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AEC RESEARCH AND
DEVELOPMENT REPORT

GA-5314

IRRADIATION TEST OF THE GAIL III-B FUEL ELEMENT IN THE GENERAL ATOMIC IN-PILE LOOP

Prepared under
Contract AT(04-3)-314
and
Contract AT(04-3)-167
Project Agreement No. 16
for the
San Francisco Operations Office
U.S. Atomic Energy Commission

July 10, 1964

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GENERAL ATOMIC
DIVISION OF
GENERAL DYNAMICS

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PREFACE

The General Atomic In-pile Loop (GAIL) was designed and constructed as part of the Research and Development Program for the Peach Bottom reactor. The original purpose of the loop experiment was to provide information confirming the performance features of the Peach Bottom type fuel element. Subsequently, the loop has become a valuable tool for studying the release of gaseous and plateout fission products from the HTGR fuel element as a function of burnup.

The initial operation of the loop began in October, 1961, with the GAIL III-A fuel element, and this element was tested until February, 1962. The GAIL III-B element was installed on February 5, 1962, and this element was irradiated until March 15, 1964. The GAIL III-B test was performed under the Peach Bottom Research and Development Contract, AT(04-3)-314, until December 16, 1963. After that date, the work was performed under Project Agreement 16 of Contract AT(04-3)-167.

The objective of the extended testing of the GAIL III-B element under Project Agreement 16 has been to confirm the exceptionally long life of which such fuels are capable and to determine more precisely the fission product release characteristics of coated-particle-graphite-matrix fuels at high burnup.

This report covers the GAIL test during the complete testing period from February 5, 1962, to March 18, 1964, on which date the GAIL III-B fuel element was removed from the reactor. The postirradiation examination of the GAIL III-B element is not included in this report. That examination is being performed under the TARGET program (Project Agreement 17 of Contract AT(04-3)-167).

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I. INTRODUCTION

The in-pile loop at the General Electric Test Reactor (GETR) was designed to obtain information of a confirmatory nature under simulated reactor conditions. In the in-pile loop test, a fuel element can be irradiated in a thermal neutron flux slightly higher than 10^{13} nv in a stream of purified helium at 350 psia. The element is designed to generate 76 kw of fission and gamma power resulting in a heat flux of about 150,000 Btu/hr-ft². Provisions are made for purging the fuel element and passing the purge stream through internal and external fission product traps. Figure 1.1 is a simplified flow diagram of the primary loop and purge stream.

The major items of equipment in the primary loop are the facility tube containing the test fuel element, circulators to pump the helium coolant through the loop, a cooler to dump the heat produced in the element, a 50-kw electric heater to provide fine control of the inlet helium temperature, and associated piping, valves, and instrumentation.

Flexibility in experimental conditions is provided by a regenerative heat exchanger that will permit fuel element inlet gas temperatures above the maximum circulator discharge temperature, and a tempering gas line that will permit fuel element outlet temperatures higher than the design temperature of the main loop piping. However, the use of these two units was not required for the GAIL III-B test.

The experiment is located in the pool of the GETR adjacent to the reactor pressure vessel, that is, at the core-reflector interface. In order to minimize heat flow from the hot facility tube to the water in the pool, the entire in-pool portion is contained in an aluminum vacuum chamber.

The facility tube assembly consists of a pressure vessel containing the fuel assembly and thermal baffles, coolant inlet and outlet piping, tempering gas piping, purge gas piping, thermocouples, disconnect joints, and internal shielding. Normally the facility tube is located in close proximity to the reactor vessel to take advantage of the high neutron flux, but means are provided to retract the vacuum chamber in the core region up to 5 in. from the reactor vessel when it is desired to operate the reactor with the loop facility shut down.

The fuel elements tested in the in-pile loop are shortened versions of HTGR type fuel elements. Instrumentation is provided to measure the

Fig. 1.1--Simplified flowsheet of the in-pool loop

temperatures of the fuel, the sleeve, and the inlet and outlet helium. Fission heat is transferred to the helium coolant at the outer surface of the graphite sleeve.

The primary loop main cooler transfers heat from the hot helium gas to a closed demineralized secondary water system which in turn transfers heat to the GETR cooling tower water through a secondary heat exchanger.

Two circulators are provided to pump the helium coolant around the closed loop. One of the circulators is normally not operated but held as an in-line spare in case the other should fail.

A full-flow filter located in the line upstream from the circulators removes graphite fragments from the main loop stream to protect the circulators in case of fuel element erosion.

The internal fission product trapping and helium purification system (FPTS) removes radioactive fission products and gaseous impurities from the fuel element purge stream and returns the essentially clean helium to the main coolant stream. It consists of a series of adsorbent beds and filters, operated at various temperatures, through which the purge stream is passed.

The purge gas is circulated by taking advantage of the pressure drop across the main loop. A booster pump is used only when the pressure differential is too small to obtain the desired flow rate.

A shielded containment vessel (called the junior cave) is provided to permit sampling the purge stream. All operations within the containment vessel are performed by a claw-type manipulator that is designed to operate valves for the control of gas flow and to handle and remove the test traps. Operations within the vessel are observed through a high-density lead-glass window.

Primary loop samples are handled in a sample blister that contains stop valves on the piping leading to and from the system sample points, a gas chromatograph analyzer, a liquid-nitrogen-cooled charcoal trap, a connection point for the sampling container, and miscellaneous piping and valves.

Two full-diameter, quarter-length fuel elements have been operated in the GAIL. These elements were essentially identical, except for the graphite material used for the sleeve. The helium permeability (at room temperature and 1/2 atm mean pressure) of the sleeve of the first element

(III-A) was 10^{-5} cm²/sec; that of the second element (III-B) was 10^{-3} cm²/sec.

Operation of the GAIL with test element III-A was initiated at low power (~6 kw) on September 23, 1961. After a succession of planned step increases, full-power operation (~72 kw) was achieved on October 12, 1961. Element III-A was removed on February 4, 1962. It had generated a total of 133 Mw-hr of heat, which is about 18% of the heat generated by a corresponding length of an average Peach Bottom element in three years at 80% load factor.

