FUEL PERFORMANCE IMPROVEMENT PROGRAM

Quarterly/Annual Progress Report

October 1978 -
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ABSTRACT

The objective of the Fuel Performance Improvement Program is to develop, test, and demonstrate basically two advanced fuel designs with the capability for improved power ramping performance and thus, increase the capability of achieving extended burnup levels to better utilize uranium resources. The irradiations are being supported by out-of-reactor experiments to evaluate the effect of graphite coatings to inhibit stress-corrosion-cracking type cladding failures that are related to pellet-cladding interaction. Instrumented test irradiations in the Halden Boiling Water Reactor (HBWR) have achieved peak burnups of 697 GJ/kgM (8.1 MWd/kgM) with reference, annular-coated-pressurized, and sphere-pac rods. Cladding elongation instrumentation indicates that graphite coating significantly reduces pellet-cladding interaction during quasi-steady state irradiation. Like vipac fuel, after the initial power ascensions, there is essentially no fuel-cladding interaction in sphere-pac fuel if the previous LHGR is not exceeded. The measured fuel centerline temperature in sphere-pac fuel continues to be lower than for reference pellet fuel operating at comparable LHGR's. Detailed plans for ramping tests in HBWR were formulated. Design, process development, and fabrication of all the full-length and segmented rods for the demonstration irradiations in BRPR was completed. Irradiation of the 48 segmented rods and 96 of the full-length rods commenced near the end of the year. After accumulating significant burnup, selected segmented rods will be ramp tested.

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SUMMARY

The projected schedules and milestones for the Fuel Performance Improvement Program have been maintained in FY-1979. The results and achievements are presented in this annual report with the most significant ones summarized below.

A program plan was adopted which focuses efforts on the annular-coated-pressurized fuel design with development of the sphere-pac design as a backup. In implementing this plan, the Halden Series H-4 test fuel consisting of sphere-pac rods was added to the program while Big Rock Point Reactor (BRPR) Series S-4 demonstration fuel was eliminated. The extended BRPR outage provided the opportunity to include all of the Series S-1 and S-2 segmented rods in the first loading of demonstration irradiations in BRPR. Thus, all the segmented FPIP rods will complete their irradiation sooner than originally planned.

All fuel rods planned for FPIP were fabricated in FY-1979. The HBWR Series H-2, H-3 and H-4 rods were fabricated in a single campaign and shipped to Halden, thus avoiding the added costs associated with multiple startups, clean-outs, and fabrication campaigns. An added economy was achieved in the case of the BRPR Series S-2 and S-3 rods because they were fabricated concurrent with the BRPR reload batch for Cycle 16.

Fabrication economies noted above would not have been realized without the timely solution to several fabrication problems. The base technology for applying an acceptable graphite coating to the inside surface of the fuel rod cladding tubes was demonstrated by a technique that can be adapted to production quantities. Sphere-pac loading techniques were developed that assured an axial density in the range of 86.5 to 87% TD over the entire length of the fuel column. Special hardware in the form of a retainer disc that assures that the microspheres are retained in the fuel column during loading and handling has been designed and tested for the sphere-pac fuel.

Irradiation of the HBWR Series H-1 test rods continued and irradiation of HBWR Series H-4 commenced in April 1979. With the exception of one centerline thermocouple in a vipac rod, all rod instrumentation is operating satisfactorily. Data evaluation to date shows that as expected, the annular fuel operates at significantly lower centerline fuel temperatures than the reference fuel while the presence of the graphite coating has no significant effect on fuel temperature after a burnup of about 2.5 MWd/kgM. Also as expected, vipac fuel had the highest centerline fuel temperature of the fuel designs under irradiation. Sphere-pac rods had centerline temperatures significantly lower than the reference rod; the helium pressurization in these rods apparently plays a significant role in increasing the effective thermal conductivity. After the first power cycle, cladding elongation sensors and vipac rods and no interaction in the annular-coated-rod where the graphite is apparently functioning as a lubricant. As in the case of vipac fuel, sphere-pac fuel also exhibited fuel-cladding mechanical interaction during the first power ascension, fuel and/or cladding relaxation during operation at the high power conditions, and elongations similar to free expansion of the cladding on subsequent startups. After the initial power ascensions, neither the vipac nor sphere-pac fuel rods undergo significant fuel-cladding interaction as evidenced by cladding elongation behavior as long as previously attained LHGR values are not exceeded. Internal pressure and temperature measurements indicate no significant degradation of the thermal conductivity of contained gas in pellet and graphite coated rods due to dilution of the helium fill gas by fission gases.

A comparative evaluation of the zircaloy cladding being used in the FPIP showed the cladding tubing to be among the most resistant to SCC failure of any tubing tested. These tests were run by the Stanford Research Institute.

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DEFINITION OF THE VARIOUS FUEL ROD TYPES^(a)

<u>Fuel Type</u>	<u>Description</u>
Standard	Standard ENC "product-line." Solid, cylindrical, dished-end-fuel pellet.
Reference	Solid, cylindrical, dished-end, chamferred-corner (except HBWR Series H-1) fuel pellet.
Annular	Cylindrical, flat-ended, chamferred-corner (except HBWR Series H-1) fuel pellet with a central hole equivalent to 10 vol% of a solid, undished pellet.
Vipac	Packed-particle fuel composed of high-density, angular fuel shards, produced by high-energy pneumatic compaction (Dynapak). The rods are pressurized with 400-500 kPa of helium, except in the HBWR Series H-1, and the lower segments of the BRPR segmented rods.
Sphere-pac	Packed-particle fuel composed of high-density, spherical particles produced by the sol-gel process. The rods are pressurized with 400-500 kPa of helium.
Coated-cladding	Cladding coated with Dag 4 ^(b) graphite, except HBWR Series H-1 which utilized Dag 154 ^(b) graphite.
Pressurized	Rods pressurized with 400-500 kPa of helium.
Reference-coated	Reference fuel pellets combined with coated cladding.
Annular-coated	Annular fuel pellets combined with coated cladding.
Reference-pressurized	Reference fuel pellets in a pressurized rod.
Annular-coated-pressurized	Annular fuel pellets combined with coated cladding in a pressurized rod.

(a) All rods are clad with cold-worked and stress-relieved Zircaloy-2 cladding.

(b) Product of Acheson Colloids Corp., Port Huron, MI.

1.0 INTRODUCTION

C. E. Crouthamel (Exxon Nuclear Company)

1.1 PROGRAM OBJECTIVES

The objectives of the Fuel Performance Improvement Program (FPIP) are to identify and demonstrate fuel concepts with improved performance and to provide the supportive technical bases for developing commercial fuel designs that are capable of achieving high burnup for better utilization of uranium.

1.2 BACKGROUND

The Fuel Performance Improvement Program focuses on improving the fuel-cladding interaction behavior of both BWR and PWR light-water reactor fuels. A complete listing of reports previously published under the auspices of the FPIP is given at the end of this section.

1.3 PROGRAM DESCRIPTION

The program description and history have been documented in the previous quarterly reports^(1.4, 1.5) which also give the task structures and brief descriptions of each task.

1.4 PROGRAM ORGANIZATION

The program is performed by Consumers Power Company (CPC), Exxon Nuclear Company (ENC), and Battelle, Pacific Northwest Laboratory (PNL). CPC serves as the prime contractor for the U.S. Department of Energy (DOE)--most of the work has been subcontracted to ENC and PNL. Figure 1.1 illustrates the functional program organization by task.

As prime contractor, CPC has overall responsibility for directing the program. This is accomplished through a steering committee under the chairmanship of the program director. CPC has designated ENC to manage a program office for the execution of the program subject to policy directions and review by the steering committee. In addition, ENC is responsible for the design, process development, and fabrication of fuel concepts under study.

PNL is primarily responsible for performing the research and development portion of the program and the interpretation of results.

The following sections of the report present the progress on program tasks.

FIGURE 1.1. Organization of the Fuel Performance Improvement Program

1.5 FPIP PUBLICATIONS

- 1.1 "Fuel Performance Improvement Program, Quarterly Progress Report, April-June 1977," compiled by C. E. Crouthamel, C00-4066-1, July 1977.
- 1.2 W. J. Bailey, C. L. Wilson, L. J. MacGowan, and P. J. Pankaskie, "State-of-the-Technology Review of Fuel Cladding Interaction," C00-4066-2, PNL-2488, December 1977.
- 1.3 W. J. Bailey and J. O. Barner, "Assessment of Fuel Concepts," C00-4066-3, PNL-2490, January 1978.
- 1.4 "Fuel Performance Improvement Program, Quarterly/Annual Progress Report, April-September 1977," compiled by C. E. Crouthamel, C00-4066-4, November 1977.
- 1.5 "Fuel Performance Improvement Program, Quarterly Progress Report, October-December 1977," compiled by C. E. Crouthamel, C00-4066-5, January 1978.
- 1.6 "Fuel Performance Improvement Program, Quarterly Progress Report, January-March 1978," compiled by C. E. Crouthamel, C00-4066-6, April 1977.
- 1.7 "Fuel Performance Improvement Program, Quarterly Progress Report, April-June 1978," compiled by C. E. Crouthamel, C00-4066-7, July 1978.
- 1.8 "Fuel Performance Improvement Program, Quarterly/Annual Progress Report, October 1977-September 1978," compiled by C. E. Crouthamel, C00-4066-8, October 1978.
- 1.9 "Fuel Performance Improvement Program, Quarterly Progress Report, October-December 1978," compiled by C. E. Crouthamel, C00-4066-9, January 1979.
- 1.10 "Fuel Performance Improvement Program, Quarterly Progress Report, January-March 1979," compiled by C. E. Crouthamel, C00-4066-10, April 1979.
- 1.11 F. W. Buckman, C. E. Crouthamel, and M. D. Freshley, "FCI-Remedy Development for the Fuel Performance Improvement Program," Proceedings Light Water Reactor Fuel Performance, Portland, Oregon, April 29 to May 3, 1979, pp. 158-168.
- 1.12 S. R. Wagoner, J. O. Barner, and R. K. Welty, "Fuel Performance Improvement Program, Description and Characterization of HBWR Series H-1 Test Rods," C00-4066-11, June 1979.
- 1.13 "Fuel Performance Improvement Program, Quarterly Progress Report, April-June 1979," compiled by C. E. Crouthamel, C00-4066-12, July 1979.
- 1.14 S. R. Wagoner, J. O. Barner, and R. J. Guenther, "Comparative Performance of FCI-Remedy Fuel Designs," Trans. Am. Nucl. Soc. 33 (1979), pp. 271-272.

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2.0 TASK 1 - ASSESS FUEL-CLADDING INTERACTION STATE-OF-THE-TECHNOLOGY
AND POTENTIAL IMPROVED CONCEPTS

W. J. Bailey (Pacific Northwest Laboratory)

The objective of Task 1 was to assess the state-of-the-technology of fuel cladding interaction and to identify fuel concepts with potential for improved performance capabilities in order to provide direction and technical support for the Fuel Performance Improvement Program. With the completion of the topical reports entitled, "State-of-the-Technology Review of Fuel - Cladding Interaction" (C00-4066-2/PNL-2488) and "Assessment of Fuel Concepts" (C00-4066-3/PNL-2490), activities associated with this task were completed.

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3.0 TASK 2 - TESTING AND DEMONSTRATION PROGRAM

M. D. Freshley (Pacific Northwest Laboratory)

The objective of the testing and demonstration program, which forms the basis for the Fuel Performance Improvement Program (FPIP), is to provide the data needed for establishing technical design bases for those fuel concepts with improved performance capabilities that are being evaluated as part of this program. The testing and demonstration program includes Task 2A, Out-of-Reactor Experiments; Task 2B, In-Reactor Experiments; and Task 2C, In-Reactor Demonstrations.

Task 2A activities provide out-of-reactor supportive data needed for the Task 2B irradiation experiments in the Halden Boiling Water Reactor (HBWR), and the Task 2C demonstration irradiations in the Big Rock Point Reactor (BRPR). Task 2B involves an in-reactor testing program that consists of screening tests conducted with instrumented fuel rods in the HBWR, followed by ramping of individual rods in the HBWR ramping rig; and primary tests that consist of the irradiation of segmented rods to significant burnup levels in BRPR, followed by ramping in a suitable test reactor. Task 2C activities involve the design, process development, fabrication, quality control, and licensing of a significant number of fuel rods comprising the primary fuel concepts for demonstration irradiations in BRPR.

Current activities and major activities that occurred in Task 2 during FY-1979 included an evaluation and development of the detailed overall program plan based on four different scenarios. "Case IV," which is based on concentrating the research and development efforts of the program on an optimized annular-coated-pressurized fuel design with the development of the sphere-pac design as a backup on a modest to minimum level of effort, was the recommended and accepted case. Implementation of the plan and changes in reactor operating schedules resulted in modifying the test matrix and plan for the ramping tests in HBWR and the loading of demonstration fuel rods in BRPR. The major change in the Halden test matrix and ramping plan was the addition of HBWR Series H-4 that included instrumented sphere-pac rods (Figure 3.1) and to focus the ramp

ROD TYPE	NO. RODS (NO. RODS TO BE RAMPED)	TEST IDENTIFICATION				
		II-1-IC	II-1-UC	II-2-UC	II-3-UC	II-4
			II-2-LC	II-3-LC		
REFERENCE	8 (7)					
ANNULAR	2 (2)					
COATED (DAG 154)	3 (3)					
COATED (DAG 4)- PRESSURIZED	6 (6)					
VIPAC	4 (4)					
SIHERE-PAC PRESSURIZED	5 (2)					

TEST IDENTIFICATION

H - TEST NUMBER

IC - LOWER CLUSTER

UC - UPPER CLUSTER

INSTRUMENTATION IDENTIFICATION

E - ELONGATION SENSOR

P - PRESSURE SENSOR

T - FUEL THERMOCOUPLE

• A ROD WITH THE
INDICATED INSTRUMENTATION

FIGURE 3.1. Halden Test Matrix

tests more on the primary fuel concepts. The major changes in the BRPR demonstrations included elimination of BRPR Series S-4 (Figure 3.2) and modification of the planned BRPR Series S-1 irradiations to facilitate loading all of the Series S-1 and S-2 segmented rods in the first loading of FPIP rods in BRPR (Figure 3.3). Thus, because of the opportunity afforded by the extended BRPR outage, which is described below, all of the segmented demonstration rods have commenced irradiation sooner than originally scheduled.

The BRPR shut down for a scheduled refueling outage on February 1, 1979. In addition to normal refueling, the outage included replacement of the emergency core cooling sparger. This work was completed in April 1979. The plant was brought critical for a brief period and on April 17, 1979, primary system leakage greater than that permitted by the Technical Specifications was identified. The plant was removed from service to locate and reduce the leakage.

<u>FUEL FORM</u>	<u>PARAMETERS</u>		<u>FULL-LENGTH RODS</u>	<u>SEGMENTED RODS</u>
	<u>COATED</u>	<u>PRESSURIZED</u>		
ANNULAR	YES	YES	146	12
	YES	NO	20	4
	NO	NO	20	4
SPHERE-PAC	—	YES	38	8
VIPAC	—	YES	15	4
REFERENCE	YES	NO	—	—
	NO	YES	—	—
	NO	NO	56	16
			295	48

FIGURE 3.2. Summary of Demonstration Irradiations for the Big Rock Point Reactor

TEST SERIES	ASSEMBLY NUMBER	FUEL ROD TYPE	FULL-LENGTH RODS/ASSEMBLY	SEGMENTED RODS/ASSEMBLY (CENTER SEGMENT)
S-1	G4-21	R	6	4
		S	2	-
		A	4	2
		AC	4	2
		ACP	6	2
		VP	2	2
S-1	G4-22	R	6	4
		S	2	-
		A	4	2
		AC	4	2
		ACP	6	2
		VP	2	2
S-2	HI-O2	R	4	4
		ACP	16	4
		SP	4	4
S-2	HI-O3	R	4	4
		ACP	16	4
		SP	4	4
			96	48

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R = REFERENCE PELLET
 S = STANDARD PELLET
 A = ANNULAR
 AC = ANNULAR-COATED
 ACP = ANNULAR-COATED-PRESSURIZED
 VP = VIPAC (PRESSURIZED)
 SP = SPHERE-PAC (PRESSURIZED)

FIGURE 3.3. BRPR Segmented Rod Bundles Comprising the First FPIP Loading in BRPR

The excessive leakage detected was determined to be due to leakage past the control rod drive O-ring seals. In correcting this leakage and performing a pressure test of the primary system, additional leakage of several milli-liters per minute was detected. This additional leakage was noted where a control rod drive housing penetrated the lower reactor vessel head and was indicative of abnormal degradation of the primary pressure boundary. Further investigation related to this leakage also disclosed that flow-directing baffles within the reactor vessel had become disengaged during service. This latter problem required removal of most reactor internal components and the installation of new flow baffles.

Investigation and repair of the control rod drive housing penetration leak and replacement of internal flow baffles required an extended outage of several months. This effort was completed, and the plant was returned to service on November 9, 1979.

Out-of-reactor experiments (Task 2A) included: developing coating technology to qualify the coating selected (Dag 4) for in-reactor use; determining the characteristics of the coating; developing an optimized application technique; and transfer of the technology to a production-type operation. These developments were successful and it is considered that the base technology for applying an acceptable graphite coating to the inside surface of cladding tubes, treating, and handling the coated tubes has been demonstrated by techniques that are adaptable to production quantities. Siloxane coatings were evaluated and further development was discontinued because the coatings contained what is considered to be excessive amounts of hydrogen.

Friction and wear tests were performed to provide comparative data on the abrasion and wear characteristics of the coatings under different testing conditions, as well as dynamic and static friction coefficient values. FCI-simulator tests are being performed in different environments and over a range of strain rates to provide comparative data on the effectiveness of graphite coatings to improve FCI behavior. Coating function studies were initiated to

study the function of the coating or the manner in which it acts to improve performance. A comparative evaluation of the zircaloy cladding being used in the FPIP, performed at Stanford Research Institute using their standard testing method, showed the FPIP cladding tubing to be among the most resistant to SCC failure of any tubing tested.

