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HTGR FUELS AND CORE DEVELOPMENT PROGRAM

QUARTERLY PROGRESS REPORT
FOR THE PERIOD ENDING
AUGUST 31, 1975

Prepared under
Contract AT(04-3)-167
Project Agreement No. 17
for the San Francisco Operations Office
U.S. Energy Research and Development Administration

DATE PUBLISHED: SEPTEMBER 30, 1975

MASTER

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ABSTRACT

This publication continues the quarterly report series on the HTGR Fuels and Core Development Program. The Program covers items of the base technology of the High-Temperature Gas-Cooled Reactor (HTGR) system. The development of the HTGR system will, in part, meet the greater national objective of more effective and efficient utilization of our national resources. The work reported here includes studies of reactions between core materials and coolant impurities, basic fission product transport mechanisms, core graphite development and testing, the development and testing of recyclable fuel systems, and physics and fuel management studies. Materials studies include irradiation capsule tests of both fuel and graphite. Experimental procedures and results are discussed and, where appropriate, the data are presented in tables, graphs, and photographs. More detailed descriptions of experimental work are presented in topical reports; these are listed at the end of the report.

1

2

3

4

5

6

7

INTRODUCTION

This report covers the work performed by the General Atomic Company under U.S. Atomic Energy Commission Contract AT(04-3)-167, Project Agreement No. 17. This Project Agreement calls for support of basic technology associated with the fuels and core of the gas-cooled, nuclear power reactor systems. The program is based on the concept of the High-Temperature Gas-Cooled Reactor (HTGR) developed by the General Atomic Company.

Large HTGR systems will be placed in operation starting in the early 1980's following the operation of the 330-MW(e) prototype in 1975. Characteristics of these advanced systems include:

1. A single-phase gas coolant allowing generation of high-temperature, high-pressure steam with consequent high-efficiency energy conversion and low thermal discharge.
2. A prestressed concrete reactor vessel (PCRv) offering advantages in field construction, primary system integrity, and stressed member inspectability.
3. Graphite core material assuring high-temperature structural strength, large temperature safety margins, and good neutron economy.
4. Thorium fuel cycle leading to U-233 fuel which allows good utilization of nuclear resources and minimum demands on separative work.

1

2

3

CONTENTS

ABSTRACT	iii
INTRODUCTION	v
TASK 4: HTGR FISSION PRODUCT MECHANISMS (189a SU001).	1
Relationship of Fission Gas Release (R/B) and Uranium	
Contamination in Fuel Rods.	1
Analysis of FTE-4 Diffusion Samples	3
Vapor Pressure of Strontium Sorbed on Irradiated H-451	
Graphite.	5
Fission Product Transport Code Development.	8
Fission Product Transport Code Validation Program	13
Cadarache Pegase Loop (CPL-2).	14
Saclay Spitfire Loop (SSL)	29
Analysis of Transport Mechanisms.	41
Coupled Two-Component Model for Metallic Fission	
Products in Graphite.	49
Tritium Permeation Rate Through Steam Generator Tube	
Materials	53
Steam Graphite Reaction Rate Constants.	64
References.	66
TASK 8: REACTOR PHYSICS (189a SU002).	71
Cross-Section Evaluation.	71
Introduction	71
Cross-Section Preparation.	72
Detailed Results of Burnup Calculations.	80
References.	83
TASK 9: HTGR FUEL DEVELOPMENT AND ENGINEERING (189a SU003).	91
Dosimeter Cross Sections for Use in P13Q and OG-2 Capsule	
Analyses.	91
Introduction and Summary	91
Calculational Scheme	91
Results.	93
Determination of Free Void Volumes and Fission and Reaction	
Gases in Irradiated Coated Fuel Particles	98
Introduction	98
Materials.	98
Calculation of Theoretical Gas Contents.	99
Experimental Determination of Fission Gas Content.	101
Determination of Free Volume Within Coated Particles	101
Results and Discussion	102
Conclusions.	111
Capsules P13R and P13S.	113

Capsule P13Q.	114
Introduction	114
Postirradiation Examination.	115
Capsule P13T.	121
Capsules P13U and P13V.	122
References.	122
TASK 11: GRAPHITE DEVELOPMENT (189a SU004).	174
Introduction.	174
Graphite Irradiations	174
Capsule OG-2	174
Capsule OG-3	188
Capsules OG-4 and OG-5	188
Analysis of Dimensional Change Data.	189
Graphite Characterization	189
Graphite Standard	191
References.	191
APPENDIX: PROJECT REPORTS PUBLISHED DURING THE QUARTER.	275

FIGURES

4-1.	Diffusion coefficients for strontium, barium, and europium obtained from analysis of FTE-4 concentration profiles. . . .	7
4-2.	Measured 1200°, 1500°, and 1800°K isotherms for strontium sorbed on irradiated H-451 graphite	10
4-3.	CPL-2 loop.	16
4-4.	Pegase reactor with eight loops in place.	17
4-5.	CPL-2 loop schematic with loop flow	18
4-6.	Fuel element.	21
4-7.	Reflector block	22
4-8.	Heat exchanger - recuperator.	23
4-9.	Average exchanger tube gamma activity versus axial distance.	26
4-10.	Average exchanger tube temperature versus axial distance. . .	27
4-11.	SSL-1 in-pile loop and instrumentation.	30
4-12.	SSL-1 fuel element.	32
4-13.	Sensitivity of FIPER predictions of Cs release from SSL-1 rod layer 5 to changes in the sorption ratio.	38
4-14.	Sensitivity of FIPER predictions of Cs release from SSL-1 rod layer 5 to changes in the diffusion coefficient in graphite.	39
4-15.	Steady-state cesium release rate as a function of reference concentration and the effect of tenfold changes in web sorptivity, diffusion coefficient, and both	43
4-16.	Distribution of total cesium between rod and web as a function of the ratio of their sorptivities	45
4-17.	Idealized variation of release with changes in the sorptivities of the rod (Φ) and web (ν) when D varies inversely with ν	47
4-18.	Cesium concentration profiles	55
4-19.	Microstructures of T22 sample after heat treatment.	60
4-20.	Effect of hydrogen on tritium permeation rate through T22 . .	61
4-21.	Oxidation rate of H-451 graphite as a function of partial pressure of H ₂ O	68
8-1.	A = 105 to A = 109 detailed scheme.	84

8-2.	A = 113 to A = 116 detailed scheme.	85
8-3.	A = 147 to A = 157 detailed scheme.	86
9-1.	Typical ORR core configuration.	128
9-2.	ORR supercell for capsule analyses.	129
9-3.	Fission source distribution in ORR supercell.	130
9-4.	Detail of OG-2 capsule as modeled in TWOTRAN.	131
9-5.	Detail of P13Q model used in TWOTRAN calculations	131
9-6.	Variation in the ratio of measured to predicted gas content for irradiated TRISO UC ₂ fuel versus temperature.	132
9-7.	Variation in the ratio of measured to predicted gas content for irradiated TRISO UO ₂ fuel versus temperature.	133
9-8.	Variation in the ratio of measured to predicted gas content for irradiated BISO ThO ₂ fuel versus temperature.	134
9-9.	Cracking pattern in the bulkhead of capsule P13Q.	135
9-10.	Severed gas inlet tube, which was corroded at the top of the capsule	136
9-11.	Irradiation-induced dimensional change of Palorite insulation disk at the bottom end (high-fluence region) of the capsule	137
9-12.	Three graphite fuel bodies after removal from the primary containment	138
9-13.	Identification scheme used to identify fuel rod columns and secondary sample "coolant" holes in the P13Q graphite bodies .	139
9-14.	Removal of secondary specimens from capsule P13Q graphite body G2	140
9-15.	Horizontal fixture used to remove capsule P13Q fuel rods from the graphite bodies	141
9-16.	Removal of capsule P13Q fuel rods from the graphite bodies. .	142
9-17.	Capsule P13Q fuel rods after removal from position G3-1 . . .	143
9-18.	Capsule P13Q fuel rods after removal from position G3-2 . . .	144
9-19.	Capsule P13Q fuel rods after removal from position G3-3 . . .	145
9-20.	Capsule P13Q fuel rods after removal from position G2-1 . . .	146
9-21.	Capsule P13Q fuel rods after removal from position G2-2 . . .	147
9-22.	Capsule P13Q fuel rods after removal from position G2-3 . . .	148
9-23.	Capsule P13Q fuel rods after removal from position G1-1 . . .	149
9-24.	Capsule P13Q fuel rods after removal from position G1-2 . . .	150
9-25.	Capsule P13Q fuel rods after removal from position G1-3 . . .	151
9-26.	Fuel rod 7161-002-19-3 after irradiation.	152

9-27.	Fuel rod 7161-002-20-3 after irradiation.	153
9-28.	Fuel rod 7161-002-21-3 after irradiation.	154
9-29.	Fuel rod 7261-002-10-3 after irradiation.	155
9-30.	Fuel rod 7261-002-11-3 after irradiation.	156
9-31.	Fuel rod 7261-002-12-3 after irradiation.	157
9-32.	Fuel rod 7261-002-13-3 after irradiation.	158
9-33.	Fuel rod 7261-002-14-3 after irradiation.	159
9-34.	Fuel rod 7261-002-15-3 after irradiation.	160
9-35.	Fuel rod 7161-002-13-3 after irradiation.	161
9-36.	Fuel rod 7161-002-14-3 after irradiation.	162
9-37.	Fuel rod 7161-002-15-3 after irradiation.	163
9-38.	Fuel rod 7261-002-16-3 after irradiation.	164
9-39.	Fuel rod 7261-002-17-3 after irradiation.	165
9-40.	Fuel rod 7261-002-18-5 after irradiation.	166
9-41.	Fuel rod 7161-002-16-3 after irradiation.	167
9-42.	Fuel rod 7161-002-17-3 after irradiation.	168
9-43.	Fuel rod 7161-002-18-3 after irradiation.	169
9-44.	Photographs taken during visual examination of ThO ₂ BISO particles (6542-02-0130-3).	170
9-45.	Photographs taken during visual examination of ThO ₂ BISO particles (6542-01-0130-5).	171
9-46.	Photographs taken during visual examination of UC ₂ TRISO particles (6151-00-0130-4).	172
9-47.	Photographs taken during visual examination of (Th,U)O ₂ TRISO particles (4163-00-0140-3).	173
11-1.	Thermal expansivity as a function of fluence for near- isotropic graphites	177
11-2.	Thermal expansivity versus fluence for H-327 graphite	179
11-3.	Thermal conductivity versus fluence for near-isotropic graphites	181
11-4.	Thermal conductivity versus fluence for H-327 graphite. . . .	182
11-5.	Ultimate tensile strength and Young's modulus versus fluence for H-451 graphite.	184
11-6.	Ultimate tensile strength and Young's modulus versus fluence for TS-1240 graphite	185
11-7.	Ultimate tensile strength and Young's modulus versus fluence for H-327 graphite.	186
11-8.	Dimensional change in near-isotropic graphites.	190

TABLES

4-1.	FTE-4 diffusion data.	6
4-2.	Heats of adsorption for strontium on irradiated H-451 graphite.	9
4-3.	Limiting test conditions for SSL-1 loop	33
4-4.	SSL-1 FIPER code input variables.	36
4-5.	Diffusion parameters obtained from fitting cesium profiles of Peach Bottom fuel test element and spine samples.	54
4-6.	Characteristics of tritium-helium mixtures.	59
4-7.	H-451 graphite oxidation rate	67
8-1.	Explicit fission products	73
8-2.	Slowly saturating aggregate	76
8-3.	Non-saturating aggregate.	77
8-4.	Broad-group energy structure.	80
8-5.	18 explicit fission products.	81
8-6.	Fission products added to aggregates for 18 nuclide calculation	81
8-7.	Burnup calculation results.	82
8-8.	Fission product yield comparison.	87
8-9.	Fractional absorptions after an irradiation of 768 days . . .	88
8-10.	Fractional absorption comparison.	89
9-1.	Effective activation cross sections	92
9-2.	Supercell atomic densities.	94
9-3.	OG-2 atomic densities	94
9-4.	P13Q atomic densities	95
9-5.	Fission source distribution	95
9-6.	Graphite damage and flux monitor cross sections	96
9-7.	Calculated flux distribution.	97
9-8.	Description of coated fuel particles and irradiation history	100
9-9.	Comparison of measured and predicted gas contents from irradiated TRISO UC ₂ batch 4413-5	103

9-10.	Comparison of measured and predicted gas contents from irradiated TRISO UO_2 batch 4413-67	104
9-11.	Comparison of measured and predicted gas contents from irradiated TRISO I (Th/U) O_2 batch 3332-141	105
9-12.	Comparison of measured and predicted gas contents from irradiated BISO ThO_2 batch 4413-75	106
9-13.	Estimate of fission gas pressure contained by irradiated TRISO UC_2 particles from batch 4413-5.	110
9-14.	Estimate of fission gas pressure contained by irradiated TRISO UO_2 particles from batch 4413-67	110
9-15.	Estimate of fission gas pressure contained by irradiated TRISO (Th/U) O_2 particles from batch 3332-141	110
9-15.	Results of free void volume determinations made on unirradiated particles from BISO ThO_2 batch 4413-75.	112
9-17.	Estimate of fission gas pressure contained by irradiated BISO ThO_2 particles from batch 4413-75	112
9-18.	Summary description of fuel rods irradiated in capsule P13Q	118
9-19.	Description of fuel rods being tested on capsules P13U and P13V	123
9-20.	General description of coated particles being tested on capsules P13U and P13V	125
11-1.	Thermal expansivity of H-429 and H-451 graphite specimens irradiated in capsule OG-2	193
11-2.	Thermal expansivity of TS-1240 graphite specimens irradiated in capsule OG-2.	195
11-3.	Thermal expansivity of H-327 graphite specimens irradiated in capsule OG-2.	196
11-4.	Thermal conductivity of H-451 graphite specimens irradiated in capsule OG-2.	197
11-5.	Thermal conductivity of TS-1240 graphite specimens irradiated in capsule OG-2.	198
11-6.	Thermal conductivity of H-327 graphite specimens irradiated in capsule OG-2.	199
11-7.	Tensile properties of TS-1240 graphite specimens irradiated in capsule OG-2.	200
11-8.	Tensile properties of H-327 graphite specimens irradiated in capsule OG-2.	204
11-9.	Summary of mechanical property data on graphites irradiated in capsules OG-1 and OG-2.	208
11-10.	Dimensional change data, H-429, axial direction, after irradiation in capsules GEH-422, 452, 482.	210

11-11.	Dimensional change data, H-429, axial direction, after irradiation in capsule OG-1.	212
11-12.	Dimensional change data, H-429, axial direction, after irradiation in capsule OG-2.	213
11-13.	Dimensional change data, H-451, axial direction, after irradiation in capsule OG-1.	214
11-14.	Dimensional change data, H-451, axial direction, after irradiation in capsule OG-2.	223
11-15.	Dimensional change data, H-429, radial direction, after irradiation in capsules GEH-422, 452, 482.	227
11-16.	Dimensional change data, H-429, radial direction, after irradiation in capsule OG-1.	229
11-17.	Dimensional change data, H-429, radial direction, after irradiation in capsule OG-2.	230
11-18.	Dimensional change data, H-451, radial direction, after irradiation in capsule OG-1.	231
11-19.	Dimensional change data, H-451, radial direction, after irradiation in capsule OG-2.	238
11-20.	Dimensional change data, TS-1240, axial direction, after irradiation in capsule OG-2.	240
11-21.	Dimensional change data, TS-1240, radial direction, after irradiation in capsule OG-2.	242
11-22.	Dimensional change data, P ₃ JHAN, axial direction, after irradiation in capsule OG-1.	243
11-23.	Dimensional change data, P ₃ JHAN, axial direction, after irradiation in capsule OG-2.	245
11-24.	Dimensional change data, P ₃ JHAN, radial direction, after irradiation in capsule OG-1.	246
11-25.	Dimensional change data, P ₃ JHAN, radial direction, after irradiation in capsule OG-2.	248
11-26.	Tensile properties of H-451 graphite, lot 426, log 6484-40.	249
11-27.	Tensile properties of TS-1240 graphite, lot 1, log 5651-74.	253
11-28.	Tensile properties of TS-1240 graphite, lot 1, log 5651-75.	257
11-29.	Tensile properties of TS-1240 graphite, lot 1, log 6484-29.	261
11-30.	Impurity content of graphites H-451 and SO-818	265
11-31.	Thermal expansivity of H-451 graphite, lot 426, log 6484-33.	266

11-32.	Thermal expansivity of H-451 graphite, lot 426, log 6484-41.	268
11-33.	Thermal expansivity of TS-1240 graphite, lot 1, log 6484-29.	270
11-34.	Thermal expansivity of SO-818 graphite, lot 1, log 6484-19.	272
11-35.	Summary of tensile strength measurements of H-451 graphite, lot 426.	274

TASK 4 (189a SU001)
HTGR FISSION PRODUCT MECHANISMS

RELATIONSHIP OF FISSION GAS RELEASE (R/B) AND URANIUM CONTAMINATION
IN FUEL RODS

An effort was made to determine the relationship between fission gas release (R/B) and uranium contamination in fuel rods. The aim of this work was to provide data for use in finalizing specifications for large plant fuel and in developing methods for determining uranium contamination levels in fuel rods.

The experimental procedure in this work consisted of the following steps:

1. Select standard (production-type) fuel rods having varying levels of uranium contamination.
2. Measure fission gas release (R/B) value for each rod.
3. Measure the level of uranium contamination in each rod using a gas-leach technique.
4. Remeasure the R/B value for each rod to determine the effectiveness of the gas-leach technique for removing uranium contamination.

Fission gas release (R/B) measurements are performed using a standard procedure, which involves irradiating the fuel rods in a TRIGA reactor, trapping the released fission gases, and gamma-counting the traps. The

gamma-counting and calculations are done by use of a Sigma II analyzer-computer, which is described in more detail in Ref. 4-1. The test yields a direct measure of the R/B value at 1100°C for 4.4-hr Kr-85m, which is taken to be the reference nuclide.

The procedure for the gas-leach technique is based upon the volatilization of exposed heavy metals by a suitable chlorinating agent, with subsequent collection and measurement of the separated chlorides of thorium and uranium. Individual sample fuel rods are placed within a specially designed and fabricated quartz furnace tube assembly and subjected to a slow, constant flow of carbonyl chloride gas at 960°C. After a suitable period of gas leaching, the samples are removed from the furnace tube, and the combined heavy metal chlorides are rinsed from the condenser end of the tube into a collecting flask. The sample rod can then be replaced in the furnace tube and the leaching continued, if desired.

An aliquot of the solution (for determination of uranium) is adjusted to pH = 2 with glycine, and is then twice extracted with 20% tributyl-phosphate in carbon tetrachloride. The extract is stripped with an arsenazo III solution, which is buffered to pH = 2 with glycine and photometrically measured at 660 nm. It is the absorption peak of the uranium (VI) complex that is measured at this wavelength.

The thorium content of an aliquot of the collected heavy metals is determined by photometric measurement of the thorium-arsenazo (III) complex at 660 nm in a medium of 0.5 molar nitric acid.

A detection limit of 1 microgram of either thorium or uranium is achieved with the reagent system employed. This appears at present to be adequate to establish the exposed heavy metal fraction to a level less than that equivalent to an $R/B = 10^{-5}$ with acceptable confidence.

Details of the procedure that need further investigation include the effects of furnace temperature, carbonyl chloride flow rate, and leaching time.

The above procedure has been performed on several Fort St. Vrain production fuel rods. The time duration of the gas-leach tests was 80 to 120 minutes. Collection samples were taken at 20-minute intervals. R/B values measured after leaching were relatively high, indicating that the gas-leach test did not remove all the uranium contamination or that fissile particle coating failure occurred during the test. It is concluded that further development work on the procedure is needed.

ANALYSIS OF FTE-4 DIFFUSION SAMPLES

The analysis of diffusion samples in fuel test element FTE-4 (irradiated for 449 effective full-power days in the Peach Bottom HTGR) has provided diffusion coefficient data for use in validating reference diffusion coefficient data for cesium, strontium, barium, and europium in graphite.

The center spine of FTE-4 and several other test elements of the FTE-series contained diffusion samples for use in:

1. Determining the diffusion behavior of selected metal fission products in graphite under HTGR conditions as a function of metal concentration and temperature.
2. Providing data on the effects of the presence of other fission product metals on the migration rate of individual metals.
3. Determining the distribution of metal fission products between matrix material and graphite.

FTE-4 contained 22 metallic diffusion samples, located in fuel element spine bodies 1, 2, and 3. The samples contained isotopes of barium, strontium, samarium, and cesium, or mixtures of these isotopes in varying concentrations.

The experimental procedure for determining diffusion coefficients of these metals is discussed in Refs. 4-2 and 4-3. In summary, metallic concentration profiles in graphite were determined by a lathe sectioning and gamma-counting technique. The resulting concentration profiles were analyzed with the computer code CPROFIT (Concentration PROfile FIT) developed at North Carolina State University. This program simultaneously treats fast path (grain boundary and in-pore) diffusion and slow path (Fickian) diffusion with uncoupled diffusion equations (Ref. 4-2).

Examination of the profiles indicated that many were more complex than was expected from a single diffusing component that obeys Fick's law. More specifically, all of the cesium profiles showed a fast component, indicated by a flat concentration profile in the graphite, which did not correspond to a Fick's law transient diffusion behavior. The crucible wall profiles were generally quite different from those of the center post since Cs from the adjacent fuel compacts permeated the graphite. There was an indication of a slow component in the cesium profiles, as evidenced by the steep concentration profile adjacent to the matrix region. Although this indication was not always prominent, it corresponded to a diffusion coefficient D of low magnitude ($D < 10^{-11} \text{ cm}^2/\text{sec}$) and showed little temperature dependence. On the other hand, the strontium and barium profiles were of the classical (Fick's law) type and could be fitted to the complementary error function equation $C = C_0 \text{erfc}(x/2\sqrt{Dt})$, where x is the depth of penetration. The Eu-154 activity profiles were predominantly of the classical type but in some cases showed an indication of a low-magnitude, fast component similar in nature to that of cesium. In a few samples, a minor fast component for strontium and barium was suggested. A depletion effect was apparent in the graphite near the source matrix in some of the Sr-85 profiles.

It was concluded from these profile data that, consistent with a number of other observations including analysis of FTE-3 data (Refs. 4-2 through 4-5), the fast component of cesium is very likely due to in-pore

surface diffusion of atoms, which is accompanied by an activated diffusion and sorption process whereby atoms are fixed to sites where they have a low mobility. Time constants are such that a quasi-steady-state is reached in a few hours (or tens of hours), and the concentration profile that is then established does not change shape with time even though its magnitude continues to increase (Ref. 4-2).

The analysis results for FTE-4 are given in Table 4-1, which summarizes the calculated fast and slow diffusion coefficients. The results for cesium are similar to those found for FTE-3 (Ref. 4-2). The diffusion coefficients for strontium, barium, and europium are compared with the reference diffusion coefficient curve for strontium in Fig. 4-1 (Ref. 4-6). The strontium diffusion coefficient for the center post of crucible 22B is somewhat low. This might be attributed to greater uncertainty in the average temperature of this crucible, which could have been irradiated at a lower temperature than the reported value of 1075°C.

It is concluded that the diffusion coefficient data obtained from the FTE-4 diffusion samples are in good agreement with reference data.

VAPOR PRESSURE OF STRONTIUM SORBED ON IRRADIATED H-451 GRAPHITE

Vapor pressure data for strontium sorbed on H-451 graphite have been measured utilizing a mass spectrometric method. The graphite used had been previously irradiated in capsule OG-1 at 1155°C to a fast neutron fluence of $3.7 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR}.

In the mass spectrometric method (described previously in Refs. 4-7 through 4-9), a sample of the graphite (with particles in the size range of 44 to 74 μm) with sorbed metal (in this case strontium) is placed in a molybdenum Knudsen cell. Initially the strontium is in the form of the nitrate, and a preliminary heating of the nitrate-impregnated graphite in

TABLE 4-1
FTE-4 DIFFUSION DATA

Crucible No.	Isotope	Location ^(a)	Temp (°C)	$10^4/T$ (°K ⁻¹)	Slow Component D_s (cm ² /sec)	Fast Component (cm ² /sec)		Remarks
						D_f	D_{eff} (b)	
10	Sr-85	CP	770	9.59	5.8×10^{-12}	--	--	Matrix loading
	Sr-85	CW	770	9.59	2.6×10^{-12}	--	--	1.0 mg Sr/g C
	Cs-134	CP	770	9.59	4.9×10^{-12}	--	4.5×10^{-9}	Cs-134 from outside
	Cs-134	CW	770	9.59	--	--	--	
12B	Sr-85	CP	770	9.59	1.2×10^{-11}	--	--	Matrix loading
	Cs-134	CP	770	9.59	6.5×10^{-12}	--	5.3×10^{-9}	10.0 mg Sr/g C
	Cs-134	CW	770	9.59	--	--	--	Cs-134 from outside
18B	Sr-85	CP	910	8.45	2.1×10^{-10}	--	--	Matrix loading
	Sr-85	CW	910	8.45	1.3×10^{-10}	--	--	10.0 mg Sr/g C
	Cs-134	CP	910	8.45	--	--	7.3×10^{-9}	Cs-134 from outside
	Cs-134	CW	910	8.45	--	--	--	
22B	Sr-85	CP	1075	7.42	1.9×10^{-9}	--	--	Matrix loading
	Sr-85	CW	1075	7.42	$>1.0 \times 10^{-9}$	--	--	10.0 mg Sr/g C
	Cs-134	CP	1075	7.42	--	--	1.4×10^{-9}	Cs-134 and
	Cs-137	CP	1075	7.42	--	--	6.4×10^{-8}	Cs-137 from outside
	Cs-134	CW	1075	7.42	--	--	--	
	Cs-137	CW	1075	7.42	--	--	--	
31	Ba-133	CP	740	9.87	3.2×10^{-12}	--	--	Matrix loading
	Ba-133	CW	740	9.87	5.7×10^{-12}	--	--	6.0 mg Ba/g C
	Cs-134	CP	740	9.84	2.8×10^{-12}	--	4.7×10^{-9}	Cs-134 from outside
	Cs-134	CW	740	9.84	--	--	--	
41	Eu-154	CP	720	10.07	1.5×10^{-12}	6.6×10^{-10}	4.1×10^{-10}	Matrix loading
	Eu-154	CW	720	10.07	1.3×10^{-12}	1.1×10^{-11}	--	1.6 mg Cs/g C
	Cs-134	CP	720	10.07	1.8×10^{-12}	--	3.3×10^{-9}	1.0 mg Sr/g C
	Cs-134	CW	720	10.07	--	--	--	1.0 mg Sm/g C
								Despite Cs loading, most Cs-134 came from outside

(a) CP = center post; CW = crucible wall.

(b) See Ref. 4-2.

Fig. 4-1. Diffusion coefficients for strontium, barium, and europium obtained from analysis of FTE-4 concentration profiles

the cell converts the sorbate to metal. The cell is then maintained at a series of temperatures and the diffusion of metal vapor from the cell is monitored by the mass spectrometer. The vapor and sorbed concentrations of the metal are determined from a knowledge of the initial and final quantities of sorbate and the time profile of the effusing metal.

A single mass spectrometric run has been performed. Table 4-2 gives the heat of adsorption, temperature range, and sorbate concentration for each determination during the run. Figure 4-2 shows 1200°, 1500°, and 1800°K isotherms derived from the data. Figure 4-2 includes the reference 1500°K isotherm for unirradiated H-327 graphite derived from Ref. 4-6. The sorption isotherms for strontium on graphite are essentially identical for sorption on H-327 and H-451 graphites as previously shown (Ref. 4-10).

Comparison of the reference 1500°K isotherm with the isotherm for irradiated graphite shows that irradiation led to a marked reduction in Sr vapor pressure at a given concentration. At the lowest concentration of the run, the Sr vapor pressure is lowered by about five orders of magnitude.

The very pronounced effect of irradiation needs to be verified. Accordingly, it is planned to repeat the experiment using a sample of irradiated H-451 graphite from capsule OG-2.

FISSION PRODUCT TRANSPORT CODE DEVELOPMENT

The TRAFIC code, which was developed under the HTGR Fuels and Core Development Program (Refs. 4-1, 4-10 through 4-12), presently employs a simplified particle release model. This model considers fractional diffusive release through intact BISO particles and 100% release from failed BISO and TRISO particles. The BISO diffusion model considers only one diffusive barrier to release; simplified zero-concentration boundary

TABLE 4-2
HEATS OF ADSORPTION FOR STRONTIUM ON IRRADIATED H-451 GRAPHITE (RUN Sr-11)

Determination No.	ΔH (kcal/mole)	Temperature Range (°K)	Sorbate Concentration (mg Sr/g graphite)
1	86.7 $\pm$ 4.4	1340-1500	6.09
2	80.2 $\pm$ 2.4	1360-1520	4.52
3	76.5 $\pm$ 1.9	1400-1560	4.04
4	87.1 $\pm$ 1.7	1390-1600	3.40
5	86.2 $\pm$ 2.2	1410-1630	2.98
6	89.1 $\pm$ 1.1	1450-1660	2.57
7	95.3 $\pm$ 3.3	1510-1690	2.16
8	98.0 $\pm$ 2.0	1540-1730	1.73
9	98.3 $\pm$ 3.1	1540-1730	1.57
10	103.4 $\pm$ 2.6	1610-1780	1.26
11	105.2 $\pm$ 4.3	1620-1790	1.08
12	115.9 $\pm$ 1.5	1660-1810	0.939
13	115.8 $\pm$ 3.7	1720-1880	0.830
14	115.1 $\pm$ 3.1	1740-1910	0.689
15	125.2 $\pm$ 4.5	1790-1930	0.580
16	126.6 $\pm$ 4.1	1820-1980	0.462
17	131.1 $\pm$ 6.0	1830-2000	0.381
18	132.2 $\pm$ 7.6	1860-2010	0.331
19	127.0 $\pm$ 5.2	1850-2010	0.310

Fig. 4-2. Measured 1200°, 1500°, and 1800°K isotherms for strontium sorbed on irradiated H-451 graphite compared to reference 1500°K isotherm for unirradiated graphite

conditions are assumed. Partition factors, the trapped fraction, and a number of other effects are ignored.

Development of a new particle release model has begun. A literature survey was performed, and the best features of all known particle release models were noted. These features were then combined, insofar as possible, in the new model. The new model was constructed with one criterion of uppermost importance: the model must be highly efficient, consistent in concept with TRAFIC, so that it can be economically employed in core survey design calculations. With this as a ground rule, the new particle release model will be applicable for use as a source term in TRAFIC, the FIPER series, SORS, and any other codes that deal with fission product release from an HTGR core. A brief description of the new model and its intended capability follows.

A given particle type is modeled as a spherical kernel inside an arbitrary number of concentric, spherical-shell coating layers. The layers are distinguished from one another by assigning different physical properties, such as diffusion coefficients, to each layer. A given particle type is considered as having two states, intact and failed. These states differ from one another only in the specification of the diffusion coefficients for the layers. Thus, one geometrical model will suffice to model BISO and TRISO particles in both intact and failed states.

Fission products are assumed to be born in the particle at an average rate that is determined from the local power density. The birth rate is then distributed spatially within the particle so that each region or layer contributes a specified fraction to the total birth. In this way the spatial effect of coating contamination is modeled. Within each layer the birth rate is assumed to be spatially uniform. Following birth, all the fission products are assumed to be recoiled a specified distance in an isotropic fashion. This results in a spatial redistribution of the source.

Finally, a certain fraction of the recoiled source is assumed to be physically trapped at its new source position. This fraction, termed the "trapped fraction," is computed as a specified function of temperature and burnup.

The part of the source that is not trapped diffuses in space and time within the particle. The differential equation that describes this process is Fick's law, with the addition of a radioactive decay term. Interface conditions that couple the internal layers are: (1) continuity of current, and (2) a step change in concentration (partition factor) between layers. The partition factors are considered to be constant in time. An evaporative boundary condition on the outer surface serves to couple the particle with the surrounding matrix material. Thus, the release mechanism is evaporation through a hypothetical boundary resistance layer on the particle surface. The release may be rate-limited either by the boundary resistance or the coating diffusion resistances. Removal inside the particle is caused by decay and, effectively, by the trapped fraction.

The solution proceeds in two stages. In the first stage, an analytical solution of the differential equation is used in the computations. The source in this case is assumed to be a single birth pulse at time zero. The release fraction is tabulated as a function of dimensionless time following the birth pulse. Four such solutions are obtained, one each for BISO intact, BISO failed, TRISO intact, and TRISO failed particles. These tabulated solution functions serve as the basic building blocks for the stage two solution. The first stage involves some rather lengthy calculations, but they only need to be performed once for a given set of particle design parameters. Stage two is a much more efficient calculation, which is repeated for every different space point and every different reactor operating history in a core survey type of calculation.

In the second stage the actual reactor operating history, including such variables as temperature and particle failure fraction, is considered. The tabulated functions of stage one are evaluated by linear interpolation, and a series of birth pulses (modeling a continuous source) are superimposed in time by adding the release contributions of all birth pulses in the past history. The superposition considers three types of particle histories: (1) particles that are intact during the birth pulse and which remain intact until the solution time; (2) particles that are failed before the birth pulse and which remain failed; and (3) particles that are intact during the birth pulse and which fail at some time between the pulse and the solution time. The total fractional release at any time is the sum, over all birth pulses in the past history, of the release fractions contributed by each of the three types of failure history.

The new particle release model is similar in concept to TRAFIC in the manner in which the solution is performed. It is also superficially similar to the previous particle release model in TRAFIC. However, the present model considers many more physical effects. Also, there are a large number of adjustable parameters in the model including, for example, the partition coefficients (ϕ factors) between layers and modifications to the diffusion coefficients upon failure. It is felt that these give the model a great deal of flexibility that will make it possible to fit the experimental data with reasonable accuracy.

FISSION PRODUCT TRANSPORT CODE VALIDATION PROGRAM

Work has commenced on the characterization of fission product behavior in loop irradiation tests carried out by the Commissariat a L'Energie Atomique (CEA) as a part of a private cooperative program between GA and CEA. These tests are being performed under CEA funding, utilizing French materials, to aid in licensing of the HTGR design in France. Fission product data obtained from these loop tests will be used to validate and/or

calibrate the FIPER, RAD, and PAD fission product transport codes (Ref. 4-13).

Cadarache Pegase Loop (CPL-2)

Two loop tests have been performed and one loop test is planned for September 1975 in the Pegase reactor at the Centre D'Etudes Nucleaires, Cadarache, France. The overall objective of all three tests is to verify design methods and the basic data used in design calculations through demonstration of their applicability in large-scale, well instrumented, in-pile tests. The first test, CPL-2/1, is intended to accomplish this objective by operating at nominal HTGR design conditions and was completed on February 6, 1975. The second test, CPL-2/3, was identical to CPL-2/1 except that irradiation was performed at various off-design coolant impurity levels. This irradiation ended July 4, 1975. The third test, CPL-2/4, will begin in September 1975 and will be conducted in an identical manner to CPL-2/1 with the exception that at the time of shutdown, loop depressurizations representative of postulated HTGR accident conditions during a design basis depressurization accident (DBDA) will be simulated. Measurements of fission product transport during the off-design operation of the CPL-2/3 and -2/4 tests will be compared to measurements obtained from the CPL-2/1 test and to analytical predictions.

Loop Description

The test section of these loops consists of a representative cylindrical section of an HTGR fuel block (12 fuel holes and 7 coolant channels) located upstream of a graphite reflector section and a heat exchanger - recuperator. The heat exchanger - recuperator tubes include most of the metal alloys used in the HTGR primary circuit. In addition, a small fraction of the fuel particles is left uncoated to provide a fission product source of known magnitude during the short irradiation period (~50

days). Complete examinations of the fuel, reflector, and heat exchanger after the irradiation give information on many aspects of fission product transport and deposition and provide realistic integral test data for verification of calculational methods.

The large pool-type Pegase reactor was constructed to afford a means of testing the performance of a wide variety of fuel element types. Large, self-contained test loops are located in the reactor pool, and experiments are initiated by rolling the loop close to the side of the core. This type of construction allows eight independent experiments to be run simultaneously. A photograph of the loop used in the CPL-2 experiments is shown in Fig. 4-3 and the reactor with all eight loops in place is shown in Fig. 4-4.

The reactor core is constructed of MTR-type plates (90% enriched uranium alloyed with aluminum). Steady-state power is 35 MW(t), producing a maximum thermal neutron flux of 0.7×10^{14} n/cm²-sec in the experimental test section. Power, or flux level, in the test section is regulated by moving the loop toward or away from the core.

A schematic of the loop is shown in Fig. 4-5. The "basket" contains the components to be tested. A heat exchanger is provided to transfer the heat generated in the test section to the reactor pool. The loop coolant temperatures are regulated by bypassing a portion of the coolant stream through the heat exchanger. Coolant is circulated by means of a variable speed blower. Out-of-pile circuits allow precise injections of impurities (e.g., water, hydrogen, etc.) as well as a means of accurately determining the resultant coolant impurity levels.

CPL-2/1 Experimental Objectives

CPL-2/1 was an integral test of fission product release and plateout under steady-state, nominal HTGR plant conditions, using an HTGR-type fuel element. The purpose of this experiment was threefold:

74K4283

Fig. 4-3. CPL-2 loop

74K4280

Fig. 4-4. Pegase reactor with eight loops in place

Fig. 4-5. CPL-2 loop schematic with loop flow

1. Verify the calculations of fission product release from HTGR fuel elements by comparing predicted and measured values of release from the experimental fuel element.
2. Calibrate calculated fission product plateout distribution in the HTGR primary coolant circuit by comparing predicted values to measured fission product plateout concentrations in the test section.
3. Study the basic fission product transport processes through graphite and the coolant circuit by relating laboratory measurements of individual barriers to release (e.g., release from particles, diffusion in graphite, vaporization, etc.) to results of an integral test; calibrate the calculations of oxidant levels in the primary coolant; and obtain laboratory fission product reentrainment (blowdown) data from representative HTGR metal surfaces.

The loop operating conditions are summarized as follows:

1. Mass flow rate = 87.66 g/sec.
2. System pressure = 55 atm.
3. Fuel block inlet temperature $\simeq 540^{\circ}\text{C}$.
4. Reflector block outlet temperature $\simeq 744^{\circ}\text{C}$.
5. Maximum fuel centerline temperature $\simeq 1300^{\circ}\text{C}$.
6. Fuel block average power $\simeq 93.25 \text{ kW(t)}$.
7. Average coolant moisture level $\simeq 10 \text{ ppm}$.

Test Section Description

The test section of the experimental basket contained a fuel element section, reflector block, and heat exchanger - recuperator. Helium was

made to flow upward through coolant channels in the fuel element, where the gas was heated and fission products entered the coolant. The gas then flowed through a reflector block and through the tube side of the straight tube heat exchanger - recuperator.

A large, representative portion of an HTGR fuel element (Fig. 4-6) was used in the CPL-2/1 experiment. The graphite fuel block (11.7 cm in diameter and 79.3 cm in length) had 7 coolant channels and 12 fuel holes. For analytical and identification purposes, the block was considered to be divided into 15 layers, each layer the length of a fuel compact (5 cm). The source for fission product release was provided by "seeding" certain fuel compacts with bare (uncoated) uranium oxide particles. As shown schematically in Fig. 4-6, layers 10 and 11 contained fuel compacts with 4% bare particles. These layers were selected since the maximum fuel centerline temperature ($\sim 1300^{\circ}\text{C}$) occurred in this region. In order to determine possible temperature effects on fission product release, bare particles were also included in cooler regions of the fuel element (fuel centerline temperature $\sim 850^{\circ}$ to $\sim 1150^{\circ}\text{C}$). Coolant hole graphite surface temperatures ranged from approximately 800° to 1150°C over the length of the fuel element.

The reflector block, shown schematically in Fig. 4-7, is 11.0 cm in diameter and 79.3 cm in length. Two cesium sorptive rods were inserted as shown in Fig. 4-7 to study the effect of helium crossflow on fission product migration in graphite.

The straight tube counterflow heat exchanger - recuperator (Fig. 4-8) was designed to fulfill two purposes: (1) permit high helium temperatures in the fuel element region of the loop without imposing unsafe stresses on other loop components, and (2) simulate temperatures and types of materials used in the steam generator and other primary circuit components of an HTGR.

The heat exchanger - recuperator consists of 186 tubes, 0.4 cm inside diameter and 125.0 cm long, arranged inside an 8.6-cm-diameter cylindrical

Fig. 4-6. Fuel element

Fig. 4-7. Reflector block

Fig. 4-8. Heat exchanger - recuperator

casing (Fig. 4-8). Several steel types (the French equivalents to T22 (2-1/4 Cr - 1 Mo), SS410, SS347, Hastelloy X, and Incoloy 800) were used in the fabrication of the tubes. Since the T22 and stainless steel alloys cannot withstand the maximum temperature that existed in the bottom (entrance) section of the heat exchanger, the tubes of these alloys were fabricated from two half-tubes joined by a welded sleeve; the bottom half-tube was made of Incoloy 800 and the top (cooler) section half-tubes were made from T22, SS410, and SS347. One entire tube was made from Hastelloy X. In addition, several tubes of each alloy were subjected to an oxidation treatment prior to assembly to permit a study of the influence of the metal surface condition on fission product plateout.

Helium flow, as shown in Fig. 4-5, traveled up the outside of the basket after leaving the blower and entered the shell side of the heat exchanger - recuperator at the top of the assembly, where the helium was preheated. The flow then exited the shell side and traveled down the outside of the assembly to the bottom of the basket, where it entered the fuel element. The flow then traveled upward through the coolant channels in the fuel and reflector blocks, finally exiting through the tube side of the exchanger.

During loop operation, helium coolant and graphite temperature measurements were made at 32 locations in the experimental assembly. Two diffusion probes, one at the inlet and the other at the outlet of the tube side of the exchanger, permitted the determination of fission product release from the fuel element and plateout on the exchanger tube walls during irradiation. The probes sampled the gas stream continuously at each location and trapped particulates and iodine that failed to plate out on the probe tube wall in the probe filters.

A cascade impactor dust analyzer was included in the loop downstream of the heat exchanger - recuperator to measure the amount and size distribution of dust particles in the coolant. In addition, prescribed

amounts of moisture and gaseous impurities injected into the coolant were measured and recorded.

Heat Exchanger Data Evaluation

Postirradiation examinations are now in progress at CEA on the CPL-2/1 reflector and fuel element. Tests are complete on the heat exchanger - recuperator, and many of these results have been communicated informally to GA. The data presented here are preliminary, and only first impressions as to the meaning of these results are possible. Evaluation of data as they are obtained will give directions to the PIE still in progress and will expedite joint CEA and GA interpretation of the final data set.

Thermocouple temperature measurements were made during irradiation at two radial locations: the tube side inlet and outlet and the entrance and exit of the shell side of the exchanger. The shell side inlet and outlet temperature measurements averaged 235° and 596°C, respectively. Temperatures measured at the tube side inlet yielded a relatively flat distribution, averaging 744°C. Conversely, the gas temperature distribution at the tube side exit shows a variation of ~80°C between the gas temperature at the center of the exchanger (460°C) and the periphery (~383°C) over a distance of 4.3 cm. Therefore, a large temperature gradient, ~20°C/cm, was established at the outlet of the exchanger. This resultant wide range of temperatures during operation could significantly affect fission product deposition (plateout) and reentrainment (liftoff) results.

CEA has provided GA with gamma scans of six tubes, including Incoloy, bimetallic, and preoxidized tubes from various positions in the exchanger. The plateout profiles for a number of different fission products have been determined, and CEA has computed an "average" plateout profile from these results. The average distributions for Cs-137 and I-131 are shown in Fig. 4-9, and it can be seen that both isotopes appear to have deposited in a similar manner. Considering the "average" axial temperature profile (Fig. 4-10), the amount of cesium and iodine plateout increases monotonically

Fig. 4-9. Average exchanger tube gamma activity versus axial distance

Fig. 4-10. Average exchanger tube temperature versus axial distance

once the tube wall temperature falls below 500°C, suggesting that an equilibrium plateout rate was achieved for the cooler tube section. This behavior appears to agree with previously determined deposition characteristics, which indicate that iodine plateout is strongly temperature dependent with negligible plateout occurring above ~500°C and that cesium plateout is dependent upon surface temperatures above ~400°C.

Fission product deposition on the heat exchanger - recuperator surfaces not only provides a test for predictions of plateout distributions based on design data and methods, but also provides specimens for measurement of reentrainment (liftoff) characteristics of deposited radionuclides.

In cooperation with CEA, work is presently directed toward a detailed evaluation of heat exchanger - recuperator performance during loop operation. As pointed out previously, meaningful comparison of measured plateout with predicted or previously determined values is contingent on an accurate evaluation of the operating temperature and flow rate distributions in the heat exchanger. From the operating information received to date, it can be inferred that the significant radial temperature gradients which existed in the heat exchanger - recuperator during operation could influence the deposition and reentrainment of fission products from tube to tube along the radius.

Once operating conditions have been established, the Plateout Activity Distribution (PAD) code will be utilized to calculate the plateout distribution in the heat exchanger - recuperator. The results of these calculations will be compared to and correlated with experimentally determined profiles. Based on these and other validation test results, modifications to the code or new laboratory test programs may be proposed to improve design calculation techniques.

Saclay Spitfire Loop (SSL)

The Saclay Spitfire Loop test experiments are designed to test the irradiation performance of candidate French and GA graphites and fuel. The SSL-1 loop test, in which irradiation was completed in May 1974 after six 20 EFPD cycles, was designed to test the behavior of $8(\text{Th/U})\text{O}_2$ TRISO/ ThO_2 TRISO GA fuel and French P_3JHAN graphite when irradiated to high fast fluence and fuel burnup. This test will be analyzed to characterize fission product behavior during irradiation.

