Dec. 2033

GA-A15584
UC-77

165
11/21/80
1-5

GAS-COOLED FAST BREEDER REACTOR STEADY-STATE IRRADIATION TESTING PROGRAM

MASTER

by

R. T. ACHARYA, R. J. CAMPANA, and S. LANGER

**Prepared under
Contract DE-AT03-76SF71023
for the San Francisco Operations Office
Department of Energy**

DATE PUBLISHED: AUGUST 1980

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

GENERAL ATOMIC COMPANY

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.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy A05; Microfiche A01

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.

GA-A15584
UC-77

GAS-COOLED FAST BREEDER REACTOR STEADY-STATE IRRADIATION TESTING PROGRAM

by
R. T. ACHARYA, R. J. CAMPANA, and S. LANGER

**Prepared under
Contract DE-AT03-76SF71023
for the San Francisco Operations Office
Department of Energy**

DISCLAIMER

This book 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.

**GENERAL ATOMIC PROJECT 6113
DATE PUBLISHED: AUGUST 1980**

DISTRIBUTION OF THIS REPORT IS UNLIMITED

GENERAL ATOMIC COMPANY

ABSTRACT

The requirements for the gas-cooled fast breeder reactor irradiation program are specified, and an irradiation program plan which satisfies these requirements is presented. The irradiation program plan consists of three parts and includes a schedule and a preliminary cost estimate: (1) a steady-state irradiation program, (2) irradiations in support of the design basis transient test program, and (3) irradiations in support of the GRIST-2 safety test program. Data from the liquid metal fast breeder reactor program are considered, and available irradiation facilities are examined.

SUMMARY

The Gas-Cooled Fast Breeder Reactor (GCFR) Steady-State Irradiation Testing Program Plan is part of the Fuels and Materials Development Plan and describes the following:

1. Overall goal and primary objectives of the GCFR irradiation testing program.
2. Available data base from the extensive liquid metal fast breeder reactor (LMFBR) fuel development program and its applicability to the GCFR program.
3. Unique features of the GCFR and the need for tests in addition to those performed by the LMFBR program.
4. Data obtained from past and current GCFR irradiations.
5. Requirements for further irradiation testing to satisfy the needs of the steady-state, design basis transient, and safety test programs.
6. Options available for GCFR irradiation tests.
7. Irradiation test schedule.

CONTENTS

ABSTRACT	iii
SUMMARY	v
1. OBJECTIVES OF THE GAS-COOLED FAST BREEDER REACTOR IRRADIATION TESTING PROGRAM	1-1
2. DATA OBTAINED FROM THE LIQUID METAL FAST BREEDER REACTOR PROGRAM	2-1
References	2-10
3. PAST AND CURRENT GCFR IRRADIATIONS	3-1
3.1. GB Series of Vented Fuel Rod Irradiations	3-1
3.1.1. Irradiation Capsule GB-9	3-3
3.1.2. Irradiation Capsule GB-10	3-12
3.2. The F Series of Fast Flux Irradiations	3-20
3.2.1. F-1 Irradiation Experiment	3-20
3.2.2. F-3 Irradiation Experiment	3-21
3.2.3. F-5 Irradiation Experiment	3-22
3.3. HELM Fuel Bundle Irradiations	3-24
References	3-28
4. GCFR IRRADIATION PROGRAM REQUIREMENTS	4-1
4.1. Steady-State Irradiation Program Requirements	4-1
4.2. Design Basis Transient Test Program Requirements	4-8
4.3. GRIST-2 Safety Test Program Fuel Requirements	4-9
References	4-12
5. IRRADIATION PROGRAM PLAN	5-1
5.1. Steady-State Irradiation Program Plan	5-1
5.1.1. FTR Steady-State Irradiations	5-1
5.1.2. GB-11 Sweep Gas Experiment	5-2
5.1.3. Future HELM Irradiations	5-6
5.2. Preirradiation Program Plan for the Design Basis Transient Tests	5-9
5.3. Irradiation Program Plan for GRIST-2 Safety Tests	5-10
6. RELATIONSHIP OF IRRADIATION PROGRAM TO GCFR LICENSING	6-1

CONTENTS (Continued)

7. RESOURCE EVALUATION AND CONTROL SYSTEM	7-1
7.1. Steady-State Irradiation of Fuel Assemblies	7-1
7.2. Design Basis Transient Tests: Phase I	7-1
7.3. Design Basis Transient Tests: Phase II	7-1
7.4. Pre-GRIST-2 Fuel	7-1
7.5. GRIST-2 Transient Overpower Fuel	7-4
7.6. GRIST-2 Loss of Flow Fuel	7-4
7.7. GB-11 Sweep Gas Experiment	7-4
7.8. HELM 2MO Experiment	7-4
7.9. HELM 4, 5, and 6 Experiments	7-4

FIGURES

2-1. Number of breached rods and total mixed oxide irradiation experience in EBR-II	2-7
3-1. Helium sweep and monitoring line arrangement for capsule GB-9	3-5
3-2. GB-9 measured fission product gas release from the vented fuel rod as a function of burnup	3-7
3-3. Sample line radioactivity and internal pressure vs time during depressurization-repressurization experiments	3-8
3-4. Radioactivity in the sample line of capsule 04-P9 during ORR scram	3-9
3-5. GB-10 sweep gas system	3-14
3-6. GB-10 fuel rod flow conductance vs fuel burnup	3-16
3-7. GB-10 release (R/B) and venting (V/B) fractions	3-18
5-1. Comparison of fuel rods used in irradiation experiments	5-4
7-1. RECS for irradiation test program.	7-2

TABLES

2-1. Summary of LMFBR irradiations in EBR-II	2-4
2-2. Planned FTR irradiations for the LMFBR program	2-5

TABLES (Continued)

3-1.	Irradiation test conditions for capsule GB-9	3-4
3-2.	Ratio of fractional release at trap outlet to that at trap inlet	3-10
3-3.	Comparison of capsules GB-10 and GB-9	3-13
4-1.	Probable licensing needs of the GCFR program	4-2
4-2.	Licensing needs of the GCFR demonstration plant which will be met by the LMFBR program	4-4
4-3.	GCFR fuel rod irradiations	4-6
5-1.	GRIST-2 preliminary test plan outline	5-11
5-2.	Preirradiation test for safety program	5-12

1. OBJECTIVES OF THE GAS-COOLED FAST BREEDER REACTOR IRRADIATION TESTING PROGRAM

The overall goal of the gas-cooled fast breeder reactor (GCFR) irradiation testing program is to provide a GCFR irradiation data base which will ensure the licensing of the GCFR demonstration plant core. This goal will be reached by satisfying the following set of objectives:

1. Obtaining as much information as possible from the liquid metal fast breeder reactor (LMFBR) sealed rod steady-state irradiations in the experimental breeder reactor (EBR-II), the fast flux test facility (FFTF), and cooperative U.S. Department of Energy (DOE) and U.K. programs. For example, data on the effects of fuel stoichiometry, smear density, plutonium enrichment, fuel-cladding chemical interaction, cladding swelling, and irradiation creep are directly applicable to GCFR design and licensing.
2. Testing features unique to the GCFR (i.e., helium cooling, vented and pressure-equalized fuel, ribbed cladding, grid-spaced subassembly, large-diameter rods, fission product traps in the fuel rod, high midwall cladding temperatures) under conditions simulating the GCFR environment to the maximum extent possible. Steady-state irradiation of fuel rods to determine the effects of these features is part of the GCFR steady-state irradiation testing program.
3. Providing the design basis transient test program and the safety test programs (GRIST-2) with preirradiated fuel rods.
4. Providing a significant number of irradiations for advanced alloy qualification and licensing. This will be the case if the GCFR

demonstration plant reference cladding material is changed from 20% cold-worked 316 stainless steel to an advanced alloy.

The GCFR steady-state irradiation testing program plan is designed to satisfy the above objectives. This limited program and its associated non-prototypical features (such as use of sodium-cooled test reactors) can be expected to provide information for design of the GCFR fuel assemblies to a burnup of ~5 at. % with confidence. At this burnup, the fluence is equal to the threshold value for the onset of swelling in the cladding and structural materials. Additional irradiations of full-size fuel assemblies will be needed. These irradiations will use the GCFR demonstration plant as a fuel test bed.

In accordance with the fuel test bed concept, the initial core will be licensed to a burnup of ~5 at. %, and advanced design fuel assemblies will be irradiated in the core as lead assemblies. The major objective of these irradiations will be to increase burnup and improve core performance. This part of the irradiation program is not described in this report.

2. DATA OBTAINED FROM THE LIQUID METAL FAST BREEDER REACTOR PROGRAM

Approximately 2800 stainless-steel-clad mixed oxide fuel rods have been irradiated in EBR-II since 1965. The first irradiations were performed to determine basic fuel rod parameters such as smear density, linear power rating, cold work of the cladding, and temperatures. Later irradiations were concerned with the effects of varying these design parameters on fuel rod/assembly performance. The primary objectives of the EBR-II LMFBR fuel rod irradiation program are as follows:

1. To obtain data on the internal behavior of the fuel rod (e.g., fission gas release, fuel-cladding chemical interaction, fuel-cladding mechanical interaction).
2. To determine the effects of fabrication variables such as fuel oxygen to metal ratio (O/M), smear density, fuel-cladding diametral gap, and fuel pellet geometry.
3. To determine the effects of cladding variables such as cold work, maximum temperature, and cladding wall thickness.
4. To ascertain the effects of assembly design (e.g., bundle porosity, wire wrap pitch) on assembly performance.
5. To obtain reliability data by irradiating a statistically significant number of reference design fuel rods.
6. To determine the failure modes for LMFBR design fuel rods and assemblies.

With the following exceptions, the EBR-II irradiations are in most respects prototypical of large LMFBRs such as the Fast Test Reactor (FTR) and the Clinch River breeder reactor (CRBR).

1. Fuel column and blanket column length.
2. Peak-to-average axial power ratio. (In EBR-II this ratio is ~ 1.05 , whereas in the FTR or CRBR it is ~ 1.2 .)
3. Fluence to burnup ratio. (The fluence to burnup ratio in the FTR or CRBR is about 2.5 times that in EBR-II.) At a burnup of 10 at. % the peak fluence in the FTR is about 2.4×10^{27} n/m² (E > 0.1 MeV); in EBR-II the peak fluence at the equivalent burnup is $\sim 1.0 \times 10^{27}$ n/m².

These nonprototypical features of EBR-II irradiations also apply to the GCFR demonstration plant. Additional nonprototypical features specific to the GCFR are

1. The EBR-II coolant is sodium; the GCFR coolant is high-pressure helium. Thus, cladding corrosion/erosion behavior and therefore external cladding wastage will be different; the wastage allowance may or may not be different.
2. Throughout their lives, pressure-equalized GCFR fuel rods will have a high internal and external helium pressure. EBR-II fuel rods will have low-pressure helium at the start of irradiation, and fission gases will build up an appreciable internal pressure at the end of life (EOL). The helium pressure in the GCFR rods is expected to reduce fuel swelling, and dilution of the fission gases with helium is expected to improve gap conductance.

3. Because of the pressure equalization system (PES), the GCFR fuel rod cladding does not, at any time in its life, have a significant primary stress caused by either high primary coolant pressure [beginning of life (BOL)] or fission gas pressure buildup (EOL).
4. GCFR fuel rods have ribbed cladding.