In-reactor experiments (Task 2B) activities were involved primarily with data acquisition associated with the continued irradiation of HBWR Series H-1 in Halden. With the exception of one centerline thermocouple in a vipac rod, all the instrumentation on the twelve rods is operating satisfactorily. Instrumented rods for HBWR Series H-2, H-3 and H-4 were designed, the process development was performed, and the rods were fabricated. Irradiation of HBWR Series H-4, which contains reference and sphere-pac rods instrumented with thermocouples to measure centerline fuel temperature, was started. Enriched UO_2 microspheres in three size fractions for the sphere-pac rods were obtained from Oak Ridge National Laboratory (ORNL). The detailed ramping plan for HBWR Series H-1 and H-4 rods was developed.

In-reactor demonstrations (Task 2C) activities included the neutronic, mechanical and thermal design, process development, fabrication, and licensing of full-length and segmented rods for BRPR Series S-2 and S-3. Some of the major developments included design and fabrication of segmented rods for irradiation in BRPR, the production of high quality annular pellets with an edge chamfer, the development of a process for applying graphite coating to the inside surface of cladding tubes, the fabrication of uniform density sphere-pac rods, and development of an internal retainer disc to contain the sphere-pac fuel column during rod fabrication, pressurization, and handling. Enriched UO_2 microspheres (66.5 kg) were procured from ORNL to fabricate the BRPR fuel rods.

4.0 TASK 2A - OUT-OF-REACTOR EXPERIMENTS

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The purpose of this task is to conduct application-oriented out-of-reactor studies in support of the development and demonstration of fuel designs that will improve fuel performance by minimizing failures caused by fuel-cladding mechanical interaction (FCI). Current activities include coating technology development and transfer of the technology for production of the BRPR Series S-2 and S-3 fuel rods, siloxane coating studies, friction and wear testing, comparative tests using the FCI simulator, coating function studies to evaluate the effectiveness of graphite coatings to improve FCI behavior, and evaluation of the iodine-SCC resistance of the cladding.

4.1 GRAPHITE COATING STUDIES

A modified method for controlling the thickness of Dag 4 graphite coatings applied to the inside surface of zircaloy cladding was described in a previous report.^(4.1) This approach, based on short draining and drying times, proved ineffective when applied to cladding tubes for the BRPR Series S-2 and S-3 fuel rods. In order to meet the fabrication schedule for Series S-2 and S-3 rods, the coating application method was modified based on what had been learned previously. The following measures were used:

1. The dag was continuously agitated to eliminate any tendency toward either settling or gelation.
2. The mixing container was modified to prevent air exposure while withdrawing dag.
3. The draining and drying times were standardized at 10 and 5 minutes, respectively.
4. At the beginning of each day's work, a trial group of tubes was coated and measured before coating more tubes to either give assurance that the production for the day would meet thickness specifications or signal a need for a change in solids content.

5. Tubes were coated in sequential order to identify trends in coating thickness with time, and solids content of the slurry was monitored to relate this parameter to coating thickness.

These measures proved effective during coating of the large number of tubes processed. The acceptance rate was >90%, and essentially all of the rejects were produced during a single day when the trial group indicated marginal results. The average coating thickness per tube, when averaged over the 200 acceptable tubes coated, was $6.0 \mu\text{m}$ with a standard deviation of $0.6 \mu\text{m}$. This compares favorably with the specified thickness of $6.4 \pm 1.3 \mu\text{m}$ for the tube average. In the case of the segmented fuel rods for BRPR, the coating thickness specifications were met even more closely. This group of twelve tubes had an average coating thickness of $6.3 \mu\text{m}$. This was accomplished by adhering to the methods described above, with some selecting and recoating of tubes to meet a more stringent specification of $6.4 \pm 0.5 \mu\text{m}$ for the tube average.

These coating results are considered to represent the best that is reasonably attainable by the flood coating technique, as well as the limit of the present capability to measure coating thickness. Further, it is considered that the base technology for applying an acceptable graphite coating to the inside surface of fuel rod cladding tubes has been demonstrated.

4.2 SILOXANE COATING STUDIES

Siloxane coating applied to the inside surface of zircaloy cladding have been reported by Canadian investigators^(4.2) to prevent stress-corrosion-cracking (SCC) involving iodine. Two forms of siloxane were evaluated in an effort to produce an acceptable protective coating; silicone vacuum grease and a Dow-Corning resin.

Vacuum grease (Dow-Corning 971V) thinned with trichloroethane was used as a dip coating for sections of zircaloy cladding. The hydrogen content of the coating after evaporation of the thinner was calculated to be 7.5 wt%, which could exceed present specifications for hydrogen contained in LWR cladding. (A hydrogen content of 3% in the coating would add about 50 ppm to BRPR

cladding if uniformly dissolved.) The grease-coated zircaloy was baked at 310°C in air for 20 hr to remove hydrogen by oxidation. (At higher temperatures the zircaloy oxidizes significantly in air and the coating becomes nonadherent and brittle.) The amount of hydrogen remaining after baking remained unacceptably high, i.e., between 3% and 4%.

Dow-Corning resin X96502, a resin-forming liquid, was also evaluated as a coating for cladding tubes. After air drying, the resin coatings contained about 2.5 wt% hydrogen. The coating was easy to apply and required only a low temperature cure, i.e., 150°C for 10 minutes. However, essentially no hydrogen was removed during the cure, and temperatures of 500°C were required to reduce the hydrogen content to an acceptable level of 1%. A treatment temperature of 500°C degraded the coating and the cladding excessively.

Work on siloxane coatings was discontinued because the hydrogen content of siloxanes, even after treatment, remained unacceptably high.

4.3 FRICTION AND WEAR TESTING

Because pellet-to-cladding friction may be involved in the effectiveness of graphite coatings to improve FCI behavior, a series of tests was performed to evaluate the friction and wear characteristics of the different types of graphite coatings of interest to this program. Initially, Dag 154 was evaluated and used as the coating type for the inside cladding surface in the first series of irradiations being conducted in the Halden Boiling Water Reactor (HBWR). Subsequently, after further evaluation of potential graphite coating types, Dag 4 was substituted for Dag 154 and is the preferred type because of its superior adherence characteristics and abrasion resistance during pellet loading. For comparison purposes, both Dag 154 and Dag 4 were included in the friction and wear evaluations.

A pin-on-disk type of apparatus, utilizing a round-tipped (1.3 cm radius) UO₂ pellet riding on coated or noncoated zircaloy disks, was used for these tests. With this apparatus, a variable load is applied and measurements made over sliding distances that are long and speeds that are high, relative to the

differential pellet-cladding movement that occurs in a fuel pin. Static friction, i.e., the friction force just before movement occurs between the UO_2 pellet and the zircaloy disk, was also measured.

It was recognized that the test conditions which would most closely simulate those that exist between UO_2 pellets and zircaloy cladding in an actual fuel rod are high load and small differential movement at very low speeds. However, it was expected that the test results obtained over long sliding distances would: 1) provide a relative measure of the effectiveness of the different graphite coatings to reduce the pellet-to-cladding friction, and 2) provide a comparison between the behavior of coated and noncoated cladding. The static friction results are considered to be more representative of the physical situation that exists between the fuel and cladding in an actual fuel rod.

During the testing, a coating was assumed to have failed when the friction coefficient reached a value of 0.2. This arbitrary standard was verified as being reasonable by inspecting the disk wear track after testing. With no coating failure during the test, the wear track was narrow with only smooth shiny graphite visible. At failure, the wear track clearly showed bare zircaloy. Further running after failure produced a wide wear track of bare zircaloy metal with UO_2 (identified by SEM) embedded in the surface, and the rider showed a correspondingly large wear scar. Coating performance was also evaluated by calculating the amount of UO_2 worn from the rider during the test, as indicated by the wear scar diameter of the pellet tip.

The friction and wear test results for conditions which are the most representative of those which exist within an operating fuel rod, i.e., 300°C in dry helium, are summarized in Table 4.1. The results indicate: 1) the friction coefficient is lower with both types of graphite coating than with no coating; 2) the wear characteristics of both graphite coatings is similar under these conditions; 3) UO_2 rider wear is increased when a graphite coating is present. The first observation is expected and the second is probably a result of the UO_2 rider shape. The third observation is consistent with the fact that graphite can become an abrasive under dry high temperature conditions.

TABLE 4.1. Friction and Wear Tests Run Through Standard Sequence of 543 Revolutions

Test No.	Zircaloy Disk Coating	Test Conditions	Life of Coating in Revolutions	Friction Coefficient, μ	Wear of UO ₂ Rider in cm ³ Worn per m of Sliding Distance (1 Rev. = 6.3 cm)
15	None	300°C, helium(b)	0	0.19-0.34(c)	2.1x10 ⁻⁶
16	None	300°C, helium	0	0.21-0.32	4.0x10 ⁻⁶
17	None	300°C, helium	0	0.21-0.42	7.0x10 ⁻⁶
18	Dag 154(a)	300°C, helium	3.8	0.05-0.42	9.5x10 ⁻⁶
19	Dag 154	300°C, helium	17.5	0.03-0.24	9.9x10 ⁻⁶
20	Dag 154	300°C, helium	17.5	0.01-0.31	7.5x10 ⁻⁶
21	Dag 4	300°C, helium	8.5	0.02-0.37	7.0x10 ⁻⁶
22	Dag 4	300°C, helium	17.5	0.03-0.42	10.0x10 ⁻⁶

- (a) Coatings were ~6 μ m thick and outgassed for 24 hr at 425°C prior to testing. Coatings were applied to a zircaloy surface ground through 600 grit.
- (b) Helium was backfilled through a 825°C zirconium getter into an evacuated chamber.
- (c) The coefficients of friction listed in the left hand column are values obtained at the beginning of the test, whereas the values listed in the right hand column were obtained at the end of the test.

The mechanical loading conditions that exist between the fuel pellet and the cladding during PCI are such that static friction behavior is probably most important. Consequently, the test apparatus was modified so that the tractive force could be slowly increased until motion occurred. The static friction coefficient was calculated using the peak force recorded before pellet sliding occurred and the results are summarized in Table 4.2. In the case of Dag 4, no peak load was discernible so the reported coefficient is kinetic. It is shown that the static friction coefficients are not significantly higher than the kinetic coefficients.

Under the extremely dry, high pellet-to-cladding loading conditions that exist within an operating fuel rod, it is doubtful that either graphite would lubricate the interface effectively over long sliding distances. However, the very small differential fuel-to-cladding movements which occur in a fuel rod would permit graphite to function as a lubricant, or at least as a parting layer to prevent pellet-cladding bonding. Hence, it is indicated that the graphite coating applied to the inside surface of the cladding acts as a lubricant which would help distribute cladding stresses and aids in reducing one of the supposed contributors to PCI-type failures.

TABLE 4.2. Static Friction Results

Coating and Testing Conditions	Static and Kinetic Friction Coefficients (μ_s and μ_k) from Static Friction Test, 3.3-13.2 kg Load	Static and Kinetic Friction Coefficients (μ_s and μ_k) from Static Friction Test, 26.3 kg Load
Noncoated, 300°C helium	0.39 _s - 0.31 _k	0.32 _s - 0.28 _k
DAG 154, 300°C helium	0.06 _s - 0.05 _k	0.035 _k
Dag 4, 300°C helium	0.06 _k	0.06 _k

NOTE: s = static
k = kinetic

4.4 FCI SIMULATOR STUDIES

The FCI simulator is a load application system designed to simulate the loading conditions in the cladding at the pellet-pellet interface with cracked fuel. It is presently being used to evaluate the effects of the selected fuel design options, coatings, and chemical environment on FCI behavior. In tests to date, alumina has been used as a stand-in for UO_2 . Figure 4.1 depicts the simulator schematically, while Figure 4.2 illustrates the details of the loading hardware.

In the present test series, it was desired to test at a variety of strain rates of the same magnitude as would occur in a realistic power ramp. To test in a strain-rate-controlled mode, it is necessary to monitor hoop strain. The original design for displacement measurement used opposing push-rods driving metal leaves with strain gauges attached. This yielded strain data at two diametrically-opposed points. In order to obtain a better method of measuring hoop strain, a fine (~ 1 mm) gold chain, lubricated with graphite, is looped around the sample at the midpoint where deformation is a maximum. Movement of the chain transmits a force to the strain-bearing leaves which provides a more valid measurement of average hoop strain. Figure 4.3 shows the prior and present arrangements.

The loading machinery for the FCI-simulator is composed mainly of a variable-rate delivery system for hydraulic fluid, the force being derived by the use of slave cylinders. The arrangement does not permit easy automatic control of strain rate, and control presently is being performed manually with adjustments being made to follow a preprogrammed schedule of strain versus time. As a first indication of failure, the load drops and strain rate increases. Another indication of cladding failure is provided by a water bubbler on the helium gas as it exits the apparatus.

Figure 4.4 is a summary of FCI-simulator tests conducted to date; all testing was done at 300°C . Total circumferential strain at failure is plotted as a function of strain rate, which was varied between 5×10^{-3} and $2 \times 10^{-2} \text{ hr}^{-1}$. Over this range, the strain-at-failure of noncoated cladding without iodine is quite linear with strain rate, and failure occurs at an average strain of 3% to 4%. When iodine is added (300 Pa partial pressure),

FIGURE 4.1. Schematic (Block) Diagram of the FCI Simulator

FIGURE 4.2. Sectional Views of an FCI-Simulator Specimen Showing Details of Loading Hardware

FIGURE 4.3. Two Different Techniques Used for Measuring Strain of an FCI-Simulator Specimen

FIGURE 4.4. Summary of FCI-Simulator Tests to Date - Strain Rate Sensitivity Series

the strain-at-failure dropped to the 1% to 2% range, as indicated by the solid triangles. Some tests have also been performed on cladding tubes coated with Dag 4 (6 μm coating, outgassed 24 hr at 425°C). On the basis of preliminary data, it appears that the strain-at-failure has been increased by the graphite coating to about the same extent that the presence of iodine reduced the strain-at-failure.

Testing with both iodine and graphite present is a condition where both the physical and chemical effects of the graphite are active simultaneously. To separate physical effects, two graphite-coated specimens were tested with no iodine present. Neither failed, even though deformation was carried to over twice the strain levels achieved in previous testing (8.5 and 10%). Thus, it is shown that the presence of the graphite coating on the inside surface of the cladding significantly reduces friction.

4.5 COATING FUNCTION STUDIES

Although a significant amount of data has been accumulated which indicates that a graphite coating applied to the inner surface of the cladding is effective in improving FCI behavior, the mechanism is largely speculative. Explanations range from a simple reduction in pellet-cladding friction to sorption of fission product such as iodine, which is a known SCC agent. Experimental activities to elucidate the manner in which graphite coatings improve FCI behavior have been undertaken.

The thermodynamic effects of adding a graphite coating to the inside of the zircaloy tubing was examined using the data from JANAF^(4.3) and Cubicciotti.^(4.4) Even though the potential reactions of carbon leading to the formation of carbon monoxide or carbon dioxide add a negative free energy to the overall reaction, the addition is not sufficient to overcome the positive free energies of the zirconium oxides. Consequently, zirconium oxide remains a barrier to the formation of the zirconium iodides, whether from free iodine or cesium iodide, at temperatures below 570°C. The formation of both uranium and zirconium carbide from the oxides is not expected at temperatures below 730°C, based on both thermodynamics and kinetic data. Based on the thermodynamic considerations, graphite also does not alter the chemical

behavior of the zirconium or uranium dioxide. The effects of the graphite on the chemical state of the fission products will be examined further.

Previous work^(4,5) has shown a correlation between iodine-SCC and Fe-Ni containing inclusions in zircaloy. A series of tests were conducted to determine the effects of I_2 vapor on the second phases normally found on the inside surface of zircaloy tubing. Samples of the Zircaloy-2 cladding used in the Halden irradiation tests were exposed to a flowing helium- I_2 mixture (40 pa I_2) at 300°C and atmospheric pressure. The second phase particles tend to grow due to exposure to the flowing gas stream. Optical micrographs of identical areas of the zircaloy tubing surface, before and after 2 hr exposure, are shown in Figure 4.5a and 4.5b, respectively. Close comparison showed that about 50% of the particles increased in size. The size increases tend to occur within the first 2 hr, as additional exposure for 12 hr did not result in further size increases.

Figure 4.6 shows higher magnification of the inside surface of the zircaloy tubing after 2 hr exposure. Due to the depth of interaction of the electron beam, quantitative analysis of the small (1 to 2 μ m) precipitates is not possible using the scanning electron microscope, so the analysis is qualitative. From the elemental analysis that was made, the precipitates after reaction are mostly Fe and I, with perhaps some Ni present. As also noticed in Figure 4.6, the growth of the precipitates gives a cracked appearance to the surface. The cracking appears to be in the precipitate. Even though the exposed surfaces of the cladding are oxidized, the zircaloy underneath the second phase may not have a protective oxide corrosion barrier. The volume expansion associated with the formation of the second phase will generate stresses that might result in localized SCC. Both the chemical interaction of the precipitate with the iodine and the resulting cracking may control the initiation phase of the iodine-SCC in the zircaloy cladding. The effect of graphite coating on growth of the second phase precipitates will be examined further. The significance of the above observation is that the iodine reacts with precipitates which are an integral part of the alloy, not with foreign inclusions such as described in Reference 4.5.

FIGURE 4.5a. Scanning Electron Micrographs of the Same Area of Cladding Inner Surface Before a 2-hr Exposure to Iodine in Helium

FIGURE 4.5b. Scanning Electron Micrographs of the Same Area of Cladding Inner Surface After a 2-hr Exposure to Iodine in Helium

FIGURE 4.6. Scanning Electron Micrographs of the Same Area of Cladding Inner Surface, Different Area with More Severe Attack, Higher Magnification

In order to study the function of the graphite coating, it was considered necessary to simplify the means by which the cladding is stressed as compared to the FCI-simulator because the surface of the specimens used in the FCI-simulator become damaged to the extent that a valid pre- and post-test examination is not possible. Consideration of the various requirements, such as well-defined chemistry and stress/strain conditions, led to the adoption of a D-ring type of test.

A D-ring test apparatus has been assembled and check-out testing is nearly complete. The test apparatus, schematically shown in Figure 4.7, consists of a means of pulling notched zircaloy tubes in the hoop direction using hardened tool steel dies and pulling devices which will be gold plated to prevent reaction with the test atmosphere. The entire pulling assembly is placed inside a stainless steel environmental chamber sealed with O-rings.

