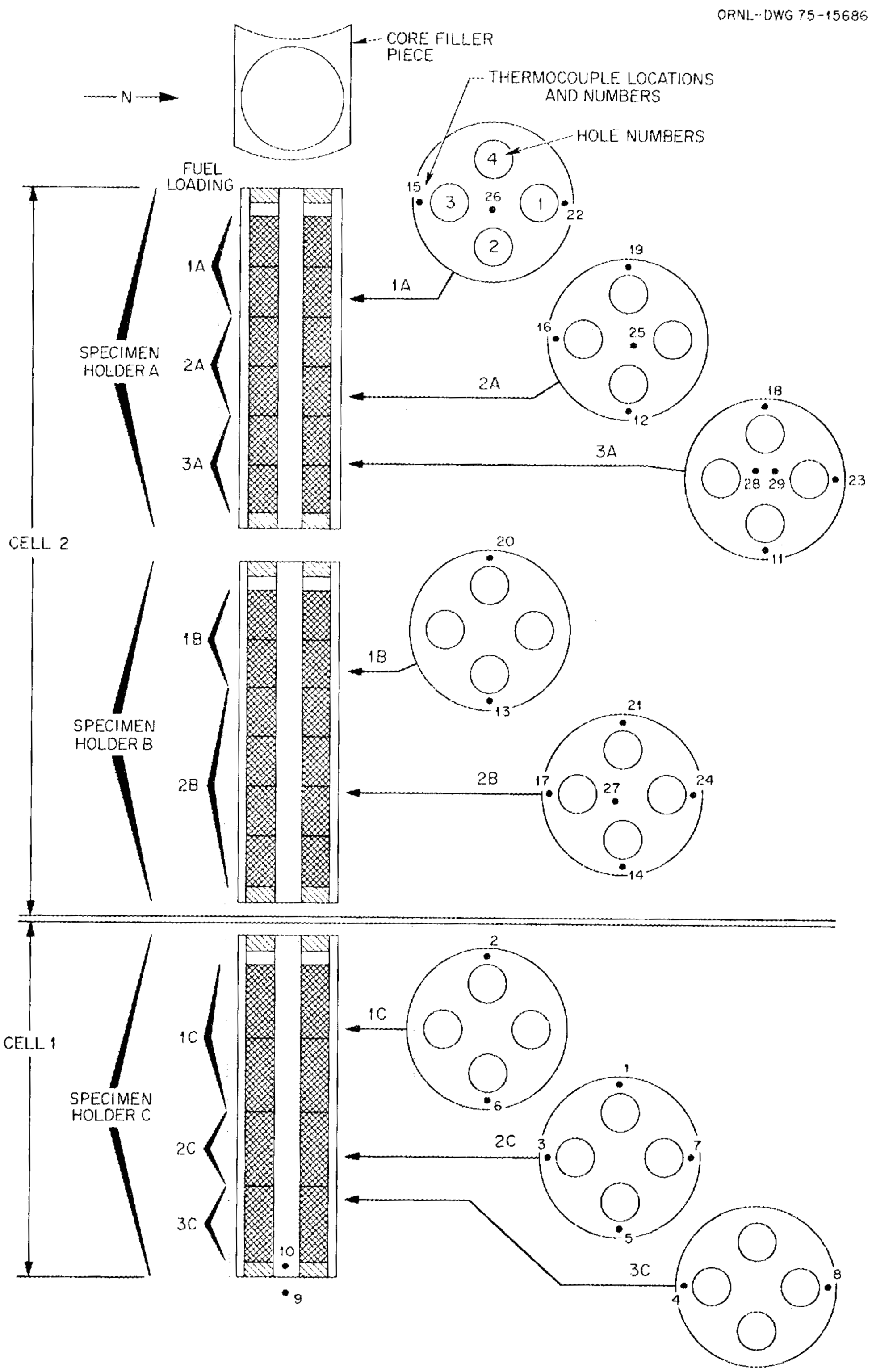
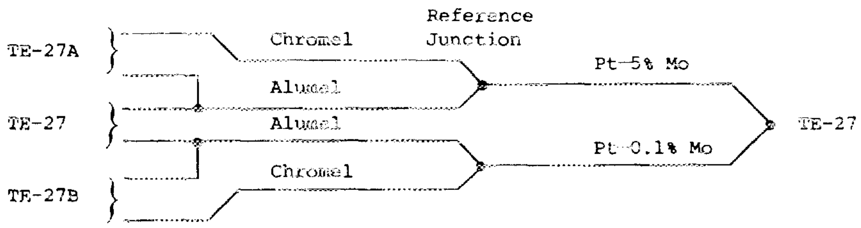


Fig. 5. General layout of specimen holders, fuel loadings, and thermocouples in capsule OF-2.

Original plans called for the incorporation of two Johnson noise thermometers (JNT) to measure fuel centerline temperatures in specimen holders A and B. These were actually installed in the capsule, but they were removed due to problems discovered at the time of capsule assembly. A more detailed explanation of this problem is presented in Chap. 5 of this report.

The C/A thermocouples used in OF-2 are 0.160 cm (0.063 in.) OD, MgO insulated, and sheathed in type 304 stainless steel. The two Pt-Mo thermocouples are 0.160 cm (0.063 in.) OD, alumina insulated, and sheathed in platinum. The Pt-Mo thermocouples are 91.44 cm (3 ft) long, and each is connected to two C/A thermocouples which measure the reference junction temperature and provide extension leads using the Alumel wires. A simplified schematic drawing is shown below.



Each of the Pt-Mo thermocouples was installed in a stainless steel guide tube, and the guide tubes were welded to the stainless steel primary containment bulkhead. One C/A thermocouple (TE-29) was placed adjacent to a Pt-Mo thermocouple (TE-28) in an attempt to measure any decalibration in the Pt-Mo thermocouple that might occur during the irradiation period.

The gas pressure between the primary and secondary containment vessels is monitored continuously by two strain-gage-type pressure transducers. A loss of pressure, either through a leak in the primary containment or a leak in the secondary containment, would automatically shut down the reactor.

The helium and neon sweep gas flows are measured by Hastings mass flowmeters. Radiation monitors are placed on the exit sweep gas lines from each cell to show relative changes in activity of gases leaving each cell.

The thermocouple outputs, secondary gas pressure, and activity of sweep gas lines are continuously recorded on millivolt strip-chart recorders. In addition to these recorded data, all thermocouple outputs and sweep gas flows are recorded four times per day on a Dextir data-acquisition system. These data are reduced weekly and stored on disks at the computer center. At the end of each reactor cycle, plots are generated to present a cycle history of each thermocouple as well as the sweep gas flow rates and reactor power.

3.3 Dosimetry

Flux monitor packages were loaded into specimen holders A and B and the center splines of both cells 1 and 2. The positions of the packages are shown in Fig. 6 along with the arrangement of the monitor wires in each package. The weights of the flux monitor wires in each package are given in Appendix A.

A flux monitor package consists of a BeO tube containing three flux monitor wires — two iron wires (100% Fe) and one vanadium-cobalt wire (V–0.216% Co). The wire materials were selected on the basis of their neutronic properties, high melting points, and chemical compatibility with BeO. The BeO tubes prevent interaction of the wires with the graphite.

Neutron fluences in OF-2 will be determined by measuring the induced activities in these wires through the following reactions:

$$^{59}\text{Co}(n,\gamma)^{60}\text{Co}$$
$$^{54}\text{Fe}(n,p)^{54}\text{Mn}$$
$$^{58}\text{Fe}(n,\gamma)^{59}\text{Fe}$$

3.4 Fuel Specimens

3.4.1 Coated Particles

Eighty-eight specimens were required for OF-2. Eighty-six of these were fabricated at ORNL and the remaining two were fabricated at LASL. The Triso-coated fissle particle test set consisted of twelve batches of WAR-derived particles of a wide range of stoichiometries, from uranium oxide to uranium carbide; one batch of WAR-derived U(C,N) particles; one

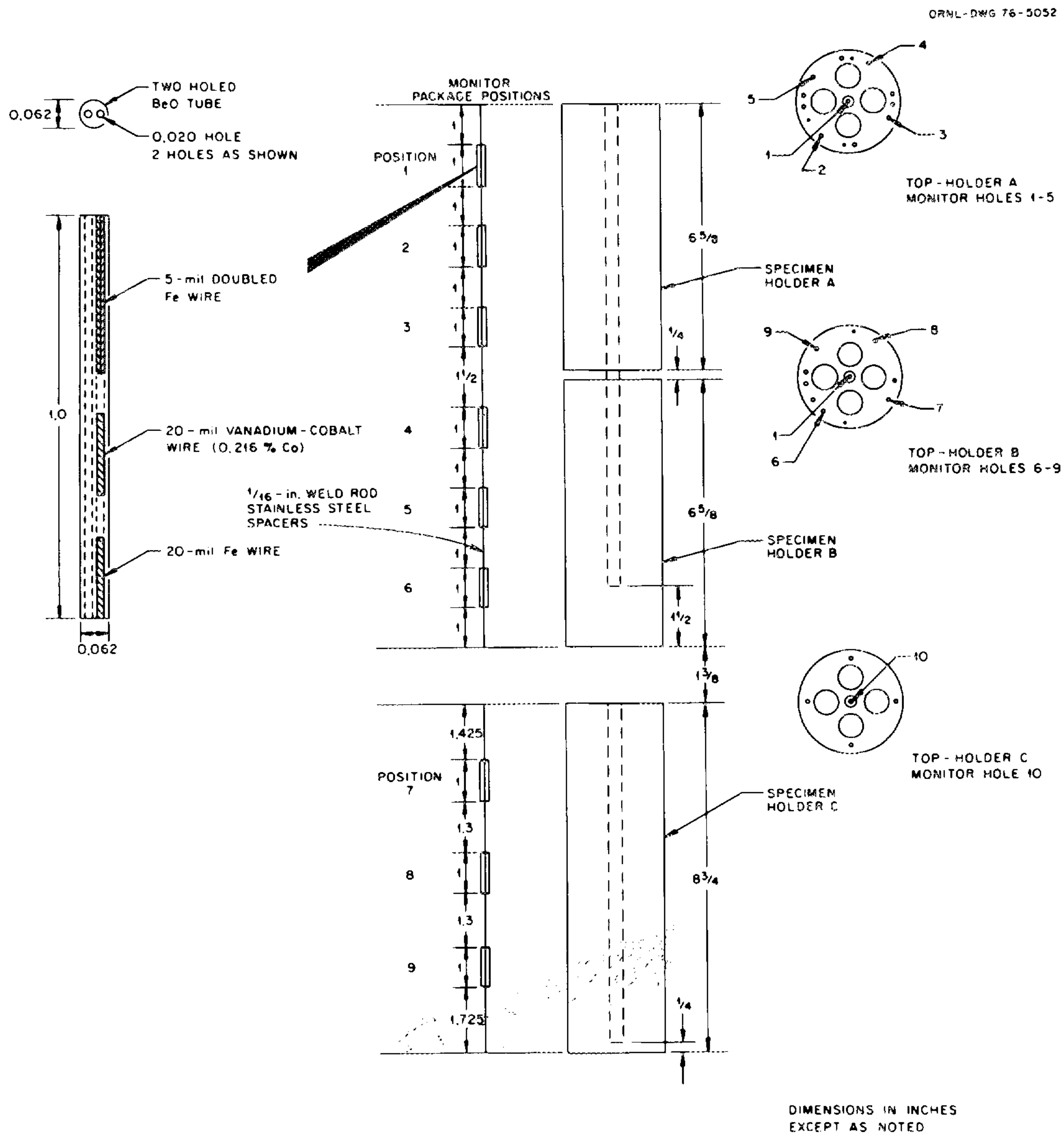


Fig. 6. Arrangement of flux monitors in capsule OF-2 (1 in. = 2.54 cm).

batch of sol-gel $(4Th,U)O_2$ particles; and one batch of General Atomic Company's (GAC) VSM UC_2 particles. A complete description of each fissile particle batch is presented in Table 1. All the particle batch types, with the exception of type 15, were included in the fuel specimens in the upper cell, cell 2. Particle types 13, 14, and 15 were fabricated for the lower experimental compartment, cell 1, using the large diameter coating furnace. Types 13 and 14 were coated using the reference fritted gas distribution system, and type 15 was coated using the cone distribution system. Particle types 1 through 11 were annealed at 1800°C for 10 min in a fluidized bed after the outer low-temperature isotropic (OLTI) coating was deposited. Particle types 13 through 15 were similarly annealed after the inner low-temperature isotropic (ILTI) coating was deposited.

