GULF GENERAL ATOMIC

VOLATILE FISSION-PRODUCT MIGRATION AND PLATEOUT IN GCFR FUEL-ROD IRRADIATIONS*

by

S. Langer, N. L. Baldwin, R. J. Campana, J. R. Lindgren
Gulf General Atomic Company

and

R. Bono, G. Hayner, L. Neimark, R. V. Strain
Argonne National Laboratory

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

A summary of this paper was presented at the American Nuclear Society Meeting held at Washington, D. C., on November 12-17, 1972, and is to be published in the Transactions.

*Work supported by the U.S. Atomic Energy Commission under Contract AT(04-3)-167, Project Agreement 23.

November 8, 1972

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

MASTER

PM

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

4

4

4

ABSTRACT

The migration, plateout, and distribution of fission products in two GCFR fuel-rod irradiations have been studied by gamma spectrometry. Data were obtained during postirradiation examination of the GCFR vented fuel-rod GB-9, which was irradiated to a burnup of 54,000 MWd/Te in the thermal flux of the Oak Ridge Research Reactor, and during the interim examination of three of the seven sealed fuel rods in the GCFR F-1 (X094) assembly, which are being irradiated to burnups of 28,000 to 100,000 MWd/Te in the fast flux of the EBR-II reactor.

The nonvolatile fission products were uniformly distributed throughout the fuel in both experiments. However, the volatile species migrated as vapor species from the hot regions of the fuel and plated out at the fuel-blanket interfaces, where the temperatures drop sharply. Transport of the volatile fission products into the blanket portion of the fuel rod in the pellet-cladding annulus did not occur in the GB-9 irradiation.

The charcoal trap located adjacent to the insulator pellet in the GB-9 fuel rod and in the plenum of one of the F-1 fuel rods showed no measurable activity, indicating that the fuel and blanket were quite effective in retaining volatile fission products.

INTRODUCTION

The Gas-Cooled Fast Breeder Reactor (GCFR), which is being designed and developed by Gulf General Atomic with the support of the U.S. Atomic Energy Commission and a large section (35%) of the electric utility industry in the U.S., is specifically designed to totally vent the fission gases from the fuel rods.⁽¹⁾ The gases are collected and stored in shielded adsorption beds that are located in the prestressed concrete reactor vessel (PCRVR). By venting the fission gases from the reactor core, several problems associated with the use of sealed fuel rods (e.g., creep collapse of the cladding and the buildup of fission-gas pressure) are avoided and, in addition, significant advantages accrue. The design and operation of the venting system, called the pressure equalization system (PES), its advantages, and the required development effort have been described by Campana.⁽²⁾

The gaseous fission products either decay in the element or are transported through the PES to the adsorption beds. The PES must also deal with the possibility that volatile, condensable, fission products may migrate along the piping of the PES. Although it is unlikely that volatile fission products will transport very far from the fuel region, an activated charcoal trap is included in the upper portion of each fuel rod to retain essentially permanently and quantitatively any volatile fission products that reach the trap. This design of the fuel rod ensures that significant quantities of volatile fission products will not migrate beyond the fuel-rod charcoal trap and enter the PES piping where they could plate out and possibly lead to plugging of the passages.* Rather strong evidence against the occurrence of plugging exists in the fact that Peach Bottom Atomic Power Station Unit No. 1 has 804 interconnected purged fuel elements that operated for 452 equivalent full-power days (EFPD) without any evidence of decreased purge

*To further minimize this possibility, each fuel rod is connected to the storage system through at least two redundant routes.

flow rate.⁽³⁾ And even though cesium was detected in the charcoal traps of the elements examined, the quantity was small. This is in agreement with the predictions of the calculation codes FREVAP and SLIDER developed to predict the transport behavior of fission products in High-Temperature Gas-Cooled Reactors.^(4,5) Nevertheless, it was clear that additional data on the transport of condensable fission products in the fuel and blanket regions of the rods and associated PES components was required in order to establish the feasibility of the vented-fuel concept and the pressure equalization system for the GCFR.

The purpose of this paper is to report the results of studies of volatile fission-product migration in two recent GCFR irradiation experiments and, further, to assess the implication of these results on the design of the pressure equalization system of the GCFR.