FIGURE 4.7. Hardware and Specimen for D-Ring Tests

Inlet and outlet ports on one of the O-ring sealed ends allow for atmosphere control in the chamber. The entire chamber is placed in a furnace providing uniform ($\pm 15^{\circ}\text{C}$) heating of the chamber. Uniform heating reduces the possibility of iodine deposition, resulting in better control of the atmosphere. All temperatures are measured using chromel-alumel or plutonium-rhodium thermocouples. An oxygen-measuring meter is used on the gas outlet to check for air leaks during the pulling of the specimens and to verify calculations of minimum purge times. The test assembly has been operated up to 8900 N force with no plastic deformation of the pulling devices (less than 8900 N are necessary for the SCC tests). The remaining system checkout tests will be completed and testing begun next quarter.

4.6 CLADDING EVALUATION FOR IODINE SCC RESISTANCE

The cladding obtained for use in the Fuel Performance Improvement Program (FPIP) was purchased according to standard specifications as used by Exxon Nuclear Company, but was of unknown resistance to iodine stress-corrosion cracking (iodine-SCC). Because initial tests had yielded variable results using the stress-ring method,^(4.1) it was decided to evaluate the iodine-SCC resistance of FPIP cladding using a standardized method in order to compare the characteristics of FPIP cladding with other cladding tubes of known behavior.

Stanford Research Institute, International (SRI) has done a great deal of work on iodine-SCC,^(4.5) primarily under the sponsorship of the Electric Power Research Institute, and has developed special procedures for testing the relative iodine-SCC resistance of cladding. The standard test used is to pressurize a capped section of cladding containing iodine ($\sim 6 \text{ mg/cm}^2$) and maintain the pressure at a fixed temperature of 317°C . The time-to-failure is noted as a function of pressure. A piece of archive cladding from the lot (Serial No. 231) that was used in the Halden irradiation tests, was subjected to the above test and the results are shown in Figure 4.8. Data representing two batches of Zircaloy-2 cladding manufactured to the same mechanical specifications by different suppliers, A and B, as well as a well-characterized lot of Zircaloy-2 (7AH11-H),^(4.6) are also shown. In the absence of iodine, the FPIP cladding showed a short-time burst strength of 518.5 MPa. The burst strength was evaluated in a ramping mode and is shown as points on the ordinate of Figure 4.8. Data for the iodine-free condition (solid squares) show only a small pressure dependence of time-to-failure. In the presence of iodine, the time-to-failure at a given stress level does not drop as rapidly as the other cladding tested. The FPIP cladding is the most resistant to iodine-SCC failure of the cladding specimens that have been examined to date by SRI. At short failure times, the failures took the form of longitudinal splits with attendant "x" marks, whereas at long times, pinholes were more common. This behavior is usual as judged by other results.

These test results indicate that the cladding used in the Halden irradiation tests is not immune to iodine-SCC, but appears to be substantially more

resistant than the types of Zircaloy-2 cladding evaluated by SRI. The absence of large Fe-Cr or Fe-Ni-Cr surface inclusions, as noted in SEM examination, may be a contributing factor. Large foreign inclusions have been found to correlate with iodine-SCC nucleation sites.^(4.5)

FIGURE 4.8. Iodine SCC Resistance, in Terms of Time-to-Fracture Versus Internal Pressure, for FPIP Cladding. (Also shown are results from other Zircaloy-2 cladding specimens.)

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5.0 TASK 2B - IN-REACTOR EXPERIMENTS

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The objective of the in-reactor experiments task is to conduct irradiation tests to study the behavioral characteristics and performance limits of those fuel concepts which have potential for improved operating behavior in LWRs. Irradiation experiments are being performed with emphasis on the annular-coated-pressurized design and, at a more modest level, the pressurized sphere-pac design as a backup. The performance of both designs is compared with a reference fuel design. The performance characteristics of the improved concepts are being evaluated in screening tests, which involve three sequential series of power cycling and ramping irradiations of instrumented rods in the Halden Boiling Water Reactor (HBWR) and the irradiation of instrumented sphere-pac rods in HBWR to measure central fuel temperature and cladding elongation behavior of this fuel type. The results of these comparative irradiations will be utilized to select the most promising fuel concept(s) and test conditions for evaluation in the primary power-ramping experiments. Rod segments for the primary ramping tests are being irradiated in the Big Rock Point Reactor (BRPR) as a part of the Task 2C in-reactor demonstrations.

Details of the general testing criteria, the selection of the irradiation facilities, and the detailed test descriptions of irradiations currently in progress were presented in previous progress reports.^(5.1,5.2) Regarding the initial HBWR Series H-1 irradiations which are in progress, the emphasis was placed upon evaluating the individual effects of design differences between reference, annular, annular-coated, and vipac designs.

5.1 SUMMARY DESCRIPTION OF HBWR TESTS

The objective of the screening tests in the HBWR is to provide comparative fuel temperature, cladding elongation, internal rod pressure, and power-ramp

data for the improved concepts and the reference fuel design. The data will be used to compare fuel performance and support the technical bases for design and licensing.

The screening tests are being performed in two test rigs in the HBWR. The IFA-518 test rig contains two six-rod clusters, and the power in the two clusters is varied by alternately moving a silver absorber shield over one of the two clusters. The IFA-517 test rig contains a single cluster of four rods. Rod instrumentation in both assemblies includes fuel centerline thermocouples, elongation sensors, and internal pressure sensors. The peak operating linear heat generation rate in both assemblies is 44.5 kW/m. IFA-518 will be sequentially loaded with rods comprising HBWR Series H-1, H-2, and H-3, respectively. Peak burnups will be in the range from 1200 to 1400 GJ/kgM (14 to 16 MWd/kgM) prior to ramping. The majority of the IFA-518 rods will be power-ramped.

The HBWR Series H-4 rods will be irradiated in IFA-517 to peak burnups in the range from 520 to 700 GJ/kgM (6 to 8 MWd/kgM) prior to ramping three of the four Series H-4 rods. The HBWR test matrix and rod instrumentation is shown in Figure 3.1.

5.2 DESIGN AND ANALYSIS - HBWR SERIES H-2, H-3, AND H-4

The HBWR Series H-2 and H-3 rods consist of three fuel types: reference, annular-coated-pressurized, and sphere-pac. Series H-4 contains only reference and sphere-pac rods. Characteristics of the Series H-2, H-3, and H-4 fuel rods are listed in Table 5.1. The fuel rods from these series are essentially the same dimensional configuration as the HBWR Series H-1 rods.^(5.1)

The major innovations in the Series H-2, H-3, and H-4 rods, compared to the Series H-1 rods, are the use of an improved graphite coating material (Dag 4), substitution of gel-derived microsphere (sphere-pac) fuel for dyna-packed, angular particle (vipac) fuel, prepressurization of the annular pellet and sphere-pac fuel rods to 455 kPa (66 psia), small edge chamfer on the annular and reference fuel pellets, and redesign of the end cap weld configuration to improve the weld performance.

The Dag 4 graphite coating, which contains alumina and silica, is preferred because of its improved abrasion resistance compared to the previously used Dag 154.^(5.1)

TABLE 5.1. Characteristics of HBWR Series H-2, H-3 and H-4 Test Rods

Reference Fuel

Type	Solid pellet
Material	UO ₂
Density, %TD	94
Diameter, mm (in.)	10.262 (0.4040)
Length, mm (in.)	8.13 (0.320)
Dish, vol%	1.0
Chamfer, vol%	0.6 (both ends)
Enrichment, wt% ²³⁵ U	11.0

End Pellets

Number (per rod)	2
Location	One at each end of fuel column
Geometry/density	Same as reference fuel, except for chamfer
Enrichment, wt% ²³⁵ U	2.78

Annular Fuel

Type	Annular pellet
Material	UO ₂
Density, %TD	94.0
Diameter, O.D., mm (in.)	10.249 (0.4035)
Diameter, I.D., mm (in.)	3.25 (0.128)
Length, mm (in.)	8.13 (0.320)
Dish	None
Chamfer, vol%	0.6 (both ends)
Enrichment, wt% ²³⁵ U	11.0

TABLE 5.1. (contd)

Sphere-pac

Type	Vibratory compacted gel-derived microspheres
Material	UO ₂
Density (particles), %TD	>98
Diameter (cladding I.D.), mm (in.)	10.516 (0.414)
Enrichment, wt% ²³⁵ U	11.0
Smear Density, %TD	87.0

Insulator Disks

Material	Alumina
Density, g/cm ³	3.89
Diameter, mm (in.)	10.01 (0.394)
Length, mm (in.)	5.08 (0.200)
Number, location	2 (one at each end of fuel column)

Plenum Spring

Material	Inconel X-750
Wire diameter, mm (in.)	0.89 (0.035)
Coil O.D., at working length, mm (in.)	9.6 (0.38)
Free length, mm (in.)	50.80 (2.00)
Spring force, N (lb)	13.12 (2.95)
Spring constant, N/m (lb/in.)	590 (3.37)
Spring volume, mm ³ (in. ³)	269 (0.0164)

Upper Fuel Retainer (Disk)

Material	Zircaloy-2
Thickness, mm (in.)	0.102 (0.004)
Diameter, O.D., mm (in.)	10.541 (0.4150)
Diameter, I.D., mm (in.)	2.489 (0.098)

TABLE 5.1. (contd)

Cladding

Material	Zircaloy-2
Condition	Cold-Worked/Stress-Relieved
O.D., mm (in.)	12.370 (0.487)
I.D., mm (in.)	10.516 (0.414)
Wall thickness, minimum, mm (in.)	0.841 (0.0331)
Length, mm (in.)	513.99 (20.236)
Allowable bow, mm/m (in./ft)	0.3 (0.012)
Coating (present in some rods with annular fuel)	Graphite (Dag 4)
Coating layer thickness, μm (in.)	6.4 $\pm$ 4 (0.00025)

End Caps

Designer/fabricator	Halden Project
Upper end caps	Non-instrumented or Thermocouple sensor
Lower end caps	Elongation sensor or Pressure sensor

Fuel Rods

O.D., mm (in.)	12.32 (0.485)
Plenum length, mm (in.)	28.55 (1.124)
Fuel column length (including end pellets), mm (in.)	463.3 (18.24)
Allowable bow, mm/m (in./ft)	0.3 (0.012)
Internal pressure, MPa (psia)	
Reference	0.10 (14.7)
Annular-coated	0.46 (66)
Sphere-pac	0.46 (66)

The use of spherical particles in sphere-pac fuel, as opposed to angular particles in vipac fuel, is expected to produce less fuel-cladding mechanical interaction and, hence, reduced stress on the cladding during irradiation.

Pressurization of the annular-coated and sphere-pac fuel designs is expected to significantly improve thermal conductivity in the gas phase and, thus, result in lower fuel temperatures. The improvement in the effective thermal conductivity due to pressurization for sphere-pac rods is expected to be more significant than for pellet type fuels.^(5.3) Pressurization in both types of rods is also expected to reduce the "thermal feedback" effect in which release of low thermal conductivity gaseous fission products causes increased fuel temperatures and accelerated rates of gas release.

The inclusion of the small edge chamfer on the annular and reference pellets was added to help prevent chipping in normal handling operations during rod fabrication.

The sphere-pac rods were designed with a thin zircaloy disk located between the plenum spring and the insulator disk (Figures 5.1, 5.2 and 5.3) to prevent relocation of the fuel microspheres into the plenum region. (See Reference 5.1 for drawings of the annular-coated-pressurized and reference designs.) A central hole in the disk permits gas communication between the plenum and the fueled region of the rod (see Section 6.0 for process development tests of retained disks).

5.3 PROCESS DEVELOPMENT - HBWR SERIES H-2, H-3, AND H-4

5.3.1 Pellet Process Development

The 11% enriched UO_2 powder used to fabricate the HBWR Series H-1 pellets was very difficult to work with due to variability in its ceramic properties. A re-evaluation of this material was performed and a decision was made to process the material in a hammer-mill to obtain more uniform ceramic properties. The UO_2 powder was passed through a Bantam hammer-mill in the following manner:

1st pass	14,000 RPM	- no screen,
2nd pass	14,000 RPM	- 0.69 mm (0.027 in.) Herringbone screen

FIGURE 5.1. Sphere-pac/Pressurized Fuel Rod Assembly

FIGURE 5.2. Sphere-pac/Pressurized Fuel Rod Assembly - Thermocouple

FIGURE 5.3. Upper Fuel Retainer

This material was then slugged on a Western Sintering press to $3.9 \pm 1 \text{ g/cm}^3$ and hand granulated through a 10 mesh screen. Sinterability testing of this powder provided very satisfactory results as summarized in Table 5.2. The results from these sinterability tests were used to establish the process variables for pellet fabrication.

5.3.2 Coated Cladding Process Development

The as-received graphite Dag 4 for coating tubes contained 12.5 wt% solids. Considerable difficulty was encountered in controlling the thickness of the graphite layer on the inside surface of the tubes tested for preproduction process verification. As a result, a procedure was instituted that required frequent checks of the coating thickness and frequent adjustment of the solids content of the Dag 4 solution. Typically, each day one or two tubes would be coated, and the graphite thickness would be measured. Adjustments would then be made to the Dag 4 solution to assure the desired thickness and several more tubes would be coated before another process check was made. Further process development was identified for the BRPR Series S-2 and S-3 fabrication (see Section 6.2.3).

5.3.3 Sphere-Pac Process Development

With the change in packed-particle fuel type from vipac fuel (fuel particles in the form of shards) to sphere-pac fuel (fuel particles in the form of spheres), new fabrication techniques and work areas had to be established.

TABLE 5.2. Sinterability Test Results^(a)

<u>Pellet Type</u>	<u>Green Density, g/cm³</u>	<u>Sintering Temperature, °C</u>	<u>Sintering Time, hr</u>	<u>Sintered Density, %TD</u>
Reference	5.40	1740	6.0	94.37
Reference	5.50	1740	6.0	94.45
Reference	5.62	1740	6.0	94.63
Annular	5.39	1740	6.0	94.54
Annular	5.48	1740	6.0	94.77
Annular	5.58	1740	6.0	94.90

(a) 0.2 wt% zinc stearate added.

The process equipment for loading microspheres into tubes was installed in the glove box that previously had been used for vipac rod fabrication. The primary differences in equipment are a low energy pneumatic vibrator (instead of the Branford variable impactor) and three controlled feeders, one for each particle size. A shape plate was also set up to segregate broken spheres from down-loaded fuel rods. Preliminary microsphere process loading tests were performed to qualify procedures for loading the production rods.

As reported previously,^(1.8) the axial density of four test rods containing depleted uranium microspheres which were loaded at ORNL, were measured using a gamma densitometer (densigauge) with a collimator window length of 5.0 mm. The linear density measurements were very uniform (86 to 88% TD) except at the top end (0.64 to 1.27 cm) of the fuel column where there was a slightly lower (approximately 85% TD) density region. Although some success was made in eliminating the low density regions in the top of the FPIP development rods, it was not possible to completely eliminate the low density regions; none of the density values were below 84% TD and all were confined in the top 25 mm of the rods.

5.4 FABRICATION - HBWR SERIES H-1, H-2, H-3, AND H-4

5.4.1 HBWR Series H-1 Characterization Report

The HBWR Series H-1 characterization report, which describes the detailed features of the Series H-1 test rods undergoing irradiation in HBWR, was completed.^(5.4) As the report is considered to be a working document, a concerted effort was made to include complete information that will be required for future fuel performance analysis. The major topics included in this report are as follows:

- experiment description
- process development for HBWR Series H-1 rods
- fabrication and characterization procedures and methods
- physical, chemical, and ceramographic characterization of the HBWR Series H-1 fuel and fuel rods.

5.4.2 HBWR Series H-2, H-3, and H-4 Pellet Fabrication

The pellets (reference and annular) for HBWR Series H-2 and H-3 were fabricated based on the results of preproduction testing as presented in Section 5.3.1. No chipping, cracking or other difficulties were encountered, as was experienced during fabrication of the Series H-1 pellets. The powder uniformity treatment discussed in Section 5.3.1 was successful in eliminating these problems. All of the pellets were categorized as excellent quality. The pellet fabrication results are listed in Table 5.3.

5.4.3 HBWR Series H-2, H-3, and H-4 Coated Cladding Fabrication

Graphite coating of the tubing for HBWR Series H-2 and H-3 resulted in a production yield of approximately 60% on the basis of the thickness specification. This is the same yield that was obtained for the BRPR Series S-1 coatings, so little improvement was made in controlling the graphite film thickness. All of the out-of-specification coated tubes had thin coatings. (Reject tubes were recycled by washing the graphite out and re-coating.)

The method used for the coating of Series H-2 and H-3 cladding tubes was essentially the same as that used for BRPR Series S-1 tubes. The flood coating technique was used in which a dispersion of graphite in water was drawn down through a vertical tube using a silastic plug. The tube was allowed to drain for a short time and then air dried by forcing hot air up through the tube. Measurements were taken on the inside diameter of the tube with an air gage before and after coating to determine the graphite coating thickness by difference. Accepted tubes were then cured under vacuum at 425°C for 24 to

TABLE 5.3. HBWR Series H-2 and H-3 Pellet Fabrication Results

Pellet Form	Green Density, g/cm ³	Sintering Temp., °C	Sintering Time, hr	Average Sintered Density, %TD	Standard Deviation, %TD	Range, %TD	
						High	Low
Reference	5.49	1720	3	94.38	0.10	94.73	94.01
Reference resinter	--	1700	24	94.44	0.07	94.56	94.29
Annular	5.49	1720	3	94.42	0.09	94.68	93.97
Annular resinter	--	1700	24	94.44	0.09	94.60	92.27

28 hr. After curing, the tubes were handled only in a helium atmosphere glove box where they were plugged on both ends with temporary end caps and stored.

The point-by-point film thickness and average thickness for the accepted coated tubes used for the Series H-2 and H-3 fuel rods are listed in Table 5.4. All of these tubes were essentially at the "nominal" value for the coating thickness specification range of 5 to 8 μm (0.0002 to 0.0003 in.)

5.4.4 HBWR Series H-2, H-3, and H-4 Sphere-Pac Fabrication

The enriched microspheres prepared at ORNL were received and chemical analyses were completed on the as-received material. The results are summarized in Table 5.5.

Five sphere-pac rods were made for the HBWR Series H-2, H-3, and H-4 fuel loadings. Fabrication of a sphere-pac rod with a graphite coating on the inside surface was attempted and abandoned because the graphite was removed from the tube wall during vibratory compaction.