After element III-A was removed from the loop, element III-B was installed. Full-power operation of element III-B was begun March 17, 1962, and continued until March 18, 1964.

The GAIL III-B fuel element operated at full power for more than 10,000 hr and generated 685.5 Mw-hr of energy. This accumulative energy is equivalent to 92% of the power produced by an equivalent length of a Peach Bottom reactor element at the end of life.

The test of the GAIL III-B fuel element has confirmed the exceptionally long life of which this type of fuel is capable, has provided fission product release data as a function of burnup, has proved that the levels of radioactive and chemical impurities can be maintained at very low levels in the helium coolant, and has proved the ease of access to loop and trapping-system components following shutdown.

A major objective of the GAIL III-B test was to prove the effectiveness of a moderately impermeable graphite sleeve as a barrier to fission product release. The helium permeability of the sleeve in this element was approximately 1×10^{-3} cm²/sec (measured at room temperature and 1/2 atm pressure). A small fraction of purge gas leaks inward through the pores of this type of graphite, thereby limiting the rate of diffusion of gaseous fission products. The 10^{-3} cm²/sec graphite in GAIL III-B has proved to be as effective in retaining fission products as the 10^{-5} cm²/sec graphite used in the GAIL III-A element tested previously.

The release of fission product gases from the fuel bodies increased with burnup at an approximately linear rate. At the end of the irradiation, the steady-state fractional release of a representative nuclide, 2.8 hr Kr⁸⁸, was 3×10^{-3} (fraction released/born). Other krypton, xenon, and iodine nuclides showed similar predictable increases in release with burnup and half life.

II. DESCRIPTION OF GAIL III-B FUEL ELEMENT ASSEMBLY

The GAIL III-B irradiation assembly was designed and fabricated as an integral in-pile vessel which contained the fuel element to be irradiated. A vacuum chamber within the GETR pool provides thermal isolation from the reactor pool water and positions the irradiation assembly adjacent to the reactor core. Flanged connectors in the upper region of the vacuum chamber are provided to connect the fuel assembly coolant pipes to the external loop system.

The pressure vessel containing the fuel element was constructed of Type 321 stainless steel and consisted of a 4-1/2 in. outside diameter seamless tube 0.100 in. thick, a hemispherical bottom cap, and a machined top head with nozzles for the attachment of coolant pipes and a penetration nozzle for instrumentation leads and two purge gas tubes.

The internal arrangement of the fuel element and flow baffles within the pressure vessel is shown in Fig. 2.1. The fuel element is supported on a stainless steel cup that is in turn supported by the outer stainless steel flow baffle. The complete internal baffle structure containing the fuel element is supported from the top head of the pressure vessel by the exit coolant tube.

Helium coolant enters at the top head and flows downward in the annular space between the outer baffle and the inside wall of the pressure vessel. At the bottom of the outer baffle the flow is turned upward; it then flows over the surface of the fuel element in the annular space between the inner baffle and the fuel element to remove heat generated by the fuel. A stagnant helium space between the inner and outer baffle, containing a concentric radiation shield, minimizes heat transfer to the inlet coolant stream.

The GAIL III-B fuel element is a graphite assembly having an overall length of about 43-3/8 in. and an outside diameter of 3-1/2 in.

The active fuel region, which is 22-1/2 in. long, is made up of 15 annular fuel compacts 1-1/2 in. long, 2-3/4 in. in outside diameter, and 1/2 in. thick radially. The fuel compacts were made by hot-pressing a graphite matrix containing approximately 30 vol-% of pyrolytic-carbon-coated (Th,U)C₂ particles of active fuel. The nearly spherical uncoated carbide particles ranged from 150 to 354 μ in diameter and contained

Fig. 2.1--GAIL III-B irradiation assembly

about 24% fully enriched uranium, 61% thorium, and 15% carbon. The average thickness of the pyrolytic carbon coating was 55μ . The total amount of U^{235} contained in the 15 compacts was 195 g, and the average Th/U ratio was about 2.5.*

A graphite spine extends the full length of the active fuel through the central hole in the annular fuel compacts. An acoustic cavity within the spine is caused to resonate at a frequency dependent upon the average helium temperature in the cavity by an acoustic signal transmitted to the cavity through a tubular wave guide. The acoustic cavity is positioned to measure the average temperature along a length from 7 to 17 in. above the bottom of the fuel column. Fuel element internal temperatures are also monitored by four tungsten-rhenium thermocouples located 15 in. above the bottom of the active fuel column. Two of the thermocouples are located on the inner surface of the annular fuel compact and two are located in the sleeve surrounding the fuel compacts near the inside surface.

The graphite sleeve surrounding the active fuel and the internal trap is 3-1/2 in. in outside diameter and 3/8 in. thick radially. The helium permeability of the sleeve and bottom connector assembly was $1.5 \times 10^{-3} \text{ cm}^2/\text{sec}$ at a mean pressure of 1/2 atm and room temperature.

A graphite top connector cemented into the sleeve forms the top closure of the fuel element. An impregnated graphite bottom connector brazed into the sleeve provides the bottom sleeve closure. A tight-fitting stainless steel tube extending into a bore within the bottom connector provides a passage for the purge gas to flow out of the fuel element and into a tube that carries the purge gas and collected fission products to the external loop trapping system.

Within the sleeve an internal trap immediately below the active fuel compacts contains silver-coated charcoal reagent. Condensable fission products carried by the purge gas stream are retained within the internal trap.

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* Details of preparation of the compacts, coated particles, and graphite components may be found in the following reports: W. V. Goeddel, G. R. Tully, Jr., and R. A. Meyer, The Use of Graphite in High-temperature Nuclear Fuel Elements, USAEC Report GA-2304, General Atomic Division, General Dynamics Corporation; September 15, 1961; W. V. Goeddel, The Development and Evaluation of Graphite-matrix Fuel Compacts for the HTGR, USAEC Report GA-2289, August 8, 1961; and W. V. Goeddel, Pyrolytic-carbon-coated Carbide Fuel Particles and their Use in Graphite-matrix Fuel Compacts, USAEC Report GA-3588, October 30, 1962; additional discussion of the coating method may be found in C. Luby, Apparatus and Procedure for Coating Thorium-Uranium Carbides with Carbon at 1000° to 1400°C, USAEC Report GA-2241, May 25, 1961.