Although the experimental designs and irradiation conditions of the two experiments were significantly different, the migration behavior observed was remarkably similar. In the first experiment, the GCFR GB-9 capsule was irradiated to 54,000 MWd/Te at 700°C mid-cladding temperature at 500 W/cm (15 kW/ft) in the thermal flux of the Oak Ridge Research Reactor (ORR). The principal features of the GB-9 experiment are shown in Fig. 1.⁽⁶⁾ The GB-9 experiment was unique in that it was a vented fuel rod in which the release of fission gases from (1) the fuel and blanket regions (i.e., the fission gases arriving at the charcoal trap) and (2) the complete rod (i.e., the fission gases effluent from the charcoal trap) could be monitored. The results obtained during the operation of this capsule have been reported previously.^(7,8) (A subsequent experiment, GB-10, which is now being irradiated in the ORR, permits sampling of the effluent gaseous fission products directly from the fuel, blanket, and trap regions of the rod and also permits direct sweeping of the fuel.⁽⁹⁾)

The second experiment is the GCFR fast-flux irradiation F-1 (X094) in EBR-II. This is an assembly of seven sealed and encapsulated fuel rods being irradiated to burnups of 28,000 to 100,000 MWd/Te. At present, the assembly has attained a burnup of ~46,000 MWd/Te. Summarized here are the studies carried out on two of the rods, G-1 and G-4, during the interim

Fig. 1 GCFR fuel-rod specimen in capsule GB-9 for irradiation in ORR poolside facility

examination at a burnup of 28,000 MWd/Te, and during the postirradiation examination (PIE) of rod G-3, which was removed from the assembly at that time.

A schematic of the design of the rods in the F-1 experiment is shown in Fig. 2.⁽¹⁰⁾ In addition to their being smaller in diameter than the GB-9 rod, several of the rods contain charcoal traps in the upper portion of the rod. These traps are designed to act as a sink for volatile fission products. At the operating temperature of $\sim 300^{\circ}\text{C}$, the charcoal will retain sorbed species, such as cesium and iodine, essentially indefinitely.

GB-9 THERMAL IRRADIATION

Irradiation of capsule GB-9 was terminated after a burnup of 54,000 MWd/Te was reached. After completion of preliminary gamma scanning, neutron radiography, NaK removal, and removal of the secondary containment at the Oak Ridge National Laboratory Hot Cell, the fuel rod and the inlet and outlet gas lines were shipped to Argonne National Laboratory (ANL) for the remainder of the postirradiation examination.

The postirradiation gamma spectra were recorded using a lithium-drifted germanium detector with a resolution of 1 keV/channel and a 2048 channel analyzer. The initial incremental gamma spectra were obtained 21 days after termination of the irradiation at 1/4-in. intervals at 0° (hot side) and 180° (cold side) from the rod orientation facing the core center of the ORR. The objective of these scans was to determine whether there was a preferential deposition of fission products due either to the lower temperature (on the cold side) or to the higher flux (on the hot side). No differences in the levels of activity of the various fission products were detected. However, electron microprobe analysis during PIE did show the expected radial burnup decrease across the rod.

The 0° gamma scan was repeated 48 days and 71 days after termination of irradiation in an effort to improve the resolution of the spectra of the longer-lived species as the short-lived activities decayed away. Additionally, the 71-day scan was done at 1/8-in. intervals to improve resolution of the shape of the profiles. The gamma spectra were recorded on punched

paper or magnetic tape at ANL and the tapes sent to GGA for analysis on the XDS Sigma II computer-analyzer system.

The 21-day and 71-day gamma scans for the 0° orientation were analyzed for the nonvolatile nuclides Ce^{141} and $\text{Ba}^{140}/\text{La}^{140}$ and for the volatile nuclides I^{131} , Cs^{134} , and Cs^{137} . The activity profiles for the nonvolatile species are shown in Figs. 3 and 4; as expected, the profiles for both Ce^{141} and $\text{Ba}^{140}/\text{La}^{140}$ are flat in the fuel region but there are precipitous drops in activity at the interfaces between the fuel and the (depleted) UO_2 blanket. The profiles in the blanket, which are generated by fission of bred plutonium and fast fission of U^{238} , are also flat and close to zero, indicating no migration of these fission products.