All of the sphere-pac rods were loaded by feeding the coarse and medium coarse microspheres from separate loading troughs directly into the fuel rod. The fine microspheres were fed simultaneously, but separately from another vibrator. This was done to control the particle mix and prevent particle size segregation as the microspheres were loaded simultaneously into the tube. All of the rods have the following microsphere size distribution:

<u>Fraction</u>	<u>Size</u>	<u>wt%</u>
Coarse	1150 to 1410 μm	58
Medium Coarse	280 to 320 μm	20
Fine	<45 μm	22

Typically, a fuel rod was vibrated at very low amplitude (vibrator air pressure of 137 kPa) during loading of the microspheres. When the calculated fuel loading had been added to the tube, air pressure to the vibrators was increased to 276 kPa and a weighted (800 grams) follower rod was placed on top of the fuel column. The fuel rod was then vibrated until the correct plenum depth was obtained. One of the important factors in achieving the specified smear density ($87 \pm 1\%$ TD) for the fuel column was controlling the feed rates of the microspheres as they entered the rod. Other major factors

TABLE 5.4. HBWR Series H-2 and H-3 Graphite Coating Thickness Measurements*

Tube No.	Fuel Rod Serial No.	Thickness at Position, max/min, μm					Average Thickness, max/min, μm	Tube Average, μm
		1	2	3	4	5		
66G	27	6.98	6.98	6.35	6.35	6.98	6.73	6.48
		6.35	6.35	6.35	6.35	5.71	6.22	
5E	28	6.35	6.35	6.35	6.35	5.08	6.09	5.97
		5.71	6.35	5.08	6.35	5.71	5.84	
170C	29	6.35	6.98	6.35	6.98	5.71	6.47	6.29
		6.98	5.71	5.71	6.35	5.71	6.09	
170D	30	5.71	5.71	6.98	6.35	5.71	6.09	6.16
		6.98	5.71	6.98	5.71	5.71	6.22	
66A	31	6.35	5.71	6.35	6.35	6.35	6.22	6.16
		6.35	6.98	5.71	6.35	5.08	6.09	
5F	32	6.35	6.35	5.71	5.08	5.71	5.84	5.97
		6.35	5.08	6.35	6.35	6.35	6.09	

*Measurements made at approximately every 7.6 cm (3 in.) spacing.
(Five axial sets of measurements per tube).

TABLE 5.5. Chemical Analysis of ORNL Microspheres

^{235}U , wt%	10.984
U, %	88.035
O/M	2.013
Total Impurity Content, ppm	148.1
Equivalent Boron Content, ppm	1.97
Carbon, ppm	6
Chloride, ppm	10
Fluoride, ppm	5
Nitrogen, ppm	5
Densities:	
Coarse (1150-1410 μm)	98.26% TD
Medium (280-320 μm)	98.17% TD
Fines* (<44 μm)	--

*Analytical procedures used not capable of analyzing fines.

were the length of time the rod was vibrated and the type of vibration applied to the rod. The fabrication process parameters are listed in Table 5.6.

In addition to the calculated smear densities, point-by-point gamma densitometer (densigage) readings were recorded for each rod. These readings are plotted in Figures 5.4 through 5.8. All of the data show the same trend. There was some scatter in localized densities at the bottom of the fuel column, very uniform density in the middle portion of the rods, and a rapid drop off in density at the very top of the rods, i.e., (the top 25 to 50 mm); however, none of the localized density values were below 84% TD. Overall standard deviations were quite small; averaging approximately $\pm 0.95\%$ TD for the five rods.

5.4.5 HBWR Series H-2, H-3, and H-4 Rod Fabrication

Fabrication of the HBWR Series H-2, H-3, and H-4 fuel rods was completed during April 1979. A description of the rods produced during this fuel fabrication campaign is:

- 2 - Reference with elongation sensor
- 2 - Reference with pressure transducer
- 4 - Annular-coated-pressurized with elongation sensor
- 2 - Annular-coated-pressurized with pressure transducer
- 3 - Sphere-pac-pressurized with elongation sensor
- 1 - Sphere-pac-pressurized with thermocouple and elongation sensor
- 1 - Sphere-pac-pressurized with thermocouple and pressure transducer.

TABLE 5.6. HBWR Series H-2, H-3, and H-4 Sphere-Pac Fabrication Variables

Rod No.	Fuel Density, %TD	Loading Time, sec	Loading Vibrator Air Pressure, kPa (psi)	Final Compaction Time, sec	Final Compaction Air Pressure, kPa (psi)
33	87.7	30	137 (20)	270	276 (40)
34	87.9	32	137 (20)	270	276 (40)
40	87.7	30	137 (20)	330	276 (40)
41	87.6	30	137 (20)	210-bottom* 17-top	276 (40)
42	87.0	30	137 (20)	195-bottom* 15-top	276 (40)

*Rods 41 and 42 have thermocouples in the top end. Filling of the tube with microspheres was stopped at a predetermined level, a thermocouple well inserted, and then the rods were topped off with microspheres. This accounts for the two compaction times. Extreme care had to be taken so as not to damage the thermocouple well.

FIGURE 5.4. Sphere-pac Rod No. 33 (density versus length)

FIGURE 5.5. Sphere-pac Rod No. 34 (density versus length)

FIGURE 5.6. Sphere-pac Rod No. 40 (density versus length)

FIGURE 5.7. Sphere-pac Rod No. 41 (density versus length)

FIGURE 5.8. Sphere-Pac Rod No. 41 (density versus length)

Neutron radiographs were made in the Triga Reactor at the Hanford Engineering Development Laboratory. The radiographs showed no pellet chipping or other anomalies in the fuel columns. Also, the regions of variable smear densities in the sphere-pac fuel columns were extremely small, i.e., no longer than approximately 1.5 mm.

While awaiting the delivery of the lower end caps which were made at Halden, the loaded annular and reference fuel rods were fitted with temporary end caps and stored in a helium atmosphere glove box. Control samples consisting of pellets and coated (Dag 4) cladding were also placed in the storage glove box. Just prior to welding the permanent lower end caps to the rods, the samples were analyzed for water and hydrogen content. These results showed that the pellets contained <2ppm H₂O. The coated cladding sample was found to contain 5190 ppm H₂O* (0.30 ppm H-fuel weight basis) as compared to

* Average of five analyses.

4180 ppm H₂O (0.24 ppm H-fuel weight basis) observed just prior to storage. Thus, the fuel rods were judged to be acceptable for closure. In addition to the process control samples, the helium atmosphere of the glove box storage area was sampled just before and just after storage with the following results:

- Just before storage - 99.7% helium
- Just after rods were removed from storage - 93.6% helium and 89.2% helium.

The reason that these fuel rods were stored briefly was that the lower end caps made at Halden required finishing of the weld preparation area. The weld design was changed slightly from Series H-1 to reduce the possibility of voids. The end plug body diameter was reduced slightly 10.43 to 10.48 mm (0.4105 to 0.4125 in.) for less interference fit, the weld lip was eliminated, and an angle up to $5^{\circ} \pm 2^{\circ}$ was added on the root of the weld. The improvement resulting from these changes was verified by the fact that no bottom end cap welds were rejected in the Series H-2, H-3, and H-4 fuel rods.

Pre-pressurization of the sphere-pac rods required a re-evaluation of the time required in the weld chamber to allow the pressure within the rods to equilibrate. A calibrated pressure transducer was attached to the upper end of the fuel rod and the time recorded for the rod to pressurize. (The rods were pressurized from the lower end due to the upper end cap configuration.) Two minutes were sufficient to pressurize the rod; however, a duration of five minutes was used to assure that the proper pressurization level had been achieved. All of the sphere-pac rods were pressurized in this manner. Previous experience with BRPR segmented vipac rods resulted in a time requirement of 20 minutes in the weld chamber for pressure equilibration.

Each fuel rod is identified by a serial number. Some important physical dimensions of each fuel rod are listed in Table 5.7.

TABLE 5.7. HBWR Series H-2, H-3, and H-4 Fuel Rods

ROD SERIAL NUMBER	DESCRIPTION	Overall Length		Rod Diameter O.D.					
		mm	(in)	0° top	0° middle	0° bottom	90° top	90° middle	90° bottom
H2UCR023	Reference with elongation sensor	715.289	(28.161)	12.327 (0.4853)	12.327 (0.4853)	12.329 (0.4854)	12.334 (0.4856)	12.324 (0.4852)	12.334 (0.4856)
H2UCR024	Reference with pressure transducer	715.239	(28.159)	12.332 (0.4855)	12.324 (0.4852)	12.329 (0.4854)	12.332 (0.4855)	12.334 (0.4856)	12.332 (0.4855)
H3UCR025	Reference with elongation sensor	715.315	(28.162)	12.327 (0.4853)	12.327 (0.4853)	12.324 (0.4852)	12.327 (0.4853)	12.324 (0.4852)	12.329 (0.4854)
H3UCR026	Reference with pressure transducer	715.188	(28.157)	12.327 (0.4853)	12.329 (0.4854)	12.339 (0.4858)	12.319 (0.4850)	12.329 (0.4854)	12.324 (0.4852)
H2UCG027	Annular-Coated-Pressurized with elongation sensor	715.442	(28.167)	12.332 (0.4855)	12.332 (0.4855)	12.329 (0.4854)	12.327 (0.4853)	12.327 (0.4853)	12.319 (0.4850)
H2UCG028	Annular-Coated-Pressurized with pressure transducer	715.620	(28.174)	12.329 (0.4854)	12.327 (0.4853)	12.337 (0.4857)	12.329 (0.4854)	12.334 (0.4856)	12.327 (0.4853)
H2UCG029	Annular-Coated-Pressurized with elongation sensor	715.061	(28.152)	12.327 (0.4853)	12.324 (0.4852)	12.327 (0.4853)	12.332 (0.4855)	12.327 (0.4853)	12.329 (0.4854)
H3UCG030	Annular-Coated-Pressurized with elongation sensor	715.162	(28.156)	12.329 (0.4854)	12.327 (0.4853)	12.324 (0.4852)	12.324 (0.4852)	12.327 (0.4853)	12.329 (0.4854)
H3UCG031	Annular-Coated-Pressurized with pressure transducer	715.061	(28.152)	12.332 (0.4855)	12.324 (0.4852)	12.324 (0.4852)	12.339 (0.4858)	12.327 (0.4853)	12.329 (0.4854)

TABLE 5.7. (Continued)

ROD SERIAL NUMBER	DESCRIPTION	Overall Length		Rod Diameter O.D.					
		mm	(in)	0° top	0° middle	0° bottom	90° top	90° middle	90° bottom
H3UCG032	Annular-Coated-Pressurized with elongation sensor	715.086	(28.153)	12.334 (0.4856)	12.334 (0.4856)	12.332 (0.4855)	12.327 (0.4853)	12.332 (0.4855)	12.332 (0.4855)
H2UCS033	Sphere-pac-Pressurized with elongation sensor	715.721	(28.178)	12.334 (0.4856)	12.344 (0.4860)	12.342 (0.4859)	12.339 (0.4858)	12.342 (0.4859)	12.342 (0.4859)
H3UCS034	Sphere-pac-Pressurized with elongation sensor	715.315	(28.162)	12.339 (0.4858)	12.332 (0.4855)	12.337 (0.4857)	12.332 (0.4855)	12.334 (0.4856)	12.332 (0.4855)
H2SPS040	Sphere-pac-Pressurized with elongation sensor	715.620	(28.174)	12.334 (0.4856)	12.337 (0.4857)	12.342 (0.4859)	12.337 (0.4857)	12.334 (0.4856)	12.334 (0.4856)
H2XXS041	Sphere-pac-Pressurized with thermocouple and elongation sensor	715.442	(28.167)	12.342 (0.4859)	12.332 (0.4855)	12.342 (0.4859)	12.339 (0.4858)	12.332 (0.4855)	12.332 (0.4855)
H2XXS042	Sphere-pac-Pressurized with thermocouple and pressure transducer	715.315	(28.162)	12.342 (0.4859)	12.339 (0.4858)	12.344 (0.4860)	12.344 (0.4860)	12.339 (0.4858)	12.344 (0.4860)

By utilizing the experience gained in fabricating HBWR Series H-1 fuel rods, fabrication of the HBWR Series H-2, H-3, and H-4 test rods proceeded smoothly as planned. There were only eight deviating material reports issued during this fabrication effort. Table 5.8 presents a summary of these reports.

5.5 IRRADIATION STATUS - HBWR TESTS

5.5.1 IFA 518-Irradiation

The irradiation of the twelve rods which comprise HBWR Series H-1 (Table 3.1) started in July 1978. At the end of September 1979, the irradiation had completed four HBWR reactor cycles in the IFA-518 test rig. The average burnups at the end of the fourth cycle were 621 GJ/kgM (7.2 MWd/kgM) in the lower cluster rods, and 501 GJ/kgM (5.8 MWd/kgM) in the upper cluster rods. Peak burnups were 697 GJ/kgM (8.1 MWd/kgM) and 561 GJ/kgM (6.5 MWd/kgM) for the lower and upper clusters, respectively. Peak linear heat generation rates have been in the range from 38 to 45 kW/m in the nonshielded cluster, and 25 to 30 kW/m in the shielded cluster. The irradiation started with the silver absorber shield in the upper position, i.e., high power in the lower cluster and lower power in the upper cluster.

The absorber shield was moved to the lower position in September 1978, at an average burnup of about 245 GJ/kgM (2.8 MWd/kgM) to change the cluster power levels in the lower cluster rods. Movement of the absorber shield back to the upper position, prior to the April 1979 startup, increased the power in the "reconditioned" lower cluster rods. The average burnup in the lower cluster rods at this time was 381 GJ/kgM (4.4 MWd/kgM). The lower cluster rods will be irradiated to a peak burnup of approximately 835 GJ/kgM (9.7 MWd/kgM) prior to power-ramp testing. Five of the lower cluster rods will be ramped after operation for a significant period at the "reconditioning" power. The projected schedule calls for the shield shift for the "reconditioning" power to occur in October 1979, with the ramp tests to start in April 1980.

The rig and rod instrumentation in IFA-518 has operated quite satisfactorily throughout the irradiation. All the rig instrumentation, i.e.,

**TABLE 5.8. HBWR Series H-2, H-3, and H-4
Deviating Material Reports**

Deviation	Description	Resolution
Hardware - Porous Frits	Dimensions	Slight deviations will not affect function of part.
Fuel - Instrumented Pellets	Center hole dimensions	Slight deviations will not affect function of part.
Fuel - Annular and Reference Pellets	N ₂ , O ₂ gas analysis	Equipment not available for analysis. Sufficient pellets have been placed in protective archive containers for future analysis.
Fuel - Sphere-pac	Off-gas measurements	Off-gas measurements were affected by atmospheric contamination during analysis.
Fuel - Sphere-pac	H ₂ analysis	H ₂ measurements were affected by atmospheric contamination. Moisture analysis for 5 samples = 4, 2, 3, 3, 4 ppm H ₂ O. $\bar{X}$ = 3.2 ppm, σ = 0.8 ppm, and upper 95:95 = 6.7 ppm H ₂ O. Sphere-pac fuel is of high density and has little porosity.
Fuel - Sphere-pac	Immersion density	Coarse = 98.16% TD Medium = 98.17% TD Analytical procedure not capable of analyzing fines ($\leq 45\mu\text{m}$).
Rod - Sphere-pac	Test equipment not available to check rod internal pressure.	Welding equipment was qualified using calibrated pressure transducer.
Rods - Sphere-pac	Small gaps (~1mm) between lower insulator discs and end caps.	Small amount of fuel between lower insulator is estimated to be at low packing density (~65% TD) and will not provide much power or very high temperature.

two flowmeters, two sets of coolant thermocouples, and eight vanadium neutron detectors, have provided reliable and stable signals.

Of the five W-3% Re/W-25% Re fuel centerline thermocouples in the lower cluster rods, four are providing reliable data. The fuel thermocouple in vipac rod No. 13 has consistently indicated a significantly lower fuel temperature than the thermocouple in sibling vipac rod No. 14. The reliability of the signal from the suspect thermocouple in rod No. 13 was checked using the code MWRAM. (5.5,5.6,5.7) This program predicts fuel temperatures during rapid power decreases, compares the predicted and actual temperatures, and provides a measure of thermocouple reliability. MWRAM was developed for previous HBWR experiments with pellet fuel rods. Using the transient power data from IFA-518 operation up to January 1979, MWRAM analysis confirmed that the thermocouple in vipac rod No. 13 was unreliable.

The eight elongation sensors and four pressure sensors have provided reliable signals, except for selected sensors during short periods when amplifier malfunctions occurred, and during the third cycle of operation when the twelve sensors were simultaneously energized. The simultaneous energizing of the linear variable differential transducer (LVDT) sensor coils was done to obtain rapid data sampling (several times a second) on the FAST SCAN data acquisition system. The data from the FAST SCAN system provide a precise indication of the linear heat generation rate at which fuel-cladding mechanical interaction occurs during power ascensions and power decreases by comparing the elongation signals from individual fuel rods to the natural cyclic reactor power. Cyclic reactor power is indicated by a cobalt neutron detector in an adjacent test rig. Prior to the simultaneous hard-wiring of the sensor coils, only one elongation signal at a time could be recorded on a strip-chart recorder, and simultaneous comparison between rods could not be made. However, the simultaneous energizing of the sensor coils caused magnetically-coupled interaction between the magnetic fields of adjacent coils, a shift in individual sensor signals at zero power, and possibly resulted in a change in the calibration factor for each individual sensor. The effects of the simultaneous hard-wiring on the elongation and pressure sensors are being evaluated.

Apparent zero shifts have also been noted in the signals from the elongation sensors and pressure sensors primarily during the first cycle of operation. Possible causes are cladding stress-relaxation, irradiation-induced growth, mechanical shifting of rig components, and electronic drift. These effects are also currently being evaluated.

5.5.2 IFA-517 Irradiation

Irradiation of the four HBWR Series H-4 rods (Table 3.1) started in April 1979 in the IFA-517 test rig. The irradiation was originally planned for two reactor cycles with the objective of comparing the operating temperatures of sphere-pac fuel and reference fuel. The irradiation has been extended to a total of four reactor cycles. Burnup at the end of the fourth cycle will be approximately 680 GJ/kgM (7.5 MWd/kgM). Because of the higher projected burnup and the general lack of power-ramping data on sphere-pac fuel, two of the sphere-pac rods from Series H-4 and the accompanying reference rod will be ramped in April 1980 with five of the lower cluster rods from Series H-1.