Because of the above features, the LMFBR data base from EBR-II irradiations provides a rather limited data base for GCFR fuel rod and assembly design. (Table 2-1 summarizes the available LMFBR data base.)

A large number of mixed oxide fuel rod/assembly irradiations are planned for the FTR. The basic deficiencies of the EBR-II irradiations, namely low fluence-to-burnup ratio, short fuel and blanket column lengths, and low peak-to-average axial power ratio, will be corrected in the FTR irradiations, which will be prototypical of reactors like the CRBR. Reference 2-1* lists 12 fuel irradiation experiments which will provide data to the GCFR project. Table 2-2 summarizes these tests. These irradiations will include driver assemblies and multiduct assemblies consisting of 37 large-diameter (6.86 and 7.37 mm) test fuel rods surrounded by two or three rows of driver rods. Four grid-spaced driver assemblies will be irradiated in the FTR, however the grid spacer design is different from those currently under consideration for the GCFR demonstration plant. Data from the large number of driver assemblies irradiated in the FTR may not be very useful to the GCFR program because the fuel rods lack axial blankets. Lack of axial blankets is an important nonprototypical feature because data on fission product migration and interaction with the blanket will not be generated.

Reliability data on LMFBR rods are expected from the statistically large number of reference design fuel rods irradiated in the LMFBR program.

*References are given at the end of each section.

TABLE 2-1
SUMMARY OF LMFBR IRRADIATIONS IN EBR-II

	No. of Rods	O/M Range	Temp Range (°C)	Linear Power Range (W/cm)	Smear Density Range (% Theoretical)	Burnup Range (MWd/kg)
High cladding temperature	~400	1.95 to 1.99	650 to 720	275 to 520	85 to 90	50 to 145
Stoichiometry effects	~360	1.93 to 1.99	650 to 720	275 to 520	85 to 90	100
Smear density effects	~400	1.95 to 1.99	650 to 720	275 to 520	82 to 92	100
Statistically significant tests, FTR support	~550	1.95 to 1.99	650	~500	85	100

TABLE 2-2
 PLANNED FTR IRRADIATIONS FOR THE LMFBR PROGRAM^(a)

	Insertion Cycle ^(b)	Removal Cycle
Grid-spaced driver assembly	ATP IV	4
Grid-spaced driver assembly	ATP IV	6
Grid-spaced driver assembly	ATP IV	4
Grid-spaced driver assembly	ATP IV	5
Radial blanket	ATP V	
Radial blanket	ATP V	10
Improved oxide	ATP V	5
Advanced alloy cladding	ATP V	4
Alternate improved oxide	2	7
Advanced alloy cladding	2	7
Alternate improved oxide	3	8
Radial blanket (open test assembly)	3	9
Alternate improved oxide	4	11
Alternate improved oxide (open test assembly)	5	10
Advanced fuel (closed loop in reactor assembly)	6	9

(a) From Ref. 2-1.

(b) ATP = reactor acceptance test program.

However, a statistical data base is a complex concept and should be used with great care. The LMFBR data base from EBR-II irradiation testing is large (Fig. 2-1). Direct application of this data base to the GCFR (and, to a lesser degree, to the LMFBR) is limited because

1. The EBR-II data base was mostly obtained from tests of wire-wrapped subassemblies.
2. EBR-II irradiations suffer from a low fluence-to-burnup ratio. The fluence to burnup ratio in a large reactor (FTR or GCFR) is 2.5 times that of EBR-II).
3. The cause of failures in EBR-II is not related to the internal components of the fuel rod, but appears to be related to hot spots caused by the wire wrap (Ref. 2-3).
4. A large number of the fuel rod failures in EBR-II were failures of encapsulated fuel rods.
5. Failures of the encapsulated fuel rods (about 12) have been traced to fuel assembly designs and handling during the interim examinations. The internal fuel rod components have not contributed to any known failures.

Statistical analysis of the performance of fuel rods from EBR-II irradiations which include encapsulated rods indicates poor reliability.* The reliability improves dramatically if the encapsulated rod data are excluded from the analysis. This shows the importance of the choice of an appropriate statistical data base.

*The reliability of the fuel rods can be obtained by analyzing the known successes (or failures) in irradiations completed to date in EBR-II. The documented failures have been traced to design of the irradiation vehicles, handling during interim examinations, etc. Hence, the reliability of the fuel rods is related to the fuel assembly design.

Fig. 2-1. Number of breached rods and total mixed oxide irradiation experience in EBR-II (from Ref. 2-2)

In summary, the LMFBR program will provide all the following data needed by the GCFR program:

1. Smear density, pellet density, pellet design, and pellet fabrication (i.e., overall fuel specifications).
2. Axial blanket pellet specifications similar to those in item 1.
3. Cladding and fabrication specifications (except for ribbing).
4. Fuel restructuring and oxygen and plutonium redistribution.
5. Irradiation performance limits for fuel rods.

The LMFBR program will supply the necessary data on most of the following:

1. Fuel stoichiometry. However, stoichiometry may be affected by the GCFR environment and the venting concept.
2. Power to melt. However, power to melt may be increased because the high-pressure helium in the fuel-cladding gap reduces degradation of gap conductance caused by diluting the fission gases with helium.
3. Axial power distribution. However, fission product transport is influenced by axial power, temperature distributions, and probably the GCFR environment and the venting concept.
4. In-reactor cladding behavior. However, the helium environment, PES, and ribs on the cladding will have a significant influence.

Little or no data will be furnished on

1. Vented, pressure-equalized fuel rod performance and the influence of venting and pressure equalization on fuel swelling, gap conductance, cladding irradiation creep, and fuel-cladding mechanical and chemical (stoichiometry) interaction.
2. Fission product transport and trap performance.
3. Ribbed cladding performance in a GCFR environment.
4. Performance of the PES during steady-state operation.
5. Performance and behavior of defective fuel rods in a GCFR environment.
6. Grid-spaced fuel assembly performance (e.g., fuel rod and assembly distortion, differential swelling between fuel rod and spacer grid, spacer-rod interaction). These parameters are expected to be the life-limiting phenomena for the GCFR assemblies.
7. Statistical data base for fuel rods irradiated in prototypical design fuel assemblies.
8. Steam inleakage effects, cladding interaction, fuel interaction, and fission product interaction and transport.

Hence, the above data must be supplied by the GCFR irradiation program.

REFERENCES

- 2-1. Second Annual Experimenters Information Meeting, Richland, Washington, October 3-5, 1978, unpublished data.
- 2-2. Hanford Engineering Development Laboratory unpublished data, November 1979.
- 2-3. Weber, J. W., M. V. Almassay, and R. A. Karnesky, "HEDL Mixed Oxide Fuel Pin Breach Experience in EBR-II," in Proceedings of the International Conference on Fast Breeder Reactor Fuel Performance, Monterey, California, March 5-8, 1979.

3. PAST AND CURRENT GCFR IRRADIATIONS

Three different series of irradiations have been completed or are under way in support of the GCFR program. The GB series irradiated single, vented fuel rods in the thermal flux of the Oak Ridge Reactor (ORR). Tests GB-9 and GB-10 have been completed.

The F series is for fast flux irradiations in EBR-II. Tests F-1 (seven encapsulated fuel rods) and F-3 (ten encapsulated fuel rods) have been completed. Irradiation test F-5 is a 31-rod grid-spaced assembly test with a current burnup of 4.3 at. % and a goal burnup of 16 at. %.

The HELM (Helium Loop Mol) series of vented rod bundle tests are being irradiated in the BR 2 reactor at Mol, Belgium. The first test, HELM-2 (12-rod, UO₂-fueled, vented bundle) has been completed. The second test, HELM-3 (12-rod, mixed oxide fueled, vented bundle), has a current burnup of ~3 at. %.

3.1. GB SERIES OF VENTED FUEL ROD IRRADIATIONS

The GB series of vented fuel rod irradiations was undertaken to support the design and licensing of GCFR fuel subassemblies and the PES. In particular, data for developing radioactivity source terms must be acquired for pressure-equalized and vented fuel. Little of the data developed in the LMFBR and high-temperature gas-cooled reactor (HTGR) programs is applicable. For example, buildup of fission gas pressure is a life-limiting factor in LMFBR fuel rod design, and therefore LMFBR irradiations have provided ample data on the release of stable fission gases since they are the predominant contributors to pressure buildup. The GCFR, however, is not concerned with pressure buildup in the fuel rods but rather with control and venting of the gaseous and volatile radioactivity released from the fuel. Thus, data on

the release of radioactive fission products are not obtained from the LMFBR data and must be obtained from GCFR fuel irradiations. The release and transport of volatile fission products in the GCFR fuel rods is also expected to be different from that in the LMFBR because of (1) venting of the gaseous precursors of the volatile (condensable) fission products and (2) the effects of coolant impurities on the internal fuel rod chemistry. The LMFBR fuel technology does not contribute to determination of the effects of in-leaking coolant impurities (H_2 and H_2O) on the chemistry of, and volatile fission product distribution in, leaking GCFR fuel rods. Because operation with a small fraction of leaking rods is considered to be a normal operating condition (as with other reactor types), these data must also be acquired in the GB series of vented rod irradiations.

Although a large amount of fission product release data have been obtained in the HTGR program (Ref. 3-1), the HTGR particle fuel is so different from the GCFR vented and clad fuel pellets that little transfer of technology can be expected. There are, however, three HTGR items which are somewhat applicable to GCFR fuel technology: the SLIDER computer code (Ref. 3-2), charcoal trapping technology, and fission product plateout technology. The SLIDER code was developed to analyze solid-state diffusion of fission products through the layers of coatings on the HTGR fuel particles, but it is also applicable to gas phase interdiffusion of gaseous and volatile fission products in the high-pressure helium inside the GCFR fuel rods. However, additional modelling of the fuel rod regions and calibration of the code are required. The GB series of irradiations provides the data for verifying the use of the SLIDER code for the GCFR.

HTGR charcoal technology can be applied to the charcoal traps in the fuel rod and the fuel and blanket subassemblies. However, the HTGR data are only relevant to the unirradiated or BOL fuel and blanket subassemblies because of the effect of fast fluence on the charcoal. The properties of charcoal (and graphite as an alternative) trap material must be determined by the GCFR fast flux irradiations (Section 5.1.1).

HTGR plateout technology is also applicable to the GCFR coolant system, although the activity levels in the GCFR coolant are expected to be even lower than those in the HTGR. Under normal steady-state operating conditions, however, the activities in the GCFR PES are expected to be slightly higher than those in the HTGR coolant. The effects of different impurity levels must be taken into account when applying the HTGR plateout technology to the GCFR because of very low H₂O levels in the HTGR coolant.