Sixteen batches of Biso-coated fertile particles were selected for OF-2. Nine of the fertile batch types were coated in the large-diameter coating furnace, with batch types G through J and M through P using a fritted gas distributor and batch type K using the cone distribution system. Specific reference to coating parameters, deposition rates, geometries, and densities are described in Table 2. Fertile particle types A through L were annealed at 1800°C for 10 min in a fluidized bed, and the remaining types were unannealed.

3.4.2 Fuel rods

One batch each of fissile and fertile particles was selected from its respective test set and combined with a particular matrix type for each fuel rod specimen fabricated. The matrix test set for OF-2 is described in Table 3.

Sixteen fuel rod specimens were fabricated for cell 1. Each specimen contained a mixture of Triso-coated fissile particles, Biso-coated fertile particles, Triso- and Biso-coated carbon particles, and H-451 shim particles. In order to keep fuel rod dimensional changes uniform in this compartment, the ratio of Biso- to Triso-coated particles was kept constant for each loading. Each specimen contained 20% by volume shim particles. Specimens were fabricated to nominal dimensions of 1.575 cm diam (0.620 in.) by 5.08 cm long (2.00 in.) using the slug-injection technique

Table 1. Fissile particle test set for OF-2

Type	Batch	Kernel composition	Nominal reduction (%)	Carbonization rate (°C/min)	Kernel density[a] (g/cm³)	Coater type	Anneal	Geometry[b] (μm)				
								Kernel	Buffer	ILTI	SiC	OLTI
1	OR-2332H[b]	WAR $UC_{5.43}O_{1.95}$	0	2	3.23	Cone[c]	Yes	373.1	39.2	32.3	32.9	32.2
2	OR-2329H[d]	WAR $UC_{5.53}O_{1.97}$	0	2	3.22	Cone[c]	Yes	371.9	23.0	40.6	31.8	30.8
3	OR-2218H[e]	WAR $UC_{4.58}O_{2.04}$	0	40	3.66	Cone[c]	Yes	371.3	69.3	42.0	30.7	44.6
4	OR-2322H[f]	WAR $UC_{5.54}O_{1.69}$	15	2	3.12	Cone[c]	Yes	379.7	49.8	35.7	32.3	39.4
5	OR-2320H	WAR $UC_{5.12}O_{1.54}$	25	2	3.17	Cone[c]	Yes	374.0	43.8	36.8	34.3	38.6
6	OR-2211H[e]	WAR $UC_{4.63}O_{0.97}$	50	2	3.11	Cone[c]	Yes	363.0	59.3	37.5	30.2	42.0
7	OR-2207H[e,g]	WAR $UC_{4.14}O_{0.53}$	75	2	3.03	Cone[c]	Yes	366.4	62.7	38.9	31.1	42.7
8	OR-2208H[e]	WAR $UC_{3.68}O_{0.01}$	100	2	3.01	Cone[c]	Yes	366.5	59.2	38.4	27.9	40.0
9	OR-2121H[h,e,g]	WAR $UC_{2.61}O_{0.16}$	100	6	5.28	Cone[c]	Yes	315.3	74.6	36.1	28.4	49.2
10	OR-2219H	WAR $UC_{3.68}N_{0.53}$		2	3.02		Yes	365.3	66.3	44.0	31.9	43.5
11	OR-2321H[f]	Sol-gel $(Th_{0.8}U_{0.2})O_2$			9.9		Yes	361.1	83.3	37.2	34.4	41.1
12	6151-00-035	VSM UC_2			10.99			196.0	99	33	32	38
13	A-601	WAR	75	2	3.03	Frit[i]	No	354.2	58.8	35.4[j]	30.0	35.8
14	A-611	WAR	15	2	3.10	Frit[i]	No	366.4	47.6	36.8	30.5	35.5
15	A-615	WAR	75	2	3.08	Cone[k]	No	354.1	51.0	30.7[j]	29.5	32.4

[a]Mercury gradient column measurement, uncorrected.

[b]Mean dimension for kernel diameter, buffer, ILTI, SiC, and OLTI thickness.

[c]6.35-cm-diam (2.5-in.) cone.

[d]Thin buffer.

[e]Irradiated in HRB-9 and -10.

[f]Similar batch irradiated in HRB-7, -8, -9, -10, and Met VII.

[g]Irradiated in Dragon Met VII.

[h]Irradiated in HRB-7 and -8.

[i]12.7-cm-diam (5.0-in.) frit.

[j]Corrected buffer thickness due to uranium in buffer during coating process.

[k]12.7-cm-diam (5.0-in.) cone.

Table 2. Fertile particle test for OF-2

Type	Batch	Coater type	Coating parameters				LTI deposition		Geometry[b] (μm)			Density[c] (g/cm^3)		Anneal
			Gas[a]	Concentration (%)	Diluent	Concentration (%)	Temperature (°C)	Rate (μm/min)	Kernel	Buffer	LTI	Uncorrected	Corrected	
A	OR-2266HT[d]	Cone[e]	MAPP	100			1275	14.1	506	94.8	91.3	2.02		Yes
B	OR-2265HT[d]	Cone[e]	MAPP	100			1325	15.7	508	96.1	94.2	1.95		Yes
C	OR-2262HT[d]	Cone[e]	MAPP	50	Ar	50	1275	6.5	507	98.0	85.1	2.01		Yes
D	OR-2261HT[d]	Cone[e]	MAPP	50	Ar	50	1325	7.4	506	95.8	88.9	1.89		Yes
E	OR-2264HT[d]	Cone[e]	MAPP	25	Ar	75	1275	3.2	507	96.5	91.6	1.99		Yes
F	OR-2263HT	Cone[e]	MAPP	25	Ar	75	1325	3.6	506	92.8	90.5	1.84		Yes
G	J-488[d,f]	Frit[g]	C_3H_6	50	He	50	1375	7.4	497.9	82.7	80.7	1.98	1.87	Yes
H	J-489[d]	Frit[g]	C_3H_6	50	He	50	1375	5.8	499.0	81.4	77.7	1.90	1.79	Yes
I	J-490[d]	Frit[g]	C_3H_6	100			1375	6.2	495.9	80.2	74.7	1.99	1.86	Yes
J	J-491[d]	Frit[g]	C_3H_6	100			1375	9.3	497.1	79.5	77.5	2.00	1.86	Yes
K	J-262[h]	Cone[i]	C_3H_6	100			1350	8.4	497	84.0	86.1	2.01		Yes
L	OR-1849HT	Cone[j]	C_3H_6	75	He	25	1400[k]	21.5	508	79.4	74.7	1.94		Yes
M	J-481[l]	Frit[g]	C_3H_6	50	He	50	1375	7.4	497.9	82.7	80.7	1.94	1.84	No
N	J-483	Frit[g]	C_3H_6	100			1375	6.2	495.9	80.2	74.7	1.96	1.83	No
O	J-482	Frit[g]	C_3H_6	50	He	50	1375	5.8	499.0	81.4	77.7	1.88	1.78	No
P	J-487	Frit[g]	C_3H_6	100			1375	9.3	497.1	79.5	77.5	1.95	1.81	No

[a] MAPP gas is marketed by AIRCO, Inc., and consists primarily of methylacetylene and propadiene, with alkanes and stabilizers.

[b] Mean dimensions for kernel diameter, buffer, and LTI thicknesses.

[c] Mercury-gradient column measurement, both corrected and uncorrected.

[d] Irradiated in HT-30.

[e] 6.35-cm-diam (2.5-in.) cone.

[f] Batch J-488 rupture load = 5.92 lb, strong particle in the matrix-interaction experiment.

[g] 12.7-cm-diam (5.0-in.) frit.

[h] Irradiated in HRB-7, -8, and OF-1.

[i] 12.7-cm-diam (5.0-in.) cone.

[j] 2.54-cm-diam (1.0-in.) cone.

[k] Temperature measured at different point in furnace; actual bed temperature approximately 1325°C.

[l] Batch J-481 rupture load = 5.04 lb, weak particle in the matrix-interaction experiment.

Table 3. Matrix test set for OF-2.

Type	Pitch	Additive	Filler	Expected coke yield (%)	Carbonization technique
a	A-240	None	Asbury 6353	20—25	Al_2O_3
b	A-240	None	Asbury 6353	35—40	In tube
c	GAC	Proprietary		20—25	In block
d	A-240	None	Asbury 6353	15—20	Graphite flour

and matrix type c. Specimens were injected at 180°C and 5.54 MPa (800 psi) except for rods containing fertile particle types M and N, which were injected at 4.16 MPa (600 psi). Placement of fuel rod specimens in cell 1 was based upon a statistical experimental design in order to minimize interaction effects. Carbonization was done using the reference in-block technique with a heating rate of 11.5°C/min, producing a coke yield of 25.7%. All fuel rods were subjected to a final heat treatment at 1800°C in argon for 30 min. The fissile and fertile particle types and matrix type, along with the total weights of ^{235}U and ^{232}Th used in each fuel rod of specimen holder C, are presented in Appendix B.

A total of 72 fuel rod specimens were fabricated for cell 2. Two of these specimens were fabricated by LASL, and 70 were fabricated by ORNL. The two LASL-fabricated fuel rods consisted of GAC Triso-coated fissile particles, LASL-graded ZrC-coated fissile particles, GAC Biso-coated fertile particles, M-3 graphite flour, and Varcum binder. These two specimens were fabricated to nominal dimensions of 1.575 cm diam (0.620 in.) by 1.27 cm long (0.500 in.).

The 70 ORNL-fabricated specimens contained a mixture of Triso-coated fissile particles, Biso-coated fertile particles and Biso-coated carbon particles. All 70 specimens were fabricated using the slug-injection technique. Forty-six of the specimens were fabricated to nominal dimensions of 1.575 cm OD (0.620 in.) by 0.330 cm ID (0.130 in.) by 1.27 cm long (0.500 in.) using matrix type d with 28.5 wt % Asbury 6353 graphite in Ashland Oil Company A-240 petroleum pitch. They were injected at 180°C and 4.16 MPa (600 psi) and carbonized in a bed of high-fired (3000°C) graphite flour, using a heating rate of 1°C/min. Twenty-four fuel specimens were fabricated to nominal dimensions of 1.575 cm diam (0.620 in.) by 2.54 cm long (1.00 in.) using matrix types a, b, and c. Matrix types a and b are the same as those used in the 1.27-cm-long (0.500-in.) specimens, and matrix type c is General Atomic Company's proprietary matrix. The specimens were injected at 180°C and 5.54 MPa (800 psi) except for those containing unannealed fertile batches M and N, which were injected at 4.16 MPa (600 psi). Eight fuel rods of matrix type a were carbonized in a bed of Al_2O_3, using a heating rate of 6°C/min and producing a coke yield of 18.3%; eight rods of matrix type b were carbonized in-tube, using a heating rate of 2°C/min and producing a coke yield of 37.1%; and eight rods of matrix type c were carbonized in-tube, using a heating rate of 11.5°C/min and producing a coke yield of 29.8%. All 70 ORNL specimens were subjected to a final heat treatment at 1800°C in argon for 30 min.

The fissile and fertile particle types and the matrix type used, along with the total weights of ^{235}U and ^{232}Th contained in each rod in specimen holders A and B, are presented in Appendix B.

4. DESIGN ANALYSIS

This chapter is divided into two parts: (1) the thermal analysis to determine the outside diameter of each of the specimen holders and the linear heat rate necessary to maintain the desired fuel centerline temperature, and (2) the neutronic analysis to determine the ^{235}U and ^{232}Th loadings.

4.1 Thermal Analysis

The thermal analysis was aimed at determining the outside diameter of the specimen holders and the linear heat rates necessary to maintain the desired maximum fuel centerline temperatures throughout the life of the capsule. During the conceptual design stage, it was decided that the linear heat rate of all fuel rods should be about 16.4 kW/m (5.0 kW/ft) and the fuel loadings should be varied along the length of the capsule in an effort to flatten the temperature and power gradients that a single fuel loading would produce.