At the end of September 1979, the Series H-4 rods had completed two reactor cycles, and had accumulated average burnups of about 289 GJ/kgM (3.3 MWd/kgM). The peak burnups were approximately 300 GJ/kgM (3.5 MWd/kgM). Peak linear heat generation rates in the Series H-4 rods have been in the range from 40 to 45 kW/m. The rods were not power-cycled by means of a neutron absorber shield as were the IFA-518 rods.

The rig and rod instrumentation in IFA-517 has operated satisfactorily, except for not being able to determine the absolute magnitude of the elongation and pressure sensor signals. These sensors were simultaneously energized during the first cycle of operation, resulting in the same difficulties which occurred in IFA-518 (see Section 5.5.1). The three fuel center-line thermocouples in the Series H-4 rods have provided reliable temperature data.

5.6 DATA ACQUISITION - HBWR TESTS

5.6.1 Types of Data Recording

Data from rig and rod instrumentation from IFA-517 and IFA-518 have been acquired on several recording systems. These systems include:

- The Test Fuel Data Report (TFDR) system is used for general data acquisition. The TFDR system samples all instrument signals every 15 minutes during reactor power operating periods. Data recorded on the TFDR are signals from rig flowmeters, rig coolant thermocouples, and axially and circumferentially-positioned vanadium neutron detectors. Rod data recorded are signals from fuel center-line thermocouples, rod elongation sensors, and rod pressure sensors. The date, time, reactor power, calculated LHGRs and positions of adjacent control rods are also recorded.
- The CALIB data acquisition system records thermocouple, elongation, pressure, and neutron detector signals; a cobalt neutron detector signal from an adjacent rig; the date and the time. The CALIB system is used during preselected normal reactor startup and shutdown periods, and records signals every 1 to 5 minutes.
- The dedicated computer system records preselected instrument signals continuously. Usually, this system is used during rapid power decreases to examine the accuracy of thermocouples and fuel temperature responses.
- A strip-chart recorder is used to continuously monitor signals from individual elongation sensors, as well as a cobalt neutron detector in an adjacent rig. The recorder is used during preselected startup and shutdown periods.
- The FAST SCAN system was used during the third cycle of IFA-518 operation to record several elongation sensor signals and the adjacent cobalt neutron detector signal several times per second for reactor startups and shutdowns. This system was selected to replace the strip-chart recorder.

The TFDR and CALIB data are transmitted in engineering units on magnetic tape at the end of each cycle. Initial CALIB data were transmitted on computer cards. The TFDR data are also transmitted at more frequent intervals on computer paper. The dedicated computer data are transmitted both on computer paper and magnetic tape. The paper output is in engineering units and the magnetic tape recordings are in millivolts. FAST SCAN data are transmitted

as raw data on magnetic tape. The strip-chart recordings are transmitted as raw data on recorder paper and signals are only relative.

5.6.2 Data Handling

The diversity of data forms, the significant number of corrections to the LHGR equations (see Section 7.0), and the desired forms of the data output have required the development or modification of computer programs. Table 5.9 lists the programs developed for the handling of IFA-517 and IFA-518 data. Standard plotting routines are used for final data presentation.

5.7 HBWR RAMPING PLAN

The initial power-ramp testing of the HBWR Series H-1 and H-4 rods will take place in April 1980, after two more cycles of irradiation. In preparation for these tests, a general ramping plan was formulated. The rods will be individually power-ramped in the IFA-517 ramping rig, using power control consisting of a combination of reactor power and ^3He depressurization of coils surrounding the rods. The rods will be irradiated for 24 hr at linear heat generation rates (LHGR) approximating their last previous peak steady-state LHGR, i.e., 28 kW/m (8.5 kW/ft), to minimize possible effects caused by handling. Reactor power will be at an intermediate level during this period. The steady-state irradiation will be followed by a reactor power increase to full power over a period of about one hour. The peak linear heat generation rate in the test rod, after the reactor power increase, will reach approximately 46 kW/m (14 kW/ft). Immediately after the reactor has achieved full power, ^3He depressurization will be used to achieve a peak linear heat generation rate of about 66 kW/m (20 kW/ft). The rate of linear heat generation rate increase during ^3He depressurization will be 0.05 to 0.07 kW/m-sec (1.0 to 1.3 kW/ft-min), and the peak linear heat generation rate will be maintained for a period of at least 8 hr. Heat balance calibrations will be performed on each test rod during the 24-hr hold period before ramping, and after the 8 hr hold at peak power. During the tests, the elongation/pressure sensors will be operative. However, the fuel centerline thermocouples cannot be reconnected and they will be inoperative. During the first ramp, the data necessary for calibrating the rod linear heat generation rate to the rig cobalt detector will be recorded.

TABLE 5.9. Data Handling Programs

Program Identification	Data System	Function
● <u>Programs Common to IFA-518 and IFA-517</u>		
HALD	TFDR	Converts original tape data in EBCDIC language (HBWR) to ASCII (PNL) for PDP 11/45.
TEST	TFDR	Reads specified number of data tape lines to verify transfer by HALD. Output to lineprinter.
CPYFL2	TFDR	"Copy file 2" eliminates unwanted data from file (e.g., very low powers, periods of no data collection, etc.). Compressed data are stored on disk file CMP518 or CMP517.
CHECK2	TFDR, CALIB	Prints specified number of lines from either PARCH file, CMP518, CMP517 or CAL518 files to verify or list disk data.
● <u>Programs Used Explicitly for IFA-518</u>		
RICKW	TFDR	Transfers ASCII tape data to PARCH file on disk storage.
FIX1	TFDR	Corrects neutron detector readings for delay time and stores corrected values on disk file CMP518.
HRTF1	TFDR, CALIB	Calculates LHGRs at the thermocouples, including all corrections except burnup, and stores new data on disk file CMP518.
POW518	TFDR	Calculates assembly power, cluster power, and average LHGRs, including all corrections, except burnup. Stores data on disk file CMP518.
BU518A	TFDR	Corrects average LHGRs for the effect of burnup and stores new values on disk file CMP518.
BU518T	TFDR	Corrects LHGRs at the thermocouples for the effect of burnup and stores new values on disk file CMP518.
SQFIT	TFDR	Calculates slope and y-intercept of specified data.

TABLE 5.9. (Continued)

<u>Program Identification</u>	<u>Data System</u>	<u>Function</u>
INTRPLT	TFDR, CALIB	Calculates desired data (e.g., temperature or elongation) by interpolation between known points for constant LHGR comparisons.
STRESS	TFDR	Calculates pressure in rods with pressure sensors using pressure signal and sibling rod elongation signals.
RWCAL8	CALIB	Analogous to RICKW for CALIB data tapes.
RTCAL	CALIB	Analogous to RICKW for CALIB data cards.
CPYCAL	CALIB	Analogous to CPYFL2 for CALIB data.
CHGTM	CALIB	Synchronizes CALIB time to TFDR time.
FIXCAL	CALIB	Analogous to FIX1 for CALIB.
POWCAL	CALIB	Analogous to POW518 for CALIB.

• Programs Used Explicitly for IFA-517

RW517	TFDR	Analogous to RICKW
NDT517	TFDR	Analogous to FIX1
ND517	TFDR	Verifies assumptions for radial flux profile.
FLX517	TFDR	Analogous to POW518. Calculates axial power profile from three neutron detector signals. Calculates radial power profile from four neutron detector signals. Stores data on disk file CMP517.
FLXTC	TFDR	Analogous to HRTF1
BU517A	TFDR	Analogous to BU518A
BU517	TFDR	Analogous to BU518T

Two sequential loadings of the IFA-517 ramping rig will be used to test eight of the ten rods available from the six lower cluster rods from IFA-518 (Series H-1) and the four Series H-4 rods. The ten available rods are listed in Table 5.10. In order to compare the restructuring in sphere-pac fuel before and after ramping, rod No. S40 (H-4) will undergo post-irradiation examination after steady-state operation. Because sphere-pac fuel is the backup design, vipac rod No. V14 was deleted from the ramp testing plan.

In order to determine the testing sequence, a priority listing of behavior comparisons for the ramps was determined. The priority of comparisons is: 1) annular-coated versus reference, 2) sphere-pac versus reference, 3) annular versus reference, 4) separation of individual effects of annular fuel and coated cladding (if possible), and 5) any other comparisons. As a result of these considerations, the order of testing is: V13, S41, AC9, AC10, A6, S40 and R1, followed by R2 or R2 followed by R1. The vipac rod No. V14 was selected to be tested first in the sequence in order to check out the ramping procedure before testing higher priority rods.

TABLE 5.10. Rods Available for Ramp Testing

<u>Series H-1</u>		<u>Series H-4</u>	
<u>Rod</u> ⁽¹⁾	<u>Sensor</u> ⁽²⁾	<u>Rod</u> ⁽¹⁾	<u>Sensor</u> ⁽²⁾
AC9	E(T)	S40	E
AC10	P	S41	E(T)
R2	E(T)	S42	P(T)
A6	E(T)	R1	E(T)
V13	E(T)		
V14	P(E)		

(1) AC = Annular-Coated, R = Reference,

A = Annular, V = Vipac, S = Sphere-pac

(2) E = Elongation Sensor, P = Pressure Sensor,

(T) = Thermocouple (Inoperative during ramping.)

A detailed ramping plan has been prepared as a working document, which interrelates the individual test results by a rational, decision-making process; provides a real time tool for modifying the testing scheme; and provides maximum flexibility for decision-making during testing.

5.8 PRIMARY RAMPING TEST STATUS

Central rodlets from the three-segment, segmented rods from BRPR Series S-1 and S-2 will be utilized for the primary ramp tests after steady-state irradiations in the Big Rock Point Reactor (BRPR). The BRPR Series S-1 rods were inserted into the BRPR core in the Spring of 1979. After a very brief operating period, the reactor was shutdown for an extended outage due to mechanical problems. Four fuel assemblies (two Series S-1 and two Series S-2) containing all the FPIP segmented rods were inserted into the reactor for the October 1979 startup. Status of these irradiations is described in Section 6.0.

5.9 REFERENCES

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- 5.5 D. D. Lanning and C. R. Hann. 1977. "Verification of Fuel Centerline Thermocouple Readings Through Response to Linear Power Decreases." BNWL-2189.
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6.0 TASK 2C - IN-REACTOR DEMONSTRATIONS

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The objective of this task is to demonstrate commercial acceptability of fuel concepts which have the greatest potential for improved power-maneuvering capability. This will be accomplished through irradiation of a significant sample of rods which will be fabricated by commercial processes that involve full industrial quality assurance.

This task is structured as a series of fuel irradiations followed by examination at selected burnup levels. A total of 359 rods comprising the fuel concepts being evaluated as part of the Fuel Performance Improvement Program will be irradiated in the Consumers Power Company's Big Rock Point Reactor (BRPR).

Fuel assemblies containing demonstration fuel rods are being inserted in BRPR with each of three annual fuel reloads through 1981. Each assembly will remain in the reactor for four years and will be subjected to the maximum power levels and power-ramping cycles that are consistent with normal operations. Selected fuel rods will be removed periodically (at intermediate burnup levels) from each series for destructive examination or power-ramping in a test reactor.

6.1 DESIGN AND ANALYSIS

6.1.1 BRPR Series S-1

One hundred and forty-three fuel rods (103 full length, 24 segmented, and 16 full-length characterized standard reference) for BRPR Series S-1 were assembled into the following assemblies:

G4-19
G4-20
G4-21
G4-22

Assemblies G4-21 and G4-22 contain the 24 segmented fuel rods that will be used for ramping at a later date.

The fuel rod loading maps for these four demonstration assemblies are shown in Figures 6.1, 6.2, 6.3, and 6.4. Rod identifications for the Series S-1 assemblies are listed in Tables 6.1, 6.2, 6.3, and 6.4. To summarize, fuel assembly G4-19 contains 35 Series S-1 rods while each of the other three assemblies contain 36 Series S-1 rods. Fuel rod location number 9K in Assembly G4-19 was originally intended to be a full-length vipac fuel rod. However, it was replaced by a standard G-4 pellet rod after the vipac rod was destructively examined to investigate a slight cross-contamination of HBWR Series H-1 feed material (11% enriched UO_2) in the BRPR Series S-1 feed material (2.52% enriched UO_2). This condition was identified and verified by use of the neutron radiographs made on the vipac rods.

6.1.2 BRPR Series S-2 and S-3

For purposes of economy, all of the rods required for BRPR Series S-2 and S-3 were fabricated at the same time as the BRPR reload Batch H-1 (Cycle 16) fabrication.

BRPR Series S-2 and S-3 each consist of 108 fuel rods; however, only BRPR Series S-2 includes segmented fuel rods. BRPR Series S-2 and S-3 rods consist of three fuel types (the same as HBWR Series H-2 and H-3): reference, annular-coated-pressurized, and sphere-pac. The fuel assembly matrix for these rods is shown in Table 6.5. Characteristics of the BRPR Series S-2 and S-3 rods are summarized in Tables 6.6 and 6.7. The reference and annular-coated-pressurized full-length demonstration rods are identical to the BRPR Series S-2 rods.

The major changes incorporated in the BRPR Series S-2 and S-3 rods, when compared to BRPR Series S-1, include a reduction in the number of different rod types, substitution of sphere-pac-pressurized fuel rods for vipac fuel rods, and placement of reference fuel in the lower as well as upper segments of all segmented rods (Table 6.8).

The schedule for fabrication, licensing, and shipment of the three BRPR Series S-2 fuel assemblies was accelerated to meet the projected November 1979 startup of the Big Rock Point Reactor, Cycle 16. Presently, two Series S-2 segmented fuel assemblies (including sphere-pac rods) have been substituted

	A	B	C	D	E	F	G	H	I	J	K
1			KE3 00593	K06 00005	KR3 00004	KP3 00002	KE3 00590	KM6 00017	KN6 00015		
2			KM6 00020						KR3 00006		
3	KP3 00001	KN6 00017								K06 00016	KM6 00018
4	KR3 00001										KN6 00016
5	K06 00004										KP3 00003
6	KE3 00594										KE3 00595
7	KP3 00004										K06 00003
8	KN6 00018										KR3 00005
9	KM6 00016	K06 00002								KN6 00019	
10			KR3 00002						KM6 00015		
11			KN6 00020	KM6 00019	KE3 00591	KP3 00005	KR3 00003	K06 00001	KE3 00592		

Spacer Serial No.
Orientation

FIGURE 6.1. BRPR Series S-1 Assembly G4-19 Rod Loading Map

	A	B	C	D	E	F	G	H	I	J	K
1			KE3	K06	KR3	KP3	KE3	KM6	KN6		
2			00581	00007	00012	00010	00582	00009	00014		
			KM6						KR3		
			00010						00011		
3	KP3	KN6								K06	KM6
	00007	00012								00017	00013
4	KR3										KN6
	00007										00013
5	K06										KP3
	00008										00011
6	KE3										KE3
	00586										00587
7	KP3										K06
	00006										00009
8	KN6										KR3
	00010										00009
9	KM6	K06								KN6	KP3
	00014	00006								00011	00012
10			KR3						KM6		
			00010						00012		
11			KN6	KM6	KE3	KP3	KR3	K06	KE3		
			00009	00011	00585	00008	00008	00010	00584		

Spacer Serial No.
Orientation

FIGURE 6.2. BRPR Series S-1 Assembly G4-20 Rod Loading Map

	A	B	C	D	E	F	G	H	I	J	K
1			KL33 0004	K06 00019	KR3 00021	KP33 0002	KE3 00165	KM6 00005	KN63 0001		
2			KM6 00007						KR3 00023		
3	K063 0003	KN6 00006								K06 00022	KP33 0003
4	KR3 00024										KN6 00004
5	K06 00023										KP3 00013
6	KR33 0003										KL33 0003
7	KP3 00016										K06 00020
8	KN6 00005										KR3 00022
9	KM63 0002	K06 00021								KN6 00007	K063 0004
10			KR3 00019						KM6 00006		
11			KN63 0002	KM6 00008	KE3 00170	KM63 0003	KR3 00020	K06 00018	KR33 0004		

Spacer Serial No.
Orientation

FIGURE 6.3. BRPR Series S-1 Assembly G4-21^(a) Rod Loading Map

(a) Lower end cap serial number (bottom segment of segmented rods).

	A	B	C	D	E	F	G	H	I	J	K
1			KL33 0002	K06 00012	KR3 00017	KP33 0004	KE3 00588	KM6 0003	KN63 0004		
2			KM6 00001						KR3 00018		
3	K063 00001	KN6 00001								K06 00015	KP33 0001
4	KR3 00015										KN6 00003
5	K06 00011										KP3 00014
6	KR33 0001										KL33 0001
7	KP3 00015										K06 00013
8	KN6 00002										KR3 00013
9	KM63 0004	K06 00014								KN6 00008	K063 0002
10			KR3 00016						KM6 00002		
11			KN63 0003	KM6 00004	KE3 00589	KM63 0001	KR3 00014	K06 00024	KR33 0002		

Spacer Serial No.
Orientation

FIGURE 6.4. BRPR Series S-1 Assembly G4-22^(a) Rod Loading Map

(a) Lower end cap serial number (bottom segment of segmented rods).

