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HTGR BASE PROGRAM
QUARTERLY PROGRESS REPORT
FOR THE PERIOD ENDING
FEBRUARY 29, 1972

MASTER

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

Date Published - March 31, 1972

GULF GENERAL ATOMIC COMPANY
P.O. BOX 608, SAN DIEGO, CALIFORNIA 92112

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ABSTRACT

This publication continues the quarterly report series on the HTGR Base 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 basic fission-product distribution mechanisms, recycle fuel studies (including designing and testing of recycle test elements) and exploration of head-end reprocessing methods (as part of a national recycle plan and of a recycle fuel plant), and physics and fuel management studies. Materials studies include irradiation and analysis of fuel particles in capsules to evaluate fuel systems, and basic studies of control materials and of carbon 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, and these are listed at the end of the report for those concerned with the field.

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INTRODUCTION

This report covers the work performed by Gulf General Atomic 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 gas-cooled, nuclear power reactor systems. The program is based on the concept of the High-temperature Gas-cooled Reactor (HTGR) developed by Gulf General Atomic.

Large HTGR systems will be placed in operation starting in the late 1970's following the operation of the 330-MW(e) prototype in 1972. 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 (PCRVR) 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.

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TASK IV
FISSION-PRODUCT MECHANISMS

STEAM-GRAPHITE REACTION STUDIES

Experiments are planned that will measure the effect of total gas pressure (helium) on the rate of the steam-graphite reaction. The graphite will be experimentally subjected to H₂O saturated helium at total pressures to 300 lb and at 800° to 1100°C for varying times. A high-pressure King furnace is presently being renovated for this work. The furnace dome is designed for total pressures to 350 psi. A high-pressure water saturator system has been built.

The reacting graphite will act as the heating element. This is being fabricated in the form of seven interlocking sections of H-327 graphite that can easily be weighed before and after reaction. The dimensions of the integrated element combine required length and terminations with impedance matching to the transformer.

DEPOSITION LOOP EXPERIMENT

A fission-product deposition loop has been assembled to study the plateout characteristics of such fission products as cesium and strontium under conditions similar to HTGR conditions. Helium at 350 psia circulates in the loop with Reynolds numbers near 15,000 and temperatures varying from 250° to 600°F. The type of steel used for the loop tubing is representative of steel used in the steam generators of HTGRs. The surface temperatures of the loop vary from 250° to 800°F. The fission products in the loop are obtained by heating graphite crucibles within the loop that are loaded with the fission products sorbed on graphite matrix material.

The objectives of this work are to obtain plateout distribution data and to obtain plateout lift-off (or blowdown) data by subjecting individual sections of the system to conditions of higher shear ratios than are obtained generally in the loop. The effects of crossflow and dust transport on the plateout and lift-off characteristics will be studied by adding crossflow tubes and dust in the loop. The plateout data will be used to test and refine the PAD code, which has been developed at Gulf General Atomic for predicting the fission-product plateout distribution in an HTGR primary coolant circuit. The lift-off data will be used for safety analyses associated with HTGR depressurization accidents.

The first experiment with the deposition loop has been completed, cesium tagged with Cs-137 being used as the depositing specie. The experiment was run for 18 hr of operation, and sufficient Cs had vaporized out of the crucibles to allow the detection of Cs-137 throughout the loop. A series of blowdown tests was then performed on various segments of the first loop. Four 1-in. segments were subjected to a shear ratio of 5 for 30, 60, 120, and 240 sec to study the effect of different blowdown times. The results for all four segments revealed a liftoff independent of time. The blowdown fractions for these four segments ranged between 0.015 and 0.017, values that are in excellent agreement with past GAIL blowdown results which yielded a blowdown fraction of approximately 0.015 at a shear ratio of 5. Additional blowdown tests at a shear ratio of 1.9 and 0.6 have yielded blowdown fractions of zero. Wipedown tests have also been performed to obtain a measurement for the fraction of cesium that could be physically removed from the surface of the loop tubing. Approximately 10% to 20% of the activity was removed after wiping.

A second deposition loop run has been made in which the loop contained a series of crossflow tubes. Graphite dust was added to the loop in order to study the effects of cross flow and graphite dust on plateout and blowdown characteristics. Strontium tagged with Sr-85 was used as source material, and measurable quantities were deposited throughout the loop. Since the source chamber was first used with a Cs-137 tagged

Cs source, there was also Cs-137 deposited throughout the loop in measurable quantities. Analyses are currently under way to determine the plateout profiles of Cs-137 and Sr-85 throughout the loop. Following these analyses blowdown experiments are planned for segments of the loop.

FLAMMABILITY STUDIES

Flammability and flame propagation of gaseous mixtures could arise under certain hypothetical accident conditions in the HTGR system. The hypothesized conditions result from two simultaneous or consecutive accidents: a steam leak followed by a depressurization. The resulting gas mixture within the secondary containment would consist of H_2 , CO, H_2O , He, O_2 , and N_2 . Measurement of the flammability characteristics of such a mixture have been initiated.

During this quarter, the major effort has been directed towards construction of an experimental apparatus required to perform the study. The U.S. Bureau of Mines has described a "standard apparatus" to be used in determining the flammability characteristics of gases and vapors (Ref. 1). This standard is based on the existence of sufficient chain-branching during an induced combustion of the test species to propagate a flame front through a standard length. The short-comings of the standard apparatus appear when it is necessary to deal with colorless flames. Hydrogen, one of the reaction products, produces a colorless flame. Consequently, the standard method has been modified slightly to correct for this inherent property. The modification has been used in recent investigations of colorless gases (Ref. 2) in the combustion field. The investigators have successfully utilized Schlieren optical methods as an aid to visual perception.

Prudent judgment dictates that the first series of experiments adhere to the gas-material constraints imposed by the Bureau of Mines, and further, that some previously published work be confirmed. Initially, our tests will be conducted at ambient temperature and pressure. Since pressure

changes (up to four atmospheres) have been found (Ref. 3) to have little or no effect on flammability ranges, an extension of the initial work will include investigations of temperature effects and finally a volume-to-surface-area study.

Figure 4.1 is a three-component system diagram showing the probable limits of the flammability regime. The components are H_2 -CO (50-50 mixture), He, and air. The region of particular interest in this study has been shaded in Fig. 4.1. This region includes the transient concentrations of flammable reaction products proposed in the steam-water inleakage accident, as well as emphasizing the lower limit of flammability determination.

FIPER CODE DEVELOPMENT

Development continued on FIPER S, a simplified version of the FIPER Q code. The FIPER S code has been tested in detail against the FIPER Q code and some of these results are given in Table 4.1.

Cesium release calculations were made using the FIPER Q and FIPER S codes for the projected six-year core life of a typical HTGR fuel block. The end-of-life value of surface concentration and release are compared in Table 4.1. The numbers in the table represent the ratio of the FIPER S results to FIPER Q results for each case examined. The reference case is a comparison of the two codes using presently accepted values of the input parameters and reactor operating conditions. Note that under normal circumstances for this block, FIPER S calculates release to within a factor of three of FIPER Q. The input values of the two codes and reactor temperature were then separately changed to measure the effect that a drastic change of data or reactor operating conditions would have on the accuracy of the FIPER S code. Notice that FIPER S always calculates a conservatively higher value than the FIPER Q code. In some cases the relative accumulated release is much higher than the reference value. This is due to the mass balance assumptions used in FIPER S.

Fig. 4.1. Flammable limits of 50% H_2 and 50% CO in helium-diluted air, transient composition

TABLE 4.1
FIPER S RESULTS COMPARED TO FIPER Q
FOR VARIOUS INPUT PARAMETER VALUES

	Relative ^(a) Concentration	Relative ^(a) Release
Reference	2.08	2.71
Diffusion coefficient, x10	1.70	1.69
Diffusion coefficient, -10	7.36	10.2
Vapor pressure, x10	12.1	15.1
Vapor pressure, -10	1.15	1.4
Sorption ratio, x2	1.87	2.55
Sorption ratio, -10	7.39	64.6
Surface temp., -100°C	1.05	1.13
Surface temp., +100°C	394.4	200.6
Nuclear graphite, -100°C	3.32	5.05
Nuclear graphite, +100°C	1.79	2.00

(a) Tabulated ratios are obtained by dividing the FIPER S result by the FIPER Q result for each case.

It is assumed in the present FIPER S formulation that the loss of metal from the graphite surface due to vaporization into the coolant does not lower the graphite surface concentration. That is, an insulated boundary condition is used to determine the concentration of fission-product metal at the graphite surface of the graphite-coolant interface. Therefore, under circumstances of large mass losses from the graphite surface and small mass transport rates through the nuclear graphite, FIPER S exhibits large conservatism. It is expected that by such comparisons of the FIPER S and FIPER Q codes, a logical procedure will be developed to correlate the use of the two codes.

REFERENCES

1. Coward, H. F., and G. W. Jones, "Limits of Flammability of Gases and Vapors," U.S. Bur. Mines, Bull. No. 503 (1952).
2. Private communication, Dr. Melvin Gerstein, U.S.C. School of Mechanical Engineering.
3. Johnson, J. E., Jr., " $H_2-O_2-NO_x$ Flammability and Explosibility, A Literature Survey," USAEC Report ICP-1002, Oct. 1971.