SSL-1 fission metal release data are currently being analyzed and will permit validation and/or calibration of FIPER code predictions of metallic release from HTGR fuel elements by comparison of predicted and measured values of release. In addition, comparison of predictions with other validation tests (CPL, FSV, Peach Bottom, and capsules) will be performed to establish confirmation and reliability of code predictions (Ref. 4-13).

Test Section Description

The SSL-1 loop is of the "nozzle injection" type with central injection. This arrangement allows confinement of the principle circuit to a smaller space, thereby limiting thermal loss. The in-pile section of the loop consists of three principle parts (Fig. 4-11):

1. A double pressure casing which allows heat exchange between hot helium leaving the fuel element and cool water and allows regulation of the fuel element temperature by varying the conductance of the helium gap (containing a mixture of helium and nitrogen in variable proportions).
2. A tube support of the nozzle and fuel element which includes the biological protections and the injector and is equipped with thermocouples that measure gas temperatures in the injection nozzle, on the level of the induced circuit, and in the cold section of the recuperator.

Fig. 4-11. SSL-1 in-pile loop and instrumentation

3. A gas-gas recuperator which consists of cylindrical tubes in a concentric arrangement on the outside of the tube support that insulate the two ring-shaped circuits for return of the gas.

The out-of-pile section of the loop consists of several principle components, including the helium purification system, on-line gas analysis apparatus, the coolant impurity injection circuit, and monitoring devices for gaseous fission products.

The fuel element was designed so that it represented a geometric unit cell of an HTGR fuel element (Fig. 4-12). The fuel element was made of Pechiney P₃JHAN graphite with 18 of the 27 GA fuel rods carbonized in place and nine fuel rods carbonized in Al₂O₃ at GA.

A graphite plateout sleeve was installed in the loop downstream from the outlet of the coolant holes of the fuel element and served to absorb a portion of the metallic fission products released from the fuel during irradiation (Fig. 4-11). The structure consisted of two concentric graphite rings with the following characteristics:

Length of rings	40 cm
Radial gap between rings	0.4 cm
Thickness of rings	0.5 cm
Inner ring diameter	3.8 cm I.D.
Outer ring diameter	5.6 cm I.D.

A summary of in-pile design basis test conditions is given in Table 4-3.

In-pile fuel characteristics were ascertained by monitoring fission gas release during irradiation. Measurements from postirradiation

Fig. 4-12. SSL-1 fuel element

TABLE 4-3
LIMITING TEST CONDITIONS FOR SSL-1 LOOP

Maximum fast fluence	$5.5 \times 10^{21} \text{ n/cm}^2 \text{ (E > 0.18 MeV)}$
Fuel particle burnups	10.5% for (8Th,U)O ₂ fissile particles 4.3% for ThO ₂ fertile particles
Steady-state maximum fuel temperature	$1200^\circ\text{C} < t < 1300^\circ\text{C}$
Maximum linear fuel rod power rating	191 W/cm
Total oxidant impurity level	$10 \pm 3 \text{ vpm}$
Coolant pressure	$60 \pm 5 \text{ atm}$

examination (PIE) were used to determine the fuel particle failure fraction and physical changes that occurred in the integral assembly of fuel rods and graphite during irradiation.

In-pile measurements important to FIPER code analyses include: (1) graphite and helium temperatures (continuous), (2) neutron flux (continuous), (3) helium flow rate and coolant impurities (daily), and (4) gaseous fission product release of Kr-85m and other isotopes (intermittently).

PIE measurements important to FIPER code validation include: (1) gamma-scan of fuel element, graphite plateout sleeve, and metallic structures surrounding the fuel element; (2) axial and radial fission product profile measurements for fuel element parts and the graphite plateout sleeve; and (3) determination of failed fuel fraction by metallography and fission gas release measurements.

Procedure Sequence

The following sequence of steps is being followed for validation analysis of the SSL-1 data and predictions. (A similar procedure will be followed for other validation tests.)

1. Design basis values of all FIPER code input parameters (see Table 4-4) affecting release are listed. Appropriate values are selected from preoperational design basis data or from the HTGR reference data file. Particular attention is given to the following inputs:
 - a. Geometry. Slab or cylindrical geometry may be used as is appropriate, but care is taken when evaluating equivalent

fuel and graphite thicknesses. When one geometry is selected for use, selective comparative runs utilizing the other geometry option are performed to allow comparison of release predictions with other code validation tests.

- b. Sorption Ratio. Due to the lack of PIE measurements of the sorption ratio, values are calculated in a manner analogous to TRAFIC code calculations, i.e., by the use of reference sorption isotherms and the expected temperature drop across the fuel rod - graphite gap.
 - c. Temperature. Since temperature has been shown to have a very marked effect on release predictions, selection of appropriate temperatures receives close scrutiny. This is particularly important when carrying out final predictions using operational and PIE temperatures.
 - d. Fraction of failed fissile or fertile particles. The release of cesium (and other mobile fission metals) from intact BISO particles can be accounted for in FIPER calculations by incorporating an added incremental fraction of failed fissile or fertile particles (using prior calculations of cesium release from an intact particle and the spherical coordinate option of FIPER Q). If this method is used, the magnitude of the effect of its inclusion in release calculations is estimated in order to allow comparison with other validation tests that may not use this option.
2. Nominal release FIPER calculations are performed for Cs and Sr (at a minimum) using input data and assumptions listed in Table 4-4. Included are metallic release to the coolant at each rod

TABLE 4-4
SSL-1 FIPER CODE INPUT VARIABLES

Geometry - slab, cylindrical, or spherical
Source - 0, constant, or two-component release model
Graphite coolant interface boundary conditions
Calculational time
Calculational time steps
Temperatures of mesh point at time t_i
Outer boundary surface area
Sorption ratio
Diffusion coefficient of metal in matrix
Activation energy for diffusion in matrix
Diffusion coefficient of metal in graphite
Activation energy for diffusion in graphite
Specific fission power
Fraction of fissions in fissile particles
Fraction of failed fissile particles
Fraction of failed fertile particles
Release constant for intact fuel particles
Release constant for failed fuel particles
Activation energy for intact fuel particles
Activation energy for failed fuel particles
Vapor pressure of metal fission products
Fission product metal condensed phase monolayer concentration
Concentration of fission product metal in coolant bulk
Diffusion coefficient of metal in He
Viscosity of gas
Helium pressure
Helium temperature
Single channel gas flow rate

layer, total release to the coolant, and predictions of metallic profiles in graphite.

3. When operational and PIE data become available, predictions are updated with revised input data. Revised input data will likely include the following: (1) temperatures at selected mesh points, (2) sorption ratio (due to temperature dependence), (3) specific fission power, (4) fraction of fissions - fissile, and (5) fraction of failed fissile and failed fertile particles.
4. Sensitivity studies with FIPER are performed about each selected nominal input variable that could affect metallic release. To allow for the use of a propagation-of-errors treatment, data are represented graphically as the log of release versus the log of the input parameter change (Figs. 4-13 and 4-14). In addition, variances of parameters are tabulated by using previously derived values, when available, or by deriving values from estimates of uncertainty in operational and PIE data. Confidence limits are assigned to predicted release.
5. Values of metallic release determined during PIE, including release to graphite, metallic circuit components, and the graphite plateout sleeve, are summed. Confidence limits are assigned to release based on uncertainties in measurement techniques.
6. Predicted and measured values of release are compared, including location and overlap of confidence bands.
7. Results are documented for comparison with validation results from other experiments. These include:

Fig. 4-13. Sensitivity of FIPER predictions of Cs release from SSL-1 rod layer 5 to changes in the sorption ratio. $\text{Log } R/R_0 = \log(\text{revised release})/(\text{nominal release})$.

Fig. 4-14. Sensitivity of FIPER predictions of Cs release from SSL-1 rod layer 5 to changes in the diffusion coefficient in graphite. $\text{Log } R/R_0 = \log(\text{revised release})/(\text{nominal release})$.

- a. Mean (or median) calculated result.
- b. 1 σ and 2 σ confidence bands on calculated data.
- c. Measured metallic release and confidence band.
- d. Numeric difference of measured value and calculated nominal value, including extent of overlap of confidence bands.

Completion of the above steps will provide calibration of the FIPER code once similar results are available from other validation tests.

Validation of the code can be accomplished by verifying that each differential step modeled by FIPER is done correctly. After calibration, the procedure list below is followed to permit validation of the input data and the code:

1. An incremental quantity measured during PIE and modeled by FIPER is selected, and appropriate confidence bands are applied. Examples of incremental quantities selected might include:
 - a. Intact BISO inventory.
 - b. Failed BISO/TRISO inventories.
 - c. Matrix inventory.
 - d. Sorption ratio.
 - e. Graphite inventory and profiles.
2. Predicted and measured incremental data results and confidence bands are compared, as well as the summation of incremental results. These results are compared to results available from other validation studies.

3. For quantities having large effects on release (as determined from sensitivity studies) and for significant differences between measured and observed results, the following steps are followed:
 - a. A detailed review of the PIE techniques, input data base, and design methods is carried out, including identification of assumptions and limitations.
 - b. Results of step (a) are correlated and compared with results from additional tests.
 - c. If results do not correlate, a scoping laboratory/PIE test or model review will be instituted.
 - d. If the anomaly persists in several validation tests, a detailed experimental program and/or recommended changes in code modeling will be developed.

To date, efforts have been directed toward collecting input and operational data (see Table 4-4) and performing nominal release calculations. FIPER sensitivity studies are currently being performed about the nominal values to identify important parameters in release calculations. Figures 4-13 and 4-14 demonstrate the effect on release of two important variables, the sorption ratio and the cesium diffusion coefficient in graphite. Analogous curves are being generated for all variables and will be utilized, in conjunction with assigned variances, to determine confidence bands on results.

ANALYSIS OF TRANSPORT MECHANISMS

A simplified yet realistic method of obtaining an estimate of metallic fission product release (specifically cesium) into the primary coolant

circuit was briefly described in Ref. 4-10, where it was applied to a non-Fickian transport mechanism. More recently this method has been applied to an analysis of the effect of sorptivities of the fuel rod and the graphite web in a typical HTGR configuration. This required taking into account the effect of changes in the diffusion coefficient in the web. Sorptivities could change, for example, by irradiation or by impregnation of the graphite.

The initial step is to consider the steady-state rate of release from the fuel block, which can be considered a function of the concentration on the inner surface of the graphite web or "reference" concentration. The steady-state release rate versus the reference concentration is plotted in Fig. 4-15a for a typical temperature of 1000°C and typical conditions. The three portions of the line represent three transport regimes in which helium film, diffusion, and transverse flow respectively are controlling. The first determines the rate of release at low concentrations, the second at intermediate concentrations, and the third at the highest concentrations.

The effect of increasing the sorptivity (v) of the graphite is shown in Fig. 4-15b. Release in the diffusion regime is unaffected although its boundaries are shifted, while in the other two regimes the release is reduced. The effect of reducing the diffusion coefficient is complementary, as shown in Fig. 4-15c. Both changes combined shift the entire line, as shown in Fig. 4-15d.

Consideration of simultaneous changes in sorptivity of the web graphite (v) and in the diffusion coefficient (D) is important because the transport of cesium is more likely to be driven in reality by the gradient of chemical activity (or vapor pressure) than by simple concentration. The diffusion coefficient is defined in terms of the concentration gradient and is independent of sorptivity. Hence if sorptivity changes and transport is

Fig. 4-15. Steady-state cesium release rate as a function of reference concentration (a) and the effect of tenfold changes in web sorptivity (b), diffusion coefficient (c), and both (d). The dashed line and the solid line would be the same in (a).

correspondingly affected, D must also change to permit correct calculations. Therefore, two situations are considered, one with D independent of v and the other with D varying inversely with v . Figure 4-15b shows the effect of varying v at constant D , and Fig. 4-15d shows the effect at inversely varying D .

The reference concentration depends on the cesium content of the block; however, for a given block content its value will depend on a number of factors among which the most significant are the relative sorptivities of the web (v) and the rod (Φ). The value of Φ has no effect on the curves in Fig. 4-15 but is important in establishing the value of the reference concentration for a given amount of cesium in the block. Figure 4-16 shows the fraction of the cesium liberated by the fuel particles that is held by the graphite in a typical case as a function of the ratio Φ/v . The reference concentration is almost proportional to this fraction.

The end-of-life release is a complicated function of the rate of liberation of cesium by the fuel particles and of its release. The block content of liberated cesium increases as liberation proceeds, but this increase is slowed down (or can be reversed) by the release. The simplest situation is when the release is small, so that its effect on block content can be neglected. The block content and the reference concentration then simply increase with liberation. However, release itself is a function of this concentration, as shown in Fig. 4-15. Hence, a semiquantitative estimate can be obtained of the effect of sorptivity upon release by considering its effect upon the reference concentration, the diffusion coefficient, and the vapor pressure.

1. In the diffusion-controlled regime, the following applies:
 - a. If the diffusion coefficient remains constant, the release rate is proportional to the reference concentration. Figure

Fig. 4-16. Distribution of total cesium between rod and web as a function of the ratio of their sorptivities

4-16 shows the dependence of the reference concentration on the ratio Φ/v . When Φ/v is low, changes in either Φ or v have no effect on the concentration and, therefore, on the release. At high Φ/v values, the release is lower and decreases proportionately with increasing Φ . However, increasing v increases the reference concentration proportionately and therefore the release.

- b. If D varies inversely with v , the effect of changing Φ is the same. However at low Φ/v , since the reference concentration does not change as v increases but the diffusion coefficient decreases, the release also decreases. At high Φ/v values, increasing v raises the reference concentration as indicated above, but in this case the diffusion coefficient is reduced in exactly the same proportion and the release remains unchanged. This situation is shown in Fig. 4-17.

- 2. In the film control regime, the diffusion coefficient plays no role, and the rate of release depends only on the vapor pressure on the outside of the web. This, in turn, depends on both the sorptivity and the concentration at that point, but under film control the latter is also essentially the reference concentration. Hence, the reference concentration and web sorptivity determine the release.

- a. At extremely low concentration, the vapor pressure is presumably proportional to the concentration. The release rate is then proportional to the concentration and inversely proportional to the sorptivity, so that the situation is exactly the same as in case 1b and Fig. 4-17.

Fig. 4-17. Idealized variation of release with changes in the sorptivities of the rod (Φ) and web (ν) when D varies inversely with ν

- b. At higher concentrations, the vapor pressure follows a Freundlich isotherm and increases faster than concentration, and therefore decreases more than proportionately with increasing v . Hence in the region where the concentration is independent of Φ/v and release is reduced by increasing v , i.e., at low Φ/v values, the effect of web sorptivity is to decrease release more than proportionately. In this case, changing rod sorptivity has no effect. On the other hand, at high Φ/v , changing web sorptivity does not change its vapor pressure, which is determined by the rod, and therefore has no effect upon release; however, changing rod sorptivity changes the vapor pressure, and the release, more than proportionately. Thus the situation is similar to that shown in Fig. 4-17, but the horizontal portions of the lines are more widely spaced and the slanted portions fall off more steeply.
3. The transverse-flow control regime shows the same characteristics as case 2b, but occurs at such high cesium block contents that it is of no practical interest.

The basic trends discussed above are, of course, subject to limitations. Thus when the release is large, all the effects are reduced in magnitude since the release cannot exceed 100% and approaches this value asymptotically. If time-lag effects become significant, i.e., the diffusion coefficient becomes small enough, then diffusion coefficient changes become more significant because the time available for release becomes effectively shortened or lengthened by the diffusional time lag. However, as discussed in connection with the non-Fickian model, this may not be a real effect. Furthermore, changes in web sorptivity and in the diffusion coefficient can cause transitions from diffusion control to film control, or vice versa, for the same cesium content.

In conclusion, the effect of changing the sorptivity of the rod or web depends on a number of factors, the most important among these being the starting conditions with regard to distribution of cesium between rod and web and the controlling release mechanism. In addition, the effect of sorptivity changes in the web upon the diffusion coefficient can determine the effect of changing this sorptivity.

As a rule, increasing rod sorptivity is beneficial (i.e., decreases release). Increasing web sorptivity is also beneficial except that at constant diffusion coefficient, increased web sorptivity may tend to increase the release in some cases.

COUPLED TWO-COMPONENT DIFFUSION MODEL FOR METALLIC FISSION PRODUCTS IN GRAPHITE

A number of recent studies of the diffusion of strontium (Ref. 4-3), barium (Ref. 4-4), and cesium (Ref. 4-5) in graphite have indicated two postulated types of transport:

1. A slow (bulk or in-grain) diffusion.
2. A relatively fast in-pore or grain boundary surface diffusion.

These occur together so that concentration profiles and permeation rates differ from expected results for simple Fickian diffusion.

Chandra and Norman (Ref. 4-5) have treated the diffusion of cesium as a process that can be described by the grain boundary model of Fisher (Ref. 4-14) and have satisfactorily applied this model to cesium concentration profiles and permeation behavior in graphite. As a more general but related approach, a set of two coupled diffusion equations is proposed as a

model for fast and slow diffusion behavior. The advantage of this model is that it can be readily programmed in a computer code (FIPER) and can be used to describe a variety of postulated reactor initial and boundary conditions.

Preliminary application of the mathematical model to in-pile cesium-graphite diffusion data obtained from metallic diffusion samples of Peach Bottom fuel test elements (Ref. 4-2) and from the spine of Peach Bottom fuel element D13-05 (Ref. 4-15) has been carried out. The coupled equations are:

$$\begin{aligned} D_1 \nabla^2 C_p - K_1 C_p + K_2 C_b &= \frac{\partial C_p}{\partial t} \\ D_2 \nabla^2 C_b - K_2 C_b + K_1 C_p &= \frac{\partial C_b}{\partial t} \end{aligned} ,$$

where $D_1 > D_2$

$K_1 > K_2$

$C^* = C_p + C_b$

C_p = concentration of atoms on graphite pore surfaces

C_b = concentration of atoms in the bulk of the graphite

D_1 = pore surface diffusion coefficient

D_2 = bulk diffusion coefficient

K_1 = rate coefficient for transfer of atoms from the pores to the bulk

K_2 = rate coefficient for transfer of atoms from the bulk to the pores

The in-pile experiments of interest had a geometry and initial and boundary conditions approximately corresponding to an infinite cylinder of radius $r = a$ and values of total concentration, $C(r,t)$, corresponding to:

$$\begin{aligned} C(r,0) &= 0 & (\text{time, } t = 0), \\ C(a,t) &= C_o & (t > 0) . \end{aligned}$$

*Total metal atom concentration.

From the equation $C = C_p + C_b$,

$$C_{po} + C_{bo} = C_o \quad .$$

Since the pore and bulk concentrations will tend to be in equilibrium at $r = a$ at all times,

$$C_{po} K_1 = C_{bo} K_2 \quad .$$

For the case of constant D and K coefficients, the solutions for C_p and C_b have been found to be:

$$C_p(r,t) = C_{po} + \sum_{n=1}^{\infty} J_o(\omega_n r) \left[B_{1n} A_{1n} \exp(\alpha_{1n} t) + B_{2n} A_{2n} \exp(\alpha_{2n} t) \right]$$

and

$$C_b(r,t) = C_{bo} + \sum_{n=1}^{\infty} J_o(\omega_n r) \left[A_{1n} \exp(\alpha_{1n} t) + A_{2n} \exp(\alpha_{2n} t) \right] \quad .$$

The total concentration (observed as a concentration profile) is then given by

$$C(r,t) = C_o + \sum_{n=1}^{\infty} J_o(\omega_n r) \left[A_{1n} (B_{1n} + 1) \exp(\alpha_{1n} t) + A_{2n} (B_{2n} + 1) \exp(\alpha_{2n} t) \right] ,$$

where ω_n are roots corresponding to the Bessel function $J_o(\omega a) = 0$

and

$$\alpha_{in} = - \frac{(D_1 + D_2) \omega_n^2 + (K_1 + K_2) \pm \sqrt{(D_1 - D_2)^2 \omega_n^4 + 2(D_1 - D_2)(K_1 - K_2) \omega_n^2 + (K_1 + K_2)^2}}{2}$$

i = 1 with + sign

i = 2 with - sign

Since $D_1 > D_2$ and $K_1 > K_2$, the α values are not imaginary and both are negative.

$$B_{1n} = \frac{\alpha_{1n} + K_2 + D_2 \omega_n^2}{K_1}$$

$$B_{2n} = \frac{\alpha_{2n} + K_2 + D_2 \omega_n^2}{K_1}$$

$$A_{1n} = - \frac{2C_o}{\omega_n a J_1(\omega_n a)} \left[\frac{B_{2n} K_1 - K_2}{(K_1 + K_2)(B_{2n} - B_{1n})} \right]$$

$$A_{2n} = \frac{2C_o}{\omega_n a J_1(\omega_n a)} \left[\frac{B_{1n} K_1 - K_2}{(K_1 + K_2)(B_{2n} - B_{1n})} \right]$$

These solutions have been programmed so that $C_p(r,t)$, $C_b(r,t)$, and $C(r,t)$ can be readily calculated from given values of the parameters C_o , a , D_1 , D_2 , K_1 , and K_2 .

The solutions have the following characteristics relative to time t and the penetration distance $a - r$:

$t < \frac{a^2}{D_1} < \frac{a^2}{D_2}$ Early transient stage; both C_p and C_b decrease rapidly with penetration ($a - r$).

$\frac{a^2}{D_1} < t < \frac{a^2}{D_2}$ Fast diffusion at approximately a steady-state and slow diffusion in transient state.

$$C_p \approx C_{po} I_o(r\sqrt{K_1/D_1}) / I_o(a\sqrt{K_1/D_1})$$

$$C_b \approx C_{bo} \operatorname{erfc}[(a - r)/\sqrt{D_2 t}], \text{ for } (a - r) \leq \sqrt{D_2 t}$$

$$\frac{a^2}{D_1} < \frac{a^2}{D_2} < t$$

Fast diffusion at steady state and slow diffusion approaching steady state, plus C_p and C_b about at equilibrium; thus, $C_p K_1 - C_b K_2 \approx 0$, which is near saturation.

At steady-state, flux is given by $J = -D_{ss} \, dc/dx$,

$$\text{where } D_{ss} = \frac{K_2 D_1 + K_1 D_2}{K_1 + K_2} .$$

Table 4-5 and Fig. 4-18 give preliminary data on diffusion parameters obtained from fitting cesium concentration profiles of two fuel test element diffusion crucible center posts (Ref. 4-2) and of one Peach Bottom D13-05 fuel element spine (position 13) (Ref. 4-15). Values of D_{ss} ["effective" diffusion coefficient for Cs flow (permeation) under steady-state conditions] are compared with reference or previously determined diffusion coefficients, D_{Cs} .

TRITIUM PERMEATION RATE THROUGH STEAM GENERATOR TUBE MATERIALS

Experiments have been performed to determine:

1. Tritium permeation rate through the steam generator tubes as a function of hydrogen concentration, temperature, tritium specific activity, and steam generator tube material.
2. Effect on tritium permeation rate of the presence of a hydrogen flux in the tube wall in a direction opposite to that of the tritium flux.

This work is needed because in an operating HTGR core, the helium coolant contains both tritium and hydrogen. In addition, the nascent hydrogen

TABLE 4-5
DIFFUSION PARAMETERS OBTAINED FROM FITTING CESIUM PROFILES OF
PEACH BOTTOM FUEL TEST ELEMENT AND SPINE SAMPLES

Experiment	Time (sec)	Temp (°C)	K_1/D_1 (cm ⁻²)	K_1/K_2	D_1 (cm ² /sec)	D_2 (cm ² /sec)	D_{ss} (cm ² /sec)	Other D (cm ² /sec)
FTE-1-2 Center post Cs-134 a = 0.559 cm	2.18×10^7	~700	7.2	72	0.5×10^{-8}	2.8×10^{-12}	6.9×10^{-11}	
D-13-05 spine Position 13 Cs-137 a = 2.21 cm	3.91×10^7	932	3.7	100	2.7×10^{-8}	1.5×10^{-9}	1.8×10^{-9}	D(FIPER) ^(a) 3.5×10^{-9}
FTE-3-66 Center post Cs-134 a = 0.559 cm	1.14×10^7	893	4.0	25	1.0×10^{-7}	6.5×10^{-9}	1.0×10^{-8}	D_{Cs} (ref.) ^(b) 1.8×10^{-8}

(a) Ref. 4-15.

(b) $D_{Cs}(\text{ref}) = 0.3706 \exp[-19,637/T(^{\circ}\text{K})]$.

Fig. 4-18. Cesium concentration profiles: (a) Cs-137 data from Peach Bottom Core 1, D13-05 fuel element, spine position

Fig. 4-18. Cesium concentration profiles: (b) Cs-134 data from FTE-1-2, center post

Fig. 4-18. Cesium concentration profiles: (c) Cs-134 data from FTE-3-66, center post

formed by the reaction between the steam and the tubes diffuses from the inside diameter of the tubes toward the outside diameter while the tritium in the helium coolant diffuses from the outside diameter of the tubes toward the inside diameter.

Previous measurements of tritium permeation rates employed tritium-helium mixtures prepared from a tritium source containing hydrogen impurity. Therefore, the tritium specific activity and the hydrogen concentration in the helium gas could not be varied independently. To resolve this difficulty, a high specific activity tritium source was procured from Holifield National Laboratory (HNL), from which a series of tritium-helium mixtures of different tritium specific activities and very low hydrogen contents were prepared. For each of these mixtures, controlled amounts of hydrogen can be introduced into the gas stream entering the permeation chamber to attain hydrogen concentrations from less than 10 ppm to about 20,000 ppm. The tritium permeation rate through the tubular sample wall is measured at each hydrogen concentration in the temperature range of interest. The results should indicate the variation of the tritium permeation rate with hydrogen concentration, temperature, and tritium specific activity for each type of sample material studied.

Measurements were completed on a new T22 tubular sample (15 cm long, 1.92 cm outside diameter, 1 mm wall thickness) with two tritium-helium mixtures in the temperature range 300° to 500°C. The characteristics of the two mixtures are given in Table 4-6. The microstructure of the sample is shown in Fig. 4-19.

The measured tritium permeation rates as a function of hydrogen concentration and temperature for tritium-helium mixtures 1 and 2 are shown in Fig. 4-20. For tritium-helium mixture 2, an additional measurement was made at 500°C; for this measurement the helium purge gas used to sweep out the tritium atoms diffusing through the sample wall was replaced by a helium-hydrogen mixture (hydrogen partial pressure = 50 torr, total

TABLE 4-6
CHARACTERISTICS OF TRITIUM-HELIUM MIXTURES

Tritium- Helium Mixture	Tritium Specific Activity ($\mu\text{Ci}/\text{standard cm}^3$)	Impurity Concentrations (ppm by volume)						
		O ₂	N ₂	H ₂ O	H ₂	CO	CH ₄	CO ₂
1	9×10^{-3}	2	5	3	<10	<1	<1	<1
2	8×10^{-5}	3.5	5	3	<10	<1	<1	<1

250X

Fig. 4-19. Microstructures of T22 sample after heat treatment (857°C for 1 hr, furnace cooled at 8°C/hr to 649°C, and then air cooled outside the furnace)

Fig. 4-20. Effect of hydrogen on tritium permeation rate through T22: (a) tritium specific activity = $9 \times 10^{-3} \mu\text{Ci/standard cm}^3$

Fig. 4-20. Effect of hydrogen on tritium permeation rate: (b) tritium specific activity = 8×10^{-5} $\mu\text{Ci}/\text{standard cm}^3$

pressure = 1 atm). The hydrogen in the purge gas diffused from the inside diameter of the sample toward the outside diameter and created a hydrogen flux in the sample wall in a direction opposite to that of the tritium flux. Such a hydrogen flux introduced about 1000 ppm of hydrogen into the tritium-helium mixture flowing through the permeation chamber at a rate of $100 \text{ cm}^3/\text{min}$. This measured tritium permeation rate is also shown in Fig. 4-20b.

The results in Fig. 4-20 can be summarized as follows:

1. For the $9 \times 10^{-3} \text{ } \mu\text{Ci/standard cm}^3$ tritium-helium mixture, the tritium permeation rates in the temperature range 300° to 500°C are not affected significantly by the presence of hydrogen impurity from less than a few hundred ppm to a concentration as high as about 10,000 ppm. This tritium specific activity is very close to that expected in the LHTGR coolant ($1 \times 10^{-2} \text{ } \mu\text{Ci/standard cm}^3$ at an operating helium pressure of 50 atm), and the range of hydrogen concentrations studied covers that expected in the LHTGR coolant (30 ppm at an operating pressure of 50 atm or 1500 ppm at 1 atm).
2. For the $8 \times 10^{-5} \text{ } \mu\text{Ci/standard cm}^3$ tritium-helium mixture, the effect of hydrogen on the tritium permeation rate varies with temperature and hydrogen concentration. The maximum reductions in the tritium permeation rates observed are less than factors of 5, 4, and 3 at 500° , 400° , and 300°C , respectively, for hydrogen concentrations from less than a few hundred ppm to 21,000 ppm.
3. At very low hydrogen concentrations where the effect of hydrogen on the tritium permeation rate can be ignored, an increase in tritium specific activity in the tritium-helium mixture by a factor of about 100 (from 8×10^{-5} to $9 \times 10^{-3} \text{ } \mu\text{Ci/standard cm}^3$) increases the tritium permeation rate by a factor of about 20

(compare Figs. 4-20a and 4-20b at 300° and 500°C). The change in tritium permeation rate with tritium specific activity does not seem to obey either a linear relationship or a square root relationship.

4. In classical kinetic and thermodynamic considerations of the permeation process, the tritium flux is directly proportional to the tritium atom concentration at the sample surface, and in the presence of hydrogen the tritium atom concentration is determined by the two simultaneous equilibrium equations $H_2 \rightleftharpoons 2H$ and $HT \rightleftharpoons H + T$. On the basis of these considerations, the tritium permeation rate can be shown to be proportional to $P_{HT}/\sqrt{P_{H_2}}$, where P_{HT} and P_{H_2} are the partial pressures of HT and H_2 in the helium coolant, respectively. The results observed, however, indicate that this relationship cannot be used to predict the effect of tritium specific activity and hydrogen concentration on the tritium permeation rate.
5. The presence of a hydrogen flux in an opposite direction to the tritium flux in the sample wall does not seem to affect the tritium permeation rate significantly. As shown by the experimental point included in Fig. 4-20b, the tritium permeation rate is essentially the same regardless of whether the hydrogen flux is in the same direction or in the opposite direction to that of the tritium flux.

STEAM GRAPHITE REACTION RATE CONSTANTS

An experimental program to measure the appropriate steam-graphite reaction rate constants used to assess the consequences of steam inleakage into the core of an HTGR is under way.

The computational methods for analyzing the reaction rates of steam with core graphite are based on a modified form of the Langmuir-Hinshelwood equation (Ref. 4-16):

$$R = \frac{K_1 P_{H_2O}^n F_b F_c}{1 + K_2 P_{H_2}^n + K_3 P_{H_2O}}$$

where R = graphite oxidation rate, %/hr
 P_{H_2O} , P_{H_2} = partial pressures of H_2O and H_2 in helium, atm
 F_b , F_c = linear modifiers for burnoff and catalyst effects
 K_1 = rate constant for formation of the water-graphite complex
 K_2 = hydrogen equilibrium constant
 K_3 = composite rate constant for formation and removal of the water-graphite complex
 n = order of reaction

To calculate the graphite oxidation rate R , it is necessary to estimate a value of the adsorption equilibrium constant K_2 for hydrogen on graphite and also K_1 and K_3 from the slopes of steam-graphite reaction rate isotherms at different burnoffs (Ref. 4-17). The relative magnitudes of these constants in turn affect the order of steam-graphite reactions; for example, reactor conditions could go from a first-order reaction regime at low steady-state partial pressures of water to a zero-order reaction regime at high concentration of water during postulated accident conditions. Therefore, determination of the transition of reaction order from one to zero is important to define the extent of oxidation.

Steam-graphite oxidation experiments were performed to determine the reaction order transition region. In these experiments, cylindrical samples (1/2 in. in diameter by 1/2 in. long) of H-451 graphite were

tested. The results obtained for isotherms at 880°, 930°, and 980°C are summarized in Table 4-7 and plotted in Fig. 4-21. The hydrogen concentration in helium was intentionally maintained at 5000 μ atm to suppress the effects of hydrogen concentration variations. The results obtained exhibit indications of an early trend (i.e., at low P_{H_2O}) to zero-order reaction. This trend is of particular interest from an operational point of view, as the P_{H_2}/P_{H_2O} ratios for the tests were lower than the predicted 10 to 100 for an HTGR. Further experiments are in progress to quantify this effect and to permit better understanding of the reaction kinetics.

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TABLE 4-7
H-451 GRAPHITE OXIDATION RATE: EFFECT OF STEAM PARTIAL PRESSURE

Temperature (°C)	Burnoff (%)	P _{H₂O} (μatm)	Correction Factor	Reaction Rate (mg/cm ² -sec)
880	0.60	500	0.21	3.95 x 10 ⁻⁷
	1.32	3,000	1.15	6.32 x 10 ⁻⁶
	1.33	7,100	1.15	1.10 x 10 ⁻⁵
	1.38	12,500	1.19	1.48 x 10 ⁻⁵
	1.40	34,800	1.19	1.84 x 10 ⁻⁵
930	0.89	540	0.81	3.69 x 10 ⁻⁶
	1.10	3,000	1.04	1.98 x 10 ⁻⁵
	1.13	6,900	1.05	4.08 x 10 ⁻⁵
	1.01	7,300	1.00	4.63 x 10 ⁻⁵
	1.18	12,000	1.09	4.45 x 10 ⁻⁵
	1.26	34,000	1.10	7.20 x 10 ⁻⁵
980	1.40	580	1.05	2.14 x 10 ⁻⁶
	1.43	3,000	1.06	3.35 x 10 ⁻⁵
	1.48	7,000	1.06	7.77 x 10 ⁻⁵
	1.58	11,900	1.07	1.17 x 10 ⁻⁴
	1.73	36,200	1.08	3.18 x 10 ⁻⁴

Fig. 4-21. Oxidation rate of H-451 graphite as a function of partial pressure of H₂O: (a) 880°C

Fig. 4-21. Oxidation rate of H-451 graphite as a function of partial pressure of H_2O : (b) 980° and 930°C

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TASK 8 (189a SU002)

REACTOR PHYSICS

CROSS-SECTION EVALUATION

Introduction

The calculation of burnup in an HTGR is presently performed with fission product cross sections and yields based upon evaluated data from various sources that may not be entirely consistent with other evaluated data sets such as the ENDF/B-IV library. A detailed calculation using the ENDF/B-IV fission product cross sections and yields has been performed in order to determine whether this possible inconsistency is significant for HTGR design applications. The comparison of the results of this 58 explicit fission product calculation with results obtained with current design approximations demonstrated that the error incurred is small, less than $\pm 0.001 \Delta k/k$, at the end of the irradiation interval. Discrepancies were observed at short irradiations (less than 10 days) and this should be considered when time delays are important.

An 18 explicit fission product model (and the corresponding fission product aggregates) based upon ENDF/B-IV data was also formulated and tested for possible future use in HTGR design calculations. Although the 18 explicit fission product model does not yield significantly different results compared to current HTGR design practice, the 18 fission product model would be consistent with recent data evaluations.

It should be noted that the simple 18 explicit fission product model described here would not be adequate for cases involving the use of plutonium fuel because of the pronounced shift in the light fission fragment yields in plutonium fission. The 58 explicit fission product

model used in the detailed calculation should, however, be quite adequate for use in plutonium fueled cases.

Cross-Section Preparation

The ENDF/B-IV data file contains cross section data for some 180 fission product nuclides. Not all of the 180 nuclides are of interest in reactor eigenvalue calculations. About 130 of the 180 nuclides initially appeared to be interesting enough from a reactor eigenvalue calculation point of view to warrant the preparation of cross-section library data in the GAM-II and GATHER-II group structures. Of these 130 nuclides, 116 were ultimately used in the large detailed burnup calculation. Fifty-eight nuclides were treated explicitly (see Table 8-1), 7 were lumped together into a slowly depleting aggregate (Table 8-2), and 51 nuclides were put into a nondepleting aggregate (Table 8-3). The terms slowly depleting and nondepleting as used above are commonly called slowly saturating and non-saturating at GA. These terms are used interchangeably in the following discussion.

The preparation of the GAM-II/GATHER-II group structure data sets was performed with the GFE/GAND codes (Ref. 8-1). All fission products were taken to be infinitely dilute in the preparation of the fine group library data sets.

The preparation of four broad-group cross sections (see Table 8-4 for the broad-group energy structure) for use in the diffusion-burnup calculations was performed with the MICROX code (Ref. 8-2). The MICROX setup was typical of large HTGR design calculation using separate fissile and fertile coated particles. The atom densities used in the MICROX spectrum calculation correspond to a C/Th ratio of 204, C/U-235 ratio of 7500, C/U-233 ratio of 11,250, and roughly mid-cycle fission product atom densities.

Separate MICROX calculations were run each time that the fission product cross sections were changed. Small changes in the initial core

TABLE 8-1
EXPLICIT FISSION PRODUCTS

Nuclide	Z	$T_{1/2}$	Decay Constant (sec^{-1})	σ_{2200} (barns)	RI (barns)	Thermal Reactor Fission Yield					
						Th-232	U-233	U-235	U-238	Pu-239	Pu-241
Kr-83	36	∞	0	208	192	$2.037 \cdot 10^{-2}^{(a)}$	$1.018 \cdot 10^{-2}$	$5.31 \cdot 10^{-3}$	$3.77 \cdot 10^{-3}$	$2.96 \cdot 10^{-3}$	$2.05 \cdot 10^{-3}$
Sr-89	38	50.5d	$1.589 \cdot 10^{-7}$	0.42	0.53	$7.829 \cdot 10^{-2}$	$6.257 \cdot 10^{-2}$	$4.846 \cdot 10^{-2}$	$2.975 \cdot 10^{-2}$	$1.709 \cdot 10^{-2}$	$1.215 \cdot 10^{-2}$
Y-89	39	∞	0	1.28	0.98	--	--	--	--	--	--
Zr-95	40	65.5d	$1.225 \cdot 10^{-7}$	0.49	5.36	$5.526 \cdot 10^{-2}$	$6.249 \cdot 10^{-2}$	$6.464 \cdot 10^{-2}$	$5.324 \cdot 10^{-2}$	$4.923 \cdot 10^{-2}$	$4.046 \cdot 10^{-2}$
Nb-95	41	35.1d	$2.286 \cdot 10^{-7}$	1.5	21.9	--	--	--	--	--	--
Mo-95	42	∞	0	14.5	113	--	--	--	--	--	--
Tc-99	43	$2.13 \cdot 10^5 \text{y}$	$1.031 \cdot 10^{-13}$	19.0	342	$3.015 \cdot 10^{-2}$	$4.957 \cdot 10^{-2}$	$6.127 \cdot 10^{-2}$	$6.247 \cdot 10^{-2}$	$6.144 \cdot 10^{-2}$	$6.208 \cdot 10^{-2}$
Ru-101	44	∞	0	3.1	95.2	$8.31 \cdot 10^{-3}$	$3.226 \cdot 10^{-2}$	$5.043 \cdot 10^{-2}$	$6.579 \cdot 10^{-2}$	$5.911 \cdot 10^{-2}$	$6.095 \cdot 10^{-2}$
Ru-103	44	39.6d	$2.026 \cdot 10^{-7}$	7.7	69.6	$1.67 \cdot 10^{-3}$	$1.707 \cdot 10^{-2}$	$3.137 \cdot 10^{-2}$	$6.336 \cdot 10^{-2}$	$6.991 \cdot 10^{-2}$	$6.261 \cdot 10^{-2}$
Rh-103	45	∞	0	148.2	1022	--	--	--	--	--	--
Rh-105	45	35.5h	$5.424 \cdot 10^{-6}$	16,000	15,850	$3.63 \cdot 10^{-4}$	$4.71 \cdot 10^{-3}$	$1.020 \cdot 10^{-2}$	$4.210 \cdot 10^{-2}$	$5.419 \cdot 10^{-2}$	$6.218 \cdot 10^{-2}$
Pd-105	46	∞	0	14.0	91.8	--	--	--	--	--	--
Ru-106	44	369d	$2.174 \cdot 10^{-8}$	0.15	2.08	$4.46 \cdot 10^{-4}$	$2.58 \cdot 10^{-3}$	$3.91 \cdot 10^{-3}$	$2.752 \cdot 10^{-2}$	$4.276 \cdot 10^{-2}$	$6.207 \cdot 10^{-2}$
Pd-106	46	∞	0	0.24	7.19	--	--	--	--	--	--
Pd-107	46	$6.5 \cdot 10^6 \text{y}$	$3.381 \cdot 10^{-15}$	10.0	69.9	$5.06 \cdot 10^{-4}$	$1.41 \cdot 10^{-3}$	$1.63 \cdot 10^{-3}$	$1.272 \cdot 10^{-2}$	$3.236 \cdot 10^{-2}$	$5.334 \cdot 10^{-2}$
Pd-108	46	∞	0	12.2	224	$5.34 \cdot 10^{-4}$	$6.15 \cdot 10^{-4}$	$7.11 \cdot 10^{-4}$	$6.23 \cdot 10^{-3}$	$2.234 \cdot 10^{-2}$	$4.019 \cdot 10^{-2}$
Ag-109	47	∞	0	91.8	1467	$5.99 \cdot 10^{-4}$	$4.34 \cdot 10^{-4}$	$2.99 \cdot 10^{-4}$	$2.84 \cdot 10^{-3}$	$1.411 \cdot 10^{-2}$	$2.284 \cdot 10^{-2}$

TABLE 8-1 (Continued)

Nuclide	Z	$T_{1/2}$	Decay Constant (sec^{-1})	σ_{2200} (barns)	RI (barns)	Thermal Reactor Fission Yield					
						Th-232	U-233	U-235	U-238	Pu-239	Pu-241
Cd-113	48	9+15y	2.441-24	19,880	405	6.02-4	1.32-4	1.24-4	4.75-4	7.81-4	1.55-3
Cd-114	48	∞	0	0.34	19.2	7.70-4	1.23-4	1.13-4	4.11-4	4.68-4	7.55-4
In-115	49	5+14y	4.393-23	20.2	3181	8.76-4	1.12-4	1.03-4	4.21-4	3.69-4	4.57-4
Te-129m	52	33.4d	2.402-7	1.10	6.02	9.24-4	3.88-3	1.58-3	2.67-3	3.61-3	1.87-3
I-129	53	1.59+7y	1.381-15	27.0	36.1	2.93-3	1.228-2	5.01-3	8.44-3	1.142-2	5.92-3
I-131	53	8.041d	9.977-7	0.70	8.02	1.453-2	3.509-2	2.836-2	3.213-2	3.743-2	3.141-2
Xe-131	54	∞	0	90	870	--	--	--	--	--	--
Xe-133	54	5.29d	1.517-6	190	356	3.658-2	6.031-2	6.790-2	6.357-2	6.966-2	6.741-2
Cs-133	55	∞	0	29.5	382	--	--	--	--	--	--
I-135	53	6.585h	2.924-5	0.02	0.015	3.518-2	4.860-2	6.349-2	6.548-2	6.303-2	6.950-2
Xe-135	54	9.17h	2.100-5	2.636+6	7,645	1.328-2	1.337-2	2.545-3	1.50-4	1.152-2	2.292-3
Cs-135	55	2.3+6y	9.556-15	8.70	61.6	1.11-6	2.104-4	1.437-5	--	7.994-5	8.47-6
Ce-141	58	32.53d	2.466-7	29.0	24.1	7.649-2	6.622-2	5.890-2	5.143-2	5.361-2	4.853-2
Pr-141	59	∞	0	11.5	19.4	--	--	--	--	--	--
Pr-143	59	13.58d	5.908-7	89	190	6.988-2	5.881-2	5.972-2	4.834-2	4.561-2	4.502-2
Nd-143	60	∞	0	325	205	--	--	--	--	--	--
Ce-144	58	284.4d	2.821-8	1.0	2.06	8.216-2	4.650-2	5.458-2	4.751-2	3.838-2	4.156-2
Nd-144	60	2.1+15y	1.046-23	3.60	5.62	--	--	--	--	--	--
Nd-145	60	∞	0	42	226	5.674-2	3.365-2	3.934-2	3.998-2	3.078-2	3.205-2
Nd-147	60	10.99d	7.300-7	49	648	3.267-2	1.775-2	2.271-2	2.711-2	2.073-2	2.260-2

TABLE 8-1 (Continued)

Nuclide	Z	$T_{1/2}$	Decay Constant (sec^{-1})	σ_{2200} (barns)	RI (barns)	Thermal Reactor Fission Yield					
						Th-232	U-233	U-235	U-238	Pu-239	Pu-241
Pm-147	61	2.623y	8.380-9	182 ^(b)	2283 ^(b)	--	--	--	--	--	--
Sm-147	62	1.07+11y	2.053-19	62	748	--	--	--	--	--	--
Pm-148m	61	41.3d	1.943-7	10,616	3608	--	--	--	--	--	--
Pm-148g	61	5.37d	1.494-6	2000	40,000	--	--	--	--	--	--
Sm-148	62	8+15y	2.746-24	2.7	27.4	--	--	--	--	--	--
Pm-149	61	53.1h	3.626-6	1400	801	9.38-3	7.69-3	1.089-2	1.765-2	1.261-2	1.463-2
Sm-149	62	>1.16y	<2.198-24	41,191	3066	--	--	--	--	--	--
Sm-150	62	∞	0	102	320	--	--	--	--	--	--
Pm-151	61	28.4h	6.780-6	700	2003	1.75-3	3.22-3	4.20-3	8.54-3	7.78-3	9.02-3
Sm-151	62	93y	2.363-10	15,000	3357	--	--	--	--	--	--
Sm-153	62	∞	0	206	3008	7.97-4	2.08-3	2.71-3	5.57-3	5.96-3	7.17-3
Sm-153	62	46.5h	4.141-6	330	2819	3.17-4	1.07-3	1.62-3	4.12-3	3.73-3	5.28-3
Eu-153	63	∞	0	453	1380	--	--	--	--	--	--
Eu-154	63	8.6y	2.556-9	1506	2287	--	--	--	--	--	--
Gd-154	64	∞	0	85	248	--	--	--	--	--	--
Sm-154	62	∞	0	5.5	33.9	9.70-5	4.56-4	7.46-4	2.30-3	2.77-3	3.80-3
Eu-155	63	4.8y	4.579-9	4040	1856	5.04-5	2.13-4	3.30-4	1.33-3	1.71-3	2.32-3
Gd-155	64	∞	0	61,000	1542	--	--	--	--	--	--
Eu-156	63	15.2d	5.278-7	482	1486	2.69-5	1.17-4	1.35-4	6.91-4	1.20-3	1.70-3
Gd-156	64	∞	0	1.5	130	--	--	--	--	--	--
Gd-157	64	∞	0	254,470	973	1.16-5	6.77-5	6.46-5	3.77-4	7.63-4	1.32-3

(a) $2.037-2 = 2.037 \times 10^{-2}$.