TABLE 6.1. BRPR Assembly G4-19

<u>Fuel Rod Location</u>	<u>Rod Type</u>	<u>Serial No.</u>
1C	Full-length; Standard pellet	KE300593
1D	Full-length; Annular-coated-pressurized	K0600005
1E	Full-length; Reference pellet	KR300004
1F	Full-length; Vipac	KP300002
1G	Full-length; Standard pellet	KE300590
1H	Full-length; Annular pellet	KM600017
1I	Full-length; Annular-coated	KN600015
2C	Full-length; Annular pellet	KM600020
2I	Full-length; Reference pellet	KR300006
3A	Full-length; Vipac	KP300001
3B	Full-length; Annular-coated	KN600017
3J	Full-length; Annular-coated-pressurized	K0600016
3K	Full-length; Annular pellet	KM600018
4A	Full-length; Reference pellet	KR300001
4K	Full-length; Annular-coated	KN600016
5A	Full-length; Annular-coated-pressurized	K0600004
5K	Full-length; Vipac	KP300003
6A	Full-length; Standard pellet	KE300594
6K	Full-length; Standard pellet	KE300595
7A	Full-length; Vipac	KP300004
7K	Full-length; Annular-coated-pressurized	K0600003
8A	Full-length; Annular-coated	KN600018

Table 6.1. (Continued)

<u>Fuel Rod Location</u>	<u>Rod Type</u>	<u>Serial No.</u>
8K	Full-length; Reference pellet	KR300005
9A	Full-length; Annular pellet	KM600016
9B	Full-length; Annular-coated-pressurized	K0600002
9J	Full-length; Annular-coated	KN600019
10C	Full-length; Reference pellet	KR300002
10I	Full-length; Annular pellet	KM600015
11C	Full-length; Annular-coated	KN600020
11D	Full-length; Standard pellet	KM600019
11E	Full-length; Standard pellet	KE300591
11F	Full-length; Vipac	KP300005
11G	Full-length; Reference pellet	KR300003
11H	Full-length; Annular-coated-pressurized	K0600001
11I	Full-length; Standard pellet	KE300592

TABLE 6.2. BRPR Assembly G4-20

<u>Fuel Rod Location</u>	<u>Rod Type</u>	<u>Serial No.</u>
1C	Full-length; Standard pellet	KE300581
1D	Full-length; Annular-coated-pressurized	K0600007
1E	Full-length; Reference pellet	KR300012
1F	Full-length; Vipac	KP300010
1G	Full-length; Standard pellet	KE300582
1H	Full-length; Annular pellet	KM600009
1I	Full-length; Annular-coated	KN600014
2C	Full-length; Annular pellet	KM600010
2I	Full-length; Reference pellet	KR300011
3A	Full-length; Vipac	KP300007
3B	Full-length; Annular-coated	KN600012
3J	Full-length; Annular-coated-pressurized	K0600017
3K	Full-length; Annular pellet	KM600013
4A	Full-length; Reference pellet	KR300007
4K	Full-length; Annular-coated	KM600013
5A	Full-length; Annular-coated-pressurized	K0600008
5K	Full-length; Vipac	KP300011
6A	Full-length; Standard pellet	KE300586
6K	Full-length; Standard pellet	KE300587
7A	Full-length; Vipac	KP300006
7K	Full-length; Annular-coated-pressurized	K0600009

TABLE 6.2. (Continued)

<u>Fuel Rod Location</u>	<u>Rod Type</u>	<u>Serial No.</u>
8A	Full-length; Annular-coated	KN600010
8K	Full-length; Reference pellet	KR300009
9A	Full-length; Annular pellet	KM600014
9B	Full-length; Annular-coated-pressurized	K0600006
9J	Full-length; Annular-coated	KN600011
9K	Full-length; Vipac	KP300012
10C	Full-length; Reference pellet	KR300010
10I	Full-length; Annular pellet	KN600012
11C	Full-length; Annular-coated	KM600009
11D	Full-length; Annular pellet	KM600011
11E	Full-length; Standard pellet	KE300585
11F	Full-length; Vipac	KP300008
11G	Full-length; Reference pellet	KR300008
11H	Full-length; Annular-coated-pressurized	K0600010
11I	Full-length; Standard pellet	KE300584

TABLE 6.3. BRPR Assembly G4-21

<u>Fuel Rod Location</u>	<u>Rod Type</u>	<u>Serial No.</u>
1C	Segmented*; Reference & reference-coated	KR310016 KR320004 KL330004
1D	Full-length; Annular-coated-pressurized	KL060019
1E	Full-length; Reference pellet	KR300021
1F	Segmented*; Vipac	KR310022 KP320002 KP330002
1G	Full-length; Standard pellet	KE300165
1H	Full-length; Annular pellet	KM600005
1I	Segmented*; Annular-coated	KR310009 KN620001 KN630001
2C	Full-length; Annular pellet	KM600007
2I	Full-length; Reference pellet	KR300023
3A	Segmented*; Annular-coated-pressurized	KR310019 K0620003 K0630003
3B	Full-length; Annular-coated	KN600006
3J	Full-length; Annular-coated-pressurized	K0600022
3K	Segmented*; Vipac	KR310023 KP320003 KP330003
4A	Full-length; Reference pellet	KR300024
4K	Full-length; Annular-coated	KN600004
5A	Full-length; Annular-coated-pressurized	K0600023
5K	Full-length; Vipac	KP300013

TABLE 6.3. (Continued)

<u>Fuel Rod Location</u>	<u>Rod Type</u>	<u>Serial No.</u>
6A	Segmented*; Reference & reference-pressurized	KR310003 KR320007 KR330003
6K	Segmented*; Reference & reference-coated	KP310015 KR320003 KL330003
7A	Full-length; Vipac	KP300016
7K	Full-length; Annular-coated-pressurized	K0600020
8A	Full-length; Annular-coated	KN600005
8K	Full-length; Reference pellet	KR300022
9A	Segmented*; Annular pellet	KR310006 KM620002 KM630002
9B	Full-length; Annular-coated-pressurized	K0600021
9J	Full-length; Annular-coated	KN600007
9K	Segmented*; Annular-coated-pressurized	KR310020 K0620004 K0630004
10C	Full-length; Reference pellet	KR300019
10I	Full-length; Annular pellet	KN600006
11C	Segmented*; Annular-coated	KR310010 KN620002 KN630002
11D	Full-length; Annular pellet	KN600008
11E	Full-length; Standard pellet	KE300170
11F	Segmented*; Annular pellet	KR310007 KM620003 KM630003

TABLE 6.3. (Continued)

<u>Fuel Rod Location</u>	<u>Rod Type</u>	<u>Serial No.</u>
11G	Full-length; Reference pellet	KR300020
11H	Full-length; Annular-coated-pressurized	K0600018
11I	Segmented*; Reference & reference- pressurized	KR310004 KR320008 KR330004

*The upper rodlet on each segmented rod contains reference pellets.

TABLE 6.4. BRPR Assembly G4-22

<u>Fuel Rod Location</u>	<u>Rod Type</u>	<u>Serial No.</u>
1C	Segmented*; Reference & reference-coated	KR310014 KR320002 KL330002
1D	Full-length; Annular-coated-pressurized	K0600012
1E	Full-length; Reference pellet	KR300017
1F	Segmented*; Vipac	KR310024 KP320004 KP330004
1G	Full-length; Standard pellet	KE300588
1H	Full-length; Annular pellet	KM600003
1I	Segmented*; Annular-coated	KR310012 KN620004 KN630004
2C	Full-length; Annular pellet	KM600001
2I	Full-length; Reference pellet	KR300018
3A	Segmented*; Annular-coated-pressurized	KR310017 K0620001 K0630001
3B	Full-length; Annular-coated	KN600001
3J	Full-length; Annular-coated-pressurized	K0600015
3K	Segmented*; Vipac	KR310021 KP320001 KP330001
4A	Full-length; Reference pellet	KR300015
4K	Full-length; Annular-coated	KN600003

TABLE 6.4. (Continued)

<u>Fuel Rod Location</u>	<u>Rod Type</u>	<u>Serial No.</u>
5A	Full-length; Annular-coated-pressurized	K0600011
5K	Full-length; Vipac	KP300014
6A	Segmented*; Reference & reference- pressurized	KR310001 KR320005 KR330001
6K	Segmented*; Reference & reference-coated	KR310013 KR320001 KL330001
7A	Full-length; Vipac	KP300015
7K	Full-length; Annular-coated-pressurized	K0600013
8A	Full-length; Annular-coated	KN600002
8K	Full-length; Reference pellet	KR300013
9A	Segmented*; Annular pellet	KR310008 KM620004 KM630004
9B	Full-length; Annular-coated-pressurized	K0600014
9J	Full-length; Annular-coated	KN600008
9K	Segmented*; Annular-coated-pressurized	KR310018 K0620002 K0630002
10C	Full-length; Reference pellet	KR300016
10I	Full-length; Annular pellet	KN600002
11C	Segmented*; Annular-coated	KR310011 KN620003 KN630003

TABLE 6.4. (Continued)

<u>Fuel Rod Location</u>	<u>Rod Type</u>	<u>Serial No.</u>
11D	Full-length; Annular pellet	KM600004
11E	Full-length; Standard pellet	KE300589
11F	Segmented*; Annular pellet	KR310005 KM620001 KM630001
11G	Full-length; Reference pellet	KR300014
11H	Full-length; Annular-coated-pressurized	K0600024
11I	Segmented*; Reference & reference- pressurized	KR310002 KR320006 KR330002

*The upper rodlet on all segmented fuel contains reference pellets.

TABLE 6.5. BRPR Series S-2 and S-3 Rod and Assembly Matrix

<u>Test Series</u>	<u>Assembly Number</u>	<u>Fuel Rod Type</u>	<u>Number Full-Length Rods/Assembly</u>	<u>Number Segmented Rods/Assembly</u>
S-2	H1-01	Reference	6	
		Annular-coated-pressurized	24	
		Sphere-pac	6	
	H1-02	Reference	4	4
		Annular-coated-pressurized	16	4
		Sphere-pac	4	4
	H1-03	Reference	4	4
		Annular-coated-pressurized	16	4
		Sphere-pac	<u>4</u>	<u>4</u>
		SUBTOTAL	84	24
		TOTAL		108
S-3	1,2 and 3	Reference	6 each	
		Annular-coated-pressurized	22 each	
		Sphere-pac	<u>8</u> each	
		SUBTOTAL	36 each	
		TOTAL FOR THREE ASSEMBLIES		108

TABLE 6.6. Product Specification Characteristics for BRPR Series S-2 and S-3 Full-Length Demonstration Fuel Rods

Reference Fuel

Type	Solid Pellet (Edge Chamfer)
Material	UO ₂
Density, %TD	93.5
Diameter, mm (in.)	9.436 (0.3715)
Length, mm (in.)	7.62 (0.300)
Dish	Both Ends
Dish Volume, %	2.0 (0.25 Edge Chamfer)
Enrichment, wt% ²³⁵ U	2.52

Annular Fuel

Type	Annular pellet
Material	UO ₂
Density, %TD	93.5
Diameter, O.D., mm (in.)	9.423 (0.3710)
I.D., mm (in.)	2.984 (0.1175)
Length, mm (in.)	7.62 (0.300)
Dish	None (0.25 Edge Chamfer)
Enrichment	2.69

Sphere-pac Fuel

Type	Vibratory compacted microsphere particles
Material	UO ₂
Density (particles), %TD	>96.5 (target >98%TD)
Diameter (cladding I.D.), mm (in.)	9.677 (0.3810)
Enrichment, wt% ²³⁵ U	2.52
Smear Density, %TD	87.0

TABLE 6.6. (Continued)

Insulator Disks

Material	Alumina
Density, g/cm ³	3.89
Diameter, mm (in.)	9.195 (0.362)
Length, mm (in.)	5.1 (0.200)
Number, location	2, one at each end of fuel column

Plenum Spring

Material	Inconel X-750
Spring force (nominal), N (lb)	49 (11)
Spring constant (nominal), N/m (lb/in)	2100 (12)
Spring volume, mm ³ (in ³)	628 (0.0383)

Fill Gas

Material	He
Purity, %	99.9
Pressurization, MPa (psia)	0.462 (67)

Cladding

Material	Zircaloy-2
Condition	Cold Worked-Stress Relieved
O.D., mm (in.)	11.455 (0.451)
I.D., mm (in.)	9.677 (0.381)
Wall thickness (minimum), mm (in.)	0.831 (0.0327)
Length, mm (in.)	1920.18 (74.889)
Allowable bow, mm/m (in/ft)	1.25 (0.015)
Coating (present in some rods with annular fuel)	Graphite
Coating layer thickness, mm (in.)	0.0064 (0.00025)

TABLE 6.6. (Continued)

Fuel Retainer

Material	Zircaloy-2 or 4
O.D., mm (in.)	9.703 (0.3820)
I.D., mm (in.)	2.500 (0.098)
Thickness, mm (in.)	0.102 (0.004)
Number per sphere-pac rod	2

Fuel Rod

O.D., mm (in.)	11.405 (0.449)
Plenum length, mm (in.)	99.08 (3.901)
Fuel column length, mm (in.)	1778.0 (70.00)
Allowable bow, mm/m (in/ft)	1.25 (0.015)

TABLE 6.7. Characteristics of BRPR Series S-2 Segmented Fuel Rods

Reference Fuel

Same as demonstration rods.

Annular Fuel

Same as demonstration rods.

Sphere-pac Fuel

Same as demonstration rods.

Insulator Disks (each segment)

Same as demonstration rods.

Upper Plenum Spring (upper segment only)

Same as demonstration rods

Fill Gas

Same as demonstration rods.

Mid and Lower Segment Plenum Spring

Material	Inconel X-750
Wire diameter, mm (in.)	0.805 (0.0317)
Coil O.D. (at working length), mm (in.)	8.64 (0.340)
Free length, mm (in.)	56.90 (2.240)
Spring force, N (lb)	9.34 (2.10)
Spring constant, N/m (lb/in)	394 (2.23)
Spring volume, mm ³ (in ³)	304 (0.0185)

Fuel Retainer (sphere-pac segments only)

Same as demonstration rods.

TABLE 6.7. (Continued)

Cladding

Material	Same as demonstration rods.
Condition	Same as demonstration rods.
O.D.	Same as demonstration rods.
I.D.	Same as demonstration rods.
Wall thickness	Same as demonstration rods.
Coating (present in some segments with reference or annular fuel)	Same as demonstration rods.
Coating thickness, μm	Same as demonstration rods.
Length (upper segment), mm (in.)	666.24 (26.230)
Length (mid and lower segment), mm (in.)	600.18 (23.629)

Fuel Rod

Number of segments	3
O.D.	Same as demonstration rods.
Allowable bow	Same as demonstration rods.
Plenum length (upper plenum)	Same as demonstration rods.
Plenum length (mid and lower plenum), mm (in.)	32.82 (1.292)
Fuel column length (upper segment), mm (in.)	544.45 (21.435)
Fuel column length (middle segment), mm (in.)	546.84 (21.529)
Fuel column length (lower segment), mm (in.)	544.45 (21.435)
Axial distance between fuel columns, mm (in.)	71.12 (2.800)
Fuel configuration (upper and lower segments)	Reference
Fuel configuration (middle segment)	Reference Annular-coated- pressurized Sphere-pac

TABLE 6.7. (Continued)

Fuel Rod (Continued)

O.D., mm (in.)	11.405 (0.449)
Plenum length, mm (in.)	99.08 (3.901)
Fuel column length, mm (in.)	1778.0 (70.0)
Allowable bow, mm/m (in/ft)	1.25 (0.015)

TABLE 6.8. BRPR Series S-2 Demonstration Fuel Rod Designations

<u>Demonstration Rod Type</u>	<u>Quantity</u>	<u>Test Requirements</u>
1	14	2.52 wt% ^{235}U , reference, full-length demonstration rod.
2	56	2.69 wt% ^{235}U , annular-coated-pressurized, full-length demonstration rod.
3	14	2.52 wt% ^{235}U , sphere-pac, full-length demonstration rod.
4	8	Segmented fuel rod with Type 1 configuration in upper, middle, and lower segments.
5	8	Segmented fuel rod with Type 1 configuration in upper and lower segments and Type 2 configuration in middle segment.
6	8	Segmented fuel rod with Type 1 configuration in upper and lower segment and Type 3 configuration in middle segment.

for two of the four BRPR Series S-1 assemblies (which contain some vipac rods). Thus, the four fuel assemblies in the reactor at the present time, two from Series S-1 (G4-21 and G4-22) and two from Series S-2 (H1-02 and H1-03), contain all of the 48 segmented rods to be irradiated in BRPR as part of FPIP. Results of the neutronics analysis show that the Series S-1 and S-2 assemblies are virtually identical with respect to power peaking. The two Series S-1 assemblies that were removed will be reinserted later and they will receive the planned irradiation.

The drawing for the annular-coated-pressurized segmented fuel rod assembly was revised by an interim document revision to add a vent to the segment connector between the middle and lower segments (Figure 6.5). The vent relieves fill gas pressurized by the heat of welding that would otherwise intrude the weld area and produce an unsatisfactory weld containing gas bubbles.

The documentation prepared for Series S-2 and S-3 prior to loading into the reactor is noted below:

- The Irradiation Test Authorization (XN-NT-ITA-1) for BRPR Series S-2 and S-3 demonstration fuel rods was approved and issued.
- A safety and licensing analysis report for BRPR Series S-2 fuel assemblies, XN-NF-79-65, Revision 0, was issued. Because of similarities in design of BRPR Series S-1 and S-2 assemblies, existing Series S-1 licensing limits with regard to thermal and LOCA limits were found to also apply to the Series S-2 assemblies.
- Fuel management guidelines for the three BRPR Series S-2 fuel assemblies were issued. The guidelines were essentially the same as those for the Series S-1 assemblies. The two segmented Series S-2 assemblies are to be loaded into symmetrical core locations with orientations that differ by 90° with respect to the adjacent control blade.

The fuel rod loading maps for the three BRPR Series S-2 assemblies are shown in Figures 6.6, 6.7, and 6.8. Corresponding rod identifications for these three assemblies are shown in Tables 6.9, 6.10, and 6.11.

FIGURE 6.5. Connector

BRPR Series S-2 and S-3 characterization data were collected and reviewed prior to shipment of the BRPR Series S-2 fuel on September 18, 1979.

6.2 PROCESS DEVELOPMENT - BRPR SERIES S-2 AND S-3

6.2.1 BRPR Pellet Process Development

The UO_2 used for the BRPR Series S-2 and S-3 fuel rods was prepared at Exxon Nuclear Company. Powder lot numbers are:

<u>Powder Lot</u>	<u>wt%²³⁵U</u>
SR-67-2, Rev. 1	2.52
SR-48-1, Rev. 1	2.69

The chemical analyses of these two lots are summarized in Table 6.12.

Standard preproduction sinterability tests were performed on both of these lots. The following steps were followed in powder preparation:

- 1) Milling at 8000 rpm with a 0.68 mm (0.027 in.) Herringbone screen
- 2) Roll-compacting at 69.9 mm clearance (2.75 in.) for SR-67-2, and at 50.8 mm (2.00 in.) for lot SR-48-1 through a 2.0 mm (10 mesh) screen
- 3) Re-roll compacting both batches at 76.2 mm clearance (3.0 in.) through a 2.0 mm (10 mesh) screen.

Results of the preproduction sinterability tests are listed in Table 6.13. Both lots sintered at predictable rates and acceptable pellets were obtained so the preproduction results were used to establish the fabrication process parameters.