The volatile species I^{131} , Cs^{134} , and Cs^{137} exhibited a slightly different behavior. The 21-day and 48-day gamma scans for I^{131} are shown in Fig. 5. These data emphasize the need for prompt examination of the capsule in order to detect the rapidly decaying iodine activity ($T_{1/2} = 8.05$ d). The Cs^{134} and Cs^{137} profiles are similar to that of I^{131} but exhibit more scatter due to the long half-lives (and consequently lower disintegration rates) and the high background activity. However, the 71-day gamma scans for Cs^{134} (Fig. 6) and Cs^{137} (Fig. 7) emphasize the precision with which the data can be obtained and the sharpness of the activity peaks. The observed activity peaking of the volatile species is most likely due to the sharp temperature drops at the interfaces. The more intense peak at the lower fuel-blanket interface can probably be attributed to the lower temperature at that interface relative to that at the upper fuel-blanket interface.

The charcoal trap located adjacent to the upper blanket pellets showed no measurable activity, indicating that the fuel and blanket were quite effective in retaining the volatile fission products. It is possible, however, that small amounts of Cs^{134} or Cs^{137} might be present in the trap and yet remain undetected in these gamma scans. Chemical analysis of the charcoal is planned to determine if stable volatile fission products were deposited in the trap.

Metallographic examination of the GB-9 fuel rod revealed the presence of two constrictions in the central hole.* Both of these constrictions

*Fuel-bearing pellets were annular cylinders and the blanket pellets were solid.

Fig. 3 Postirradiation gamma scan for Ce^{141} in capsule GB-9

Fig. 4 Postirradiation gamma scan for $\text{Ba}^{140}/\text{La}^{140}$ in capsule GB-9

Fig. 5 Postirradiation gamma scan for I^{131} in capsule GB-9

Fig. 6 Postirradiation gamma scan (hot side) for Cs^{134} in capsule GB-9

Fig. 7 Postirradiation gamma scan (hot side) for Cs^{137} in capsule GB-9

occurred in the low-enriched pellets at the ends of the fueled region. Composite photomacrographs of these regions are shown in Figs. 8 and 9. The constrictions are clearcut evidence of fuel transport by a vaporization-condensation mechanism, since plutonium was found in the deposit in the UO_2 pellet at the end of the fuel column by microprobe analysis. Electron microprobe analysis of the constriction also indicated the presence of the expected nonvolatile fission products. Cesium is usually found only in the outer third of the pellet radius. Furthermore, the axial peaks in cesium activity were found beyond the constrictions in the region of the interface between the low enriched pellets and the depleted blanket pellets and into the first blanket pellet. No cesium activity was found in the second blanket pellet.

Measurements of the effluent fission-gas activity during operation of the capsule did not indicate the presence of flow restrictions, which would tend to decrease the R/B^* of the various nuclides from the capsule. Flow measurements across these constrictions during predestructive PIE showed that both constrictions permitted adequate flow to ensure pressure equalization.

FAST-FLUX IRRADIATION

Fuel rod G-3, which was irradiated to 28,000 MWd/Te at 700°C maximum cladding surface temperature at beginning of life (BOL) in the F-1 (X094) experiment, is currently undergoing postirradiation examination at ANL and some data from this examination are reported here. However, the principal information on fission-product concentrations in the various sections of the fuel rod was obtained by gamma spectrometry during the interim examination of the F-1 assembly at the EBR-II site. Rod G-1, which is to be irradiated to a burnup of 50,000 MWd/Te at ~780°C maximum cladding surface temperature (BOL), and rod G-4, which is to be irradiated to a burnup of 100,000 MWd/Te at ~700°C maximum cladding surface temperature, were also gamma scanned during the interim examination, but those examinations were not as detailed as that for rod G-3.

*Release rate to birth rate for a given fission-gas nuclide.

Fig. 8 Upper fuel-blanket interface and low-enriched pellets in GCFR fuel rod GB-9 irradiated in ORR

Fig. 9 Lower fuel-blanket interface and low-enriched pellets in GCFR fuel rod GB-9 irradiated in ORR

As with the GB-9 irradiation, a prime objective of the gamma scanning was to obtain information on the release of iodine from the fuel. Consequently, the removal of the F-1 subassembly from EBR-II and its transfer to the hot cell was expedited by the ANL staff. The first gamma scan was performed 16 days after the reactor was shut down; this period included a mandatory two-week retention of the subassembly in the fuel storage racks in the reactor vessel.