TASK V
RECYCLE FUEL STUDIES

HTGR FUEL RECYCLE PLANT STUDY

A joint study by ORNL, ICPP, AEC, and Gulf General Atomic was made to review the hot demonstration of reprocessing and the overall progress of the recycle program. Gulf General Atomic has prepared a flow-sheet for the hot head-end demonstration of reprocessing, and this is presented as Fig. 5.1.

The process shown on the flow-sheets encompasses what is frequently called the "head-end" process. The head-end process described here begins with the receipt of fuel in a reprocessing cell and ends with the fuel (U-233 normally) and the fission products in solution and ready to be sent to adjustment tanks as feed for an extraction process.

The process basically consists of crushing Fort St. Vrain-type fuel elements to -3/16-in. size material and burning the product in an exothermic (EXO) fluid bed burner. The fertile particles are separated from the product from the exothermic burner and crushed to break their silicon carbide coatings. They are then fed along with the rest of the EXO burner product, to an endothermic (ENDO) fluid bed burner to which heat must be supplied.

The product from the ENDO burner (consisting of silicon carbide coated fissile particles, silicon carbide hulls and heavy metals, and fission product oxides) are then fed to a dissolver where the oxides are dissolved with nitric acid. After complete dissolution the solids are separated and stored, the liquid product being then ready for feed adjustment to an extraction process for the recovery of the U-233.

Fig. 5.1. Sheet 1 of 3, hot head-end reprocessing; receiving and crushing operations

STREAM NO.		1	2	3	4	5	6	7	8	8A	8B	9
DESCRIPTION		1ST STAGE PRIMARY CRUSHER FEED	1ST STAGE CRUSHER DUST STREAM	2ND STAGE CRUSHER FEED	2ND STAGE CRUSHER DUST STREAM	FILTER BLOW BACK GAS	FILTER OFF-GAS	FILTER FINES RETURN	PNEUMATIC TRANSPORT GAS	PNEUMATIC TRANSPORT GAS	RETURN PNEUMATIC TRANSPORT GAS	EXOTHERMIC BURNER FEED
NOTE 2	FUEL ELEMENTS, BLOCK/DAY (✓/HR)	12(0.75)										
	TOTAL CARBON, KG/HR	72	0.05	71.95	0.05		0.10					71.9
	PARTICLE CARBON, KG/HR	4.0		4.0								4.0
	OPyC CARBON, KG/HR	2.3		2.3								2.3
	THORIUM, KG/HR	7.15		7.15								7.15
	URANIUM, KG/HR	0.64		0.64								0.64
	SiC, KG/HR	3.4		3.4								3.4
NOTE 1	FERTILE PARTICLES, KG/HR	8.2		8.2								8.2
	FISSILE PARTICLES, KG/HR	9.3		9.3								9.3
	VOLATILE METALS, KG/HR	0.19		0.19								0.19
	KCl/HR	10.1		10.1								10.1
	VOLATILE NON-METALS, KG/HR	0.018		0.018								0.018
	Ci/HR	346		346								346
	NON-VOLATILE METALS, KG/HR	0.506		0.506								0.506
	KCl/HR	36		36								36
	H ₂ , GM/HR	1.1x10 ⁻³		1.1x10 ⁻³								1.1x10 ⁻³
	Ci/HR	11		11								11
	Kr+Xe, GM/HR	102		102								102
	Ci/HR	423		423								423
	I, GM/HR											
	Ci/HR											
	BqC, GM/HR	17.5		17.5								17.5
	N ₂ , SCFM											
	AIR, SCFM											
		1	2	3	4	5	6	7	8	8A	8B	9

NOTES:

1. INCLUDES Th (OR U) AND CARBIDES, F.P.'S, BUFFER & IPyC COATING, SiC & OPyC COATING.
2. BASIS IS 16 OPERATING HOURS/DAY.
3. LONGITUDINAL BLOCK FEED.

Fig. 5.1 (Cont.) Sheet 1 of 3, notes

Fig. 5.1 (Cont.) Sheet 2 of 3, hot head-end reprocessing; burning, screening, and hull grinding

STREAM NO		9	10	11	11A	12	13	13A	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28					60	34	35	36	37	61	
DESCRIPTION		EXOTHERMIC BURNER FEED	EXOTHERMIC BURNER PRODUCT	SIC CARBON PARTICLES FEED	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	SIC CARBON PARTICLES FROM EXO BURNER	
TOTAL CARBON		71.9	2.5	2.3	0.2																													
PARTICLE CARBON		1.5	4.0	1.5	2.5																													
THORIUM		7.2	7.2	4.46	2.74																													
URANIUM		0.6	0.6	0	0.6																													
SiC		3.4	3.4	0.89	2.52																													
FERTILE PARTICLES		8.2	8.2	8.2	-																													
FISSILE PARTICLES		9.3	9.3	-	9.3																													
INERT PARTICLES																																		
VOLATILE METALS		0.19	0.15	0.015	0.135	0.000	0.014																											
KCl/HR		10.1	8.1	0.80	7.3	0.08	0.72																											
VOLATILE NON METALS		0.018	0.014	0.001	0.013	5x10 ⁻⁵	5x10 ⁻⁵																											
C/HR		346	277	28	249	3	25																											
NON VOLATILE METALS		0.506	0.506	0.005	0.501	-	0.005																											
KCl/HR		36.0	36.0	3.6	32.4	-	3.6																											
H ₂		11x10 ³	11x10 ³	10 ⁴	11x10 ³	10 ⁴	-																											
C/HR		11	10.89	11	9.79	11	-																											
Kr		19.8	15.4	1.5	13.9	1.5	-																											
C/HR		423	339	34	305	34	-																											
I ₂		8.0	6.5	0.7	5.8	0.7	-																											
B ₄ C		17.5	17.5	-	-	-	-																											
Xe		82	66	7	59	7	-																											
C/HR		7x10 ⁴	5.8x10 ⁴	10 ⁴	5.2x10 ⁴	5.2x10 ⁴	-																											
N ₂		SCFH																																
O ₂		SCFH																																
CO		SCFH																																
CO ₂		SCFH																																
AIR		SCFH																																
H ₂ O		SCFH																																
			9	10	11	11A	12	13	13A	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28					60	34	35	36	37	61

NOTE {

1 INCLUDE
BUFFER
INTACT

2 NO "CR
MATERIAL
WILL BE

NOTES

- 1 INCLUDES TH (OR U) AND CARBIDES, F.P.'S. BUFFER & IPYC COATING & SIC COATING AS INTACT PARTICLES
- 2 NO "CROSSOVER" HAS BEEN INCLUDED IN THE MATERIAL BALANCE, EVEN THOUGH SOME (1% TO 10%) WILL BE EXPECTED

Fig. 5.1 (Cont.) Sheet 2 of 3, notes

Fig. 5.1 (Cont.) Sheet 3 of 3, head-end reprocessing; fuel dissolution and waste leaching

STREAM NO.		26	38	38A	38B	38C	38D	39	40	41	42	43	44	45	45A	46	47	48	49	49A	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	64A	64B	65											
DESCRIPTION		LEACHER FEED	LEACHER SPRING GAS	LEACHER SLURRY	PRODUCT TANK	SOLIDS RECEIVER	SOLIDS SEPARATOR	SOLIDS DRYING GAS	ACID TROUSX SOLUTION	SEPARATED SOLIDS	RINSE SOLUTION	LEACHER TUBS	LEACHER TUBS	LEACHER OFF-GAS	LEACHER CONDENSATE	LEACHER CONDENSATE	LEACHER PRODUCT	LEACHER RINSE SLURRY	LEACHER RESIDUE	LEACHER RINSE SOLUTION	LEACHER HEAT SUPPLY	CENTRIFUGE FEED	CENTRIFUGE RINSE SOLUTION	SEPARATOR FEED	SEPARATOR RINSE SOLUTION	SOLIDS SEPARATOR & DRYER OFF-GAS	CENTRIFUGE PRODUCT	CENTRIFUGE SLUDGE	SLUDGE DRYER OFF-GAS	SOLIDS SEPARATOR OFF-GAS	CONDENSER OFF-GAS	FILTER PRESS OFF-GAS	FILTER CONDENSATE	FILTER CONDENSER	DRIED FINES RETURN	OPTIONAL WERT PARTICLE FLUIDIZATION	SIC COATED PARTICLES	SIC PAUL WASTE	COMBINED DRIED WASTE	PNEUMATIC TRANSPORT	RETURN TRANSPORT GAS	FILTER BLOW-BACK GAS							
NOTE 1	KG/DAY	UNBURNED CARBON	1.9																																														
		FERTILE PARTICLES	0																																														
		FISSILE PARTICLES	149																				149	-																									
		Th (NON SIC COATED)	115																						115																								
	U (SIC COATED)	9.6																					9.6																										
	SIC	54.4																					3.4																										
	B ₄ C																																																
	INERT PARTICLES																																																
	VOLATILE F.P. (GRAMS)	385																																															
	OTHER F.P.	10.5																																															
	C/DAY																																																
		VOLATILE F.P.	1750																				1000		200																								
		OTHER F.P.	87.000																				50.000		33.000																								
		Th ⁴⁺	1																																														
		UO ₂ ⁺⁺	0.12																																														
		H ⁺	13																																														
		Al ⁺⁺⁺	0.08																																														
		Fe ⁺⁺⁺	0.075																																														
		NO ₃ ⁻	0.075																																														
		F ⁻	0.04																																														
		F.P. ³⁺	0.04																																														
		LITERS/DAY	500																																														
		GALS/DAY	131																																														
		AIR	0.5																																														
		N ₂ (NO ₂)	300																																														
		H ₂ O VAPOR	200																																														
		STEAM	200																																														
		H ₂ O	10																																														
		H ₂ O	10																																														

NOTES:
1. INCLUDES BUFFER & INTACT PA

NOTES:

1. INCLUDES TH (OR U) AND CARBIDES, F.P.'S, BUFFER & IPYC COATING & SIC COATING AS INTACT PARTICLES.

Fig. 5.1 (Cont.) Sheet 3 of 3, notes

Fuel Element Definition

Fuel having a composition typical of HTGR recycle elements is used as the basis, since recycle fuel elements are more reactive and have a higher fissile metal loading than do initial core elements. The initial core uranium loading is 773 kg uranium (0.522 kg U for an average initial core fresh fuel element) and the equivalent recycle core loading is 1255 kg uranium (0.847 kg U for an average reload core fresh fuel element). Components of a recycle fuel element are given on Table 5.1.