6.2.2 BRPR Sphere-Pac Process Development

Several six-foot long BRPR sphere-pac development rods were loaded with depleted UO_2 microspheres to determine the effectiveness of the loading technique on full-length rods. In addition, the problems that appeared during fabrication of HBWR Series H-2, H-3, and H-4, namely the problem of levitation

	A	B	C	D	E	F	G	H	I	J	K
1			LR3 00024	LN6 00058	LN6 00057	LN6 00001	LN6 00038	LN6 00053	LS3 00006		
2			LS3 00003						LN6 00055		
3	LN6 00050	LR3 00030								LN6 00054	LN6 00052
4	LS3 00005										LR3 00017
5	LN6 00009										LN6 00051
6	LN6 00022										LN6 00024
7	LN6 00047										LN6 00023
8	LR3 00025										LS3 00004
9	LN6 00049	LN6 00043								LR3 00021	LN6 00039
10			LN6 00040						LS3 00007		
11			LS3 00008	LN6 00042	LN6 00045	LN6 00048	LN6 00041	LN6 00046	LR3 00022		

Spacer Serial No.
Orientation

FIGURE 6.6. BRPR Series S-2 Assembly H1-01 Demonstration Rod Serial Number Map

	A	B	C	D	E	F	G	H	I	J	K
1			LN62 0001*	LN6 00004	LN6 00012	LS32 0007*	LN6 00030	LR3 00019	LR32 0001*		
2			LR3 00028						LN6 00029		
3	LR32 0003*	LS3 00014								LN6 00026	LS32 0005*
4	LN6 00003										LN6 00013
5	LN6 00028										LS3 00016
6	LN62 0006*										LN62 0004*
7	LS3 00013										LN6 00006
8	LN6 00008										LN6 00027
9	LS32 0002*	LN6 00021								LS3 00015	LR32 0004*
10			LN6 00010						LR3 00018		
11			LR32 0008*	LR3 00033	LN6 00031	LS32 0003*	LN6 00011	LN6 00002	LN62 0008*		

Spacer Serial No.
Orientation

* Serial No. of Middle Rodlet of Segmented Rods

FIGURE 6.7. BRPR Series S-2 Assembly H1-02 Demonstration Rod Serial Number Map

	A	B	C	D	E	F	G	H	I	J	K
1			LN62	LN6	LN6	LS32	LN6	LR3	LR32		
			0010*	00016	00017	0001*	00007	00034	0006*		
2			LR3						LN6		
			00032						00005		
3	LR32	LS3								LN6	LS32
	0007*	00011								00033	0008*
4	LN6										LN6
	00014										00037
5	LN6										LS3
	00032										00009
6	LN62										LN62
	0003*										0009*
7	LS3										LN6
	00010										00035
8	LN6										LN6
	00020										00018
9	LS32	LN6								LS3	LR32
	0010*	00019								00012	0005*
10			LN6						LR3		
			00025						00029		
11			LR32	LR3	LN6	LS32	LN6	LN6	LN62		
			0010*	00023	00036	0009*	00034	00015	0007*		

Spacer Serial No.
Orientation

* Serial No. of Middle Rodlet of Segmented Rods

FIGURE 6.8. BRPR Series S-2 Assembly H1-03 Demonstration Rod Serial Number Map

TABLE 6.9. BRPR Series S-2 Assembly H1-01

<u>Fuel Rod Location</u>	<u>Rod Type</u>	<u>Serial No.</u>
1C	Full-length; Reference pellet	LR300024
1D	Full-length; Annular-coated-pressurized	LN600058
1E	Full-length; Annular-coated-pressurized	LN600057
1F	Full-length; Annular-coated-pressurized	LN600001
1G	Full-length; Annular-coated-pressurized	LN600038
1H	Full-length; Annular-coated-pressurized	LN600053
1I	Full-length; Sphere-pac-pressurized	LS300006
2C	Full-length; Sphere-pac-pressurized	LS300003
2I	Full-length; Annular-coated-pressurized	LN600055
3A	Full-length; Annular-coated-pressurized	LN600050
3B	Full-length; Reference pellet	LR300030
3J	Full-length; Annular-coated-pressurized	LN600054
3K	Full-length; Annular-coated-pressurized	LN600052
4A	Full-length; Sphere-pac-pressurized	LS300005
4K	Full-length; Reference pellet	LR300017
5A	Full-length; Annular-coated-pressurized	LN600009
5K	Full-length; Annular-coated-pressurized	LN600051
6A	Full-length; Annular-coated-pressurized	LN600022
6K	Full-length; Annular-coated-pressurized	LN600024

TABLE 6.9. (Continued)

<u>Fuel Rod Location</u>	<u>Rod Type</u>	<u>Serial No.</u>
7A	Full-length; Annular-coated-pressurized	LN600047
7K	Full-length; Annular-coated-pressurized	LN600023
8A	Full-length; Reference pellet	LR300025
8K	Full-length; Sphere-pac-pressurized	LS300004
9A	Full-length; Annular-coated-pressurized	LN600049
9B	Full-length; Annular-coated-pressurized	LN600043
9J	Full-length; Reference pellet	LR300021
9K	Full-length; Annular-coated-pressurized	LN600039
10C	Full-length; Annular-coated-pressurized	LN600040
10I	Full-length; Sphere-pac-pressurized	LS300007
11C	Full-length; Sphere-pac-pressurized	LS300008
11D	Full-length; Annular-coated-pressurized	LN600042
11E	Full-length; Annular-coated-pressurized	LN600045
11F	Full-length; Annular-coated-pressurized	LN600048
11G	Full-length; Annular-coated-pressurized	LN600041
11H	Full-length; Annular-coated-pressurized	LN600046
11I	Full-length; Reference pellet	LR300022

TABLE 6.10. BRPR Series S-2 Assembly H1-02

<u>Fuel Rod Location</u>	<u>Rod Type</u>	<u>Serial No.</u>
1C	Segmented; Annular-coated-pressurized middle rodlet	LR310020 LN620010 LR330020
1D	Full-length; Annular-coated-pressurized	LN600016
1E	Full-length; Annular-coated-pressurized	LN600017
1F	Segmented; Sphere-pac-pressurized middle rodlet	LR310001 LS320001 LR330001
1G	Full-length; Annular-coated-pressurized	LN600007
1H	Full-length; Reference pellet	LR300034
1I	Segmented; Reference pellet	LR310026 LR320006 LR330026
2C	Full-length; Reference pellet	LR300032
2I	Full-length; Annular-coated-pressurized	LN600005
3A	Segmented; Reference pellet	LR310027 LR320007 LR330027
3B	Full-length; Sphere-pac-pressurized	LS300011
3J	Full-length; Annular-coated-pressurized	LN600033
3K	Segmented; Sphere-pac-pressurized middle rodlet	LR310008 LS320008 LR330008
4A	Full-length; Annular-coated-pressurized	LN600014
4K	Full-length; Annular-coated-pressurized	LN600037

TABLE 6.10. (Continued)

<u>Fuel Rod Location</u>	<u>Rod Type</u>	<u>Serial No.</u>
5A	Full-length; Annular-coated-pressurized	LN600032
5K	Full-length; Sphere-pac-pressurized	LS300009
6A	Segmented; Annular-coated-pressurized middle rodlet	LR310013 LN620003 LR330013
6K	Segmented; Annular-coated-pressurized middle rodlet	LR310019 LN620009 LR330019
7A	Full-length; Sphere-pac-pressurized	LS300010
7K	Full-length; Annular-coated-pressurized	LN600035
8A	Full-length; Annular-coated-pressurized	LN600020
8K	Full-length; Annular-coated-pressurized	LN600018
9A	Segmented; Sphere-pac-pressurized middle rodlet	LR310010 LS320010 LR330010
9B	Full-length; Annular-coated-pressurized	LN600019
9J	Full-length; Sphere-pac-pressurized	LS300012
9K	Segmented; Reference pellet	LR310025 LR320005 LR330025
10C	Full-length; Annular-coated-pressurized	LN600025
10I	Full-length; Reference pellet	LR300029
11C	Segmented; Reference pellet	LR310030 LR320010 LR330030
11D	Full-length; Reference pellet	LR300023

TABLE 6.10. (Continued)

<u>Fuel Rod Location</u>	<u>Rod Type</u>	<u>Serial No.</u>
11E	Full-length; Annular-coated-pressurized	LN600036
11F	Segmented; Sphere-pac-pressurized middle rodlet	LR310009 LS320009 LR330009
11G	Full-length; Annular-coated-pressurized	LN600034
11H	Full-length; Annular-coated-pressurized	LN600015
11I	Segmented; Annular-coated-pressurized middle rodlet	LR310017 LN620007 LR330017

TABLE 6.11. BRPR Series S-2 Assembly H1-02

<u>Fuel Rod Location</u>	<u>Rod Type</u>	<u>Serial No.</u>
1C	Segmented; Annular-coated-pressurized middle rodlet	LR310011 LN620001 LR330011
1D	Full-length; Annular-coated-pressurized	LN600004
1E	Full-length; Annular-coated-pressurized	LN600012
1F	Segmented; Sphere-pac-pressurized middle rodlet	LR310007 LS320007 LR330007
1G	Full-length; Annular-coated-pressurized	LN600030
1H	Full-length; Reference pellet	LR300019
1I	Segmented; Reference pellet	LR310021 LR320001 LR330021
2C	Full-length; Reference pellet	LR300028
2I	Full-length; Annular-coated-pressurized	LN600029
3A	Segmented; Reference pellet	LR310023 LR320003 LR330023
3B	Full-length; Sphere-pac-pressurized	LS300014
3J	Full-length; Annular-coated-pressurized	LN600026
3K	Segmented; Sphere-pac-pressurized middle rodlet	LR310005 LS320005 LR330005
4A	Full-length; Annular-coated-pressurized	LN600003
4K	Full-length; Annular-coated-pressurized	LN600013
5A	Full-length; Annular-coated-pressurized	LN600028
5K	Full-length; Sphere-pac-pressurized	LS300016

TABLE 6.11. (Continued)

<u>Fuel Rod Location</u>	<u>Rod Type</u>	<u>Serial No.</u>
6A	Segmented; Annular-coated-pressurized middle rodlet	LR310016 LN620006 LR330016
6K	Segmented; Annular-coated-pressurized middle rodlet	LR310014 LN620004 LR330014
7A	Full-length; Sphere-pac-pressurized	LS300013
7K	Full-length; Annular-coated-pressurized	LN600006
8A	Full-length; Annular-coated-pressurized	LN600008
8K	Full-length; Annular-coated-pressurized	LN600027
9A	Segmented; Sphere-pac-pressurized middle rodlet	LR310002 LS320002 LR330002
9B	Full-length; Annular-coated-pressurized	LN600021
9J	Full-length; Sphere-pac-pressurized	LS300015
9K	Segmented; Reference pellet	LR310024 LR320004 LR330024
10C	Full-length; Annular-coated-pressurized	LN600010
10I	Full-length; Reference pellet	LR300018
11C	Segmented; Reference pellet	LR310028 LR320008 LR330028
11D	Full-length; Reference pellet	LR300033
11E	Full-length; Annular-coated-pressurized	LN600031

TABLE 6.11. (Continued)

<u>Fuel Rod Location</u>	<u>Rod Type</u>	<u>Serial No.</u>
11F	Segmented; Sphere-pac-pressurized middle rodlet	LR310003 LS320003 LR330003
11G	Full-length; Annular-coated-pressurized	LN600011
11H	Full-length; Annular-coated-pressurized	LN600002
11I	Segmented; Annular-coated-pressurized middle rodlet	LR310018 LN620008 LR330018

TABLE 6.12. Chemical Analysis - Lot Average

Element	Lot Designation	
	SR-67-2	SR-48-1
Ag	1.0 ppm	n.d.
Al	7.0 ppm	11.0 ppm
B	0.27 ppm	0.12 ppm
Ba	1.6 ppm	8.3 ppm
Be	0.5 ppm	0.10 ppm
Ca	16.0 ppm	16.7 ppm
Co	5.0 ppm	4.0 ppm
Cr	25.0 ppm	18.7 ppm
Cs	35.0 ppm	45.0 ppm
Cu	70.0 ppm	21.0 ppm
Dy	0.11 ppm	0.12 ppm
Eu	0.01 ppm	0.12 ppm
Fe	115.0 ppm	116.0 ppm
Gd	0.11 ppm	0.21 ppm
Hf	0.85 ppm	6.34 ppm
Li	0.50 ppm	0.80 ppm
Mg	5.0 ppm	7.0 ppm
Mn	1.0 ppm	1.5 ppm
Mo	3.1 ppm	6.0 ppm
Ni	15.0 ppm	6.0 ppm
P	27.0 ppm	25.0 ppm
Pb	6.2 ppm	0.5 ppm
Si	102.0 ppm	87.0 ppm
Sm	0.09 ppm	0.28 ppm
Sn	3.7 ppm	2.0 ppm
Ta	0.03 ppm	5.0 ppm
Ti	3.0 ppm	3.0 ppm
V	1.0 ppm	1.0 ppm
W	0.06 ppm	0.21 ppm
Zn	13.0 ppm	0.32 ppm
Zr	0.17 ppm	2.4 ppm
K	15.0 ppm	n.d.
Na	23.0 ppm	n.d.
F	39.0 ppm	11.0 ppm
U	87.453 wt%	87.327 wt%
O/M	2.098 wt%	2.132 wt%
²³⁵ U	2.536 wt%	2.703 wt%

n.d. - below the limit of detection

and lifting of the lower insulator disc during vibratory compaction and the extent of the low density regions in the top of the fuel column, had to be resolved prior to fabricating Series S-2 and S-3 sphere-pac rods.

Levitation of the lower insulator disc during vibratory compaction is caused by the migration of microspheres under the insulator disc. This condition permits fuel particles to come in contact with the zircaloy end cap. It was determined that the heat rating in the lower end of the rod is less than about 6 kW/m, which means that the presence of the microspheres under the insulator disc result in an insignificant temperature rise in the lower end cap. Nevertheless, a solution to prevent the insulator disc from levitating was addressed. A thin zircaloy retainer disc designed to hold the insulator disc against the lower end cap during vibration of the sphere-pac rods was developed and tested. The gap between the insulator disc and end cap when not using the retainer disc was 0.18 to 0.22 mm; with the retainer disc, the gap was 0 to 0.1 mm.

The BRPR Series S-2 and S-3 sphere-pac rods were also designed with a zircaloy fuel retainer at the top of the fuel column. The upper fuel retainer disc is located between the plenum spring and upper insulator disc and prevents small microspheres from spilling into the upper plenum region during horizontal handling and shipping of the rods.

In arriving at a design for the sphere-pac fuel retainer disc, there was some speculation that axial thermal expansion of the fuel column could be impeded by bonding between the retainer disc at the upper end of the fuel column and the cladding. The retainer disc for the Halden rods, which used a fuel retainer disc only at the top of the rod, was designed for an interference fit with about 2.3 to 4.5 kg (5 to 10 lb) insertion force. The sphere-pac fuel retainer disc design for the BRPR rods was modified to open the center hole to 5.56 mm (0.219 in.) (Figure 6.9). This increased disc flexibility and decreased the contact area with the fuel. Development tests demonstrated that this disc design prevented fuel from intruding between the lower insulator disc and the zircaloy end cap.

TABLE 6.13. Preproduction Sinterability Tests (BRPR Series S-2 and S-3).

Lot Number	Tooling Used	Lubricant and Pore Former, wt%	Green Density, gm/cc cm ³	Sintering Temp., °C	Sintering Time, hr.	Sintered Density, %TD
SR-67-2	11.6 mm chamfered & dished	0.7 zinc	5.21	1770	2.85	94.79
		stearate and	5.35	1770	2.85	94.91
		0.2 Sterotex	5.51	1770	2.85	95.08
SR-67-2	11.6 mm chamfered & dished	0.1 zinc	5.08	1770	2.85	93.89
		stearate and	5.29	1770	2.85	94.15
		0.4 Sterotex	5.51	1770	2.85	94.47
SR-48-1	11.6 mm chamfered, flat face, 3.68 mm core	0.1 zinc	4.97	1770	2.85	93.63
		stearate and	5.18	1770	2.85	94.15
		0.2 Sterotex	5.40	1770	2.85	94.50
SR-48-1	11.6 mm chamfered, flat face, 3.68 mm core	0.1 zinc	4.93	1770	2.85	92.82
		stearate and	5.19	1770	2.85	93.33
		0.4 Sterotex	5.41	1770	2.85	93.68

Target sintered density = 93.5±1.5% TD

Process tests were performed to evaluate the possible effect of these discs on the inside of the fuel rods. In the first test, a disc was sealed with fuel pellets and insulators inside a cladding tube and heated to 500°C for 72 hours. Results showed that normal internal cladding oxidation did not cause any galling or seizing between the retainer disc and the cladding. After the test, the retainer fell out of the cladding with no applied force. Because the oxide film was very thin in this test, a second test was performed in which the possible effect of the retainer disc was evaluated by autoclaving two discs in an open tube for 72 hours at 400°C. The initial force to seat the two retainers, as measured by a Chatillon gauge, was 6.2 kg (13.5 lbs) and 4.99 kg (11.0 lbs). After autoclaving, the force required to move the retainers dropped to 3.63 kg (8 lbs) and 2.72 kg (1 lb), respectively. It appeared that the autoclave film acted as a lubricant and actually lowers the friction between the disc and tube instead of locking the disc and inhibiting the fuel stack expansion.

The top of the sphere-pac fuel columns had variable smear densities ranging from 86% TD down to 60% TD with the density dropping rapidly near the very top of the fuel column. The length of fuel column over which the density variation occurred was with 25 to 50 mm of the top with the most pronounced effect in the top 5 to 10 mm of fuel. The low density region was caused by either an excess of fines in the top of the fuel column or a lack of fines due to excessive infiltration into the fuel column.

The previous method of filling a rod with microspheres was to pre-weight the required amount of fuel and load the tubes vibrationally until all the fuel was emptied from the feeders. This usually resulted in the variable densities described above because the amounts of the three microsphere components tailed off at different rates when the very last of the fuel exited from the feeders.

The final solution to this problem was the use of an overfill technique wherein an excess of fuel is added, filling the rod into the plenum area; then the rod is vibrated and the excess microspheres are removed by aspiration down to the correct plenum length. Rods loaded in this manner have

FIGURE 6.9. Fuel Retainer

86.5 to 87.0% TD up to the very end of the fuel column. The spheres that are removed from the rod can easily be separated and recycled back to the feed stock.