III. IRRADIATION TEST

PRENUCLEAR PROCEDURE

Before the irradiation of the GAIL III-B fuel element in the GETR, many operations were performed in the reactor pool area and also in the GAIL facility. These major operations were as follows:

1. The GAIL loop was evacuated to a slight vacuum (approximately 5 in. of water).
2. The vacuum box shielding and cover were removed.
3. The GAIL III-B was inserted into the vacuum chamber (February 6, 1962).
4. The Marman Conoseal-type flanges of the experiment and of the out-of-pile loop were connected with a bolted coupling.
5. A mass spectrometer helium leak test was performed on the in-pool Marman flanges.
6. The GAIL III-B and the vacuum box thermocouple Cannon plugs were connected.
7. The vacuum box cover was installed and the shielding was replaced.
8. The complete loop was then evacuated and filled with helium.
9. The GAIL pumps, compressors, traps, heaters, coolers, instrumentation, and all other equipment necessary for loop operation were activated.
10. The flow and scram set-point tests were performed.

NUCLEAR OPERATION

Initial Operation

The nuclear operation of the GAIL III-B was started on February 19, 1962, with GETR criticality. During the first four weeks of nuclear operation (GETR Cycle 31) the experiment was operated at a reduced power of 25.5 and 50.7 kw, in order to obtain both heat transfer and fractional release data.

Abnormal difficulty in maintaining purge flow was encountered during the beginning of Cycle 31. The $\text{H}_2\text{O}-\text{CO}_2$ trap could only be operated for about 6 hr before it would plug up. The trap would then have to be isolated, heated up, and blown down. It was thought that the plugging was due either to the use of a helium cylinder with high moisture content or to the outgassing of the GAIL III-B assembly.

The Beckman hygrometer indicated only a slight amount (~ 6 ppm) of moisture. Gas chromatograph samples of the main loop helium indicated no impurities (oxygen, nitrogen, CO , CO_2 , or CH_4) greater than approximately 5 ppm. Finally, after the molecular sieve in the helium purification system had been replaced, the $\text{H}_2\text{O}-\text{CO}_2$ trap functioned normally and purge flow was maintained.

During the period of initial difficulty, the facility tube was retracted from the reactor and the cadmium shutter was in position between the two. The facility tube was moved into position during the following cycle (GETR Cycle 32) to bring GAIL III-B up to full normal power.

Lifetime Performance

The GAIL III-B performed in the GETR for 10,482 hr at full-power operation (i. e., with the GETR at a power of 27-Mw or higher). During this time the experiment was operated at an average power of 65.4 kw and accumulated burnup of 685 Mw-hr. This is equivalent to a burnup of 41,500 Mwd/tonne of total uranium and thorium. In addition, the GAIL III-B experienced approximately 193 reactor scrams and run downs. A summary of the incremental burnup and average power output of the GAIL III-B for each cycle is shown on Figure 3.1.

The only significant difficulty in operation that might be attributed directly to the GAIL III-B fuel element occurred on January 13, 1964, when there was an increase in purge flow accompanied by a drop in pressure across the fuel element sleeve. This operating difficulty is discussed in detail in "Purge Flow" on p. 19.

The GAIL III-B fuel and sleeve thermocouples, which were fabricated of tungsten and rhenium, failed before 225 Mw-hr of burnup were accumulated. Sleeve thermocouple TE-9 never functioned; fuel and sleeve thermocouples TE-5 and -10 failed during Cycle 37; and fuel thermocouple TE-6 failed during Cycle 39. All other thermocouples were operating until the GAIL III-B was removed from GETR.

In-pool data for the GAIL at various power levels of operation are given in Table 3.1.

Fig. 3.1--GAIL III-B operational hours versus accumulative megawatt hours:

Table 3.1

SUMMARY OF GAIL III-B TEST DATA AT VARIOUS POWER LEVELS

	Average Power Level 27.7 kw	Average Power Level 49.6 kw	Average Power Level 62.2 kw	Average Power Level 72.7 kw	Average Power Level 81.8 kw
Main loop flow, lb/min	3.75-3.98	4.18-4.32	3.86-4.26	4.02-4.38	4.65-4.88
Main loop pressure, psia	335	350	341	350	350
Thermal power gen., kw	25.5-30.3	48.9-50.7	46.6-65.3	71.1-75.4	79.8-82.6
Fuel temp., °F:					
TE-5, reactor side	1195-1395	1950-2000	1965-2420	2480-2627	2693-2758
TE-6, pool side	1117-1290	1745-1805	1820-2185	2247-2370	2417-2480
Sleeve temp., TE-10 (reactor side), °F	920-1030	1350-1400	1467-1757	1850-1975	2015-2068
Pool inlet gas temp., TE-20, °F	495	480	488-500	485-495	470
Facility tube inlet gas temp., TE-15, °F	488	477-484	471-510	484-501	474-482
Test section turnabout temp., TE-1, °F	532-545	543-550	515-615	589-604	571-591
Outlet test section temp., TE-16, °F	782-858	1004-1031	1116-1269	1271-1301	1242-1292
Transition temp., standoff, TE-62, °F	541-550	554-558	536-628	606-621	588-600
Internal trap temp., °F:					
TE-3, top	610-626	632-645	651-741	713-727	648-673
TE-4, bottom	572-582	589-598	582-664	628-643	600-612
Differential pressure, psia:					
Facility tube, DPR-1	4.6-5.0	6.1-6.6	6.3-7.0	6.5-7.7	8.0-9.0
Graphite sleeve, DPR-2	5.0-5.1	6.5-7.1	6.6-7.4	6.9-7.9	8.5-9.2

NOTE: These data were taken from specific thermal power instances during Cycles 31 and 32 and are not necessarily averages or typical data for other similar thermal power levels during the later cycles.

Heat Transfer

The average lifetime power output of the GAIL III-B was 65.4 kw and the peak power 87 kw. This peak power was obtained from a fairly uniform GETR neutron flux on May 9, 1962, prior to the failure of the two fuel compact thermocouples (TE-5 and 6).