The first step in the thermal analysis was to perform a three-dimensional analysis of each of the fuel specimen holders at beginning-of-life (BOL) conditions. The HEATING3 code,[1] which was used for this analysis, allows the incorporation of the axial-dependent gamma heating and thermal neutron flux (fission heating) profiles as well as temperature-dependent material thermal conductivities. An iterative process was used to determine the outside diameter of the graphite fuel specimen holders and the peak linear heat rate of each of the eight fuel loadings. The relative location of each of the fuel loadings is shown in Fig. 5.

In Figs. 7 through 9, the predicted BOL axial temperature profiles through the fuel centerline and various regions of the graphite are presented for specimen holders A, B, and C, respectively. After operation began, it was discovered that the reaction rates used to determine the end fuel loadings (1A and 3C) were incorrect. This error resulted in a higher than desired linear heat rate for these two loadings and therefore a different temperature profile, which is shown in Figs. 7 and 9 for loadings 1A and 3C, respectively. This problem is discussed in greater detail in Chap. 6 of this report.

When the three-dimensional analyses were completed, a two-dimensional model was made of the capsule cross section at the peak temperature location in each fuel loading. These two-dimensional models were necessary because the radiation-induced dimensional changes vary along the length of each specimen holder, producing tapered gas gaps at end-of-life (EOL). The HEATING3 code and the three-dimensional model used initially could not handle the EOL tapered gas gaps.

The EOL analyses were based on an operating life of 9600 hr, at which time the peak damage fluence should be the desired 9×10^{21} neutrons/cm^2 ($E > 0.18$ MeV). With the use of an axial damage flux profile,[2] the appropriate fluence was determined for each of the two-dimensional models. The thermal conductivity and dimensional change data for both the fuel rods and graphite holders at EOL were determined from the references listed in Table 4.

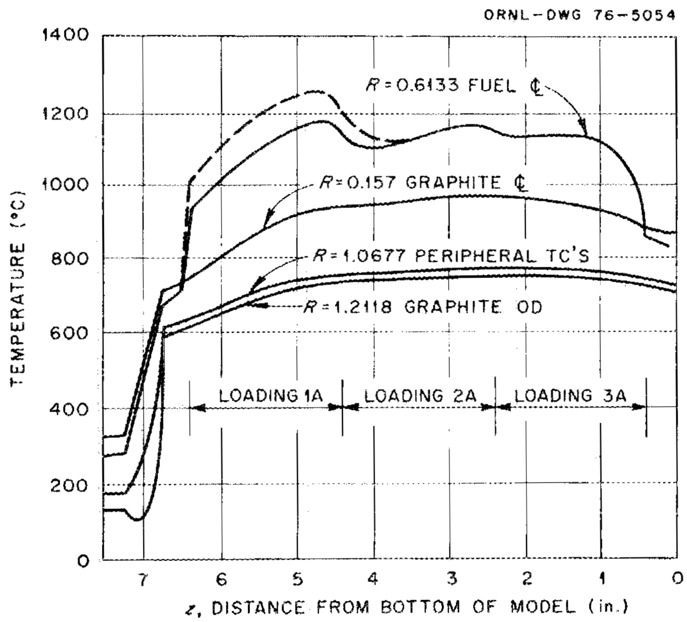


Fig. 7. Axial temperature profiles calculated by the HEATING3 program for OF-2 specimen holder A at beginning of life. Solid lines represent design conditions; dashed line represents fuel centerline temperature (1 in. = 2.54 cm).

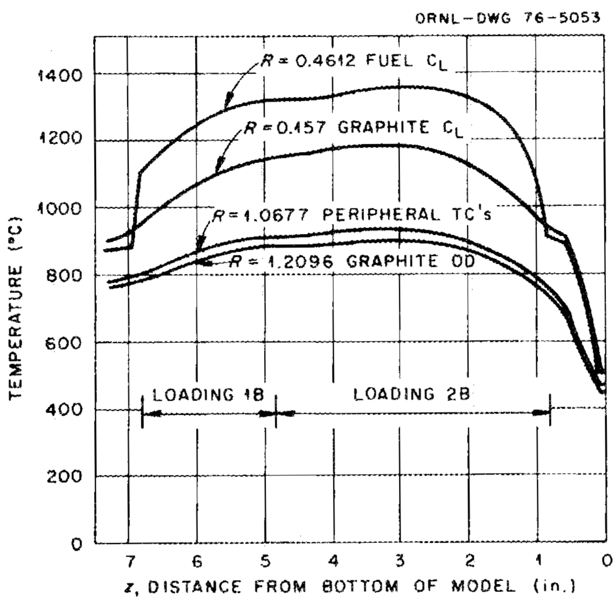


Fig. 8. Axial temperature profiles calculated by the HEATING3 program for OF-2 specimen holder B at beginning of life (1 in. = 2.54 cm).

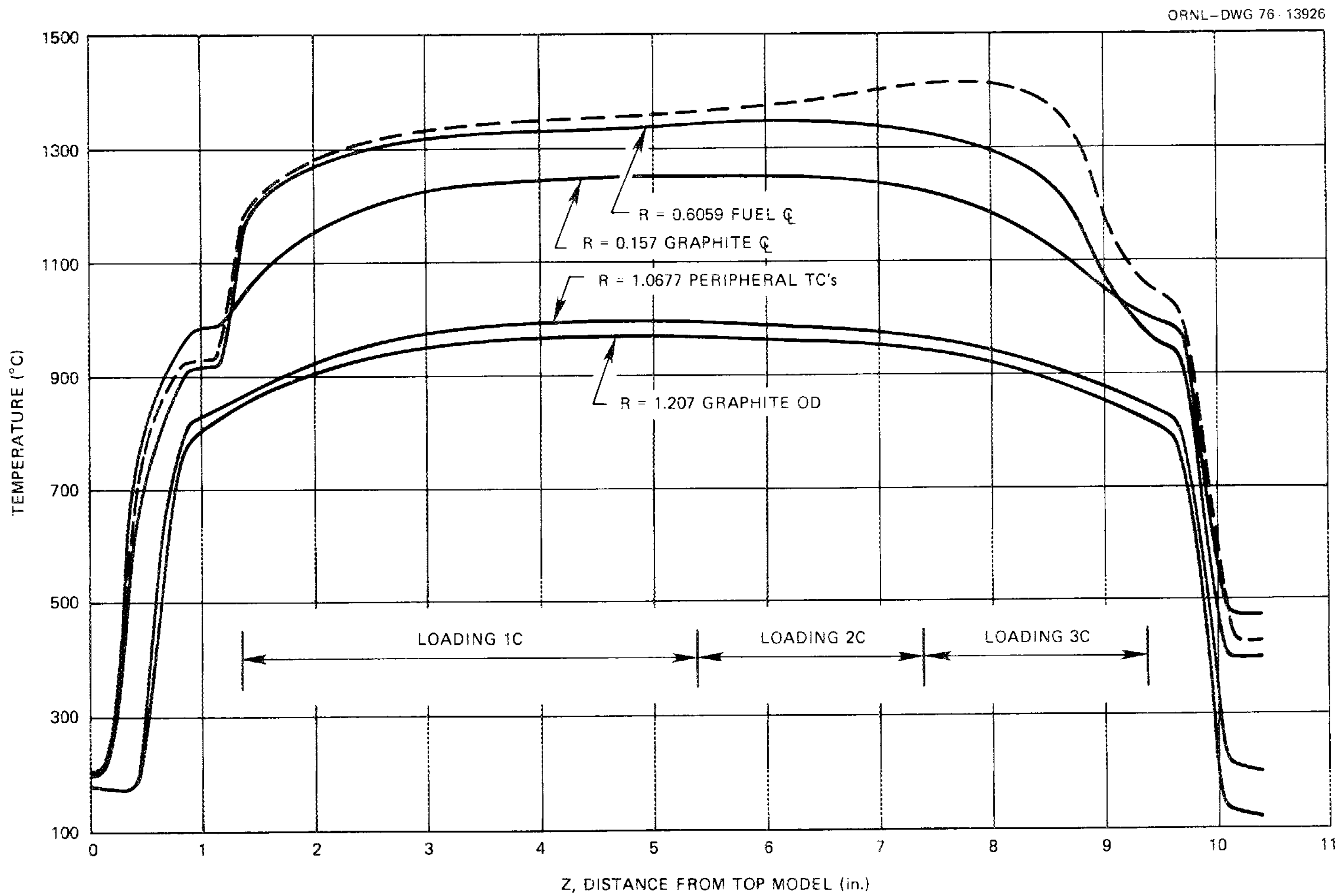


Fig. 9. Axial temperature profiles calculated by the HEATING 3 program for OF-2 specimen holder C at beginning of life. Solid lines represent design conditions; dashed line represents fuel centerline temperature (1 in. = 2.54 cm).

Table 4. References used to determine various parameters at EOL conditions in capsule OF-2

Parameter	Reference
H-451 graphite thermal conductivity	R. J. Price, *Review of the Thermal Conductivity of Nuclear Graphite Under HTGR Conditions*, GA-A12615, pp. 60–61 (Sept. 7, 1973)
Fuel thermal conductivity	W. R. Johnson, *Thermal Conductivity of Large HTGR Fuel Rods*, GA-A12910, pp. 21–23 (Mar. 15, 1974)
H-451 graphite dimensional change and thermal expansivity	R. J. Price and L. A. Beavan, *Final Report on Graphite Irradiation Test OG-1*, GA-A13089 (Aug. 1, 1974)
Fuel rod dimensional change (holders A and B)	Personal communication with E. L. Long, Jr., PIE data from HRB-8 Triso-Biso fuel rods
Fuel rod dimensional change (holder C)	Personal communication with J M Robbins, PIE data from HT-24 and -25

After the EOL geometry was determined for each of the 2-D models, an iteration process was again used to find the linear heat rate necessary to maintain the design fuel centerline temperature. A summary of BOL and EOL fission linear heat rates, heat transfer gaps, and maximum temperatures for capsule OF-2 is presented in Table 5.

4.2 Neutronic Analysis

The ^{235}U and ^{232}Th loadings were calculated from the total reaction rates and neutron fluxes provided[2] for the E-7 position of the ORR core. The ^{235}U loadings were calculated from the required BOL linear heat rates determined in the three-dimensional thermal analysis. The FABGEN code[3] was used in an iterative process to determine the ^{232}Th loading necessary to produce EOL linear heat rates to maintain the design fuel centerline temperatures as determined by the two-dimensional thermal analyses. The resultant fuel loadings are presented in Table 6.

Table 5. Summary of BOL and EOL fission powers, heat transfer gaps, and maximum temperatures for capsule OF-2

Graphite crucible	Fuel loading	Linear heat rate (kW/m)	Radial gaps (in.)[a]: Fuel to crucible, Room temp.	Radial gaps (in.)[a]: Fuel to crucible, Design temp.	Radial gaps (in.)[a]: Crucible to primary tube, Room temp.	Radial gaps (in.)[a]: Crucible to primary tube, Design temp.	Peak temperature[b] (°C): Fuel centerline	Peak temperature[b] (°C): Crucible centerline	Peak temperature[b] (°C): Crucible peripheral TC
				BOL conditions					
A	1A	19.7	0.0040	0.0036	0.0119	0.0115	1170	935	745
	2A	16.4	0.0040	0.0036	0.0119	0.0115	1160	970	770
	3A	16.4	0.0040	0.0036	0.0119	0.0115	1135	965	770
B	1B	16.4	0.0040	0.0036	0.0155	0.0137	1320	1140	905
	2B	16.4	0.0040	0.0036	0.0155	0.0137	1350	1180	950
C	1C	16.4	0.0035	0.0028	0.0184	0.0163	1330	1250	990
	2C	18.0	0.0035	0.0028	0.0184	0.0163	1345	1250	990
	3C	19.7	0.0035	0.0028	0.0184	0.0163	1270	1150	925
				EOL conditions					
A	1A	12.1		0.0100		0.0125	1120	940	675
	2A	9.8		0.0133		0.0154	1150	980	720
	3A	9.8		0.0149		0.0168	1145	980	730
B	1B	9.5		0.0159		0.0253	1350	1210	930
	2B	8.9		0.0159		0.0253	1350	1210	940
C	1C	10.2		0.0081		0.0298	1330	1255	1020
	2C	11.5		0.0092		0.0285	1340	1255	1000
	3C	13.1		0.0109		0.0272	1265	1195	915

[a] 1 in. = 25.4 mm.