3.1.1. Irradiation Capsule GB-9

Irradiation capsule GB-9, originally designated P9, was the ninth in a series of GCFR fuel rod concept screening irradiations (Ref. 3-3). Prior capsules contained sealed rods and tested Hastelloy-X cladding, free-standing and fuel-supported cladding, flexcan, and prepressurized sealed rods with cladding temperatures $\leq 800^{\circ}\text{C}$ and heating rates $< 72 \text{ kW/m}$ (Ref. 3-4). The principal purpose of GB-9 was to demonstrate that pressure-equalized and vented fuel could be operated at GCFR temperature, pressure, and linear heating rates, was mechanically and chemically stable, and could be operated to a high burnup without plugging of its passages by volatile fission product deposition. The GB-9 rod was irradiated in the ORR and had an original burnup goal of 5.5 at. %. This goal was revised to ~ 8 at. % when the initial goal was reached and sufficient fuel remained for continuing the irradiation. Table 3-1 gives the characteristics and irradiation conditions for GB-9, and Fig. 3-1 shows the venting and sweep gas arrangement. Note that only the charcoal rod trap and not the fuel column could be swept with helium. The results of irradiation of GB-9 are as follows:

1. The feasibility of using vented fuel was established, and there were no fundamental phenomena precluding its use for the GCFR. Questions of economics and life can be answered by subsequent and more specific GCFR simulations.

TABLE 3-1
IRRADIATION TEST CONDITIONS FOR CAPSULE GB-9

Cladding material	316 stainless steel
Cladding o.d. (mm)	9.02
Cladding thickness (mm)	0.610
Cladding o.d. surface temperature (°C)	700
Fuel	[88 wt % U (9% enrichment), 12 wt % Pu]O ₂
Linear power generation (maximum) (W/cm)	525 under steady-state conditions
Burnup exposure (at. %)	8
External pressure (MPa)	6.6
Initial internal trap pressure (hot) (MPa)	6.8
EOL internal trap pressure (hot) (MPa)	6.8
Trap temperature (surface) (°C)	300 (can be varied from room temperature to 400°C)
Number of power (temperature) cycles	100 standard: 700° → 300° → 700°C 6 nonstandard: 700° → x → 700°C
Number of pressure cycles	22 standard: 6.8 → 0.68 → 6.8 MPa 4 nonstandard: 6.8 → x → 6.8 MPa

Fig. 3-1. Helium sweep and monitoring line arrangement for capsule GB-9

2. Stable gases of interest in LMFBR fuel rod pressurization were of no consequence in pressure-equalized and vented GCFR fuel rods. Although ~90% of stable gases was released as in LMFBR rods, venting of radioactive fission gases of interest in GCFRs were half-life dependent, as shown in Fig. 3-2.
3. High-pressure helium in the fuel rods effectively delayed venting of gaseous and volatile fission products.
4. Volatile fission products were largely contained in the fuel and at the fuel-blanket interface. Decay heat outside the fuel region was negligible under steady-state conditions, and volatile fission product transport was far less than predicted (Ref. 3-3). Only 0.2% of the total design inventory reached the charcoal trap.
5. The fuel rod exhaled during increasing power and temperature transients and during decreasing pressure transients. It inhaled during decreasing power and temperature transients and during increasing pressure transients. Figures 3-3 and 3-4 show vent line activity during a pressure cycling test and following ORR scram, respectively.
6. The charcoal trap performed as predicted based on HTGR technology (Table 3-2).
7. The R_i/B_i^* values could not be determined independent of V/B^{**} measurements.

* R_i/B_i is the ratio of the rate of release of nuclide i from the fuel matrix to the birth rate of nuclide i in the fuel. It is the instantaneous value of the fractional release.

** V_i/B_i is the ratio of the rate at which nuclide i is vented from the fuel rod to its birth rate in the fuel. V_i/B_i and R_i/B_i are related as follows: $V_i/B_i = R_i/B_i \times V_i/R_i$.

Fig. 3-2. GB-9 measured fission product gas release from the vented fuel rod as a function of burnup

Fig. 3-3. Sample line radioactivity and internal pressure vs time during depressurization-repressurization experiments

Fig. 3-4. Radioactivity in the sample line of capsule 04-P9 during ORR scram

TABLE 3-2
 RATIO OF FRACTIONAL RELEASE AT TRAP OUTLET
 TO THAT AT TRAP INLET

	Kr-85m	Kr-88	Kr-87	Kr-89	Xe-133	Xe-135	Xe-138
Calculated ratio	0.71	0.59	0.37	10^{-4}	0.98	0.25	0.10
Typical measured ratio	0.61	0.51	0.45	ND ^(a)	0.79	0.30	0.06

(a) ND = not determined.

8. To a first approximation, fission products in thermal flux rods behaved in the same manner as in fast flux rods.
9. The fuel rod was mechanically stable; i.e., no excessive bowing ratcheting, or cladding strain occurred. The $\Delta D/D$ values were 1%.
10. The fuel-cladding chemical interaction was small (≤ 1 mil maximum depth of attack).
11. Much higher burnup could have been attained if the GB-9 fixture had not failed during handling (rod failure was not a factor).

Irradiation of capsule GB-9 was terminated in November 1971 by failure of an attachment lug and rupture of a nearby gas line during reinstallation of the capsule in its irradiation fixture following its removal for neutron radiography. The GB-9 test provided the following results for design verification and support (DV&S) for fuel and PES methods development:

1. Decay heat generation could be neglected in the design of the rod and subassembly charcoal traps.
2. Charcoal traps could be designed to retain volatile fission products, particularly cesium and iodine, that reach them.
3. The qualitative behavior of the GB-9 capsule during the breathing operation was as expected. Thus, models and codes can be developed to predict the breathing performance of GCFR fuel rods quantitatively.
4. Bursts of fission gases during startup and shutdown did not occur and thus could be neglected in fuel and PES design.

5. Data on the solid phase migration time of the fission products in the fuel is essential but could not be determined independent of the gas phase transport time from the fuel to the vent in capsule GB-9. That is, the release rate to birth rate fraction (R/B) could not be determined independent of the venting rate to release rate fraction (V/R). The measured V/B data in GB-9 could only be combined with an assumed model for either R/B or V/R fractions to allow calculation of the remaining fraction. In addition, the linear power and operating temperature were coupled in GB-9. These factors prevented the measurement of independent R/B and V/R fractions as a function of power and temperature. Such determinations were made during the GB-10 (Section 3.1.2) and HELM3 (Section 3.3) experiments.

3.1.2. Irradiation Capsule GB-10

Irradiation capsule GB-10, also irradiated in the ORR, continued the work begun with capsule GB-9. Although the design of the GB-10 fuel rod and capsule was similar to that of GB-9, GB-10 differed markedly in its sweep gas capabilities and thus capability to acquire important data. Table 3-3 gives the differences in the design and Fig. 3-5 shows the GB-10 sweep gas system. The fuel, upper blanket, charcoal rod trap, and fuel rod vent can be selectively swept with helium, either individually or in combination. Using this arrangement, the R/B and V/B of the fission gases can be independently determined, gas phase transport from region to region can be measured, cladding leaks can be simulated, and conductance of the gas flow passages in the fuel rod can be measured, all at operating fast breeder reactor fuel rod conditions. GB-10 was irradiated under the conditions listed on the next page.

TABLE 3-3
COMPARISON OF CAPSULES GB-10 AND GB-9

	GB-10	GB-9
Fuel pellets	Solid	Annular
Cladding outer surface	Roughened	Smooth
Charcoal trap length (mm)	~23	~81
Blanket length (mm)	~53	~47
Fuel length (mm)	~226	~251
Bottom blanket pellet	Heated	Unheated
Deposition tube	0.69-mm i.d. x 48.26-mm length	None
Power level (kW/m)	39, 44, 48	48
Sweep capability	Fuel, upper blanket, trap, and combinations	Trap
Leaking fuel rod	Simulated	No simulation

Fig. 3-5. GB-10 sweep gas system

Linear Heating Rate (kW/m)	Nominal Maximum Cladding (Midwall) Temperature (°C)	(MWd/kg)
39	570	0 to 28
44	645	28 to 80
48	700	80 to 105

The burnup goal for GB-10 was initially set at 8 at. % and subsequently raised to ~11 at. %. The fission gas release rate R/B was directly measured and has been correlated with the diffusion parameters for gas release in the GAREL subroutine used with the LIFE-III code (Ref. 3-5); but the data are subject to fairly large uncertainties. Postirradiation analysis is currently in progress to reduce the uncertainty in the fuel temperature data associated with the R/B values. However, until further measurements are made in capsule GB-11, the GB-10 R/B data are the best available. The R/B and V/B values of the gaseous fission products were measured separately, but the measured V/B values are not consistently comparable to the values predicted by the SLIDER code (Ref. 3-2). End effects in the short (53 mm) blanket of the GB-10 rod may influence gaseous diffusion more strongly than in the long blanket, accounting for the difference of the measured and calculated V/B values in the GB-10 experiment.

The flow conductance of the GB-10 fuel rod was continually measured over the full burnup range. At first, the flow conductance of the fuel region increased. Then it decreased exponentially, reaching immeasurably low flow at full steady-state power after a burnup of ~10 at. %. However, when the rod power was reduced, the conductance increased to significant levels in every case. Although the shutdown flow conductance decreased slightly as shown in Fig. 3-6, it remained high throughout the irradiation.

Measuring flow conductance and R/B provides a simulation of leaking rod conditions (breached cladding). Figure 3-3 shows the change in the activity

Fig. 3-6. GB-10 fuel rod flow conductance vs fuel burnup

of gaseous fission products swept into the monitor lines when a cladding leak occurs. However, loss of flow conductance toward the end of the irradiation prevented the acquisition of data in quantitative tests simulating leaks, flow rate and power cycling, and tritium permeation and venting. Each of these tests will be included in the GB-11 irradiation experiment described in Section 5.1.2.

Figure 3-7 shows the effects of helium pressure on the release and venting of gaseous fission products from capsule GB-10. Helium pressures were reduced from 6.8 to 1.7 and 2 MPa for burnup intervals of ~0.5 at. % each. The expected qualitative effects of pressure reduction on V/B were observed, but quantitative analyses remain to be done. There was also an unexpected but discernible effect of pressure reduction on the R/B values of the gaseous isotopes during a transient lasting over a sizable burnup.

Contrary to observations in GB-9, transport of cesium to the charcoal trap in GB-10 reached ~4% of the total cesium inventory produced during the irradiation. The isotopic distribution in the trap was 40% Cs-133, 20% Cs-135, and 40% Cs-137. These quantities are much greater than can be accounted for by the factor of two difference in burnup of GB-10 relative to GB-9, which raises questions about alteration of the cesium distribution by the sweep gas operation. In addition, the equal transport of the 133 and 137 mass chains appears to indicate significant transport of the cesium vapor species. The data imply that vapor transport was the dominant transport mode under simulated leak conditions in the GB-10 experiment. In the F-1 sealed fuel rods (with no sweep gas), Cs-133 and Cs-135 are primarily transported by diffusion as precursor Xe-133 and Xe-135, but Cs-137 transport must contain a significant cesium vapor contribution. The distribution found in the F-1 charcoal traps was 81% Cs-133, 17% Cs-135, and 20% Cs-137. Comparison of these data with the GB-10 data again suggests cesium vapor transport by the sweep gas in capsule GB-10. Thus, the GB-10 results may indicate how cesium may be transported in leaking GCFR fuel rods.