(b) 53.7% to Pm-148m, 46.3% to Pm-148g.

TABLE 8-2
SLOWLY SATURATING AGGREGATE (SSAG)

Nuclide	Z	$T_{1/2}$	Decay Constant (sec^{-1})	σ_{2200} (barns)	RI (barns)	Thermal Reactor Fission Yield					
						Th-232	U-233	U-235	U-238	Pu-239	Pu-241
Ge-73	32	∞	0	15	69.9	$4.97-6$ (a)	$1.13-5$	$1.06-6$	$4.63-7$	$2.37-6$	$6.06-7$
Se-77	34	∞	0	42	36.5	$1.26-4$	$2.61-4$	$8.29-5$	$3.04-5$	$7.30-5$	$2.02-5$
Er-79	35	∞	0	11.1	137	$7.17-4$	$1.43-3$	$5.08-4$	$1.57-4$	$4.78-4$	$1.67-4$
Cd-111	48	∞	0	24.3	54.6	$8.50-4$	$2.03-4$	$1.98-4$	$8.17-4$	$2.74-3$	$5.73-3$
Sb-121	51	∞	0	6.26	207	$5.24-4$	$1.42-4$	$1.29-4$	$3.61-4$	$3.64-4$	$2.39-4$
Sb-123	51	∞	0	4.33	128	$3.57-4$	$3.27-4$	$1.63-4$	$3.97-4$	$4.41-4$	$2.50-4$
I-127	53	∞	0	6.2	155	$9.54-4$	$6.79-3$	$1.30-3$	$1.30-3$	$4.92-3$	$2.30-3$
						$3.53-3$	$9.16-3$	$2.38-3$	$3.06-3$	$9.02-3$	$8.71-3$

(a) $4.97-6 = 4.97 \times 10^{-6}$.

TABLE 8-3
NON-SATURATING AGGREGATE (NSAG)

Nuclide	Z	$T_{1/2}$	Decay Constant (sec^{-1})	σ_{2200} (barns)	RI (barns)	Thermal Reactor Fission Yield					
						Th-232	U-233	U-235	U-238	Pu-239	Pu-241
Ge-72	32	∞	0	0.98	1.14	$3.51 \cdot 10^{-6} \text{ (a)}$	$5.17 \cdot 10^{-6}$	$2.49 \cdot 10^{-7}$	$2.90 \cdot 10^{-7}$	$1.05 \cdot 10^{-6}$	$2.63 \cdot 10^{-7}$
Ge-74	32	∞	0	0.38	0.61	$8.03 \cdot 10^{-6}$	$2.81 \cdot 10^{-5}$	$3.48 \cdot 10^{-6}$	$1.28 \cdot 10^{-6}$	$5.61 \cdot 10^{-6}$	$1.01 \cdot 10^{-6}$
As-75	33	∞	0	4.3	61.8	$2.21 \cdot 10^{-5}$	$8.45 \cdot 10^{-5}$	$1.13 \cdot 10^{-5}$	$4.52 \cdot 10^{-6}$	$1.31 \cdot 10^{-5}$	$3.03 \cdot 10^{-6}$
Ge-76	32	∞	0	0.14	1.35	$5.71 \cdot 10^{-5}$	$1.50 \cdot 10^{-4}$	$3.59 \cdot 10^{-5}$	$8.24 \cdot 10^{-6}$	$2.90 \cdot 10^{-5}$	$1.01 \cdot 10^{-5}$
Se-78	34	∞	0	0.40	4.58	$3.40 \cdot 10^{-4}$	$6.22 \cdot 10^{-4}$	$1.66 \cdot 10^{-4}$	$8.73 \cdot 10^{-5}$	$2.81 \cdot 10^{-4}$	$7.30 \cdot 10^{-5}$
Se-80	34	∞	0	0.61	1.08	$1.76 \cdot 10^{-3}$	$2.44 \cdot 10^{-3}$	$1.23 \cdot 10^{-3}$	$5.00 \cdot 10^{-4}$	$1.16 \cdot 10^{-3}$	$3.35 \cdot 10^{-4}$
Br-81	35	∞	0	2.69	50.2	$3.88 \cdot 10^{-3}$	$3.12 \cdot 10^{-3}$	$2.10 \cdot 10^{-3}$	$1.27 \cdot 10^{-3}$	$1.77 \cdot 10^{-3}$	$6.47 \cdot 10^{-4}$
Se-82	34	∞	0	0.05	0.09	$1.024 \cdot 10^{-2}$	$5.64 \cdot 10^{-3}$	$3.64 \cdot 10^{-3}$	$2.55 \cdot 10^{-3}$	$2.15 \cdot 10^{-3}$	$1.16 \cdot 10^{-3}$
Kr-84	36	∞	0	0.08	3.53	$3.722 \cdot 10^{-2}$	$1.703 \cdot 10^{-2}$	$9.88 \cdot 10^{-3}$	$7.53 \cdot 10^{-3}$	$4.80 \cdot 10^{-3}$	$3.54 \cdot 10^{-3}$
Kr-85	36	10.73y	$2.048 \cdot 10^{-9}$	1.66	1.67	$3.821 \cdot 10^{-2}$	$2.195 \cdot 10^{-2}$	$1.314 \cdot 10^{-2}$	$7.58 \cdot 10^{-3}$	$5.68 \cdot 10^{-3}$	$3.96 \cdot 10^{-3}$
Kr-86	36	∞	0	0.06	0.14	$6.095 \cdot 10^{-2}$	$2.864 \cdot 10^{-2}$	$1.952 \cdot 10^{-2}$	$1.195 \cdot 10^{-2}$	$7.59 \cdot 10^{-3}$	$6.14 \cdot 10^{-3}$
Rb-87	37	long	$4.699 \cdot 10^{-19}$	0.12	2.09	$6.483 \cdot 10^{-2}$	$4.009 \cdot 10^{-2}$	$2.546 \cdot 10^{-2}$	$1.523 \cdot 10^{-2}$	$9.49 \cdot 10^{-3}$	$7.57 \cdot 10^{-3}$
Sr-88	38	∞	0	0.006	0.012	$6.848 \cdot 10^{-2}$	$5.495 \cdot 10^{-2}$	$3.627 \cdot 10^{-2}$	$2.292 \cdot 10^{-2}$	$1.370 \cdot 10^{-2}$	$9.75 \cdot 10^{-3}$
Sr-90	38	29y	$7.549 \cdot 10^{-10}$	0.90	0.51	$7.998 \cdot 10^{-2}$	$6.796 \cdot 10^{-2}$	$5.914 \cdot 10^{-2}$	$3.354 \cdot 10^{-2}$	$2.118 \cdot 10^{-2}$	$1.536 \cdot 10^{-2}$
Zr-91	40	∞	0	1.03	5.84	$7.105 \cdot 10^{-2}$	$6.519 \cdot 10^{-2}$	$5.919 \cdot 10^{-2}$	$3.874 \cdot 10^{-2}$	$2.497 \cdot 10^{-2}$	$1.831 \cdot 10^{-2}$
Zr-92	40	∞	0	0.26	0.86	$7.182 \cdot 10^{-2}$	$6.594 \cdot 10^{-2}$	$5.960 \cdot 10^{-2}$	$4.211 \cdot 10^{-2}$	$3.018 \cdot 10^{-2}$	$2.278 \cdot 10^{-2}$
Zr-93	40	long	$2.314 \cdot 10^{-14}$	2.5	28.2	$7.752 \cdot 10^{-2}$	$7.009 \cdot 10^{-2}$	$6.371 \cdot 10^{-2}$	$4.843 \cdot 10^{-2}$	$3.901 \cdot 10^{-2}$	$2.964 \cdot 10^{-2}$
Zr-94	40	∞	0	0.06	0.36	$6.081 \cdot 10^{-2}$	$6.808 \cdot 10^{-2}$	$6.424 \cdot 10^{-2}$	$4.527 \cdot 10^{-2}$	$4.442 \cdot 10^{-2}$	$3.402 \cdot 10^{-2}$
Zr-96	40	∞	0	0.02	5.29	$4.889 \cdot 10^{-2}$	$5.676 \cdot 10^{-2}$	$6.253 \cdot 10^{-2}$	$5.292 \cdot 10^{-2}$	$5.097 \cdot 10^{-2}$	$4.436 \cdot 10^{-2}$

TABLE 8-3 (Continued)

Nuclide	Z	$T_{1/2}$	Decay Constant (sec^{-1})	σ_{2200} (barns)	RI (barns)	Thermal Reactor Fission Yield					
						Th-232	U-233	U-235	U-238	Pu-239	Pu-241
Mo-97	42	∞	0	2.17	16.1	4.121-2	5.453-2	5.963-2	5.530-2	5.599-2	4.821-2
Mo-98	42	∞	0	0.13	6.88	3.997-2	5.159-2	5.781-2	5.554-2	5.857-2	5.227-2
Mo-100	42	∞	0	0.20	3.85	1.497-2	4.410-2	6.305-2	6.133-2	6.983-2	6.231-2
Ru-102	44	∞	0	1.3	4.01	4.09-3	2.449-2	4.199-2	6.792-2	6.008-2	6.484-2
Ru-104	44	∞	0	0.44	6.53	9.26-4	1.028-2	1.824-2	5.437-2	5.953-2	6.976-2
Pd-110	46	∞	0	0.22	7.07	6.43-4	2.54-4	2.24-4	1.32-3	6.22-3	1.209-2
Cd-112	48	∞	0	2.20	13.81	9.06-4	1.46-4	1.28-4	5.13-4	1.07-3	2.30-3
Cd-116	48	∞	0	0.08	2.43	6.84-4	1.21-4	1.06-4	3.80-4	3.43-4	3.00-4
Sn-117	50	∞	0	2.6	18.6	5.86-4	1.10-4	1.08-4	3.61-4	3.43-4	2.62-4
Sn-118	50	∞	0	0.08	6.25	6.29-4	1.17-4	1.21-4	3.58-4	3.39-4	2.51-4
Sn-119	50	∞	0	2.30	3.91	5.61-4	1.20-4	1.12-4	3.49-4	3.50-4	2.51-4
Sn-120	50	∞	0	0.14	1.27	5.40-4	1.33-4	1.17-4	3.50-4	3.50-4	2.40-4
Sn-122	50	∞	0	0.18	0.77	4.14-4	2.18-4	1.33-4	3.68-4	3.80-4	2.36-4
Sn-124	50	∞	0	0.13	7.16	3.18-4	5.26-4	2.20-4	4.34-4	5.50-4	2.93-4
Te-125	52	∞	0	1.55	23.7	3.64-4	1.11-3	2.97-4	5.40-4	1.26-3	4.16-4
Sn-126	50	long	2.198-13	0.30	0.19	4.84-4	2.41-3	5.79-4	6.98-4	2.00-3	7.71-4
Te-128	52	∞	0	0.22	2.41	1.87-3	9.46-3	3.50-3	5.09-3	8.51-3	3.56-3
Te-130	52	∞	0	0.29	0.35	8.29-3	2.371-2	1.447-2	1.776-2	2.507-2	1.662-2
Xe-132	54	∞	0	0.95	1.73	2.661-2	4.804-2	4.248-2	5.029-2	5.264-2	4.641-2
Xe-134	54	∞	0	0.25	0.57	4.874-2	6.130-2	7.681-2	7.099-2	7.393-2	7.099-2
Xe-136	54	∞	0	0.16	0.12	5.117-2	6.906-2	6.277-2	6.011-2	6.729-2	7.305-2
Cs-137	55	30.1y	7.302-10	0.11	0.49	7.019-2	6.803-2	6.269-2	6.194-2	6.694-2	6.698-2

TABLE 8-3 (Continued)

Nuclide	Z	T _{1/2}	Decay Constant (sec ⁻¹)	σ_{2200} (barns)	RI (barns)	Thermal Reactor Fission Yield					
						Th-232	U-233	U-235	U-238	Pu-239	Pu-241
Ba-138	56	∞	0	0.35	0.20	6.914-2	5.886-2	6.824-2	5.960-2	5.714-2	6.445-2
La-139	57	∞	0	9.0	13.0	6.729-2	6.385-2	6.486-2	6.110-2	5.642-2	6.228-2
Ce-140	58	∞	0	0.57	0.44	7.914-2	6.434-2	6.326-2	5.890-2	5.575-2	5.894-2
Ce-142	58	long	4.396-25	0.95	0.83	6.638-2	6.630-2	5.931-2	4.931-2	5.016-2	4.815-2
Nd-146	60	∞	0	1.40	3.30	4.845-2	2.537-2	2.993-2	3.610-2	2.538-2	2.740-2
Nd-148	60	∞	0	2.5	20.1	2.109-2	1.287-2	1.691-2	2.259-2	1.694-2	1.926-2
Nd-150	60	∞	0	1.2	16.8	3.44-3	5.01-3	6.47-3	1.362-2	9.96-3	1.196-2
Gd-158	64	∞	0	2.5	63.1	6.58-6	2.23-5	3.22-5	1.65-4	4.09-4	8.67-4
Tb-159	65	∞	0	25.5	455	1.41-6	9.23-6	1.04-5	7.71-5	2.12-4	4.67-4
Gd-160	64	∞	0	0.77	8.57	9.42-7	2.78-6	3.75-6	2.89-5	9.74-5	1.93-4

(a) $3.51-6 = 3.51 \times 10^{-6}$.

TABLE 8-4
BROAD-GROUP ENERGY STRUCTURE

Group	Energy Limits (eV)	
	Upper	Lower
1	14.9+6	1.83+5
2	1.83+5	1.76+1
3	1.76+1	2.38
4	2.38	0.001

reactivity were observed due to the changes in graphite and heavy metal cross sections that occurred when the fission product cross sections were changed.

The 18 explicit fission product model used the explicit fission products listed in Table 8-5. The nondepleting aggregate used in the 18 explicit fission product model was constructed from the nuclides in Tables 8-2 and 8-3 plus the nuclides listed in Table 8-6. The Ag-109, Cd-113, In-115, and Gd-157 have been omitted because the cross sections for these nuclides are too large to be included in nondepleting aggregates. A smaller error (in a conservative direction with respect to end-of-life reactivity) is incurred when these nuclides are omitted. Certain yields were adjusted to approximately account for the capture parent sources (see comments in Table 8-6).

The standard HTGR design practice is to use 17 explicit fission products (all the nuclides in Table 8-5 except Kr-83) and old nondepleting aggregates dating back to the work of Garrison and Ross (Ref. 8-3).

Detailed Results of Burnup Calculations

The burnup calculations were performed with the GAUGE code (Ref. 8-4). The calculation was for a 3000-MW(t) HTGR in 120° symmetry. The time steps and resulting eigenvalues are listed in Table 8-7. The column entitled

TABLE 8-5
18 EXPLICIT FISSION PRODUCTS

Kr-83	Pm-147
Mo-95	Pm-148m
Tc-99	Sm-149
Rh-103	Sm-150
Xe-131	Sm-151
Xe-135	Sm-152
Cs-133	Eu-153
Nd-143	Eu-154
Nd-145	Eu-155

TABLE 8-6
FISSION PRODUCTS ADDED TO AGGREGATES FOR 18 NUCLIDE CALCULATION

Nuclide	Comment
Y-89	
Ru-101	
Pd-105	
Pd-106	
Pd-107	
Pd-108	
Cd-114	Yield doubled to approximate Cd-113 capture parent
I-129	Yield of Te-129m + I-129
Cs-135	Yield of (I-135 + Xe-135 + Cs-135)/1.17
Pr-141	
Nd-148	Nd-148 was already present in the NSAG; this is an addition to approximate the capture parent
Nd-150	Same as for Nd-148
Sm-154	Yield doubled to approximately account for a capture parent
Gd-156	
Gd-158	Yield of (Eu-155 + Eu-156)(0.14) + (Gd-157)(1.0)

TABLE 8-7
BURNUP CALCULATION RESULTS

Large Step (days)	No. of Small Time Steps	Small ΔT (days)	Total Time (days)	Ref. 3 σ	Ref. 3 σ 's + 58 Version 4 Fission Products + New NSAGs and Yields	Ref. 3 σ 's + 18 Version 4 Fission Products + New NSAGs and Yields
			0	1.0981 (-0.0002)	1.0983 (ref.)	1.0982 (-0.0001)
0.5	1	0.5	0.5	1.0635 (-0.0125)	1.0760	1.0635 (-0.0125)
1.5	3	0.5	2	1.0603 (-0.0020)	1.0623	1.0601 (-0.0022)
2	2	1	4	1.0572 (-0.0020)	1.0592	1.0570 (-0.0022)
4	2	2	8	1.0531 (-0.0013)	1.0544	1.0528 (-0.0016)
8	2	4	16	1.0481 (-0.0005)	1.0488	1.0476 (-0.0012)
16	2	8	32	1.0426 (-0.0010)	1.0436	1.0419 (-0.0017)
32	2	16	64	1.0394 (-0.0012)	1.0406	1.0384 (-0.0022)
64	4	16	128	1.0394 (-0.0010)	1.0404	1.0378 (-0.0026)
64	4	16	192	1.0316 (-0.0005)	1.0321	1.0297 (-0.0024)
64	4	16	256	1.0164 (-0.0003)	1.0167	1.0144 (-0.0023)
64	4	16	320	0.9974 (0.0)	0.9974	0.9953 (-0.0021)
64	4	16	384	0.9768 (+0.0001)	0.9767	0.9748 (-0.0019)
64	4	16	448	0.9560 (+0.0003)	0.9557	0.9540 (-0.0017)
64	4	16	512	0.9356 (+0.0004)	0.9352	0.9337 (-0.0015)
64	4	16	576	0.9163 (+0.0005)	0.9158	0.9145 (-0.0013)
64	4	16	640	0.8984 (+0.0006)	0.8978	0.8967 (-0.0011)
64	4	16	704	0.8822 (+0.0007)	0.8815	0.8807 (-0.0008)
64	4	16	768	0.8678 (+0.0007)	0.8671	0.8665 (-0.0006)

"Ref. 3 σ " is the standard large HTGR Reference 3 design calculation. The values given are the computed eigenvalues; the differences with respect to the detailed 58 nuclide calculation are given in parentheses.

The 58 fission product nuclide calculation used the depletion schemes shown in Figs. 8-1 through 8-3 to account for coupling between fission product nuclides.

In the 18 fission product nuclide calculation, the $A = 147$ to $A = 155$ nuclides were coupled in a linear parent/daughter chain with the exception of Pm-148m for which a fractional yield of 53.7% with respect to captures in Pm-147 was assumed. The standard (Reference 3) HTGR design calculations made the same simplification in the $A = 147$ to $A = 155$ mass range. The yields used in the standard HTGR calculation were taken from Ref. 8-5 and are compared with the ENDF/B-IV yields in Table 8-8 (for selected nuclides).

The fractional absorptions in the various fission products for the Reference 3 design calculation are compared with the 58 ENDF/B-IV fission product nuclide calculation in Tables 8-9 and 8-10. (Only the more important of the 58 explicit fission products are included.) Some reasons for the observed differences in fractional absorptions are listed in Table 8-10. Model refers to the nuclide coupling scheme and how capture and decay parents are treated.

A more detailed account of this work and the reasoning behind the selection of the specified aggregates will be included in a topical report.

REFERENCES

- 8-1. Archibald, R. A., and D. R. Mathews, "The GAF/GAR/GAND Fast Reactor Cross-Section Preparation System," USAEC Report GA-7452, Gulf General Atomic, March 1973.
- 8-2. Wälti, P., and P. Koch, "MICROX, A Two-Region Flux Spectrum Code for the Efficient Calculation of Group Cross Sections," Gulf General Atomic Report Gulf-GA-A10827, April 14, 1972.

FRACTIONAL YIELD

U-233 =	4.71-3	2.58-3	1.41-3	6.15-4	4.34-4
U-235 =	1.020-2	3.91-3	1.63-3	7.10-4	2.99-4
U-239 =	6.218-2	4.276-2	3.236-2	2.234-2	1.411-2

Fig. 8-1. A = 105 to A = 109 detailed scheme

Fig. 8-2. A = 113 to A = 116 detailed scheme

Fig. 8-3. A = 147 to A = 157 detailed scheme

TABLE 8-8
FISSION PRODUCT YIELD COMPARISON

Nuclide	U-233 Yield			U-235 Yield		
	Ref. 3	Version 4	Version 4	Ref. 3	Version 4	Version 4
			Ref. 3			Ref. 3
Mo-95	0.0640	0.06249	0.976	0.0652	0.06464	0.991
To-99	0.0516	0.04957	0.961	0.0616	0.06127	0.995
Rh-103	0.0160	0.01707	1.067	0.0285	0.03137	1.101
Xe-131	0.0351	0.03509	1.000	0.0279	0.02836	1.016
Xe-135	0.0610	0.06197	1.016	0.0651	0.06604	1.014
Cs-133	0.0606	0.06031	0.995	0.0675	0.06790	1.006
Nd-143	0.0585	0.05881	1.005	0.0593	0.05972	1.007
Nd-145	0.0337	0.03365	0.999	0.0392	0.03934	1.004
Pm-147	0.0178	0.01775	0.997	0.0223	0.02271	1.018
Pm-148m	0.0	0.0	--	0.0	0.0	--
Sm-149	0.0077	0.00769	0.999	0.0106	0.01089	1.027
Sm-150	0.0	0.0	--	0.0	0.0	--
Sm-151	0.0037	0.00322	0.870	0.0042	0.00420	1.000
Sm-152	0.0019	0.00208	1.095	0.0026	0.00271	1.042
Eu-152	0.0010	0.00107	1.070	0.0016	0.00162	1.013
Eu-154	0.0	0.0	--	0.0	0.0	--
Eu-155	0.0004	0.000213	0.533	0.0005	0.000330	0.660
NSAG 25	1.274			1.0		

TABLE 8-9
FRACTIONAL ABSORPTIONS AFTER AN
IRRADIATION OF 768 DAYS

Ref. 3 Design Calculation			58 ENDF/B-IV Fission Products		
Rank	Nuclide	Fractional Absorption	Rank	Nuclide	Fractional Absorption
1	Xe-135	2.00-2 ^(a)	1	Xe-135	2.02-2
2	Nd-143	1.76-2	2	Nd-143	1.71-2
3	NSAG 25	1.37-2	3	Cs-133	8.21-3
4	Xe-131	8.32-3	4	Xe-131	7.96-3
5	Cs-133	8.18-3	5	Rh-103	7.90-3
6	Rh-103	7.38-3	6	Sm-149	6.92-3
7	Pm-147	6.91-3	7	To-99	6.24-3
8	Sm-149	6.12-3	8	Pm-147	5.70-3
9	Nd-145	5.53-3	9	Sm-151	4.30-3
10	To-99	4.81-3	10	Nd-145	4.29-3
11	Sm-151	3.91-3	11	Sm-152	4.27-3
12	Sm-152	3.74-3	12	Eu-153	3.50-3
13	Mo-95	3.66-3	13	Sm-150	3.16-3
14	Eu-153	3.17-3	14	Mo-95	3.14-3
15	Pm-148m	3.11-3	15	Pm-148m	2.84-3
16	Eu-155	2.97-3	16	Eu-154	2.79-3
17	Eu-154	2.86-3	17	Eu-155	2.67-3
18	Sm-150	2.61-3	18	NSAG 35	2.27-3
		<u>1.247-1</u>	19	NSAG 33	2.23-3
			20	Kr-83	1.93-3
			21	Ru-101	1.41-3
			22	Pr-141	1.43-3
			23	Pm-148g	1.20-3
			24	Sm-147	6.30-4
			25	I-129	5.80-4
					<u>1.228-1</u>

(a) $2.00-2 = 2.00 \times 10^{-2}$.

TABLE 8-10
FRACTIONAL ABSORPTION COMPARISON

Rank		Nuclide	Fractional Absorption Ratio (58 Version 4) Ref. 3	Reason For Difference
58 Version 4	Ref. 3 NSAG 25 Excluded			
1	1	Xe-135	1.01	---
2	2	Nd-143	0.97	---
3	4	Cs-133	1.00	---
4	3	Xe-131	0.96	---
5	5	Rh-103	1.07	Yields
6	7	Sm-149	1.13	Model
7	9	To-99	1.30	Cross sections
8	6	Pm-147	0.82	Model
9	10	Sm-151	1.10	Yields and model
10	8	Nd-145	0.78	Cross sections
11	11	Sm-152	1.14	Cross sections
12	13	Eu-153	1.10	Cross sections
13	17	Sm-150	1.21	Cross sections and model
14	12	Mo-95	0.86	Model
15	14	Pm-148m	0.91	Model
16	16	Eu-154	0.98	---
17	15	Eu-155	0.90	Cross sections

- 8-3. Garrison, J. D., and B. W. Roos, "Fission Product Capture Cross Sections," Nucl. Sci. Eng. 12, 115 (1962) (GA-2112).
- 8-4. Wagner, M. R., "GAUGE - A Two Dimensional Few Group Neutron Diffusion-Depletion Program for a Uniform Triangular Mesh," USAEC Report GA-8307, Gulf General Atomic, March 1968.
- 8-5. Mathews, D. R., and B. G. McGehee, "A Review of Fission Product Yields and Cross Sections," Gulf General Atomic Report Gulf-GA-B12071, September 1971.

TASK 9 (189a SU003)
HTGR FUEL DEVELOPMENT AND ENGINEERING

DOSIMETER CROSS SECTIONS FOR USE IN P13Q AND OG-2 CAPSULE ANALYSES*

Introduction and Summary

Calculations have been performed to determine the following for use in postirradiation analysis of capsules P13Q and OG-2:

1. Effective activation cross sections for iron and titanium flux monitors.
2. The relationship between the equivalent fission fluence for graphite damage (Φ_D) and the fast ($E > 0.18$ MeV) fluence (Φ_f).

The results of these calculations are given in Table 9-1. Based upon these calculations, a neutron fluence of 9.0×10^{21} n/cm² ($E > 0.18$ MeV) in the ORR OG-2 and P13Q irradiations would produce the same number of displaced carbon atoms as a neutron fluence of 8.0×10^{21} n/cm² ($E > 0.18$ MeV) in a large HTGR (ratio = 1.12). Capsules OG-2 and P13Q were located in the C-3 and E-3 positions, respectively, of the ORR (Fig. 9-1).** The method of analysis used to generate these results is described below.

Calculational Scheme

The technique used to obtain this information was essentially identical to that employed in similar analyses of the GETR (Refs. 9-2, 9-3). It consists of the definition of an appropriate supercell and then the use of the TWOTRAN (Ref. 9-4) computer code to obtain the neutron flux

*This work was also funded under Task 11.
**Figures appear at the end of Section 9.

TABLE 9-1
EFFECTIVE ACTIVATION CROSS SECTIONS

	OG-2 (Position C-3 of ORR)	P13Q (Position E-3 of ORR)
$\sigma_{\text{Fe-54}}^{\text{n,p}}$	46.56	46.58
$\sigma_{\text{Ti-46}}^{\text{n,p}}$	6.61	6.63
$\frac{\Phi_D}{\Phi_f}$	1.118	1.120

spectrum at the point of interest. For reasons of accuracy and economy, a representative fission source distribution is defined and an inhomogeneous source calculation is performed.

Figure 9-2 depicts the supercell geometry used in the TWOTRAN calculations. Since the C-3 and E-3 locations are similar with respect to the proximity of fuel, control rods, and reflector blocks and since no precise loading data were available, one supercell was used for both sets of calculations. Table 9-2 contains the atomic densities assumed and Fig. 9-3 contains the fission source distribution used.

The details of the geometry used to describe the OG-2 capsule are shown in Fig. 9-4 and the atomic densities are given in Table 9-3. Analogous information for the P13Q capsule is contained in Fig. 9-5 and Table 9-4.

The fifteen group cross sections used in this study were the same as those used in the GETR analyses (Ref. 9-3). The similarity of the reactors and the large number of groups makes this an acceptable procedure. Table 9-5 contains the energy group boundaries and the fission spectrum used to distribute the source. Table 9-6 contains the cross sections of interest for irradiation analyses.

Results

The fluxes determined by the TWOTRAN calculations are listed in Table 9-7. This table shows that the fast fluence experienced by the samples in the OG-2 capsule will be ~1.3% lower than that observed by the dosimeter. The samples in the P13Q capsule, however, will see approximately the same fluence as the dosimeters. Presumably, this is because the P13Q dosimeters are centrally positioned, while the OG-2 dosimeters are located along the periphery.

Table 9-1 contains the effective activation cross sections that were obtained by averaging the cross sections given in Table 9-5 over the

TABLE 9-2
SUPERCELL ATOMIC DENSITIES

Region	H	O	Al	U-235
1	0.0400	0.0200	0.0230	7.18×10^{-5}
2	0.0400	0.0200	0.0230	7.18×10^{-5}
3	0.0309	0.0154	0.0322	9.45×10^{-5}
4	0.0406	0.0203	0.0234	1.47×10^{-4}
5	0.0406	0.0203	0.0234	7.01×10^{-5}
6	0.0406	0.0203	0.0234	1.057×10^{-4}
7	0.0406	0.0203	0.0234	1.386×10^{-4}
8	0.0309	0.0155	0.0322	4.29×10^{-5}

TABLE 9-3
OG-2 ATOMIC DENSITIES

Region	C	Al	Fe
1	--	0.0602	--
2	--	--	0.0873
3	--	0.0602	--
4	--	--	0.0810
5	0.0688	--	--

TABLE 9-4
P13Q ATOMIC DENSITIES

Region	C	Al	Fe		
1	--	0.0602	--	--	--
2	--	--	0.0873	--	--
3	0.0852	--	--	--	--
4	0.0738	--	--	8.66×10^{-6}	1.96×10^{-4}
5	0.0852	--	--	--	--
6	--	--	--	--	--

TABLE 9-5
FISSION SOURCE DISTRIBUTION

Group	E_L (eV)	χ_i
1	6.06×10^6	0.0232
2	4.49×10^6	0.0508
3	3.68×10^6	0.0574
4	3.01×10^6	0.0752
5	2.47×10^6	0.0882
6	2.02×10^6	0.0946
7	1.00×10^6	0.2999
8	4.98×10^5	0.1788
9	3.02×10^5	0.0647
10	1.83×10^5	0.0340
11	5.25×10^4	0.0279
12	9.61×10^2	0.0053
13	2.38	0
14	0.18	0
15	0	0

TABLE 9-6
GRAPHITE DAMAGE AND FLUX MONITOR CROSS SECTIONS

Group	Fe-54 (barns)	Ti-46 (barns)	$\sigma_d^{(a)}$
1	0.595	0.143	603.6
2	0.452	0.0809	581.2
3	0.306	0.0453	905.0
4	0.151	0.0163	902.7
5	0.0654	0.00144	735.9
6	0.0326	0.00009	647.9
7	0.0081	0	701.5
8	0	0	775.4
9	0	0	702.6
10	0	0	588.8
11	0	0	353.0
12	0	0	59.7
13	0	0	0.8

(a) These values differ slightly (<0.4%) from the values quoted in Ref. 9-3, which were based upon an earlier calculation.

TABLE 9-7
CALCULATED FLUX DISTRIBUTION

Energy Group	OG-2		P13Q	
	Dosimeter ^(a)	Experiment	Dosimeter ^(b)	Experiment
1	0.1076	0.1050	0.1064	0.1048
2	0.2360	0.2320	0.2359	0.2329
3	0.2590	0.2520	0.2534	0.2519
4	0.3503	0.3375	0.3346	0.3349
5	0.4789	0.4716	0.4729	0.4716
6	0.5841	0.5776	0.5801	0.5789
7	2.1960	2.1670	2.1529	2.1585
8	1.9470	1.9140	1.8810	1.8936
9	0.9883	0.9806	0.9745	0.9773
10	0.8217	0.8323	0.8496	0.8450
11	1.4560	1.4780	1.5330	1.5200
12	2.8700	2.8920	2.9640	2.9480
13	3.8720	3.8720	3.8820	3.8770
14	2.1580	2.3260	2.2780	2.234
15	4.9820	4.9980	5.0520	5.061

(a) These dosimeters are adjacent to the aluminum thermal bond.

(b) These dosimeters are located along the central spline.

spectrum of the fast ($E > 0.18$ MeV) flux incident upon the dosimeters. This table also contains the relationship between the equivalent fission fluence for damage in graphite (Φ_D) and the fast fluence within the experiment (ϕ_f). This was calculated from the relationship

$$\frac{\Phi_D}{\phi_f} = \frac{1}{720 \times 10^{-24}} \times \frac{\sum_{g=1}^{15} \sigma_D^g \phi_g}{\sum_{g=1}^{15} \phi_g}, \quad (9-1)$$

which is consistent with the assumption that 1 nvt of fission spectrum fluence leads to 720×10^{-24} atomic displacements per atom (Ref. 9-2).

DETERMINATION OF FREE VOID VOLUMES AND FISSION AND REACTION GASES IN IRRADIATED COATED FUEL PARTICLES

Introduction

This section summarizes work performed by Studiengesellschaft für Atomenergie (SGAE) in Seibersdorf, Austria on irradiated fuel particles supplied by GA. The purpose of the program was to compare measured and predicted quantities of Kr, Xe, and CO within PyC and SiC coated LHTGR type fissile and fertile fuel particles in the temperature range 1000° to 1800°C. In addition, gas pressures contained within the coated particles were estimated from the measured gas contents and the free volume within coated particles that is available to contain the gaseous species.

Materials

The fuel particles included in the test series were irradiated in fuel capsules P13F and P13L. The samples were TRISO coated UO_2 or UC_2 , TRISO I

coated (Th/U)O₂, or BISO coated ThO₂ fuel kernels. Nominal particle parameters and irradiation conditions are given in Table 9-8. The Kr and Xe contents of the TRISO UC₂ and UO₂ batches had been measured previously at GA (Ref. 9-5).

Calculation of Theoretical Gas Contents

The quantities of Kr, Xe, and CO contained within each coated particle were estimated theoretically from the fission product activity of the individual coated particles. Each particle was gamma counted at GA using a Li-drifted Ge detector interfaced with a SDS Sigma II computer analyzer. The quantities of Kr (83, 84, 85, 86) and Xe (129, 131, 132, 134, 136) within each particle were estimated at GA from the Ru-106 activity. The calculations are based on Ru-106 since Ru remains within the kernels during irradiation. The calculations leading to Kr and Xe contents were made using the FISS/PROD program. The quantities were supplied to SGAE in terms of atoms of Kr or Xe; however, they were compared (by SGAE) with experimental values in terms of volume (cubic centimeters) at standard temperature (0°C) and pressure (1 atm) (STP).

The CO content of oxide kernels was estimated at SGAE assuming the formation of 2CO atoms per fission of UO₂ or ThO₂. This assumption should result in an overestimate of CO content, since many of the fission products formed from U-235 and U-233 fission have a high affinity for oxygen. The CO contents were based on the Cs activity determined for each particle at GA using $6.14 \times 10^{-5} \text{ cm}^3 \text{ CO}/\mu\text{Ci Cs-137}$ for fissions of U-235 and $6.28 \times 10^{-5} \text{ cm}^3 \text{ CO}/\mu\text{Ci Cs-137}$ in U-233 fissions. The CO volumes are at STP. The SGAE calculations were checked at GA by estimating the number of CO atoms from the burnup and activity of individual particles. The ratio between the GA and SGAE CO contents is approximately 1.5/1. The ratio of experimental-to-calculated CO content that is reported later is therefore low by a factor of 1/1.5.

TABLE 9-8
DESCRIPTION OF COATED FUEL PARTICLES AND IRRADIATION HISTORY

	Batch 4413-67	Batch 4413-5	Batch 4413-75	Batch 3332-141
Coating type	TRISO	TRISO	BISO	TRISO I ^(a)
Fuel kernel				
Type	UO ₂	UC ₂	ThO ₂	(Th,U)O ₂
Nominal size, μm	124	106	576	183
Density, g/cm^3	9.32	10.2	9.9	(b)
Th/U ratio	0	0	∞	3
Buffer layer				
Thickness, μm	46	53	69	37
Density, g/cm^3	1.26	1.30	1.23	1.10
Inner isotropic layer				
Thickness, μm	22	24	--	--
Density, g/cm^3	1.85	1.83	--	--
SiC layer				
Thickness, μm	20	20	--	28
Density, g/cm^3	3.16	3.20	--	3.17
Outer isotropic layer				
Thickness, μm	22	23	85	33
Density, g/cm^3	1.75	1.80	1.89	2.00
Irradiation conditions				
Capsule	P13L-CIT4	P13L-C3T3	P13L-C4T6	P13F-C2T3
Burnup, % FIMA	72	74	4.5	13
Temperature, °C	1450	1250	1325	1255
Fast neutron fluence, 10^{21} n/cm^2 (E > 0.18 MeV)	7.1	7.8	7.2	2.8

(a) The TRISO I particle design did not contain an inner pyrocarbon layer.

(b) Not available.

(c) Reported average temperatures. P13L-C4T6 did not contain a thermocouple and its average temperature could be as low as 1200°C.

Experimental Determination of Fission Gas Content

The Kr, Xe, and CO contents were determined experimentally at 1000°, 1200°, 1400°, 1600°, or 1800°C. The gas content of individual particles was determined by:

1. Heating particles to temperature in a microresistance tube furnace.
2. Crushing the particles after 10 min at temperature.
3. Passing a fraction of the gas through a quadruple type mass spectrometer capable of determining gas contents in four mass ranges simultaneously.

The system was calibrated by inserting known quantities of Kr, Xe, and CO. The resolution of the spectrometer was adjusted so that an integral measurement of both Kr and Xe was obtained, since the calibration gases and the measured gases from the sample may have different isotopic compositions.

Determination of Free Volume Within Coated Particles

In order to estimate the fission gas pressure within coated particles, the free volume available for fission gas within each particle had to be measured. The free volume in the fuel particles was measured by a microvolumetric technique. The closed system consists of two high-pressure chambers (a reference and a measurement chamber) connected by a differential pressure manometer, which can be isolated by means of ball valves. To measure free volume, a fuel particle was introduced into the measurement chamber and the entire system was filled with gas at a pressure of 100 kp/cm². After pressure equilibrium, the chambers were isolated by

means of a ball valve. The fuel particle was then crushed with a trapped nut type piston. The motion of the piston did not change the volume of the chamber. The presence of the failed particle increased the accessible volume of the chamber, thereby decreasing pressure, because of the accessible volume within the buffer layer of the particle. The volume change was compensated for by using a calibrated piston to reequilibrate the pressures in the measurement and reference chambers. Free volumes in excess of $5 \times 10^{-6} \text{ cm}^3$ can be measured with this equipment.

Results and Discussion

Gas content measurements were made on three particles of each type listed in Table 9-8 at 1000°, 1200°, 1400°, 1600°, or 1800°C. No failure was observed during heating of the particles included in this series. The fissile fuel experienced nearly peak LHTGR fast neutron fluence and burnup. The fact that no fuel failed suggests that the fuel can withstand very high temperatures without catastrophic failure.

The values for estimated and measured Kr, Xe, and CO contents at each temperature are given in Tables 9-9 through 9-12 for the four fuel types. The gas contents are presented as the volume occupied at STP. The quantities of Kr and Xe released from the TRISO I coated (Th/U)O₂ batch (see Table 9-11) ranged from 76 to 156% of the predicted quantities. This sample showed the largest disagreement between measured and theoretical gas contents. The (Th/U)O₂ samples had been irradiated in capsule P13F. Because of the long time between the end of irradiation and the gamma ray spectroscopy, on which the Kr and Xe predictions were based, the particles were relatively "cool." The Xe and Kr predictions are therefore less accurate than those made for the samples irradiated in capsule P13L. The results from the (Th/U)O₂ samples will not be discussed further because of this difficulty.

TABLE 9-9
COMPARISON OF MEASURED AND PREDICTED^(a) GAS CONTENTS^(b) FROM
IRRADIATED TRISO UC₂ BATCH 4413-5

Particle No.	Cs-137 (μCi)	Temp (°C)	Measured CO (10 ⁻³ cm ³)	Predicted CO (10 ⁻³ cm ³)	Percent ^(c)	Measured Xe (10 ⁻³ cm ³)	Predicted Xe (10 ⁻³ cm ³)	Percent ^(c)	Measured Kr (10 ⁻³ cm ³)	Predicted Kr (10 ⁻³ cm ³)	Percent ^(c)
1	22.6	1000	--	--	--	0.166	0.185	89.7	0.021	0.032	65.6
2	22.1	1000	--	--	--	0.161	0.202	79.7	0.021	0.035	60.0
3	27.7	1000	--	--	--	0.198	0.255	77.6	0.026	0.045	57.8
6	30.0	1200	--	--	--	0.216	0.272	79.4	0.028	0.048	58.3
7	24.4	1200	--	--	--	0.180	0.209	86.1	0.023	0.037	62.2
8	17.3	1200	--	--	--	0.129	0.144	89.6	0.020	0.025	80.0
9	17.7	1400	--	--	--	0.127	0.152	83.6	0.019	0.027	70.4
10	29.3	1400	--	--	--	0.225	0.257	87.5	0.030	0.045	66.7
11	17.7	1400	--	--	--	0.113	0.161	70.2	0.015	0.028	53.6
13	12.8	1600	--	--	--	0.088	0.106	83.0	0.014	0.019	73.7
14	13.7	1600	--	--	--	0.096	0.114	84.2	0.012	0.020	60.0
15	14.9	1600	--	--	--	0.120	0.131	91.6	0.017	0.023	73.9
18	18.8	1800	--	--	--	0.145	0.170	85.3	0.020	0.029	69.0
19	18.6	1800	--	--	--	0.140	0.180	87.5	0.020	0.028	71.4
20	22.8	1800	--	--	--	0.172	0.222	77.5	0.024	0.039	61.5

(a) Based on Ru-106 activity after irradiation.

(b) Reported as volume (10⁻³ cm³) at STP.

(c) Measured/predicted x 100.

TABLE 9-10^(a)
COMPARISON OF MEASURED AND PREDICTED^(a) GAS CONTENTS^(b) FROM
IRRADIATED TRISO UO₂ BATCH 4413-67

Particle No.	Cs-137 (μCi)	Temp (°C)	Measured CO (10 ⁻³ cm ³)	Predicted CO (10 ⁻³ cm ³)	Percent ^(c)	Measured Xe (10 ⁻³ cm ³)	Predicted Xe (10 ⁻³ cm ³)	Percent ^(c)	Measured Kr (10 ⁻³ cm ³)	Predicted Kr (10 ⁻³ cm ³)	Percent ^(c)
3	21.9	1000	0.004	1.34	0.3	0.156	0.180	86.7	0.026	0.032	81.3
4	18.9	1000	0.004	1.16	0.3	0.142	0.160	88.8	0.022	0.028	78.6
5	21.6	1000	0.004	1.33	0.3	0.111	0.191	58.1	0.016	0.033	48.5
6	26.9	1200	0.008	1.65	0.5	0.195	0.250	78.0	0.021	0.044	47.7
7	21.5	1200	0.010	1.32	0.8	0.159	0.153	103.9	0.023	0.027	85.2
8	26.2	1200	0.008	1.61	0.5	0.161	0.220	73.2	0.021	0.038	55.3
10	21.9	1400	0.013	1.34	1.0	0.132	0.188	70.2	0.021	0.033	63.6
12	26.4	1400	0.010	1.62	0.6	0.197	0.221	89.1	0.028	0.039	71.8
13	26.2	1400	0.010	1.61	0.6	0.170	0.237	71.7	0.022	0.041	53.7
16	22.3	1600	0.036	1.37	2.6	0.166	0.198	83.8	0.022	0.035	62.9
17	15.4	1600	0.025	0.95	2.6	0.118	0.134	88.1	0.017	0.023	73.9
18	21.1	1600	0.028	1.30	2.2	0.160	0.182	87.9	0.022	0.032	68.8
21	21.7	1800	0.053	1.33	4.0	0.140	0.179	78.2	0.020	0.031	64.5
23	18.7	1800	0.054	1.15	4.7	0.140	0.164	85.4	0.019	0.029	65.5
9	26.6	1800	0.042	1.63	2.6	0.204	0.245	83.3	0.026	0.043	60.5

(a) Based on Ru-106 activity after irradiation.

(b) Reported as volume (10⁻³ cm³) at STP.

(c) Measured/predicted x 100.