[b] Peak-temperature data for BOL were obtained from three-dimensional mockups, while those for EOL were obtained from two-dimensional mockups.

Table 6. Design fuel loadings for capsule OF-2

Specimen holder	Loading No.	Loading (g/in.)	
		^{235}U	^{232}Th
A	1A	0.238	3.98
	2A	0.135	2.61
	3A	0.106	2.19
B	1B	0.0815	1.53
	2B	0.0691	1.26
C	1C	0.0669	1.39
	2C	0.0795	1.73
	3C	0.182	3.95

5. EXPERIMENTAL ASSEMBLY FABRICATION

A detailed description of the experimental assembly fabrication procedure is presented in Engineering Document Q-11552-RB-10-S-0. A general description of the fabrication process is given below.

The copper bulkhead separating cells 1 and 2 was brazed into the primary containment vessel, and the thermocouples, gas lines, and guide tubes were brazed into the primary containment end caps. The Johnson noise thermometers and the Pt-Mo thermocouples were brazed into their respective guide tubes. The components of each cell were then loaded on their respective primary bulkhead subassemblies, and the primary containment vessel was slid over the cell components and welded to the primary bulkhead. The internal components of cells 1 and 2 are shown in Figs. 10 and 11, respectively.

The gas lines and thermocouple leads from the bottom cell were bent into position, and the secondary containment vessel was slid over the primary vessel. As this was being done, the leads and gas lines were fed

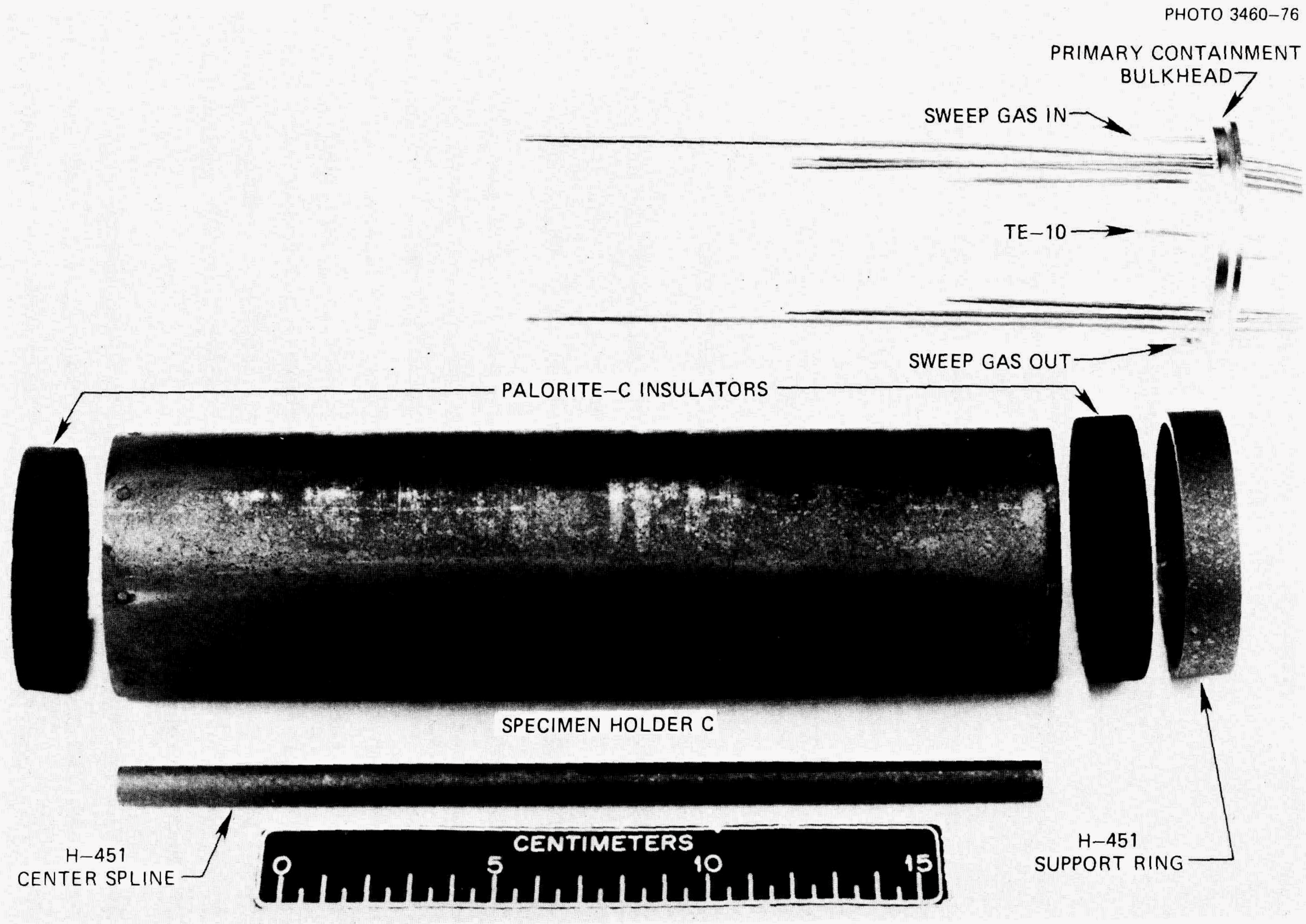


Fig. 10. Components of cell 1 in capsule OF-2.

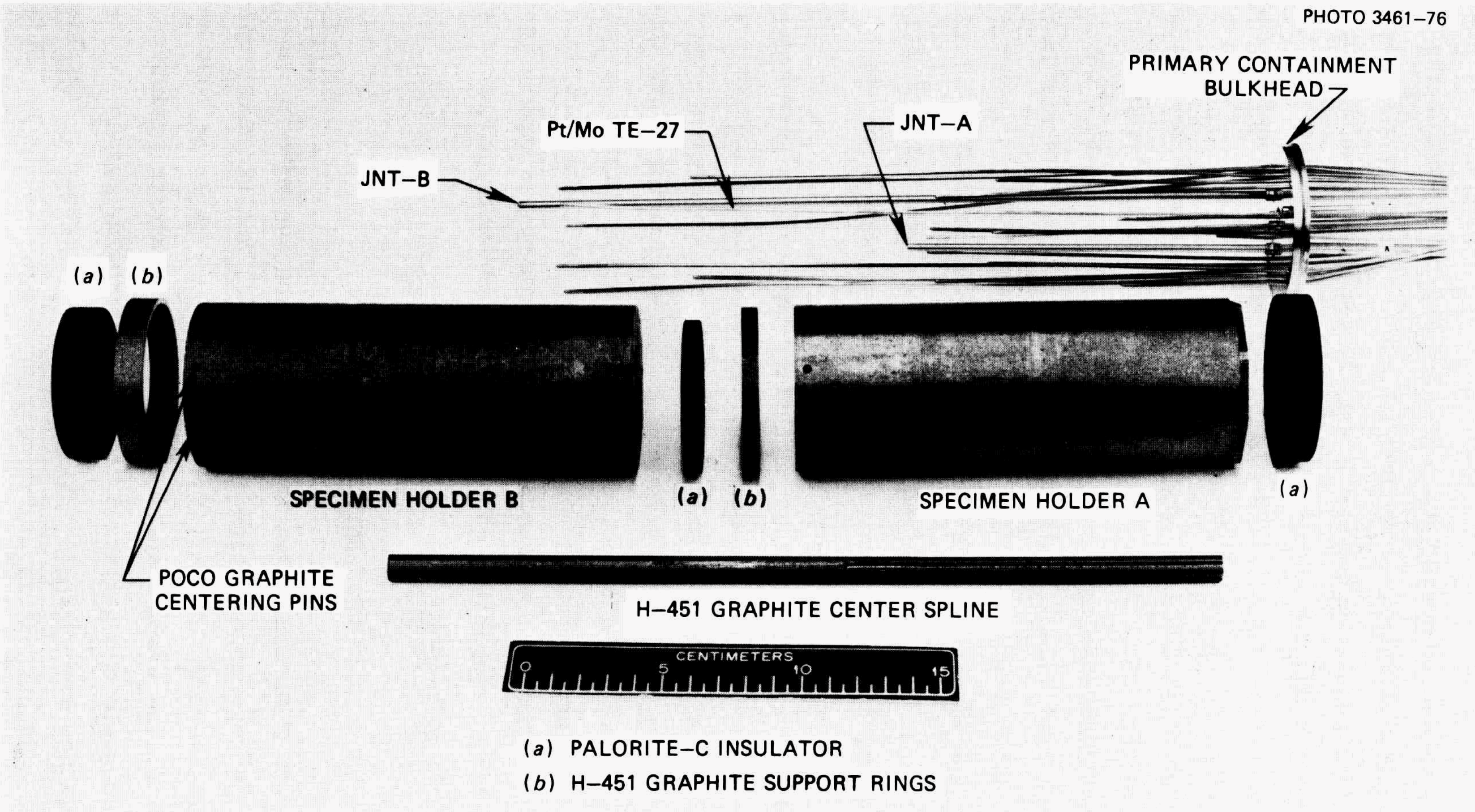


Fig. 11. Components of cell 2 in capsule OF-2.

through the 1.27-cm-OD (0.50-in.) stainless steel tube that carried them back into the secondary vessel above the primary bulkhead for the top cell.

Next, an approximately 61-cm-long (2.0-ft) adapter section was welded to the secondary containment vessel, and the gas lines and thermocouple leads were fed through the secondary containment bulkhead, which was then welded to the adapter section. The gas lines and thermocouple leads were then silver soldered to the secondary bulkhead.

At this point in the assembly, it was requested that the Johnson noise thermometers (JNT) be removed because of problems discovered during the postirradiation examination of HTGR-HFIR capsule HRB-10,[4] which was in progress at that time. The decision to remove the JNTs was based on recognition of two problems: (1) the Mo-Re sheath outside diameter was too large to accommodate the differential swelling between the fuel rods and graphite specimen holders; and (2) there was a possibility of a chemical reaction occurring between the Mo-Re sheath and the carbon-coated fuel causing fuel failure.

The sensors were recovered intact after three holes were made in the completed secondary containment. These three holes are shown in Fig. 12 along with the sealed guide tubes and patches used to cover the holes. The recovered sensors were used in out-of-reactor tests to explore parallel processing of noise voltage and noise current signals and the chemical and thermal stability of the Pt-Mo thermocouples.

After the JNTs were removed and the holes in the secondary containment were patched, completion of the lead pipe assembly proceeded without any unusual problems.