A test was performed on February 28, 1962, under the following conditions to determine whether the GAIL III-B would overtemperature:

1. The GAIL facility tube was retracted and positioned behind the shutter;
2. The helium pressure was 350 psia;
3. There was no helium circulation in either the main loop or FPTs;
4. The power level of the GETR was 30 Mw; and
5. There was helium gas in the vacuum chamber.

After about 1-3/4 hr at these conditions the standoff temperature, TE-62, was at its maximum allowable limit and the test was terminated.

During Cycle 32 the vacuum chamber pump was removed from service to be overhauled. Over a period of about a week the vacuum in the vacuum chamber decayed from approximately 50 μ to 5.5 in. Hg. A comparison of the operating data at a vacuum of 5.5 in. Hg and 10 to 15 μ indicated that only about 10% more heat was transferred to the GETR pool water when the vacuum chamber contained gases at 5.5 in. Hg vacuum.

A typical average heat balance for the loop is shown in Fig. 3.2. It should be realized that the temperatures shown are an average over the entire irradiation period of various thermocouples around the loop and that the piping heat losses are not included. The heat-transferred values shown are, likewise, an approximate average over the entire irradiation period.

During the first week of a reactor cycle when the control rods had been withdrawn only 19 to 22 in., there was a sharp neutron flux peak in the lower fuel compacts of the GAIL III-B. Since the fuel thermocouples were located in the center of the fuel section of the vertical length, the actual fuel temperatures in this lower section had to be estimated. Initially, the helium coolant flow was adjusted to give lower than normal fuel temperatures (TE-5 and -6) during the period of peak flux. Later, when the fuel thermocouples had failed, a minimum helium coolant flow rate was established in order to ensure that design fuel element temperatures would not be exceeded during operation.

Fig. 3.2--Average heat balance diagram for GAIL III-B

Acoustic Thermometers

Because of the limited life of the thermocouples at fuel temperatures (approximately 2800°F), an acoustic type of thermometer was installed in the GAIL III-B. This device measures the resonant frequency of a cavity in the fuel element by means of an electro-acoustic transducer that supplies energy to a tube connected to the fuel element cavity. The frequency at resonance is proportional to the square root of the absolute temperature. The resonant chamber in the GAIL III-B fuel element was machined in the center graphite spine of the fuel compacts.

A plot of the acoustic thermometer temperature versus GAIL III-B thermal power at constant GETR rod bank is shown on Fig. 3.3. Also shown on the plot are fuel element thermocouples TE-5 and TE-6. With this addition, the plot indicates that the acoustic thermometer gives an average temperature between TE-5 and TE-6 within a very limited range of GAIL III-B thermal power.

The acoustic thermometer temperature for Cycle 41 and fuel temperature TE-5 for Cycle 35 versus GETR average control rod positions were plotted on Fig. 3.4. As the cycle progresses and the control rods are withdrawn with the facility tube position held constant, the fuel temperatures increase. This is a result of a flux shift that is due to the control rods being withdrawn from the reactor.

Helium Gas Coolant

Normally, Bureau of Mines reactor grade A helium was used for loop flushing, filling, and makeup. The analyses of the helium used in GAIL during the irradiation of GAIL III-B are shown in Table 3.2. On one occasion during Cycle 31, a supplementing source of reactor grade A helium had to be used for about two weeks in order to maintain the loop at operating pressure, because a bellows on a main loop helium valve failed, thus causing a large helium leak.

Makeup helium was normally added to the loop in batches through the gas purification system. Occasionally, when the leak rate was high due to abnormal conditions, such as a failure of a valve bellows, the helium was added continuously to the loop through the purification system.

Throughout the irradiation period of GAIL III-B, the helium gas was periodically analyzed with a gas chromatograph that could detect gas impurities as low as approximately 1 ppm oxygen or nitrogen and approximately 5 ppm CO or CO₂. All reasonable precautions were taken to prevent prolonged exposure of the fuel to helium impurity concentrations greater than 10 ppm nitrogen, 10 ppm oxygen, 100 ppm CO, 100 ppm CO₂, and 10 ppm H₂O.

Fig. 3.3--Acoustic thermometer temperature versus GAIL III-B thermal power at a constant GETR rod bank (21.0 to 22.0 in. rod bank)

Fig. 3.4--Acoustic thermometer temperature versus rod position; cycle 41;
GAIL facility tube 9-5/8 in. from pressure vessel; average GAIL power 57.8 kw

Table 3.2
ANALYSIS OF BUREAU OF MINES GRADE A HELIUM

Cylinder Analyzed	Impurities* (ppm)								Total Impurities
	H ₂	H ₂ O	Ne	N ₂	O ₂	A	CO ₂	CH ₄	
107176	0.1	0.7	10.6	0.2	0.1	Tr*	Tr*		11.7
107931	0.1	0.4	23.3	3.9	0.9	Tr	0.2		28.8
190718	0.0	4.0	11.4	3.2	0.8	Tr	0.2		19.6
106306	0.1	0.4	4.5	3.2	0.9	Tr	Tr		9.1
108324	Tr	0.8	9.9	2.3	0.3	Tr	0.0		13.3
101546	0.1	0.2	7.8	0.8	0.2	Tr	0.0		9.1
102073	0.0	0.2	12.4	2.7	0.6	Tr	Tr		15.9
103646	Tr	8.4	8.0	0.3	0.1	Tr	0.2	Tr	17.0
248930	1.8	1.6	12.2	0.2	0.1	0.0	Tr	0.0	15.9
248433	0.1	0.7	12.1	13.8	0.3	Tr	Tr	0.1	27.1
No Analysis									
142175	Tr	0.4	10.1	1.1	0.1	Tr	Tr	0.0	11.7
251685	0.0	0.5	8.9	Tr	0.0	0.0	Tr	0.0	9.4
100125	0.0	2.5	9.6	2.3	0.7	Tr	Tr	0.0	15.1
106396	0.0	0.8	14.8	0.5	0.1	0.0	0.0	0.0	16.2
H-121955	0.0	0.5	14.8	0.3	0.0	5.4	0.1	0.0	21.1
H-135012	0.0	0.7	13.8	2.0	0.2	0.0	Tr	0.0	10.9
H-163834	0.0	0.4	12.8	4.7	0.1	0.0	Tr	0.0	18.0
J-184528	1.9	1.2	12.9	1.1	0.3	0.1	Tr	0.0	17.5
H-141557	Tr	0.4	14.1	3.0	0.6	Tr	Tr	0.0	18.1
No Analysis									
H-140628	0.0	0.4	13.2	0.5	0.2	0.3	Tr	0.0	14.6
142509	0.0	2.4	14.0	1.2	0.3	0.0	0.1	0.0	18.0
Average	0.2	1.3	12.0	2.3	0.3	0.3	0.04	0.0	16.1

* Trace, Tr, less than 0.05 ppm.