AXIAL SCANS

Gamma scanning of the encapsulated rods was carried out continuously using a lithium-drifted germanium detector with an energy resolution of 0.78 keV/channel and the automated features of the scanning equipment. The data were analyzed at Aerojet Nuclear Company using an automated computer analysis and also at GGA where complex spectral peaks were resolved on the XDS Sigma-II Computer.

The axial gamma scans of all three fuel rods were carried out first at intervals of 0.25 cm (0.1 in.). Following this, the regions near the fuel-blanket interfaces of rod G-3 were rescanned at 0.063-cm (0.025-in.) intervals. These later detailed scans were useful in revealing features of the axial profiles missed in the initial (gross) scans.

The axial scans for all fission-product species exhibited essentially flat profiles in both the fuel and blanket regions of the rods. No activity was found outside of the fuel and blanket regions except for the Cs¹³⁷ background in the hot cell. The charcoal trap in rod G-4 showed no measurable activity. The detailed scan of the fuel-blanket interfaces for the representative nonvolatile fission products in rod G-3 is shown in Figs. 10 and 11.

The upper fuel-blanket interface was displaced by ~0.9 mm due to a gap between the first and second fuel pellets. This is readily visible on the neutron radiograph of rod G-3 in Fig. 12. The existence of this gap is also shown by the (small) peak in Ba¹⁴⁰/La¹⁴⁰ activity at this location in Fig. 10. The small peak of Ba¹⁴⁰/La¹⁴⁰ at the upper fuel-blanket interface, although not matched by a similar peak at the lower fuel-blanket

Fig. 10 Detailed gamma scans of lower fuel-blanket interface of capsule G-3 of F-1 (X094) experiment at 2×10^{22} nvt

Fig. 11 Detailed gamma scans of upper fuel-blanket interface of capsule G-3 of F-1 (Xo94) experiment at 2×10^{22} nvt

Fig. 12 Neutron radiograph of fuel penetration of capsules G-3, standard (G-8, replacement capsule), and G-4 from F-1 (X094) subassembly

interface, appears to be real and may be due to migration of short-lived Cs^{140} (66 sec) over small distances.

The axial profile of rod G-3 for the volatile nuclide I^{131} is shown in Figs. 13 and 14. The peaks in the gamma activity are in the region of the fuel-blanket interfaces where the pellet temperatures drop precipitously. Additionally, there is a large iodine peak in the gap between the first two fuel pellets, indicating that the temperature in this region (relative to the surrounding fuel) is low enough to permit the concentration of significant amounts of iodine. Figure 13 illustrates the necessity for closely-spaced intervals in scanning the fuel-blanket interface. The peak in iodine activity at the upper interface (~ 38.55 in.) was not detected in the initial scan, but was observed when the interval was decreased. The secondary activity peak, in the blanket region, was puzzling since it implied that iodine was migrating up a concentration gradient in a region of fairly constant temperature. Examination of the neutron radiograph taken after the end of the irradiation shows some evidence of a longitudinal crack in the first upper blanket pellet, which might account for the presence of the increased iodine concentration.

The axial profile of the Cs^{137} activity is shown in Fig. 15. These data are taken directly from the Aerojet Nuclear Company computer printout plot of the cesium activity. In contrast to the high precision of the cesium data obtained in capsule GB-9, the data from the G-3 rod is highly scattered owing to the high level of activity from short-lived nuclides still present ~ 16 to 20 days after termination of irradiation. It is clear that, in the future, the fuel rods should be rescanned at a later date, when short-lived activities have decayed away, in order to improve the precision of the Cs^{137} data.

DIAMETRAL SCANS

Diametral scans of the relative fission-product activities were obtained by moving the vertically held fuel pins horizontally (in 0.0254 cm increments) across a vertically oriented collimating slit (1.252 cm long by 0.0254 cm wide) in front of the Ge(Li) detector. Thus, a diametral profile of a 1.252-cm-thick cross section of the fuel was obtained. The relative activity of such a section, as a function of the diameter, was calculated

Fig. 13 Axial gamma scan of I^{131} activity at lower fuel-blanket interface of capsule G-3 fuel rod in F-1 (X094) experiment at 2×10^{22} nvt

Fig. 14 Axial gamma scan of I^{131} activity at upper fuel-blanket interface of capsule G-3 fuel rod in F-1 (X094) experiment at 2×10^{22} nvt

(a)

(b)

Fig. 15 Axial gamma scan for Cs^{137} at (a) lower fuel-blanket interface and (b) upper fuel-blanket interface in capsule G-3 of F-1 (X094) experiment at 2×10^{22} nvt

assuming (1) uniform distribution of fuel and fission products and (2) no self-adsorption of the gamma rays in the sample. This calculated diametral profile is shown in Fig. 16.