Nuclide inventory data for irradiated fuel elements were generated. These data included fission product and activation heavy metal nuclides for end-of-year conditions following full power operation for one year through six years. For each case, the nuclide inventory data included element decay periods after reactor shutdown periods of 6 months, one year, and two years. Although these data are now available for decay heat load calculations and shielding studies, they are not presented here owing to their size.

Material Balance

The material balance has been broken down into a number of different categories for convenience in tracing the various constituents of the fuel block through the process. The fuel block used in the material balance is a nominal reload block with six years of reactor exposure and six months of cooling. The material balance has been calculated for processing twelve fuel blocks per day rather than the ten blocks per day that is the nominal design; this assumes the handling of one cask load per shift and gives a slight overallowance. The burner feed rates have been calculated for a burning time of 16 hr/day and, therefore, the rates are one-third higher than if the burners were operating continuously.

Material descriptions on the flow-sheets are explained below, all other categories being considered self-explanatory:

Total Carbon	- All carbon existing outside of the SiC coating on the particles
Particle Carbon	- All carbon inside the SiC shell but not SiC carbon
Thorium	- Thorium metal
Uranium	- Uranium metal
SiC	- Silicon carbide
Fertile Particles	- Fertile particle including all coatings
Fissile Particles	- Fissile particle including all coatings
Al_2O_3	- Included to allow for the addition of inert particles (possibly alumina) to the burners, if desired.
Volatile Metals	- Includes the following components: Ru, Cs, Rb, Sr, Eu, Sm, and Ba.
Volatile Nonmetals	- Includes only Te.
Nonvolatile Metals	- Includes the following fission products: Pm, Pd, Pr, Nd, Zr, Y, Tc, Ce, La, Rh, Mo, and Nb. It also includes what is normally called the heavy metals exclusive of uranium and thorium in mass balances but includes them in activity balances. These are Pa, Pu, Ra, Ac, Am, Cm, and Np.
H_2	- Includes hydrogen and its isotopes.

Functional Description for Normal Operation

The fuel blocks, which have been weighed before receipt, are received in the crushing cell in groups of four. The blocks are fed one at a time through two crushers in series where they are reduced to a product that will pass through a 3/16-in. screen. The product passes by gravity from

TABLE 5.1
FRESH RECYCLE FUEL ELEMENT COMPOSITION

<u>Component</u>	<u>Weight (kg/FE)</u>
Graphite block including fuel plugs and dowels	89.0
Fuel rod matrix	3.92
Fissile particles (Avg $p=2.00 \text{ g/cm}^3$)	
Outer PyC Coat	1.29
SiC Coat	3.37
Silicon	2.38
Carbide	0.99
Inner PyC Coat	1.50
Buffer Coat	1.29
Kernel	4.95
U	0.85
Th	3.60
Carbide	0.50
Fertile particles (Ave. $p=3.52 \text{ g/cm}^3$)	
Outer PyC Coat	1.77
SiC Coat	1.17
Silicon	0.83
Carbide	0.34
Inner PyC Coat	0.61
Buffer Coat	0.74
Kernel	6.61
Th	5.95
Carbide	0.66
Boron Carbide	0.023
B	1.83×10^{-2}
Carbide	5.00×10^{-3}

the first crusher (CR-1) through the second (CR-2) and then into a hopper (WH-1) for weighing. As indicated on the flow-sheet, the -3/16-in. product is then transferred pneumatically, or by gravity if space is available, to a storage hopper (HO-1).

The material in the storage hopper (HO-1) is then transferred to one of the two EXO burner feed hoppers (FH-1, FH-2) for distribution to their associated EXO burners (XB-1, XB-2) by means of a screw feeder. Excellent results have been obtained with screw feeders in cold pilot plant studies, but pneumatic feeders might be preferable from a reliability standpoint.

The EXO burners (XB-1, XB-2) fluidize the bed of graphite and fuel with air and oxygen. Oxidation of the carbon in the fluid bed occurs after the fluid bed has been raised to a temperature of approximately 800°C with a CO and O₂ flame ignited at the bottom of the bed by a spark gap. An external ignition system or one using pyrophoric compounds might be more reliable than the method presented. The upper section of the EXO burner contains an air-cooled heat exchanger that both cools the effluent gases and acts as a particle separator recycling fines to the fluid bed internally. In addition, the burner wall is jacketed and cooled by air. The feed to the EXO burner is at the top of the burner with product removal at the bottom, which maximizes the particle concentration at the bottom of the bed.

The cooled gas effluent from the EXO burners passes through a series cyclone and a sintered metal filter. The sintered metal filter is equipped with a pulsed-blowback system to clear it of fines. The fines from both the cyclone and filter are then fed to the ENDO burner (NB-1).

The product withdrawn from the bottom of the EXO burners is pneumatically fed to a three-deck screen, where the product is split into three hoppers -- the fertile particles to HO-2, fissile particles to HO-4, and fines to HO-3. The fissile particles are weighed and sent to the feed hopper (FH-5) as are the fines. The fertile particles are weighed and then sent to the feed hopper (FH-3) for a particle crusher (CR-3). The

fertile particles are crushed in the particle crusher and then transported pneumatically to the feed hopper (FH-4) for the ENDO burner. Again screw feeders are indicated though pneumatic feeders may be preferred.

The function of the ENDO burner (NB-1) is similar to the EXO burners, except that the carbon content of the bed is insufficient to maintain a bed temperature at which burning can be sustained ($\sim 800^{\circ}\text{C}$). Heat is therefore externally added to the bed through a heater around the vessel jacket. The carbon content of the bed is reduced to less than 1% and then the bed is transferred to the leacher in batches.

The fertile ash and the silicon coated fissile particles and silicon carbide hulls are transferred to the leacher (LCH-1) pneumatically from the ENDO burner product hopper. In the leacher the ash is dissolved with 13M NH_4OH containing 0.05M HF, 0.08M $\text{Al}(\text{NO}_3)_3$ for complexing the HF to prevent corrosion, and 0.075M CdNO_3 for criticality control. Sufficient acid is added to the tank to give a terminal thorium concentration of 1M.

The dissolution operation is started cold, air-lift recirculation is commenced, and the leacher temperature raised to approximately 240°F , where boiling occurs. The leacher is equipped with a reflux condenser (E-1) to prevent loss of liquid. It appears that an eight-hour leaching cycle is more than adequate, after which the leacher contents are cooled to about 100°F .

After cooling the entire leacher contents are jetted to the leacher solids separator and dryer (F-4). This is a filter, equipped with a $74\text{-}\mu\text{m}$ screen, which separates the solids from the leacher solution. The screened leacher solution goes to a fuel stream centrifuge (F-6) for further clarification.

The solids in F-4 are rinsed with fresh acid thorex solution, which serves as the acid feed to the fuel leacher (LCH-1). After rinsing, the solids are dried with hot air and transferred by gravity to a screen

apparatus (SC-2) to separate fissile particles from waste, primarily silicon carbide hulls, using a 210- μ m screen. Figure 5.2 shows the size distribution of SiC coated particles. The waste flows by gravity from the screen to a portable solid waste hopper (HO-10 or HO-11) before packaging. The fissile particles flow by gravity to a portable fissile product hopper (HO-8 or HO-9). Provision has also been made to handle inert fluidizing media as well, if necessary.

The fissile particles are then transferred to a weighing hopper (WH-3) for weighing and then back to the portable fissile product hopper (HO-8 or HO-9) before being sent to storage or to reprocessing.

The filtered leacher solution from the leacher solids separator and dryer (F-4) flow to the fuel stream centrifuge for the removal of undissolved solids smaller than 74- μ m. This is a standard remote centrifuge having low solids loading. The clarified liquid goes to the product receiver tank before transfer by means of the product solution pump (P-2) to the acid thorex solvent extraction system. The solids from the centrifuge (F-6) are rinsed and slurried out intermittently to the sludge dryer (F-7). The solids are dried by heating with air and then flow by gravity to a portable solid waste hopper (HO-10 or HO-11). These wastes are packaged, weighed, and sent to waste storage.