6. INITIAL OPERATION

Capsule OF-2 was installed in the ORR during the week of June 16 to 20, 1975. The reactor was started up on June 21, and the sweep gas to both cells was kept at 100% helium until June 23. While at 100% helium sweep gas flow, the thermocouples measuring the graphite periphery were indicating very close to expected temperatures (below design values) for all fuel loadings except 1A and 3C. Peripheral temperatures at loadings 1A and 3C were significantly higher than expected. At the beginning of

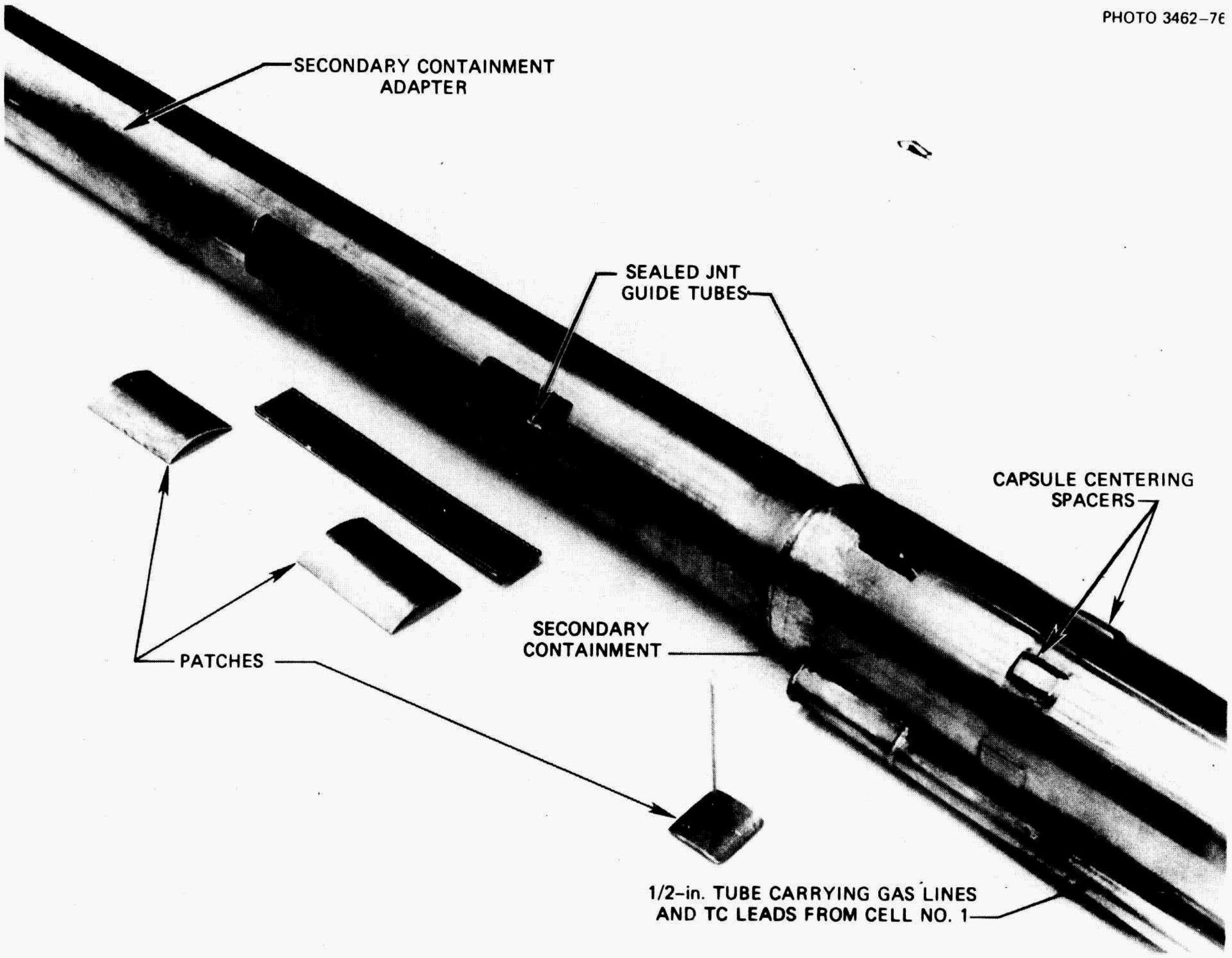


Fig. 12. Removal of Johnson noise thermometers (JNTs) from the OF-2 capsule (1 in. = 2.54 cm).

a fuel cycle, the temperature of fuel loading 1A, which is located at the top of the capsule, was anticipated to be lower than design temperature. This was based on the fact that at the beginning of a fuel cycle the flux profile is peaked toward the bottom of the reactor core, while the operating temperatures were calculated with a time-averaged flux profile.

On June 23, after having operated with 100% helium flow for about 60 hr, neon was added to the sweep gas in an effort to obtain the desired operating temperatures. The amount of neon added to cell 1 was less than the design value because of the high peripheral graphite temperatures in loading 3C. In cell 2, the sweep gas mixture was set close to the design values: 60% helium and 40% neon, with good agreement between thermocouple readings and predicted temperatures. The operating temperature of loading 1A was again higher than anticipated for the same reasons described above.

An investigation of the higher temperatures at the two end fuel loadings revealed that the design information that was used to determine fuel loadings 1A and 3C was incorrect. It was found that the reaction rates used to calculate fuel loadings at the capsule ends were actually higher than the design values. When the corrected reaction rates and the as-built fuel loadings were used, it was found that loadings 1A and 3C were operating at linear heat rates about 20% higher than desired.

A new thermal analysis was initiated to determine the effect of this increased heat-generation rate and to compare calculated and observed temperatures after 175 hr of irradiation. The 175-hr time was chosen because it occurred approximately halfway through the first ORR fuel cycle and should therefore reflect typical time-averaged operating conditions for an entire reactor fuel cycle. After 175 hr of irradiation, the maximum damage fluence in the fuel specimen holders was 2.5×10^{20} neutrons/cm^2 ($E > 0.18$ MeV), which is not high enough to cause any significant dimensional changes but is high enough to cause some change in the thermal conductivity of the H-451 graphite fuel specimen holders. Two analyses were performed; the first utilized the calculated thermal conductivity of graphite as presented by Price,[5] and the second was performed using 85% of the thermal conductivity presented by Price. A comparison of the second analysis with observed temperatures is presented in Table 7.

Table 7. Comparison of calculated and observed temperatures in capsule OF-2 after 175 hr irradiation

Fuel loading	Temperatures predicted with HEATING3 code (°C)				Observed temperatures (°C)		
	Fuel centerline	Graphite		ΔT graphite centerline to periphery	Graphite		ΔT graphite centerline to periphery
		Centerline	Periphery		Centerline	Periphery	
				Specimen holder A			
1A	1290	1052	785	267	1060	771	289
2A	1187	1022	776	246	1021	767	254
3A	1155	998	765	233	1000[a]	752	248
				Specimen holder B			
1B	1336	1177	893	284	*b*	906	*b*
2B	1380	1226	922	304	1233	930	303
				Specimen holder C			
1C	1260	1200	917	283	*b*	907	*b*
2C	1295	1232	950	282	*b*	910	*b*
3C	1357	1278	962	316	*b*	961	*b*
9.48[c]		1040			1010		
10.105[d]		533[d]			521[d]		

[a]The temperature at this location was measured by both a C/A and a Pt-Mo thermocouple. The reported 1000°C was indicated by the C/A thermocouple, while the Pt-Mo thermocouple indicated 1060°C.

[b]There are no thermocouples located at the graphite centerline for these fuel loadings.

[c]Distance from copper bulkhead dividing OF-2 into compartments.

[d]This thermocouple is located on the inside surface of the stainless steel primary containment bulkhead.

The first case produced very good agreement with observed graphite periphery temperatures but poor agreement with observed graphite centerline temperatures. In the second case, where the graphite thermal conductivity was reduced by 15%, agreement with observed graphite centerline temperatures was very good without significantly changing the graphite periphery temperature agreement. Perhaps a more accurate comparison between calculated and observed temperatures is the ΔT between the graphite centerline and the periphery. Table 7 shows that this ΔT agreement between the second case and observed temperatures is no worse than 8%.

During the thermal analysis, it was found that the Pt-Mo thermocouple used to measure the graphite centerline temperature of fuel loading 3A was indicating a temperature approximately 60° C higher than that calculated. This difference between the Pt-Mo and C/A thermocouples at this location was noted earlier. The real temperature was assumed to be an average of the two. However, as can be seen in Table 7, the C/A thermocouple agrees very well with the calculated temperatures and the calculated axial temperature profile. The other Pt-Mo thermocouple which measures the graphite centerline temperature in fuel loading 2B agrees very well with the predicted temperature.

As a result of the higher heat-generation rate in fuel loading 1A, temperature control in cell 2 became more complex. At the beginning of a reactor fuel cycle, the maximum fuel centerline temperature of specimen holder B can be brought to 1350°C with the maximum fuel centerline temperature of specimen holder A at about 1150°C. As the reactor fuel cycle progresses and the control rods are withdrawn, the fuel centerline temperature of holder A continues to rise and, depending on the length of the cycle, could also reach 1350°C. A decision was made to allow the fuel centerline temperature of holder A to reach a maximum of 1200°C and then adjust the sweep gas mixture to maintain holder A at 1200°C, thus causing holder B temperatures to decrease.

The higher heat-generation rate of fuel loading 3C has also forced a compromise in the operating temperatures in cell 1. The maximum fuel centerline temperature in this cell occurs in loading 3C, and it is maintained at 1350°C, causing loadings 1C and 2C to operate at significantly lower than design temperatures.

Sweep gas samples are taken once per week to determine the release-to-birth rate ratios (R/B) for five fission gas isotopes. The results of these analyses through the first cycle of operation are presented in Table 8. Note that the first sample taken in each cell was with the sweep gas at 100% helium, and therefore operating temperatures are significantly lower for these samples.

A complete operating history for all thermocouples during the first cycle of operation is presented in Appendix C.

Table 8. R/B ratios for the first cycle of operation of capsule OF-2

Cell No.	Sample No.	Date	Time	Operating time (hr)	Estimated maximum fuel centerline temperature (°C)			R/B ratios (× 10^{-5})				
					Holder A	Holder B	Holder C	^{85m}Kr	^{87}Kr	^{88}Kr	^{133}Xe	^{135}Xe
1	1-A-1	6-23-75	0949	53.7			1230	1.0	0.63	0.50	1.2	0.35
	1-A-3	6-24-75	1112	79.1			1350	2.8	1.9	1.7	5.4	0.76
	1-A-5	7-2-75	1009	270			1340	1.7	0.60	1.0	2.2	0.75
	1-A-7	7-9-75	1330	436			1350	3.1	1.0	0.71	3.2	0.60
	1-A-9	7-18-75	1235	652			1340	1.9	1.4	1.1	3.1	0.75
	1-A-11	7-25-75	0855	811			1360	3.0	0.88		4.3	0.62
	1-A-13	8-6-75	1035	1095			1350	2.2	1.2	1.0	5.1	0.19
2	2-A-2	6-23-75	1001	53.9	990	1190		1.1	0.46	0.35	1.3	0.42
	2-A-4	6-24-75	1127	79.3	1170	1350		15	2.0	3.2	33	1.4
	2-A-6	7-2-75	1020	270	1280	1360		21	7.7	8.9	57	3.9
	2-A-8	7-9-75	1341	436	1190	1340		10	4.4	5.8	57	1.9
	2-A-10	7-18-75	1252	652	1170	1350		9.8	4.1	2.3	36	1.1
	2-A-12	7-25-75	0906	811	1225	1340		7.5	5.0	5.7	56	3.1
	2-A-14	8-6-75	1040	1095	1210	1300		8.8	4.0	4.7	44	1.2

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Appendix A

OF-2 FLUX MONITOR WEIGHTS

Table A-1. OF-2 Flux monitor weights

Monitor package No.	Hole No.	Position No.	V-Co (mg)	5-mil Fe (mg)	20 mil Fe (mg)
1	1	1	4.016	2.643	8.880
2	1	2	3.896	2.590	10.014
3	1	3	3.686	2.634	11.923
4	1	4	4.026	2.638	12.610
5	1	5	3.657	2.614	11.530
6	2	1	3.888	2.634	11.145
7	2	2	3.544	2.565	10.586
8	2	3	3.531	2.494	10.805
9	3	1	3.792	2.654	10.240
10	3	2	3.866	2.649	10.245
11	3	3	4.002	2.466	8.891
12	4	1	3.379	2.610	9.778
13	4	2	3.465	2.645	10.426
14	4	3	3.855	2.618	8.059
15	5	1	3.635	2.674	10.309
16	5	2	3.602	2.627	9.747
17	5	3	3.505	2.653	10.270
18	6	4	4.817	2.627	8.758
19	6	5	3.827	2.617	10.585
20	6	6	3.975	2.635	10.580
21	7	4	4.417	2.633	9.227
22	7	5	3.456	2.612	8.760
23	7	6	3.804	2.616	10.247
24	8	4	3.199	2.670	10.310
25	8	5	4.037	2.640	11.184
26	8	6	3.976	2.472	9.919
27	9	4	4.691	2.641	12.101
28	9	5	3.400	2.533	12.426
29	9	6	3.986	2.600	9.892
30	10	7	3.654	2.630	9.241
31	10	8	4.431	2.634	11.540
32	10	9	3.771	2.591	10.822