TABLE 9-11
COMPARISON OF MEASURED AND PREDICTED^(a) GAS CONTENTS^(b) FROM
IRRADIATED TRISO I (Th/U)₂O₃ BATCH 3332-141

Particle No.	Cs-137 (μCi)	Temp (°C)	Measured CO (10 ⁻³ cm ³)	Predicted CO (10 ⁻³ cm ³)	Percent ^(c)	Measured Xe (10 ⁻³ cm ³)	Predicted Xe (10 ⁻³ cm ³)	Percent ^(c)	Measured Kr (10 ⁻³ cm ³)	Predicted Kr (10 ⁻³ cm ³)	Percent ^(c)
1	12.2	1000	<0.002	0.75	0.3	0.072	0.077	93.5	0.010	0.013	76.7
2	19.3	1000	<0.002	1.19	0.2	0.120	0.147	81.4	0.014	0.025	56.1
4	17.6	1000	0.002	1.08	0.2	0.103	0.122	83.8	0.015	0.021	72.0
6	11.3	1200	<0.002	0.69	0.3	0.097	0.072	134	0.012	0.012	100
7	18.0	1200	0.002	1.11	0.2	0.144	0.138	104	0.023	0.023	100
18	14.9	1200	0.002	0.91	0.2	0.124	0.112	110	0.018	0.019	94.8
10	12.1	1400	0.004	0.74	0.5	0.102	0.084	121	0.016	0.014	113
12	11.3	1400	0.004	0.69	0.5	0.076	0.081	93.2	0.012	0.014	87.7
13	12.5	1400	0.003	0.77	0.4	0.097	0.062	156	0.014	0.010	134
9	13.7	1600	0.010	0.84	1.2	0.116	0.105	110	0.014	0.018	78.4
15	21.6	1600	0.008	1.33	0.6	0.167	0.165	101	0.023	0.028	82.4
16	19.7	1600	0.011	1.21	0.9	0.163	0.168	96.9	0.022	0.029	76.8
20	13.1	1800	0.013	0.80	1.5	0.102	0.080	128	0.017	0.013	127
22	16.4	1800	0.007	1.01	0.7	0.132	0.146	90.5	0.020	0.025	81.4
24	18.2	1800	0.015	1.12	1.3	0.151	0.125	120	0.020	0.021	94.3

(a) Based on Ru-106 activity after irradiation.

(b) Reported as volume (10⁻³ cm³) at STP.

(c) Measured/predicted x 100.

TABLE 9-12
COMPARISON OF MEASURED AND PREDICTED^(a) GAS CONTENTS^(b) FROM
IRRADIATED BISO ThO₂ BATCH 4413-75

Particle No.	Cs-137 (μCi)	Temp (°C)	Measured CO (10 ⁻³ cm ³)	Predicted CO (10 ⁻³ cm ³)	Percent ^(c)	Measured Xe (10 ⁻³ cm ³)	Predicted Xe (10 ⁻³ cm ³)	Percent ^(c)	Measured Kr (10 ⁻³ cm ³)	Predicted Kr (10 ⁻³ cm ³)	Percent ^(c)
1	100.7	1000	0.004	6.32	0.06	0.182	0.673	27.0	0.039	0.173	22.5
4	93.7	1000	0.004	5.88	0.07	0.294	0.599	49.1	0.058	0.154	37.7
25	95.8	1000	0.005	5.97	0.08	0.203	0.599	33.9	0.041	0.154	26.6
5	100.5	1200	0.005	6.31	0.08	0.302	0.718	42.1	0.058	0.185	31.4
6	105.8	1200	0.005	6.64	0.08	0.395	0.763	51.8	0.076	0.196	38.9
7	103.6	1200	0.005	6.51	0.08	0.327	0.644	50.8	0.062	0.166	37.3
11	111.6	1400	0.022	7.01	0.32	0.455	0.722	63.0	0.089	0.186	47.8
12	97.5	1400	0.014	6.12	0.23	0.337	0.651	51.8	0.060	0.167	36.0
24	93.1	1400	0.028	5.85	0.48	0.378	0.651	58.1	0.064	0.167	38.3
13	93.8	1600	0.055	5.89	0.93	0.349	0.636	54.9	0.062	0.164	37.8
14	117.5	1600	0.019	7.38	0.26	0.346	0.788	43.9	0.069	0.170	40.6
16	120.0	1600	0.028	7.54	0.37	0.264	0.759	34.8	0.054	0.196	27.6
19	111.0	1800	0.074	6.97	1.06	0.355	0.703	50.5	0.055	0.182	30.2
20	105.6	1800	0.077	6.63	1.16	0.336	0.744	45.2	0.058	0.191	30.4
23	94.0	1800	0.055	5.90	0.93	0.232	0.640	36.3	0.043	0.165	26.1

(a) Based on Ru-106 activity at end of irradiation.

(b) Reported as volume (10⁻³ cm³) at STP.

(c) Measured/predicted x 100.

The measured-to-predicted ratios for Kr, Xe, and CO are plotted versus temperature in Figs. 9-6, 9-7, and 9-8, respectively, for the UC_2 , UO_2 , and ThO_2 samples. Within the scatter of the data, there is no variation in the Kr and Xe ratios with temperature for the UC_2 , UO_2 , and ThO_2 samples. The average ratio for Kr is 66% for the UC_2 sample and 65% for the UO_2 sample. The average ratio for Xe is 84% for UC_2 and 82% for UO_2 . The agreement between the UC_2 and UO_2 samples is expected since they were irradiated in the same capsule to similar burnups. Any errors in the method used to predict Kr and Xe contents should therefore have a consistent effect on the predicted values. The fact that the relationship between the measured and predicted Kr and Xe values is the same for the two kernel types suggests that the gas measurement technique used at SGAE yields reproducible results.

The gas contents of the UC_2 and UO_2 samples were also measured at GA (Refs. 9-5, 9-6). Measurements were made at 25°C and 820° to 1310°C. The measurements made at GA recorded total gas content. The ratio between experimental gas content and theoretical Kr and Xe contents for UC_2 was 51% (standard deviation 7%) at 25°C and 65% (standard deviation 2%) in the temperature range 820° to 1310°C. The agreement between the higher temperature data and the data determined at SGAE indicates that the measurement techniques used at the two laboratories yield consistent results. The similarity in results over the temperature range 25° to 1800°C confirms the SGAE results showing that temperature has a small effect on Kr and Xe release. The GA and SGAE results from UO_2 cannot be compared directly because of the effect of gas composition (Ref. 9-6) on the GA results.

The ratio between measured and predicted Kr and Xe release (34 and 46%, respectively) from the ThO_2 is less than similar data for UC_2 and UO_2 . The burnup of the ThO_2 kernels is 4.5% FIMA, while the UC_2 and UO_2 kernels experienced 72 to 74% FIMA. A possible explanation for the difference in

gaseous release between the fertile and fissile materials is that fission gases remain trapped in the low burnup fertile kernels.

The quantity of CO present in the UC_2 , UO_2 , and ThO_2 kernels was also measured at SGAE. No CO was detected in the carbide particles. The quantities of CO detected in the UO_2 and ThO_2 increased with increasing temperature. The maximum quantities released were $\sim 1\%$ (ThO_2) and 4% (UO_2) of the quantity predicted assuming all oxygen atoms freed by U fission form CO. This is not surprising since many of the fission products formed during fission have a high affinity for oxygen.

One reason for conducting these experiments is to compare measured gaseous contents with gas content assumptions used in coated particle stress models. The models assume 100% Kr and Xe release to the buffer layer, which is conservative relative to the quantities measured by SGAE. The models also assume that 8% of the oxygen formed during U-235 fission is present in UO_2 fuel particles as CO, while 13% of the oxygen formed by U-233 fission is present in ThO_2 fuel. Comparison of the model assumptions with data presented above suggests that the stress models overestimate the CO content. The model assumptions will be reevaluated after results of additional experimental work on oxygen release being conducted at ORNL are published.

A second reason for conducting these tests was to obtain data that can be used directly to estimate the fission gas pressure contained within the coated fuel particles. The partial pressures of Kr, Xe, and CO were calculated using the Redlich-Kwing equation of state.

$$P_i = \frac{RT}{\frac{V}{n} - b} - \frac{a}{\frac{V}{n} (\sqrt{T}) (\frac{V}{n} + b)} \quad , \quad (9-2)$$

where P_i = pressure (atm) of the i^{th} gas
 V = free volume within a particle
 n = moles of the i^{th} gas
 T = temperature ($^{\circ}\text{K}$)
 R = gas constant

The constants a and b have the following values:

	<u>a</u>	<u>b</u>
CO	1.73×10^7	27.2
Xe	7.25×10^7	35.3
Kr	3.45×10^7	27.4

The variation in gas pressure with temperature is given in Tables 9-13 through 9-15 for the TRISO UC_2 , TRISO UO_2 , and TRISO $(\text{Th/U})\text{O}_2$ samples, respectively, used in this test series. The free volume was too small to measure on samples of the three TRISO coated fissile particle batches. The values used for free volume in Eq. 9-2 were consequently estimated from the batch average particle properties given in Table 9-8. The number of moles of gas within a particle at any given temperature was assumed to be the average number of moles calculated from the data in Tables 9-9 through 9-11 for each specific temperature.

The estimated gas pressure contained by the TRISO UC_2 fuel (Table 9-13) ranged from 532 to 914 atm. Much of the uncertainty is caused by the assumption that the void volume within each particle equals the void for a nominal particle from batch 4413-5.

The estimated fission gas pressures within the oxide fissile particles (Tables 9-14 and 9-15) account for the presence of Kr, Xe, and CO. The pressure within the UO_2 fuel ranges from 420 to 1019 atm, while the pressure within the $(\text{Th/U})\text{O}_2$ ranges from 174 to 422 atm. As with the UC_2 ,

TABLE 9-13
ESTIMATE OF FISSION GAS PRESSURE CONTAINED
BY IRRADIATED TRISO UC₂ PARTICLES FROM BATCH 4413-5

(Void Volume = $1.6 \times 10^{-6} \text{ cm}^3$)

Temperature, °C	1000	1200	1400	1600	1800
Xe pressure, atm	558	656	659	470	809
Kr pressure, atm	70	85	84	63	104
Total pressure, atm	628	741	743	533	913

TABLE 9-14
ESTIMATE OF FISSION GAS PRESSURE CONTAINED BY
IRRADIATED TRISO UO₂ PARTICLES FROM BATCH 4413-67

(Void Volume = $1.9 \times 10^{-6} \text{ cm}^3$)

Temperature, °C	1000	1200	1400	1600	1800
Xe pressure, atm	356	534	589	587	715
Kr pressure, atm	54	65	81	75	92
CO pressure, atm	10	27	37	114	213
Total pressure, atm	420	626	707	776	1020

TABLE 9-15
ESTIMATE OF FISSION GAS PRESSURE CONTAINED BY
IRRADIATED TRISO (Th/U)O₂ PARTICLES FROM BATCH 3332-141

(Void Volume = $3.1 \times 10^{-6} \text{ cm}^3$)

Temperature, °C	1000	1200	1400	1600	1800
Xe pressure, atm	154	224	192	353	335
Kr pressure, atm	20	33	29	46	48
CO pressure, atm	--	4	8	23	31
Total pressure, atm	174	261	229	422	414

much of the scatter is due to uncertainties in the void volume of the individual particles. One interesting observation, however, is that the contribution of CO to the total pressure ranges from approximately 2% at 1000°C to 20% at 1800°C for UO_2 and from 0 to 7% for the $(\text{Th/U})\text{O}_2$ fuel.

The void volume within the ThO_2 particles was large enough to measure. The measurements were made on unirradiated samples from batch 4413-75. The results are given in Table 9-16. During irradiation, however, BISO particles shrink and the void is reduced. Batch 4413-75 was irradiated at 1325°C. Recent irradiation results have shown that reference ThO_2 BISO fuel shrinks 4 to 6% in diameter during irradiation in the range 1250° to 1500°C (Ref. 9-7). Assuming that (1) the particles shrink 5% and (2) all shrinkage is accommodated by a decrease in buffer thickness, the calculated void volume after irradiation is 42% of the void volume before irradiation. Assuming a similar fractional decrease in void during irradiation of batch 4413-75, gas pressures were estimated assuming a void volume of $5.5 \times 10^{-6} \text{ cm}^3$. The results (Table 9-17) are similar to those for the other oxides. In this case, the CO partial pressure ranges from 1% of the total pressure at 1000°C to 15% at 1800°C.

Conclusions

The following conclusions can be drawn from the experimental data:

1. Particles were heated to temperatures as high as 1800°C without observing any failure.
2. Measured Kr and Xe contents were 66 and 84%, respectively, of the predicted values for the UC_2 particles. This suggests a systematic overestimate of the Kr and Xe inventories.
3. Measured Kr and Xe contents were 65 and 82%, respectively, of the predicted values for the UO_2 particles. The quantity of CO

TABLE 9-16
RESULTS OF FREE VOID VOLUME DETERMINATIONS MADE ON UNIRRADIATED
PARTICLES FROM BISO ThO₂ BATCH 4413-75

Individual values, 10 ⁻⁵ cm ³	0.79
	1.18
	1.57
	0.94
	1.57
	1.18
	1.41
	1.18
	1.41
	1.73
Mean value, 10 ⁻⁵ cm ³	1.30
Standard deviation, 10 ⁻⁵ cm ³	0.30 (= 22.8%)

TABLE 9-17
ESTIMATE OF FISSION GAS PRESSURE CONTAINED BY
IRRADIATED BISO ThO₂ PARTICLES FROM BATCH 4413-75

(Void Volume = 5.5 x 10⁻⁶ cm³)

Temperature, °C	1000	1200	1400	1600	1800
Xe pressure, atm	200	361	478	434	462
Kr pressure, atm	40	65	81	79	73
CO pressure, atm	3	5	24	43	98
Total pressure, atm	243	431	583	556	633

present increased with temperature to ~4% of the predicted value at 1800°C. The prediction of CO content assumed the formation of 2CO atoms per fission.

4. Measured Kr and Xe contents were 34 and 46%, respectively, of the predicted values for the ThO₂ particles. The quantity of CO present increased with temperature to ~1% of the predicted value at 1800°C. The CO predictions assume 2CO atoms per fission.
5. Comparison of gas contents measured in the UC₂ particles at GA and SGAE showed that the two laboratories obtained similar results.
6. With the exception of CO, temperature appears to have little or no effect on fission gas content in the range 25° to 1800°C.
7. Gas pressures calculated from the gas content measurements ranged from 243 to 1020 atm. The contribution of CO in the oxide kernels ranged from 0 to 2% at 1000°C to 20% of the total pressure at 1800°C.

CAPSULES P13R AND P13S

Capsules P13R and P13S are the seventh and eighth in a series of irradiation tests to demonstrate the integrity of reference and alternate LHTGR fuels over a wide range of irradiation conditions. The capsules were discharged from the GETR on October 31, 1974 and the disassembly and postirradiation examination commenced at the GA hot cell facility on December 5, 1974.

Capsule disassembly, dosimetry and burnup analyses, fuel rod dimensional changes, and the results of the fuel rod and unbonded particle

visual examinations were summarized in the previous quarterly report (Ref. 9-8). Fission gas release (TRIGA activation), metallography, and gamma-ray spectrometry examinations of the fuel specimens are currently in progress. The results of these examinations will be reported in a future quarterly progress report.

CAPSULE P13Q

Introduction

Capsule P13Q was designed to evaluate the performance of LHTGR fresh fuel irradiated in integral bodies under nominal LHTGR operating conditions. Experiment P13Q was the GA portion of GA-ORNL cooperative experiment OF-1. The GA portion of the test contained three near-isotropic graphite bodies with a fuel - coolant hole pattern that was representative of the geometry envisioned for a LHTGR. Each body contained six fuel rods nominally 1.57 cm (0.62 in.) in diameter and 5.35 cm (2.1 in.) long and a number of secondary fuel particle and graphite specimens. This experiment was the first test of fuel rods that were fabricated by the cure-in-place process and also contained reference-type TRISO UC_2 and BISO ThO_2 fuel particles and graphite shim particles. A complete description of the fuel materials tested in capsule P13Q is given in Ref. 9-9.

The capsule completed its scheduled irradiation in the E-3 position of the ORR on February 27, 1975 after receiving a peak fast neutron fluence of $9.5 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR}. After irradiation, the OF-1 capsule assembly was separated at the bulkhead and the GA segment (P13Q) was shipped intact to the GA hot cell facility, where the disassembly and postirradiation examination commenced on April 21, 1975. The major objectives of the irradiation test and subsequent postirradiation examinations were summarized in the previous quarterly report (Ref. 9-8).

Postirradiation Examination

Capsule Disassembly

The end caps were girdle cut and both containments were slit at 0° and 180° orientations to expose the three graphite fuel bodies. The bulkhead at the bottom of the capsule was cracked in a radial pattern with five cracks propagating from the center to the circumference as shown in Fig. 9-9. The bulkhead will be returned to ORNL for metallographic examination. The gas inlet tube at the top of the capsule was severed near the end cap due to corrosion as shown in Fig. 9-10. The Palorite carbon insulation disk at the bottom end of the capsule (highest fluence region) exhibited considerable irradiation-induced dimensional change. The bottom of the disk shrank to form a frustrum of a cone as shown in Fig. 9-11. The Palorite disk at the top end of the capsule did not exhibit any significant dimensional change; however, the disk split circumferentially when the end cap of the containment vessel was girdle cut. The inner surface of the bottom third of the containment was discolored, which indicates body 1 operated hotter than bodies 2 and 3. All of the dosimeter vials were recovered from the niobium tube containers with the exception of the primary dosimeters from body 1, which were completely disintegrated.

All three graphite fuel bodies were removed from the primary containment vessel in good condition as shown in Fig. 9-12. No cracks or signs of oxidation of the bodies were observed. Dimensional measurements revealed the graphite bodies exhibited irradiation-induced shrinkages ranging from -0.33% in the low fluence region to -1.49% in the high fluence region.

Prior to removal of the fuel rod and secondary specimens, each fuel body was submitted for postirradiation fission gas release measurements. These data are currently being analyzed to determine what effect, if any,

the severed gas inlet tube had on the measured in-pile fission gas release values.

The identification scheme used to identify fuel rod columns and secondary sample "coolant" holes in the P13Q graphite bodies is shown in Fig. 9-13. All the secondary specimens were removed with the graphite bodies in a vertical position as shown in Fig. 9-14. The fuel rods were then removed in a horizontal fixture using a 3/8-in.-diameter push rod driven by an electric screw jack, as shown in Fig. 9-15. The breakaway force required to start each fuel column moving was recorded by a Dillon force gage placed between the screw jack and push rod.

A maximum breakaway force of 15 kg was required to start the G1-2 fuel column moving. Breakaway forces ranging from 0 to 5 kg were required to remove the other eight fuel columns. Representative photographs showing the removal of fuel rods from a graphite body are shown in Fig. 9-16. All 18 fuel rods were removed in good condition. No evidence of surface damage resulting from mechanical interaction between the fuel rods and walls of the graphite bodies was observed on any of the fuel rods. Photographs of the rods taken after they were pushed out of the graphite bodies are shown in Figs. 9-17 through 9-25.

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

Fuel Rod Examinations

After removal from the graphite bodies, the fuel rods were examined visually using an in-cell stereomicroscope. The criteria for evaluating fuel rod integrity after irradiation are that the fuel rods remain intact and exhibit negligible cracking or particle debonding. Representative postirradiation photographs taken of each fuel rod during the visual examination are shown in Figs. 9-26 through 9-43. The visual appearance of each fuel rod after irradiation is summarized in Table 9-18.

All fuel rods were judged to be in excellent condition. No significant matrix cracking or particle debonding was observed. Slight circumferential cracking was noted on the bottom of eleven rods, which was accompanied by slight (0 to 29 particles) particle debonding. Although some of the cracking occurred at the matrix end cap of the hot-injected rods, which is usual, some of the rods may have been damaged slightly during unloading. The fuel rod fabrication variables tested (admixture compaction versus hot-injection, fired in block versus packed bed, and fired at 1500° versus 1800°C) did not have any effect on fuel rod integrity.

Dimensional measurements were made on each fuel rod using a dial gage comparator. Six diametral and one axial measurement were made to tolerances of ± 0.0005 and ± 0.001 in., respectively. The orientation relative to the preirradiation measurements was maintained by a scribe mark on the grafoil disk on the ends of all but two of the rods, which increased the confidence in the dimensional change measurements.

Irradiation-induced dimensional change data for each fuel rod are given in Table 9-18. The fuel rods exhibited diametral shrinkages ranging from -1.09 to -2.02% and axial shrinkages ranging from -0.17 to -1.67%. The dimensional changes exhibited a turnaround in the fluence range of 5 to 6×10^{21} n/cm² ($E > 0.18$ MeV)_{HTGR}, which is consistent with previous fuel rod dimensional change data. At higher fluences the dimensional change

TABLE 9-18
SUMMARY DESCRIPTION OF FUEL RODS IRRADIATED IN CAPSULE P13Q

Fuel Rod Description						Postirradiation						
						Fast Fluence (10^{21} n/cm ²) (E > 0.18 MeV)		Appearance	Number of Particles Debonded	Dimensional Change		
						ORR	HTGR			$\Delta D/D_0$ (%)	$\Delta L/L_0$ (%)	$\Delta D/D_0$ $\Delta L/L_0$
Position	Data Retrieval Number	Fertile Particle Data Retrieval Number (a)	Matrix Composition (b)	Fuel Rod Fabrication Process	Firing Medium							
G3-1A ^(c)	7161-002-19-3	6542-01-010	(d)	Hot injection	H-451 ^(g)	4.8	4.2	Excellent	2	-1.24	-1.06	1.17
G3-2A ^(c)	7161-002-20-3	6542-01-010	(d)	Hot injection	H-451	4.8	4.2	Excellent	6	-1.25	-0.93	1.34
G3-3A ^(c)	7161-002-21-3	6542-02-010	(d)	Hot injection	H-451	4.8	4.2	Excellent	0	-1.55	-1.41	1.10
G3-1B	7261-002-10-3	6542-01-010	(d)	Admix-compaction	H-451	6.3	5.6	Excellent	0	-1.64	-1.18	1.39
G3-2B	7261-002-11-3	6542-01-010	(d)	Admix-compaction	H-451	6.3	5.6	Excellent	0	-1.85	-1.61	1.15
G3-3B	7261-002-12-3	6542-02-010	(d)	Admix-compaction	H-451	6.3	5.6	Excellent	0	-2.02	-1.67	1.21
G2-1A	7261-002-13-3	6542-01-010	(d)	Admix-compaction	H-451	8.0	7.2	Excellent	2	-1.83	-1.10	1.66
G2-2A	7261-002-14-3	6542-01-010	(e)	Admix-compaction	H-451	8.0	7.2	Excellent	10	-1.88	-1.34	1.40
G2-3A	7261-002-15-3	6542-01-010	(f)	Admix-compaction	H-451	8.0	7.2	Excellent	2	-1.96	-0.67	2.92
G2-1B	7161-002-13-3	6542-01-010	(d)	Hot injection	H-451	9.1	8.1	Excellent	15	-1.84	-0.54	3.41
G2-2B	7161-002-14-3	6542-01-010	(e)	Hot injection	H-451	9.1	8.1	Excellent	0	-1.81	-1.05	1.72
G2-3B	7161-002-15-3	6542-01-010	(f)	Hot injection	H-451	9.1	8.1	Excellent	14	-1.98	-0.99	2.00
G1-1A	7261-002-16-3	6542-01-010	(d)	Admix-compaction	H-451	10.1	9.0	Excellent	7	-1.49	-0.17	8.76
G1-2A	7261-002-17-3	6542-01-010	(d)	Admix-compaction	PB ^(h)	10.1	9.0	Excellent	0	-1.09	-0.18	6.06
G1-3A	7261-002-18-5	6542-02-010	(d)	Admix-compaction	H-451	10.1	9.0	Excellent	1	-1.57	-0.42	3.74
G1-1B	7161-002-16-3	6542-01-010	(d)	Hot injection	H-451	10.6	9.4	Excellent	0	-1.36	-0.52	2.62
G1-2B	7161-002-17-3	6542-01-010	(d)	Hot injection	PB	10.6	9.4	Excellent	29	-1.22	-0.40	3.05
G1-3B	7161-002-18-3	6542-02-010	(d)	Hot injection	H-451	10.6	9.4	Excellent	4	-1.57	-0.88	1.78

(a) All fuel rods also contain TRISO UC₂ particles (6151-00-010), TRISO inert particles (4361-00-010), and BISO inert particles (6641-00-040).

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

(c) Thermocouple fuel rod.

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

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

(f) 30% type 6353 natural-flake graphite filler, 57% type A240 petroleum pitch, and 3% SC011 additive.

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

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

became anisotropic, with the axial shrinkages consistently less than the observed diametral shrinkages. No differences were observed in the dimensional change behavior of the fuel rods fabricated by the hot-injection or admix-compaction processes.

Postirradiation fission gas release measurements were performed on each fuel rod. Metallographic examination will be performed on 8 to 10 fuel rods to observe the irradiation-induced changes in the fuel particle coatings and fuel kernel microstructure and to evaluate the condition of the carbonaceous fuel rod matrix. The results of these examinations will be presented in a future quarterly report.

Unbonded Particle Examinations

Eighteen particle batches were tested in the secondary "coolant" hole positions of the graphite fuel bodies at a design temperature of 750°C. These samples were intended primarily for postirradiation out-of-pile heating tests. Thirty particles from each batch were contained in individual holes of disk-shaped graphite crucibles with sliding lids.

Each sample was photographed and examined with the crucible lid removed prior to unloading. All 30 fuel particles in each sample were present; however, one particle was lost from three different samples when the particles were removed from the graphite crucibles. Representative photographs taken during the visual examination of each particle type tested are shown in Figs. 9-44 through 9-47.

Coating failure was only observed in one of the 18 samples tested. A UC_2 TRISO particle batch (6151-00-013) irradiated to a fast fluence of $8.6 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G1-PB2/3-A exhibited 16.6% OPyC coating failure and 3.3% total coating failure. A companion sample of the same particle batch, also tested in body G1, did not experience any coating

failure. This particle batch had a low OPyC coating rate of $\sim 1.5 \mu\text{m}/\text{min}$ and the results are consistent with capsule P13R, where the parent batch (6151-00-010) exhibited OPyC coating and total coating failure levels of 32.8 and 0.7%, respectively, after irradiation to a fast neutron fluence of $12.2 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} at 1075°C (Ref. 9-8).

Summary

The postirradiation examination results obtained to date for capsule P13Q are summarized below:

1. All three graphite fuel bodies were removed from the containment vessel in good condition. Dimensional measurements revealed the bodies exhibited irradiation-induced shrinkages ranging from -0.33% in the low fluence region to -1.49% in the high fluence region.
2. Postirradiation fission gas release (R/B Kr-85m) of each body with the fuel rods still in place was in the 10^{-5} to 10^{-6} range, which is in fair agreement with the EOL in-pile fission gas release.
3. All 18 fuel rods were pushed from the graphite bodies without difficulty. A maximum breakaway force of 15 kg was required to start the G1-2 fuel column moving. Breakaway forces ranging from 0 to 5 kg were required to remove the other eight fuel columns.
4. All fuel rods were removed intact and were judged to be in excellent condition. No significant irradiation-induced matrix cracking or particle debonding was observed in any of the fuel rods.

5. The fuel rods exhibited irradiation-induced diametral shrinkages ranging from -1.09 to 2.02% and axial shrinkages ranging from -0.17 to 1.67%. The dimensional changes exhibited a turnaround in the fluence range of $5 \text{ to } 6 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR}, which is consistent with previous fuel rod dimensional change data.
6. Coating failure was only observed in one of the 18 unbonded particle samples tested. A UC_2 TRISO particle sample with a low OPyC coating rate of $\sim 1.5 \text{ }\mu\text{m/min}$ exhibited OPyC coating and total coating failure levels of 16.6 and 3.3%, respectively, after irradiation in the peak exposure position at 750°C (design).

CAPSULE P13T

Capsule P13T is the ninth in a GA series of LHTGR fuel irradiation tests conducted under the HTGR Fuels and Core Development Program. P13T is a large-diameter capsule containing two cells in which reference fresh and recycle fuels are being irradiated in the ORR reactor to peak HTGR temperatures and fluence conditions.

The estimated average fast fluence for cell 1 and cell 2 of capsule P13T is $1.8 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{ORR}. The measured temperatures are close to the design temperatures, which are 1300°C for cell 1 and 1100°C for cell 2, except for body 4 in cell 2. Since the temperature of cell 2 is controlled by a thermocouple in body 2 and the neutron flux profile changes during each cycle, the temperatures measured in body 4 fuel rods range from about 1000° to 1200°C from the beginning to the end of each cycle. The fission gas releases for both cells are low. Cell 1, containing only reference fresh fuel, has gone from about 4×10^{-7} to $2 \times 10^{-6} \text{ R/B (Kr-85m)}$. The fission gas release of cell 2, containing both VSM and WAR fissile particles, has been less than cell 1 since the beginning of the irradiation test and is now at approximately $1 \times 10^{-6} \text{ R/B (Kr-85m)}$.

CAPSULES P13U and P13V

Capsules P13U and P13V will test WAR fissile ThO_2 BISO particles under normal and thermal cycling conditions to peak LHTGR temperature and fluence conditions. Each capsule will be 31.75 mm in diameter and similar in design to capsules P13R and P13S. Five fuel rod cells and one unbonded particle cell be contained in each capsule.

Fuel rods of the 23 types to be irradiated (see Table 9-19) have been fabricated, and no major difficulties have occurred. Each rod type was evaluated in the green and fired state and found to be acceptable for the irradiation tests. The rods selected for capsules P13U and P13V have been loaded into the graphite bodies and cured-in-place. The fired fuel bodies appear to be in excellent condition and will be measured for initial fission gas release. Preliminary quality control measurements on the fuel rods are given in Table 9-19. A summary description of the coated fuel particles used in the fuel rods is given in Table 9-20.

Work has now begun on the unbonded particle samples. The fissile and fertile particles will be loaded into individual holes in the graphite trays. Selected particle batches are being density separated to obtain either the mean or high density fraction for particle model studies. The fabrication of fuel samples has proceeded smoothly and both the fuel rod bodies and loaded unbonded particle samples will be ready for insertion into the two capsules on schedule.

REFERENCES

- 9-1. Allen, E. J., and H. T. Kerr, "Neutron Flux Computational Model of the Oak Ridge Research Reactor," ERDA Report ORNL-TM-4814, Oak Ridge National Laboratory, April 1975.

TABLE 9-19
DESCRIPTION OF FUEL RODS BEING TESTED IN CAPSULES P13U AND P13V

Fuel Rods Irradiated in				Coated Particles ^(a)				Shim Particle Type	Green Rod Dimensions (cm)				Green Rod Packing Fraction ^(d)	Matrix				Fuel Loading Uniformity ^(h)				Exposed Heavy Metal ^(e,i) (g heavy metal/g heavy metal)	Fission Gas Release ^(e,j)
P13U		P13V		Fissile		Fertile			Green Rod Dimensions (cm)					Filler ^(e) (wt %)	Apparent Fired Density ^(d,e) (g/cm ³)	Macro-porosity ^(e,f) (%)	Coke Yield ^(e,g) (%)	U-235		Th-232			
Rod Type	Data Retrieval Number (7161-010-)	Rod Type	Data Retrieval Number (7161-010-)	Type ^(b)	Data Retrieval Number	Type ^(c)	Data Retrieval Number		Length		Diameter							P13U Rod	P13V Rod	P13U Rod	P13V Rod		
									P13U	P13V	P13U	P13V											
UV-1A ^(k)	01-5	UV-1A	01-10	U(C,O) ₂	6157-02-015	ThO ₂	6542-35-015	H-451 ⁽¹⁾	1.885	1.897	1.244	1.243	0.566	45.65	0.703	35.2	31.6	1.04	1.01	1.01	1.04	<2 x 10 ⁻⁶	1.2 x 10 ⁻⁶
UV-1B	02-14	UV-1B	02-6	U(C,O) ₂	6157-04-015	ThO ₂	6542-33-025	TS-1240X ⁽¹⁾	1.912	1.900	1.243	1.243	0.592	42.30	0.684	45.5	28.5	1.07	1.04	1.04	1.05	<4 x 10 ⁻⁶	7 x 10 ⁻⁸
UV-1C	03-4	UV-1C	03-1	U(C,O) ₂	6157-04-035	ThO ₂	6542-31-015	H-451 ⁽¹⁾	1.916	1.908	1.243	1.244	0.552	41.11	0.682	43.2	27.0	1.04	1.06	1.06	1.06	2.0 x 10 ⁻⁶	3.1 x 10 ⁻⁶
UV-1D	04-12	UV-1D	04-8	U(C,O) ₂	6157-04-025	ThO ₂	6542-29-015	X4029A	1.907	1.900	1.244	1.243	0.577	41.18	0.725	32.8	33.0	1.07	1.05	1.00	1.03	3.9 x 10 ⁻⁶	2.1 x 10 ⁻⁶
UV-1E ^(k)	05-9	UV-1E	05-2	U(C,O) ₂	6157-02-015	ThO ₂	6542-27-015	H-451 ⁽¹⁾	1.900	1.905	1.244	1.243	0.568	43.93	0.714	40.2	32.4	1.02	1.00	1.01	1.04	<2 x 10 ⁻⁶	1.4 x 10 ⁻⁶
U-2A ^(k)	06-5	--	--	UC ₂	6151-19-015	ThO ₂	6542-29-015	TS-1240X ⁽¹⁾	1.895	--	1.244	--	0.589	45.47	0.714	37.3	32.2	1.02	--	1.04	--	2.8 x 10 ⁻⁴	1.9 x 10 ⁻⁶
U-2B	07-4	--	--	UC ₂	6151-19-015	ThO ₂	6542-36-015	H-451 ⁽¹⁾	1.902	--	1.243	--	0.560	39.16	0.719	43.2	32.9	1.02	--	1.01	--	<2 x 10 ⁻⁶	9.9 x 10 ⁻⁷
U-2C	08-1	--	--	UC ₂	6151-19-015	ThO ₂	6542-34-015	X4029A	1.893	--	1.244	--	0.580	41.91	0.735	40.1	36.7	1.04	--	1.05	--	2.0 x 10 ⁻⁵	9.9 x 10 ⁻⁷
--	--	V-2A ^(k)	09-15	U(C,O) ₂	6157-04-015	ThO ₂	6542-29-015	TS-1240X ⁽¹⁾	--	1.884	--	1.243	0.590	45.91	0.700	25.6	30.7	--	1.02	--	1.03	<2 x 10 ⁻⁶	1.2 x 10 ⁻⁶
--	--	V-2B	10-13	U(C,O) ₂	6157-04-025	ThO ₂	6542-36-015	H-451 ⁽¹⁾	--	1.909	--	1.243	0.559	41.24	0.717	39.6	29.9	--	1.05	--	1.03	<2 x 10 ⁻⁶	5.6 x 10 ⁻⁷
--	--	V-2C	11-9	U(C,O) ₂	6157-02-015	ThO ₂	6542-34-015	X4029A	--	1.898	--	1.244	0.562	41.37	0.759	35.4	32.9	--	1.03	--	1.03	<2 x 10 ⁻⁶	1.4 x 10 ⁻⁶
--	--	V-2D	12-8	U(C,O) ₂	6157-04-015	ThO ₂	6542-33-025	H-451 ⁽¹⁾	--	1.884	--	1.244	0.537	40.96	0.684	42.9	26.8	--	1.06	--	1.06	2.4 x 10 ⁻³	6.5 x 10 ⁻⁷
--	--	V-2E ^(k)	13-15	U(C,O) ₂	6157-04-035	ThO ₂	6542-31-015	TS-1240X ⁽¹⁾	--	1.888	--	1.243	0.589	42.68	0.703	30.2	31.9	--	1.00	--	1.02	<2 x 10 ⁻⁶	2.3 x 10 ⁻⁶
UV-3A ^(k)	14-9	UV-3A	14-4	--	--	ThO ₂	6542-27-015	H-451 ⁽¹⁾	1.903	1.902	1.244	1.243	0.554	47.17	0.709	32.7	31.7	--	--	1.07	1.08	4.1 x 10 ⁻⁶	--
UV-3B	15-5	UV-3B	15-1	--	--	ThO ₂	6542-36-015	X4029A	1.885	1.883	1.244	1.244	0.581	41.25	0.708	36.0	32.8	--	--	1.04	1.03	2.0 x 10 ⁻⁷	--
UV-5A ^(k)	16-9	UV-5A	16-3	U(C,O) ₂	6157-04-025	ThO ₂	6542-29-015	H-451 ⁽¹⁾	1.905	1.915	1.244	1.243	0.552	43.91	0.689	35.4	32.1	1.01	1.03	1.02	1.04	<2 x 10 ⁻⁶	1.4 x 10 ⁻⁶
UV-5B	17-6	UV-5B	17-16	U(C,O) ₂	6157-04-035	ThO ₂	6542-35-015	TS-1240X ⁽¹⁾	1.871	1.863	1.244	1.244	0.597	40.67	0.693	43.0	29.3	1.05	1.01	1.03	1.00	5.8 x 10 ⁻⁴	2.4 x 10 ⁻⁶
UV-5C	18-14	UV-5C	18-6	U(C,O) ₂	6157-04-015	ThO ₂	6542-31-015	H-451 ⁽¹⁾	1.902	1.899	1.243	1.243	0.568	45.16	0.717	37.9	30.4	1.06	1.06	1.06	1.08	1.5 x 10 ⁻⁶	5.7 x 10 ⁻⁷
UV-5D	19-12	UV-5D	19-8	U(C,O) ₂	6157-02-015	ThO ₂	6542-33-025	X4029A	1.924	1.919	1.244	1.243	0.572	42.92	0.719	36.7	32.7	1.04	1.03	1.03	1.05	4.7 x 10 ⁻⁴	1.7 x 10 ⁻⁶
UV-5E ^(k)	20-7	UV-5E	20-5	U(C,O) ₂	6157-04-025	ThO ₂	6542-27-015	H-451 ⁽¹⁾	1.883	1.882	1.243	1.243	0.573	44.06	0.729	30.3	32.2	1.03	1.02	1.02	1.01	<1.5 x 10 ⁻⁶	6.8 x 10 ⁻⁷
UV-6A ^(k)	21-10	UV-6A	21-7	U(C,O) ₂	6157-04-025	--	--	TS-1240X ⁽¹⁾	1.887	1.891	1.243	1.243	0.587	45.80	0.716	29.3	31.6	1.01	1.03	--	--	1.4 x 10 ⁻⁵	2.6 x 10 ⁻⁷
UV-6B	22-2	UV-6B	22-15	U(C,O) ₂	6157-02-015	--	--	H-451 ⁽¹⁾	1.863	1.926	1.244	1.244	0.546	41.50	0.723	41.9	29.0	1.00	1.01	--	--	<10 ⁻⁵	1.4 x 10 ⁻⁶
UV-6C	23-16	UV-6C	23-13	U(C,O) ₂	6157-04-015	--	--	X4029A	1.896	1.901	1.244	1.244	0.573	39.17	0.743	35.2	33.4	1.01	1.02	--	--	6 x 10 ⁻⁵	2.0 x 10 ⁻⁷

- (a) All fuel rod types contain inert TRISO batch 6351-04-010, except UV-1B, UV-5A, and UV-5B rod types.
 (b) All fissile particles are TRISO coated.
 (c) All fertile particles are BISO coated.
 (d) Calculated from rod and mean particle data.
 (e) Measured on companion rod or rods.
 (f) Measured on metallographic cross section at 30X.
 (g) Coke weight divided by initial weight of pitch plus additives.
 (h) Determined by gamma counting both ends of rod and calculating ratio of maximum and mean values.
 (i) Determined by hydrolysis test; each sample heated for 1 hr at 1800°C.
 (j) Release rate/birth rate for Kr-85m at 1100°C.
 (k) Thermocouple rod; a hole [approximately 0.36 cm (0.14 in.) in diameter] through entire axis of rod.
 (1) Impregnated with a 95% alcohol base material.

TABLE 9-20
GENERAL DESCRIPTION OF COATED PARTICLES BEING TESTED IN CAPSULES P13U AND P13V

Particle Batch Data Retrieval Number	Kernel		Coatings												Diameter (μm)	Density ^(h) (g/cm ³)	Metal Loading (wt %)		Fission Gas Release ⁽ⁱ⁾	Exposed Heavy Metal			Burn Leach (g U/g U)	
			Type ^(b)	Buffer		Inner Isotropic		SiC		Outer Isotropic ^(g)				Total Coating Thick- ness (μm)						Leach Test		Hydrolysis Test ^(j) (g Th/g Th)		
				Thick- ness ^(c) (μm)	Density ^(d) (g/cm ³)	Thick- ness (μm)	Density ^(e) (g/cm ³)	OPTAF ^(f)	Thick- ness (μm)	Density ^(e) (g/cm ³)	Thick- ness (μm)	Density ^(e) (g/cm ³)	Mean Coating Rate (μm/min)							OPTAF ^(f)	Uranium (g U/g heavy metal)			Thorium (g Th/g heavy metal)
	Type ^(a)	Diameter (μm)																						
Fissile Particles																								
6151-19-015 ^(k)	UC ₂	201	TRISO	104 ⁽¹⁾	1.10 ⁽¹⁾	32 ⁽¹⁾	1.89 ⁽¹⁾	1.13	33	3.21	37	1.82	3.90	1.15	191	589	2.34	17.88	0.42	3.5 x 10 ⁻⁶	8.4 x 10 ⁻⁷	1.3 x 10 ⁻⁵	ND ^(m)	4.9 x 10 ⁻⁴
6157-02-015	U(C,O) ₂	297	TRISO	38	1.09	32	1.96	1.15	34	3.22	30	1.89	3.57	1.17	132	572	2.29	16.26	0.07	5.5 x 10 ⁻⁶	8.6 x 10 ⁻⁷	<1 x 10 ⁻⁷	ND	7.3 x 10 ⁻⁴
6157-04-015	U(C,O) ₂	301	TRISO	46	1.02	30	1.92	1.13	35	3.22	33	1.80	5.32	1.13	145	592	2.23	15.34	NA ⁽ⁿ⁾	2.5 x 10 ⁻⁶	2.9 x 10 ⁻⁵	<1 x 10 ⁻⁷	ND	9.8 x 10 ⁻⁷
6157-04-025	U(C,O) ₂	298	TRISO	50	1.10	29	1.88	1.17	34	3.22	37	1.83	5.10	1.14	145	583	2.19	15.53	NA	6.7 x 10 ⁻⁷	1.1 x 10 ⁻⁶	<1 x 10 ⁻⁷	ND	6.1 x 10 ⁻⁷
6157-04-035	U(C,O) ₂	306	TRISO	44	2.04	32	1.93	1.15	31	3.22	33	1.77	4.02	1.10	136	576	2.31	17.31	NA	5.3 x 10 ⁻⁵	5.5 x 10 ⁻⁵	<1 x 10 ⁻⁷	ND	6.8 x 10 ⁻⁴
Fertile Particles																								
6542-27-015	ThO ₂	512	BISO	84	1.09						81	1.86	4.59	1.09	164	836	3.47	ND	56.70	3.4 x 10 ⁻⁶	<1.0 x 10 ⁻⁷	3.7 x 10 ⁻⁶	5.6 x 10 ⁻⁵	NA
6542-29-015	ThO ₂	499	BISO	81	1.18						76	1.96	4.31	1.18	157	797	3.60	ND	59.65	≤1.0 x 10 ⁻⁶	<1.0 x 10 ⁻⁷	3.9 x 10 ⁻⁶	7.5 x 10 ⁻⁵	NA
6542-31-015	ThO ₂	501	BISO	83	1.10						75	1.92	6.00	1.10	158	814	3.61	ND	57.32	4.6 x 10 ⁻⁵	<1.0 x 10 ⁻⁷	3.2 x 10 ⁻⁵	9.0 x 10 ⁻⁵	NA
6542-33-025	ThO ₂	505	BISO	81	1.08						66	1.86	4.31	1.13	147	802	3.66	ND	61.29	5.3 x 10 ⁻⁵	1.1 x 10 ⁻⁵	7.1 x 10 ⁻⁶	1.1 x 10 ⁻⁴	NA
6542-34-015	ThO ₂	505	BISO	84	1.09						80	1.86	6.40	1.12	164	839	3.48	ND	57.80	4.3 x 10 ⁻⁵	3.3 x 10 ⁻⁷	2.8 x 10 ⁻⁶	2.3 x 10 ⁻⁴	NA
6542-35-015	ThO ₂	505	BISO	86	1.09						70	1.94	5.60	1.13	156	824	3.57	ND	58.71	5.3 x 10 ⁻⁵	1.3 x 10 ⁻⁷	1.1 x 10 ⁻⁶	1.1 x 10 ⁻⁴	NA
6542-36-015 ^(o)	ThO ₂	509	BISO	82 ⁽¹⁾	1.11 ⁽¹⁾						76	1.87	5.22	1.15	158	824	3.54	ND	57.56	ND	5.1 x 10 ⁻⁶	4.7 x 10 ⁻⁶	1.0 x 10 ⁻⁴	NA
Inert Particles																								
6351-04-010	C	304	TRISO	44	1.10	23	1.93	1.14	24	3.22	38	1.85	5.43	1.10	ND	578	1.85	NA	NA	NA	<5	<15	NA	NA

(a) Kernels are VSM UC₂, weak-acid-resin U(C,O)₂, and sol-gel ThO₂.

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

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

(d) Determined by mathematical calculation.

(e) Measured by density gradient technique.

(f) Optical anisotropy factor, relative units.

(g) Coating gas is a mixture of C₂H₂/C₃H₆.

(h) Determined using air pycnometer.

(i) Release rate/birth rate for Kr-85m at 1100°C. R/B of fissile particles measured in TRIGA reactor; R/B of fertile particles measured in linear accelerator.

(j) Value given is the measured value multiplied by five in order to correct for total conversion of ThO₂ to ThC₂.

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

(l) Estimated by averaging individual batches composited.

(m) ND = not determined.

(n) NA = not applicable.

(o) Composite of batches 6542-27-015, -29-015, -31-015, -34-015, and -35-010.