The wet air streams from the drying operations in F-4 and F-7 flow through a condenser (E-2), where excess liquid is collected in the liquid waste hold tank (T-1), and then pumped to the waste calcining facility. The cooled air is then filtered (F-5) and sent to the off-gas cleanup system. Solids from the solids separator off-gas filter (F-5) flow by gravity to the sludge dryer for disposal.

Functional Description for Test Modes

Provision has been made to facilitate the operation of the process in a mode that will simulate the functioning of the equipment during

Fig. 5.2. Particle size distribution of SiC-coated particles

actual receiving of a fuel block containing BISO-fertile, TRISO-fissile particles as described in the National Program Plan (ORNL-4702).

After the separation of the fissile and fertile particles in the screening apparatus (SC-1), the fertile particles after crushing can be sent back to the exothermic burners. Depending on batching philosophy, the cracked fertile particles can be those associated with the fuel blocks being fed to the burner at that time or from the previous lot of burned blocks. The latter approach will give the most accurate simulation of a BISO-TRISO system.

This process is adequate for fuel from a large HTGR type reactor, except that the crushing step in CR-3 and the need for the hoppers FH-3 and HO-6 can be eliminated. The process has allowed for the bypassing of this equipment. However, the screening and weighing system using SC-1, HO-2, -3, -4, and WH-2 is still desirable from an analytical point.

Equipment

Primary Crusher (CR-1). It is contemplated that primary crushing of the whole fuel block will be performed in a conventional single-roll crusher. Various commercially available machines have been investigated that are capable of crushing a whole block down to 3 or 4 in. in a form suitable to feed the secondary crusher. A 24 by 24 in. single-roll crusher is typical of the type of machine studied for the design descriptions.

The single-roll crusher is a heavy-duty machine that is used in the mining industry for crushing all types of rock on a continuous basis, and machines of this type reportedly are operated for years without shutdown for repairs or overhaul. Single-roll crushers are compact machines requiring minimal head room (compared to a jaw crusher) and overall floor space. As a result they could be mounted on a pedestal about 5 ft above grade which would permit direct gravity feed of the product to the secondary crusher.

Various other types of crushers have been investigated for the primary crushing step, including jaw crushers and a disintegrator. Actual crushing tests performed with jaw crushers on whole blocks containing simulated fuel rods were conducted. It was found that in order to properly crush a block, the angle between the fixed plate and the moving plate must be between 11° and 13° , rather than the conventional 20° . A jaw crusher suitable for whole-block crushing is manufactured, but its size makes it impractical for the current plan.

Secondary Crusher (CR-2). The secondary crusher is required to take the primary crusher product and, in turn, reduce it to -3/16-in. fragments. A double-roll type crusher, which appears to be the best choice for this operation, consists of two 20-in.-diameter rolls that revolve toward each other at the same speed. One of the shafts moves in fixed bearings, the other in movable bearings. The rolls can be provided with a remote control system to adjust the roller position and change the crushing characteristics.

Particle Crusher (CR-3). The particle crusher will be used to crush the SiC shell of the fertile particle. Good results have been obtained for this operation utilizing a small double-roll crusher.

A 3-in. double roll-crusher has been built that will satisfactorily crush about 5 kg of particles an hour. It appears that a double roll crusher having a 6-in. roll would adequately meet the projected particle crush rate.

Dust Separation. Those portions of the process generating large quantities of dust will be vented to a cyclone type separator followed by sintered metal filters.

The cyclone separator is a conventional chamber type having a tangential gas entry giving the particle-laden gas sufficient spin to separate the particles. The gas path is a double vortex with gas spiraling downward on the outside and upward on the inside. The gas leaves through an outlet pipe located concentrically at the top end of the cyclone. This device is about

90% efficient on particle sizes of 30 to 150 μm , has no moving parts, is troublefree, and substantially reduces the load requirements imposed on the finer sintered metal filters.

Sintered Metal Filters Assembly. These filters consist of a nest of sintered metal filter elements, each of which has the gas effluent end welded into a common tube sheet or end plate. The end plate is tightly fitted into a plenum chamber sufficiently thick-walled (about 3/8 in.) for a low-pressure (2-psig) container.

Gas-containing dust particles flow into the chamber and through the filter element leaving the dust on the outside of the element. Clean gas from each filter element flows past the end plate into the outlet plenum and on to the next process step.

The surface of each filter is kept clean by a pulse of inert gas which is directed into the center of each filter element by an inlet nozzle. The inert gas is introduced through a solenoid valve actuated by a cycle timer. The cleaning gas is introduced in pulses, because it is this shock, rather than a continuous gas backflow, that keeps the filter clean of dust buildup.

Screeners (SC-1, -2). Burned particles leaving the EXO burners are fed into a screen separator where the fissile particles, fertile particles, and ash residue are each separated from the others.

The separator consists of an 18-in.-diameter vibrating screen that can be operated continuously if properly fed from a hopper while the product is continuously withdrawn. The screen will be fitted with two individual screens in series and located one above the other. One screen will divert particles having a diameter greater than 500 μm to a hopper. Materials less than 210 μm in diameter, such as ash and broken particle fines, are diverted to a third holder.

EXO Burner Assembly. Crushed graphite containing all of the fuel particles is fed into the EXO burner at a controlled rate by a screw feeder

capable of handling 1500 g/min. Feed to the burner enters above the controlled bed height and product is removed from the bottom.

The burner is 16-in. in diameter and made of 1/2-in.-thick type 304 stainless steel tube with a 10 ft straight section flanged at top and bottom. Attached to the bottom flange is a removable, conical section. This section is fitted with the initial ignition burner, gas inlet, and product removal connections.

A clamshell fits concentrically about the straight section of the burner forming an annulus through which cooling air is passed, serving as a heat exchanger and removing the heat generated by the burner. A gas distributor plate is tentatively located at the flanged connection between the straight burner section and the bottom cone.

Initially the burner is loaded with a charge of graphite and ignited with a CO-O₂ burner flame which, in turn, is ignited by a high voltage spark. When the starter graphite reaches a temperature of about 750°C, the fluidization of the charge is completed and the main feed is started at a low rate with the immediate objective to build up the bed to the required level. The burner is instrumented to enable continuous automatic operation.

When the burner is at equilibrium, the graphite and fuel feed rate, the combustion oxygen, and the product removal rates are in balance and there is stable burner temperatures as well as a stable off-gas analysis ($\cong 8\%$ CO and 9% O₂). To achieve this result, the inlet O₂ is regulated by a controller actuated by a thermocouple located inside the burner that senses the hottest bed temperature. If the temperature rises above the set point, the oxygen feed is trimmed.

Bed height is measured by pressure drop; if the pressure drop becomes excessive, indicating too high a bed, a differential pressure controller decreases the speed of the variable speed feeder, thus decreasing the bed height.

The carbon monoxide and oxygen content of the burner off-gas are continuously monitored. An O_2 content of about 5% is a definite indication of improper combustion. If corrective action cannot reduce the O_2 level and it reaches the 10% level, the burners are shut down. The CO level is a good indicator of the carbon content of the bed. As burnable carbon decreases, the CO content decreases, and this gives warning of an impending O_2 breakthrough due to a lack of burnable carbon.

Thermocouples are located inside the burner at 1 ft intervals and at the center line. Thermocouples are also located at the clamshell cooler inlet and outlet and at the off-gas cooler inlet and outlet. A multipoint temperature recorder provides the required temperature readout.

Preliminary calculations indicate that one 16 in. burner will provide adequate capacity to burn at the required rate of 1200 g/min. It appears, however, that to cover this relatively uncertain area, two burners should be provided, which would require individual burner controls.

Off-gas Cooler. The off-gas leaving the burners will contain unburned fines at about 400°C. A special cooler is required to reduce the gas temperature before it enters the filters.

Heat exchange surface area is provided by vertically aligned plate-type coolers with about 1/2-in. gap between plates. The plates are headered at the inlet and outlet to the cooling air supply and exhaust. Air cooling connections are seal welded to avoid contamination of the air effluent.

Hot combustion gases containing solid particles flow along the outside surface of each plate. Particles entrained in the gas are free to pass through the cooler without fouling the surface area. Approximately 15 plates are required with each plate having an effective total transfer area of about 150 ft².

ENDO Burner. The ENDO burner is designed to burn crushed fuel particles on a semicontinuous basis. The burner is 5 in. in diameter, about 8 ft high,

and is made of 1/4-in. thick type 304 stainless steel. The feed and product removal equipment are variable speed driven screws.

The carbon content of the particles is insufficient to be properly burned to the required constituency and requires an external heat source. The required heat is supplied by a clamshell-type electrical heater with heat rate remotely controlled manually.

As in the case of the EXO burners, the off-gas is monitored for CO and O₂ and is cooled by a small air cooler before running through a cyclone separator and a sintered metal filter. Oxygen is fed into the burner at a controlled rate while the off-gas is continuously monitored for O₂. When the off-gas O₂ content rises to 10%, as it will at the end of a batch burn, the unit is shut down.

Numerous thermocouples strategically located are connected to a multi-point recorder affording adequate temperature indication.