Appendix B

DESCRIPTION OF FUEL RODS IN THE OF-2 CAPSULE

Table B-1. Fuel rods for OF-2 irradiation capsule

Specimen location[a]	Length (in.)[b]	Particle type		Matrix type[e]	^{235}U (g)	^{232}Th (g)
		Fissile[c]	Fertile[d]			
A-1-1	1.00	14	M	b	0.2380	3.980
-2	1.00	13	M	a	0.2380	3.980
-3	1.00	14	G	a	0.1350	2.610
-4	1.00	14	G	c	0.1350	2.610
-5	1.00	13	G	b	0.1060	2.190
-6	1.00	13	M	c	0.1060	2.190
A-2-1	1.00	14	M	a	0.2380	3.980
-2	1.00	14	G	b	0.2380	3.980
-3	1.00	13	M	b	0.1350	2.610
-4	1.00	13	G	c	0.1350	2.610
-5	1.00	14	M	c	0.1060	2.190
-6	1.00	13	G	a	0.1060	2.190
A-3-1	0.50	12	M	d	0.1190	1.990
-2	0.50	2	I	d	0.1190	1.990
-3	0.50	11	H	d	0.1190	1.990
-4	0.50	2	G	d	0.1190	1.990
-5	0.50	4	K	d	0.0675	1.805
-6	0.50	6	J	d	0.0675	1.805
-7	0.50	8	G	d	0.0675	1.805
-8	0.50	10	H	d	0.0675	1.805
-9	0.50	4	I	d	0.0530	1.095
-10	0.50	2	C	d	0.0530	1.095
-11	0.50	8	A	d	0.0530	1.095
-12	0.50	12	B	d	0.0530	1.095
A-4-1	0.50	9	G	d	0.1190	1.990
-2	0.50	1	H	d	0.1190	1.990
-3	0.50	9	I	d	0.1190	1.990
-4	0.50	1	J	d	0.1190	1.990
-5	0.50	3	A	d	0.0675	1.805
-6	0.50	5	B	d	0.0675	1.805
-7	0.50	7	C	d	0.0675	1.805
-8	0.50	11	D	d	0.0675	1.805
-9	0.50	3	E	d	0.0530	1.095
-10	0.50	1	F	d	0.0530	1.095
-11	0.50	7	A	d	0.0530	1.095
-12	0.50	LASL	LASL	LASL	0.0530	1.095
B-1-1	1.00	13	M	b	0.0814	1.530
-2	1.00	13	G	a	0.0814	1.530
-3	1.00	13	G	c	0.0690	1.260
-4	1.00	14	M	a	0.0690	1.260
-5	1.00	14	G	b	0.0690	1.260
-6	1.00	14	M	c	0.0690	1.260
B-2-1	1.00	13	S	b	0.0814	1.530
-2	1.00	14	M	b	0.0814	1.530
-3	1.00	14	G	a	0.0690	1.260
-4	1.00	13	M	a	0.0690	1.260
-5	1.00	13	M	c	0.0690	1.260
-6	1.00	14	G	c	0.0690	1.260

Table B-1 (continued)

Specimen location[a]	Length (in.)[b]	Particle type		Matrix type[e]	^{235}U (g)	^{232}Th (g)
		Fissile[c]	Fertile[d]			
B-3-1	0.50	12	A	d	0.0407	0.765
-2	0.50	2	B	d	0.0407	0.765
-3	0.50	4	C	d	0.0407	0.765
-4	0.50	6	D	d	0.0407	0.765
-5	0.50	8	E	d	0.0345	0.630
-6	0.50	10	F	d	0.0345	0.630
-7	0.50	2	L	d	0.0345	0.630
-8	0.50	4	G	d	0.0345	0.630
-9	0.50	3	H	d	0.0345	0.630
-10	0.50	8	I	d	0.0345	0.630
-11	0.50	2	J	d	0.0345	0.630
-12	0.50	4	K	d	0.0345	0.630
B-4-1	0.50	11	G	d	0.0407	0.765
-2	0.50	1	H	d	0.0407	0.765
-3	0.50	3	I	d	0.0407	0.765
-4	0.50	5	J	d	0.0407	0.765
-5	0.50	7	A	d	0.0345	0.630
-6	0.50	9	B	d	0.0345	0.630
-7	0.50	1	C	d	0.0345	0.630
-8	0.50	3	D	d	0.0345	0.630
-9	0.50	5	E	d	0.0345	0.630
-10	0.50	7	F	d	0.0345	0.630
-11	0.50	1	A	d	0.0345	0.630
-12	0.50	LASL	LASL	LASL	0.0345	0.630
C-1-1	2.00	13	N	c	0.1338	2.780
-2	2.00	13	I	c	0.1338	2.780
-3	2.00	14	G	c	0.1590	3.460
-4	2.00	13	O	c	0.3640	7.900
C-2-1	2.00	15	O	c	0.1338	2.780
-2	2.00	13	G	c	0.1338	2.780
-3	2.00	15	H	c	0.1590	3.460
-4	2.00	15	P	c	0.3640	7.900
C-3-1	2.00	14	M	c	0.1338	2.780
-2	2.00	14	P	c	0.1338	2.780
-3	2.00	13	J	c	0.1590	3.460
-4	2.00	14	M	c	0.3640	7.900
C-4-1	2.00	15	H	c	0.1338	2.780
-2	2.00	14	J	c	0.1338	2.780
-3	2.00	13	I	c	0.1590	3.460
-4	2.00	13	N	c	0.3640	7.900

[a]Specimen holder designation — hole number — specimen position from top.

[b]1 in. = 25.4 mm.

[c]Fissile particle type described in Table 1 of text.

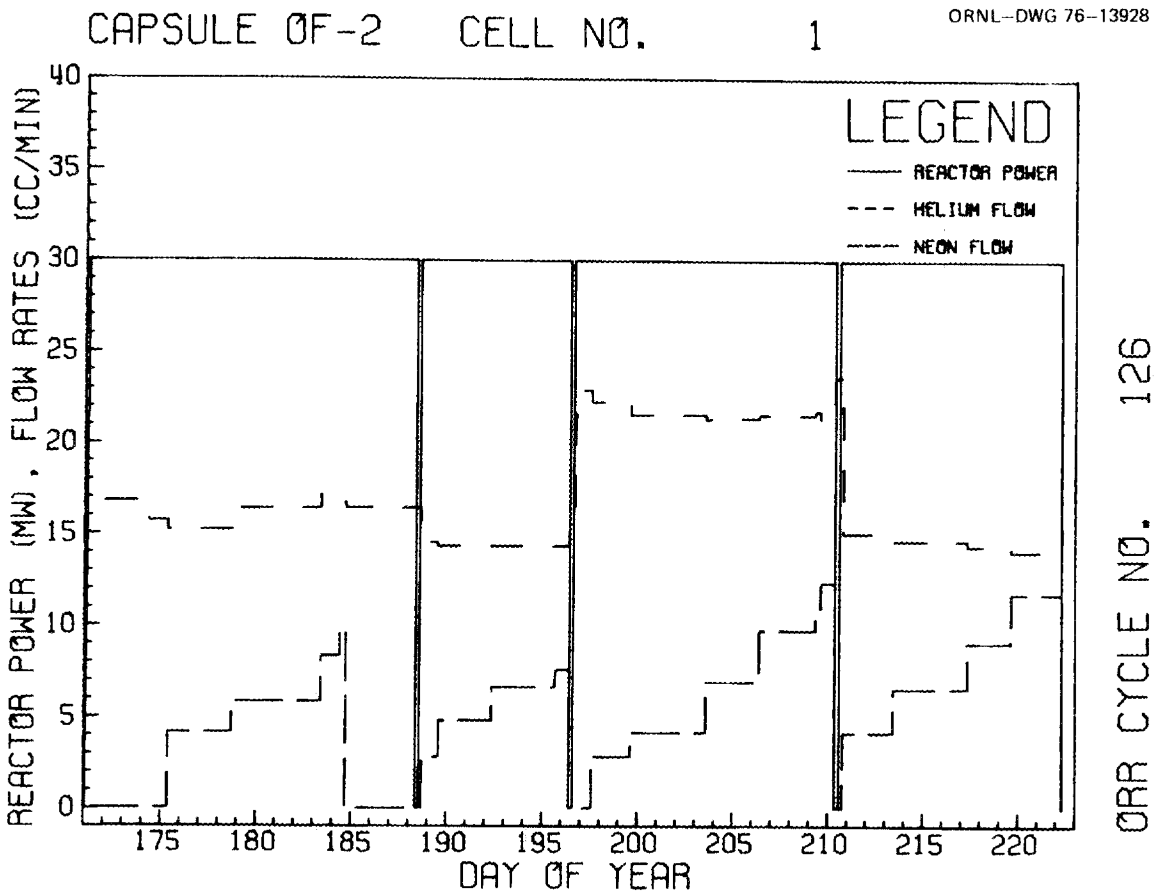
[d]Fertile particle type described in Table 2 of text.

[e]Matrix type described in Table 3 of text.