The observed diametral activity profiles for several nonvolatile fission-product nuclides are shown in Fig. 17 for the fuel region and in Fig. 18 for the blanket region. In the blanket region the scan was taken just below the lower fuel-blanket interface. The profiles for the two regions are remarkably similar. The presence of the double peaks in the Ba^{140}/La^{140} profile in the fuel region is not understood although it may indicate a tendency of Cs^{140} to migrate to the colder outside diameter of the fuel pellet, whereas the precursors I^{140} and Xe^{140} migrate as gases up the temperature gradient to the central void. Some support for these postulated mechanisms rests with the diametral profiles of I^{131} and Cs^{137} shown in Figs. 19 and 20 for the fuel and blanket regions of rod G-3. The iodine activity clearly maximizes at the fuel outside diameter, whereas this profile is apparent for Cs^{137} only in the blanket region because of the scatter of the Cs^{137} data in the mid-fuel region (Fig. 20).

Data obtained from rods G-1 and G-4 of the F-1 (X094) irradiation experiment generally support the detailed fission-product migration data obtained from rod G-3. Of especial importance is the axial scan of rod G-4, which contained a charcoal trap in the upper portion of the rod. No fission-product activity whatever was detected in the charcoal. Again, this supports the conclusion reached from the PIE of the GB-9 capsule: Refractory fission products remain close to their sites of generation and exhibit relatively uniform profiles in the fuel which are proportional to local burnup. Volatile fission products migrate by vapor-phase transport to a relatively cool location and plate out in the blanket region close to the fuel.

CONCLUSIONS AND IMPLICATIONS FOR THE PRESSURE EQUALIZATION SYSTEM OF GAS-COOLED FAST REACTORS

Data obtained by gamma spectrometry during PIE of thermal irradiation capsule GB-9 and interim examination of the three capsules from the fast-flux irradiation experiment F-1 (X094) show that the nonvolatile fission products remain fairly uniformly distributed throughout the mixed-oxide

Fig. 16 Uniform fuel and fission-product distribution in F-1 fuel rods

Fig. 17 Relative diametral activity profiles of midfuel region ($z = 31.5$) of capsule G-3 of F-1 (X094) experiment at 2×10^{22} nvt

Fig. 18 Relative diametral activity profiles of blanket region ($z = 24.75$) of capsule G-3 of F-1 (X094) experiment at 2×10^{22} nvt

(a)

(b)

Fig. 19 Radial scan for I^{131} in capsule G-3 (a) in the fuel region ($z = 31.5$) and (b) in the blanket region ($z = 24.75$) at 2×10^{22} nvt

(a)

(b)

Fig. 20 Radial scan for Cs^{137} in capsule G-3 (a) in the fuel region ($z = 31.5$) and (b) in the blanket region ($z = 24.75$) at 2×10^{22} nvt

fuel, both radially and axially. In contrast, the volatile fission products cesium and iodine migrate by vapor transport to the cooler portions of the fuel region. This migration occurs both radially and axially, the axial transport ceasing abruptly at the fuel-blanket interface where the temperature dropped sharply. At a burnup of $\sim 54,000$ MWd/Te, no movement of the volatile species farther into the blanket has been observed. Although half-life of I^{131} (8.05 d) is too short to permit the firm conclusion that its behavior is representative of that of long-lived I^{129} (1.6×10^7 yr) or stable iodine, Cs^{137} , with a half-life of 30 yr, confirms that stable cesium will conform with the observed behavior. The results of these experiments support the feasibility of the conceptual design of the PES⁽²⁾ of the GCFR for the reasons discussed below.

The mass and volume of stable volatile fission products or of the decay-chain products of gaseous and volatile fission products generated over the life of a GCFR demonstration plant fuel element (~ 750 full power days) and the life of the monitor lines (30 yr) are substantial compared with the gas-space volumes within these components. Although the probability of plugging is believed to be quite small, the possibility exists that local accumulation of stable solid material could plug passages of the PES and prevent further flow.