HEAD-END REPROCESSING

During the quarter the system being studied of separating crushed fuel blocks into a fuel-free graphite stream and a fuel stream has been redirected because more advanced fuel element designs have made this system apparently less practical. This decision will simplify the crushing steps, though it may complicate fuel burner operation somewhat owing to the larger quantities of carbon present in the feed.

Whole blocks have been crushed by crusher manufacturers and preliminary results indicate that there should be no difficulty in obtaining suitable equipment for this step. The objective is to crush the whole fuel element down to burner feed size without recycle using as little vertical height as possible.

Five satisfactory runs have been carried out on the 8-in burner, and the two 4-in burners are being assembled in their positions in the pilot plant.

Results of experiments carried out in the 5-in-diameter leacher have shown that a 1-hr leach is satisfactory for recovering more than 99% of the uranium from a burned carbide feed.

Change in Flowsheet

Flowsheet development for head-end reprocessing of HTGR fuels has included graphite-fuel separation. The reasons for considering separation were mainly economic:

1. Use of moderator reduction facilities located near concentrations of HTGR stations to burn a large fraction of the graphite while shipping only concentrated fuel would reduce shipping costs.
2. The fuel-free graphite can be burned in larger (no criticality limits) and hence fewer burners, thus reducing cell space requirements, instrumentation, etc.
3. The offgases from burning graphite would contain fewer fission products and could be exhausted with less expensive cleanup equipment.

A review conducted during the quarter included the following considerations:

1. Potential bonding of the fuel rod to the graphite to increase thermal conductivity at the rod-block interface leads to increased difficulty of separation.
2. Potential use of large fuel rods having various diameters will lead to a smaller fraction of fuel-free graphite.
3. The trend in fuel element development is to increase the fuel rod length, which again reduces the fraction of fuel-free graphite.

4. Alternative graphites to H-327 are being considered, and these may not have the same fracturing properties as H-327.
5. Because of potential bonding of the fuel to the graphite, the latter could not be assumed to be 100% free of fuel, and the graphite burner would thus be criticality limited.
6. Graphite burner offgas would have to be scrubbed to the same degree as the fuel burner offgas.
7. The alternative approach of full-flow crushing leads to a smaller, and hence less expensive, crushing cell.

Based on these considerations, emphasis is being shifted from a separation to a no-separation system in the development of a more flexible HTGR reprocessing plant.

In the full-flow approach, the fuel element is crushed to burner-feed size and fed directly to criticality-safe burners. The feed is more concentrated in carbon, but this presents no difficulties to the burners. This change in emphasis simplifies the overall flowsheet and should accelerate the program. A conceptual flowsheet for this approach is shown on Fig. 5.3.

Crushing

In crushing studies full-size blocks were crushed at crusher manufacturers. Primary size-reduction was done using an auger/orifice plate crusher, a single-roll crusher, and a jaw crusher. Secondary size-reduction was performed in a double-roll crusher and in a gyratory crusher. Third-stage size-reduction was performed in double-roll crushers.

It was concluded from these trials that the primary machine must be either a jaw crusher or a single-roll crusher. The product size is 4- to 6-in lumps. For the second- and third-stage machines, double-roll crushers appear

Fig. 5.3. Processing flow sheet for one TRISO/BISO fuel element through pilot plant

best, and the product is -3/16-in grains that can be fed immediately to the burner. The crushing train is to be arranged so that no recycle of oversize material is necessary.

Another condition being included in the crushing stages is that gravity-feed will be used to feed each successive machine, thus making cell headroom a premium. For this reason, machines of low vertical height are an advantage, and the use of two crushing stages rather than three is desirable.

In order to test the feasibility of using only two stages, one block has already been sent out for trial, and a second block will be sent to another vendor when the machines are available for testing purposes.

Burning

The support platforms for the 4-in. EXO burner and the 4-in. ENDO burner have been completed, and assembly of the burners have been started.

Five experiments were completed in the 8-in. EXO burner, all using a graphite-only bed. The reactor base has been dismantled for modifications to add a distributor plate and to convert this "graphite" burner to a "graphite-fuel" burner. Some pertinent data obtained from the five experiments are presented in Table 5.2.

Experiment F8B-M8 was run to test the following:

1. Shakedown of the newly installed burner and auxiliary equipment.
2. Test -3/16-in graphite as a feed for the "nonalumina" operation.
3. Measure recycle rates by filter and cyclone systems.
4. Check data logging and process indicators for overall accuracy and reliability in run analysis.

TABLE 5.2
DETAILS OF 8-IN BURNER RUNS

	F8B Experiment Series				
	M8	M9	M10	M11	M12
<u>Run Duration</u>					
Ignition time, min	9	8	11	10	9
Feed on time, min	<u>106^(a)</u>	<u>41^(b)</u>	<u>105^(c)</u>	<u>72^(d)</u>	<u>165^(e)</u>
Total time, min	115	49	116	82	174
<u>Run Data^(f)</u>					
Bed Graphite, g	8,192	7,652	10,392	15,553	9,923
% Graphite	<u>100</u>	<u>100</u>	<u>100</u>	<u>100</u>	<u>100</u>
Total bed wt, g	8,192	7,652	10,392	15,553	9,923
Avg Offgas Comp., vol-%:					
CO	6-7	5-7	10-15	12-18	16-19
CO ₂	50-70	50-65	72-82	80-82	80-82
O ₂	2-4	2-4	0-0.5	0-0.5	0-0.5
N ₂	← To Balance →				
Recycle rate, g/min:					
Cyclone	51.6	---	93	---	63.3
Filter	<u>9.3</u>	<u>---</u>	<u><1</u>	<u>---</u>	<u>0.2</u>
Total	60.9	---	94	---	63.5
Total Burned, g	11,884.5	6,598	25,366	14,600	32,800
Avg burn rate, g/min ^(g)	112.1	170	242	216	199

- (a) Run terminated when fines dropping back into bed caused bed to cool below acceptable operating temperature.
- (b) Run terminated due to problems with auxiliary equipment.
- (c) Bed extinguished with nitrogen to analyze for bed segregation and particle size.
- (d) Run terminated due to problems with auxiliary equipment.
- (e) Run terminated when all available feed was consumed.
- (f) No alumina used in bed during this series.
- (g) During feed-on time.

The results indicate that the equipment installed needs few modifications, that the -3/16-in graphite (size analysis not completed) is a satisfactory feed material, and that the "nonalumina" operation is a promising method. A long-term run of about 8 to 16 hr will define the potential problems of process stability and potential fines buildup.

Experiment F8B-M9 was performed to test the same items as F8B-M10, but a fault in the bed differential pressure detector forced shutdown early in the run.

Experiment F8B-M10 was made to test the following:

1. Eliminate the problems occurring in Runs F8B-M7, -M8, and -M9 in burning -3/16-in graphite.
2. Test the new ignition system modifications and procedures.
3. Measure burn rates with a 15-Kg bed.

The ignition system proved to work satisfactorily and, although it required about 2 to 3 min longer to ignite than previous methods, it was proved to be safe and efficient. The ability to burn -3/16-in graphite feed in a graphite-only bed was shown to be easy and an operable run mode. Maximum burn rates with a 15-Kg bed were not achieved, but an operable burn condition was attained and held for about 90 min. Experiment F8B-M11 was therefore planned to run for a longer period of time and with a slightly larger bed (about 15 Kg) to show the safe maximum burn rates. The bed for F8B-M10 was not segregated to any large degree, and fines did not appear to be accumulating in the fines recycle stream.

Experiment F8B-M11 was made to test the following:

1. Measure burn rates with a 15-Kg bed.
2. Recheck the new ignition system.

3. Run long enough (~5 hr) to achieve a steady-state operating mode for at least 1 hr in order to make mass and heat balances.

The ignition system worked well, and the time required for ignition was reduced by 1 min. The burn rate was very good (~10 min) and the startup of the burner went smoothly. However, a leak in the auger feed system forced the experiment to be terminated prematurely.

Experiment F8B-M12 was designed to measure run parameters with a 10-Kg bed and to run until all the available feed was consumed. The ignition and startup proceeded smoothly, and the run continued under normal operating conditions until all the available feed was consumed.

Leaching

Additional leaching tests were performed on the 5-in-diameter leacher (described in earlier quarterly report Gulf-GA-A10930). The operating conditions and available results are given in Tables 5.3 and 5.4. Acid Thorex of 16M HNO_3 /0.05M HF/0.1M $\text{Al}(\text{NO}_3)_3$ was used for runs 7 and 8, and acid thorex 8M HNO_3 /0.12M HF/0.1M $\text{Al}(\text{NO}_3)_3$ was used for run 9. Runs 10 through 15 were made with 13M HNO_3 /0.05M HF/0.1M $\text{Al}(\text{NO}_3)_3$. As with the first six runs, runs 7, 10, 11, 12, and 13 were made using ground burned fissile particles as a feed material. The 8th and 9th runs were made with insoluble residue from other leaching experiments. Ground and burned fertile particles were the feed material for runs 14 and 15.

The results indicate that a batch air-sparged leacher can be used successfully. Up to 4.7 kg/hr of crushed and burned fissile particles were successfully processed with uranium and thorium recoveries greater than 99%.