Fig. 3-7. GB-10 release (R/B) and venting (V/B) fractions

The GB-10 test provided the following results for DV&S for fuel and PES methods development:

1. R/B data for gaseous fission products at 39 kW/m and 570°C and as a function of burnup have been used to determine empirical diffusion parameters for the fission gas release model in the GAREL code.
2. R/B data for gaseous fission products at 44 and 48 kW/m and 620°C and 685°C, respectively, and as a function of burnup will be used to verify the GAREL code.
3. V/R data for the gaseous fission products diffusing through long blanket regions in Helium Loop MOL (HELM) bundles 2 and 3 will be used to verify the applicability of the SLIDER model and code under reactor conditions for the calculation of values for V/R in the design of GCFR fuel rods. Since the SLIDER code has also been verified by laboratory diffusion tests, GB-10 data may only demonstrate that relative to convective transport, gaseous diffusion transport is the dominant transport process in nonleaking rods.
4. Monitor station [on-line Ge(Li) spectrometer] data will provide model and code verification of the COUNT code.*
5. Decay heating of charcoal rod traps caused by decay heating of fission products can be neglected under nonleaking and leaking rod conditions.
6. Bursts of fission gases from initially solid pellets during startup and shutdown do not occur in GCFR fuel rods and can be eliminated as a design consideration.

*The COUNT code calculates the fission product activity spectrum passing through the monitor lines as a function of leak rate and operating conditions.

7. Charcoal is effective in trapping volatile fission products in leaking rods.

3.2. THE F SERIES OF FAST FLUX IRRADIATIONS

3.2.1. F-1 Irradiation Experiment

The primary objectives of the F-1 experiment (Refs. 3-6, 3-7) were

1. To determine fuel rod irradiation behavior at cladding temperatures higher than those in the LMFBR program to establish temperature margins for GCFR fuel rod design.
2. To compare the behavior of fuel rods irradiated in a thermal flux environment (i.e., GB-9 and GB-10) with those irradiated in a fast flux environment.
3. To investigate the behavior of active charcoal traps in fuel rods subjected to fast neutron irradiation.

This experiment consisted of a seven-fuel-rod irradiation subassembly using encapsulated rods in the reflector position (row 7) of EBR-II. The fuel rods contained mixed oxide fuel and UO₂ blanket pellets and large fission gas plena to reduce the fission gas pressure and simulate the pressure equalization behavior of the GCFR fuel rods. The experiment was subjected to two interim examinations at 3 and 6 at. % burnup and was discharged when the burnup of the lead rod reached ~13 at. %.

The F-1 experiment indicated there would be no new problems at temperatures even higher than those expected in the GCFR demonstration plant and to burnups in excess of the maximum design burnup for the demonstration plant. In addition, the F-1 experiments provided the following information:

1. Semiquantitative measurements of cesium distribution in the F-1 fuel rods indicated that noble gas transport is responsible for essentially all migration of 133 and 135 mass chains to charcoal traps.
2. Accumulation of the 137 mass chain at the fuel-blanket interface appeared to be the result of Cs-137 transport. Both the Xe-137 and Cs-137 species transport the 137 mass chain to the charcoal traps.
3. Volumetric shrinkage of charcoal by 45% to 60% occurred in irradiated rods which attained burnups of 2.5 to 13.6 at. % at fast fluences of 2 to 9×10^{26} nvt ($E > 0.1$ MeV).
4. The total alkali metal loadings in the charcoal of the sealed rods were in the range of milligrams of metal per gram of charcoal. At these concentrations, the energy of adsorption was still high, and the charcoal remained highly retentive and will provide a significant delay in the release of cesium from GCFR fuel rods.
5. There was no significant difference in the behavior of the ribbed and smooth rods.

3.2.2. F-3 Irradiation Experiment

The primary objectives of the F-3 irradiation experiment (Refs. 3-6, 3-7) were

1. To study the effect of the fuel O/M over the range 1.94 to 1.98.
2. To evaluate the effect of fuel density variations over the range 88% to 92% of theoretical density.

The irradiation vehicle was a subassembly containing 19 encapsulated fuel rods, 10 of which were GCFR fuel rods with surface-roughened cladding and 9 of which were part of the ANL-08 experiment. This subassembly was irradiated in the core region (row 4) of the EBR-II reactor. In addition, piggy-back experiments to study the behavior of shielding materials (BeO, Be, and ZrH_x) were included.

Irradiation was initiated in December 1974, and the subassembly was discharged at a burnup of ~ 5.7 at. %. Examination showed that nine of the ten fuel rods had failed in the capsules. These failures, which could conceivably have occurred anytime during irradiation, have been traced to inadequate sodium bonding between the fuel rods and the capsules (Refs. 3-4, 3-5). However, as a consequence of the F-1 and F-5 experimental matrices, the only significant loss was data on the effects of irradiation on graphite as a trapping material.

3.2.3. F-5 Irradiation Experiment

The F-5 irradiation experiment is the first attempt to irradiate nearly prototypical GCFR fuel rods in a fast flux environment. All the parameters internal to the fuel rod are prototypical except for the length of the fuel and blanket columns, with the former being limited to 343 mm by the EBR-II core and the latter being scaled to the fuel column length. The effect of the PES is simulated by limiting the fission gas pressure buildup in the fuel rod plenum to 3.1 MPa. The plenum pressure reaches this limit at a burnup of approximately 5 at. %, at which time the fuel rods are removed, depressurized, and resealed prior to further irradiation. This mode of operation limits the effects of irradiation and thermal creep due to fission gas pressure buildup, thus partially simulating pressure-equalized behavior.

The primary objectives of the F-5 experiment (Refs. 3-6, 3-7) are

1. To study the effect of a step change in power similar to that caused by rotation of a fuel assembly at the core - radial blanket interface in the GCFR demonstration plant.
2. To determine the reliability of the GCFR fuel rod.
3. To determine the failure modes, if any, for GCFR design fuel rods.
4. To study improved blanket pellet designs to reduce the possibility of blanket pellet - cladding mechanical interaction caused by cesium transport and reaction with blanket pellets.
5. To irradiate prototypical GCFR rods to high burnup.

This experiment uses a 37-rod grid-spaced irradiation vehicle with 31 fuel rods and 6 corner rods for grid spacer support. The corner rods also function as bypass flow tubes. The burnup goal for this experiment is 16.5 at. %. Depressurization and resealing are performed twice, i.e., at 5 and 10 at. % burnup.

The fuel assemblies at the core - radial blanket interface of the GCFR demonstration plant will have a large flux gradient and a corresponding power gradient. These gradients can be expected to contribute to assembly distortions owing to differential swelling and irradiation creep. To reduce these distortions, it was planned to rotate* these assemblies 180 deg at about 6 at. % burnup. This rotation would have subjected some fuel rods to a severe step change in power, i.e., from ~60% to 100% of full power. This

*Although fuel assembly rotation may no longer be required with the upflow core and core restraint, the fuel management scheme still considers fuel assembly rotation. Thus, step changes in power due to fuel shuffling and/or rotation necessitate studying the effects of power changes.

effect will be simulated by operating the F-5 experiment at full power in row 5 to ~5 at. % burnup, followed by operation at low power (~70% of full power) in row 7 for about two EBR-II cycles (~1 at. % burnup), and resumption of irradiation in row 5 at full power to about 10 at. % burnup. Interim examination at the end of this operation is expected to yield data on the effect of a step change in power.

The improved blanket pellet design uses two low-density UO₂ blanket pellets, which are expected to provide sufficient free volume to accommodate excess cesium transported to the fuel-blanket interface.

As of this writing, the F-5 irradiation experiment has reached a burnup of ~5 at. % and has been discharged for the first interim examination. Visual examination of the fuel rods indicates some rod-spacer interaction, which was limited to what appears to be a peening mechanism. This interaction is small, and no significant wear of the rods has been observed.

3.3. HELM FUEL BUNDLE IRRADIATIONS

A series of GCFR fuel bundles are being irradiated in the HELM in the BR 2 test reactor in Belgium. These irradiations are sponsored by the Federal Republic of Germany as part of the internationally coordinated GCFR development program. This program is being led by Kernforschungsanlage (KFA) with the collaboration of Kraftwerk Union (KWU) and the Centrum d'Etudes Nucleares (CEN) and the participation of Kernforschungs Karlsruhe (KFK) and General Atomic (GA). The fuel bundles irradiated to date (HELM 1, 2, and 3) were designed and fabricated by KWU. They are 12-rod GCFR fuel bundles, and their design is described in Ref. 3-6. These fuel bundles are based upon the GCFR downflow core design described in Ref. 3-7; HELM 4, 5, and 6 will be based on the upflow core now being designed. The HELM fuel bundles and the associated development program are described in Section 5.1.3.

HELM 1 is a dummy bundle in which the mixed oxide fuel pellets were replaced by steel pellets. The purpose of HELM 1 was to debug and qualify HELM for fuel irradiation and to acquire baseline data on gamma heating, heat transfer from the HELM to the reactor coolant, and activation of He-3 in the coolant to tritium. Irradiation of HELM 1 was completed in August 1977.

HELM 2 is a UO_2 -fueled bundle which was the first GCFR pressure-equalized and vented fuel bundle to be irradiated. Its purpose was to demonstrate adequate cooling of ribbed fuel rods by pressurized, dynamic helium coolant (5.85 MPa) and the operation of a complete PES. Its irradiation to 0.8 at. % in two BR 2 reactor cycles of ~23 days each qualified the HELM for irradiation of plutonium-bearing fuel to high burnup. Irradiation of HELM 2 was completed in February 1978, and it is currently undergoing postirradiation examination (PIE) in the KFA hot cells.

HELM 3 is a mixed plutonia-urania-fueled bundle. It was irradiated to 28 MWd/kg, at which point irradiation was interrupted by the shutdown of the BR 2 reactor for exchange of its beryllium moderator. Irradiation of HELM 3 is scheduled to be resumed when BR 2 is returned to operation. It is planned to irradiate HELM 3 to a total burnup of 7 at. % by mid-1981. HELM 3 was the first GCFR irradiation bundle to operate with prototypical levels of H_2 and H_2O in the helium coolant, i.e., 525 and 175 Pa, respectively. At the conclusion of the HELM 3 irradiation, PIE will be conducted at KFA; however, two fuel rods may be examined at Argonne National Laboratory (ANL) if arrangements can be made for their transfer. The following results have been obtained with HELM 3:

1. The power level [285 kW(t)], inlet and outlet temperatures, mass flow rate, and pressure drop in the coolant are consistent with design predictions and out-of-pile, electrically heated bundle tests; i.e., the heat transfer and fluid flow design for a bundle using ribbed cladding was verified.

2. The suction hole flow rate and pressure drop are consistent with design values and out-of-pile tests, and little or no change occurred during burnup to 3 at. %. Activity leakage at the vent connection and through the suction hole was unaffected by breathing during transients. During steady-state operation, activity leakage as a function of suction hole flow rate was unaffected for flow rates >25% of the design level. For flow rates <25%, the coolant activity level increased with decreased flow rate. V/B data for venting into the PES and E/B* data for escape (or leakage) into the coolant were obtained. The measured E/B to the coolant will produce a coolant activity level less than those typical of other types of reactors owing to cladding defects. E/B to the coolant is $\sim 10^3$ smaller than V/B to the PES. The source of coolant activity has not yet been determined, but exterior fuel rod surface contamination with tramp fissile material is not thought to be a significant source. V/B to the PES is consistent with design calculations based on GB-10 data.
3. No iodine was vented from the fuel bundle during a burnup to 28 MWd/kg.
4. Very low cesium activity levels were measured in the vent line, consistent with its transport as a precursor gas.
5. Data on the relative rates of tritium permeation of the cladding and venting to the PES were acquired. The molecular form of the tritium (i.e., as HT or HTO) was measured. Permeation was the dominant process for loss of tritium from the fuel bundle, and HT was found at higher levels with respect to HTO than were expected from the H_2/H_2O ratio. The reasons for this is not yet understood.