First, to show the degree of blockage that could be tolerated, the fission gas, at an equilibrium generation rate for the entire core of 665 cm^3/day , would flow, with only 1 psi pressure differential, through a hole 1 ft long with a diameter of only 0.05 mil (0.00005 in.). The equilibrium fission-gas generation rate in a single rod is 2.5×10^{-7} cm^3/sec at operating conditions (4.5×10^{-5} std cm^3/sec), which may be compared to the limits of detectability for helium mass spectrometer leak detectors (10^{-9} std cm^3/sec). Thus, very small leaks are effective in pressure-equalizing the fuel element, but seals approaching hermetic quality are necessary to constitute an effective plug.

Effective plugging of the passages through the upper blanket region is unlikely. A large number of sealed fuel rods fabricated to test fast breeder fuel-rod designs for the LMFBR and GCFR programs have been irradiated to high burnups in the U.S. and in Europe under conditions similar to GCFR design conditions. These rods are very similar in concept, diameter, and

design to the GCFR fuel rods except that they are sealed and include a fission-gas accumulation plenum at the end of each rod. In no instance has positive evidence been reported of a plug effectively preventing communication between the fueled region and the plenum. Experiences with similar rods irradiated to high burnup in thermal reactors has been the same. Results have also been similar with a series of GCFR development rods of sealed design irradiated in ORR capsules.

Protection against plugging is afforded by two sets of traps in the elements, which remove or delay the release of the condensable molecules. The rod traps protect the manifold connecting individual rods; the annular traps in the fuel element protect the PES monitor lines. The void fraction of each trap is about 75% of the total bed volume, and thus a substantial fraction of the bed is available for deposition without plugging within the traps.

Although it is the stable and long-lived isotopes that could cause plugging, they will be deposited along with radioactive precursors. Thus, if material accumulates, the local decay-heat generation rate increases, tending to increase the local temperature. Elevated temperature will raise the vapor pressures of compounds in the deposit and will produce a vaporization-condensation couple, with the cooler regions downstream. Thus, deposits may tend to become widely distributed rather than locally accumulated.

The temperatures of surfaces along the PES from the upper blanket region of the fuel element to the helium purification system are expected to be nearly uniform. This would tend to result in whatever plateout occurs being nearly uniform.

The transit time for passage through the monitor lines is designed to be ~1 sec for several reasons, one of them being to limit the rate of deposition of decay-chain products by making the residence time for decay quite short compared to the half-lives of most of the gaseous isotopes. The very-short-lived isotopes will usually have decayed before entering the monitor lines. Thus, the decay-chain products of the short-lived precursors will be trapped in the fuel element and never enter the monitor lines and only a small fraction of the decay-chain products of the longer-lived isotopes will be generated during transit through the monitor lines.

The low probability of forming effective plugs seems to be substantiated by the performance of systems using sweep gases carrying fission products. For example, no evidence of passage plugging has been observed to date in the operation of the Peach Bottom HTGR plant, in which ~1.1 lb/hr of helium is used to purge each of 804 fuel elements where the flow passes through a 3/16 in. hole in the stand-off pin at the exit to each fuel element. This plant accumulated 52,000 MWd/Te on its first core loading. No significant amounts of Cs¹³⁷ were found in the charcoal traps of the elements that underwent PIE.

The GAIL loop was a pressurized helium-cooled loop in the GETR that was used to test HTGR fuel elements for the Peach Bottom HTGR plant.⁽¹²⁾ The loop was operated from 1961 through most of 1964, with brief downtime periods to change test elements. It logged more operating time than any other U.S. gas-cooled in-pile loop to date. The HTGR fuel elements tested in the loop were the purged sleeve type, and the release, plateout and distribution of fission products were studied. A helium purification and radiochemical analysis system utilizing a series of traps was employed on the purge stream. In operation, the purge stream passed through the narrow annulus between the fuel compacts and the sleeve at about 0.5 to 0.7 lb/hr per element to sweep fission products released from the fuel compacts through a charcoal trap at 350°C and then out of the fuel element through small lines (~3/16 in. diam) about 50 ft long into the external purification system. Although plateout and some graphite dust were observed, no plugging or constriction of the passages from fission products were found anywhere at any time.