TABLE 5.3
OPERATING VARIABLES FOR
5-IN.-DIAMETER
STAINLESS STEEL LEACHER

Run No.	Leach Time (hr)	Thorex Charged (l)	Solids Charged (g)
7	1	7.5	2500
8	1	3.0	1000
9	1	3.0	1000
10	1	7.5	4700
11	0.5	7.5	4700
12	1	7.78	4867
13	0.5	7.75	4867
14	1	3.5	1000
15	1	2.89	823

NOTE: Air sparge = 12 liters (STP)/
min; leaching temp $\approx 118^{\circ}\text{C}$.

TABLE 5.4
DETAILS OF RUN RESULTS

Run No.	Undissolved Solids After Leach (g)	U and Th in Feed to Leacher (%)		U and Th in Undissolved Solids (%) (a)		Recoveries (%)		Material Balance Closure (%)	
		U	Th	U	Th	U	Th	U	Th
7	1337	6.83	42.3	<0.1	<0.1	99.21	99.87	106.5	102.7
8	244	8.88	43.1	0.57	4.62	98.43	97.39	102.2	99.4
9	261	8.88	43.1	1.42	7.51	95.82	95.44	97.0	94.8
10	1293	6.04	42.4	0.08	0.12	99.64	99.92	99.87	99.37
11	2754	5.73	23.5	0.08	0.14	99.18	99.65	99.96	100.16
12	1383	4.51	52.6	0.28	0.79	98.24	99.57	93.93	99.5
13(b)	1211	3.03	55.1	4.1	53.4	66.8	76.0	107.4	110.3
14	148	(c)	(c)	(c)	(c)	--	--	--	--
15	171	(c)	(c)	(c)	(c)	--	--	--	--

(a) Based on analysis by X-ray fluorescence.

(b) Leachate saturated with Th that crystalized upon cooling.

(c) Analyses not available to date.

TASK VIII
PHYSICS AND FUEL MANAGEMENT

HTLTR STUDIES

Preliminary results for the Gulf General Atomic analysis of HTLTR Lattice 4 ($\text{PuO}_2/\text{ThO}_2$) were obtained. The calculated values of k_∞ for the lattice at various temperatures have changed somewhat since the original estimates made during early 1970. (Table 8.1 compares the calculated k_∞ values to the earlier estimates.) For example, the room temperature k_∞ value is lower by 2.5% and $\Delta k(T)$ to 1500°K is down by 0.030, or over 30%, compared to the earlier results.

The changes noted are not unexpected, since the model used, the cross sections employed, and the methods of analysis utilized have been changed. The 1972 values were obtained using finite critical bucklings, ENDF/B-II cross sections, and the MICROX and GAZE-2 codes. The 1970 values reflect use of zero bucklings, GGA cross sections, and the GTF and GGC-4 codes. Further, the 1970 calculations used suggested lattice loadings while the 1972 calculations used as-built lattice parameters. Analysis is continuing to isolate the change in results due to each of the changes in calculation.

FUEL TEST ELEMENT

Phase 2 Operation

The three Base Program test elements (FTE-3, -4, and -6) already installed in the Peach Bottom core continued to operate acceptably during the quarter.

TABLE 8.1
CALCULATED VALUES COMPARED TO PRELIMINARY RESULTS
AT VARIOUS TEMPERATURES

Temp (°K)	Orig. Calc. 1970		Prelim. Results	
	k_{∞}	$\Delta k(T)$	k_{∞}	$\Delta k(T)$
300	1.108	--	1.081	--
423	--	--	1.074	0.007
573	--	--	1.066	0.015
600	1.086	0.022	1.066	0.015
773	--	--	1.061	0.020
900	1.068	0.040	1.057	0.024
1023	--	--	1.051	0.030
1200	1.046	0.062	1.041	0.040
1273	--	--	1.036	0.045
1500	1.011	0.097	1.014	0.067

It is now planned to remove FTE-3 from the core for postirradiation examination during the forthcoming spring shutdown. At that time this element will have approximately 200 equivalent full-power days (EFPD) of exposure. FTE-4 is now scheduled for 450 EFPD and FTE-6 for 650 EFPD.

Phase 3 Operation

The following description discusses the design and operational evaluation of fuel test elements FTE-14 and FTE-15. These elements are identical in most respects to the fuel test elements presently being irradiated in the reactor. The primary difference between FTE-14 and -15 and the fuel test elements now in the Peach Bottom reactor is that FTE-14 and -15 contain fuel bodies with 0.615-in.-diameter (rather than 0.490 in. dia.) fuel rods contained in a telephone dial array of six rather than eight fuel holes.

It is planned to irradiate FTE-14 for about 150 EFPD and FTE-15 until the end-of-life for Core 2 (about 500 EFPD). FTE-14 will be placed in core position B03-02 and FTE-15 in core position A03-03.

Phase 3 Fuel Element Design and Description

Fuel Element

The phase 3 fuel elements have the same design (shown in Fig. 8.1) as the FTEs 3 and 4, which are currently in operation.

Fuel Body

The fuel body, shown in Fig. 8.2, is a graphite circular cylinder with an array of six fuel holes in a circular pattern. Each hole has a diameter of 0.625 ± 0.001 in. and is equally spaced on a 1.875-in. circle. The 31.0-in.-long cylinder is 2.740 (+0.000, -0.002) in. (max.) in diameter. The outside diameter of the middle body will be stepped to 2.704 (+0.000, -0.002), 2.724 (+0.000, -0.002), and 2.730 (+0.002, -0.002) to increase the fuel rod temperatures. These steps will permit maximum centerline fuel temperatures

Fig. 8.1. Phase 3 fuel test element design for FTE-14 and -15

Fig. 8.2. Cross section of fuel test element, FTE-14 and -15

of 2630°, 2505°, and 2380°F respectively. The normal outside diameter of 2.740 (+0.000, -0.002) will cause centerline temperatures in that area to run at 2260°F maximum. The above temperatures are for reactor conditions of 100% power and flow.

Only the middle body diameter is stepped. The top and bottom fuel bodies are not stepped to increase the fuel rod temperatures, but the bottom fueled half of the top fuel body is tapered so that the fuel temperatures achieved in this area will be relatively constant at 2380°F. The bottom fueled half of the top fuel body in both FTE-14 and -15 is tapered from 2.740 (+0.000, -0.002) to 2.690 (+0.000, -0.002). The top fueled half of the top fuel bodies for FTE-14 and -15 remains at a constant 2.690 (+0.000, -0.002) in.

The fuel bodies are machined from H-327 graphite, an extruded anisotropic needle coke graphite. A graphitized log is about 18 in. in diameter and 34 in. The portion of the high-strength log from which the fuel bodies for FTE-14 and -15 are machined has minimum tensile strengths of 2000 psi in the parallel direction and 1000 psi in the perpendicular direction.

The outside diameter of the bottom fuel body will be 2.740 (+0.000, -0.002) as on the fuel test elements presently in the reactor. The top fuel body will be both stepped and tapered to increase the temperature in this body. The bottom half will be tapered from 2.740 (+0.000, -0.002) to 2.690 (+0.000, -0.002) in. The top half of the top fuel body will be stepped to 2.690 (+0.000, -0.002) in. Each fuel hole is about 29.91 in. deep. All fuel bodies will be loaded with fuel rods made from conventional uranium-thorium fuel particles. The central spine, which is 0.80 in. in diameter, will be used to test nine small thermal stability samples, each one of which contains in a sealed graphite container 2.4 g of fuel particles used in the fuel test element.

Six equally spaced axial purge grooves on the outer surface of the fuel body provide adequate flow area for the helium purge gas. The grooves are each 0.055 in. deep and 0.14 in. wide. The ends of the fuel body cylinders

are chamfered to provide a continuous axial flow path regardless of the azimuthal orientation of the fuel bodies. All the purge gas flows in the purge grooves and the annular clearance gap between the fuel body and the sleeve; none flows through the central irradiation hole. The total purge flow rate is determined by the pressure drop in the porous plug; it is not limited by the cross-sectional area of the purge channel.

Each fuel hole of the fuel bodies for FTE-14 and -15 is closed at the top with a 0.25-in.-thick threaded graphite plug. The plug provides positive containment of the fuel rods in the graphite fuel body. The central irradiation region (i.e., the spine region) is also closed with a threaded 0.38-in.-thick graphite plug.

Fuel Particles

Particle types used in FTE-14 and -15 are summarized in Table 8.2. All of these particles are representative of types being studied for use in HTGR type fuel elements. Particles of designs similar to these have been used in previous test elements. All are designed to survive nominal operating conditions to exposures of greater than $4 \times 10^{21} \text{ n/cm}^2$. The maximum exposure of the particles in FTE-14 for 150 EFPD is approximately $0.7 \times 10^{21} \text{ n/cm}^2$ and in FTE-15 for 500 EFPD is approximately $2.3 \times 10^{21} \text{ n/cm}^2$.

Fuel Rods

The fuel rods in FTE-14 and -15 will be 0.615 ± 0.003 in. in diameter and 2.50 in. long. The overall stack length of rods in a fuel hole of the 31-in. bodies will be 27.50 ± 0.16 in. The minimum axial clearance between the rods and the fuel hole cap is 1.86 in.

The particle combinations of interest which might be used in fuel rods in the fuel test elements are shown in Table 8.3.