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Be - BERYLLIUM ELEMENT
 FUEL - FUEL ELEMENT
 Sr - SHIM ROD
 EXP - EXPERIMENT OR
 EXPERIMENTAL FACILITY

POOL

W

S	A-1 Be	A-2 Be	A-3 FUEL	A-4 FUEL	A-5 FUEL	A-6 FUEL	A-7 Be	A-8 Be	A-9 Be	N
	B-1 Be	B-2 FUEL	B-3 FUEL	B-4 Sr	B-5 FUEL	B-6 Sr	B-7 FUEL	B-8 Be	B-9 Be	
	C-1 Be	C-2 FUEL	C-3 EXP	C-4 FUEL	C-5 FUEL	C-6 FUEL	C-7 FUEL	C-8 EXP	C-9 Be	
	D-1 Be	D-2 FUEL	D-3 FUEL	D-4 Sr	D-5 FUEL	D-6 Sr	D-7 FUEL	D-8 EXP	D-9 Be	
	E-1 Be	E-2 FUEL	E-3 EXP	E-4 FUEL	E-5 FUEL	E-6 FUEL	E-7 FUEL	E-8 EXP	E-9 Be	
	F-1 Be	F-2 FUEL	F-3 FUEL	F-4 Sr	F-5 FUEL	F-6 Sr	F-7 EXP	F-8 Be	F-9 Be	
	G-1 Be	G-2 Be	G-3 Be	G-4 Be	G-5 Be	G-6 Be	G-7 Be	G-8 Be	G-9 Be	

E

Fig. 9-1. Typical ORR core configuration (Ref. 9-1)

Fig. 9-2. ORR supercell for capsule analyses

380	380	380	460
335	300	315	435
530			340
465			330
450			320
370	425	470	210
370	450	490	190

Fig. 9-3. Fission source distribution in ORR supercell (averages of the actual detailed distribution employed)

Fig. 9-4. Detail of OG-2 capsule as modeled in TWOTRAN

Fig. 9-5. Detail of P13Q model used in TWOTRAN calculations

Fig. 9-6. Variation in the ratio of measured to predicted gas content for irradiated TRISO UC_2 fuel versus temperature

Fig. 9-7. Variation in the ratio of measured to predicted gas content for irradiated TRISO UO_2 fuel versus temperature

Fig. 9-8. Variation in the ratio of measured to predicted gas content for irradiated BISO ThO_2 fuel versus temperature

K7507-5

Fig. 9-9. Cracking pattern in the bulkhead of capsule P13Q [view from bottom end (HNL) side]

K7507-28

(a)

K7507-27

(b)

Fig. 9-10. Severed gas inlet tube, which was corroded at the top of the capsule: (a) Palorite insulation disk and primary containment still in place, and (b) after Palorite disk and containment had been removed from graphite fuel body

K7507-8

K7507-7

Fig. 9-11. Irradiation-induced dimensional change of Palorite insulation disk at the bottom end (high-fluence region) of the capsule

K7507-75

Fig. 9-12. Three graphite fuel bodies after removal from the primary containment. The bodies were in good condition and no signs of cracking or oxidation were observed.

Fig. 9-13. Identification scheme used to identify fuel rod columns and secondary sample "coolant" holes in the P13Q graphite bodies

K7515-20

Fig. 9-14. Removal of secondary specimens from capsule P13Q graphite body G2

K7515-88, 89

Fig. 9-15. Horizontal fixture used to remove capsule P13Q fuel rods from the graphite bodies. The breakaway force of each fuel stack was recorded by a force gage placed between the electric screw jack and the push rod.

K7515-43

K7515-77

Fig. 9-16. Removal of capsule P13Q fuel rods from the graphite bodies. No evidence of surface damage resulting from mechanical interaction between the fuel rods and walls of the graphite bodies was observed on any of the fuel rods.

K7515 (46-48)

Fig. 9-17. Capsule P13Q fuel rods after removal from position G3-1

K7515 (51-53)

Fig. 9-18. Capsule P13Q fuel rods after removal from position G3-2

K7515 (56-58)

Fig. 9-19. Capsule P13Q fuel rods after removal from position G3-3

K7515 (61-63)

Fig. 9-20. Capsule P13Q fuel rods after removal from position G2-1

K7515 (66-68)

Fig. 9-21. Capsule P13Q fuel rods after removal from position G2-2

K7515 (71-73)

Fig. 9-22. Capsule P13Q fuel rods after removal from position G2-3

K7515 (78-80)

Fig. 9-23. Capsule P13Q fuel rods after removal from position G1-1

K7515 (83-85)

Fig. 9-24. Capsule P13Q fuel rods after removal from position G1-2

K7515 (90-92)

Fig. 9-25. Capsule P13Q fuel rods after removal from position G1-3

S7515-53

S7515-54

S7515 (57,58)

0.5 cm

Fig. 9-26. Fuel rod 7161-002-19-3 after irradiation to a fast fluence of $4.2 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G3-1A of capsule P13Q

S7515-51

S7515-52

S7515 (49.50)

0.5 cm

Fig. 9-27. Fuel rod 7161-002-20-3 after irradiation to a fast fluence of $4.2 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G3-2A of capsule P13Q

S7515-30

S7515-29

S7515 (33,34)

0.5 cm

Fig. 9-28. Fuel rod 7161-002-21-3 after irradiation to a fast fluence of $4.2 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G3-3A of capsule P13Q

S7515-39

S7515-40

S7515 (37,38)

0.5 cm

Fig. 9-29. Fuel rod 7261-002-10-3 after irradiation to a fast fluence of $5.6 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G3-1B of capsule P13Q

S7515-41

S7515-42

S7515 (43,44)

0.5 cm

Fig. 9-30. Fuel rod 7261-002-11-3 after irradiation to a fast fluence of $5.6 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G3-2B of capsule P13Q

S7515-28

S7515-27

S7515 (25,26)

0.5 cm

Fig. 9-31. Fuel rod 7261-002-12-3 after irradiation to a fast fluence of $5.6 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G3-3B of capsule P13Q

S7515-59

S7515-60

S7515 (63,64)

0.5 cm

Fig. 9-32. Fuel rod 7261-002-13-3 after irradiation to a fast fluence of $7.2 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G2-1A of capsule P13Q

S7515-71

S7515-72

S7515 (73,74)

0.5 cm

Fig. 9-33. Fuel rod 7261-002-14-3 after irradiation to a fast fluence of $7.2 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G2-2A of capsule P13Q

S7515-83

S7515-84

S7515 (87,88)

0.5 cm

Fig. 9-34. Fuel rod 7261-002-15-3 after irradiation to a fast fluence of $7.2 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G2-3A of capsule P13Q

S7515-70

S7515-69

S7515 (65,66)

0.5 cm

Fig. 9-35. Fuel rod 7161-002-13-3 after irradiation to a fast fluence of $8.1 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G2-1B of capsule P13Q

S7515-82

S7515-81

S7515 (77,78)

0.5 cm

Fig. 9-36. Fuel rod 7161-002-14-3 after irradiation to a fast fluence of $8.1 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G2-2B of capsule P13Q

S7515-94

S7515-93

S7515 (91,92)

0.5 cm

Fig. 9-37. Fuel rod 7161-002-15-3 after irradiation to a fast fluence of $8.1 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G2-3B of capsule P13Q

S7515-96

S7515-95

S7515 (97,98)

0.5 cm

Fig. 9-38. Fuel rod 7261-002-16-3 after irradiation to a fast fluence of $9.0 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G1-1A of capsule P13Q

S7515-105

S7515-106

S7515 (103,104)

0.5 cm

Fig. 9-39. Fuel rod 7261-002-17-3 after irradiation to a fast fluence of $9.0 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G1-2A of capsule P13Q

S7515-117

S7515-118

S7515 (123,124)

0.5 cm

Fig. 9-40. Fuel rod 7261-002-18-5 after irradiation to a fast fluence of $9.0 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G1-3A of capsule P13Q

S7515-107

S7515-108

S7515 (109,110)

0.5 cm

Fig. 9-41. Fuel rod 7161-002-16-3 after irradiation to a fast fluence of $9.4 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G1-1B of capsule P13Q

S7515-119

S7515-120

S7515 (115, 116)

0.5 cm

Fig. 9-42. Fuel rod 7161-002-17-3 after irradiation to a fast fluence of $9.4 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G1-2B of capsule P13Q

S7515-126

S7515-125

S7515 (129,130)

0.5 cm

Fig. 9-43. Fuel rod 7161-002-18-3 after irradiation to a fast fluence of $9.4 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in position G1-3B of capsule P13Q

S7515-154

S7515-156

Fig. 9-44. Photographs taken during visual examination of ThO_2 BISO particles (6542-02-0130-3) irradiated to a fast neutron fluence of $8.6 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in holder No 13, position G1-PB3/1-A, of capsule P13Q

S7515-145

S7515-147

Fig. 45. Photographs taken during visual examination of ThO₂ BISO particles (6542-01-0130-5) irradiated to a fast neutron fluence of $9.6 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in holder No. 17, position G1-PB1/2-D, of capsule P13Q

S7515-134

S7515-136

Fig. 9-46. Photographs taken during visual examination of UC_2 TRISO particles (6151-00-0130-4) irradiated to a fast neutron fluence of $8.6 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in holder No. 14, position G1-PB1/2-A, of capsule P13Q

S7515-131

S7515-133

Fig. 9-47. Photographs taken during visual examination of (Th,U)O₂ TRISO particles (4163-00-0140-3) irradiated to a fast neutron fluence of $8.4 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$)_{HTGR} in holder No. 11, position G2-PB1/2-D, of capsule P13Q

TASK 11 (189a SU004)
GRAPHITE DEVELOPMENT

INTRODUCTION

The objective of the Graphite Development Program is to evaluate and identify near-isotropic graphites for core blocks of HTGRs. The graphites under investigation have been supplied by major carbon and graphite producers in the United States and Europe. The major emphasis in this program is on the United States graphites, with a much smaller effort devoted to the European materials. The work on the European graphites is to provide confirmatory and comparative data with European HTGR programs where United States graphites are also being evaluated.

GRAPHITE IRRADIATIONS (SUBTASK 200)

Capsule OG-2

Temperatures and Fluences

Physics calculations to determine the effective activation cross sections for iron and titanium flux monitors and the relationship between fast fluence ($E > 0.18$ MeV) and equivalent fission fluence for graphite damage were completed for the OG-2 capsule in the C-3 position of the Oak Ridge Reactor (ORR) (see Task 9). The effective activation cross section [46.56 mb for the $\text{Fe-54}(n,p)\text{Mn-54}$ reaction and 6.61 mb for the $\text{Ti-46}(n,p)\text{Sc-46}$ reaction] were virtually the same as those used in the preliminary data reduction, and fluences in terms of neutrons with energies greater than 0.18 MeV in the ORR spectrum [n/cm^2 ($E > 0.18$ MeV)_{ORR}] are unchanged from those given in the previous quarterly report (Ref. 11-1). However, these units are not the most convenient either for HTGR design work or for comparisons with other test facilities. Consequently a

change is being made in the units used to report fast neutron fluences. In this and subsequent reports the following two sets of units will be used:

1. Fluence of neutrons with energies greater than 0.18 MeV in a typical HTGR spectrum [n/cm^2 ($E > 0.18 \text{ MeV}$)_{HTGR}]. These are the units used in HTGR design work.
2. Equivalent fission fluence for graphite damage (n/cm^2 , EFFGD). These units were recommended by an international working group sponsored by the International Atomic Energy Agency (Ref. 11-2) and form the basis of the ASTM recommended practice for reporting irradiation data for graphite.

Conversion factors are based on the number of carbon atoms displaced, calculated according to the Thompson and Wright model. One n/cm^2 , EFFGD creates 720×10^{-24} displaced carbon atoms per atom. The appropriate conversion factors for the C-3 position of the ORR are:

$$\text{Fluence } (E > 0.18 \text{ MeV})_{\text{HTGR}} = 0.893 \times \text{fluence } (E > 0.18 \text{ MeV})_{\text{ORR}}$$

$$\text{Fluence (EFFGD)} = 1.118 \times \text{fluence } (E > 0.18 \text{ MeV})_{\text{ORR}}$$

$$\text{Fluence (EFFGD)} = 1.25 \times \text{fluence } (E > 0.18 \text{ MeV})_{\text{HTGR}}$$

If no fluence units are specified, n/cm^2 ($E > 0.18 \text{ MeV}$)_{HTGR} should be understood.

Thermal Expansivity

Thermal expansivity measurements were made on 98 specimens of irradiated graphite measuring either 0.2 in. in diameter by 0.45 in. long or 0.25 in. in diameter by 0.9 in. long. Measurements were made in a silica dilatometer between room temperature and 100°C less than the irradiation temperature (maximum 1000°C). The graphites tested were near-isotropic

grades H-451, H-429 (subsize prototype of H-451), and TS-1240 and needle-coke grade H-327. The H-451, H-429, and H-327 graphite specimens had been irradiated in previous capsules; the lower fluence thermal expansivity data are given in Ref. 11-3.

The thermal expansivities between room temperature and 500°C are listed in Tables 11-1 through 11-3,* together with mean values for unirradiated material. The fractional changes in thermal expansivity are plotted as a function of fluence for the near-isotropic graphites in Fig. 11-1 and for H-327 (needle-coke graphite) in Fig. 11-2. These figures also include data obtained during postirradiation tests on specimens from capsule OG-1 (Ref. 11-3). The near-isotropic graphites (Fig. 11-1) show a small increase in thermal expansivity (generally less than 10%) in both axial and radial directions when irradiated at 590° to 680°C and no significant changes when irradiated at 765° to 925°C. At higher irradiation temperatures, there is a pronounced decrease in thermal expansivity, with the values falling 30% after irradiation to about 7×10^{21} n/cm² above 1100°C. These irradiation-induced changes are similar in nature, but smaller in magnitude, to those reported for Gilsocarbon-based isotropic nuclear graphites. H-327 graphite showed a small decrease in thermal expansivity upon irradiation, with some indication of recovery at high fluences for the highest irradiation temperatures (Fig. 11-2).

Thermal Conductivity

Thermal diffusivity measurements were made on 87 discs (0.45 in. in diameter by 0.05 in. thick) of graphite irradiated in three crucibles in the OG-2 capsule. The graphite grades were near-isotropic H-451 and TS-1240 and needle-coke H-327; both axial and radial specimens were tested. The H-451 and H-327 specimens had been irradiated previously in the OG-1 capsule; the lower fluence data are reported in Ref. 11-3. Thermal diffusivity measurements were made by the heat-pulse method (ASTM Method of Test C-741), and thermal conductivity values were calculated by multiplying the thermal diffusivity by the density of the irradiated specimen and

*Tables appear at the end of Section 11.

Fig. 11-1. Thermal expansivity as a function of fluence for near-isotropic graphites: (a) 590° to 1060°C

Fig. 11-1. Thermal expansivity versus fluence for near-isotropic graphites: (b) 1105° to 1500°C

Fig. 11-2. Thermal expansivity versus fluence for H-327 graphite

values for the heat capacity taken from the literature. Readings were taken at 100°C intervals between room temperature and 100°C below the irradiation temperature (maximum 800°C).

The measurements are tabulated in Tables 11-4 through 11-6, together with extrapolated values at the irradiation temperature. The thermal conductivity at the irradiation temperature is plotted as a function of fast fluence in Fig. 11-3 for the near-isotropic graphites and in Fig. 11-4 for H-327 (needle-coke graphite). These figures also include data from previous capsules (GEH-13-422 and OG-1) (Ref. 11-3). Irradiation reduces the thermal conductivity to a saturation level that increases with increasing irradiation temperature. For fluences above about 7×10^{21} n/cm² at 1225° to 1350°C, H-327 graphite undergoes a second decline in thermal conductivity as the density of the material is reduced. The effect of grain orientation on the conductivity of the oriented needle-coke H-327 is evident in Fig. 11-4. There is no significant difference in thermal conductivity between irradiated H-451 graphite and irradiated TS-1240 graphite.

Tensile Properties

Tensile tests were conducted in air at room temperature on 0.25-in.-diameter by 0.9-in.-long cylinders of H-451, TS-1240, and H-327 graphite from capsule OG-2. All specimens were from the midlength-center region of the parent log. The specimens of H-451 and some of the H-327 specimens had been irradiated previously in capsule OG-1. An Instron tensile testing machine with a crosshead speed of 0.005 in./min was used, and strains were measured with a 0.5 in. gauge length extensometer. The specimens were cemented to metal end pieces with high-strength epoxy cement and the load was applied through roller-link chains to maintain uniaxial alignment. The specimens were loaded to 1000 psi, unloaded to 100 psi, and reloaded to failure. Young's modulus was measured from the 100 psi to 1000 psi reloading part of the curve.

The tensile strengths, strains to failure, Young's moduli, and secant moduli (tensile strength divided by strain to failure) for H-451 graphite

○ H-451, PERPENDICULAR TO EXTRUSION
 △ TS-1240, PERPENDICULAR TO EXTRUSION

● H-451, PARALLEL TO EXTRUSION
 ▲ TS-1240, PARALLEL TO EXTRUSION
 ■ H-328, PERPENDICULAR TO MOLDING

Fig. 11-3. Thermal conductivity versus fluence for near-isotropic graphites

Fig. 11-4. Thermal conductivity versus fluence for H-327 graphite

and some of the data for TS-1240 graphite were reported in the previous quarterly report (Ref. 11-1). Complete tensile data for TS-1240 and the data for H-327 graphite are given in Tables 11-7 and 11-8, together with test data on unirradiated companion specimens. The changes in strength and Young's modulus are plotted as a function of fast neutron fluence in Figs. 11-5 through 11-7 for H-451, TS-1240, and H-327 graphites, respectively. These figures also include the data from specimens irradiated in capsule OG-1 (Ref. 11-3). A summary of tensile data from both capsules is given in Table 11-9.

The increases in Young's modulus follow the pattern established by Dragon project measurements of the dynamic modulus of irradiated graphites. During irradiation the modulus rises to a plateau, the level of which decreases with increasing irradiation temperature. There is an indication of a second increase at higher fluences in the data for H-451 graphite irradiated at 890° to 970°C to 5×10^{21} n/cm² (Fig. 11-5). The fractional increases in Young's modulus are greater than the increases in dynamic Young's modulus found during the Dragon project work. The difference probably occurs because a static determination of Young's modulus on unirradiated graphite is usually lower than a dynamic determination, but the two methods give similar results on irradiated graphite. The present results become consistent with Dragon project data on similar graphites if it is assumed that the static Young's modulus of unirradiated graphite is 80% of the dynamic modulus, while the two values are the same for irradiated graphite.

Increases in tensile strength followed a similar pattern to that for increases in Young's modulus; however, for given irradiation conditions, the fractional increase in strength was always less than the fractional increase in Young's modulus. The condition of constant strain energy to failure would require that the irradiated and unirradiated strengths, S_i and S_o , be related to the irradiated and unirradiated Young's moduli, E_i and E_o , as follows:

$$\frac{S_i}{S_o} = \sqrt{\frac{E_i}{E_o}} \quad .$$

Fig. 11-5. Ultimate tensile strength and Young's modulus versus fluence for H-451 graphite

Fig. 11-6. Ultimate tensile strength and Young's modulus versus fluence for TS-1240 graphite

Fig. 11-7. Ultimate tensile strength and Young's modulus versus fluence for H-327 graphite: (a) 640° to 900°C

Fig. 11-7. Ultimate tensile strength and Young's modulus versus fluence for H-327 graphite: (b) 940° to 1200°C

The strengths of all groups of irradiated H-451 specimens and most groups of H-327 specimens were higher than expected from this relationship, but the strengths of the TS-1240 specimen groups and some H-327 specimen groups were about as predicted.

Irradiation-induced changes in the coefficient of variation of the strength (standard deviation divided by the mean) were not statistically significant, with the exception of the specimens of TS-1240 irradiated at 1105°C to 2.9×10^{21} n/cm² and the H-327 irradiated at 940° to 1035°C to 5.7×10^{21} n/cm² and at 1040° to 1200°C to 6.3×10^{21} n/cm², where there was an increase in the coefficient of variation significant at the 95% confidence level.

Capsule OG-3

Capsule OG-3 was inserted in the C-3 position of the ORR on June 17, 1975, and at-power operation started on June 21, 1975. Operating temperatures have remained within about 50°C of design in all crucibles.

Capsules OG-4 and OG-5

Because of changes in program funding and reactor operating charges at ORR, the schedules and test holes for capsules OG-4 and OG-5 have been changed. The new test holes and insertion dates are as follows:

<u>Capsule</u>	<u>Test Hole</u>	<u>Approx. Insertion Date</u>
OG-4	E-3	8/1/76
OG-5	E-7	10/1/76

Capsule OG-4 will contain all virgin specimens, primarily of H-451 and SO-818 graphite. Capsule OG-5 will be used to re-irradiate specimens from OG-3. Thermal design calculations are being made to determine the effect on operating temperature of changing from test hole C-3 to test holes E-3 and E-7.

Analysis of Dimensional Change Data (Capsules OG-1 and OG-2)

Dimensional change data for H-451, H-429, TS-1240, and P₃JHAN graphites have been analyzed for all experiments through OG-2. All fluences have been expressed in equivalent HTGR fluences ($E > 0.18 \text{ MeV}$)_{HTGR} from the following correlations:

$$\text{Fluence } (E > 0.18 \text{ MeV})_{\text{HTGR}} = 0.893 \times \text{fluence } (E > 0.18 \text{ MeV})_{\text{ORR}}$$

$$\text{Fluence } (E > 0.18 \text{ MeV})_{\text{HTGR}} = 0.871 \times \text{fluence } (E > 0.18 \text{ MeV})_{\text{ETR}}$$

The dimensional change data for H-429, H-451, TS-1240, and P₃JHAN are given in Tables 11-10 through 11-25.

The differences in dimensional change are evident in Fig. 11-8, which is a plot of the dimensional change versus fluence at 900° to 1000°C. The behavior shown in Fig. 11-8 is typical of the differences observed to date in these graphites.

GRAPHITE CHARACTERIZATION (SUBTASK 300)

In-depth characterization of grades TS-1240 and H-451 is continuing. Preliminary characterization of grade SO-818 (lot 1) has started. Initial characterization data (density, impurities, tensile properties, thermal expansion, and thermal conductivity) for grades H-451 and TS-1240 were reported previously (Refs. 11-1 and 11-4 through 11-9). Additional density and tensile property data for grades H-451 and TS-1240 are given in Tables 11-26 through 11-29. Impurity data for H-451 and SO-818 are given in Table 11-30. Additional thermal expansivity data for grades H-451, TS-1240, and SO-818 are given in Tables 11-31 through 11-34. A summary of tensile strength measurements for H-451, lot 426, is given in Table 11-35.

The tensile property data presented in Tables 11-26 through 11-29 and Table 11-35 were obtained on specimens 0.505 in. in diameter by 3.00 in.

Fig. 11-8. Dimensional change in near-isotropic graphites, radial orientation, 900° to 1000°C

long. Each specimen was loaded to 1000 psi, unloaded to zero stress, and reloaded to fracture while recording the stress-strain curve. The elastic modulus for the second loading was taken as the chord modulus between 100 and 1000 psi. Values of ultimate strength, strain to fracture, and permanent deformation in the specimens after the first loading cycle were also obtained from the stress-strain curve.

GRAPHITE STANDARD

A revised draft of the proposed RDT standard E6-1 "Near-Isotropic Petroleum-Coke-Based Graphites for High-Temperature Gas-Cooled Reactor Core Components," was submitted to RRD for approval in July 1975.

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- 11-3. Price, R. J., and L. A. Beavan, "Final Report on Graphite Irradiation Test OG-1," USAEC Report GA-A13089, General Atomic Company, August 1974.
- 11-4. "HTGR Base Program Quarterly Progress Report for the Period Ending February 28, 1974," USAEC Report GA-A12916, General Atomic Company, March 29, 1974.
- 11-5. "HTGR Base Program Quarterly Progress Report for the Period Ending May 31, 1974," USAEC Report GA-A13030, General Atomic Company, June 28, 1974.
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- 11-7. Engle, G. B., R. J. Price, W. R. Johnson, and L. A. Beavan, "Development Status of Near-Isotropic Graphites for Large HTGRs," USAEC Report GA-A12944, General Atomic Company, June 1, 1974.

- 11-8. "HTGR Fuels and Core Development Program Quarterly Progress Report for the Period Ending November 30, 1974," USAEC Report GA-A13253, General Atomic Company, January 31, 1975.
- 11-9. "HTGR Fuels and Core Development Program Quarterly Progress Report for the Period Ending February 28, 1975," USAEC Report GA-A13353, General Atomic Company, March 31, 1975.

TABLE 11-1
THERMAL EXPANSIVITY OF H-451 AND H-451 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-2

Graphite Grade	Specimen No.	Log Location (a)	Orien- tation	Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) _{HTGR}	Coefficient of Thermal Expansivity x 10 ⁶ °C ⁻¹ (22°-500°C)
H-451	.305.	MLC	Axial	1	4	640-680	3.7	3.84
↓	.306.	↓	Axial	↓	4	↓	↓	3.87
↓	.307.	↓	Axial	↓	5	↓	↓	4.00
↓	.430.	↓	Radial	↓	4	↓	↓	4.87
↓	.431.	↓	Radial	↓	4	↓	↓	5.21
H-451	.432.	MLC	Radial	1	5	640-680	3.7	4.94
H-451	.616.	MLE	Axial	0	3	820-850	3.6	3.83
↓	.617.	↓	Axial	↓	3	↓	↓	4.06
↓	.618.	↓	Axial	↓	4	↓	↓	3.95
↓	.716.	↓	Radial	↓	3	↓	↓	4.85
↓	.717.	↓	Radial	↓	3	↓	↓	4.93
H-451	.718.	MLE	Radial	9	4	820-850	3.6	4.92
H-451	.371.	MLC	Axial	8	1	920-940	4.5	3.08
↓	.372.	↓	Axial	↓	1	↓	↓	3.24
↓	.373.	↓	Axial	↓	2	↓	↓	3.35
↓	.496.	↓	Radial	↓	1	↓	↓	4.43
↓	.497.	↓	Radial	↓	1	↓	↓	3.55
H-451	.498.	MLC	Radial	8	2	920-940	4.5	4.78
H-429	389	--	Axial	8	8	890-925	5.2	4.01
↓	390	--	Axial	↓	8	890-925	5.2	4.10
↓	391	--	Axial	↓	8	890-925	5.2	4.20
↓	424	--	Radial	↓	20	850-890	5.6	5.22
↓	425	--	Radial	↓	20	850-890	5.6	5.21
H-429	426	--	Radial	8	20	850-890	5.6	4.75
H-451	.602.	MLL	Axial	7	7	980-990	5.3	3.33
↓	.603.	↓	Axial	↓	7	↓	↓	2.96
↓	.604.	↓	Axial	↓	8	↓	↓	2.99
↓	.702.	↓	Radial	↓	7	↓	↓	3.99
↓	.703.	↓	Radial	↓	7	↓	↓	3.88
H-451	.704	MLE	Radial	7	8	980-990	5.3	4.04

TABLE 11-1. (continued)

Graphite Grade	Specimen No.	Log Location (a)	Orientation	Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) _{HTGR}	Coefficient of Thermal Expansivity x 10 ⁶ °C ⁻¹ (22°-500°C)
H-451	.582.	MLE	Axial	4	1	1155-1255	6.3	2.75
↓	.583.	↓	Axial	↓	2	↓	↓	2.93
↓	.584.	↓	Axial	↓	2	↓	↓	2.46
↓	.682.	↓	Radial	↓	1	↓	↓	3.30
↓	.683.	↓	Radial	↓	2	↓	↓	3.64
H-451	.684.	MLE	Radial	4	2	1155-1255	6.3	3.62
H-429	408	--	Axial	4	9	1140-1235	8.6	2.94
↓	409	--	Axial	4	9	1140-1235	8.6	3.18
↓	438	--	Radial	4	9	1140-1235	8.6	3.68
H-429	439	--	Radial	4	9	1140-1235	8.6	3.45
H-451	.331.	MLC	Axial	5	1	1380-1395	6.1	2.17
↓	.332.	↓	Axial	↓	1	↓	↓	2.64
↓	.333.	↓	Axial	↓	7	↓	↓	2.64
↓	.456.	↓	Radial	↓	1	↓	↓	2.80
↓	.457.	↓	Radial	↓	1	↓	↓	3.32
H-451	.458.	MLC	Radial	5	7	1380-1395	6.1	3.22
H-429	.141	--	Axial	5	2	1380-1425	8.8	3.33
↓	.142	↓	Axial	↓	2	↓	↓	2.90
↓	.143	↓	Axial	↓	3	↓	↓	2.67
↓	.161	↓	Radial	↓	2	↓	↓	4.38
↓	.162	↓	Radial	↓	2	↓	↓	3.43
H-429	.163	--	Radial	5	3	1380-1425	8.8	2.70
H-451	(Mean)	MLC	Axial	--	--	--	0.0	3.78
↓	↓	MLE	Axial	--	--	--	0.0	3.86
↓	↓	MLC	Radial	--	--	--	0.0	4.68
H-451	(Mean)	MLE	Radial	--	--	--	0.0	4.81
H-429	(Mean)	--	Axial	--	--	--	0.0	4.25
H-429	(Mean)	--	Radial	--	--	--	0.0	5.00

(a) MLC = midlength center, MLE - midlength edge.

TABLE 11-2
THERMAL EXPANSITIVITY OF TS-1240 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-2

Specimen No.	Log Location	Orien- tation	Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) _{HTGR}	Coefficient of Thermal Expansivity x 10 ⁶ °C ⁻¹ (22°-500°C)
T40105	MLC	Axial	10	10	620	1.2	4.18
T40107	↓	Axial	↓	10	620	↓	4.26
T40109	↓	Axial	↓	11	620	↓	5.25
T40149	↓	Radial	↓	32	590	↓	4.89
T40151	↓	Radial	↓	32	590	↓	4.86
T40153	MLC	Radial	10	33	590	1.2	4.66
T40069	MLC	Axial	9	28	765	1.7	4.14
T40071	↓	Axial	↓	28	765	↓	4.53
T40073	↓	Axial	↓	29	765	↓	4.30
T40129	↓	Radial	↓	12	805	↓	4.66
T40131	↓	Radial	↓	12	805	↓	4.47
T40133	MLC	Radial	9	13	805	1.7	4.86
T40053	MLC	Axial	7	25	920	2.5	4.69
T40055	↓	Axial	↓	25	↓	↓	4.06
T40057	↓	Axial	↓	26	↓	↓	3.90
T40121	↓	Radial	↓	29	↓	↓	4.67
T40123	↓	Radial	↓	29	↓	↓	4.73
T40125	MLC	Radial	7	30	920	2.5	4.55
T40017	MLC	Axial	4	28	1105	2.9	3.98
T40019	↓	Axial	↓	28	1105	↓	4.40
T40021	↓	Axial	↓	29	1105	↓	4.49
T40157	↓	Radial	↓	10	1200	↓	4.15
T40159	↓	Radial	↓	10	1200	↓	4.67
T40161	↓	Radial	4	11	1200	2.9	4.12
Mean	↓	Axial	--	--	--	0.0	4.26
Mean	MLC	Radial	--	--	--	0.0	4.84

TABLE 11-3
THERMAL EXPANSIVITY OF H-327 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-2

Specimen No.	Log Location	Orien- tation	Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) _{HTGR}	Coefficient of Thermal Expansivity x 10 ⁶ °C ⁻¹ (22°-500°C)
.203.	MLE	Axial	1	21	560-615	3.7	1.58
.204.	↓	Axial	↓	21	↓	↓	1.34
.205.	↓	Axial	↓	22	↓	↓	1.58
.253.	↓	Radial	↓	21	↓	↓	3.94
.254.	↓	Radial	↓	21	↓	↓	3.49
.255.	MLE	Radial	1	22	560-615	3.7	3.63
140	MLC	Axial	8	6	890-1225	8.5	2.28
141	MLE	Axial	↓	6	↓	↓	1.60
138	MLC	Radial	↓	6	↓	↓	3.36
139	MLE	Radial	8	6	890-1225	8.5	3.87
.225.	MLE	Axial	7	5	980-990	5.3	1.70
.28.	MLC	Axial	↓	21	920-945	↓	1.55
.275.	MLE	Radial	↓	5	980-990	↓	2.98
.127.	MLC	Radial	↓	21	920-945	↓	3.53
.128.	MLC	Radial	7	21	920-945	5.3	3.50
T-263	MLC	Axial	4	21	1040-1105	6.3	1.21
T-264	↓	Axial	↓	21	1040-1105	6.3	1.27
T-265	↓	Axial	↓	22	1040-1105	6.3	1.20
216	MLC	Axial	↓	3	1115-1500	12.0	2.29
217	MLE	Axial	4	3	1115-1500	↓	2.06
214	MLC	Radial	4	3	1115-1500	↓	3.62
215	MLE	Radial	4	3	1115-1500	12.0	4.33
Mean	--	Axial	--	--	--	0.0	1.96
Mean	--	Radial	--	--	--	0.0	3.70

TABLE 11-4
THERMAL CONDUCTIVITY OF H-451 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-2

(All specimens midlength center location)

Specimen No.	Orientation	Crucible No.	Mean Irradiation Temperature (°C)	Fluence $\times 10^{-21}$ (n/cm ²) (E 0.18 MeV) _{HTGR}	Thermal Conductivity (cal/cm-sec-°C)					
					22°C	200°C	400°C	600°C	800°C	Irrad Temp (Extrapolated)
201	Axial	1	600-635	3.7	0.069	0.077	0.064	-	-	0.064
202					0.072	0.080	0.079	-	-	0.077
203					0.073	0.095	0.095	-	-	0.088
204	Axial				0.074	0.089	0.086	-	-	0.082
221	Radial				0.067	-	-	-	-	-
222					0.055	-	-	-	-	-
223					0.068	-	-	-	-	-
224					0.068	-	-	-	-	-
225					0.060	0.101	0.083	-	-	0.080
226					0.067	0.074	0.076	-	-	0.067
227					0.065	0.081	0.082	-	-	0.073
228	Radial	1	600-635	3.7	0.081	0.071	0.067	-	-	0.062
205	Axial	7	920-945	5.3	0.069	0.085	0.083	0.097	0.095	0.085
206					0.104	0.132	0.127	0.127	0.113	0.100
207					0.109	0.132	0.129	0.118	0.113	0.100
208	Axial				0.113	0.137	0.122	0.114	0.103	0.095
231	Radial				0.076	-	-	-	-	-
232					0.077	-	-	-	-	-
233					0.069	-	-	-	-	-
234					0.100	-	-	-	-	-
235					0.087	0.090	0.085	0.087	0.082	0.076
236					0.091	0.100	0.086	0.080	0.075	0.071
237					0.080	0.098	0.085	0.077	0.085	0.071
238	Radial	7	920-945	5.3	0.073	0.081	0.078	0.071	0.068	0.064
210	Axial	5	1350	6.1	0.198	0.213	0.183	0.161	0.137	0.095
211					0.204	0.183	0.176	0.169	0.149	0.098
212					0.188	0.208	0.183	0.158	0.154	0.098
213	Axial				0.183	0.196	0.184	0.165	0.152	0.098
242	Radial				0.140	-	-	-	-	-
243					0.136	-	-	-	-	-
244					0.150	-	-	-	-	-
245					0.135	-	-	-	-	-
246					0.187	0.177	0.161	0.142	0.133	0.090
247					0.170	0.169	0.145	0.130	0.128	0.084
248					0.173	0.185	0.170	0.145	0.143	0.092
249	Radial	5	1350	6.1	0.166	0.183	0.147	0.136	0.121	0.082
Mean of 12	Axial	-	-	0.0	0.347	0.302	0.247	0.206	0.174	-
Mean of 12	Radial	-	-	0.0	0.294	0.262	0.222	0.185	0.158	-

TABLE 11-5
THERMAL CONDUCTIVITY OF TS-1240 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-2

(All specimens midlength center location)

Specimen No.	Orientation	Crucible No.	Mean Irradiation Temperature (°C)	Fluence $\times 10^{-21}$ (n/cm ²) (E=0.18 MeV) _{HTGR}	Thermal Conductivity (cal/cm-sec-°C)					Irrad Temp (Extrapolated)
					22°C	200°C	400°C	600°C	800°C	
74D-63	Axial	1	635	1.7	0.077	0.092	0.087	-	-	0.077
74D-64	↓	1	635	1.7	0.071	0.097	0.087	-	-	0.079
74D-65	↓	1	635	1.7	0.071	0.100	0.094	-	-	0.085
74D-66	Axial	1	635	1.7	0.073	0.093	0.091	-	-	0.085
74D-93	Radial	1	635	1.7	0.065	-	-	-	-	-
74D-94	↓	1	635	1.7	0.068	-	-	-	-	-
74D-95	↓	1	635	1.7	0.067	-	-	-	-	-
74D-96	↓	1	635	1.7	0.067	-	-	-	-	-
74D-97	↓	1	635	1.7	0.056	0.084	0.084	-	-	0.078
74D-98	↓	1	635	1.7	0.075	0.084	0.083	-	-	0.079
74D-99	↓	1	635	1.7	0.069	0.092	0.082	-	-	0.077
74D-100	Radial	1	635	1.7	0.078	0.088	0.084	-	-	0.078
74D-71	Axial	7	945	2.5	0.097	0.108	0.104	0.100	0.091	0.085
74D-72	↓	7	945	2.5	0.116	0.125	0.120	0.109	0.103	0.094
74D-73	↓	7	945	2.5	0.115	0.123	0.114	0.104	0.096	0.098
74D-74	Axial	7	945	2.5	0.107	0.117	0.110	0.102	0.094	0.088
74D-109	Radial	7	945	2.5	0.091	-	-	-	-	-
74D-110	↓	7	945	2.5	0.088	-	-	-	-	-
74D-111	↓	7	945	2.5	0.088	-	-	-	-	-
74D-112	↓	7	945	2.5	0.086	-	-	-	-	-
74D-113	↓	7	945	2.5	0.085	0.094	0.085	0.071	0.080	0.068
74D-114	↓	7	945	2.5	0.082	0.088	0.079	0.068	0.083	0.068
74D-115	↓	7	945	2.5	0.087	0.102	0.100	0.080	0.084	0.076
74D-116	Radial	7	945	2.5	0.100	0.101	0.090	0.077	0.088	0.074
74D-67	Axial	5	1345	2.9	0.178	0.162	0.162	0.144	0.126	0.092
74D-68	↓	5	1345	2.9	0.162	0.191	0.154	0.138	0.127	0.092
74D-69	↓	5	1345	2.9	0.170	0.176	0.158	0.138	0.127	0.092
74D-70	Axial	5	1345	2.9	0.154	0.167	0.153	0.138	0.118	0.085
74D-101	Radial	5	1345	2.9	0.139	-	-	-	-	-
74D-102	↓	5	1345	2.9	0.139	-	-	-	-	-
74D-103	↓	5	1345	2.9	0.146	-	-	-	-	-
74D-104	↓	5	1345	2.9	0.156	-	-	-	-	-
74D-105	↓	5	1345	2.9	0.167	0.170	0.133	0.111	0.112	0.082
74D-106	↓	5	1345	2.9	0.148	0.162	0.112	0.110	0.107	0.078
74D-107	↓	5	1345	2.9	0.167	0.173	0.142	0.120	0.112	0.083
74D-108	Radial	5	1345	2.9	0.172	0.147	0.129	0.108	0.105	0.077
Mean of 8	Axial	-	-	0.0	0.234	0.223	0.192	0.165	0.145	-
Mean of 8	Radial	-	-	0.0	0.247	0.231	0.195	0.167	0.148	-

TABLE 11-6
THERMAL CONDUCTIVITY OF H-327 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-2

(All specimens midlength edge location)

Specimen No.	Orientation	Crucible No.	Mean Irradiation Temperature (°C)	Fluence $\times 10^{-21}$ (n/cm ²) (E=0.18 MeV) _{HTGR}	Thermal Conductivity (cal/cm-sec-°C)					
					22°C	200°C	400°C	600°C	800°C	Irrad Temp (Extrapolated)
81	Axial	1	600-635	4.3	0.069	0.118	0.120	-	-	0.105
82	Axial	↓	↓	↓	0.086	0.108	0.109	-	-	0.095
1	Radial	↓	↓	↓	0.046	0.055	0.053	-	-	0.049
2	Radial	↓	↓	↓	0.047	0.057	0.056	-	-	0.051
13	Radial	1	600-635	4.3	0.052	0.060	0.064	-	-	0.056
83	Axial	7	900-945	7.1	0.074	0.087	0.076	0.077	0.077	0.072
84	Axial	↓	900-945	↓	0.072	0.076	0.074	0.073	0.069	0.064
3	Radial	↓	875-945	↓	0.048	0.064	0.057	0.054	0.051	0.048
4	Radial	↓	875-945	↓	0.053	0.060	0.058	0.061	0.068	0.056
32	Radial	7	875-945	7.1	0.056	0.064	0.062	0.065	0.069	0.062
86	Axial	5	1225-1345	11.7	0.120	0.127	0.105	0.100	0.092	0.064
87	Axial	↓	↓	↓	0.131	0.123	0.108	0.103	0.105	0.069
43	Radial	↓	↓	↓	0.114	0.115	0.097	0.086	0.085	0.060
44	Radial	↓	↓	↓	0.102	0.104	0.092	0.113	0.095	0.062
45	Radial	5	1225-1345	11.7	0.088	0.084	0.073	0.066	0.071	0.053
Mean of 6	Axial	-	-	0.0	0.450	0.367	0.293	0.240	0.194	-
Mean of 6	Radial	-	-	0.0	0.331	0.261	0.201	0.170	0.140	-

TABLE 11-7
TENSILE PROPERTIES OF TS-1240 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-2
(All specimens midlength center location)

Specimen No.	Orien- tation	Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence $\times 10^{-21}$ (n/cm ²) (E>0.18 Mev) _{HTGR}	Ultimate Tensile Strength (psi)	Strain at Failure (%)	Young's Modulus $\times 10^{-6}$ (psi)	Secant Modulus $\times 10^{-6}$ (psi)
T40105	Axial ↓	10 ↓	10	620 ↓	1.2 ↓	1940	0.104	2.16	1.87
T40107			10			1426	0.116	1.34	1.23
T40109			11			1104	0.100	1.22	1.10
T40111			11			1492	0.096	1.99	1.55
T40113			12			2221	0.156	1.64	1.42
T40115			12			2528	0.148	1.93	1.71
T40117			13			2202	0.133	2.09	1.66
T40118			13			1653	-	1.54	-
T40119			14			1629	0.114	1.70	1.43
T40120			14			<u>2246</u>	<u>0.167</u>	<u>1.57</u>	<u>1.34</u>
Mean						1844	0.126	1.72	1.48
Std. dev.						±452	±0.026	±0.32	±0.24
T40069	Axial ↓	9 ↓	28	765 ↓	1.7 ↓	1204	0.089	1.56	1.35
T40071			28			1981	0.140	1.62	1.42
T40073			29			2270	0.182	1.47	1.25
T40075			29			1964	0.127	1.78	1.55
T40077			30			2354	0.150	2.05	1.57
T40079			30			1822	0.122	1.67	1.49
T40081			31			2309	0.144	1.84	1.60
T40083			31			2516	0.163	1.81	1.54
T40085			32			2385	0.153	1.85	1.56
T40087			32			<u>1895</u>	<u>0.143</u>	<u>1.58</u>	<u>1.32</u>
Mean						2070	0.141	1.72	1.47
Std. dev.						±385	±0.025	±0.17	±0.12

TABLE 11-7 (continued)

Specimen No.	Orien- tation	Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E 0.18 MeV) _{HTGR}	Ultimate Tensile Strength (psi)	Strain at Failure (%)	Young's Modulus x 10 ⁻⁶ (psi)	Secant Modulus x 10 ⁻⁶ (psi)
T40129	Radial	9	12	805	1.7	2163	0.140	1.74	1.55
T40131	↓	↓	12	↓	↓	1940	0.113	1.88	1.72
T40133	↓	↓	13	↓	↓	1816	0.131	1.56	1.39
T40135	↓	↓	13	↓	↓	1899	0.168	1.33	1.13
T40137	↓	↓	14	↓	↓	2180	0.166	1.48	1.31
T40139	↓	↓	14	↓	↓	1181	0.138	0.99	0.86
T40141	↓	↓	15	↓	↓	2302	0.174	1.54	1.32
T40143	↓	↓	15	↓	↓	2100	0.144	1.62	1.46
T40145	↓	↓	16	↓	↓	1979	0.160	1.38	1.24
T40147(a)	Radial	9	16	805	1.7	<u>1084^(a)</u>	<u>0.194^(a)</u>	<u>0.66^(a)</u>	<u>0.56^(a)</u>
Mean						1951	0.148	1.50	1.33
Std. dev.						+327	±0.020	-0.26	±0.25
T40053	Axial	7	25	920	2.5	2330	0.162	1.72	1.44
T40055	↓	↓	25	↓	↓	1696	0.136	1.63	1.25
T40057	↓	↓	26	↓	↓	2385	0.178	1.55	1.34
T40059	↓	↓	26	↓	↓	2467	0.166	1.83	1.49
T40061	↓	↓	27	↓	↓	1918	0.138	1.50	1.39
T40063	↓	↓	27	↓	↓	2042	0.144	1.81	1.42
T40065	↓	↓	28	↓	↓	2122	0.151	1.74	1.41
T40067	Axial	7	28	920	2.5	<u>2023</u>	<u>0.172</u>	<u>1.52</u>	<u>1.18</u>
Mean						2123	0.156	1.66	1.37
Std. dev.						±259	-0.016	±0.13	±0.10

TABLE 11-7 (continued)

Specimen No.	Orien- tation	Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) _{HTGR}	Ultimate Tensile Strength (psi)	Strain at Failure (%)	Young's Modulus x 10 ⁻⁶ (psi)	Secant Modulus x 10 ⁻⁶ (psi)
T40017	Axial	4	28	1105	2.9	2485	0.197	1.64	1.26
T40019	↓	↓	28	↓	↓	1438	0.114	1.56	1.26
T40021	↓	↓	29	↓	↓	1729	0.125	1.70	1.38
T40023	↓	↓	29	↓	↓	2798	0.220	1.56	1.27
T40025	↓	↓	30	↓	↓	2205	0.144	1.92	1.53
T40027	↓	↓	30	↓	↓	2328	0.153	1.91	1.52
T40029	↓	↓	31	↓	↓	1235	0.098	1.48	1.26
T40031	↓	↓	31	↓	↓	1706	0.154	1.40	1.11
T40033	↓	↓	32	↓	↓	1214	-	1.70	-
T40035	Axial	4	32	1105	2.9	1855	0.106	2.06	1.75
Mean						1899	0.146	1.69	1.37
Std. dev.						±540	±0.041	±0.21	±0.20
3A-6B	Axial	↓	↓	↓	0.0	1427	0.210	0.90	0.68
3A-7B	↓	↓	↓	↓	↓	1711	0.270	0.95	0.63
3A-12B	↓	↓	↓	↓	↓	2015	0.310	1.00	0.65
3A-13B	↓	↓	↓	↓	↓	1896	0.320	0.90	0.59
3A-18B	↓	↓	↓	↓	↓	1469	0.200	0.86	0.73
3A-19B	↓	↓	↓	↓	↓	1406	0.285	0.69	0.49
3A-24B	↓	↓	↓	↓	↓	1796	0.275	0.95	0.65
3A-25B	↓	↓	↓	↓	↓	1691	0.250	1.00	0.68
3A-27B	↓	↓	↓	↓	↓	1449	0.245	0.86	0.59
3A-28B	↓	↓	↓	↓	↓	1672	0.265	0.90	0.63
3B-6B	↓	↓	↓	↓	↓	1976	0.323	1.00	0.61
3B-7B	↓	↓	↓	↓	↓	1670	0.245	1.00	0.68
3B-12B	↓	↓	↓	↓	↓	1438	0.185	1.00	0.78
3B-13B	↓	↓	↓	↓	↓	1141	0.145	0.95	0.79
3B-18B	↓	↓	↓	↓	↓	1080	0.240	0.60	0.45
3B-19B	↓	↓	↓	↓	↓	1283	0.190	0.86	0.68
3B-24B	↓	↓	↓	↓	↓	1487	0.215	0.88	0.69
3B-25B	↓	↓	↓	↓	↓	1569	0.295	0.90	0.53
3B-27B	↓	↓	↓	↓	↓	1507	0.275	0.86	0.55
3B-28B	Axial	↓	↓	↓	0.0	1731	0.335	0.86	0.52
Mean						1571	0.254	0.90	0.63
Std. dev.						±252	±0.051	±0.10	±0.09

Specimen No.	Orien- tation	Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) _{HTGR}	Ultimate Tensile Strength (psi)	Strain at Failure (%)	Young's Modulus x 10 ⁻⁶ (psi)	Secant Modulus x 10 ⁻⁶ (psi)
3A-36B		-	-	-	0.0	957	0.140	-	0.68
3A-37B		-	-	-		1428	0.220	0.95	0.65
3A-42B		-	-	-		1367	0.205	1.00	0.67
3A-43B		-	-	-		1266	0.300	0.78	0.42
3A-48B		-	-	-		1388	0.245	0.72	0.57
3A-49B		-	-	-		1120	0.130	1.00	0.86
3A-54B		-	-	-		1450	0.210	0.90	0.69
3A-55B		-	-	-		1531	0.250	0.95	0.61
3A-60A		-	-	-		2400	0.350	1.06	0.69
3A-60B		-	-	-		1170	0.175	0.90	0.67
3B-36B		-	-	-		1448	0.330	0.75	0.44
3B-37B		-	-	-		958	0.165	-	0.58
3B-42B		-	-	-		1428	0.210	0.95	0.68
3B-43B		-	-	-		1287	0.195	0.88	0.66
3B-48B		-	-	-		1594	0.252	0.90	0.63
3B-49B		-	-	-		1491	0.255	0.95	0.58
3B-54B		-	-	-		1384	0.205	1.00	0.68
3B-55B		-	-	-		1428	0.233	0.91	0.61
3B-60A		-	-	-		1428	0.295	0.83	0.48
3B-60B		-	-	-	0.0	<u>1144</u>	<u>0.255</u>	<u>0.68</u>	<u>0.45</u>
Mean						1383	0.231	0.90	0.62
Std. dev.						±298	+0.058	+0.11	±0.11

(a) Specimen flawed – excluded from averages.