* E_1/B_1 is the rate at which the fission product activity of nuclide i escapes to the coolant from the fuel relative to its birth rate.

6. Decay heat generation by gaseous fission products was too low to be measured, even by depressurization of the residual fission gases in the fuel bundle to the helium purification system (HPS) traps. The maximum fraction of normal bundle power transferred to the HPS as decay heat from gaseous fission products was $<10^{-5}$.
7. Breathing of the fuel bundles during normal transients and exhalation of activity to the PES were observed. However, breathing had no measurable effect on coolant activity. Krypton was chromatographically separated from xenon activities during these transients, and exhalation under power, temperature, and pressure cycling was measured. Quantitative analyses are yet to be done. These data will be used for verification of the model and computer program to be developed for fuel subassembly breathing.

HELM 3 bundle irradiation test measurements will be used as follows for DV&S for fuel and PES methods development:

1. $(V/B)_i$ to the PES will be used to verify the capability of the GAREL (R/B) and SLIDER (V/R) codes to calculate V/B for GCFR conditions.
2. $(E/B)_i$ to the coolant will provide a measure of the margin between assumed design and expected values.
3. Vent connection performance (i.e., seal and suction hole back diffusion of the activity to the coolant) will furnish a measure of the margin between assumed design and expected values.
4. Activity vented during breathing in power, temperature, and pressure cycling tests will be used to develop and verify models for a breathing computer program.

5. Fission gas spectra at the monitor station during steady-state and transient operation will provide baseline (i.e., no leak) data for developing design criteria and selecting photopeaks for demonstration plant monitor station design. These data [with additional data from the GB-10 monitor station and HELM 2MO test (see Section 5.3)] will be used to verify the COUNT computer program used in monitor station design.
6. The observed chromatographic separation of krypton and xenon during venting will provide a basis for understanding and modelling this effect in the breathing code.
7. Volatile fission product distribution obtained during PIE will provide data on rods which are long enough to be prototypical of GCFRs and which operate with prototypical radial and axial distributions of power, temperature, and fission product birth.
8. Fuel rod chemistry during PIE will verify the prediction that H₂ and H₂O impurities in the coolant can be neglected as a design consideration in nonleaking fuel rods.

REFERENCES

- 3-1. "Final Hazards Summary Report, Peach Bottom Atomic Power Station. Part C, Plant Description and Safeguards Analysis," Annexes, Philadelphia Electric Company, pp. A35, A-50-A-58.
- 3-2. Jadhov, K. B., and B. W. Roos, 'SLIDER, A Fortran-V Program for the Computation of Release of Fission Products From One-Dimensional Multilayered Fuel Configuration, "USAEC Report GA-8566, General Atomic Company, August 1967.
- 3-3. Lindgren, J. R., et al., "Planned Thermal Irradiation of Manifolded-Vented (U,Pu)O₂-Fueled Rod in ORR Capsule P-9 (GB-9)," USAEC Report GA-9896, General Atomic Company, March 1970.

- 3-4. "Gas-cooled Fast Breeder Reactor Annual Progress Report for the Period Ending July 31, 1967," General Atomic Report GA-8107, June 25, 1968.
- 3-5. Billone, M. C., et al., "The LIFE-III Fuel-Element Performance Code," ERDA Report 77-56, Argonne National Laboratory, July 15, 1977.
- 3-6. Langer, S., et al., "Fission Product Release and Transport in Gas-Cooled Fast Breeder Reactor Sealed and Vented Rod Irradiation Experiments," in Proceedings of the International Conference on Fast Breeder Reactor Performance, Monterey, California, March 5-8, 1979.
- 3-7. Lindgren, J., et al., "GCFR Irradiation Experiments," in Proceedings of the International Conference on Fast Breeder Reactor Performance, Monterey, California, March 5-8, 1979.
- 3-8. Jung, W., and W. Krug, "Gas-Cooled Fast Breeder Reactor Fuel Bundle Irradiations in the BR2 Helium Loop," Nucl. Eng. Design 40, 157 (1977).
- 3-9. "300-MW(e) Gas-Cooled Fast Breeder Reactor Demonstration Plant," General Atomic Report GA-A13045, July 15, 1974.

3-30

4. GCFR IRRADIATION PROGRAM REQUIREMENTS

The GCFR irradiation programs which are presently under way or complete will not satisfy the overall licensing needs of the GCFR demonstration plant. Additional steady-state irradiations, i.e., vented and pressure-equalized fuel rod irradiations and fast flux irradiations of fuel assemblies, are required to meet licensing needs. In addition, some irradiations are required to provide preirradiated fuel for the design basis transient program and the GRIST-2 safety test program. A preliminary listing of licensing needs of the GCFR program has been completed. Tables 4-1 and 4-2 present this listing and show the source of the data which satisfy these licensing needs.

4.1. STEADY-STATE IRRADIATION PROGRAM REQUIREMENTS

The need for a steady-state irradiation program which goes beyond the present F-5 and HELM 3 experiments is subject to significant debate. The basic problem is that it is impossible to irradiate a full-size or nearly full-size fuel assembly with prototypical GCFR demonstration plant features in a GCFR environment. Hence, separation of the problem into two prime areas is essential: (1) performance of the PES and (2) performance of the fuel assembly, i.e., overall effect of fluence on assembly distortion and the effect of assembly-rod interaction on rod failure and thus on fuel assembly lifetime.

The GB-9 and GB-10 experiments were initial scoping tests of vented fuel rod performance. HELM 2 and HELM 3 are the first of a series of experiments to determine the performance of the PES in a filtered epithermal flux and helium-cooled environment. Further testing is required to determine system performance for

1. Assemblies with defective fuel rods.

TABLE 4-1
PROBABLE LICENSING NEEDS OF THE GCFR PROGRAM

Performance of the PES during steady-state operation
Initial data from HELM-2 irradiation test
Majority of integral data from HELM series of tests
Laboratory tests and analysis of fuel rod chemistry from ANL
Laboratory tests on plateout and plugging (GA)
Gas phase diffusion studies
GB series of irradiation tests

Performance of the PES with defective fuel rods
Initial data from HELM-2MO irradiation test
Additional data from HELM series of irradiation tests

Defective fuel rod behavior
HELM series of irradiation tests
GB series of irradiation tests

Fission product transport and trap performance (rod and assembly traps)
Rod trap performance and fission product transport data from GB-9
and GB-10
Fast neutron effects on trap material from F-1, F-5, and future
steady-state irradiations
Rod and assembly trap performance from HELM series and future
steady-state FTR irradiations
Effect of axial power distribution on fission product transport from
steady-state irradiation tests in FTR
Rod trap performance from GB-11

Ribbed cladding performance
Mechanical property tests on cladding in prototypical GCFR environment
at ANL and PNL
Oxidation tests on cladding at GA
F series of fast flux irradiation in EBR-II (low fluence)
In-reactor creep tests at ANL
Steady-state fuel assembly irradiations in FTR
Ribbed cladding performance in prototypical helium in the HELM series
of irradiations

Fuel assembly performance
F-5 grid-spaced irradiation test
Steady-state irradiation of fuel assemblies in FTR

Spacer grid performance
F-5 grid-spaced irradiation test
Steady-state irradiation of fuel assemblies in FTR

TABLE 4-1 (Continued)

Assembly components (grid manifold, assembly shielding, etc.)
 F-5 grid-spaced irradiation test
 Steady-state irradiation of fuel assemblies in FTR

Fuel and failure modes (if any)
 F-5 irradiation test
 Steady-irradiation of fuel assemblies in FTR
 LMFBR grid-spaced bundle irradiations in FTR

Statistical data base
 Steady-state irradiation of fuel assemblies in FTR to prove that
 similar LMFBR data base is valid for GCFR

Steam inleakage effects
 Oxidation tests on GCFR cladding
 Mechanical property tests on cladding (ANL and PNL)
 Laboratory tests and analysis of fuel rod chemistry from ANL
 GB series of tests
 HELM series of tests

Fuel rod transient performance
 Fuel rods from EBR-II and FTR irradiations tested under the GCFR
 program

TABLE 4-2
LICENSING NEEDS OF THE GCFR DEMONSTRATION PLANT
WHICH WILL BE MET BY THE LMFBR PROGRAM

Fuel material

Data on smear and pellet density, fabrication, and overall fuel specifications

Performance data, i.e., stoichiometry effects, FCCI, fuel restructuring, oxygen and plutonium redistribution, fission gas release, FCMI, material properties. These data are from ~2800 fuel rod irradiations in EBR-II and additional laboratory tests in the national laboratories. Some of these data are available in the Nuclear Systems Materials Handbook (Ref. 4-1) and some in performance prediction codes such as LIFE (Ref. 4-2).

Axial blanket material

Essentially the same as above, but of smaller magnitude

Cladding material

Cladding material and fabrication specifications (except ribbing)

Data on material properties and mechanical in-reactor behavior

Data on effects of cold-working and other fabrication variables

Data in integral fuel rod performance and limits. These data will mostly be from the Nuclear Systems Materials Handbook, supplemented by data from the GCFR programs on cladding and integral fuel and irradiations

Advanced alloy data from the advanced alloy program

Fuel rods

Data on integral fuel rod behavior from EBR-II irradiation data base, e.g., LIFE code, Nuclear Systems Materials Handbook

Data on effect of fabrication variables and different commercial vendors

Power-to-melt data

Fuel rod failure data in EBR-II

Data from future FTR irradiations

Assembly performance

Data on grid-spaced fuel assembly performance in EBR-II

Data on grid-spaced fuel assembly performance in FTR

Transient performance

LMFBR data base

2. Upflow cooling configuration (previous tests used downflow configuration with stainless steel cladding).
3. Fuel assemblies with advanced alloy cladding with and without defective fuel rods. Defective rods with advanced alloy cladding may behave differently because of the lower cladding swelling and creep.

Data are required on GCFR fuel assembly performance in a fast flux environment. The life-limiting phenomena for the fuel assembly are expected to be differential swelling, creep, and conditions which lead to fuel rod/assembly distortions, which in turn cause fuel rod failures.

The F-5 irradiation experiment is the first GCFR experiment which has some GCFR fuel assembly features, but it lacks a prototypical fluence-to-burnup ratio, fuel and blanket column lengths, and other features. It is also perturbed by necessary interim examinations and associated fuel rod handling. Hence, testing of full-size or nearly full-size fuel assemblies in a prototypical fast flux environment is required. The options considered for FTR irradiation of fuel assemblies are

1. A high-pressure, helium-cooled, vented bundle in a closed-loop in reactor assembly (CLIRA) position.
2. A low-pressure, sodium-cooled, vented bundle in a CLIRA position.
3. A sodium-cooled, sealed rod bundle in an open test assembly (OTA) position.
4. A sodium-cooled, sealed rod bundle in a driver position.