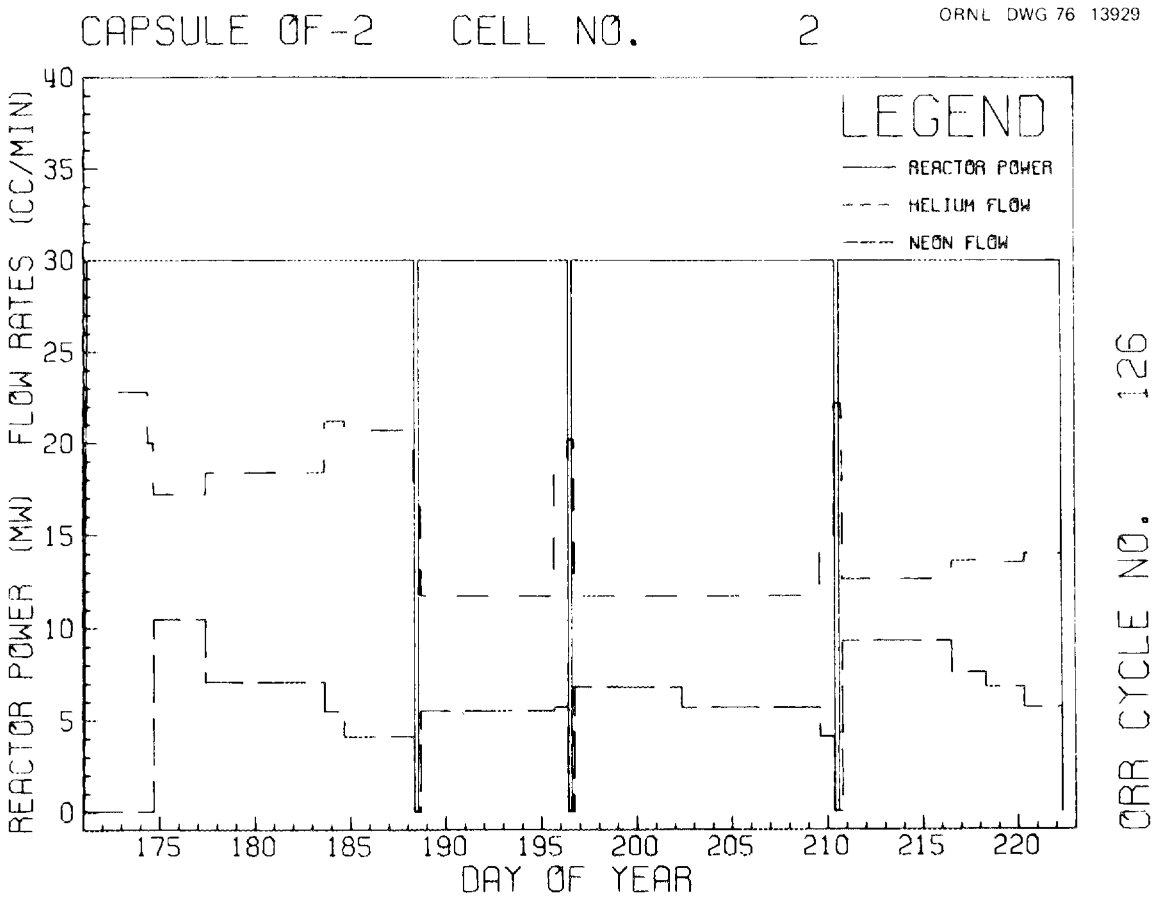
Appendix C

THERMOCOUPLE OPERATING TEMPERATURE HISTORY FOR OF-2 DURING CYCLE 126

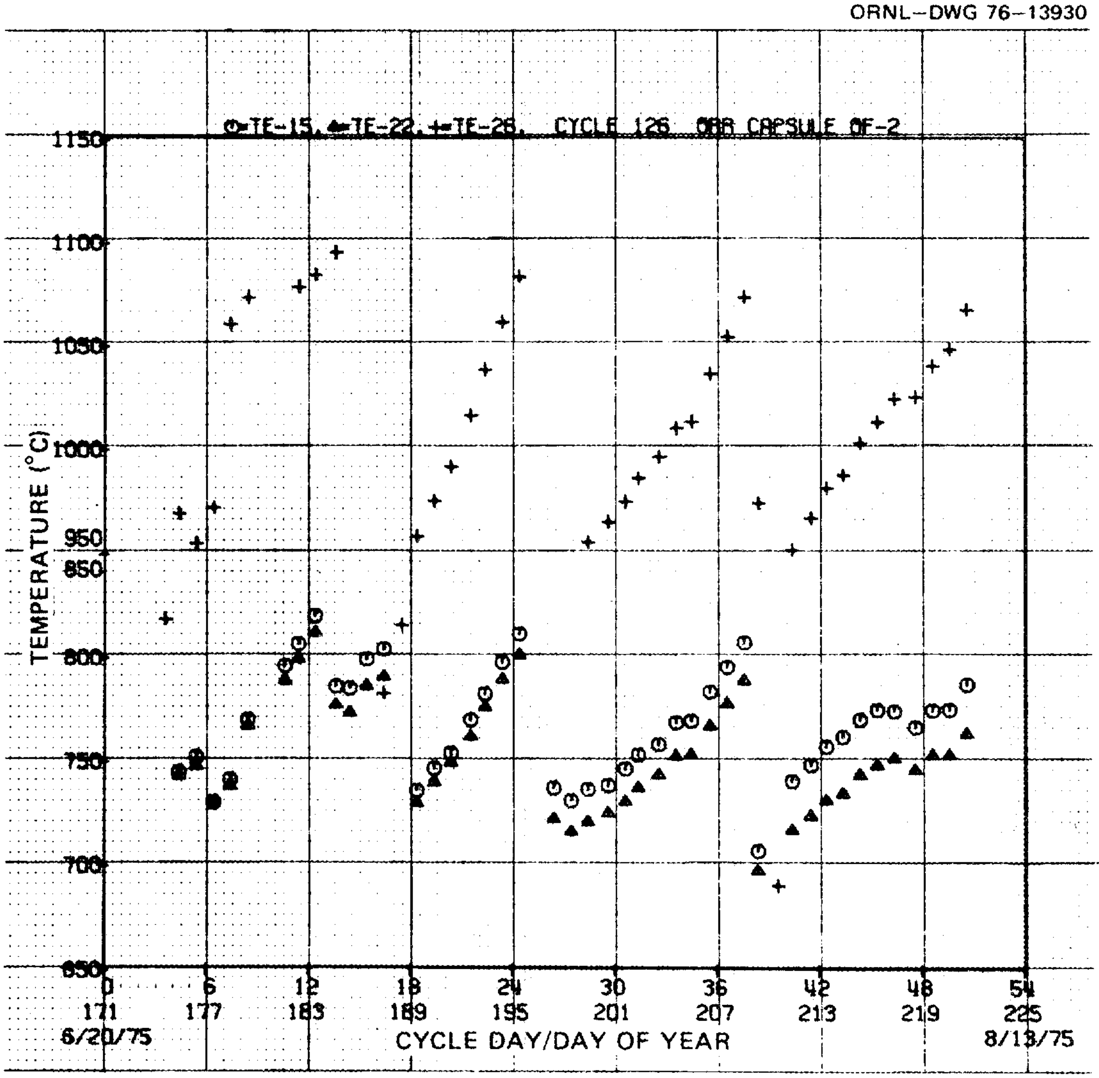
ORNL–DWG 76–13928

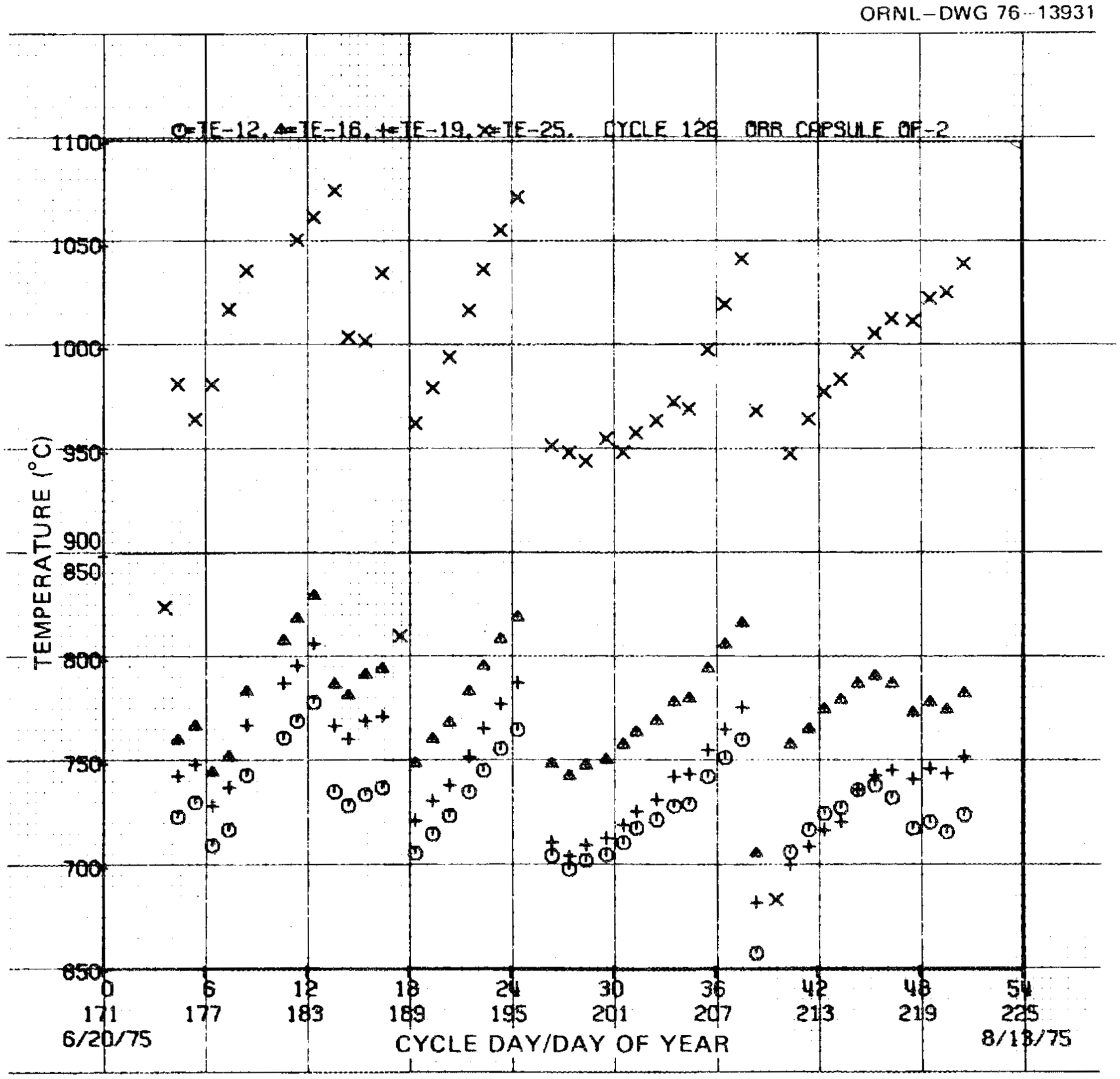


ORNL DWG 76 13929

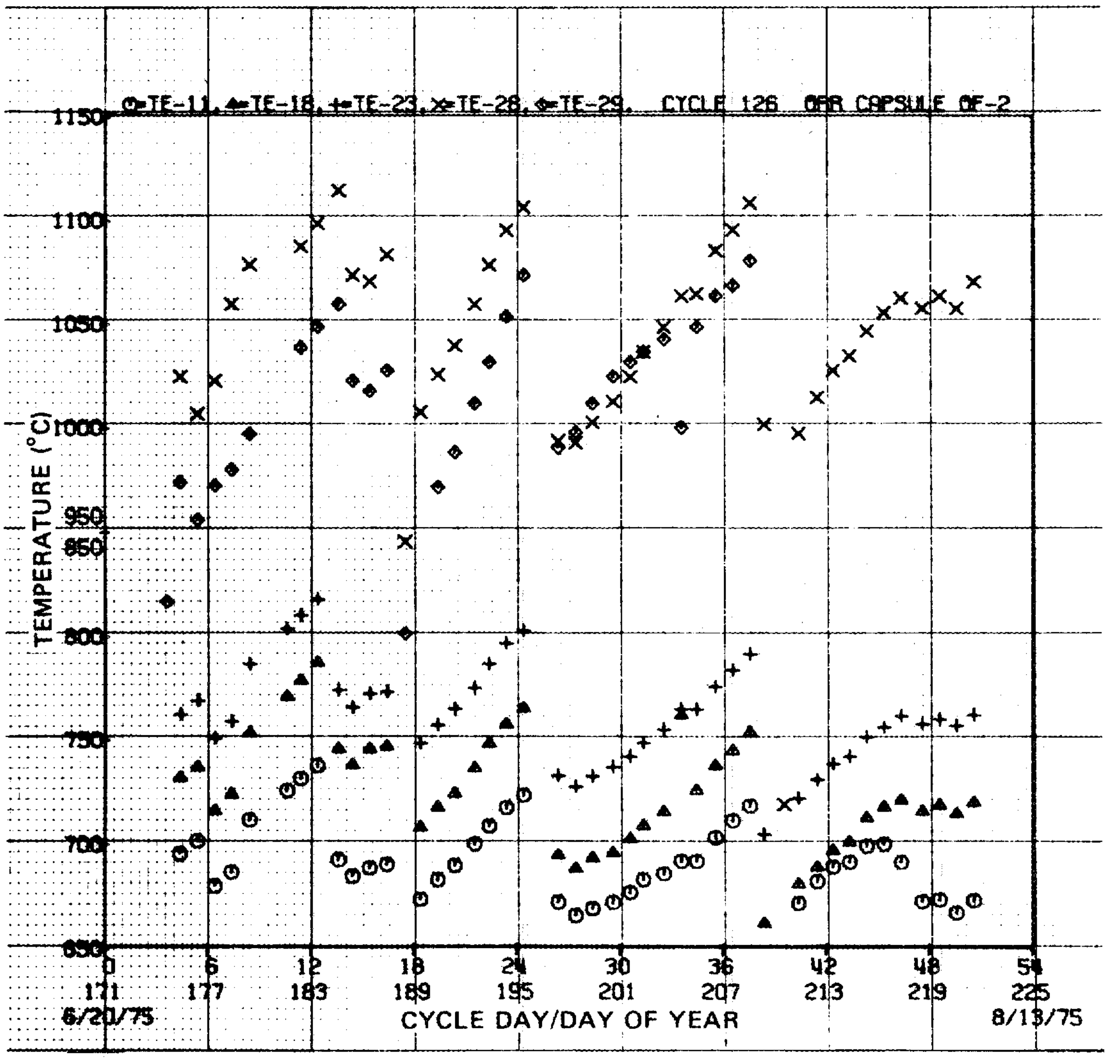


ORNL-DWG 76-13930

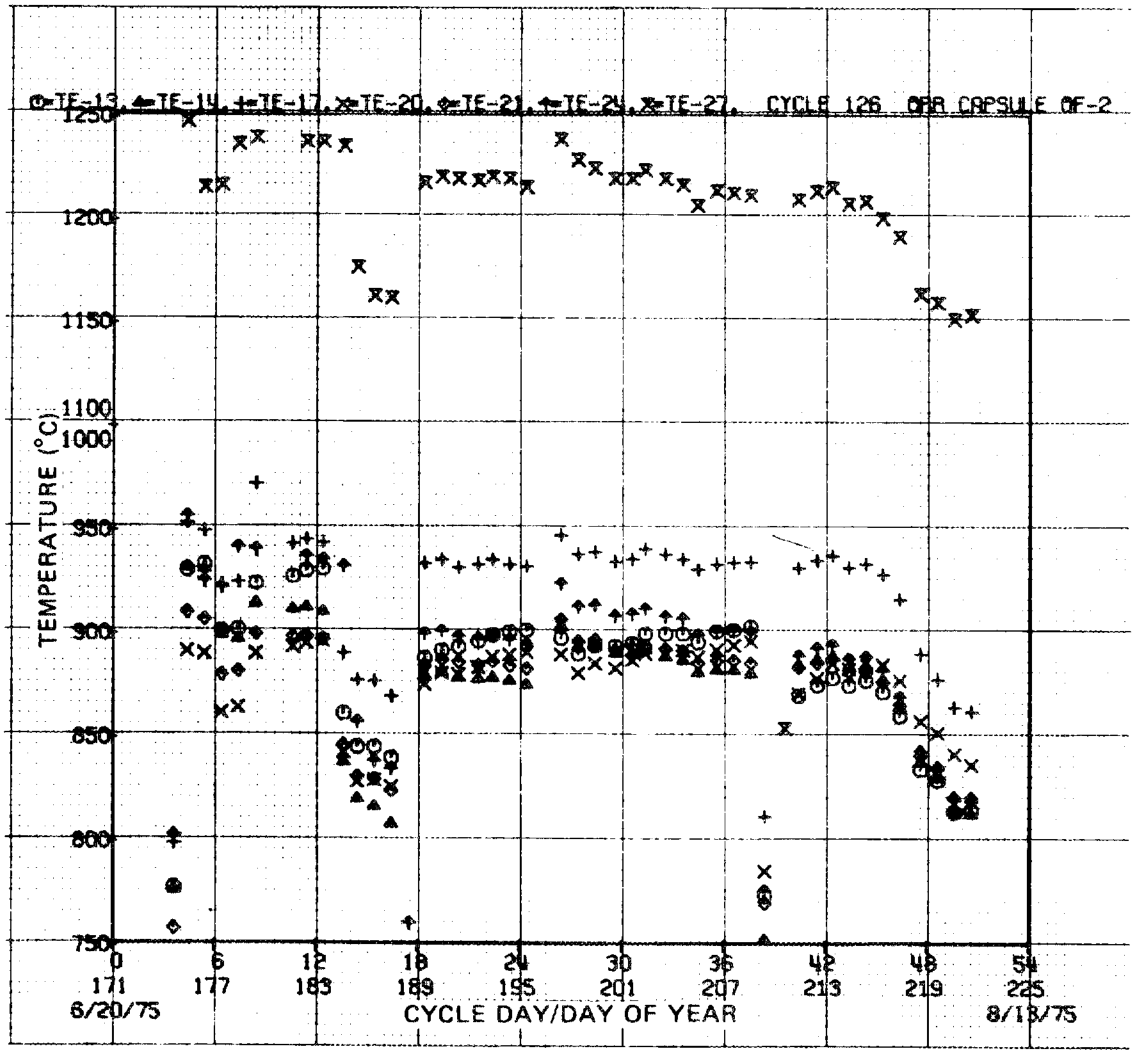


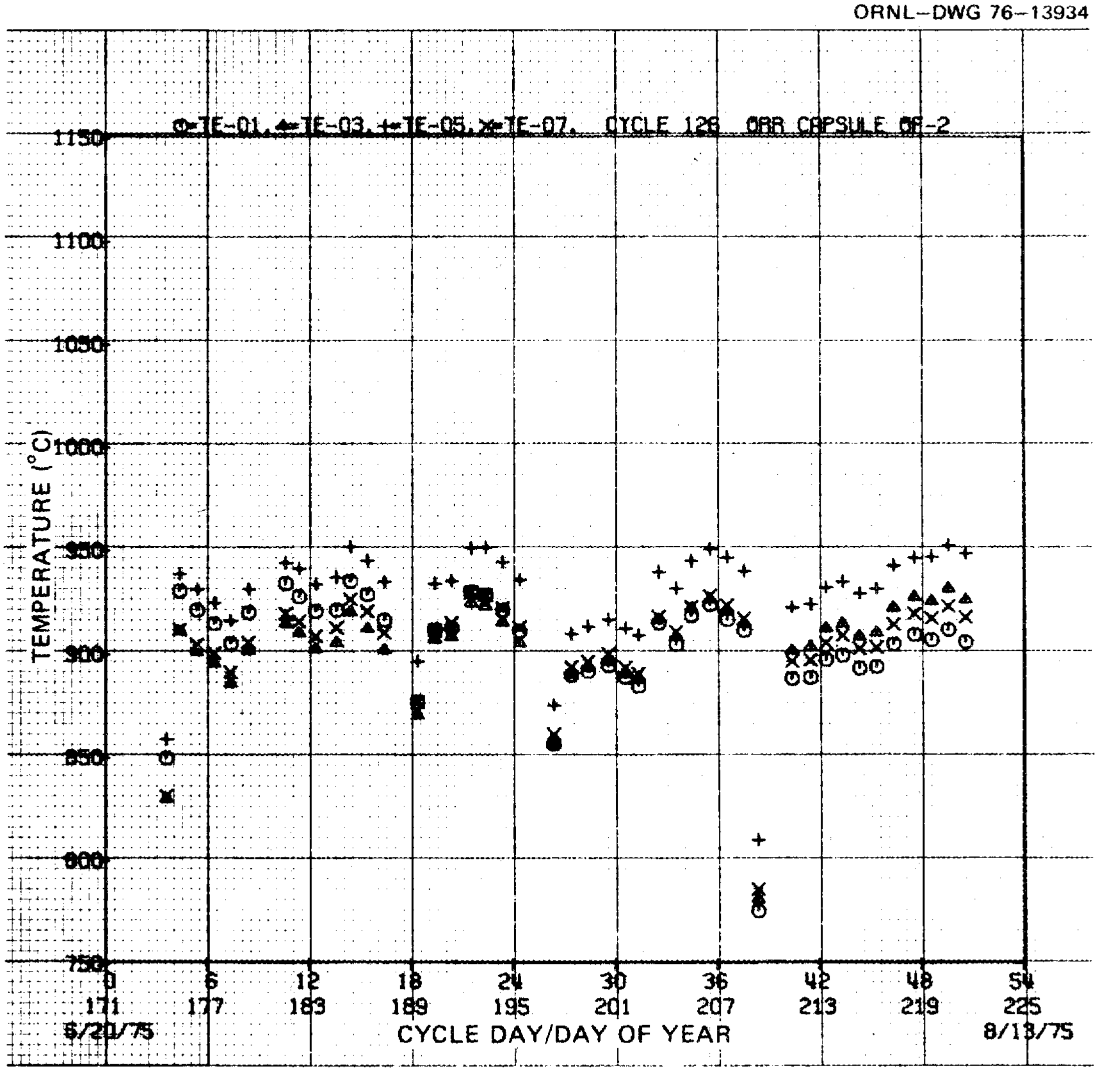

ORNL–DWG 76–13931
⊙=TE-12, ▲=TE-16, +=TE-19, x=TE-25. CYCLE 128 ORR CAPSULE OF-2
TEMPERATURE (°C)
1100
1050
1000
950
900
850
800
750