TABLE 11-8
TENSILE PROPERTIES OF H-327 GRAPHITE SPECIMENS IRRADIATED IN CAPSULE OG-2

(All specimens midlength center location)

204

Specimen No.	Orien- tation	Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) _{HTGR}	Ultimate Tensile Strength (psi)	Strain at Failure (%)	Young's Modulus x 10 ⁻⁶ (psi)	Secant Modulus x 10 ⁻⁶ (psi)
T-307	Axial	2	10	740	2.2	1682	0.102	1.90	1.65
T-308	↓	↓	10	↓	↓	1962	0.136	2.03	1.44
T-309	↓	↓	11	↓	↓	2267	0.116	2.41	1.95
T-310	↓	↓	11	↓	↓	1945	0.123	2.15	1.58
T-311	↓	↓	12	↓	↓	1722	0.133	1.81	1.29
T-312	↓	↓	12	↓	↓	1500	-	3.14	-
T-313	↓	↓	13	↓	↓	2551	0.147	1.90	1.74
T-314	↓	↓	13	↓	↓	2324	0.112	2.59	2.08
T-315	↓	↓	14	↓	↓	2105	0.114	2.27	1.85
T-316	Axial	2	14	740	2.2	<u>1378</u>	<u>0.076</u>	<u>2.29</u>	<u>1.81</u>
Mean						1944	0.118	2.25	1.71
Std. dev.						±377	±0.021	±0.40	±0.25
T-297	Axial	9	10	810	3.6	2015	0.098	2.20	2.06
T-298	↓	↓	10	↓	↓	2606	0.132	2.56	1.97
T-299	↓	↓	11	↓	↓	2421	0.104	2.96	2.33
T-300	↓	↓	11	810	↓	1892	0.093	2.56	2.03
T-301	↓	↓	25	750-765	↓	2319	0.113	2.44	2.05
T-302	↓	↓	25	↓	↓	2518	0.102	3.05	2.47
T-303	↓	↓	26	↓	↓	2341	0.124	2.36	1.89
T-304	↓	↓	26	↓	↓	3133	0.102	3.91	3.07
T-305	↓	↓	27	↓	↓	2603	0.138	2.64	1.89
T-306	Axial	9	27	750-765	3.6	2382	0.096	2.97	2.48
Mean						2423	0.110	2.77	2.22
Std. dev.						±341	±0.016	±0.49	±0.37

TABLE 11-8 (continued)

Specimen No.	Orien- tation	Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) _{HTGR}	Ultimate Tensile Strength (psi)	Strain at Failure (%)	Young's Modulus x 10 ⁻⁶ (psi)	Secant Modulus x 10 ⁻⁶ (psi)
T-289	Axial	8	24	835-850	4.5	2467	0.111	2.71	2.22
T-290	↓	↓	24	↓	↓	2482	-	2.82	-
T-291	↓	↓	25	↓	↓	3199	0.144	2.65	2.22
T-292	↓	↓	25	↓	↓	2297	0.108	2.44	2.13
T-293	↓	↓	26	↓	↓	2510	0.101	2.98	2.49
T-294	↓	↓	26	↓	↓	2425	0.105	2.53	2.31
T-295	↓	↓	27	↓	↓	2020	0.087	2.39	2.32
T-296	Axial	8	27	835-850	4.5	<u>2077</u>	<u>0.136</u>	<u>1.91</u>	<u>1.53</u>
Mean						2435	0.113	2.55	2.17
Std. dev.						+361	+0.020	+0.32	±0.31
T-325	Axial	6	12	1035	2.7	2120	0.107	2.33	1.98
T-326	↓	↓	12	↓	↓	2385	0.149	2.53	1.60
T-327	↓	↓	13	↓	↓	2085	0.123	2.00	1.70
T-328	↓	↓	13	1035	↓	1328	0.053	3.02	2.51
T-329	↓	↓	24	960	↓	1899	0.106	2.14	1.79
T-330	↓	↓	24	↓	↓	2336	0.118	2.46	1.98
T-331	↓	↓	25	↓	↓	1714	0.061	3.24	2.81
T-332	↓	↓	25	↓	↓	1590	-	2.08	-
T-333	↓	↓	26	↓	↓	1862	0.087	2.39	2.14
T-334	Axial	6	26	960	2.7	<u>2078</u>	<u>0.096</u>	<u>2.59</u>	<u>2.16</u>
Mean						1940	0.100	2.48	2.07
Std. dev.						+331	±0.030	±0.40	±0.39

TABLE 11-8 (continued)

Specimen No.	Orien- tation	Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) _{HTGR}	Ultimate Tensile Strength (psi)	Strain at Failure (%)	Young's Modulus x 10 ⁻⁶ (psi)	Secant Modulus x 10 ⁻⁶ (psi)
T-269	Axial	6	10	1020-1035	5.7	2206	0.116	2.07	1.90
T-270	↓	↓	10	↓	↓	2829	0.150	2.05	1.89
T-271	↓	↓	11	↓	↓	2161	0.099	2.58	2.18
T-272	↓	↓	11	1020-1035	↓	1904	0.135	2.01	1.41
T-273	↓	↓	21	940-960	↓	1907	0.104	2.30	1.83
T-274	↓	↓	21	↓	↓	2289	0.140	1.81	1.64
T-275	↓	↓	22	↓	↓	1412	0.071	2.54	1.99
T-276	↓	↓	22	↓	↓	2095	0.090	2.71	2.33
T-277	↓	↓	23	↓	↓	3058	0.134	2.65	2.28
T-278	Axial	6	23	940-960	5.7	<u>2360</u>	<u>0.122</u>	<u>2.44</u>	<u>1.93</u>
Mean						2222	0.116	2.32	1.94
Std. dev.						±468	±0.025	±0.31	±0.28
T-261	Axial	4	14	1110-1200	6.3	2185	0.110	2.19	1.99
T-262	↓	↓	14	1110-1200	↓	1148	0.055	2.48	2.09
T-263	↓	↓	21	1040-1105	↓	1711	0.082	2.52	2.09
T-264	↓	↓	21	↓	↓	3046	0.142	2.50	2.15
T-265	↓	↓	22	↓	↓	2489	0.104	2.69	2.39
T-266	↓	↓	22	↓	↓	1695	0.110	1.72	1.54
T-267	↓	↓	23	↓	↓	1658	0.090	2.17	1.84
T-268	Axial	4	23	1040-1105	6.3	<u>2094</u>	<u>0.105</u>	<u>2.32</u>	<u>1.99</u>
Mean						2003	0.100	2.32	2.01
Std. dev.						±585	±0.025	±0.30	±0.25

TABLE 11-8 (continued)

Specimen No.	Orien- tation	Crucible No.	Hole No.	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) _{HTGR}	Ultimate Tensile Strength (psi)	Strain at Failure (%)	Young's Modulus x 10 ⁻⁶ (psi)	Secant Modulus x 10 ⁻⁶ (psi)
11	Axial	--	--	--	0.0	1141	0.112	1.15	1.02
12		↓	↓	↓		1508	0.147	1.43	1.03
13		↓	↓	↓		1182	0.124	1.32	0.95
15		↓	↓	↓		1324	0.160	1.12	0.83
16		↓	↓	↓		1569	0.176	1.22	0.89
17		↓	↓	↓		1222	0.105	1.43	1.16
18		↓	↓	↓		1406	0.134	1.41	1.05
19	Axial	--	--	--	0.0	1222	--	1.33	--
Mean Std. dev.						1321 ±158	0.137 ±0.026	1.30 ±0.12	0.99 ±0.11
21	Radial	--	--	--	0.0	815	0.144	0.73	0.57
22		↓	↓	↓		896	0.216	0.67	0.42
24		↓	↓	↓		1161	0.256	0.63	0.45
25		↓	↓	↓		896	0.160	0.77	0.56
26		↓	↓	↓		957	0.230	0.70	0.42
28		↓	↓	↓		713	0.249	0.51	0.29
29		↓	↓	↓		244	--	--	--
30		↓	↓	↓		488	--	--	--
31		↓	↓	↓		468	--	--	--
32		↓	↓	↓		957	0.262	0.58	0.37
33		↓	↓	↓		1120	0.240	0.56	0.47
34		↓	↓	↓		754	0.196	0.62	0.38
35		--	--	--		1201	0.336	0.64	0.36
Mean Std. dev.						820 ±286	0.229 ±0.055	0.64 ±0.08	0.43 ±0.09

TABLE 11-9
SUMMARY OF MECHANICAL PROPERTY DATA ON GRAPHITES IRRADIATED IN CAPSULES OG-1 AND OG-2

Material	Orientation	Location in Log	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) _{HTGR}	Ultimate Tensile Strength (psi)		Young's Modulus x 10 ⁻⁶ (psi)	
					Observed ± Std. Dev.	Predicted (a)	Observed ± Std. Dev.	Predicted (a)
H-451	Axial	Midlength Center	--	0.0	1564 ± 135	--	1.14 ± 0.09	--
			580-630	1.4	2424 ± 265	2140	2.63 ± 0.20	2.2
			580-630	2.0	2485 ± 177	2160	2.22 ± 0.11	2.2
			580-630	2.6	2481 ± 322	2180	2.54 ± 0.20	2.2
			910-950	3.0	2371 ± 271	2040	2.06 ± 0.24	2.0
			890-970	5.3	2777 ± 261	2200	2.55 ± 0.15	2.4
			1340-1370	3.2	2233 ± 115	2000	1.79 ± 0.08	1.9
H-451	Axial	Midlength Center	--	0.0	1671 ± 242	--	1.00 ± 0.05	--
	Radial	Center	900-950	2.8	2648 ± 270	2190	1.88 ± 0.13	1.8
TS-1240	Axial	Midlength Center	--	0.0	1571 ± 252	--	0.90 ± 0.10	--
			620	1.2	1844 ± 452	2140	1.72 ± 0.32	1.7
			765	1.7	2070 ± 385	2100	1.72 ± 0.17	1.6
			920	2.5	2123 ± 259	2070	1.66 ± 0.13	1.6
	Axial	Midlength Center	1105	2.9	1899 ± 540	2050	1.69 ± 0.21	1.6
TS-1240	Radial	Midlength Center	--	0.0	1383 ± 298	--	0.90 ± 0.11	--
	Radial	Center	805	1.7	1951 ± 327	1850	1.50 ± 0.26	1.6

TABLE 11-9 (continued)

Material	Orientation	Location in Log	Mean Irradiation Temperature (°C)	Fluence x 10 ⁻²¹ (n/cm ²) (E>0.18 MeV) _{HTGR}	Ultimate Tensile Strength (psi)		Young's Modulus x 10 ⁻⁶ (psi)	
					Observed ± Std. Dev.	Predicted (a)	Observed ± Std. Dev.	Predicted (a)
H-327	Axial ↓ Axial Radial Radial	Midlength Center	--	0.0	1321 ± 158	--	1.30 ± 0.12	--
		↓	740	2.2	1944 ± 377	1790	2.25 ± 0.40	2.4
			750-810	3.6	2423 ± 341	1800	2.77 ± 0.49	2.4
			835-850	4.5	2435 ± 361	1810	2.55 ± 0.32	2.5
			860-900	2.3	2127 ± 281	1740	3.02 ± 0.27	2.3
		↓	960-1035	2.7	1940 ± 331	1730	2.48 ± 0.40	2.3
		Midlength Center	940-1035	5.7	2222 ± 468	1890	2.32 ± 0.31	2.6
			1040-1200	6.3	2003 ± 585	1850	2.32 ± 0.30	2.5
		Midlength Edge	--	0.0	2186 ± 293	--	1.93 ± 0.25	--
		↓	640-700	2.6	3152 ± 278	3000	3.85 ± 0.33	3.7
		Midlength Edge	770-810	1.9	2787 ± 249	2930	3.10 ± 0.26	3.5
			1050-1100	3.3	2822 ± 254	2860	3.23 ± 0.19	3.4
H-327		Midlength Center	--	0.0	820 ± 286	--	0.64 ± 0.08	--
			960-1020	3.0	962 ± 198	1070	1.23 ± 0.20	1.1

(a) Predicted from Figs. 11-12 and 11-13.

TABLE 11-10
 DIMENSIONAL CHANGE DATA, H-429, AXIAL DIRECTION,
 AFTER IRRADIATION IN CAPSULES GEH-422, 452, 482

Record No.	Total Fluence (10^{21} n/cm ²) (E=0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
3624	2.75	525	-0.72	
3600	2.75	↓	-0.66	
3601	2.80	↓	-0.69	
3602	2.90	↓	-0.73	
3603	3.00	↓	-0.74	
3604	3.07	↓	-0.81	
3605	3.10	525	-0.82	
2444	0.27	625	+0.05	
2448	↓	↓	+0.02	
2452	↓	↓	+0.07	
2473	↓	↓	+0.03	
2489	↓	↓	+0.04	
2492	↓	↓	+0.04	
2500	↓	↓	+0.02	
2522	0.27	625	+0.05	
3700	2.75	775	-0.45	
3724	2.75	↓	-0.54	
3701	2.80	↓	-0.53	
3702	2.90	↓	-0.52	
3703	3.00	↓	-0.55	
3704	3.07	↓	-0.51	
3705	3.10	775	-0.63	
2537	0.73	900	-0.03	
2594	↓	↓	-0.06	
2605	↓	↓	-0.01	
2606	↓	↓	-0.03	
2612	0.73	900	-0.02	
2653	1.10	1000	-0.14	
2659	↓	↓	-0.11	
2667	↓	↓	-0.15	
2671	↓	↓	-0.23	
2673	↓	↓	-0.20	
2680	↓	↓	-0.12	
2648	↓	↓	-0.15	
2649	↓	↓	-0.21	
2642	1.10	1000	-0.19	

TABLE 11-10. (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10 ⁻²)	Dimensional Change, ℓ/ℓ_0 (%)
2440	1.55	1100	-0.26	
2689	↓	↓	-0.28	
2692			-0.21	
2694	↓	↓	-0.23	
2706	1.55	1100	-0.28	
2402	2.20	1275	-1.08	
2403	↓	↓	-0.80	
2419			-0.97	
2426	↓	↓	-1.18	-1.17
2754		1275	-1.06	-1.05
2761	↓	1325	-1.22	-1.21
2764	2.20	1325	-1.36	-1.35
2850	2.65	1475	-1.86	-1.84
2853	2.65	1475	-1.91	-1.89
2791	↓	1500	-1.83	-1.81
2815		↓	-2.08	-2.05
2816			-1.85	-1.83
2821			-1.84	-1.82
2866			-1.98	-1.96
2870			-2.36	-2.33
2871	↓	↓	-2.19	-2.16
2872			-2.00	-1.98
2882			-2.22	-2.19

TABLE 11-11
DIMENSIONAL CHANGE DATA, H-429, AXIAL DIRECTION, AFTER IRRADIATION IN CAPSULE OG-1

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain ln(ℓ/ℓ_0) (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
5540	2402	2.20	1275	3.3	1045	5.50	1135	-1.86	-1.84
5542	2403		1275				1135	-1.50	-1.50
5563	2764		1325				1155	-2.14	-2.12
5565	2761		1325				1155	-1.45	-1.44
5571	2426		1275				1135	-2.10	-2.08
5573	2419	2.20	1275	3.3	1045	5.50	1135	-1.71	-1.69
5614	2791	2.65	1500	3.2	1370	5.85	1430	-3.12	-3.07
5616	2816							-2.83	-2.79
5618	2815							-3.74	-3.67
5620	2821				1370		1430	-3.52	-3.46
5653	2882				1335		1410	-3.43	-3.37
5654	2866							-2.84	-2.80
5655	2871							-3.29	-3.23
5665	2872							-3.09	-3.04
5666	2870		1500				1410	-3.40	-3.34
5669	2853		1475				1400	-3.15	-3.10
5670	2850	2.65	1475	3.2	1335	5.85	1400	-2.95	-2.95
5947	2605	0.73	900	2.3	890	3.00	890	-0.54	
5948	2612							-0.48	
5949	2594							-0.36	
5950	2606							-0.61	
5951	2537	0.73	900			3.00	890	-0.53	
5952	2649	1.10	1000			3.40	925	-0.62	
5953	2642				890	3.40	925	-0.56	
6003	2671				850	3.40	900	-0.72	
6004	2653							-0.62	
6005	2673							-0.52	
6010	2659							-0.52	
6011	2680							-0.58	
6012	2648							-0.56	
6013	2667	1.10	1000	2.3	850	3.40	900	-0.46	
6269	2522	0.27	625	1.4	630	1.67	630	-0.24	
6271	2448							-0.20	
6273	2500							-0.24	
6275	2452	0.27	625	1.4	630	1.67	630	-0.16	

TABLE 11-12
 DIMENSIONAL CHANGE DATA, H-429, AXIAL DIRECTION, AFTER IRRADIATION IN CAPSULE OG-2

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm 2) (E>0.18 MeV) _{HTGR}	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm 2) (E>0.18 MeV) _{HTGR}	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm 2) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
6924	5540	5.50	1135	2.95	1235	8.45	1170	-2.48	-2.45
6926	5542	↓	1135	↓	↓	8.45	1170	-2.26	-2.19
6928	5563	↓	1155	↓	↓	8.45	1185	-2.75	-2.72
6930	5565	↓	1155	↓	↓	↓	1185	-2.80	-2.76
6932	5571	↓	1135	↓	↓	↓	1170	-2.72	-2.69
6934	5573	5.50	1135	2.95	1235	8.45	1170	-2.74	-2.71
6990	5614	5.85	1430	2.90	1380	8.75	1415	-3.69	-3.62
6992	5616	↓	↓	↓	↓	↓	1415	-3.78	-3.63
6994	5618	↓	1430	↓	↓	↓	1415	-3.73	-3.67
6996	5620	↓	1410	↓	↓	↓	1415	-3.71	-3.64
6997	5653	↓	↓	↓	↓	↓	1400	-3.88	-3.81
6998	5654	↓	↓	↓	↓	↓	1400	-3.74	-3.67
6999	5655	↓	↓	↓	↓	↓	1400	-3.77	-3.70
7005	5665	↓	↓	↓	↓	↓	1400	-3.61	-3.55
7006	5666	↓	1410	↓	↓	↓	1400	-3.95	-3.88
7009	5669	↓	1400	↓	↓	↓	1395	-3.22	-3.17
7010	5670	5.85	1400	2.90	1380	8.75	1395	-3.60	-3.53
7354	5947	3.00	890	2.15	925	5.15	905	-1.40	-1.39
7355	5948	↓	↓	↓	↓	↓	905	-1.32	-1.31
7356	5949	↓	↓	↓	↓	↓	905	-1.25	-1.24
7357	5950	↓	↓	↓	↓	↓	905	-1.60	-1.59
7358	5951	3.00	890	↓	↓	5.15	905	-1.34	-1.33
7359	5952	3.40	925	↓	↓	5.55	925	-1.34	-1.33
7360	5953	↓	925	↓	↓	↓	925	-1.24	-1.23
7391	6003	↓	900	↓	850	↓	880	-1.51	-1.50
7392	6004	↓	↓	↓	↓	↓	880	-1.30	-1.29
7393	6005	↓	↓	↓	↓	↓	880	-1.42	-1.41
7394	6010	↓	↓	↓	↓	↓	880	-1.36	-1.35
7395	6011	↓	↓	↓	↓	↓	880	-1.39	-1.38
7396	6012	↓	↓	↓	↓	↓	880	-1.29	-1.28
7397	6013	3.40	900	2.15	850	5.55	880	-1.28	-1.27
7557	6269	1.67	630	1.15	635	2.82	630	-0.48	
7559	6271	↓	↓	↓	↓	↓	630	-0.34	
7561	6273	↓	↓	↓	↓	↓	630	-0.51	
7563	6275	1.67	630	1.15	635	2.82	630	-0.30	

TABLE 11-13
 DIMENSIONAL CHANGE DATA, H-451, AXIAL DIRECTION,
 AFTER IRRADIATION IN CAPSULE OG-1

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
5000	2.0	660	-0.05	
5001	2.0	660	-0.10	
5004	2.0	645	-0.12	
5008			-0.11	
5012			-0.10	
5016			-0.10	
5020			-0.14	
5024			-0.09	
5028		645	-0.05	
5032		620	-0.12	
5036			-0.24	
5040			-0.19	
5044			-0.11	
5045			-0.13	
5048			-0.12	
5049			-0.15	
5050			-0.12	
5051			-0.11	
5054			-0.10	
5055			-0.14	
5058			-0.14	
5059			-0.26	
5060			-0.16	
5061			-0.19	
5064			-0.12	
5065			-0.14	
5068		620	-0.17	
5069		570	-0.14	
5090			-0.18	
5091			-0.15	
5092			-0.16	
5093			-0.36	
5096			-0.18	
5097			-0.19	
5100			-0.21	
5101			-0.26	
5102			-0.07	
5103	2.0	570	-0.12	

TABLE 11-13. (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
5104	2.0	570	-0.16	
5105	↓	↓	-0.19	
5108	↓	↓	-0.16	
5109	↓	↓	-0.15	
5112	↓	↓	-0.16	
5113	↓	↓	-0.22	
5122	↓	↓	-0.18	
5123	↓	↓	-0.14	
5132	↓	↓	-0.15	
5133	2.0	570	-0.35	
5142	2.6	760	-0.14	
5143	2.6	760	-0.23	
5146	2.6	740	-0.12	
5150	↓	↓	-0.15	
5154	↓	↓	-0.16	
5158	↓	↓	-0.22	
5162	↓	↓	-0.28	
5166	↓	↓	-0.17	
5170	↓	↓	-0.13	
5174	↓	740	-0.12	
5178	↓	700	-0.17	
6472	↓	↓	-0.24	
5187	↓	↓	-0.16	
5188	↓	↓	-0.23	
5191	↓	↓	-0.10	
5192	↓	↓	-0.12	
5197	↓	↓	-0.19	
5198	↓	↓	-0.27	
5201	↓	↓	-0.21	
5202	↓	↓	-0.02	
5207	↓	↓	-0.22	
5208	↓	↓	-0.24	
5211	↓	↓	-0.26	
5212	↓	700	-0.30	
5243	↓	630	-0.15	
5244	↓	↓	-0.17	
5247	↓	↓	-0.24	
5248	↓	↓	-0.23	
5253	↓	↓	-0.25	
5254	2.6	630	-0.28	

TABLE 11-13. (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E=0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
5301	3.0 ↓	995	-0.72	-1.05
5303		995	-0.78	
5305		995	-1.06	
5307		980	-0.64	
5309		↓	-0.90	
5311		↓	-0.77	
5313		↓	-0.61	
5315		↓	-0.79	
5317		980	-0.99	
5352		950	-0.68	
5353		↓	-0.86	
5364		↓	-0.61	
5365		↓	-0.86	
5371		↓	-0.56	
5372		↓	-0.74	
5373		↓	-0.78	
5374		↓	-0.59	
5375		↓	-0.77	
5377		↓	-0.59	
5378		↓	-0.82	
5379		↓	-0.51	
5380		↓	-0.60	
5381		↓	-0.80	
5382		↓	-0.83	
5383		↓	-0.67	
5384		950	-0.85	
5422		900	-0.50	
5423		↓	-0.63	
5425		↓	-0.50	
5426		↓	-0.57	
5427		↓	-0.57	
5428		↓	-0.48	
5429		↓	-0.60	
5430		↓	-0.62	
5431		↓	-0.51	
5432		↓	-0.65	
5434		↓	-0.48	
5435		↓	-0.54	
5436		↓	-0.54	
5437		↓	-0.47	
5438	3.0	900	-0.58	

TABLE 11-13. (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
5439	3.0 ↓	900 ↓	-0.58	
5440			-0.43	
5441			-0.58	
5443			-0.41	
5444			-0.50	
5445			-0.42	
5446			-0.37	
5447			-0.52	
5448			-0.43	
5449			-0.41	
5450			-0.55	
5452			-0.42	
5453			-0.45	
5454			-0.50	
5455			-0.39	
5456			-0.51	
5457			-0.54	
5458			-0.42	
5459			-0.54	
5461			-0.41	
5462			-0.49	
5463			-0.56	
5464			-0.47	
5465			-0.51	
5468			-0.46	
5469			-0.57	
5471			-0.47	
5472			-0.55	
5475			-0.68	
5476	3.0	900	-0.41	
5479	3.3	1180	-1.09	-1.08
5480	3.3	1180	-1.20	-1.20
5483	3.3	1160	-1.07	-1.06
5484	↓	↓	-1.14	-1.13
5487			-1.02	-1.01
5488			-1.13	-1.13
5491			-1.07	-1.06
5492			-1.11	-1.10
5495	↓	↓	-1.04	-1.03
5496			-0.99	-0.98

TABLE 11-13. (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E 0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
5498	3.3	1160	-1.01	-1.00
5499	↓	↓	-1.17	-1.17
5502	↓	↓	-0.97	-0.97
5503	↓	1160	-1.08	-1.07
5516	↓	1115	-1.27	-1.26
5574	↓	1045	-1.22	-1.21
5576	3.3	1045	-1.19	-1.19
5577	3.2	1395	-3.00	-2.96
5578	3.2	1395	-2.74	-2.70
5581	3.2	1385	-2.85	-2.81
5582	↓	↓	-2.99	-2.94
5585	↓	↓	-3.06	-3.01
5586	↓	↓	-3.05	-3.00
5589	↓	↓	-2.92	-2.87
5590	↓	↓	-3.07	-3.03
5593	↓	↓	-3.01	-2.97
5594	↓	↓	-3.05	-3.01
5597	↓	↓	-2.88	-2.84
5598	↓	↓	-3.02	-2.98
5601	↓	↓	-3.07	-3.03
5602	↓	↓	-3.00	-2.96
5605	↓	↓	-2.76	-2.73
5607	↓	↓	-2.81	-2.77
5609	↓	↓	-2.77	-2.74
5611	↓	1385	-3.09	-3.05
5625	↓	1370	-2.88	-2.84
5626	↓	↓	-2.63	-2.60
5639	↓	↓	-2.90	-2.86
5640	↓	1370	-2.71	-2.68
5649	↓	1335	-2.61	-2.58
5650	↓	↓	-2.43	-2.40
5659	↓	↓	-2.43	-2.40
5660	↓	↓	-2.45	-2.42
5661	↓	↓	-2.58	-2.54
5662	↓	↓	-2.49	-2.46
5671	↓	↓	-2.50	-2.47
5672	↓	↓	-2.21	-2.19
5673	↓	↓	-2.35	-2.32
5675	↓	↓	-1.80	-1.78
5680	3.2	1335	-2.59	-2.55

TABLE 11-13. (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
5681	3.2	1335	-2.25	-2.23
5682	↓	↓	-2.61	-2.58
5683	↓	↓	-2.30	-2.28
5688	↓	↓	-2.48	-2.45
5690	3.2	1335	-2.39	-2.36
5692	3.0	1085	-1.26	-1.25
5693	↓	1085	-1.23	-1.22
5696	↓	1065	-1.16	-1.15
5697	↓	↓	-1.11	-1.11
5700	↓	↓	-1.15	-1.15
5701	↓	↓	-1.08	-1.07
5704	↓	↓	-1.17	-1.16
5705	↓	↓	-1.05	-1.04
5710	↓	↓	-1.14	-1.14
5711	↓	↓	-1.09	-1.09
5714	↓	↓	-1.13	-1.12
5715	↓	↓	-1.10	-1.09
5718	↓	↓	-1.13	-1.12
5719	↓	↓	-1.08	-1.07
5722	↓	↓	-1.17	-1.16
5723	↓	↓	-1.06	-1.05
5726	↓	↓	-1.12	-1.12
5727	↓	1065	-1.03	-1.02
5730	↓	1025	-1.10	-1.09
5731	↓	1025	-0.97	-0.96
5764	↓	1025	-0.63	-0.62
5773	↓	960	-0.57	
5777	↓	↓	-0.54	
5781	↓	↓	-0.50	
5782	↓	↓	-0.68	
5786	↓	↓	-0.61	
5788	↓	↓	-0.50	
5789	↓	↓	-0.67	
5793	↓	↓	-0.62	
5795	↓	↓	-0.70	
5799	↓	↓	-0.72	
5801	3.0	960	-0.66	
5803	2.8	995	-0.81	
5810	↓	980	-0.69	
5814	2.8	980	-0.73	

TABLE 11-13. (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%) _o
5818	2.8	980	-0.74	
5822			-0.73	
5826			-0.73	
5827			-0.71	
5830			-0.65	
5831			-0.69	
5834			-0.74	
5835			-0.68	
5838			-0.83	
5839		980	-0.71	
5842		950	-0.60	
5843			-0.60	
5846			-0.65	
5847			-0.64	
5850			-0.72	
5852			-0.56	
5854			-0.78	
5868		950	-0.47	
5879		900	-0.50	
5889			-0.53	
5891			-0.53	
5897			-0.52	
5900			-0.42	
5902			-0.52	
5904	2.8	900	-0.49	
5906	2.3	930	-0.54	
5910		915	-0.46	
5914			-0.50	
5918			-0.52	
5922			-0.49	
5926			-0.51	
5930			-0.46	
5931			-0.42	
5934			-0.51	
5935			-0.41	
5938			-0.45	
5939		915	-0.42	
6020		850	-0.32	
6021			-0.30	
6040			-0.48	
6042	2.3	850	-0.28	

TABLE 11-13. (continued)

Record No.	Total Fluence (10^{21} n/cm ²) ($E > 0.18$ MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
6044	2.3	850	-0.32	
6046	2.3	850	-0.25	
6048	1.9	865	-0.21	
6052		850	-0.18	
6056			-0.18	
6060			-0.18	
6064			-0.17	
6068			-0.21	
6072			-0.18	
6076			-0.16	
6080		850	-0.22	
6084		820	-0.34	
6088			-0.10	
6094			-0.22	
6098			-0.13	
6104			-0.16	
6108			-0.15	
6114			-0.14	
6118		820	-0.16	
6150		770	-0.15	
6154			-0.13	
6160			-0.14	
6194			-0.13	
6195			-0.14	
6200			-0.12	
6201			-0.23	
6204			-0.14	
6205	1.9	770	-0.16	
6208	1.4	650	-0.06	
6212		645	-0.04	
6216			0.00	
6220			-0.07	
6224			-0.10	
6228			-0.07	
6232			-0.10	
6236			-0.22	
6240		645	-0.08	
6256		630	-0.16	
6257			-0.13	
6266	1.4	630	-0.12	

TABLE 11-13. (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
6267	1.4 ↓	630	-0.09	
6276		630	-0.11	
6277		630	-0.02	
6298		605	-0.15	
6299		↓	-0.06	
6300			-0.11	
6304			+0.05	
6305			-0.05	
6308			-0.13	
6309			-0.13	
6310			-0.14	
6311			-0.03	
6312			-0.12	
6313			-0.11	
6316			-0.14	
6317			-0.13	
6320			-0.13	
6321			-0.10	
6322			-0.13	
6323			-0.16	
6326			-0.15	
6327			-0.12	
6330			-0.15	
6331			-0.12	
6340			-0.23	
6341	1.4	605	-0.12	

TABLE 11-14
DIMENSIONAL CHANGE DATA, H-451, AXIAL DIRECTION, AFTER IRRADIATION IN CAPSULE 06-2

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E 0.18 MeV) _{HFGR}	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm ²) (E 0.18 MeV) _{HTGR}	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm ²) (E 0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\frac{l}{l_0})$ (10^{-2})	Dimensional Change, / ° (%)
6500	5000	2.0	660	1.7	690	3.7	675	-0.26	
6501	5001		660		690	3.7	675	-0.33	
6504	5004		645		680	3.7	660	-0.28	
6508	5008		645		680		660	-0.30	
6512	5012				680		660	-0.28	
6513	5016				680			-0.32	
6516	5020							-0.28	
6517	5024	2.0	645			3.7	660	-0.30	
6520 ^(a)	5696	3.0	1065			4.7	945	-1.68	-1.67
6521 ^(a)	5697							-1.67	-1.66
6524 ^(a)	5700							-1.68	-1.66
6525 ^(a)	5701							-1.64	-1.63
6528 ^(a)	5704							-1.64	-1.63
6529 ^(a)	5705							-1.60	-1.58
6532 ^(a)	5710							-1.61	-1.60
6533 ^(a)	5711	3.0	1065		680	4.7	945	-1.65	-1.63
6536	--	--	--		660	1.7	660	-0.11	
6537	--	--	--					-0.13	
6538	--	--	--					-0.09	
6539	--	--	--					-0.14	
6540	--	--	--					-0.12	
6541	--	--	--					-0.15	
6542	--	--	--					-0.08	
6543	--	--	--					-0.16	
6544	--	--	--					-0.08	
6545	--	--	--					-0.03	
6546	--	--	--					-0.11	
6547	--	--	--		660	1.7	660	-0.14	
6605	5102	2.0	570		615	3.7	590	-0.42	
6606	5103							-0.55	
6607	5112							-0.41	
6608	5113							-0.58	
6609	5122							-0.43	
6610	5123							-0.55	
6611	5132							-0.42	
6612	5133	2.0	570			3.7	590	-0.65	
6613	--	--	--			1.7	615	-0.12	
6614	--	--	--					-0.15	
6615	--	--	--					-0.16	
6616	--	--	--					-0.23	
6617	--	--	--					-0.11	
6618	--	--	--					-0.16	
6619	--	--	--					-0.21	
6620	--	--	--					-0.23	
6621	--	--	--					-0.13	
6622	--	--	--					-0.16	
6623	--	--	--					-0.13	
6624	--	--	--	1.7	615	1.7	615	-0.15	
6625	5142	2.6	760	2.2	780	4.8	770	-0.49	
6626	5143		760	2.2	780		770	-0.62	
6629	5146		740	2.2	765		750	-0.47	
6633	5150						750	-0.53	
6637	5154						750	-0.53	
6641	5158							-0.52	
6645	5162							-0.62	
6649	5166							-0.54	
6653	5170							-0.50	
6657	5174		740		765		750	-0.49	
6691	5243		630		680		655	-0.59	
6692	5244							-0.65	
6695	5247							-0.64	
6696	5248							-0.62	
6699	5253							-0.63	
6700	5254	2.6	630	2.2	680	4.8	655	-0.67	
6731	5301	3.0	995	2.7	1000	5.7	995	-2.10	-2.08
6733	5303	3.0	995		1000	5.7	995	-2.09	-2.06
6735	5305	3.0	995		1000	5.7	995	-2.54	-2.51
6776	--	--	--		970	2.7	970	-0.41	
6777	--	--	--					-0.52	
6778	--	--	--					-0.56	
6779	--	--	--					-0.42	
6780	--	--	--					-0.58	
6781	--	--	--					-0.67	
6782	--	--	--	2.7	970	2.7	970	-0.47	

TABLE 11-14. (continued)

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) HTGR	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm ²) (E>0.18 MeV) HTGR	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) HTGR	Irrad Temp (°C)	Irrad Strain ln(ϵ/ϵ_0) (10 ⁻²)	Dimensional Change, $\Delta\epsilon/\epsilon_0$ (%)
6783	--	--	--	2.7	970	2.7	970	-0.60	
6784	--	--	--					-0.71	
6785	--	--	--					-0.45	
6786	--	--	--					-0.74	
6787	--	--	--			2.7	970	-0.51	
6800	5371	3.0	950			5.7	960	-1.95	-1.93
6801	5372							-2.29	-2.26
6802	5373							-2.33	-2.30
6803	5377							-1.95	-1.94
6804	5378							-2.34	-2.32
6805	5379							-2.39	-2.36
6806	5380							-1.93	-1.91
6807	5381							-2.34	-2.31
6808	5382		950		970		960	-2.38	-2.35
6815	5440		900		920		910	-1.60	-1.58
6816	5441							-1.85	-1.84
6818	5449							-1.58	-1.56
6819	5450							-1.85	-1.83
6821	5458							-1.55	-1.53
6822	5459							-1.88	-1.86
6824	5468							-1.64	-1.63
6825	5469							-1.89	-1.88
6839	5425							-1.81	-1.79
6840	5426							-2.02	-2.00
6841	5427							-2.09	-2.07
6842	5428							-1.69	-1.68
6843	5429							-2.04	-2.02
6844	5430							-2.10	-2.07
6845	5434							-1.59	-1.58
6846	5435							-1.82	-1.80
6847	5436							-1.85	-1.83
6848	5437							-1.52	-1.51
6849	5438							-1.82	-1.80
6850	5439	3.0	900	2.7	920	5.7	910	-1.97	-1.95
6899	5479	3.3	1180	2.95	1255	6.25	1215	-2.29	-2.26
6900	5480		1180		1255		1215	-2.34	-2.31
6903	5483		1160		1235		1195	-2.29	-2.26
6904	5484	3.3	1160	2.95	1235	6.25	1195	-2.37	-2.34
6911	5491	3.3	1160	2.95	1235	6.25	1195	-2.35	-2.32
6912	5492	3.3	1160	2.95	1235	6.25	1195	-2.36	-2.33
6985	5577	3.2	1395	2.9	1390	6.10	1395	-3.89	-3.82
6986	5578	3.2	1395		1390	6.10	1395	-3.80	-3.73
7011	5581	3.2	1385		1380	6.10	1385	-3.60	-3.53
7021	--	--	--		1365	2.9	1365	-1.94	-1.93
7022	--	--	--					-1.88	-1.87
7023	--	--	--					-2.06	-2.04
7024	--	--	--					-1.98	-1.96
7025	--	--	--					-2.22	-2.19
7026	--	--	--					-2.11	-2.09
7027	--	--	--					-2.27	-2.24
7028	--	--	--					-1.09	-1.09
7029	--	--	--					-2.07	-2.05
7030	--	--	--		1365	2.9	1365	-1.86	-1.85
7072	5673	3.2	1335		1325	6.10	1330	-3.53	-3.47
7074	5675							-3.18	-3.13
7075	5661							-3.71	-3.65
7076	5662							-3.64	-3.57
7077	5671							-3.72	-3.65
7078	5672							-3.52	-3.46
7079	5680							-3.84	-3.77
7080	5681							-3.61	-3.54
7081	5682							-3.73	-3.66
7082	5683	3.2	1335			6.10	1330	-3.49	-3.43
7083	--	--	--			2.9	1325	-2.04	-2.02
7084	--	--	--					-2.03	-2.01
7085	--	--	--					-2.00	-1.98
7086	--	--	--					-1.94	-1.92
7087	--	--	--					-1.88	-1.86
7088	--	--	--					-1.83	-1.82
7089	--	--	--					-1.82	-1.80
7090	--	--	--					-1.81	-1.79
7091	--	--	--					-1.73	-1.72
7092	--	--	--	2.9	1325	2.9	1325	-1.66	-1.64
7097	5764	3.0	1025	2.7	1085	5.7	1055	-2.64	-2.61

TABLE 11-14. (continued)

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E 0.18 MeV) HTGR	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm ²) (E 0.18 MeV) HTGR	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm ²) (E 0.18 MeV) HTGR	Irrad Temp (°C)	Irrad Strain ln(ϵ/ϵ_0) (10^{-2})	Dimensional Change, / ° (%)
7099	5773	3.0	960	2.7	1065	5.7	1010	-2.36	-2.33
7101	5777	↓	↓	↓	↓	↓	↓	-2.23	-2.20
7103	5781	↓	↓	↓	↓	↓	↓	-2.29	-2.27
7104	5782	↓	↓	↓	↓	↓	↓	-2.55	-2.51
7106	5789	↓	↓	↓	↓	↓	↓	-1.16	-1.15
7108	5793	↓	↓	↓	↓	↓	↓	-2.44	-2.41
7110	5795	3.0	960	↓	1065	5.7	1010	-2.42	-2.39
7127(a)	5092	2.0	570	↓	1035	4.7	835	-0.19	-1.46
7128(a)	5093	↓	↓	↓	↓	↓	↓	-1.47	-1.33
7131(a)	5096	↓	↓	↓	↓	↓	↓	-1.34	-1.28
7132(a)	5097	↓	↓	↓	↓	↓	↓	-1.28	-1.35
7135(a)	5104	↓	↓	↓	↓	↓	↓	-1.36	-1.36
7136(a)	5105	↓	↓	↓	↓	↓	↓	-1.37	-1.43
7139(a)	5108	↓	↓	↓	↓	↓	↓	-1.44	-1.32
7140	5109	2.0	570	↓	↓	4.7	835	-1.33	-2.42
7144	5799	3.0	960	2.7	↓	5.7	995	-2.45	-2.31
7146	5801	3.0	960	2.5	1035	5.7	995	-2.34	-2.16
7215	5803	2.8	995	↓	1000	5.3	1000	-2.18	-2.04
7219	5810	↓	980	↓	990	↓	985	-2.06	-2.10
7223	5814	↓	↓	↓	↓	↓	↓	-2.12	-2.15
7227	5818	↓	↓	↓	↓	↓	↓	-2.17	-2.14
7231	5822	↓	↓	↓	↓	↓	↓	-2.16	-1.92
7235	5826	↓	↓	↓	↓	↓	↓	-1.93	-2.05
7236	5827	↓	↓	↓	↓	↓	↓	-2.07	-1.89
7239	5830	↓	↓	↓	↓	↓	↓	-1.91	-2.11
7240	5831	↓	↓	↓	↓	↓	↓	-2.13	-2.10
7243	5834	↓	↓	↓	↓	↓	↓	-2.12	-2.03
7244	5835	↓	980	↓	990	↓	985	-2.05	-2.10
7249	5868	↓	950	↓	970	↓	960	-2.13	-1.82
7307	5879	↓	900	↓	920	↓	910	-1.84	-1.74
7308	5889	↓	↓	↓	↓	↓	↓	-1.76	-1.83
7309	5891	↓	↓	↓	↓	↓	↓	-1.85	-1.68
7310	5897	↓	↓	↓	↓	↓	↓	-1.70	-1.76
7311	5902	↓	↓	↓	↓	↓	↓	-1.78	-1.68
7312	5904	2.8	900	2.5	920	5.3	910	-1.70	-1.55
7325	5930	2.3	915	2.15	940	4.45	930	-1.57	-1.40
7326	5931	↓	↓	↓	940	↓	930	-1.41	-1.43
7329	5934	↓	↓	↓	925	↓	920	-1.44	-1.26
7330	5935	↓	↓	↓	↓	↓	↓	-1.27	-1.42
7333	5938	↓	↓	↓	↓	↓	↓	-1.42	-1.41
7334	5939	2.3	915	↓	925	4.45	920	-1.36	-1.35
7361	--	--	--	↓	905	2.15	905	-0.30	--
7362	--	--	--	↓	↓	↓	↓	-0.26	--
7363	--	--	--	↓	↓	↓	↓	-0.30	--
7364	--	--	--	↓	↓	↓	↓	-0.22	--
7365	--	--	--	↓	↓	↓	↓	-0.30	--
7366	--	--	--	↓	↓	↓	↓	-0.22	--
7367	--	--	--	↓	↓	↓	↓	-0.32	--
7368	--	--	--	↓	↓	↓	↓	-0.28	--
7369	--	--	--	↓	↓	↓	↓	-0.34	--
7370	--	--	--	↓	↓	↓	↓	-0.23	--
7371	--	--	--	↓	↓	↓	↓	-0.29	--
7372	--	--	--	↓	905	↓	905	-0.23	--
7410	--	--	--	↓	850	↓	850	-0.24	--
7412	--	--	--	↓	↓	↓	↓	-0.26	--
7413	--	--	--	↓	↓	↓	↓	-0.18	--
7414	--	--	--	↓	↓	↓	↓	-0.26	--
7415	--	--	--	↓	↓	↓	↓	-0.19	--
7416	--	--	--	↓	↓	↓	↓	-0.23	--
7417	--	--	--	↓	850	2.15	850	-0.23	--
7422	6048	1.9	865	1.7	835	3.6	850	-0.67	--
7424	6052	↓	850	↓	835	↓	845	-0.54	--
7426	6056	↓	↓	↓	820	↓	835	-0.57	--
7428	6060	↓	↓	↓	↓	↓	↓	-0.52	--
7430	6064	↓	↓	↓	↓	↓	↓	-0.60	--
7432	6068	↓	↓	↓	↓	↓	↓	-0.51	--
7434	6072	↓	↓	↓	↓	↓	↓	-0.60	--
7436	6076	↓	↓	↓	↓	↓	↓	-0.49	--
7438	6080	↓	850	↓	↓	↓	835	-0.62	--
7440	6084	↓	820	↓	↓	↓	820	-0.49	--
7442	6088	↓	↓	↓	↓	↓	↓	-0.52	--
7444	6094	↓	↓	↓	↓	↓	↓	-0.40	--
7446	6098	↓	↓	↓	↓	↓	↓	-0.52	--
7448	6104	1.9	820	1.7	820	3.6	820	-0.35	--
7528	6208	1.4	650	1.15	645	2.55	650	-0.24	--

TABLE 11-14. (continued)

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm ²) (E 0.18 MeV) _{HTGR}	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm ²) (E 0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain ln(ϵ/ϵ_0) (10^{-2})	Dimensional Change, $\Delta L/L_0$ (%)
7532	6212	1.4	645	1.15	635	2.55	640	-0.27	
7536	6216	↓	↓	↓	↓	↓	↓	-0.27	
7540	6220	↓	↓	↓	↓	↓	↓	-0.23	
7544	6224	↓	645	↓	635	↓	640	-0.22	
7589	6304	↓	605	↓	590	↓	600	0.01	
7590	6305	↓	↓	↓	↓	↓	↓	-0.24	
7593	6312	↓	↓	↓	↓	↓	↓	-0.32	
7594	6313	↓	↓	↓	↓	↓	↓	-0.28	
7605	6310	↓	↓	↓	↓	↓	↓	-0.35	
7606	6311	↓	↓	↓	↓	↓	↓	-0.24	
7607	6320	↓	↓	↓	↓	↓	↓	-0.25	
7608	6321	↓	↓	↓	↓	↓	↓	-0.18	
7609	6330	↓	↓	↓	↓	↓	↓	-0.33	
7610	6331	↓	↓	↓	↓	↓	↓	-0.24	
7611	6340	↓	↓	↓	↓	↓	↓	-0.42	
7612	6341	1.4	605	1.15	590	2.55	600	-0.25	

(a) Temperature change samples.