TABLE 8.2
FUEL PARTICLE DESIGNS FOR FTE-14 AND -15

Item No.	Kernel		Designed Coating Parameters						
	Type	Nominal Diameter (μm)	Type	Nominal Thicknesses (μm)					OPyC Density (g/cm ³)
				Buffer	IPyC	SiC	OPyC	Total	
12	UO ₂	200	TRISO ^(a)	95	35	30	35	195	1.70-1.90
13	ThO ₂	400	BISO ^(b)	65	--	--	70	135	1.90-2.05
14	UC ₂	150	TRISO	55	20	22	25	122	1.70-1.90
15	ThC ₂	375	TRISO	55	25	25	40	145	1.70-1.90
16	UO ₂	150	TRISO	60	20	22	25	127	1.70-1.90
17	ThC ₂	375	BISO	65	--	--	70	135	1.90-2.05
18	ThO ₂	400	TRISO	65	25	22	25	137	1.70-1.90
21	UC ₂	200	TRISO	85	25	20	35	165	1.70-1.90
23	(Th, U)O ₂ ^(c)	250	TRISO	72	35	37	60	205	1.70-1.90
24a	ThC ₂	450	BISO	82	--	--	64	146	1.80-2.05
24b	ThC ₂	450	BISO	68	--	--	59	127	1.80-2.05
24c	ThC ₂	450	BISO	56	--	--	49	105	1.80-2.05

(a) TRISO denotes a coated particle having an inner coating over the fuel kernel of porous buffer pyrolytic carbon, a layer of isotropic pyrolytic carbon over this, then a layer of silicon carbide and another, outer coating of PyC.

(b) BISO denotes a coated particle having two types of coatings over the fuel kernel, an inner coating of porous buffer pyrolytic carbon and an outer of isotropic pyrolytic carbon.

(c) Th/U ratio = 1.0, I = Inner, O = Outer, PyC = pyrolytic carbon, and SiC = Silicon Carbide.

TABLE 8.3
FUEL ROD PARTICLE LOADING COMBINATIONS
FOR FTE-14 AND -15

Upper End						
Body No. 3	<u>Body No. 3</u>					
	<u>Fuel Hole No.</u>	<u>Item No.</u>	<u>Fissile Particle</u>	<u>Item No.</u>	<u>Fertile Particle</u>	
	1	21	(200 μ m)UC ₂ TRISO	17	(400 μ m)ThC ₂ BISO	
	2	21	(200 μ m)UC ₂ TRISO	15	(400 μ m)ThC ₂ TRISO	
	3	12	(200 μ m)UO ₂ TRISO	13	(400 μ m)ThO ₂ BISO	
	4	23	(250 μ m)(Th,U)O ₂ TRISO	24a	(450 μ m)ThC ₂ BISO	
	5	16	(150 μ m)UO ₂ TRISO	24a	(450 μ m)ThC ₂ BISO	
	6	12	(200 μ m)UO ₂ TRISO	18	(400 μ m)ThO ₂ TRISO	
Body No. 2	<u>Body No. 2</u>					
	1	21	(200 μ m)UC ₂ TRISO	17	(400 μ m)ThC ₂ BISO	
	2	21	(200 μ m)UC ₂ TRISO	15	(400 μ m)ThC ₂ TRISO	
	3	12	(200 μ m)UO ₂ TRISO	13	(400 μ m)ThO ₂ BISO	
	4	23	(250 μ m)(Th,U)O ₂ TRISO	24a	(450 μ m)ThC ₂ BISO	
	5	16	(150 μ m)UO ₂ TRISO	24a	(450 μ m)ThC ₂ BISO	
	6	12	(200 μ m)UO ₂ TRISO	18	(400 μ m)ThO ₂ TRISO	
Body No. 1	<u>Body No. 1</u>					
	1, 2, 3	14	(150 μ m)UC ₂ TRISO	24c	(450 μ m)ThC ₂ BISO	
	4, 5, 6	14	(150 μ m)UC ₂ TRISO	24b	(450 μ m)ThC ₂ BISO	

Instrumentation

FTE-14 and -15 will be instrumented with two thermocouples located in the graphite fuel body as shown in Fig. 8.2. The hot junctions are located at the peak fuel temperature positions approximately 70 in. from the bottom of the element. The inner thermocouple is tungsten-rhenium and the outer thermocouple is chromel-alumel. The inner thermocouples are doubly clad with niobium-1% zirconium, and the outer thermocouple has an inner clad of Inconel and outer clad of Nb-1% Zr. The outside diameter is 0.087 in. The thermocouples terminate at the base of the bottom connector with contact springs, and make contact with the lead wires in the same manner as an instrumented Core 2 element. The tungsten-rhenium thermocouple is designated Type A, the chromel-alumel Type B.

Phase 3 Test Element Composition and Performance

Fuel Bodies/Fuel Rods

FTE-14 and -15 are each composed of three 31-in. bodies and each will be instrumented with two thermocouples. Each element will contain 177.5 g of U-235 and about 1.5 kg of thorium. The element will produce 125 kw maximum. The maximum fuel particle burnups achieved will be in the center fuel body. Burnups of 40% FIMA in the uranium oxide or carbide fissile particles will be achieved. The maximum fast fluence at the end of 450 EFPD will be 2.1×10^{21} nvt. Maximum fuel bed temperatures over the irradiation period of these elements will be 2630°F in the area of the largest step in the center fuel body. An axial temperature distribution for FTE-14 and -15 is shown in Fig. 8.3. The overall contents of either FTE-14 or FTE-15 excluding center hole contents are shown in Table 8.4. The loading scheme for FTE-14 and -15 is shown in Table 8.4. FTE-14 and -15 are identically loaded.

The volume average temperature of the FTE-14 and -15 fuel rods at the beginning of life has been estimated to be not greater than 2100°F, and the fuel is expected to perform satisfactorily under these conditions. These

Fig. 8.3. Axial temperature distribution

TABLE 8.4
FTE-14 AND 15 MATERIAL WEIGHTS

Material	Weight ^(a) (g)
Uranium	190.4
Thorium	~1.5 kg
Particle coating material	2 kg
Bonded rod filler materials	300
Graphite	33 kg
Stainless steel ^(b)	16
Polystyrene ^(c)	3.7
Polyethylene ^(c)	6.6
Thermocouple cold junction: ^(d)	
Stainless steel	140
Nickel	<1
Inconel	<10
Rhodium	<1
Alumina	16
Thermocouples: ^(d)	
Niobium	16
BeO	5
MgO	12
Tungsten-rhenium wire (W/3% Rh and W/25% Rh)	3.6
Chromel-Alumel wire	3.2
Inconel	16

- (a) Except kg where noted.
- (b) The steel is part of the bottom connector of an instrumented test element, identical to standard Core 2 instrumented elements.
- (c) The maximum quantity of hydrogen which could be released from the polystyrene, polyethylene, and uncured cement joints is 0.006 lb.
- (d) Similar to standard Core 2 element thermocouple components.

higher temperature tests are designed to determine the performance and integrity limits of these fuels.

Natural-flake graphite filler material and pitch binder will be used in the rod bonding matrix. During irradiation, the rod matrix material and the fuel particles are expected to contract axially and radially, thus ensuring a continuous clearance between the fuel rod and fuel hole.

Fuel Body Center Hole Samples

The design of the fuel body center hole samples is shown in Fig. 8.4. FTE-14 and -15 will each contain nine thermal stability center samples. Each of the six-hole graphite crucibles will contain 2.4 g of fuel particles. These samples will provide additional information regarding the irradiation exposure and integrity of the fuel particles. The performance of these samples will in no way affect the integrity of the fuel element.

Fuel Body Mechanical Performance

Fuel Body/Center Sample Clearance. The center hole will contain either a solid graphite rod or irradiation samples enclosed in graphite containers. In all cases the outer diameter will be a maximum of 0.75 in., leaving a minimum 0.05-in.-diametral clearance between the fuel body and spine or container. This clearance is equivalent to 6.7% of the center hole diameter and is more than adequate clearance to accommodate any unexpected differential radial dimensional changes between the fuel body and center hole graphite.

The minimum axial clearance between the stack of center hole crucibles or rods and the bottom of the threaded plug at the top of the center hole is 0.50 in. This clearance is equivalent to about 1.7% of the 31.0-in. body length and is more than adequate to accommodate any unexpected differential axial dimensional changes between the fuel body and the center samples.

SECTION A-A

Fig. 8.4. Thermal stability center hole sample

The fuel bodies, graphite rods, and sample containers are all fabricated from H-327 graphite and have the same orientation with respect to the extrusion axis. The fuel body and center graphite will have the same fast fluence history, and the temperature of the center hole graphite will be the same as, or higher than, the fuel body center hole wall temperature. The radial and axial graphite contraction of the center hole graphite will therefore be the same as, or greater than, the fuel body and the beginning-of-life radial and axial minimum clearance will be maintained. Fast fluences for the 450 EFPD lifetime will not be sufficient to produce any dimensional reversal to contraction for the center hole graphite.

Fuel Body and Sleeve Stresses. Since the fuel test elements having the six-hole design will only be subjected to a fraction of the total life of the core, analyses were done for fast fluences up to $2.1 \times 10^{21} \text{ n/cm}^2$ (450 EFPD exposure). Analysis methods are the same as those for the eight-hole design test elements.