The main loop helium was continuously monitored for moisture by passing a side stream through a hygrometer that could detect moisture down to about 0.05 ppm of water. Daily readings of the moisture level in the loop helium indicated an average concentration of 0.15 to 0.25 ppm water during normal operation.

After scheduled shutdowns when the loop was depressurized and major maintenance performed, the loop was evacuated and back filled with helium at least three times. Gas chromatograph samples taken, after the helium was circulated to ensure mixing, would indicate about 25 to 50 ppm nitrogen, 5 to 10 ppm oxygen, and a moisture content as high as 2 ppm. These residual impurities were removed before reactor startup by activating the liquid-nitrogen cooled traps in the fission product trapping system.

The helium makeup to the loop (or leak rate) averaged about 1 vol-%/day during normal operation. After the failure of a valve bellows the helium makeup rate (or leak rate) has been as high as 400 vol-%. No effort was made to reduce leakage below 1%, because it was not practical.

Radiation

During normal operation of the loop there were no extreme radiation safety hazards. The auxiliary containment and pump room cubicles could be entered without masks. Personnel dressed in protective clothing and fresh air masks have entered the main cubicle on various occasions while the GAIL was at full power. Some difficulties with activity occurred in the pump room whenever the purge flow was significantly decreased. This activity was attributed to leaks from the stuffing box of the stack gas blower.

When the main loop piping was cut into for maintenance or modification, the major source of radiation was the tantalum oxide circulating in the loop. The tantalum oxide was deposited in the loop before the installation of GAIL III-B. This particulate activity tended to adhere to the inside of the loop piping, and when the piping was knocked with a hammer, the particulates would come loose. At low gas velocities the particulates tended to accumulate in the bends of the pipe, but when normal gas circulation was again established, the particulate activity would be more evenly distributed in the piping.

Circulators

The DeHavilland circulator, GBC-1002, which is located in the inboard position close to the reactor, operated very satisfactorily throughout the irradiation of GAIL III-B. It accumulated about 12,375 hr of

operation, during which time it was cycled on and off approximately 90 times.

The Turbocraft circulator initially located in the outboard position never operated successfully for more than about 500 hr. Early in 1963, after a bearing failure, inspection revealed that its shaft was bent and the impeller was touching the housing. Major repair of this unit necessitated its removal from the loop. On February 25, 1963, it was removed and DeHavilland circulator GBC-1001 was installed in the outboard position. This unit has accumulated approximately 3642 hr of operation and approximately 30 starts and stops.

Purge Flow

Normally a helium purge flow rate of about 0.7 lb/hr was maintained through the GAIL III-B element. The available pressure head for purge flow was controlled by throttling a main loop block valve. However, when GAIL III-B was operated at high power levels, approximately 80 kw, insufficient head was available to obtain the desired 0.7 lb/hr purge flow. The purge flow rate was measured by means of an extended orifice (designated FE-4) which was located downstream of the liquid-nitrogen-cooled charcoal trap.

Purge flow was interrupted occasionally owing to moisture plugging in the liquid nitrogen cooled traps to failure of a block valve, and, possibly, to plugging in the FE-4 orifice. The purge flow could be decreased to about 0.4 to 0.5 lb/hr without any noticeable activity increase in the main loop gas as indicated on the radiation monitors.

If the purge flow was stopped, the gross activity in the main loop would increase to an equilibrium activity level in ~12 hr. The gross activity of the main loop under these conditions would be about the same as the purge stream gross activity before the cessation of purge flow. If an external cleanup system was initiated with the above zero purge condition, the main loop activity would be reduced by less than 10%.

On January 13, 1964, for no apparent reason, the purge flow increased from 0.7 lb/hr to 1.1 lb/hr, and the pressure drop across the fuel element sleeve decreased from 7.6 psi to 2.4 psi. Immediately after these indications the main loop gross activity began to rise as if there were no purge flow. Flow tests were conducted to pinpoint the difficulty, and these indicated a failure within the facility tube in an inaccessible location. This difficulty with the purge flow continued for the remainder of the irradiation of the GAIL III-B.

Thermal Power Adjustments

The thermal power of GAIL III-B was adjusted by moving the facility tube with a jacking mechanism. Until Cycle 45 the reactor missile shield had to be moved and the reactor power reduced to 50 kw in order to get at the jacking mechanism. Reactor operating personnel were reluctant to move the GAIL facility tube under these conditions. During Cycle 45, however, the jacking mechanism was successfully modified in order that it could be operated remotely.

A thermal power of 70 kw was first achieved with GAIL III-B on March 30, 1962, with the facility tube approximately $9\frac{1}{16}$ in. away from the reactor pressure vessel. It should also be noted that at that date an increase of approximately 25% in power could be obtained for each $\frac{3}{8}$ -in. movement of the facility tube.

During the last cycle of irradiation, GAIL III-B had to be moved to within $\frac{5}{16}$ in. of the reactor pressure vessel to achieve 70 kw. At high GAIL III-B burnup during the last cycle of operation, each $\frac{3}{8}$ -in. move of the facility tube increased the power by only 10%.

PLATEOUT STUDIES

Since the GAIL III-B fuel element was a type in which a fraction of the fission products could diffuse into the coolant stream, the plateout of the solid daughter elements in the main loop piping was of interest.

During the irradiation, plateout sleeves, cold fingers, and bypass traps were installed in the GAIL facility to study plateout. In addition, the piping, valves, and fittings removed from the loop were labeled and transported to the General Atomic chemistry laboratory.