TABLE 11-15
 DIMENSIONAL CHANGE DATA, H-429, RADIAL DIRECTION,
 AFTER IRRADIATION IN CAPSULES GEH-422, 452, 482

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})
3609	3.35	475	-0.60
3610	3.40	475	-0.59
3611	3.45	475	-0.60
3625	2.80	525	-0.59
3606	3.20	525	-0.62
3607	3.25	525	-0.65
3608	3.30	525	-0.61
2461	0.27	625	0.00
2467	↓	↓	-0.01
2488			+0.02
2497			+0.01
2518			+0.02
2521			+0.00
2524	↓	↓	+0.02
2532	0.27	625	+0.00
3725	2.80	775	-0.34
3706	3.20	775	-0.43
3707	3.25	775	-0.47
3708	3.30	775	-0.52
3709	3.35	800	-0.50
3710	3.40	800	-0.45
3711	3.45	800	-0.53
2564	0.73	900	+0.12
2580	↓	↓	+0.01
2598			+0.03
2601	↓	↓	+0.01
2608	0.73	900	+0.03
2645	1.10	1000	-0.20
2652	↓	↓	-0.10
2655			-0.10
2662			-0.10
2663			-0.06
2665			-0.05
2672			-0.14
2681	↓	↓	-0.08
2687	1.10	1000	-0.03
2688	1.50	1100	-0.06
2690	↓	↓	-0.08
2691			-0.14
2702	↓	↓	-0.14
2712	1.50	1100	-0.12

TABLE 11-15. (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})
2428	2.20	1275	-0.64
2430	↓	↓	-0.86
2436	↓	↓	-0.81
2442	↓	1275	-0.98
2748	2.20	1325	-1.11
2855	2.65	1475	-1.61
2861	↓	1475	-1.60
2800	↓	1500	-1.55
2804	↓	↓	-1.46
2807	↓	↓	-1.59
2823	↓	↓	-1.48
2849	↓	↓	-1.54
2858	↓	↓	-1.62
2864	↓	↓	-1.68
2875	↓	↓	-1.66
2877	2.65	1500	-1.64

TABLE 11-16
 DIMENSIONAL CHANGE DATA, H-429, RADIAL DIRECTION, AFTER IRRADIATION IN CAPSULE OG-1

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain ln($\frac{l}{l_0}$) (10 ⁻²)	Dimensional Change, $\frac{\Delta l}{l_0}$ (%)
5539	2436	2.2	1275	3.3	1045	5.5	1135	-1.16	-1.15
5541	2428	↓	1275	↓	↓	↓	1135	-1.01	-1.00
5562	2748	↓	1325	↓	↓	↓	1155	-1.47	-1.46
5570	2442	↓	1275	↓	↓	↓	1135	-1.40	-1.39
5572	2430	2.2	1275	3.3	1045	5.5	1135	-1.25	-1.24
5613	2823	2.65	1500	3.2	1370	5.85	1430	-2.19	-2.17
5615	2804	↓	↓	↓	↓	↓	↓	-2.12	-2.10
5617	2807	↓	↓	↓	↓	↓	↓	-2.33	-2.30
5619	2800	↓	↓	↓	1370	↓	1430	-2.14	-2.12
5656	2858	↓	↓	↓	1335	↓	1410	-2.38	-2.35
5657	2849	↓	↓	↓	↓	↓	↓	-2.23	-2.21
5658	2875	↓	↓	↓	↓	↓	↓	-2.23	-2.21
5663	2864	↓	↓	↓	↓	↓	↓	-2.25	-2.23
5664	2877	↓	1500	↓	↓	↓	1410	-2.28	-2.26
5667	2861	↓	1475	↓	↓	↓	1400	-2.15	-2.13
5668	2855	2.65	1475	3.2	1335	5.85	1400	-2.37	-2.34
5942	2598	0.73	900	2.3	890	3.0	890	-0.31	
5943	2580	↓	↓	↓	↓	↓	↓	-0.30	
5944	2601	↓	↓	↓	↓	↓	↓	-0.22	
5945	2564	↓	↓	↓	↓	↓	↓	-0.28	
5946	2608	0.73	900	↓	890	3.0	890	-0.33	
5998	2665	1.1	1000	↓	850	3.4	900	-0.37	
5999	2663	↓	↓	↓	↓	↓	↓	-0.38	
6000	2672	↓	↓	↓	↓	↓	↓	-0.48	
6001	2655	↓	↓	↓	↓	↓	↓	-0.33	
6002	2681	↓	↓	↓	↓	↓	↓	-0.37	
6014	2662	↓	↓	↓	↓	↓	↓	-0.37	
6015	2652	↓	↓	↓	↓	↓	↓	-0.40	
6016	2645	↓	↓	↓	↓	↓	↓	-0.41	
6017	2687	1.1	1000	2.3	850	3.4	900	-0.26	
6268	2497	0.27	625	1.4	630	1.67	630	-0.24	
6270	2524	0.27	625	1.4	630	1.67	630	-0.15	
6272	2488	0.27	625	1.4	630	1.67	630	-0.23	

TABLE 11-17
DIMENSIONAL CHANGE DATA, H-429, RADIAL DIRECTION, AFTER IRRADIATION IN CAPSULE OG-2

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
6923	5539	5.5	1135	2.95	1235	8.45	1170	-1.27	-1.26
6925	5541	↓	1135	↓	↓	↓	1170	-1.20	-1.19
6927	5562	↓	1155	↓	↓	↓	1185	-1.62	-1.61
6931	5570	↓	1135	↓	↓	↓	1170	-1.43	-1.42
6333	5572	5.5	1135	2.95	1235	8.45	1170	-1.35	-1.34
6989	5613	5.85	1430	2.9	1380	8.75	1415	-2.17	-2.14
6991	5615	↓	↓	↓	↓	↓	↓	-1.87	-1.85
6993	5617	↓	↓	↓	↓	↓	↓	-1.79	-1.78
6995	5619	↓	1430	↓	↓	↓	1415	-1.06	-1.06
7000	5656	↓	1410	↓	↓	↓	1400	-2.30	-2.28
7001	5657	↓	↓	↓	↓	↓	↓	-2.18	-2.16
7002	5658	↓	↓	↓	↓	↓	↓	-2.36	-2.34
7003	5663	↓	↓	↓	↓	↓	↓	-2.04	-2.02
7004	5664	↓	1410	↓	↓	↓	1400	-2.07	-2.05
7007	5667	↓	1400	↓	↓	↓	1395	-1.42	-1.41
7008	5668	5.85	1400	2.9	1380	8.75	1395	-1.68	-1.67
7349	5942	3.0	890	2.15	925	5.15	905	-0.78	
7350	5943	↓	↓	↓	↓	↓	↓	-0.73	
7351	5944	↓	↓	↓	↓	↓	↓	-0.61	
7352	5945	↓	↓	↓	↓	↓	↓	-0.74	
7353	5946	3.0	890	↓	925	5.15	905	-0.76	
7386	5998	3.4	900	↓	850	5.55	880	-0.91	
7387	5999	↓	↓	↓	↓	↓	↓	-0.86	
7388	6000	↓	↓	↓	↓	↓	↓	-0.95	
7389	6001	↓	↓	↓	↓	↓	↓	-0.91	
7390	6002	↓	↓	↓	↓	↓	↓	-0.80	
7398	6014	↓	↓	↓	↓	↓	↓	-0.97	
7399	6015	↓	↓	↓	↓	↓	↓	-0.92	
7400	6016	↓	↓	↓	↓	↓	↓	-0.88	
7401	6017	3.4	900	2.15	850	5.55	880	-0.48	
7556	6268	1.67	630	1.15	635	2.82	630	-0.46	
7558	6270	1.67	630	1.15	635	2.82	630	-0.33	
7560	6272	1.67	630	1.15	635	2.82	630	-0.45	

TABLE 11-18
 DIMENSIONAL CHANGE DATA, H-451, RADIAL DIRECTION,
 AFTER IRRADIATION IN CAPSULE OG-1

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
5002	2.0	660	-0.04	
5014		645	-0.10	
5010		645	-0.11	
5006		645	-0.07	
5003		660	-0.06	
5111		570	-0.19	
5110			-0.14	
5107			-0.19	
5106			-0.15	
5099			-0.22	
5098			-0.15	
5095			-0.02	
5094		570	-0.18	
5067		620	-0.12	
5066			-0.15	
5063			-0.08	
5062			-0.15	
5057			-0.03	
5056			-0.14	
5053			-0.11	
5052			-0.12	
5047			-0.18	
5046			-0.13	
5042			-0.16	
5038		620	-0.19	
5034		645	-0.09	
5030			-0.09	
5026			-0.10	
5022			-0.05	
5018	2.0	645	-0.04	
5144	2.6	760	-0.19	
5148		740	-0.08	
5145		760	-0.13	
5164		740	-0.16	
5160			-0.13	
5156			-0.10	
5152		740	-0.10	
5256		630	-0.23	
5255		630	-0.14	
5250	2.6	630	-0.15	

TABLE 11-18. (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
5249	2.6	630	-0.15	
5246	↓	630	-0.16	
5245	↓	630	-0.06	
5214	↓	700	-0.16	
5213	↓	↓	-0.19	
5210	↓	↓	-0.16	
5209	↓	↓	-0.20	
5204	↓	↓	-0.18	
5203	↓	↓	-0.16	
5200	↓	↓	-0.16	
5199	↓	↓	-0.10	
5194	↓	↓	-0.13	
5193	↓	↓	-0.12	
5190	↓	↓	-0.19	
5189	↓	↓	-0.15	
5183	↓	↓	-0.11	
5180	↓	700	-0.05	
5176	↓	740	-0.06	
5172	↓	740	-0.13	
5168	2.6	740	-0.14	
5302	3.0	995	-0.43	
5318	↓	980	-0.59	
5316	↓	↓	-0.54	
5314	↓	↓	-0.39	
5312	↓	↓	-0.31	
5310	↓	↓	-0.46	
5308	↓	980	-0.43	
5306	↓	995	-0.48	
5304	↓	995	-0.55	
5433	↓	900	-0.30	
5424	↓	900	-0.37	
5385	↓	950	-0.44	
5376	↓	↓	-0.38	
5368	↓	↓	-0.41	
5367	↓	↓	-0.29	
5366	↓	↓	-0.33	
5361	↓	↓	-0.36	
5360	↓	↓	-0.33	
5356	↓	↓	-0.52	
5355	↓	↓	-0.31	
5354	↓	↓	-0.40	
5351	↓	↓	-0.42	
5350	3.0	950	-0.38	

TABLE 11-18. (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
5349	3.0 ↓	950	-0.34	
5348		950	-0.55	
5347		950	-0.41	
5346		950	-0.31	
5345		980	-0.44	
5344		↓	-0.54	
5343			-0.45	
5342			-0.67	
5341			-0.55	
5340			-0.46	
5339			-0.55	
5338			-0.50	
5337		980	-0.32	
5442		900	-0.30	
5470		↓	-0.30	
5460			-0.31	
5451		900	-0.33	
5481	3.3 ↓	1180	-0.81	
5489		1160	-0.82	
5486		1160	-0.68	
5485		1160	-0.94	
5482		1180	-0.63	
5575		1045	-0.65	
5518		1115	-0.59	
5512		1115	-0.65	
5505		1160	-0.83	
5504		↓	-0.81	
5501			-0.58	
5500			-0.87	
5497			-0.54	
5494			-0.60	
5493			-0.71	
5490			-0.67	
6471		1160	-0.91	
5579		1395	-2.08	-2.06
5587		1385	-2.06	-2.04
5584		1385	-1.77	-1.75
5583		1385	-2.09	-2.07
5580		1395	-1.89	-1.87
5588		1385	-1.90	-1.88
5592	3.2 ↓	↓	-1.60	-1.58
5591			-2.10	-2.08
5600		1385	-1.78	-1.76

TABLE 11-18. (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
5599	3.2	1385	-2.00	-1.98
5596			-1.94	-1.92
5595			-2.04	-2.02
5603			-2.10	-2.08
5606			-1.97	-1.95
5604		1385	-2.03	-2.01
5674		1335	-1.60	-1.58
5612		1385	-1.87	-1.85
5610		1385	-2.02	-2.00
5608		1385	-1.64	-1.62
5691		1335	-1.47	-1.46
5689	3.2	1335	-1.74	-1.74
5695	3.0	1085	-0.53	
5694		1085	-0.60	
5703		1065	-0.50	
5702			-0.61	
5699			-0.49	
5698			-0.64	
5721			-0.49	
5720			-0.55	
5717			-0.50	
5716			-0.56	
5713			-0.51	
5712			-0.57	
5709			-0.52	
5708			-0.60	
5724		1065	-0.63	
5778		960	-0.28	
5774		960	-0.31	
5765		1025	-0.50	
5733		1025	-0.49	
5732		1025	-0.47	
5729		1065	-0.71	
5728		1065	-0.58	
5725		1065	-0.52	
5802		960	-0.34	
5800			-0.41	
5796			-0.33	
5794			-0.27	
5790			-0.33	
5787			-0.30	
5783	3.0	960	-0.33	
5820	2.8	980	-0.33	

TABLE 11-18. (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(\ell/\ell_0)$ (10^{-2})	Dimensional Change, $\Delta\ell/\ell_0$ (%)
5816	2.8	980	-0.41	
5812		980	-0.38	
5808		995	-0.41	
5855		950	-0.35	
5853			-0.20	
5851			-0.50	
5849			-0.23	
5848			-0.36	
5845			-0.14	
5844		950	-0.30	
5841		980	-0.26	
5840			-0.34	
5837			-0.32	
5836			-0.40	
5833			-0.42	
5832			-0.37	
5829			-0.16	
5828			-0.51	
5824		980	-0.40	
5869		950	-0.31	
5905		900	-0.23	
5903			-0.24	
5901			-0.25	
5899			-0.32	
5898			-0.27	
5880			-0.22	
5892			-0.24	
5890	2.8	900	-0.27	
6045	2.3	850	-0.18	
6047			-0.13	
6043			-0.10	
6041			-0.11	
6023			-0.15	
6022		850	-0.09	
5941		915	-0.04	
5908		930	-0.18	
5916		915	-0.22	
5912			-0.21	
5940			-0.18	
5937			-0.20	
5936			-0.25	
5933			-0.17	
5932	2.3	915	-0.19	

TABLE 11-18. (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
5928	2.3	915	-0.28	
5924	2.3	915	-0.22	
5920	2.3	915	-0.23	
6050	1.9	865	-0.12	
6066		850	-0.08	
6062			-0.10	
6058			-0.04	
6054			-0.09	
6070			-0.07	
6078			-0.05	
6074		850	-0.06	
6096		820	-0.09	
6090		820	-0.03	
6086		820	-0.12	
6082		850	-0.08	
6207		770	-0.08	
6206			-0.14	
6203			-0.06	
6202			-0.09	
6197			-0.12	
6196			-0.08	
6162			-0.12	
6156			-0.03	
6152		770	-0.07	
6120		820	-0.12	
6116			-0.07	
6110			-0.03	
6106			-0.04	
6100	1.9	820	-0.10	
6214	1.4	645	-0.03	
6210		650	-0.03	
6218		645	-0.07	
6306		605	-0.15	
6302		605	-0.13	
6242		645	-0.02	
6238			-0.11	
6234			-0.12	
6230			-0.04	
6226			-0.06	
6222		645	-0.05	
6329		605	-0.06	
6328		605	-0.15	
6315	1.4	605	-0.03	

TABLE 11-18. (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})	Dimensional Change, $\Delta l/l_0$ (%)
6314	1.4	605	-0.11	
6307	↓	↓	-0.10	
6325			-0.04	
6324			-0.06	
6319	↓	↓	-0.14	
6318	1.4	605	-0.05	

TABLE 11-19
DIMENSIONAL CHANGE DATA, H-451, RADIAL DIRECTION,
AFTER IRRADIATION IN CAPSULE OG-2

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) HTGR	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm ²) (E>0.18 MeV) HTGR	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) HTGR	Irrad Temp (°C)	Irrad Strain ln(t/t_0) (10 ⁻²)	Dimensional Change, $\Delta z/t_0$ (%)
6502	5002	2.0	660	1.7	690	3.7	675	-0.27	
6503	5003		660		690		675	-0.28	
6506	5006		645		680		660	-0.29	
6510	5010		570				620	-0.29	
6514	5014		645				660	-0.31	
6515	5018							-0.30	
6518	5022							-0.29	
6519	5026	2.0	645			3.7	660	-0.28	
6522(a)	5698	3.0	1065			4.7	925	-1.07	-1.06
6523(a)	5699							-0.98	
6526(a)	5702							-1.00	-0.99
6527(a)	5703							-0.96	
6530(a)	5708							-0.97	
6531(a)	5709							-0.88	
6534(a)	5712							-0.91	
6535	5713	3.0	1065	1.7	680	4.7	925	-0.93	
6627	5144	2.6	760	2.2	780	4.8	770	-0.39	
6628	5145		760		765		770	-0.46	
6631	5148		740				750	-0.38	
6635	5152							-0.36	
6639	5156							-0.41	
6643	5160							-0.44	
6647	5164							-0.41	
6651	5168							-0.40	
6655	5172		740		765		750	-0.39	
6693	5245		630		680		655	-0.49	
6694	5246							-0.50	
6697	5249							-0.52	
6698	5250							-0.46	
6701	5255							-0.48	
6702	5256	2.6	630	2.2	680	4.8	655	-0.49	
6732	5302	3.0	995	2.7	1000	5.7	1000	-0.89	
6734	5304		995		1000		1000	-0.87	
6736	5306		995		1000		1000	-0.87	
6755	5337		980		990		985	-0.98	
6756	5338							-1.08	-1.08
6757	5339							-1.11	-1.10
6758	5340							-1.15	-1.14
6759	5341							-1.08	-1.07
6760	5342							-1.18	-1.17
6761	5343							-1.05	-1.05
6762	5344							-1.07	-1.06
6763	5345		980		990		985	-0.98	
6788	5346		950		970		960	-0.98	
6789	5347							-1.03	-1.02
6790	5348							-1.19	-1.18
6791	5349							-1.01	-1.00
6792	5350							-0.97	
6793	5351							-1.00	-1.00
6794	5355							-1.01	-1.01
6795	5356							-1.17	-1.16
6796	5360							-1.01	-1.01
6797	5361							-0.92	
6798	5367							-1.01	-1.00
6799	5368				970		960	-1.04	-1.03
6809	5354				920		935	-1.05	-1.04
6810	5366							-1.02	-1.01
6811	5376							-1.03	-1.02
6812	5385		950				935	-1.03	-1.02
6813	5424		900				910	-1.05	-1.05
6814	5433							-1.00	-1.00
6817	5442							-0.94	
6820	5451							-0.97	
6823	5460							-0.93	
6826	5470	3.0	900			5.7	910	-0.92	
6827	--	--	--			2.7	920	-0.26	
6828	--	--	--			2.7	920	-0.30	
6829	--	--	--					-0.37	
6830	--	--	--					-0.23	
6831	--	--	--					-0.32	
6832	--	--	--					-0.37	
6833	--	--	--					-0.29	
6834	--	--	--					-0.33	
6835	--	--	--	2.7	920	2.7	920	-0.38	

TABLE 11-19. (continued)

Record No.	Previous Record No.	Previous Fluence (10^{21} n/cm ²) (E>0.18 MeV) HTGR	Previous Temp (°C)	Fluence This Irrad (10^{21} n/cm ²) (E>0.18 MeV) HTGR	Temp This Irrad (°C)	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) HTGR	Irrad Temp (°C)	Irrad Strain ln(ℓ/ℓ_0) (10 ⁻²)	Dimensional Change, $\Delta\ell/\ell_0$ (%)
6836	---	---	---	2.7	920	2.7	920	-0.27	
6837	---	---	---	↓	↓	↓	↓	-0.35	
6838	---	---	---	↓	↓	↓	↓	-0.33	
6901	5481	3.3	1180	2.95	1255	6.25	1215	-1.08	-1.08
6902	5482	↓	1180	↓	1255	↓	1215	-1.20	-1.19
6905	5485	↓	1160	↓	1235	↓	1195	-1.15	-1.14
6913	5493	3.3	1160	2.95	1235	6.25	1195	-1.05	-1.04
6987	5579	3.2	1395	2.9	1390	6.1	1395	-1.65	-1.63
6988	5580	↓	1395	↓	1390	↓	1395	-1.76	-1.74
7012	5583	↓	1385	↓	1380	↓	1385	-1.58	-1.57
7073	5674	3.2	1385	↓	1325	6.1	1360	-1.72	-1.71
7093	---	---	---	↓	↓	2.9	1325	-1.55	-1.54
7094	---	---	---	↓	↓	↓	↓	-1.31	-1.31
7095	---	---	---	↓	↓	↓	↓	-1.51	-1.50
7096	---	---	---	2.9	1325	2.9	1325	-1.45	-1.44
7098	5765	3.0	1025	2.7	1085	5.7	1055	-1.24	-1.23
7100	5774	↓	960	↓	1065	↓	1010	-1.19	-1.18
7102	5778	↓	↓	↓	↓	↓	↓	-1.06	-1.05
7105	5783	↓	↓	↓	↓	↓	↓	-1.18	-1.17
7107	5790	↓	↓	↓	↓	↓	↓	-2.41	-2.38
7109	5794	3.0	960	↓	1065	5.7	1010	-1.09	-1.09
7129(a)	5094	2.0	570	↓	1035	4.7	840	-0.84	
7130(a)	5095	↓	↓	↓	↓	↓	↓	-0.81	
7133(a)	5098	↓	↓	↓	↓	↓	↓	-0.83	
7134(a)	5099	↓	↓	↓	↓	↓	↓	-0.82	
7137(a)	5106	↓	↓	↓	↓	↓	↓	-0.85	
7138(a)	5107	↓	↓	↓	↓	↓	↓	-0.85	
7141(a)	5110	↓	↓	↓	↓	↓	↓	-0.89	
7142(a)	5111	2.0	570	↓	↓	4.7	840	-0.86	
7143	5796	3.0	960	↓	↓	5.7	995	-1.15	-1.15
7145	5800	3.0	960	↓	↓	5.7	995	-1.19	-1.18
7147	5802	3.0	960	2.7	1035	5.7	995	-1.13	-1.13
7217	5808	2.8	995	2.5	1000	5.3	1000	-0.97	
7221	5812	↓	980	↓	990	↓	985	-0.98	
7225	5816	↓	↓	↓	↓	↓	↓	-1.01	-1.00
7229	5820	↓	↓	↓	↓	↓	↓	-0.89	
7233	5824	↓	↓	↓	↓	↓	↓	-1.01	-1.00
7237	5828	↓	↓	↓	↓	↓	↓	-0.94	
7238	5829	↓	↓	↓	↓	↓	↓	-0.78	
7241	5832	↓	↓	↓	↓	↓	↓	-0.99	
7242	5833	↓	↓	↓	↓	↓	↓	-1.03	-1.03
7245	5836	↓	↓	↓	↓	↓	↓	-0.93	
7246	5837	2.8	980	2.5	990	5.3	985	-0.82	
7327	5932	2.3	915	2.15	940	4.45	930	-0.59	
7328	5933	↓	↓	↓	940	↓	930	-0.56	
7331	5936	↓	↓	↓	925	↓	920	-0.65	
7332	5937	↓	↓	↓	925	↓	920	-0.59	
7335	5940	2.3	915	↓	925	4.45	920	-0.51	
7411	---	---	---	↓	850	2.15	850	-0.17	
7418	---	---	---	↓	↓	↓	↓	-0.16	
7419	---	---	---	↓	↓	↓	↓	-0.12	
7420	---	---	---	2.15	↓	2.15	↓	-0.11	
7421	---	---	---	↓	850	↓	↓	-0.11	
7423	6050	1.9	865	1.7	835	3.6	850	-0.28	
7425	6054	↓	850	↓	835	↓	845	-0.21	
7427	6058	↓	↓	↓	820	↓	835	-0.21	
7429	6062	↓	↓	↓	↓	↓	↓	-0.22	
7431	6066	↓	↓	↓	↓	↓	↓	-0.22	
7433	6070	↓	↓	↓	↓	↓	↓	-0.18	
7435	6074	↓	↓	↓	↓	↓	↓	-0.24	
7437	6078	↓	↓	↓	↓	↓	↓	-0.18	
7439	6082	↓	850	↓	↓	↓	835	-0.23	
7441	6086	↓	820	↓	↓	↓	820	-0.12	
7443	6090	↓	↓	↓	↓	↓	↓	-0.22	
7445	6096	↓	↓	↓	↓	↓	↓	-0.20	
7447	6100	↓	↓	↓	↓	↓	↓	-0.20	
7449	6106	1.9	820	1.7	820	3.6	820	-0.17	
7530	6210	1.4	650	1.15	645	2.55	650	-0.12	
7534	6214	↓	645	↓	635	↓	640	-0.15	
7538	6218	↓	↓	↓	↓	↓	↓	-0.14	
7542	6222	↓	↓	↓	↓	↓	↓	-0.10	
7546	6226	↓	645	↓	635	↓	640	-0.10	
7591	6306	↓	605	↓	590	↓	600	-0.03	
7592	6307	↓	↓	↓	↓	↓	↓	-0.13	
7595	6314	↓	↓	↓	↓	↓	↓	-0.24	
7596	6315	1.4	605	1.15	590	2.55	600	-0.15	

(a) Temperature change samples.

TABLE 11-20
 DIMENSIONAL CHANGE DATA, TS-1240, AXIAL DIRECTION,
 AFTER IRRADIATION IN CAPSULE OG-2

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})
6967	2.95	1105	-0.78
6968	↓	↓	-0.82
6969	↓	↓	-0.67
6970	↓	↓	-0.74
6971	↓	↓	-0.65
6972	↓	↓	-0.72
6973	↓	↓	-0.66
6974	↓	↓	-0.72
6975	↓	↓	-0.69
6976	↓	↓	-0.75
6977	↓	↓	-0.72
6978	↓	↓	-0.76
6979	↓	↓	-0.64
6980	↓	↓	-0.74
6981	↓	↓	-0.68
6982	↓	↓	-0.73
6983	↓	↓	-0.76
6984	2.95	1105	-0.83
7251	2.5	970	-0.31
7252	↓	↓	-0.24
7253	↓	↓	-0.26
7254	↓	↓	-0.21
7255	↓	↓	-0.27
7256	↓	↓	-0.24
7257	↓	↓	-0.26
7258	↓	970	-0.20
7313	↓	920	-0.23
7314	↓	↓	-0.25
7315	↓	↓	-0.25
7316	↓	↓	-0.20
7317	↓	↓	-0.23
7318	↓	↓	-0.19
7319	↓	↓	-0.22
7320	2.5	920	-0.20
7510	1.70	765	-0.13
7511	↓	↓	-0.02
7512	↓	↓	-0.02
7513	↓	↓	-0.06
7514	1.70	765	-0.01

TABLE 11-20. (continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})
7515	1.7	765	-0.02
7516			-0.03
7517			-0.03
7518			-0.05
7519			-0.02
7520			-0.03
7521			-0.01
7522			+0.01
7523			-0.04
7524			-0.04
7525			-0.04
7526			-0.06
7527	1.7	765	-0.03
7564	1.15	620	-0.07
7565			-0.06
7566			-0.06
7567			-0.02
7568			-0.04
7569			-0.02
7570			-0.05
7571			-0.02
7572			-0.06
7573			-0.07
7574			-0.11
7575		620	-0.08
7613		590	-0.07
7614			-0.09
7615			-0.10
7616			-0.08
7617			-0.09
7618			-0.07
7619			-0.08
7620	1.15	590	-0.08

TABLE 11-21
 DIMENSIONAL CHANGE DATA, TS-1240, RADIAL DIRECTION,
 AFTER IRRADIATION IN CAPSULE OG-2

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})
6935	2.95	1200	-0.48
6936	↓	↓	-0.45
6937	↓	↓	-0.45
6938	↓	↓	-0.45
6939	↓	↓	-0.47
6940	↓	↓	-0.49
6941	↓	↓	-0.53
6942	2.95	1200	-0.46
7321	2.5	920	-0.05
7322	↓	↓	-0.04
7323	↓	↓	-0.05
7324	2.5	920	-0.04
7462	1.7	805	+0.02
7463	↓	↓	+0.02
7464	↓	↓	-0.05
7465	↓	↓	0.00
7466	↓	↓	-0.02
7467	↓	↓	-0.02
7468	↓	↓	+0.01
7469	↓	↓	-0.02
7470	↓	↓	0.00
7471	1.7	805	-0.01
7621	1.15	590	-0.13
7622	↓	↓	-0.07
7623	↓	↓	-0.11
7624	1.15	590	-0.07

TABLE 11-22
 DIMENSIONAL CHANGE DATA, P₃JHAN, AXIAL DIRECTION,
 AFTER IRRADIATION IN CAPSULE OG-1

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-3})
5319	3.0	980	-1.53
5321	↓	↓	-2.04
5323	↓	↓	-2.02
5325	↓	↓	-1.48
5327	↓	↓	-1.99
5329	↓	↓	-2.00
5331	↓	↓	-1.44
5333	↓	↓	-1.82
5335	3.0	980	-2.11
5676	3.2	1335	-3.96
5678	↓	↓	-4.00
5684	↓	↓	-4.19
5686	3.2	1335	-4.06
5734	3.0	1025	-2.42
5736	↓	↓	-1.97
5740	↓	↓	-2.31
5742	↓	↓	-1.83
5744	↓	↓	-2.17
5746	↓	↓	-1.87
5750	↓	↓	-2.13
5752	↓	↓	-1.83
5754	↓	↓	-2.03
5756	↓	↓	-1.77
5760	↓	↓	-2.21
5762	3.0	1025	-1.82
6164	1.9	770	-0.26
6165	↓	↓	-0.23
6170	↓	↓	-0.37
6171	↓	↓	-0.24
6174	↓	↓	-0.35
6175	↓	↓	-0.23
6180	↓	↓	-0.28
6181	↓	↓	-0.28
6184	↓	↓	-0.28
6185	↓	↓	-0.28
6190	↓	↓	-0.30
6191	1.9	770	-0.28

TABLE 11-22 (Continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain ln(ℓ/ℓ_0) (10^{-2})
6332	1.4	605	-0.23
6334	↓	↓	-0.16
6336			-0.20
6338			-0.19
6342			-0.20
6344			-0.22
6347	↓	↓	-0.17
6349	1.4	605	-0.21

TABLE 11-23
DIMENSIONAL CHANGE DATA, P₃JHAN, AXIAL DIRECTION,
AFTER IRRADIATION IN CAPSULE OG-2

Record No.	Previous Record No.	Previous Fluence (10 ²¹ n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp (°C)	Fluence This Irrad (10 ²¹ n/cm ²) (E>0.18 MeV) _{HTGR}	Temp This Irrad (°C)	Total Fluence (10 ²¹ n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain ln(l/l ₀) (10 ⁻²)
6737	5319	3.0	980	2.7	990	5.7	985	-3.36
6739	5321	↓	↓	↓	↓	↓	↓	-3.59
6741	5323	↓	↓	↓	↓	↓	↓	-3.54
6743	5325	↓	↓	↓	↓	↓	↓	-3.52
6745	5327	↓	↓	↓	↓	↓	↓	-3.74
6747	5329	3.0	980	2.7	990	5.7	985	-3.44
7013	5676	3.2	1335	2.9	1380	6.1	1355	-3.67
7015	5678	↓	↓	↓	↓	↓	↓	-3.60
7017	5684	↓	↓	↓	↓	↓	↓	-4.12
7019	5686	3.2	1335	2.9	1380	6.1	1355	-3.68
7170	5734	3.0	1025	2.7	960	5.7	995	-3.88
7172	5736	↓	↓	↓	↓	↓	↓	-3.68
7174	5740	↓	↓	↓	↓	↓	↓	-3.69
7176	5742	↓	↓	↓	↓	↓	↓	-3.39
7178	5744	↓	↓	↓	↓	↓	↓	-3.46
7180	5746	↓	↓	↓	↓	↓	↓	-3.64
7182	5750	↓	↓	↓	↓	↓	↓	-3.46
7184	5752	3.0	1025	2.7	960	5.7	995	-3.72
7450	6164	1.9	770	1.7	820	3.6	795	-0.98
7451	6165	↓	↓	↓	↓	↓	↓	-0.88
7454	6170	↓	↓	↓	↓	↓	↓	-1.07
7455	6171	↓	↓	↓	↓	↓	↓	-0.90
7488	6184	↓	↓	↓	↓	↓	↓	-0.88
7489	6185	↓	↓	↓	↓	↓	↓	-0.80
7492	6190	↓	↓	↓	↓	↓	↓	-0.97
7493	6191	↓	↓	↓	↓	↓	↓	-0.89
7496	6174	↓	↓	↓	↓	↓	↓	-0.95
7497	6175	↓	↓	↓	↓	↓	↓	-0.77
7500	6180	↓	↓	↓	↓	↓	↓	-0.90
7501	6181	1.9	770	1.7	765	3.6	770	-0.78
7597	6332	1.4	605	1.15	590	2.55	600	-0.50
7599	6334	↓	↓	↓	↓	↓	↓	-0.40
7601	6336	↓	↓	↓	↓	↓	↓	-0.49
7603	6338	1.4	605	1.15	590	2.55	600	-0.38

TABLE 11-24
 DIMENSIONAL CHANGE DATA, P₃JHAN, RADIAL DIRECTION,
 AFTER IRRADIATION IN CAPSULE OG-1

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})
5320	3.0	980	-0.69
5322	↓	↓	-0.76
5324	↓	↓	-0.58
5326	↓	↓	-0.73
5328	↓	↓	-0.87
5330	↓	↓	-0.83
5332	↓	↓	-0.66
5334	↓	↓	-0.78
5336	3.0	980	-0.73
5677	3.2	1335	-1.66
5679	↓	↓	-1.44
5685	↓	↓	-1.65
5687	3.2	1335	-1.68
5735	3.0	1025	-0.81
5737	↓	↓	-0.90
5741	↓	↓	-0.87
5743	↓	↓	-0.84
5745	↓	↓	-0.81
5747	↓	↓	-0.86
5751	↓	↓	-0.71
5753	↓	↓	-0.67
5757	↓	↓	-0.70
5761	↓	↓	-0.81
5763	3.0	1025	-0.83
6166	1.9	770	-0.11
6167	↓	↓	-0.08
6172	↓	↓	-0.17
6173	↓	↓	-0.13
6176	↓	↓	-0.18
6177	↓	↓	-0.01
6182	↓	↓	-0.22
6183	↓	↓	-0.11
6186	↓	↓	-0.10
6187	↓	↓	-0.09
6192	↓	↓	-0.16
6193	1.9	770	-0.11
6333	1.4	605	-0.15
6335	↓	↓	-0.10
6337	↓	↓	-0.17
6339	1.4	605	-0.06

TABLE 11-24 (Continued)

Record No.	Total Fluence (10^{21} n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain $\ln(l/l_0)$ (10^{-2})
6343	1.4	605	-0.18
6345	↓	↓	-0.06
6348			-0.15
6350	1.4	605	-0.13

TABLE 11-25
DIMENSIONAL CHANGE DATA, P₃JHAN, RADIAL DIRECTION,
AFTER IRRADIATION IN CAPSULE OG-2

Record No.	Previous Record No.	Previous Fluence (10 ²¹ n/cm ²) (E>0.18 MeV) _{HTGR}	Previous Temp (°C)	Fluence This Irrad (10 ²¹ n/cm ²) (E>0.18 MeV) _{HTGR}	Temp This Irrad (°C)	Total Fluence (10 ²¹ n/cm ²) (E>0.18 MeV) _{HTGR}	Irrad Temp (°C)	Irrad Strain ln(l/l ₀) (10 ⁻²)
6738	5320	3.0	980	2.7	990	5.7	985	+0.19
6740	5322	↓	↓	↓	↓	↓	↓	+0.82
6742	5324	↓	↓	↓	↓	↓	↓	+1.64
6744	5326	↓	↓	↓	↓	↓	↓	+0.06
6746	5328	3.0	980	2.7	990	5.7	985	+0.71
7014	5677	3.2	1335	2.9	1380	6.1	1355	+3.43
7016	5679	↓	↓	↓	↓	↓	↓	2.66
7018	5685	↓	↓	↓	↓	↓	↓	3.46
7020	5687	3.2	1335	2.9	1380	6.1	1355	2.02
7171	5735	3.0	1025	2.7	960	5.7	995	+0.32
7173	5737	↓	↓	↓	↓	↓	↓	-0.91
7175	5741	↓	↓	↓	↓	↓	↓	+0.10
7177	5743	↓	↓	↓	↓	↓	↓	-0.60
7179	5745	↓	↓	↓	↓	↓	↓	+0.72
7181	5747	↓	↓	↓	↓	↓	↓	-0.67
7183	5751	3.0	1025	2.7	960	5.7	995	+0.55
7452	6166	1.9	770	1.7	820	3.6	795	-0.43
7453	6167	↓	↓	↓	↓	↓	↓	-0.36
7456	6172	↓	↓	↓	↓	↓	↓	-0.43
7457	6173	↓	↓	↓	↓	↓	↓	-0.35
7490	6186	↓	↓	↓	↓	↓	↓	-0.41
7491	6187	↓	↓	↓	↓	↓	↓	-0.35
7494	6192	↓	↓	↓	↓	↓	↓	-0.46
7495	6193	↓	↓	↓	↓	↓	↓	-0.36
7498	6176	↓	↓	↓	↓	↓	↓	-0.37
7499	6177	↓	↓	↓	↓	↓	↓	-0.32
7502	6182	↓	↓	↓	↓	↓	↓	-0.41
7503	6183	1.9	770	1.7	765	3.6	770	-0.32
7598	6333	1.4	605	1.15	590	2.55	600	-0.37
7600	6335	↓	↓	↓	↓	↓	↓	-0.33
7602	6337	↓	↓	↓	↓	↓	↓	-0.08
7604	6339	1.4	605	1.15	590	2.55	600	-0.27

TABLE 11-26
TENSILE PROPERTIES OF H-451 GRAPHITE, LOT 426
Log 6484-40 (GLCC 155), density = 1.72 g/cm³, 0.505-in.-diameter by 3.00-in.-long samples

Specimen No.	Position and Orientation (a)	Density (g/cm ³)	Elastic Modulus on Second Loading (10 ⁶ psi)	Permanent Set After First Loading (%)	Fracture Strain (%)	Ultimate Strength (psi)
6484-40-1A-L002A	EC(11)	1.713	1.18	0.019	0.296	2390
-L002B						2332
-L003B						2590
-L005A		1.718	1.23	0.015	0.297	2471
-L005B						2425
-L006A		1.721	1.20	0.016	0.293	2430
-L006B						2681
-L008A		1.711	1.18	0.021	0.344	2625
-L008B						2386
-L009B						2643
-1B-L002A		1.710	1.47	0.010	0.221	2394
-L002B						2394
-L003B						2434
-L005A		1.710	1.15	0.014	0.300	2346
-L005B						2389
-L006A		1.715	1.22	0.022	0.294	2336
-L006B						2107
-L008A		1.722	1.27	0.023	0.260	2217
-L008B						2545
-L009B						2219
Mean		1.715	1.24	0.017	0.288	2418
Std. dev.		0.005	0.01	0.004	0.035	147
-1A-L011	EC(1)	1.724	1.06	0.022	0.333	2354
-L012						2339
-L013		1.723	1.11	0.015	0.288	2165
-L014						2270
-L015						1990
-L017		1.724	1.06	0.014	0.290	2086
-L018						2127
-L019		1.720	1.06	0.016	0.331	2350
-L020						2329
-L021		1.724	1.10	0.023	(b)	2295
-1B-L011						(b)
-L012		1.712	1.10	0.015	(b)	2299
-L013						(b)
-L014						2219
-L015		1.714	1.11	0.014	0.308	2075
-L017						2384
-L018		1.710	1.05	0.015	0.310	2314
-L019						2279
-L020						2200
-L021		1.719	1.08	0.017	0.310	2091
Mean						2231
Std. dev.		0.006	0.03	0.004	0.019	117

TABLE 11-26 (continued)

Specimen No.	Position and Orientation ^(a)	Density (g/cm ³)	Elastic Modulus on Second Loading (10 ⁶ psi)	Permanent Set After First Loading (%)	Fracture Strain (%)	Ultimate Strength (psi)
6484-40-3A-L031A	MLE(11)	1.737	1.28	0.010	0.319	2747
-L031B						2606
-L034A		1.735	1.28	0.014	0.308	2701
-L034B						2693
-L035A		1.738	1.27	0.011	0.312	2661
-L035B						2475
-L038A		1.732	1.27	0.014	0.328	2774
-L038B						2600
-L039A						2560
-L039B						2680
-3B-L031A		1.721	1.28	0.011	0.281	2545
-L031B						2788
-L034A		1.725	1.22	0.012	0.254	2292
-L034B						2390
-L035A		1.718	1.25	0.012	0.291	2510
-L035B						(b)
-L038A		1.716	1.22	0.010	0.270	2390
-L038B						2536
-L039A						2853
-L039B						2919
Mean		1.728	1.26	0.012	0.295	2617
Std. dev.		0.009	0.03	0.002	0.026	165
-3A-L041	MLE(1)	1.729	1.10	0.018	0.241	1895
-L042						2323
-L043		1.717	1.05	0.015	0.275	2070
-L044						2173
-L045						2248
-L047						2192
-L048		1.729	1.07	0.019	0.299	2203
-L049						2223
-L050		1.728	1.06	0.016	0.304	2222
-L051						2333
-3B-L041		1.726	1.07	0.016	0.294	2198
-L042						2072
-L043		1.726	1.08	0.016	0.228	2108
-L044						2047
-L045						2052
-L047						1393
-L048		1.718	1.02	0.021	0.245	1827
-L049						1788
-L050		1.716	1.02	0.015	0.237	1801
-L051						1845
Mean		1.724	1.06	0.017	0.272	2050
Std. dev.		0.006	0.03	0.002	0.027	231

TABLE 11-26 (continued)

Specimen No.	Position and Orientation ^(a)	Density (g/cm ³)	Elastic Modulus on Second Loading (10 ⁶ psi)	Permanent Set After First Loading (%)	Fracture Strain (%)	Ultimate Strength (psi)
6484-40-1A-L031A	EE(11)	1.739	1.47	0.017	0.280	2450
-L031B						2580
-L034A		1.720	1.41	0.015	0.300	2638
-L034B						2375
-L035A		1.728	1.23	0.010	0.299	2546
-L035B						2207
-L038A		1.725	1.36	0.021	0.289	2349
-L038B						2512
-L039A						2385
-L039B						2650
-1B-L031A		1.735	1.32	0.013	0.297	2606
-L031B						2236
-L034A		1.719	1.18	0.015	0.282	2274
-L034B						2421
-L035A		1.722	1.15	0.014	0.264	2151
-L035B						2335
-L038A		1.720	1.25	0.014	0.302	2470
-L039A						2665
-L039B						2539
Mean		1.726	1.30	0.015	0.289	2441
Std. dev.		0.007	0.11	0.003	0.013	157
-1A-L041	EE(1)	1.726	1.07	0.019	0.231	1784
-L042						2120
-L043		1.726	1.18	0.031	0.268	2003
-L044						2191
-L045						2165
-L047						2196
-L048		1.722	1.15	0.023	0.304	2249
-L049						2355
-L050		1.731	1.10	0.015	0.317	2273
-L051						2419
-1B-L041		1.732	1.05	0.020	0.296	2074
-L042						2135
-L043		1.725	1.05	0.019	0.316	2218
-L044						2360
-L045						2454
-L047						2219
-L048		1.724	1.10	0.018	0.308	2249
-L049						2096
-L050		1.710	1.05	0.015	0.290	2139
-L051						2231
Mean		1.724	1.09	0.016	0.291	2196
Std. dev.		0.007	0.05	0.007	0.029	150

TABLE 11-26 (continued)

Specimen No.	Position and Orientation ^(a)	Density ^(b) (g/cm ³)	Elastic Modulus on Second Loading (10 ⁶ psi)	Permanent Set After First Loading (%)	Fracture Strain (%)	Ultimate Strength (psi)
6484-40-3A-L002A	MLC(11)	1.703	1.18	0.012	0.276	2268
-L002B						2391
-L003B						1997
-L005A		1.706	1.10	0.015	0.217	1764
-L005B						2237
-L006A		1.705	1.18	0.018	0.260	2073
-L006B						2097
-L008A		1.704	1.15	0.017	0.248	1974
-L008B						1847
-L009B						2057
-3B-L002A		1.702	1.14	0.018	0.222	1758
-L002B						1767
-L003B						1737
-L005A		1.703	1.10	0.012	0.211	1727
-L005B						1438
-L006A		1.703	1.11	0.022	0.192	1568
-L006B						1662
-L008A		1.702	1.15	0.016	0.265	2137
-L008B						1887
-L009B						1288
Mean		1.703	1.14	0.016	0.236	1884
Std. dev.		0.001	0.03	0.003	0.030	238
-3A-L011	MLC(1)	1.703	1.01	0.024	0.220	1565
-L012						1687
-L013		1.702	0.99	0.025	0.168	1229
-L014						1757
-L015		1.706	1.05	0.023	0.239	1638
-L017						1847
-L018						1750
-L019		1.702	1.02	0.015	0.266	1697
-L020						1969
-L021						1957
-3B-L011		1.700	1.05	0.019	0.268	1901
-L012						1767
-L013		1.704	1.03	0.019	0.206	1608
-L014						2017
-L015		1.704	1.01	0.019	0.249	1372
-L017						1383
-L018						1763
-L019		1.706	1.01	0.018	0.250	1737
-L020						1737
-L021						1767
Mean		1.703	1.02	0.020	0.233	1588
Std. dev.		0.002	0.02	0.003	0.034	204

(a) Position in parent (~34 in. long) extrusion: EC = end center, MLC = midlength center, EE = end edge, MLE = midlength edge.