The fuel body maximum combined thermal and irradiation-induced contraction axial and in-plane stresses for designed operation and reactor shutdown are shown in Table 8.5. A plot of the local maximum tensile and compressive stresses versus fast fluence throughout core life is shown in Fig. 8.5. Figures 8.6 and 8.7 show axial stress distributions across the fuel body at maximum stress conditions (fast fluence = $6.0 \times 10^{20} \text{ n/cm}^2$) for operation and shutdown, respectively.

TABLE 8.5
FUEL BODY INTERNAL STRESSES

Direction	Time	Local Max. Tensile Stress (psi)
Axial	Operation	740
Axial	Shutdown (thermal)	840
Axial	Shutdown (total)	1580
In-plane	Operation	200
In-plane	Shutdown (total)	700

Fig. 8.5. Predicted maximum axial operating and shutdown stresses in graphite fuel body versus fast fluence

Fig. 8.6. Axial stress distribution for the maximum operating case; fast fluence, $6 \times 10^{20} \text{ n/cm}^2$; 30° segment of FTE fuel body cross section

Fig. 8.7. Axial stress distribution for the maximum shutdown case; fast fluence, $6 \times 10^{20} \text{ n/cm}^2$; 30° segment of FTE fuel body cross section

Since the stress level at end of life are steady and at an acceptable level as shown in Figures 8.6 and 8.7, stress levels that would be encountered should FTE-14 and -15 be irradiated for a period longer than 500 EFPD will not present a problem. The maximum local axial and in-plane tensile stresses as shown in Table 8.5 are below the measured minimum strengths of the H-327 graphite of 2000 psi and 1000 psi in the axial and in-plane directions, respectively. When the reactor is shut down, the reverse thermal strains add to the current operational contraction strains and the maximum stresses in the fuel body occur at this time. When the reactor returns to full operation, the thermal strains are relieved and the stresses are again reduced.

The maximum shutdown tensile stresses occur away from the ends of the fuel body and are located at the point of maximum power density along the length of the body. At all planes where the power density (or linear heat rating) is less, the stresses are also less. At reactor shutdown, the reverse thermal strain produces a maximum axial thermal stress shutdown component of 840 psi. The maximum axial shutdown stress of (1580 psi) is the sum of the maximum operating stress and the maximum axial shutdown thermal stress. The thermal shutdown stresses are based on the elastic analysis and thus have a maximum uncertainty of only 5%. The operating stress is conservatively calculated using the FESIC and SAFE-GRAPHITE codes and has a maximum combined uncertainty of 25%. These uncertainties could contribute an additional 400 psi to the nominal maximum value; consequently, the maximum axial tensile shutdown stress is about 1980 psi. Since the tested minimum strength of graphite is about 2000 psi, failure in this mode appears improbable. The maximum in-plane shutdown stress of 775 psi is well below the mean transverse strength of 1000 psi.

TASK IX
FUELS MATERIALS DEVELOPMENT

FUEL IRRADIATIONS

A series of capsule irradiations is being conducted to evaluate recyclable fuel systems for the large HTGR under the expected irradiation environments.

Capsule P13M

Capsule P13M is the second full-exposure test of large HTGR initial and recycle core fuel particles, and the first test of such particles made in production type equipment; it is also the first test of large HTGR type fuel rods under maximum reactor design conditions. Some of the particle samples are duplicates of those now being tested in the Phase I and Phase II Peach Bottom test elements, and capsule P13M will provide full-exposure data on these materials. In addition to the particle and rod cells, the capsule also contains two thermocouple decalibration cells.

Capsule P13M was inserted in the ETR (I13 core position) in cycle 110C in March 1971. The ETR recently completed cycle 114, and P13M has now reached an estimated peak fast fluence of 7×10^{21} n/cm² (E > 0.18 MeV). The capsule continues to operate well with 75% of the thermocouples still operative. The temperatures for cell 3 (fuel rods) have remained about 225°C over the design temperature of 1000°C, even though the thermal flux in the region of this experiment has been lowered to the original design value.

The tungsten/rhenium thermocouple decalibration experiments show a progressive downward drift with increased exposure. The most recent data,

which are given in Figs. 9.1 and 9.2, indicate that the thermocouples in the two cells are decalibrating at different rates. The W/Re thermocouples operating at 1250°C have drifted about 400°C after $5 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ Mev}$) and those operating at 950°C have drifted about 300°C after $5 \times 10^{21} \text{ n/cm}^2$.

P13M will remain in the reactor for one more cycle of irradiation before it is discharged. The peak exposure is expected to reach between 8.3 and $8.7 \times 10^{21} \text{ n/cm}^2$.

Capsules P13N and P13P

Capsules P13N and P13P are the fourth and fifth in a series of irradiation tests of typical HTGR recyclable type fuels. These are the first capsules that will be monitored for in-pile fission gas release during the irradiation. The two capsules are very similar in design; each contains five cells in which both fuel rods and loose particle samples will be tested. Tests of oxide and carbide fuels are included in each capsule. Irradiation exposures will span a wide range of conditions in an effort to define operating limits for these fuels. Capsule P13N is designed to go to approximately $5 \times 10^{21} \text{ n/cm}^2$ (peak fluence) and the fuel will be irradiated at 1350° and 1500°C. Capsule P13P is designed for $\geq 8 \times 10^{21} \text{ n/cm}^2$ and design fuel temperatures will be 1050° and 1350°C.

Capsule P13N contains 22 fuel rods, 24 loose particle samples, and 175 piggyback samples. Figure 9.3 gives a schematic layout for the fuel specimens in P13N.

This capsule began its irradiation in ETR cycle 114E on January 27, 1972. Periodic fission gas release samples are being taken, and the data are in the process of being analyzed. In cells 2, 3, and 4 problems were encountered in achieving design temperatures in the fuel rods because of temperature differences between the loose particle beds and the rods. Fissile particle beds in these cells are operating 100° to 300°C above the fuel rod temperatures. These temperature differences are believed to be due to higher fuel rod thermal conductivities than assumed in the design.

Fig. 9.1. Irradiation-induced drift in W-3% Re/W-25% Re thermocouples irradiated at approximately 1200°C

Fig. 9.2. Irradiation-induced drift in W-3% Re/W-25% Re and Chromel-Alumel thermocouples irradiated at approximately 950°C

Fig. 9.3 Layout for Capsule P13N

The fuel for capsule P13P, which will be irradiated in J-10-NE position of the ETR, has been fabricated, and the assembly of this capsule is scheduled to begin shortly. The capsule will be ready for insertion in the ETR for cycle 116, which is currently scheduled to begin early in the second quarter.

ORNL Capsule HRB-3

Capsule HRB-3 is sponsored by ORNL and is primarily a test of candidate recycle fuels fabricated at ORNL, but it also contains two Gulf General Atomic fabricated fuel rods. HRB-3 is designed to reach approximately 9×10^{21} n/cm² (peak) and all samples will operate at 1250°C.

The capsule is now in its second cycle of operation and has reached 1.2×10^{21} n/cm². The temperatures have decreased during this cycle to 1100°C, and the reasons for this temperature drop are being investigated. Recent fission gas-release data from HRB-3 show the R/B (release to birth ratio) for Kr-85m to be about 4×10^{-5} .

TASK XI

GRAPHITE RESEARCH

Work during the quarter on this task consisted primarily of the preparation and characterization of LTI carbon specimens for irradiation experiments. Samples were prepared for irradiation as unrestrained specimens in the form of 0.040-in.-wide strips obtained by stripping the coatings from small graphite disks that had been introduced into a fluidized bed of particles during a coating run. Samples were also prepared for irradiation as restrained specimens in the form of the coated disks. For each unrestrained specimen, the density was measured by a sink-float technique, and the distance between fiducial holes was measured in a toolmaker's microscope. Similar measurements after irradiation will make possible calculation of the dimensional changes parallel and perpendicular to the deposition plane. For the restrained disks, the distance between fiducial holes was also measured in the toolmaker's microscope. A similar measurement after irradiation plus the dimensional changes of a companion unrestrained specimen will permit the calculation of the accommodated strain (creep strain plus elastic strain) in the specimen.

The purpose of the experiments with the unrestrained specimens will be to determine the effect of small deviations from perfect isotropy on the dimensional changes. The deviations from perfect isotropy will be determined by the optical response of the carbons in polarized light. Irradiation of the restrained specimens is the first step in a series of experiments to determine the effect of irradiation-induced creep on the subsequent dimensional changes.

Specimens were prepared for irradiation in piggyback positions in Capsules P13N, P13P, F30, FTE-14 and FTE-15. The expected temperatures and fluences are given in Table 11.1.

TABLE 11.1
TEMPERATURE AND FLUENCE
FOR FIVE CAPSULES

Capsule	Temp (°C)	Fluence (10 ²¹ n/cm ²)
P13N	900	5.0
P13N	1000	4.5
F30	750	8.0
F30	1000	4.5
P13P	800	8.0
FTE14	1200	1
FTE14	1300	1
FTE14	1350	1
FTE14	1400	1
FTE15	1200	2
FTE15	1300	2
FTE15	1350	2
FTE15	1400	2

APPENDIX
PROJECT REPORTS PUBLISHED DURING THE QUARTER

There were no topical reports published during this period.