References 4-3 through 4-6 discuss these options, and Table 4-3 lists their conditions. The first option, a high-pressure, helium-cooled CLIRA,

TABLE 4-3
GCFR FUEL ROD IRRADIATIONS

	Thermal Flux Irradiation		Epithermal Flux Irradiation				EBR-11 Irradiation		Possible FTR Option(a)		GCFR Demonstration Plant
	GB-9	GB-10	GB-11	HELM 2	HELM 3	HELM 4	F-1	F-5	High-P Vented CLIRA	Driver Position	
No. of rods in assembly	1	1	2 to 4	12	12	12	7	31	13	121	264
Total no. of rods	1	1	2 to 4	12	12	12	13	43	~20	~130	44,600
Rod support	Caps	Caps	Caps	Grid	Grid	Grid	Caps	Grid	Grid	Grid	Grid
Fuel length (mm) ^(b)	254	254	600	600	600	600	343	343	914	914	1200
Blanket length (mm)	47	52	420	420	420	420	76	76	95	95	600
Coolant	Na/H ₂ O ^(c)	Na/H ₂ O ^(c)	NaK/H ₂ O ^(d)	He	He	He	Na	Na	He	Na	He
Flow Direction	Up	Up	Down	Down	Down	Up	Up	Up	Up	Up	Up
Fast fluence (n/cm ² x 10 ⁻²²)	Low	Low	2.0	--	2.0	2.0	8.0	10.0	24	24	24
Fluence/burnup ratio ^(e)	Low	Low	~0.1	--	~0.1	~0.1	0.8	1.0	2.4	2.4	2.4
Radial power profile	Flat at end of life		Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat
Axial power profile (peak/average power)	1.05	1.05	1.2	1.2	1.2	1.2	1.05	1.05	1.2	1.2	1.2
Venting	Top	Top	Bottom	Top	Top	Bottom	None	None	Bottom	None	Bottom
Venting pressure (MPa)	6.9	6.9	8.7	6.1	6.1	6.1	-	-	8.7	-	-
Charcoal trap length (mm)	75	75	75	50	50	50	200	100	50	50	300
Cost (\$ million)	0.7	1.4	3.2	15	15	18	1.3	1.7	50	2	NA ^(f)
Status	Complete	Complete	Planned	Complete	In Progress	Planned	Complete	In progress	Under consideration	Under consideration	NA

(a) Six unfueled corner rods for grid support.

(b) Vented end only.

(c) Static Na bond/natural circulation H₂O.

(d) Static NaK bond/forced circulation H₂O.

(e) Fluence x 10⁻²²/burnup (at. %).

(f) NA = not applicable.

has been found to be feasible (Ref. 4-4). A 19-rod fuel assembly with 13 or 16 fuel rods and 6 or 3 corner support rods is the largest gas-cooled bundle that can be accommodated in a CLIRA loop. This experiment would be prototypical of the GCFR demonstration plant fuel assembly in every feature except the following:

1. The active core length would be 914 mm compared with 1200 mm in the present GCFR design.
2. The space available for the lower axial blanket and the rod charcoal trap would be severely limited.
3. The 19-rod bundle would not be large enough to demonstrate subassembly performance.

When the features and data expected from a high-pressure, helium-cooled CLIRA experiment are compared with those of the HELM 4 experiment, data enhancement appears to be limited to a high fast fluence and a prototypical fluence-to-burnup ratio. Irradiation of a 19-rod bundle (with 13 or 16 fuel rods) in a CLIRA loop does not provide a significant data gain over a 12-rod HELM bundle. Preliminary estimates for this program show that the cost of an FTR helium loop is high, i.e., \$40 to \$50 million or more. Because the demonstration plant itself is considered a test bed for fuel and HELM is available in BR 2, this experimental option cannot be justified at this time.

The second option is not considered to be as desirable as the other options, mainly because the low pressure of the venting system is limited by sodium system requirements for low pressure and accommodation of only 19 rod bundles. The third and fourth options are essentially alike. Use of an OTA position allows for additional instrumentation close to the subassembly to measure subassembly flow, outlet temperature, and other variables; otherwise, it is identical to a driver assembly irradiation. It is possible to

irradiate a 127-rod fuel assembly with 121 fuel rods in either the OTA or the driver position. This bundle size is more prototypical of the GCFR than the CLIRA loop (nearly prototypical bundle size with nonprototypical features of sodium cooling and nonventing). This provides a large statistical data base for design verification.

4.2. DESIGN BASIS TRANSIENT TEST PROGRAM REQUIREMENTS

The fuels and materials program is responsible for providing irradiation program planning and irradiation and postirradiation services to the design basis and safety test program. Justification of the design basis transient test program is not an integral part of this document. References 4-7 and 4-8 describe the need for the design basis transient test program.

A brief description of the design basis transient test program is given below. Two basic types of transient tests are planned:

1. Tests to validate the applicability of the LMFBR fuel rod transient response data base to GCFR fuel rod design and performance prediction. These tests will cover events up through emergency events and are expected to be single-rod tests performed to simulate both limiting design basis events, i.e., transient overpower (TOP) and loss of flow (LOF).
2. Tests (expected to use 19-rod fuel assemblies) to validate the GCFR faulted design basis cladding temperature limit. The GCFR faulted cladding temperature limit (1300°C) is somewhat higher than that contained in the data base being developed and adopted by the LMFBR program. Thus, it is essential to establish the validity of the GCFR faulted cladding temperature limit.

A two-phase approach will be adopted to validate the GCFR faulted cladding temperature limit. The validity of using LMFBR-type sealed rods

for the majority of the design basis transient tests will initially be established by determining the effect of high helium pressure on the transient behavior of fuel rods. To do this, transient tests will be performed on fuel rods irradiated in EBR-II with and without high helium hydrostatic pressure. Assuming that these initial tests show that the transient behavior of GCFR rods does not significantly differ from that of LMFBR rods, the second phase of the design basis transient test program will use LMFBR-type sealed rods irradiated in a driver subassembly in the FTR. One such assembly is expected to be sufficient for this program.

4.3. GRIST-2 SAFETY TEST PROGRAM FUEL REQUIREMENTS

The requirements for preirradiation of the fuel rods for the safety test program are given in Refs. 4-8 and 4-9. The strategy advocated necessitates procurement of fuel preirradiated in an LMFBR-type environment for the majority of GRIST-2 tests and fuel irradiated under high helium pressure (for a pre-GRIST-2 program to determine the effects of irradiation under high helium pressure on transient behavior).

The fuel rod requirements for the pre-GRIST-2 program can be met by a series of high-pressure-helium encapsulated irradiations and a corresponding series of LMFBR-type (low-pressure) irradiations in EBR-II. These preirradiated fuel rods will be subjected to metallurgical examination, direct electrical heating tests, and transient reactor test facility (TREAT) capsule tests. Differences in behavior caused by differences in the fission gas and helium contents of LMFBR and GCFR preirradiated fuel rods will be studied along with the effect of helium implantation in the GCFR cladding on overall transient behavior. The feasibility of prepressurized capsule-type irradiation has been investigated by ANL and GA (Ref. 4-10).

References 4-8 and 4-11 define the preirradiation requirements for LMFBR-type rods for the GRIST-2 test program. Basically, two types of GRIST-2 tests are planned: TOP and LOF tests. The preirradiation fuel

requirements for these tests are essentially the same except for some minor differences. These requirements are listed below.

1. The TOP fuel should have a prototypical concentration of PuO_2 in natural or depleted UO_2 .
2. The LOF fuel should contain fully enriched uranium in addition to having a prototypical PuO_2 concentration.
3. A prototypical fluence-to-burnup ratio is necessary for TOP but not LOF fuel.
4. High- and low-power rods are required for both TOP and LOF tests.
5. The high-power rods are characterized by full zonal restructuring inclusive of the central void. These rods represent GCFR fuel rods with the peak power rating (36.1 kW/m).
6. The low-power rods are defined by a power rating which causes, at most, equiaxed restructuring (perhaps less than 26.3 kW/m).
7. The active core and axial blanket lengths should be prototypical of the GCFR demonstration plant. Variations of perhaps 10% to 20% are tolerable.
8. The fuel rods should have prototypical cladding and fuel pellet dimensions (Ref. 4-7).
9. The power profile in the central half of the fuel rod should be represented to within $\pm 5\%$ of the ideal axial power profile (i.e., a maximum-to-minimum power ratio of 2.0 and a maximum-to-average power ratio of 1.21).

Since the fuel rods should have prototypical cladding diameter and fuel pellet dimensions, it is not possible to use rods irradiated in the FTR by the LMFBR program because they are of smaller diameter. The requirements listed in items 1, 3, and 7 can only be achieved by irradiation of fuel rods in the FTR or a similar fast reactor, such as the prototype fast reactor (PFR). Even if this is done, the active core and blanket length requirements cannot be completely satisfied. The FTR core length is 914 mm compared with the present GCFR core length of 1200 mm, and the maximum length of the lower axial blanket is about 150 mm compared with 600 mm in the latest GCFR design. All other requirements for TOP fuel can be satisfied by irradiation of fuel rods in the FTR. A grid-spaced driver fuel assembly and a multiple duct assembly are candidate irradiation test vehicles.

The LOF fuel rods must be fully enriched, but there is no requirement for a prototypical fluence-to-burnup ratio. Hence, this irradiation can be performed in either the Engineering Test Reactor (ETR) or FTR. Since the availability of the ETR is uncertain, the FTR has been chosen for the irradiation. However, the FTR is a high-flux reactor, and irradiation of highly enriched fuel rods at normal power rating is not permitted. This (HEFA),* problem can be circumvented by using a high-enrichment fuel assembly which has 37 test fuel rods surrounded by a row of B₄C absorber rods (Ref. 4-12).

*HEFA is a multiple duct assembly with 37 test fuel rods surrounded by B₄C absorber rods which will be irradiated in the reflector position of the FTR.

REFERENCES

- 4-1. Nuclear Systems Materials Handbook, Hanford Engineering Development Laboratory (TID-26666).
- 4-2. Billone, M. C., et al., "The LIFE-III Fuel-Element Performance Code," ERDA Report 77-5, Argonne National Laboratory, July 15, 1977.
- 4-3. Langer, S., "Vented Helium Cooled Bundle in CLIRA Loop at FFTF," General Atomic unpublished data, August 18, 1977.
- 4-4. Hanford Engineering Development Laboratory unpublished data, July 22, 1977.
- 4-5. Hanford Engineering Development Laboratory unpublished data, June 1978.
- 4-6. Simon, R. H., "ANL Recommendations for the GCFR Core Development Plan," General Atomic unpublished data, April 6, 1978.
- 4-7. LaBar, M. P., "Tentative Design Basis Transient (DBT) Testing Fuel Requirements," General Atomic unpublished data, March 1, 1979.
- 4-8. "GRIST-2 Test Program Plan, S6100-0001-AP," Argonne National Laboratory, Partial Draft, March 1979.
- 4-9. Frank, M. V., "GRIST-2 Fuel Requirements Development Task," General Atomic unpublished data, June 20, 1979.
- 4-10. Acharya, R. T., "EBR-II Irradiation of Pressurized Capsules," General Atomic unpublished data, October 16, 1978.
- 4-11. Day, J. M., "Design Basis Transient (DBT) Testing Fuel Requirements," General Atomic unpublished data, June 18, 1979.
- 4-12. "FTR Users Guide for the Irradiation of Experiments in the FTR," Hanford Engineering Laboratory Report HEDL-MG-22.