(b) Bond failure.

TABLE 11-27
TENSILE PROPERTIES OF TS-1240 GRAPHITE, LOT 1
Log 5651-74(UCC 42), density = 1.82 g/cm³, 0.505-in.-diameter by 3.00-in.-long samples

Specimen No.	Position and Orientation(a)	Density (g/cm ³)	Elastic Modulus on Second Loading (10 ⁶ psi)	Permanent Set After First Loading (%)	Fracture Strain (%)	Ultimate Strength (psi)
5651-74-3A-L051A	MLC(11)					2028
-L057A						1987
-L057B						2035
-L054B						2038
-L055A						1895
-L058B						2137
-3B-L068B						2175
-L062A						1918
-L062B						2035
-L064B						2150
-L067A						1986
-L067B						1970
-3A-L050		1.797	1.10	0.018	0.306	2238
-L053		1.798	1.12	0.014	0.285	2186
-L054A		1.795	1.08	0.021	0.275	2010
-L058A		1.798	1.11	0.019	0.260	1914
-3B-L061		1.793	1.06	0.020	0.221	1661
-L064A		1.791	1.10	0.025	0.271	1890
-L065		1.784	1.05	0.024	0.286	1943
-L069		<u>1.789</u>	<u>1.06</u>	<u>0.024</u>	<u>0.284</u>	<u>1944</u>
Mean		1.793	1.08	0.021	0.273	2007
Std. Dev.		0.005	0.026	0.004	0.025	131
5651-74-3A-L079	MLC(1)					1588
-L081						1642
-L082						1672
-L084						1641
-3B-L090						2120
-L091						2409
-L093						1621
-L094						1692
-L096						1237
-3A-L075		1.785	0.97	0.045	0.206	1445
-L076		1.791	1.02	0.024	0.250	1692
-L077		1.790	1.02	0.026	0.260	1749
-L080		1.792	1.03	0.028	0.265	1505
-3B-L087		1.791	1.03	0.026	0.261	1835
-L088		1.795	1.05	0.022	0.335	2284
-L089		1.793	1.03	0.022	0.221	1630
-L092		<u>1.789</u>	<u>1.01</u>	<u>0.021</u>	<u>0.189</u>	<u>1372</u>
Mean		1.791	1.02	0.027	0.248	1714
Std. Dev.		0.003	0.023	0.008	0.045	305

TABLE 11-27 (continued)

Specimen No.	Position and Orientation ^(a)	Density (g/cm ³)	Elastic Modulus on Second Loading (10 ⁶ psi)	Permanent Set After First Loading (%)	Fracture Strain (%)	Ultimate Strength (psi)
5651-74-1A-L002A	EC(11)					2140
-L002B						2135
-L003A						2088
-L003B						2391
-L006A						2196
-L006B						1959
-1B-L012A						2520
-L012B						2444
-L016A						2238
-L016B						1842
-L017A						2142
-L017B						2143
-1A-L001		1.800	1.15	0.018	0.250	1944
-L004		1.814	1.20	0.028	0.333	2418
-L005		1.802	1.18	0.013	0.310	2344
-L009		1.797	1.18	0.019	0.330	2404
-1B-L011		1.807	1.23	0.025	0.295	2256
-L014		1.802	1.14	0.020	0.265	1987
-L015		1.798	1.15	0.023	0.320	2298
-L019		1.815	1.18	0.023	0.315	2342
Mean		1.804	1.18	0.021	0.302	2211
Std. Dev.		0.007	0.030	0.005	0.030	187
5651-74-1A-L028	EC(1)					1633
-L032						2077
-L033						1818
-L034						1942
-1B-L040						2171
-L041						1992
-L045						1932
-L037		1.824				(b)
-1A-L025		1.816	1.17	0.032	0.365	2462
-L026		1.811	1.10	0.023	0.310	2145
-L027		1.807	1.02	0.025	0.280	1948
-L030		1.823	1.14	0.024	0.450	2980
-1B-L044		1.720	0.94	0.020	0.260	1946
-L038		1.815	1.11	0.029	0.378	2534
-L039		1.808	1.07	0.030	0.360	2369
-L042		1.812	1.05	0.025	0.450	2843
Mean		1.804	1.08	0.026	0.363	2186
Std. Dev.		0.032	0.073	0.004	0.063	380

TABLE 11-27 (continued)

Specimen No.	Position and Orientation (a)	Density (g/cm ³)	Elastic Modulus on Second Loading (10 ⁶ psi)	Permanent Set After First Loading (%)	Fracture Strain (%)	Ultimate Strength (psi)
5651-74-1A-L102A	EE(11)					2290
-L102B						2203
-L104A						2284
-L104B						2569
-L108A						2115
-L108B						2135
-1B-L117A						2199
-L117B						2469
-L119A						2384
-L119B						2368
-L120A						2241
-L120B						2139
-1A-L101		1.808	1.18	0.018	0.308	2369
-L103		1.813	1.18	0.016	0.350	2666
-L105		1.815	1.18	0.022	0.335	2494
-L107		1.802	1.10	0.020	0.295	2110
-1B-L111		1.788	1.12	0.018	0.230	1794
-L112		1.786	1.08	0.023	0.306	2148
-L114		1.777	1.07	0.023	0.325	2197
-L116		<u>1.792</u>	<u>1.11</u>	<u>0.027</u>	<u>0.318</u>	<u>2244</u>
Mean		1.798	1.13	0.021	0.308	2271
Std. Dev.		0.014	0.046	0.004	0.036	193
5651-74-1A-L127	EE(1)					1547
-L131						2196
-L132						2197
-L133						1886
-L134						1717
-1B-L140						2022
-L141						1596
-L145						2132
-L148						1926
-L149						1551
-L144						1831
-1A-L125		1.822	1.08	0.016	0.372	2544
-L126		1.818	1.07	0.025	0.314	2150
-L129		1.822	1.08	0.019	0.366	2510
-L130		1.813	1.08	0.024	0.327	2300
-1B-L142		1.820	1.11	0.021	0.410	2760
-L143		1.810	1.08	0.021	0.354	2406
-L146		1.806	1.01	0.022	0.337	2247
-L147		<u>1.798</u>	<u>1.06</u>	<u>0.017</u>	<u>0.325</u>	<u>2185</u>
Mean		1.814	1.07	0.021	0.351	2090
Std. Dev.		0.009	0.028	0.003	0.031	345

TABLE 11-27 (continued)

Specimen No.	Position and Orientation ^(a)	Density (g/cm ³)	Elastic Modulus on Second Loading (10 ⁶ psi)	Permanent Set After First Loading (%)	Fracture Strain (%)	Ultimate Strength (psi)
5651-74-3A-L154A	MLE(11)					(b)
-L154B						2539
-L156B						2384
-L157B						2340
-L158A						2197
-L158B						2160
-3B-L163A						2097
-L163B						2055
-L167A						2189
-L167B						2026
-L169A						2324
-L169B						2424
-3A-L151		1.809	1.18	0.020	0.336	2489
-L153		1.809	1.18	0.022	0.356	2586
-L155		1.793	1.12	0.020	0.301	2157
-L157A		1.808	1.12	0.016	0.275	2064
-3B-L161		1.792	1.10	0.024	0.292	1995
-L162		1.797	1.10	0.020	0.253	1603
-L164		1.799	1.10	0.021	0.305	2199
-L166		1.809	1.15	0.030	0.332	2458
Mean		1.802	1.13	0.022	0.306	2226
Std. Dev.		0.007	0.034	0.004	0.034	236
5651-74-3A-L178	MLE(1)					2037
-L181						1906
-L182						1802
-L183						1687
-L184						2001
-3B-L191						2092
-L192						1138
-L196						1970
-L199						1372
-L200						1371
-3A-L175		1.805	1.02	0.023	0.300	2004
-L176		1.805	1.03	0.020	0.291	1981
-L179		1.810	1.06	0.029	0.259	1785
-L180		1.804	1.05	0.030	0.275	1861
-3B-L193		1.804	1.06	0.026	0.262	1796
-L194		1.805	1.06	0.020	0.292	1987
-L197		1.796	0.98	0.021	0.179	1248
-L198		1.794	0.98	0.025	0.196	1347
Mean		1.803	1.03	0.024	0.257	1744
Std. Dev.		0.005	0.034	0.004	0.045	307

(a) Position in parent (34 in. long) extrusion: EC = end center, MLC = midlength center, EE = end edge, MLE = midlength edge.

(b) Bond failure.

TABLE 11-28
TENSILE PROPERTIES OF TS-1240 GRAPHITE, LOT 1
Log 5651-75(UCC 46), density = 1.84 g/cm³, 0.505-in.-diameter by 3.00-in.-long samples

Specimen No.	Position and Orientation ^(a)	Density (g/cm ³)	Elastic Modulus on Second Loading (10 ⁶ psi)	Permanent Set After First Loading (%)	Fracture Strain (%)	Ultimate Strength (psi)
5651-75-3A-L050B	MLC(11)					2781
-L053B						2643
-L054B						2317
-L056A						2594
-L056B						2570
-L058B						2685
-3B-L061B						2826
-L064B						2949
-L065B						2921
-L068B						2937
-L069B						2681
-3A-L050		1.808	1.30	0.000	(b)	(b)
-L054		1.807	1.36	0.006	(b)	(b)
-3B-L061		1.810	1.34	0.013	(b)	(b)
-L064		1.809	1.45	0.013	(b)	(b)
-L065		1.805	1.27	0.016	(b)	(b)
-L069		1.810	1.36	0.012	(b)	(b)
-3A-L051		1.822	1.23	0.013	0.325	2590
-L053		1.806	1.47	0.005	0.305	2592
-L055		1.819	1.27	0.020	(b)	(b)
-L058		1.810	1.41	0.013	0.314	2605
-3B-L062		1.820	1.25	0.025	0.378	2836
-L066		1.817	1.23	0.012	0.335	2851
-L067		1.820	1.25	0.023	(b)	(b)
-L068		1.824	1.27	0.015	0.327	2450
Mean		1.813	1.30	0.016	0.323	2696
Std. Dev.		0.007	0.091	0.006	0.029	177
5651-75-3A-L079	MLC(1)					1197
-L081						1511
-L082						1302
-L078		1.812				803
-L079		1.812				817
-L084		1.814				1762
-3B-L090		1.816				920
-L093		1.813				(b)
-L094		1.816				2327
-L091X ^(c)		1.812				666
-3A-L075		1.807	(d)	(d)	0.108	996
-L076		1.804	(d)	(d)	0.150	596
-L077		1.807	(d)	(d)	0.130	865
-L080		1.806	1.15	0.016	0.235	1821
-3B-L087		1.809	1.03	0.020	0.140	1056
-L096		1.809	1.14	0.008	0.360	2666
-L089		1.807	(d)	(d)	0.084	833
-L092		1.808	1.14	0.007	0.390	2696
Mean		1.810	1.11	0.013	0.199	1343
Std. Dev.		0.004	0.057	0.006	0.117	683

TABLE 11-28 (continued)

Specimen No.	Position and Orientation ^(a)	Density (g/cm ³)	Elastic Modulus on Second Loading (10 ⁶ psi)	Permanent Set After First Loading (%)	Fracture Strain (%)	Ultimate Strength (psi)
5651-75-1A-L002A	EC(11)					1752
-L002B						1788
-L003A						1208
-L006A						2021
-L008A						2035
-L008B						1611
-1B-L012A						1858
-L012B						1975
-L016A						1775
-L016B						2161
-L017A						1774
-L017B						1318
-1A-L001		1.815	1.22	0.020	0.270	2060
-L004		1.815	1.23	0.014	0.222	1920
-L005		1.815	1.23	0.012	0.200	1770
-L009		1.817	1.30	0.012	0.230	2007
-1B-L011		1.815	1.30	0.015	0.290	2338
-L014		1.823	1.25	0.015	0.272	2190
-L015		1.815	1.20	0.016	0.270	2130
-L019		<u>1.816</u>	<u>1.30</u>	<u>0.020</u>	<u>0.245</u>	<u>2038</u>
Mean		1.816	1.25	0.015	0.250	1886
Std. Dev.		0.003	0.041	0.003	0.031	278
5651-75-1A-L028	EC(1)					801
-L029						689
-L032						2217
-L033						2223
-L034						(b)
-1B-L040						1728
-L041						1425
-L045						2894
-L046						2909
-1A-L025		1.814	1.22	0.008	0.323	2390
-L026		1.811	1.08	0.022	0.280	2007
-L027		1.811	1.07	0.020	0.155	1235
-L030		1.808	1.12	0.019	0.320	2319
-1B-L037		1.821	1.11	0.020	0.387	2600
-L038		1.817	1.08	0.020	0.278	1996
-L039		1.813	1.07	0.023	0.288	1997
-L042		<u>1.812</u>	<u>1.11</u>	<u>0.016</u>	<u>0.397</u>	<u>2793</u>
Mean		1.813	1.11	0.018	0.303	2014
Std. Dev.		0.004	0.049	0.005	0.075	688

TABLE 11-28 (continued)

Specimen No.	Position and Orientation ^(a)	Density (g/cm ³)	Elastic Modulus on Second Loading (10 ⁶ psi)	Permanent Set After First Loading (%)	Fracture Strain (%)	Ultimate Strength (psi)
5651-75-1A-L101	EE(11)	1.783	1.10	0.014	(b)	(b)
-L104A						1925
-L104B						1930
-L108A						1895
-L108B						2123
-1B-L113A						1717
-L113B						2235
-L117A						2330
-L117B						2255
-L119A						2092
-L119B						2090
-L120A						2264
-L120B						(b)
-L114		1.788	1.12	0.020	(b)	(b)
-1A-L102		1.821	1.14	0.018	0.270	2050
-L103		1.786	1.16	0.017	0.308	2339
-L105		1.777	1.13	0.020	0.260	1994
-L107		1.778	1.08	0.016	0.183	1467
-1B-L111		1.779	1.11	0.018	0.335	2335
-L112		1.788	1.10	0.020	0.320	2353
-L118		1.802	1.05	0.017	0.335	2341
-L116		<u>1.781</u>	<u>1.10</u>	<u>0.017</u>	<u>0.277</u>	<u>2089</u>
Mean		1.788	1.11	0.018	0.286	2096
Std. Dev.		0.013	0.035	0.001	0.051	238
5651-75-1A-L127	EE(1)	1.805	1.14	0.023	(b)	1786
-L128						1670
-L130						(b)
-L132						2258
-L133						2186
-L134						1596
-1B-L140						2046
-L141						2021
-L145						2038
-L148						1995
-L149						1787
-1A-L125		1.810	1.07	0.017	0.335	2301
-L126		1.800	1.07	0.022	0.290	2037
-L129		1.811	1.14	0.009	0.310	2300
-L131		1.816	1.14	0.017	(b)	(b)
-1B-L142		1.818	1.00	0.018	0.308	2208
-L143		1.810	1.03	0.020	0.330	2113
-L146		1.807	1.07	0.020	0.340	2310
-L147		<u>1.808</u>	<u>1.05</u>	<u>0.018</u>	<u>0.290</u>	<u>2175</u>
Mean		1.809	1.08	0.018	0.315	2049
Std. Dev.		0.005	0.05	0.004	0.021	223

TABLE 11-28 (continued)

Specimen No.	Position and Orientation ^(a)	Density (g/cm ³)	Elastic Modulus on Second Loading (10 ⁶ psi)	Permanent Set After First Loading (%)	Fracture Strain (%)	Ultimate Strength (psi)
5651-75-3A-L151	MLE(11)					2824
-L152A						2689
-L152B						2623
-L153B					(b)	
-L154A						2743
-L154B						2399
-L156B						2240
-L157B						2688
-3B-L163A						3012
-L163B						2794
-L170A						3032
-L170B						3037
-3A-L155		1.804	1.32	0.013	(b)	(b)
-L157A		1.804	1.34	0.014	(b)	(b)
-3B-L164		1.812	1.45	0.006	(b)	(b)
-3B-L166		1.815	1.32	0.010	(b)	(b)
-3A-L151A		1.808	1.27	0.013	0.356	2828
-L153		1.807	1.34	0.015	0.340	2703
-L158		1.818	1.17	0.017	0.345	2597
-L160		1.827	1.22	0.019	0.360	2752
-3B-L161		1.828	1.27	0.016	0.400	3152
-L162		1.826	1.29	0.015	0.365	2928
-L167		1.825	1.27	0.015	0.295	2569
-L169		1.826	1.27	0.009	0.295	2578
Mean		1.817	1.29	0.013	0.344	2741
Std. Dev.		0.009	0.07	0.004	0.035	233
5651-75-3A-L182	MLE(1)					1756
-L183						1857
-L184						1961
-3B-L191						1961
-L192						2619
-L196						1237
-L199						2741
-L200						1766
-3A-L175			1.20	0.009	0.215	1740
-L176			1.10	0.024	0.255	1884
-L179			1.12	0.015	0.216	1692
-L180			1.12	0.016	0.196	1615
-3B-L193			1.12	0.022	0.150	1315
-L194			1.12	0.010	0.165	1497
-L197			1.15	0.020	0.367	2571
-L198			1.20	0.010	0.360	2600
Mean			1.14	0.016	0.240	1912
Std. Dev.			0.039	0.006	0.082	471

(a) Position in parent (~34 in. long) extrusion: EC = end center, MLC = midlength center, EE = end edge, MLE = midlength edge.

(b) Bond failure.

(c) Sample machined from extra core taken adjacent to core L091.

(d) Sample broke during first loading cycle.

TABLE 11-29
TENSILE PROPERTIES OF TS-1240 GRAPHITE, LOT 1
Log 6484-29(UCC 8-1S-ID-23), density = 1.83 g/cm³, 0.505-in.-diameter by 3.00-in.-long samples

Specimen No.	Position and Orientation ^(a)	Density (g/cm ³)	Elastic Modulus on Second Loading (10 ⁶ psi)	Permanent Set After First Loading (%)	Fracture Strain (%)	Ultimate Strength (psi)
6484-29-1A-L102A	EE(11)	1.798	1.22	0.010	0.228	2095
-L102B						2378
-L104A						2524
-L104B		1.804	1.23	0.011	0.254	2703
-L109A						2320
-L109B						2314
-L110A		1.801	1.25	0.017	0.294	2149
-L110B						1921
-1B-L119A						2460
-L119B		1.804	1.27	0.015	(b)	2338
-L120A						2411
-L118A						2685
-L118B		1.807	1.27	0.020	(b)	3049
-1A-L101						(b)
-L103						(b)
-L105		1.807	1.23	0.020	(b)	(b)
-L107						(b)
-1B-L111			1.25	0.011	0.311	2440
-L112		1.793				2545
-L114		1.785				2435
-L116		1.791	1.16	0.017	0.320	(b)
		1.791	1.20	0.022	(b)	(b)
		<u>1.809</u>	<u>1.25</u>	<u>0.013</u>	<u>0.314</u>	<u>2655</u>
Mean		<u>1.800</u>	<u>1.23</u>	<u>0.016</u>	<u>0.293</u>	<u>2437</u>
Std. dev.		0.008	0.04	0.004	0.038	260
6484-29-1A-L127	EE(1)	1.820	1.12	0.020	0.355	2202
-L128						2057
-L131						2007
-L132						2244
-L133						1896
-L134						2443
-1B-L140						2047
-L141						1698
-L144						2258
-L145						2257
-L148		1.809	1.08	0.023	0.329	1538
-L149						1483
-1A-L125						2566
-L126						2323
-L129						2327
-L130						2471
-1B-L142						2421
-L143						2383
-L146						1997
-L147						1927
		<u>1.800</u>	<u>1.08</u>	<u>0.019</u>	<u>0.266</u>	<u>1927</u>
Mean		<u>1.808</u>	<u>1.12</u>	<u>0.022</u>	<u>0.314</u>	<u>2127</u>
Std. dev.		0.006	0.03	0.003	0.035	306

TABLE 11-29 (continued)

Specimen No.	Position and Orientation ^(a)	Density (g/cm ³)	Elastic Modulus on Second Loading (10 ⁶ psi)	Permanent Set After First Loading (%)	Fracture Strain (%)	Ultimate Strength (psi)
6484-29-3A-L051A	MLC(11)					2519
-L051B						2186
-L055A						2517
-L055B						2426
-L056A						2111
-L056B						2328
-3B-L062A						2119
-L062B						2338
-L066A						2079
-L066B						2248
-L067A						2243
-L067B						2339
-3A-L050		1.794	1.34	0.009	0.312	2596
-L053		1.798	1.22	0.016	0.291	2390
-L054		1.798	1.27	0.014	0.324	2651
-L058		1.795	1.14	0.016	0.261	2116
-3B-L061		1.797	1.19	0.022	0.302	2338
-L064		1.792	1.22	0.017	0.259	2152
-L065		1.792	1.17	0.106	0.252	2072
-L069		<u>1.792</u>	<u>1.20</u>	<u>0.016</u>	(b)	(b)
Mean		1.795	1.22	0.016	0.286	2304
Std. dev.		0.003	0.06	0.004	0.029	179
6484-29-3A-L078	MLC(1)					1144
-L079						1189
-L081						1338
-L083						1368
-L084						1244
-3B-L090						1389
-L091						1374
-L093						1290
-L094						1658
-L095						1439
-L096						1633
-3A-L075		1.799	1.02	0.022	0.147	1235
-L076		1.795	1.02	0.020	0.160	1240
-L077		1.794	1.02	0.026	0.164	1229
-L080		1.792	1.04	0.014	0.200	1563
-3B-L087		1.792	(c)	(c)	(c)	894
-L088		1.792	0.94	0.017	0.145	1054
-L089		1.793	0.07	0.023	0.134	1108
-L092		<u>1.794</u>	<u>1.08</u>	<u>0.019</u>	<u>0.156</u>	<u>1328</u>
Mean		1.794	1.03	0.020	0.155	1301
Std. dev.		0.002	0.04	0.004	0.023	192

TABLE 11-29 (continued)

Specimen No.	Position and Orientation ^(a)	Density (g/cm ³)	Elastic Modulus on Second Loading (10 ⁶ psi)	Permanent Set After First Loading (%)	Fracture Strain (%)	Ultimate Strength (psi)
6484-29-1A-L002A	EC(11)					2186
-L002B						1989
-L006A						2220
-L006B						2421
-L007A						2264
-L007B						2557
-1B-L012A						2177
-L012B						2045
-L016A						2358
-L016B						2491
-L017A						2486
-L017B						2133
6484-29-1A-L001		1.796	1.17	0.018	0.265	2041
-L004		1.802	1.22	0.020	0.314	2527
-L005		1.804	1.22	0.014	0.288	2381
-L009		1.799	1.19	0.015	0.299	2441
-1B-L011	EC(1)	1.798	1.23	0.017	0.319	2565
-L014		1.794	1.27	0.021	0.325	2585
-L015		1.795	1.23	0.018	0.325	2603
-L019		1.802	1.23	0.019	0.304	2425
Mean		1.799	1.22	0.018	0.305	2345
Std. dev.		0.004	0.03	0.002	0.021	198
6484-29-1A-L028	EC(1)					1254
-L029						1553
-L031						2238
-L032						2032
-L033						1653
-L034						1597
-1B-L040						1018
-L043						2551
-L044						1771
-L045						1962
-L046						2057
-1A-L025		1.801	1.13	0.025	0.350	2500
-L026		1.802	1.14	0.019	0.289	2191
-L027		1.801	1.09	0.018	0.234	1808
-L030		1.809	1.19	0.018	0.342	2596
-1B-L037		1.805	1.19	0.016	0.333	2575
-L038		1.801	1.14	0.018	1.241	1887
-L039		1.801	1.17	0.022	0.239	1875
-L042		1.809	1.20	0.017	0.239	2007
Mean		1.804	1.16	0.019	0.284	1954
Std. dev.		0.004	0.04	0.003	0.052	436

TABLE 11-29 (continued)

Specimen No.	Position and Orientation ^(a)	Density (g/cm ³)	Elastic Modulus on Second Loading (10 ⁶ psi)	Permanent Set After First Loading (%)	Fracture Strain (%)	Ultimate Strength (psi)
6484-29-3A-L154A	MLE(11)	1.795	1.23	0.013	0.320	(b)
-L154B						2742
-L156B						2665
-L160A						2733
-L160B						2582
-3B-L163A		1.800	1.22	0.015	0.223	2489
-L163B						1863
-L165B						1995
-L166A						2700
-L166B						2837
-L169A						2490
-L169B						(b)
-3A-L151		1.804	1.27	0.021	0.335	2743
-L153		1.803	1.34	0.016	(b)	(b)
-L155		1.807	1.32	0.019	(b)	(b)
-L157		1.805	1.23	0.018	0.354	2753
-3B-L161		1.800	1.22	0.018	0.365	2804
-L162		1.792	1.20	0.014	0.302	2467
-L164		1.797	1.27	0.020	0.336	2665
-L165		<u>1.797</u>	<u>1.23</u>	<u>0.014</u>	<u>0.316</u>	<u>2605</u>
Mean		<u>1.800</u>	<u>1.25</u>	<u>0.017</u>	<u>0.319</u>	<u>2571</u>
Std. dev.		0.005	0.05	0.003	0.044	275
6484-29-3A-L177	MLE(1)					1349
-L178						1419
-L181						1649
-L182						1732
-L184						1104
-3B-L191						1507
-L192						1018
-L195						1408
-L196						1437
-L199						948
-L200						1013
-3A-L175		1.807	1.09	0.019	0.192	1549
-L176		1.807	1.10	0.025	0.241	1758
-L179		1.802	1.09	0.022	0.251	1844
-L180		1.803	1.08	0.024	0.229	1724
-3B-L193		1.802	1.09	0.020	0.189	1543
-L194		1.799	1.09	0.024	0.170	1394
-L197		1.793	0.97	0.026	0.136	1023
-L198		<u>1.791</u>	<u>(c)</u>	<u>(c)</u>	<u>0.136</u>	<u>998</u>
Mean		<u>1.800</u>	<u>1.07</u>	<u>0.023</u>	<u>0.201</u>	<u>1390</u>
Std. dev.		0.006	0.05	0.003	0.041	293

(a) Position in parent (34 in. long) extrusion: EC = end center, MLC = midlength center, EE = end edge, MLE = midlength edge.

(b) Bond failure.

(c) Sample broke during first loading cycle.

TABLE 11-30

IMPURITY CONTENT (IN PPM) OF GRAPHITES H-451 (LOT 426) AND SO-818 (LOT 1)

Graphite and Sample No.	Location in Log ^(a)	Ash	B	Fe	V	Ti	S
(H-451: 6484-40)							
6484-40-3A-L016	MLC	110	1.0	<1.0	<0.5	<1.0	<1.0
-3B-L016	MLC	60	1.0	<1.0	<0.5	<1.0	<1.0
-3A-L036	MLE	140	0.5	<1.0	<0.5	<1.0	<1.0
-3B-L036	MLE	70	<0.5	<1.0	<0.5	<1.0	<1.0
-1A-L016	EC	90	1.0	<1.0	<0.5	<1.0	<1.0
-1B-L016	EC	50	1.0	<1.0	<0.5	<1.0	<1.0
-1A-L036	EE	70	<0.5	<1.0	<0.5	<1.0	<1.0
-1B-L036	EE	<u>120</u>	<u>0.5</u>	<u><1.0</u>	<u><0.5</u>	<u><1.0</u>	<u><1.0</u>
Mean	Whole log	89	<6.3	<1.0	<0.5	<1.0	<1.0
(SO-818: 6484-19)							
6484-19-3A-L016	MLC	150	<0.5	<1.0	<0.5	<1.0	9.0
-3B-L016	MLC	70	<0.5	<1.0	<0.5	<1.0	4.9
-3A-L036	MLE	60	<0.5	<1.0	<0.5	<1.0	16.1
-3B-L036	MLE	40	<0.5	<1.0	<0.5	<1.0	8.9
-1A-L016	EC	50	<0.5	<1.0	<0.5	<1.0	9.2
-1B-L016	EC	70	<0.5	<1.0	<0.5	<1.0	6.7
-1A-L036	EE	50	<0.5	<1.0	<0.5	<1.0	7.0
-1B-L036	EE	<u>40</u>	<u><0.5</u>	<u><1.0</u>	<u><0.5</u>	<u><1.0</u>	<u><1.0</u>
	Whole log	66	<0.5	<1.0	<0.5	<1.0	<7.9

(a) Position in parent extrusion (H-451, ~34 inches long; SO-818, ~68 inches long): MLC = mid-length center, EC = end center, MLE = mid-length edge, and EE = end edge.

TABLE 11-31
THERMAL EXPANSIVITY OF H-451 GRAPHITE, LOT 426
Log 6484-33, density = 1.75 g/cm³

Specimen No.	Position and Orientation(a)	Mean Coefficient of Thermal Expansion, $\alpha \times 10^6 \text{ }^\circ\text{C}^{-1}$ (22°-500°C)
6484-33-1A-L007A	EC(11)	4.10
-L007B		4.16
-L010A		3.81
-L010B		4.17
-1B-L032A		4.02
-L032B		4.15
-L035A		3.69
-L035B		<u>3.90</u>
Mean		4.00
Std. dev.		0.18
-1A-L063A	EC(1)	4.66
-L063B		4.67
-L066A		4.68
-L066B		4.87
-1B-L073A		4.53
-L073B		4.74
-L076A		4.53
-L076B		<u>4.90</u>
Mean		4.70
Std. dev.		0.14
-1A-L052A	EE(11)	3.78
-L052B		3.96
-L054A		3.75
-L054B		3.93
-1B-L057A		3.97
-L057B		3.97
-L059A		3.83
-L059B		<u>3.89</u>
Mean		3.88
Std. dev.		0.09
-1A-L081A	EE(1)	4.58
-L081B		4.41
-L083A		5.12
-L083B		4.79
-1B-L085A		4.80
-L085B		4.60
-L087A		4.59
-L087B		<u>4.69</u>
Mean		4.70
Std. dev.		0.21

TABLE 11-31. (continued)

Specimen No.	Position and Orientation(a)	Mean Coefficient of Thermal Expansion, $\alpha \times 10^6 \text{ } ^\circ\text{C}^{-1}$ (22°-500°C)
6484-33-3A-L107A	MLC(11)	4.19
-L107B		4.27
-L110A		4.26
-L110B		4.09
-3B-L132A		3.96
-L132B		3.90
-L135A		4.04
-L135B		<u>3.94</u>
Mean		4.08
Std. dev.		0.14
-3A-L163A	MLC(1)	4.62
-L163B		4.35
-L166A		5.19
-L166B		4.37
-3B-L173A		4.37
-L173B		4.29
-L176A		4.45
-L176B		<u>4.45</u>
Mean		4.51
Std. dev.		0.29
-3A-L152A	MLE(11)	3.78
-L152B		3.92
-L154A		3.81
-L154B		4.24
-3B-L157A		3.70
-L157B		3.58
-L159A		3.80
-L159B		<u>4.03</u>
Mean		3.86
Std. dev.		0.20
-3A-L181A	MLE(1)	4.80
-L181B		4.61
-L183A		4.59
-L183B		4.85
-3B-L185A		4.66
-L185B		4.60
-L187A		4.65
-L187B		<u>4.43</u>
Mean		4.65
Std. dev.		0.13

(a) Position in parent (~34 in. long) extrusion: EC = end center, EE = end edge, MLC = midlength center, MLE = midlength edge.

TABLE 11-32
THERMAL EXPANSIVITY OF H-451 GRAPHITE, LOT 426
Log 6484-41, density = 1.72 g/cm³

Specimen No.	Position and Orientation(a)	Mean Coefficient of Thermal Expansion, $\alpha \times 10^6 \text{ } ^\circ\text{C}^{-1}$ (22°-500°C)
6484-41-1A-004A	EC(11)	3.80
-004B		4.11
-014A		4.00
-014B		3.88
-1B-004A		4.00
-004B		3.79
-014A		3.93
-014B		<u>3.70</u>
Mean		3.90
Std. dev.		0.13
-1A-031A	EC(1)	4.35
-031B		4.68
-044A		4.57
-044B		4.20
-1B-031A		4.44
-031B		4.26
-044A		4.48
-044B		<u>4.48</u>
Mean		4.43
Std. dev.		0.16
-1A-053A	EE(11)	3.99
-053B		3.76
-058A		3.98
-058B		3.89
-1B-053A		3.92
-053B		3.92
-058A		3.76
-058B		<u>3.90</u>
Mean		3.89
Std. dev.		0.09
-1A-071A	EE(1)	4.46
-071B		4.30
-084A		4.71
-084B		4.85
-1B-071A		4.50
-071B		4.59
-084A		4.80
-084B		<u>4.54</u>
Mean		4.59
Std. dev.		0.18

TABLE 11-32. (continued)

Specimen No.	Position and Orientation ^(a)	Mean Coefficient of Thermal Expansion, $\alpha \times 10^6 \text{ }^\circ\text{C}^{-1}$ (22°-500°C)
6484-41-3A-004A	MLC(11)	3.87
-004B		4.02
-014A		3.95
-014B		4.02
-3B-004A		3.86
-004B		3.93
-014A		3.85
-014B		<u>3.84</u>
Mean		3.92
Std. dev.		0.07
-3A-031A	MLC(1)	4.57
-031B		4.68
-044A		4.18
-044B		4.31
-3B-031A		4.43
-031B		4.49
-044A		4.18
-044B		<u>4.50</u>
Mean		4.42
Std. dev.		0.18
-3A-053A	MLE(11)	3.91
-053B		3.86
-058A		3.78
-058B		3.81
-3B-053A		4.03
-053B		4.04
-058A		3.92
-058B		<u>3.88</u>
Mean		3.90
Std. dev.		0.09
-3A-071A	MLE(1)	4.48
-071B		4.63
-084A		4.82
-084B		4.25
-3B-071A		4.46
-071B		4.60
-084A		4.29
-084B		<u>4.48</u>
Mean		4.50
Std. dev.		0.18

(a) Position in parent (~34 in. long) extrusion: EC = end center, EE = end edge, MLC = midlength center, MLE = midlength edge.

TABLE 11-33
THERMAL EXPANSIVITY OF TS-1240 GRAPHITE, LOT 1
Log 6484-29, density = 1.83 g/cm³

Specimen No.	Position and Orientation(a)	Mean Coefficient of Thermal Expansion, $\alpha \times 10^6 \text{ }^\circ\text{C}^{-1}$ (22 ^o -500 ^o C)
6484-29-1A-L007A	EC(11)	4.46
-L007B		4.67
-L010A		4.63
-L010B		4.61
-1B-L032A		4.85
-L032B		4.91
-L035A		4.45
-L035B		<u>4.29</u>
Mean		4.61
Std. dev.		0.21
-1A-L063A	EC(1)	5.59
-L063B		5.40
-L066A		5.03
-L066B		5.08
-1B-L073A		5.53
-L073B		5.94
-L076A		5.30
-L076B		<u>5.24</u>
Mean		5.39
Std. dev.		0.30
-1A-L052A	EE(11)	4.63
-L052B		4.98
-L054A		4.61
-L054B		4.61
-1B-L057A		4.48
-L057B		4.72
-L059A		4.80
-L059B		<u>4.72</u>
Mean		4.69
Std. dev.		0.15
-1A-L081A	EE(1)	5.01
-L081B		5.01
-L083A		4.92
-L083B		4.88
-1B-L085A		5.17
-L085B		5.22
-L087A		4.97
-L087B		<u>5.06</u>
Mean		5.03
Std. dev.		0.12

TABLE 11-33. (continued)

Specimen No.	Position and Orientation ^(a)	Mean Coefficient of Thermal Expansion, $\alpha \times 10^6$ °C ⁻¹ (22°-500°C)
6484-29-3A-L107A	MLC(11)	4.45
-L107B		4.51
-L110A		4.39
-L110B		4.76
-3B-L132A		4.71
-L132B		4.81
-L135A		4.81
-L135B		<u>4.63</u>
Mean		4.63
Std. dev.		0.17
-3A-L163A	MLC(1)	4.91
-L163B		4.97
-L166A		4.92
-L166B		5.02
-3B-L173A		4.93
-L173B		5.28
-L176A		4.93
-L176B		<u>5.06</u>
Mean		5.00
Std. dev.		0.12
-3A-L152A	MLE(11)	4.36
-L152B		4.74
-L154A		4.80
-L154B		4.62
-3B-L157A		4.48
-L157B		4.59
-L159A		4.55
-L159B		<u>4.61</u>
Mean		4.59
Std. dev.		0.14
-3A-L181A	MLE(1)	4.96
-L181B		4.97
-L183A		5.30
-L183B		5.34
-3B-L185A		5.11
-L185B		5.11
-L187A		5.53
-L187B		<u>5.11</u>
Mean		5.18
Std. dev.		0.20

(a) Position in parent (~34 in. long) extrusion: EC = end center, EE = end edge, MLC = midlength center, MLE = midlength edge.

TABLE 11-34
THERMAL EXPANSIVITY OF SO-818 GRAPHITE, LOT 1
Log 6484-19, density - 1.74 g/cm³

Specimen No.	Position and Orientation ^(a)	Mean Coefficient of Thermal Expansion, $\alpha \times 10^6$ °C ⁻¹ (22°-500°C)
6484-19-1A-004A	EC(11)	5.16
-004B		5.29
-014A		5.21
-014B		5.44
-1B-004A		5.47
-004B		5.28
-014A		5.61
-014B		<u>5.55</u>
Mean		5.38
Std. dev.		0.16
-1A-031A	EC(1)	5.73
-031B		5.93
-044A		5.77
-044B		6.05
-1B-031A		5.90
-031B		6.12
-044A		5.42
-044B		<u>5.78</u>
Mean		5.84
Std. dev.		0.22
-1A-053A	EE(11)	5.38
-053B		5.51
-058A		5.07
-058B		5.57
-1B-053A		5.14
-053B		5.52
-058A		4.92
-058B		<u>5.36</u>
Mean		5.31
Std. dev.		0.24
-1A-071A	EE(1)	5.77
-071B		5.64
-084A		5.59
-084B		5.95
-1B-071A		5.78
-071B		6.09
-084A		6.05
-084B		<u>6.09</u>
Mean		5.87
Std. dev.		0.20

TABLE 11-34. (continued)

Specimen No.	Position and Orientation ^(a)	Mean Coefficient of Thermal Expansion, $\alpha \times 10^6 \text{ }^\circ\text{C}^{-1}$ (22°-500°C)
6484-19-3A-004A	MLC(11)	4.86
-004B		4.72
-014A		5.01
-014B		4.88
-3B-004A		4.95
-004B		4.97
-014A		5.15
-014B		<u>5.01</u>
Mean		4.94
Std. dev.		0.13
-3A-031A	MLC(1)	6.40
-031B		5.67
-044A		5.37
-044B		5.28
-3B-031A		5.50
-031B		5.54
-044A		5.51
-044B		<u>5.64</u>
Mean		5.61
Std. dev.		0.34
-3A-053A	MLE(11)	4.93
-053B		5.21
-058A		4.98
-058B		5.21
-3B-053A		5.07
-053B		5.14
-058A		5.09
-058B		<u>5.19</u>
Mean		5.10
Std. dev.		0.11
-3A-071A	MLE(1)	5.66
-071B		5.48
-084A		5.52
-084B		5.70
-3B-071A		5.60
-071B		5.66
-084A		5.89
-084B		<u>5.59</u>
Mean		5.64
Std. dev.		0.12

(a) Position in parent (~68 in. long) extrusion: EC = end center, EE = end edge, MLC = midlength center, MLE = midlength edge.

TABLE 11-35
SUMMARY OF TENSILE STRENGTH MEASUREMENTS OF H-451 GRAPHITE, LOT 426 (FURNACE 77)
(0.505-IN.-DIAMETER BY 3.00-IN.-LONG SPECIMENS)

Log No.	Mean Strength, psi; (Standard Deviation, psi); and [No. of Replicates]							
	Axial				Radial			
	MLC ^(a)	EC ^(a)	EE ^(a)	MLE ^(a)	MLC ^(a)	EC ^(a)	EE ^(a)	MLE ^(a)
6484-33	2073(216) [20]	2675(185) [20]	2922(227) [19]	2924(338) [15]	1515(223) [20]	2303(347) [20]	2534(177) [20]	2036(336) [20]
6484-34	2057(108) [20]	2046(134) [20]	2701(275) [20]	2817(260) [20]	1506(300) [18]	1786(432) [20]	2138(335) [19]	1986(419) [18]
6484-41	1876(178) [20]	1720(120) [20]	2398(207) [20]	2706(226) [20]	1515(417) [20]	1788(294) [20]	1948(277) [19]	1995(253) [20]
6484-40	1884(283) [20]	2418(147) [20]	2441(157) [19]	2616(165) [19]	1700(204) [20]	2231(117) [18]	2196(150) [20]	2050(231) [20]
Lot 426 (4 logs)	1972(223) [80]	2216(391) [80]	2613(303) [78]	2758(269) [73]	1560(304) [78]	2022(384) [78]	2208(326) [78]	2017(318) [77]

APPENDIX

PROJECT REPORTS PUBLISHED DURING THE QUARTER

Smith, C. L., "Preirradiation Report, Fuel Materials for Irradiation, P13Q," ERDA Report GA-A13265, General Atomic Company, June 13, 1975.

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Wattier, J. B., "Final Test Operations Report - Capsule P13P," ERDA Report GA-A13332, General Atomic Company, July 31, 1975.