Plateout sleeves were placed inside the Marman flanges in both the hot and the cold coolant gas lines located in the vacuum box. Different pairs of plateout sleeves were in place during reactor cycles 34, 35-37, 38-40, 41-44, and 45-52.

Cold fingers were installed immediately upstream of the regenerative heat exchanger and immediately downstream of the main cooler. Cold fingers were exposed to main coolant gas for one to three cycles. The number exposed are given in Table 3.3.

Table 3.3
COLD FINGERS EXPOSED

Identification Number	Cycles Exposed	Location
45-46-01	45-46	Downstream of cooler
47-48-01	47-48	Upstream of exchanger
47-48-02	47-48	Downstream of cooler
49-51-01	49-51	Upstream of exchanger
49-51-02	49-51	Downstream of cooler
52-52-06	52	Upstream of exchanger
52-52-07	52	Downstream of cooler

Bypass traps for plateout study were coupled into the main coolant piping at locations upstream and downstream of the main cooler and downstream of the helium circulator. The Number One charcoal trap was redesigned and replaced with provisions for installing other test traps in parallel with the permanent trap.

The plateout specimens are being analyzed as part of the postirradiation studies on this experiment.

REMOVAL OF EXPERIMENT

On March 18, 1964, the GAIL III-B assembly was disconnected from the in-pile loop (instrumentation and piping) and moved into the GETR canal to await packaging and shipment to General Atomic. The major operations performed after the GAIL facility was shut down preparatory to shipment of the GAIL III-B fuel element are as follows:

1. The GAIL facility was depressurized and evacuated to a vacuum of 5 in. of water.
2. The GAIL III-B Marman couplings were disassembled, the flanges separated, and the plateout sleeves removed.
3. Turn Tite or Snap Tite rubber plugs were inserted and secured in the hot, cold, and tempering line flanges.
4. The Marman flanges were removed from the purge and bypass lines and Swagelock caps were secured on the open ends.
5. The acoustic transducer line was cut, pinched, and sealed with silver solder.
6. The thermocouple Cannon plugs were disconnected in the vacuum box.

7. A water gate and half cover was installed to secure the vacuum box. It was pressurized to approximately 10 psig with nitrogen.
8. The reactor pool water level was raised to the canal level.
9. The water gates between the reactor pool and the canal were removed.
10. While the pool level was being raised, the GAIL III-B pipes and tube ends were maintained above the reactor water level.
11. The GAIL III-B was moved into the canal and secured.
12. A preliminary fuel element growth measurement test was performed by inserting a specially modified flexible cable down the hot gas line. It appeared that the expansion space above the fuel compacts and graphite specimens had decreased by 0.3 in.
13. Sonic measurements were made in order to determine the volume characteristics of the cavity. It appeared there were two cavities instead of one.
14. Fuel length measurements were also attempted by sliding a 1/4-in. -thick glass cylinder over the fuel section. The glass tube was irradiated for 1/2 hr. No measurements could be made owing to the high gamma scatter at the ends of the pipe.
15. The GAIL III-B tubing was sealed by pumping in sufficient EPON resin to just seal the tubing. Sufficient resin was then added to fill the tubing above the saw cut location.
16. The pipes were sealed by dropping steel balls coated with Sea Jay resin into the pipes. After the Sea Jay had cured, EPON resin was poured down each pipe to seal just above saw cut. Later, when the resin had hardened, additional EPON was added to each pipe to fill it.
17. GAIL III-B was then lowered into a jig and the pipes were cut under water with a reciprocating saw driven by an airmotor.
18. The shipping cask was lowered into the water, and the fuel section of GAIL III-B assembly was loaded into the shipping cask.

IV. THERMAL PERFORMANCE

Thermal analyses of the GAIL III-B fuel element were made in order to better understand its performance.

The temperature of the GAIL element was found to be a function of both the power output of the element and the control rod setting in the GETR core. As the control rods of the GETR core are lowered, the hot spot in the GAIL element tends to be lower. Therefore, it was found necessary to make the thermal analysis of the element at several control rod positions. The calculations were checked against the GAIL thermocouple readings which were observed at four GETR control rod positions. A more complete analysis was then made of temperatures over the entire GAIL fuel element for five control rod positions. The results included in this report show the temperature distribution of GAIL fuel element compacts and sleeve surface.

The temperature profiles across the diameter of the fuel element at the location of the thermocouples are shown in Figs. 4.1 through 4.4 for four GETR control rod positions. The agreement between the analytical method and the measured temperatures can be observed in these plots. For reference, the axial profile of the thermal neutron flux in the GETR pool is shown as a function of control rod position in Fig. 4.5. There is also a strong radial neutron gradient from the side of the GAIL adjacent to the GETR core to the side away from the core, as shown on Fig. 4.6. This gradient causes the high difference in temperature from one side of the element to the other.

Axial plots of the fuel compact temperature at the hot side and the cold side of the element are presented in Figs. 4.7 through 4.11 for five different control rod settings. In each of these cases the temperature is plotted for fuel element powers of both 70 and 75 kw. Axial plots of the fuel element surface temperature and coolant temperature are given in Figs. 4.12 through 4.16 for the same five control rod settings. Again, the maximum and minimum temperature designations refer to the hot side and cold side of the fuel element.

Finally, calculations were made of the percentages of fuel material at different temperatures. These curves are given in Figs. 4.17 and 4.18 for fuel element power levels of 70 and 75 kw, respectively.

Fig. 4.1--Radial temperature distribution; axis of fuel element normal to core;
 $h = 198.0 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$

Fig. 4.2--Radial temperature distribution; axis of fuel element normal to core;
 $h = 205.0 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$

Fig. 4.3--Radial temperature distribution; axis of fuel element normal to core;
 $h = 261.0 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$

Fig. 4.4--Radial temperature distribution; axis of fuel element normal to core;
 $h = 226.0 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$

Fig. 4.5--Axial flux shape at GAIL III-B
fuel element as a function of
control rod position.

Fig. 4.6 --Circumferential flux distribution in GAIL III-B fuel element

Fig. 4.7--Maximum and minimum fuel temperature distribution; estimated performance for control rod height of 17 in.