5. IRRADIATION PROGRAM PLAN

Section 4 sets forth the requirements for irradiations in EBR-II, the FTR, and other facilities. This section describes a coordinated irradiation program plan to satisfy these requirements.

5.1. STEADY-STATE IRRADIATION PROGRAM PLAN

The steady-state irradiations can be divided into two distinct categories: (1) steady-state fast flux assembly irradiations and (2) PES performance irradiations. The assembly irradiations will be performed in the FTR; other irradiations will use BR 2 or a similar facility.

5.1.1. FTR Steady-State Irradiations

Part of the GCFR irradiation program requirements (Section 4.1) can be satisfied by irradiating nearly full-size fuel assemblies in an FTR driver position. This type of irradiation will provide overall fuel assembly performance data on sealed rod, sodium-cooled assemblies. This type of data will be useful because the design of the irradiation vehicle will attempt to have essentially all the special features of the GCFR demonstration plant fuel assembly, with the exception of the PES and helium cooling. The low stress on the cladding will be simulated by utilizing a large fuel rod plenum volume connected to a large fuel assembly trap volume through a suitably designed grid manifold structure. It may also be feasible to include the specially designed grid plate shielding structure of the GCFR assembly. The FTR steady-state irradiations (ITSS-1 and ITSS-2) will determine the following:

1. Overall fuel assembly performance in a neutron flux environment prototypical of the GCFR.

2. Failure modes, if any, related to fuel assembly design.
3. Performance of the special design features of the GCFR fuel assembly such as grid spacers, grid plate shielding, and grid manifold.
4. Performance data upon which a statistical data base for fuel rods irradiated in a nearly prototypical fuel assembly can be developed.

The present GCFR program plan is based on the use of the GCFR demonstration plant as the final fuel test bed for demonstrating that a fuel assembly with a maximum cladding midwall temperature of 700°C can be designed to achieve goal burnup. Strategies have been developed to increase the cladding midwall maximum temperature in a stepwise fashion to 750°C based on satisfactory operation of the 700°C fuel assembly design. Experimental verification of the performance of the fuel assembly with a 700°C maximum cladding temperature does not exist at this time, but steady-state irradiation of assemblies in the FTR is designed to verify the performance of the 700°C assembly design. The irradiation plan includes two 127-rod assemblies. These tests are designated ITSS-1 and ITSS-2.

Some failures in the EBR-II irradiations have been traced to interim examinations and handling during the examinations. This external influence on failures can easily be removed by eliminating interim examinations. Therefore, the irradiations will have the basic objective of proving the performance to goal burnup. Once goal burnup has been reached, the assemblies will be subjected to PIE.

5.1.2. GB-11 Sweep Gas Experiment

The GB-11 sweep gas experiment is expected to complete the GB series of pressure-equalized and vented fuel rod irradiations. GB-11 will provide significantly improved simulation of GCFR conditions over capsule GB-10.

After an extensive evaluation of test reactors in the U.S. and Europe, BR 2 was selected for GB-11 irradiation of three single-rod capsules, since it offered the best combination of a large number of technical and nontechnical factors. Among the more important factors is the use of a cadmium-filtered flux, which permits simulation of fast flux radial and axial power, temperature, and fission product birth distributions. In addition, fuel rods with more prototypical fuel and blanket region lengths can be irradiated. Figure 5-1 compares the fuel and blanket regions of GB-10, HELM (including GB-11), and GCFR fuel rods.

The GB-11 sweep gas experiment will be conducted by KFA assisted by CEN as part of an internationally coordinated program for the development of the GCFR. These organizations have much experience in the irradiation and instrumentation of HTGR fuel capsules which they can apply to the design and testing of GB-11 capsules. A preliminary design, cost estimate, and schedule was completed in August 1978. Fabrication of the capsule was scheduled for 1980, and initial irradiation for 1981. However, the shutdown of BR 2 at the end of 1978 for replacement of its beryllium moderator has disrupted the schedule. The BR 2 is scheduled to return to operation in October 1980, but the GB-11 experiment has not yet been rescheduled. Development of a backup plan for the GB-11 tests was scheduled for early 1980.

The GB-11 experiment will consist of simultaneous irradiation of three or four identical capsules, each containing a GCFR-type pressure-equalized and vented fuel rod. The capsules will be irradiated under similar flux conditions at symmetrical positions in the BR 2 core, and their operation will be identical except for the sweep gas operations. One capsule will be operated over its full burnup without sweeping gas through the rod except to measure the flow conductance at full power just after the start of the irradiation and at EOL. A second capsule will be continuously swept over the same burnup interval to simulate operation of a leaking rod. Flow conductance data will also be acquired during the entire test. The third capsule will be operated in the same manner as GB-10; i.e., the fuel rod

Fig. 5-1. Comparison of fuel rods used in irradiation experiments

will be periodically swept over the life of the test to measure flow conductance, release and venting of gaseous and volatile fission products, convective transport of volatile fission products, and performance of graphite trap materials.

The capsule for the GB-11 sweep gas experiment must be designed to take account of the change in the design of the GCFR to an upflow, bottom-vented core. The axial temperature profile will have to be reversed and the fuel rods vented from the bottom. It is desirable to add a fourth capsule in which the upflow temperature distribution would be simulated but the fuel rod would be top vented. However, a fourth capsule may exceed the capability of the BR 2 core to compensate for the negative reactivity of the capsules. In that case, if bottom venting increases the potential for plugging in the GB-11 sweep gas experiment, further irradiation testing will be required. No GB tests beyond GB-11 are planned. The GB-11 sweep gas experiment will provide the following data for DV&S for fuel and PES methods development:

1. R/B at GCFR linear heating rates, axial and radial fuel and cladding temperatures, power and fission product birth distributions, and helium pressure and impurities as a function of burnup.
2. V/R for the same conditions as in item 1 as a function of burnup.
3. V/R during breathing (exhalation) as a result of power, temperature, and helium pressure cycling.
4. Radioactivity from the monitor station as a function of simulated leak flow rate.
5. Fuel chemistry (with helium impurities) determined during PIE of rods operated under nonleaking, leaking, and intermittent leaking conditions.

6. Flow conductance of rods as a function of burnup under nonleaking, continuous leaking, and intermittent leaking conditions.
7. Comparison of volatile fission product (cesium and iodine) transport and sorption in nonleaking and leaking rods and sorption/desorption in intermittently leaking rods (with helium impurities).

5.1.3. Future HELM Irradiations

Future HELM fuel bundle irradiations are necessary to complete the HELM program and acquire the data necessary to support fuel subassembly and PES development. The data will be provided by the HELM 2MO, 4, 5, and 6 irradiations, which are described below.

5.1.3.1. HELM 2MO Fuel Bundle. HELM 2MO will be a modification and reirradiation of the HELM 2 fuel bundle (Section 3.3). HELM 2 will be modified by removing two of the 12 urania-fueled rods from the bundle in the KFA hot cells and replacing them with two fresh, mixed-oxide-fueled rods from a group of unused spare rods fabricated for the HELM 3 fuel bundle. The cladding of one of the two mixed oxide rods will have an artificial defect so that a leak of known size and flow rate can be produced.

HELM 2 is presently in the KFA hot cells for PIE, and the design details for HELM 2MO, including selection of the two mixed oxide rods to be used in the bundle, are being developed. The location of the defect, size and shape of the defect hole(s), leak rate, and defect fabrication method are being considered. HELM 2MO will be irradiated immediately after completion of the HELM 3 bundle test (between the completion of HELM 3 and the end of 1981, when the current KFA contract with CEN for the use of the BR 2 expires). HELM 3 is scheduled to reach its burnup goal of 65 MWd/kg in mid-1981. Thus, the maximum time and burnup available for the mixed oxide rods in HELM 2MO are 6 months and ~15 MWD/kg, respectively. The 10 urania rods

previously irradiated and to be irradiated again with the mixed oxide rods will attain a final burnup of ~22 MWd/kg.

The principal purpose of the HELM 2MO test is to verify the effectiveness of the PES design in maintaining low activity levels in the coolant stream under steady and transient operating conditions when there is a cladding defect. In addition, the data acquired from HELM 2MO will serve the same purposes and uses as those for HELM 3. The leaking bundle test will also

1. Verify that inleakage of coolant at the cladding defect will occur and will prevent or limit the rate of escape of the gaseous and volatile fission products through the defect into the coolant stream.
2. Verify that fuel-cladding mechanical interaction will not prevent inleakage of coolant or significantly reduce its effectiveness in maintaining low coolant activity levels.
3. Verify that impurities in the coolant will not enlarge the defect hole or chemically react near or in the defect so as to significantly reduce the effectiveness of the inleakage in maintaining low coolant activities.
4. Verify that flow through the defect to the vent connection will not change the hydraulic conditions at the vent connection and suction hole in an adverse way with respect to containing the activity in the fuel bundle and PES.
5. Verify that chemical reactions between fuel, cladding, fission products, and coolant impurities at GCFR levels in leaking fuel rods can be tolerated and will permit continued operation over a significant burnup period.

6. Verify the COUNT code for monitor station design under leaking rod conditions.
7. Verify the tritium escape model and computer program to be developed. Because of the sweeping action in the leaking rod, a larger fraction of tritium is expected to be vented, and a smaller fraction should permeate the cladding.
8. Determine the effect of leakage flow through the fuel rod and traps on the distribution of volatile fission products, especially iodine and cesium.

5.1.3.2. HELM 4, 5, and 6 Fuel Bundles. Although irradiation of fuel bundles beyond HELM 3 has always been expected, no specific plans have been made, and only the general purposes of HELM 4, 5, and 6 have been defined to date. No commitment for irradiation of fuel bundles beyond HELM 3 has been made yet by Germany, although there have been discussions and general agreements among the members of the GCFR Fuel Irradiation Coordinating Committee (made up of KFA, KWU, and GA representatives). Irradiations beyond HELM 3 and HELM 2MO (Sections 3.3 and 5.1.3.1) require a further German commitment to the GCFR program. Alternatives to HELM fuel bundle irradiations need to be developed now, since very long lead times are required when major facilities are involved.

HELM 4 is conceived to be a fuel bundle which will reflect the design changes made in GCFR fuel between 1972 and the time that HELM 4 is designed. It is expected to be nearly prototypical of the current GCFR demonstration plant fuel subassembly design and thus to represent a fuel subassembly designed for an upflow GCFR core. Redesign of the HELM in-pile section will be required since HELM was originally designed for downflow of coolant in the fuel bundle. Compared with HELM 3, HELM 4 can be characterized as a 12-rod upflow fuel bundle which is bottom vented, mixed oxide fueled, and stainless steel clad. Its purpose is to verify updated design items and the results of HELM 3 for reverse coolant flow and venting.

HELM 5 differs from HELM 4 primarily in the use of advanced cladding and duct materials. HELM 6 is similar to HELM 5, but its design is prototypical of the GCFR demonstration plant or lead fuel assemblies for the first commercial GCFR plant. HELM 6 might incorporate fuel rods vented from the top and a subassembly vented from the bottom if bottom venting of fuel rods appears to have a significant potential for flow blockage. The specific DV&S purposes of HELM 4, 5, and 6 will be defined as the bundles are designed. Both design and definition of the DV&S program depend upon the results of previous fuel subassembly and PES R&D and irradiation programs.