700
650
0
171
6/20/75
6
177
12
183
18
189
24
195
30
201
36
207
42
213
48
219
54
225
8/13/75
CYCLE DAY/DAY OF YEAR

ORNL–DWG 76–13932



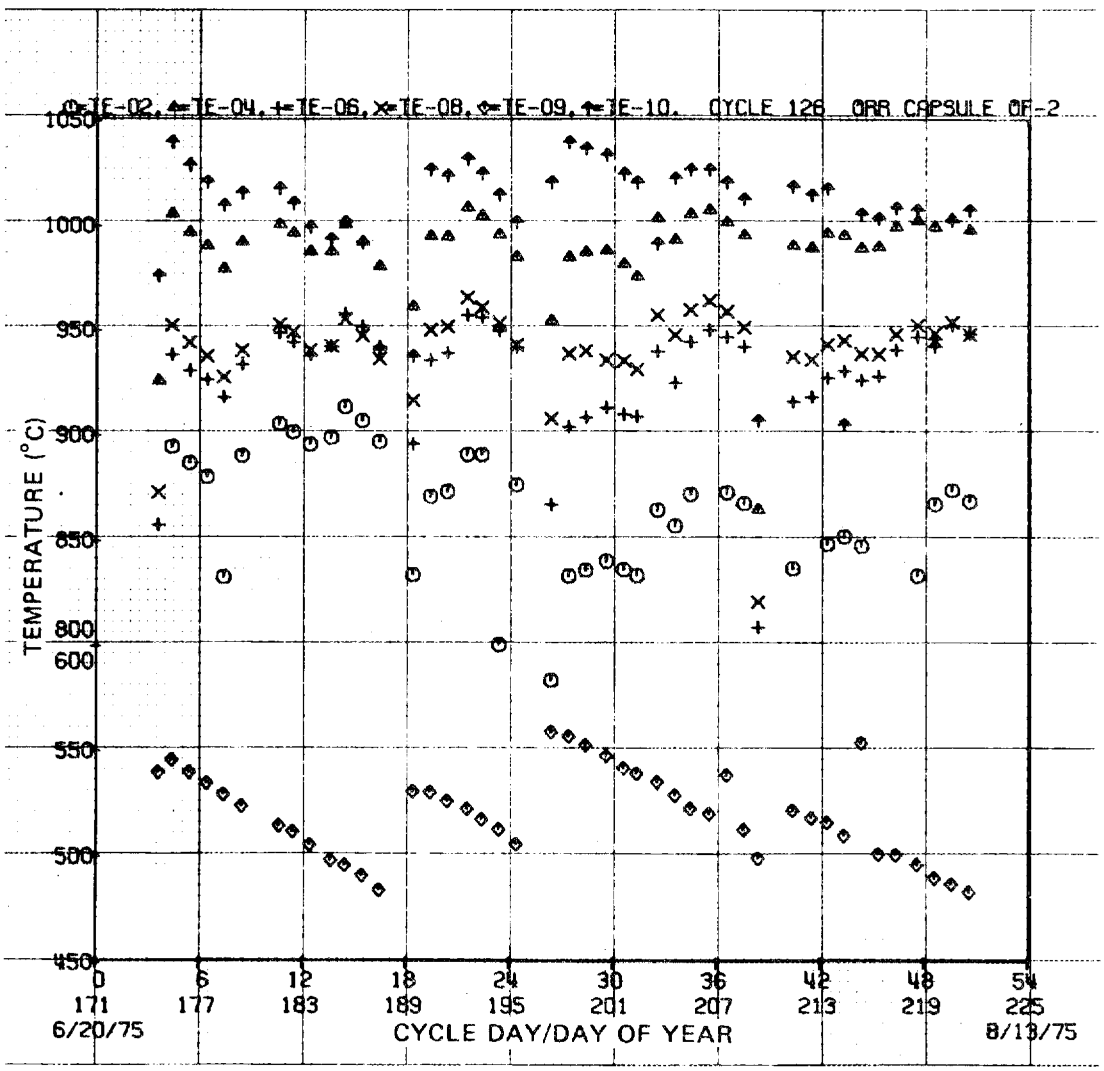
ORNL--DWG 76--13933





ORNL–DWG 76–13934
⊙=TE-01, ▲=TE-03, +=TE-05, ×=TE-07, CYCLE 128 ORR CAPSULE OF-2
TEMPERATURE (°C)
1150
1100
1050
1000
950
900
850
800
750
0 171
6 177
12 183
18 189
24 195
30 201
36 207
42 213
48 219
54 225
6/20/75
8/13/75
CYCLE DAY/DAY OF YEAR

ORNL--DWG 76--13935



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