Fig. 4.8--Maximum and minimum fuel temperature distribution;
control rod height 21.4 in.; cycle 32

Fig. 4.9--Maximum and minimum fuel temperature distribution; control rod height 24.1 in.; cycle 35

Fig. 4-10--Maximum and minimum fuel temperature distribution;
control rod height 26.8 in.; cycle 32

Fig. 4.11--Maximum and minimum fuel temperature distribution;
control rod height 30.7 in.; cycle 33

Fig. 4.12--Maximum and minimum surface temperature distribution; control rod height 17 in.; estimated performance

Fig. 4.13--Maximum and minimum surface temperature distribution; control rod height 21.4 in.; cycle 32

Fig. 4.14--Maximum and minimum surface temperature distribution; control rod height 24.1 in.; cycle 35

Fig. 4, 15--Maximum and minimum surface temperature distribution;
control rod height 26.8 in.; cycle 32

Fig. 4.16--Maximum and minimum surface temperature distribution; control rod height 30.7 in.; cycle 33

Fig. 4.17--Fuel temperature distribution for various control rod positions;
GAIL power 70 kw

Fig. 4.18--Fuel temperature distribution for various control rod positions;
GAIL power 75 kw.

V. RADIOCHEMISTRY STUDIES

RELEASE FRACTIONS AND CALIBRATION

During the course of the GAIL III-B irradiation, routine and special test gas samples were taken from the main coolant and from the element purge stream for fission product release studies.

The routine samples were taken into glass vials (2.7 cm^3 from purge stream and 630 cm^3 from the main coolant) at atmospheric pressure and analyzed at the loop site by gamma spectrometry. A 256-channel nuclear-data analyzer was used, employing a 3-in NaI(Tl) detector.

The counting efficiencies used were obtained from a TRIGA reactor irradiation of normal uranium stearate which is known to release completely the noble gas isotopes of interest here.* The gas samples taken from this calibration test were counted under physical conditions identical with those at the test site, thus allowing a direct comparison of GAIL data with a "standard." The GAIL gas samples were taken only after the system had reached steady-state conditions. The following gamma photopeaks were used in determining their associated nuclides: 80 kev (Xe^{133}), 150 kev ($\text{Kr}^{85\text{m}}$), 191 kev (Kr^{88}), 250 kev (Xe^{135}), and 403 kev (Kr^{87}). Kr^{89} and Xe^{138} were determined through their daughter-product photopeaks-- 1.05 Mev (Rb^{89}) and 1.43 Mev (Cs^{138}).

Purge stream specific activities were used in conjunction with purge flow rate and element fission power to determine the release fraction of the noble gas fission products; the results are presented in Figs. 5.1 through 5.7 logarithmically to best indicate the initial rise in release. The shaded circles in Figs. 5.1 through 5.14 represent data points taken when all instruments functioned normally and with full purge flow. The open circles represent data points taken after the scintillation detector crystal had lost sensitivity. The half-shaded points indicate the range in release observed during one complete reactor cycle, when the change in flux profile caused a change in fuel temperatures. The cross-hatched circles show the release observed during the time the fuel element was not being purged. In the latter case, the release fractions were calculated from activities measured in the main coolant gas. The release fraction was

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* A. C. Wahl, "Nuclear Charge Distribution in Fission: Cumulative Yields of short-lived Krypton and Xenon Isotopes from Thermal-Neutron Fission of U^{235} ," J. Inorg. Nuclear Chem., 6, pp. 263-277 (1958).

Fig. 5.1-- $\text{Kr}^{85\text{m}}$ release fraction (logarithmic scale) versus accumulated burnup

Fig. 5.2-- Kr^{87} release fraction (logarithmic scale) versus accumulated burnup

Fig. 5.3-- Kr^{88} release fraction (logarithmic scale)
versus accumulated burnup

Fig. 5.4-- Kr^{89} release fraction (logarithmic scale)
versus accumulated burnup

Fig. 5.5-- Xe^{133} release fraction (logarithmic scale) versus accumulated burnup

Fig. 5.6-- Xe^{135} release fraction (logarithmic scale)
versus accumulated burnup

Fig. 5.7-- Xe^{138} release fraction (logarithmic scale)
versus accumulated burnup

Fig. 5.8-- $\text{Kr}^{85\text{m}}$ release fraction (linear scale)
versus accumulated burnup

Fig. 5.9-- Kr^{87} release fraction (linear scale)
versus accumulated burnup

Fig. 5.10-- Kr^{88} release fraction (linear scale)
versus accumulated burnup

Fig. 5.11-- Kr^{89} release fraction (linear scale)
versus accumulated burnup

Fig. 5.12-- Xe^{133} release fraction (linear scale)
versus accumulated burnup

Fig. 5.13-- Xe^{135} release fraction (linear scale)
versus accumulated burnup

Fig. 5.14-- Xe^{138} release fraction (linear scale)
versus accumulated burnup

initially in the 10^{-6} to 10^{-5} range with an increase of about two orders of magnitude during the first hundred megawatt-hours of operation. The remainder of the irradiation (approximately 600 Mw-hr) resulted in a further increase in release fraction of less than one order of magnitude. The latter part of the irradiation release results are best shown in Figs. 5.8 through 5.14 on a linear scale. These figures tend to indicate that the release of noble gas fission products is initially logarithmic but quickly levels off to a very small linear increase with time. All of the isotopes analyzed showed a release fraction of less than 10^{-2} at the completion of the experiment.

The data points shown on Figs. 5.1 through 5.14 as open circles are results obtained with a scintillation detector that had an unnoticed gradual loss of resolution. The data most affected by this phenomenon are the Kr⁸⁸ results. This is as might be expected, because the 191-keV photopeak used is sandwiched closely between two other photopeaks. The one least affected is Xe¹³³ with its 80-keV photopeak, which is counted free of any other isotopes.

There is some scattering of data points apparent in these graphs owing to differences in GETR control rod positions (therefore a difference in flux profile and GAIL temperature). The data are at operating temperature. This is best illustrated by the half-shaded circles in Figs. 5.1 through 5.14, which show a complete cycle variation.