5.2. PREIRRADIATION PROGRAM PLAN FOR THE DESIGN BASIS TRANSIENT TESTS

The fuel rod requirements for the design basis transient tests are described in Section 4.2. The following irradiations will be conducted to supply the fuel rods for the design basis transient tests:

1. Test ITDB-1 is an irradiation test for the design basis transient program and consists of irradiation of fuel rods encapsulated in high-pressure helium in EBR-II. Because the number of rods required has not yet been determined, irradiation of one subassembly consisting of seven capsules with one fuel rod each has been assumed. Burnup requirements have also not been defined, but for purposes of cost estimation and scheduling, a burnup of ~5 at. % has been assumed.
2. Test ITDB-2 is similar to item 1, but without helium pressure. A seven-capsule subassembly with a burnup of ~5 at. % is assumed.
3. Test ITDB-3 is an irradiation of LMFBR-type fuel rods with prototypical GCFR dimensions. A subassembly consisting of 121 fuel rods irradiated in an FTR drive position has been assumed to be satisfactory. Burnups of 4, 7, and 10 at. % are required.

5.3. IRRADIATION PROGRAM PLAN FOR GRIST-2 SAFETY TESTS

The preirradiation and fuel rod requirements for the GRIST-2 program given in Refs. 4-7 and 4-8 are summarized in Section 4.3. The program is divided into the pre-GRIST-2 and GRIST-2 programs. The following irradiations will be conducted to supply fuel rods for the pre-GRIST-2 program:

1. Test ITSP-1 is an irradiation test for the safety program and consists of irradiation of fuel rods encapsulated in high-pressure helium in EBR-II. A seven-capsule irradiation vehicle with one fuel rod in each capsule is used. A burnup of 2 at. % is required.
2. Test ITSP-2 is similar to item 1, but without helium pressure. A seven-capsule irradiation vehicle with one fuel rod in each capsule is used. A burnup of 2 at. % is required.

In addition, eleven unirradiated fuel rods are required for the pre-GRIST-2 program. The requirements for the design basis transient test program and the pre-GRIST-2 program are almost identical. However, the fuel rod requirements for each program do not permit a reduction in the total number of rods to be irradiated.

Table 5-1 gives the requirements for the GRIST-2 program. Two types of fuel rods are required: (1) TOP fuel rods with a prototypical plutonium concentration and (2) fully enriched fuel rods. In both cases, high- and low-power rod irradiations are required. This means four separate irradiations must be performed in the FTR. Table 5-2 shows the number of rods and the irradiation requirements for each type of fuel rod and identifies the irradiation vehicle. The four irradiations for the GRIST-2 program are as follows:

1. Test ITSP-3 is either an irradiation of 121 fuel rods in a driver-type assembly or an irradiation of 37 fuel rods in a multiduct

TABLE 5-1
GRIST-2 PRELIMINARY TEST PLAN OUTLINE (FIRST 5 YR)

Test	Type	Bundle Size	Fuel Condition	Fuel Type	Rod Power Type(a)	LOF Fuel Failure State	TOP Ramp Rate (\$/s)	Priority
Phase I: fresh fuel tests								
GL1	LOF	7	No preconditioning	UO ₂	NA	Molten		1
GL2	LOF	7	No preconditioning	UO ₂	NA	Vapor		1
GT1	TOP	7	No preconditioning	UO ₂	NA		1	1
Phase II: preconditioned BOL fuel tests								
GT2	TOP	7	1 month preirradiation	Mixed oxide	LP		1	2
GT3	TOP	7	1 month preirradiation, restructured	Mixed oxide	HP		1	1
GL3	LOF	7	1 month preirradiation	Mixed oxide	LP	Molten		1
GL4	LOF	7	1 month preirradiation, restructured	Mixed oxide	HP	Vapor		1
Phase III: preirradiated fuel tests								
GL5	LOF	7	9 months preirradiation	Mixed oxide	HP	Molten		2
GL6	LOF	7	9 months preirradiation	Mixed oxide	HP	Vapor		1
GL7	LOF	3	15 months preirradiation	Mixed oxide	LP	Just melting		1
GL8	LOF	7	15 months preirradiation	Mixed oxide	LP	Molten		1
GT4	TOP	3	9 months preirradiation	Mixed oxide	HP	Rod failure	1	1
GT5	TOP	7	9 months preirradiation	Mixed oxide	HP		1	1
GT6	TOP	7	15 months preirradiation	Mixed oxide	LP		1	2
GT7	TOP	7	9 months preirradiation	Mixed oxide	HP		0.10	1
GT8	TOP	7	15 months preirradiation	Mixed oxide	LP		0.10	2
Phase IV: scaling tests								
GL9	LOF	19	No preconditioning	UO ₂	NA	Molten		2
GT9	TOP	19	No preconditioning	UO ₂	NA		1	2

(a) NA = not applicable; LP = low power; HP = high power.

TABLE 5-2
PREIRRADIATION TESTS FOR SAFETY PROGRAM

Safety Test							Irradiation for Safety Test		
Test	Type	No. of Rods	Irradiation Time (months)	Rod Power (a)	Fuel Type (b)	Test Phase	Test	No. of Rods	Irradiation Device
GT 2	TOP	7	1.0	LP	TYP	II	I	21	Driver
GT 6	TOP	7	15	LP	TYP	III	I	21	or
GT 8	TOP	7	15	LP	TYP	III	I	21	multiduct
GT 3	TOP	7	1.0	HP	TYP	II	II	24	Driver
GT 4	TOP	3	9	HP	TYP	II	II	24	or
GT 5	TOP	7	9	HP	TYP	III	II	24	multiduct
GT 7	TOP	7	9	HP	TYP	III	II	24	
GL 3	LOF	7	1	LP	F	II	III	17	High-
GL 7	LOF	3	15	LP	F	III	III	17	enrichment
GL 8	LOF	7	15	LP	F	III	III	17	fuel assembly
GL 4	LOF	7	1.0	HP	F	II	IV	21	High-
GL 5	LOF	7	9	HP	F	III	IV	21	enrichment
GL 6	LOF	7	9	HP	F	III	IV	21	fuel assembly

(a) LP = low power; HP = high power.

(b) TYP = GCFR prototypical fuel rods; F = fully enriched fuel rods.

assembly to provide 24 high-power rods for TOP tests. These rods will have prototypical plutonium concentrations.

2. Test ITSP-4 is identical to test ITSP-3, but the rods are irradiated at low power to provide 21 low-power rods for TOP tests.
3. Test ITSP-5 uses a HEFA with 37 fully enriched fuel rods to provide 21 high-power rods for LOF tests.
4. Test ITSP-6 is identical to test ITSP-5, but will provide 17 low-power rods for LOF tests.

Irradiation tests ITSP-3 and ITSP-4 can be combined into one test if a lower than normal cladding temperature for the low-power rods can be tolerated. Irradiation tests ITSP-5 and ITSP-6 can be combined under similar constraints. At this time, however, the fuel rod requirements are subject to change because of the recent change in the flow direction of the GCFR core. Because of the remaining uncertainty about GRIST-2 test rod requirements, all four FTR irradiation tests for the GRIST-2 program are being retained. All the design basis transient irradiations and the GRIST-2 irradiations will include PIE and characterization of rods. The PIE provides additional data for the GCFR steady-state statistical data base.

6. RELATIONSHIP OF IRRADIATION PROGRAM TO GCFR LICENSING

The irradiation program outlined in this document is thought to provide a sound basis for licensing the pressure-equalized and vented fuel rods and subassemblies in the GCFR core. However, the extent of the irradiation program required for licensing GCFR fuel for the demonstration plant is not clear and will not become so until the Nuclear Regulatory Commission (NRC) completes its review of the Preliminary Safety Analysis Report (PSAR) and indicates whether or not the program is adequate.

Vented rod irradiation experiments GB-9 and GB-10 and vented bundle experiments HELM-2, 3, 4, and 5 are expected to provide all the physical data and demonstrate that the PES system will operate with a high reliability and only a minimal chance of rod plugging. Fast flux irradiation experiments F-1 and F-5, the high-pressure bundles proposed for EBR-II, and the four to seven FTR bundles should establish a sound statistical basis for rod performance in a fast flux. The steady-state bundle proposed for FTR operation should yield data on subassembly design even though it will be irradiated in sodium. There are no facilities in existence in which a GCFR vented, pressure-equalized, helium-cooled subassembly with more than 13 or 16 fuel rods could be operated in a fast flux. It is thought that the additional information that would be provided by operating a vented 13- or 16-rod bundle in a fast flux would not be sufficient to justify the added cost. Thus, it is believed that the program outlined in this document is the optimum one for the GCFR.

7. RESOURCE EVALUATION AND CONTROL SYSTEM

Figure 7-1 presents irradiation test schedules in terms of required elapsed time and approximate costs. These tests are described below.

7.1. STEADY-STATE IRRADIATION OF FUEL ASSEMBLIES

Two FTR driver assemblies are required for steady-state irradiation of fuel assemblies. No interim examinations are planned.

7.2. DESIGN BASIS TRANSIENT TESTS: PHASE I

Irradiation of two EBR-II assemblies with seven encapsulated fuel rods each is required for the phase I tests. This is a critical path item because (1) these fuel rods are needed as early as possible to validate the use of LMFBR-type rods from FTR irradiations for the balance of the design basis transient tests, and (2) there is uncertainty about the future operation of EBR-II.

7.3. DESIGN BASIS TRANSIENT TESTS: PHASE II

Phase II is a follow-on test for the phase I irradiations. One FTR driver assembly with 121 GCFR-type fuel rods is required. This irradiation will be subject to two interim examinations so that rods at different burnups can be provided for the design basis transient tests.

7.4. PRE-GRIST-2 FUEL

Three EBR-II subassemblies similar to those used for design basis transient test phase I fuel are required for pre-GRIST-1 fuel tests. This is also a critical path item.

Fig. 7-1. RECS for irradiation test program; D104 = duration of 104 weeks (sheet 1 of 2)

Fig. 7-1. RECS for irradiation test program; D104 = duration of 104 weeks (sheet 2 of 2)

7.5. GRIST-2 TRANSIENT OVERPOWER FUEL

Two FTR driver or multiduct assemblies, one each for low-and high-power rods, are required for GRIST-2 TOP fuel tests. These irradiations will be subject to one interim examination.

7.6. GRIST-2 LOSS OF FLOW FUEL

Two FTR high-enrichment fuel assemblies are required for GRIST-2 LOF fuel tests, one each for low- and high-power rods. One interim examination is required.

7.7. GB-11 SWEEP GAS EXPERIMENT

The GB-11 sweep gas experiment consists of simultaneous irradiation of three or four identical capsules, each containing a GCFR-type pressure-equalized, vented rod. This irradiation will be performed in BR-2 or a similar facility.

7.8. HELM 2MO EXPERIMENT

The HELM 2MO experiment is the first experiment to determine the effect of a fuel rod with an artificial defect on PES performance. This test is planned for the BR 2 HELM facility.

7.9. HELM 4, 5, AND 6 EXPERIMENTS

At the present time, the HELM 4, 5, and 6 experiments are not sufficiently defined to allow development of realistic schedules.