The results of PIE on irradiation capsule GB-9, which operated at conditions more severe than the GCFR design* to a burnup of ~54,000 MWd/Te, showed that movement of the volatile fission products will probably be limited to the fuel-end region of the axial blankets. The principal constriction of the central void is that due to axial migration of fuel material similar to that observed in LMFBR irradiations and, as noted above, the latter have never shown clear evidence of hermetic plugging. There have

*GB-9 operated at 500 W/cm (15 kW/ft), whereas the GCFR demonstration plant reference design will operate at 415 W/cm (12.5 kW/ft).

been no indications of potential plugging in other irradiation tests of vented fuel rods. (13,14)

Transport and deposition of gaseous and volatile fission products and the possibility of their local accumulation into effective plugs is a complex of processes in the PES that requires further study involving both in-pile irradiation and out-of-pile test programs. Irradiation capsules GB-9, GB-10, and those in the F-1 experiment are the first irradiations in the GCFR development program in which the study of fission-product transport and deposition is one of the prime objectives.

ACKNOWLEDGMENT

The authors wish to acknowledge the assistance of and invaluable advice and consultation from Edwin Anderson of Gulf General Atomic and Marie Putnam and Susan McClure of Aerojet Nuclear Company in processing of the gamma spectrometry data.

REFERENCES

1. Fortescue, P., and W. I. Thompson, "The GCFR Demonstration Plant Design," Proceedings, ORNL Gas-Cooled Reactor Information Meeting, Oak Ridge, Tenn., April 27-29, 1970.
2. Campana, R. J., *Nuclear Technology*, Vol. 12, October 1971, p. 185.
3. Schwartz, A., et al., "Post-Irradiation Examination of Peach Bottom Fuel Elements E05-05 and C05-05 and Related Analyses," USAEC, Report GAMD-8743, Gulf General Atomic, March 17, 1969.
4. Zumwalt, L. R., "FREVP-8 Code for Estimating the Release of Metallic Fission Products from HTGR Fuel Elements," USAEC, Report GAMD-7535 Rev., General Dynamics Corporation, General Atomic Division, March 24, 1964.
5. Jadhov, K. B., and B. W. Roos, "SLIDER, A Fortran V Program for the Computation of the Release of Fission Products from One-dimensional Multilayered Fuel Configurations," USAEC, Report GA-8566, Gulf General Atomic, August 1, 1969.
6. Lindgren, J. R., et al., "Planned Thermal Irradiation of Manifolded-Vented (U,Pu) O_2 -fueled Rod in ORR Capsule P-9 [GB-9]," USAEC, Report GA-9896, Gulf General Atomic, March 15, 1970.
7. Lindgren, J. R., et al., "Irradiation Testing and Development of Fast Breeder Reactor (U,Pu) O_2 Fuel Rods," American Nuclear Society Conference on Fast Reactor Fuel Element Technology, New Orleans, La., April 13-15, 1971.
8. Campana, R. J., et al., "Fuel Element Development for Gas-Cooled Fast Breeder Reactor (GCFR). Part 2. Vented Fuel-rod Development," American Nuclear Society Meeting, Boston, Mass., June 13-17, 1971..
9. Lindgren, J. R., et al., "Planned Thermal Irradiation of Manifolded-Vented (U,Pu) O_2 -fueled Rod in ORR Capsule GB-10," USAEC, Report Gulf-GA-A12123, Gulf General Atomic, July 31, 1972.
10. Flynn, P. W., et al., "High-temperature Fast-flux Irradiation Experiment for Mixed-oxide Fuel Rods," USAEC, Report GA-10264, Gulf General Atomic, October 15, 1970.

11. Lofing, D. R., and R. D. Burnette, "High-temperature Adsorption Studies for the PSC Reactor Development Program," USAEC, Report GA-8083, Gulf General Atomic, November 30, 1967.
12. "Preliminary Hazards Summary Report, Peach Bottom Atomic Power Station," Philadelphia Electric Co., Section II.J.2.e.
13. O'Neal, G. L., et al., "A Technical and Economic Evaluation of Vented Fuel for Sodium-cooled Fast Ceramic Reactors," USAEC, Report GEAP-4770, General Electric Company, Atomic Power Division, May 1964.
14. Longest, A. W., and J. A. Conlin, "Fission-gas Release Experiment with a UO_2 Fuel Element in a High-temperature Helium Recirculating Loop," USAEC, Report ORNL-TM-926, Oak Ridge National Laboratory, February 1965.