The data points for Xe¹³³ (see Fig. 5.12) indicate a sudden upward trend after about 500 Mw-hr of operation. This effect has not been observed in the other isotope release curves. The observation seems to be spurious and related to a relocation of the scintillation detector and its associated lead shielding within the GETR containment. The Xe¹³³ counting was probably affected by moving the lead shielding. Since the Xe¹³³ is determined from its 80-keV photopeak (which is very close to the energy of X-rays produced by excitation of lead by gamma ray bombardment), any increase in higher gamma ray background in the reactor containment building could have increased the amount of lead X-ray background and the apparent Xe¹³³ activity.

SHORT-LIVED ISOTOPE RELEASE

Since the first delay bed fission product trap will receive most of its load from the short-lived isotopes and since the isotopes mentioned above are longer lived, another method was employed to determine the release values of the shorter lived isotopes.

A five-hour normal-flow-purge gas sample was collected on a room-temperature charcoal delay bed with the experiment operating under

full-power steady-state conditions. This sample was then allowed to decay to the long-lived daughter product activities. By radiochemical methods the amounts of Sr^{89} , Sr^{90} , Cs^{137} , and Ba^{140} present on the trap were determined. From these daughter-product activities and from the experiment fission power at that time, the release fractions were calculated for Kr^{89} , Kr^{90} , Xe^{137} , and Xe^{140} with very good results. Figure 5.15, which shows release fraction versus half life, presents these results together with the results for the longer-lived isotopes determined at an equivalent time. These data points show a square root of half-life relationship, as would be expected if the release of noble gas fission products follows Fick's law of diffusion.

The difference in the Kr^{89} results shown from the different methods can be explained as being due to the difficulties in accurately separating the 1.05-Mev Rb^{89} photopeak from a multicomponent photopeak, usually resulting in high values. The low Kr^{88} results can be similarly explained, with the values usually being low. The high value for Xe^{137} can probably best be explained as due to cesium transport on dust.

IODINE RELEASE

During the lifetime of the GAIL III-B irradiation, two tests were performed to determine the amount of iodine released from the fuel. Iodine-133 and I^{135} were determined through the analysis of their daughter products Xe^{133} and Xe^{135} . This could only be done following a reactor shutdown in order to eliminate the activity contributed by the direct release of xenon. The results of these analyses are shown in Fig. 5.16, which also shows the xenon release curves taken from Figs. 5.12 and 5.13.

The results of the first analysis tend to indicate that I^{135} release accounts for essentially all of the Xe^{135} activity in the purge gas, and I^{133} accounts for about half of the Xe^{133} activity. (This would seem to explain the high Xe^{133} value shown in Fig. 5.15.)

In the second analysis an attempt was made to determine the fractions of iodine deposited in the purge grooves and the internal trap. To do this, alternate samples were taken through the internal trap and through the trap bypass with the expectation that the difference in specific activities of the samples would indicate the fraction of iodine that was in the purge grooves. The results, however, were inconclusive, since the data showed the bypass samples with a higher specific activity than the internal trap samples.

It should be noted that since the iodine results are obtained from xenon analyses, the background effect discussed previously also applies to this data, and the I^{133} data at 540 Mw-hr is probably too high.

Fig. 5.15--Release fraction versus half life at ~575 Mw-hr

Fig. 5.16--Iodine release fraction versus burnup

KRYPTON-85 RELEASE

In order to extend the release data upward past the Xe^{133} (5.28-day) half life, attempts have been made to determine the amount of Kr^{85} release from the GAIL III-B fuel element. The results obtained have been very scattered; however, the best data seem to indicate a release fraction of about 16% after about 400 Mw-hr of operation.

GRAPHITE SLEEVE EFFECTIVE PERMEABILITY (K_{eff})

During the course of the experiment, routine samplings were made from both the purge stream and the main coolant stream for the purpose of evaluating the permeability of the graphite sleeve. Figures 5.17 and 5.18 show the results of these determinations to be about $10^{-5} \text{ cm}^2/\text{sec}$ for Kr and $4 \times 10^{-5} \text{ cm}^2/\text{sec}$ for Xe, with no indication of any significant increase in effective permeability throughout the life of the irradiation. The longer-lived isotopes indicate an occasional deviation from the average with a high calculated K_{eff} value. This can be explained as being due to an occasional contamination of the main coolant gas by activity released from the liquid-nitrogen-cooled charcoal trap, which had inadvertently been allowed to warm slightly.

NO-PURGE FLOW TEST

Early in the life of the GAIL III-B test (at 71 Mw-hr) a no-purge flow test was conducted in order to determine the rate of buildup and the final equilibrium activity level in the main coolant gas in the event of purge system failure. This test was conducted for about 15 hr with no flow sweeping the fuel bodies and with the fission product trapping system isolated.

Owing to the geometry of the element, very little, if any, holdup due to the sleeve is expected under these conditions. It was found that the main loop activity increased by a factor of about 15 within 30 min and by a factor of about 100 within 90 min. Thereafter, a gradual increase was noted until apparent equilibrium was reached in about 12 hr. The isotopes analyzed were all in good agreement (see Fig. 5.19).

Calculation of release fraction values from the no-purge flow test data yields numbers in fairly good agreement with those obtained from previous purge stream samples (see Table 5.1).

Fig. 5.17--Effective sleeve permeability for krypton

Fig. 5.18--Effective sleeve permeability for xenon

Fig. 5, 19--Krypton and xenon build up in main loop during no-purge flow test

Table 5.1
CALCULATED RELEASE FRACTION VALUES

Isotope	Release Fraction	
	No-purge Flow Test	Purge Gas Prior to Test
Kr ^{85m}	1.3×10^{-3}	1.9×10^{-3}
Kr ⁸⁷	5.7×10^{-4}	7.7×10^{-4}
Kr ⁸⁸	3.3×10^{-4}	6.1×10^{-4}
Xe ¹³⁵	2.9×10^{-4}	6.0×10^{-4}

The activity buildup in various places throughout the loop was also monitored using prepositioned ion chambers. The results of this analysis are shown in Fig. 5.20 with the circulator and heater showing the largest increase in activity.

Fig. 5.20--Radiation monitor readings during no-purge flow test