The aspiration technique can also be used to rework a rod that has some discontinuity in the fuel columns (e.g., low density). The microspheres can be removed by aspiration down to a point just below the variable density region and the rod can then be refilled as described above. Two development rods were reworked by this method: regions with 71% TD were removed, and the rods were refabricated to meet acceptance specifications.

Data collected for test rod D-1 (Table 6.14) are representative of the average process variables using the standard formulation of microspheres for rod fabrication. The coarse and medium size microspheres are fed into the tube from separate troughs attached to a single vibrator. The fines are simultaneously fed into the tube from another, independently controlled, vibrator. The time required to feed all the microspheres into a 1.8 m long tube is 90 seconds. Small pneumatic vibrations(*) attached to the tube continuously operate at a low energy input during this fill-step. After the microspheres are loaded into the tube, the pneumatic vibrators are allowed to run for an additional 30 seconds. The 1000 g follower rod is then inserted on top of the fuel column and the larger pneumatic vibrators(**) that are attached to the rod support channel are then operated at a moderate energy input for 60 seconds to achieve the specified density of $87 \pm 1\%$ TD.

Rod density uniformity is quite good over the full-length, with the standard deviation ranging from ± 0.8 to $\pm 1.0\%$. There were no measured localized fuel densities as low as 84% TD which is the specification limit. The uniform sphere-pac fuel densities are a marked improvement over the vipac fuel.

(*) VIBCO Vibrator Products, Model BB190.

(**) Cleveland Vibrator Company, springless 25.4 mm dia piston.

TABLE 6.14. BRPR Series S-2 and S-3 Sphere-pac Process Development
Average Loading Results

<u>Test No.</u>	<u>Average Fill Density, %TD</u>	<u>Loading Time, sec.</u>	<u>Loading Vibrator Air Pressure, Pa x 10⁴ (psi)</u>	<u>Pre Compaction Vibrator Time, Sec.</u>	<u>Average Final Compaction Time, Sec.</u>	<u>Average Final Compaction Air Pressure, Pa x 10⁴ (psi)</u>
D-1	87.7	90	13.7 (20)	30	60	55.2 (80)

Microsphere Particle Size Distribution

<u>Test No.</u>	<u>Coarse (1150-1410μm), wt%</u>	<u>Medium (280-320μm), wt%</u>	<u>Fine (<45μm), wt%</u>	<u>Average Smear Density, %TD</u>
D-1	58	20	22	87.6

The 2.52% enriched microspheres for BRPR demonstration rods in Series S-2 and S-3 were received from ORNL in April, 1979. This shipment contained 29.6 kg of acceptable coarse spheres and 8.5 kg of coarse spheres that were tentatively rejected. The latter spheres were analyzed to determine if they were usable. The surface of the spheres was examined using scanning electron microscopy and compared to acceptable coarse microspheres from the same batch. There were an estimated 50% more surface irregularities present on these microspheres, but none appeared significant. A representative sampling of the microspheres was also examined ceramographically. Grain size was the same as the acceptable microspheres, and no porosity or gross cracking was present. Total gas measurements made on vacuum outgassed (no heat) microsphere samples were extremely low ($0.001 \text{ cm}^3/\text{gm}$), indicating low porosity and high density. Density measurements (by water immersion) were 99% TD (ORNL data results were 98.75% TD by Toluene immersion). Based on these analyses, the "usable" coarse reject spheres were blended with the coarse feed material and used for loading the Series S-2 and S-3 sphere-pac rods.

6.2.3 BRPR Graphite Coating Process Development

Process development activities were conducted on graphite coating techniques in an attempt to obtain more consistent coating thickness control. Typically, the thickness range of applied coatings shifts over a short period of time (approximately one day). This necessitates checking a sample tube about every 10 production tubes to avoid accumulating a large number of coated tubes that are out of specification.

Several process changes were made to achieve more uniform coating thickness control. The Dag 4 is maintained in a closed, continuously-stirred container and a hypodermic syringe is used to withdraw an aliquot of Dag 4 for each tube. The drain time after coating was fixed at 10 minutes minimum. Longer drain times do not seem to affect the coating thickness control. The solids content of the Dag 4 solution required to achieve the correct thickness control varied between 14 and 16 wt%. The technique used was to coat several preproduction tubes with 15 wt% Dag 4 (these can be short tubes), dry, measure coating thickness, adjust the Dag 4 solution if necessary, and then proceed with coating of the production tubes. This procedure was repeated approximately every 24 hours.

6.3 FABRICATION - BRPR SERIES S-2 AND S-3

6.3.1 BRPR Pellet Fabrication

Pressing of the reference and annular pellets was performed using a single station Western Sintering press. Tooling and pressing data for both pellet lots are listed in Tables 6.15 and 6.16. Fabrication of the pellets was completed using standard production equipment and practices in the UO_2 production facility. Results of the preproduction sinterability tests were used to establish the pressing and sintering variables for production. A total of 105 kg's of reference and 197 kg's of annular pellets were made. Very high yields were obtained after grinding. Yield information is listed in Table 6.17. The significantly reduced pellet reject rate because of chipping is mainly attributed to the edge chamfer design of the pellets.

The higher percentage loss of the annular pellets due to being undersize is thought to be caused by the lighter annular pellets (10% less volume) raising up off the work guide on the grinder and thus being positioned differently than the reference pellets.

One thousand reference and one thousand annular pellets were characterized (diameters measured) and arranged in fuel stacks on the outgas trays and loaded into the middle rodlets of the segmented rods. Each pellet is identified by a scribed letter and number. To help keep track of each fuel stack layout, the pellets were segregated according to similar letters for each rod. For each fuel column, the last two pellets were adjusted as necessary using "short" pellets prepared in three different lengths [7.11 mm (0.280 in.), 6.6 mm (0.260 in.), 6.1 mm (0.240 in.)] to permit adjusting to fuel column length requirements.

6.3.2 BRPR Graphite Coated Tube Fabrication

Graphite coating of the tubes for BRPR Series S-2 and S-3 was completed with an overall yield of nearly 100% following an initial adjustment of the DAG 4 solids content. The improvements that led to this high yield were continuous agitation of the Dag 4 solution and determination of the relationship between the drain time (after applying the graphite) and the Dag 4

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Graphite coating of the tubes for BRPR Series S-2 and S-3 was completed with an overall yield of nearly 100% following an initial adjustment of the DAG 4 solids content. The improvements that led to this high yield were continuous agitation of the Dag 4 solution and determination of the relationship between the drain time (after applying the graphite) and the Dag 4

TABLE 6.15. Production Summary - BRPR Series S-2 and S-3 Reference Pellets

<u>Lot Number</u>	<u>Tooling Used</u>	<u>Lubricant and Pore Former, wt%</u>	<u>Green Density, gm/cm³</u>	<u>Sintering Temp., °C actual</u>	<u>Sintering Time, hr</u>	<u>Sintered Density, %TD</u>
SR 67-2 Rev. 1 2.52%	11.8 mm (0.465 in.) dished and chamfered tool- ing design; green density = 5.25 gm/cm ³	0.1 zinc stearate and 0.4 Sterotex	5.25	1740	2.82	93.45 = 0.27

Resinter test (1700°C for 24 hours)

Density before resinter = 93.30% TD $\sigma = 0.31$

Density after resinter = 93.74% TD $\sigma = 0.27$

- 1) Powder was milled at 8000 RPM with an 0.686 mm (0.27 in.) Herringbone screen.
- 2) Roll compacted at 6.99 mm (2.75 in.); granulated through a 10 mesh screen to minimize protrusions.
- 3) Lubricant and pore former added to prepped powder; tumbled for 12 minutes.

TABLE 6.16. Production Summary - BRPR Series S-2 and S-3 Annular Pellets

<u>Lot Number</u>	<u>Tooling Used</u>	<u>Lubricant and Pore, Former, wt%</u>	<u>Green Density, gm/cm³</u>	<u>Sintering Temp., °C actual</u>	<u>Sintering Time, hr</u>	<u>Sintered Density, %TD</u>
SR-48-1 Rev. 1 2.69%	11.8 mm (0.465 in.) flat faced, annular and chamfered tool- ing design; green density =5.25 gm/cm ³ ; core rod diameter =3.7 mm (0.1459 in.)	0.1 zinc stearate and 0.4 Sterotex	5.25	1780	3.4	94.35 = 0.24

Resinter test (1700°C for 24 hours)

Density before resintering = 93.57% TD $\sigma = 0.17$

Density after resintering = 93.89% TD $\sigma = 0.10$

- 1) Powder was milled at 8000 RPM with an 0.686 mm (0.027 in.) Herringbone screen.
- 2) Roll compacted at 50.8 mm (2.00 in.); granulated through a 10 mesh screen. Re-roll compacted at 76.2 mm (3.00 in.) granulated through a 10 mesh screen to minimize protrusions.
- 3) Lubricant and pore former added to prepped powder; tumbled for 12 minutes.

TABLE 6.17. BRPR Series S-2 and S-3 Pellet Yield Data

<u>Pellet Type</u>	<u>Chip Loss, %</u>	<u>Undersize, %</u>	<u>Misc. Loss,* %</u>	<u>Overall Yield, %</u>
Reference	1.96	0.32	--	97.7
Annular	2.07	1.52	1.27	95.1

* Dropped, etc. pellets

solids content. Present production practice is to fix the drain time at 10 minutes minimum and vary the solids content of the Dag 4 slightly between 14 and 16 wt% to meet required thickness.

During this production campaign, 201 full-length tubes and 12 segmented tubes were satisfactorily coated. During processing this number of tubes, the solids content of the Dag 4 solution was adjusted five times. A description of the coating experience is summarized in Table 6.18.

6.3.3 BRPR Sphere-Pac Fabrication

Fabrication of the S-2 and S-3 sphere-pac rods was completed. The number of rods produced was:

- 38 - full-length
- 2 - archive (full-length)
- 2 - spares (full-length)
- 10 - rodlets

The microspheres used for loading the S-2 and S-3 fuel rods were outgassed using standard process equipment and process variables developed for microspheres ($550^{\circ}\text{C} \pm 25^{\circ}\text{C}$, 10^{-3} Torr, 4 hours minimum). Subsequent measurements of water and hydrogen were quite low, being 2 ppm and 0.1 ppm, respectively.

At the outset of sphere-pac rod fabrication, considerable difficulty was encountered in achieving uniform densities on full-length rods. Initially, this was attributed to the new 2.52% enriched microspheres not having dust like the depleted microspheres used in developing the loading procedure (the latter microspheres were used over and over again). Several production rods were downloaded as a result of this variable density.

TABLE 6.18. BRPR Series S-2 and S-3 Graphite Coating Experience

Dag Adjustment Sequence (Run No.)	Description of Tubes Coated
1	Coated tubes 20 to 59. Coated thickness acceptable.
2	Coated tubes 60 to 59. Batch rejected due to thin coatings. Average film thickness from 0.004-0.005 mm (0.00016-0.00019 in.).
3	Solids content of Dag 4 used in Run 2 was increased to 15wt%. Coated tubes 80 to 159. Coated thickness acceptable.
4	Dag 4 solution used in Run 3 was diluted with 40 cc deionized water because the solution had stood inactive for four days. Coated tubes 160 to 179. Coated thickness acceptable.
5	Diluted the Dag 4 solution used in Run 4 with 20 cc deionized water. Recoated tubes 60 to 79. Coated thickness acceptable. A slightly thinner Dag 4 solution is required when recoating tubes.
6	Coated tubes 180 to 201; coated thickness acceptable. The solution from Run 5 did not need adjustment as it stood inactive for two days and had thickened to a point where additional thickening of the Dag 4 solution was not necessary to coat the remaining cladding.

NOTE:

The average coating thickness for the full-length tubes (average thicknesses for five readings) was nominally 6 μ m (0.00024 in.). The coating thickness (average for five readings) for the segmented fuel rods was controlled tightly at 6.29 μ m (0.000248 in.). The coatings on the segmented rods was ± 0.14 mm.

After repeated attempts to revibrate some rods, it was found that repositioned rods in the clamping mechanism that holds the rods during vibration resulted in an increase in overall rod density of approximately 0.5% TD. As a result, standard production practice is to vibrate half the time in one position, then rotate the rod 180° in the clamps and finish the vibration. All of the rods loaded in this manner are between 86.5% TD and 87% TD (Specification = 87 $\pm$ 1% TD).

Table 6.19 lists the calculated average densities and measured average densities for the 42 full-length rods and 10 segmented rods.

The calculated and measured average rod densities agreed closely, especially on the full-length rods. The shorter segmented rods showed a slightly larger variation in point-to-point density measurements. In all cases, no localized densities below 84% TD were measured. Some of the average values are missing for the measured (gamma densigage) rods. The actual point-to-point readings (readings were taken every 5 mm over the full length of the rods) are available and can be calculated if the need arises.

Density variations at the top of the fuel columns were eliminated by the over-fill technique. Excess fuel in the plenum region after vibration is removed by aspiration down to the correct fuel column length. Rods loaded in this manner have 86.5 to 87.0% TD up to the very end of the fuel column. This technique was also used to rework some rods that had density discontinuities in the top of the fuel column (densities below 84% TD).

Gas atmosphere analysis of a full-length, randomly selected sphere-pac rod indicated that the gas in the rod was 95.5% helium, which is within specifications instead of the expected value of about 97% helium. Most of the other gas component was nitrogen; so either the welding procedure did not succeed in removing all the trapped air in the fuel, or the fuel, initially high in absorbed gas, released some of the absorbed N_2 and O_2 during rod autoclaving.

TABLE 6.19. Calculated and Measured Average Densities for BRPR Series S-2 and S-3 Sphere-Pac Rods

Rod No.	Calculated Avg. Density, wt% TD ¹	Measured Avg. Density, wt% TD ²
LS300001	86.5	86.6
LS300002	86.7	86.5
LS300003	86.8	--
LS300004	86.9	--
LS300005	86.8	--
LS300006	86.6	86.6
LS300007	86.5	86.3
LS300008	87.0	--
LS300009	86.3	86.4
LS300010	86.7	86.8
LS300011	86.9	87.1
LS300012	86.4	86.9
LS300013	86.6	86.7
LS300014	87.2	86.8
LS300015	86.8	86.8
LS300016	86.5	87.2
Avg.	86.7	86.7
σ	0.24	0.27
MS300001	87.0	86.8
MS300002	87.0	86.8
MS300003	86.7	86.7
MS300004	86.9	87.2
MS300005	87.1	87.2

¹ Calculated from wt/vol rod data

² Measured with a gamma densigauge Cs-137 source.

TABLE 6.19. (Continued)

Rod No.	Calculated Avg. Density, wt% TD ¹	Measured Avg. Density, wt% TD ²
MS300006	86.5	86.4
MS300007	87.3	87.3
MS300008	86.8	86.9
MS300009	86.8	--
MS300010	86.8	--
MS300011	87.3	87.3
MS300012	86.9	87.0
MS300013	87.0	87.1
MS300014	87.2	87.3
MS300015	87.2	86.7
MS300016	86.7	86.9
MS300017	87.3	87.3
MS300018	87.1	87.1
MS300019	86.4	86.8
MS300020	87.1	87.1
MS300021	86.8	86.6
MS300022	86.7	--
MS300023	87.0	86.9
MS300024	86.6	86.3
MS300025	87.1	87.0
MS300026	<u>87.0</u>	<u>86.6</u>
Avg.	86.9	86.9
σ	0.24	0.29
LS320001	86.3	--
LS320002	86.1	--
LS320003	86.1	86.6

¹ Calculated from wt/vol rod data

² Measured with a gamma densigauge Cs-137 source.

TABLE 6.19. (Continued)

<u>Rod No.</u>	<u>Calculated Avg. Density, wt% TD¹</u>	<u>Measured Avg. Density, wt% TD²</u>
LS320004	86.6	86.8
LS320005	86.8	86.7
LS320006	86.6	86.8
LS320007	86.3	86.4
LS320008	86.8	86.5
LS320009	86.6	86.8
LS320010	<u>86.5</u>	<u>--</u>
Avg.	86.5	86.7
σ	0.26	0.16

¹ Calculated from wt/vol rod data

² Measured with a gamma densigauge Cs-137 source.

7.0 TASK 3 - FUEL PERFORMANCE EVALUATIONS

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This task serves as a focal point for the integration and evaluation of data developed from the Fuel Performance Improvement Program (FPIP) and evaluates the results of other FCI-related programs as they may pertain to the FPIP. The task activities are intended to provide the basic resources for establishing technical bases for fuel design. Most of the activities in this task during the year were directed towards determining the validity of the IFA-518 and IFA-517 power equations and monitoring the fuel rod behavior in IFA-518 and IFA-517.

7.1 HBWR SERIES H-1 PERFORMANCE EVALUATION

7.1.1 HBWR Series H-1 Power Equations

The Series H-1 fuel rods under irradiation in the Halden Boiling Water Reactor (HBWR) assembly IFA-518 include 12 fuel rods with six of these rods hexagonally arrayed in an upper cluster and the remaining six rods in the lower cluster. Four fuel forms are included in HBWR Series H-1: reference, annular, annular-coated, and vipac. An axially moveable neutron absorber shield covers one or the other of the clusters at any one time, permitting the power of the shielded cluster to be reduced approximately 40%. The IFA-518 assembly is instrumented with neutron detectors, fuel centerline thermocouples, cladding elongation sensors, and internal pressure transducers.

The IFA-518 assembly power equation, average linear heat generation rate equations for each fuel rod, and local linear heat generation rate equations at the thermocouple tips of each rod were supplied by the Institut for Atomenergi. These equations were based upon previous experience from similar experiments. A calibration factor between the measured assembly heat balance and the vanadium neutron detector readings during steady state operation was determined. Corrections were made in the original equation for

the estimated gamma heating in the test rig structural materials, the estimated effect of the silver absorber shield on the adjacent neutron detector readings, burnup, and the fissile content in each individual fuel rod.

As part of the experiment analysis, calculations of rod-average and local linear heat generation rates (LHGR) are made to compare performance of the various fuel designs. Errors in these calculations were noted after the first shield shift on September 26, 1978 when the silver shield was moved from the upper to the lower cluster position. It was found that with the shield down, the linear heat generation rates at the thermocouple (LHRTF) location as indicated by the neutron detectors, was lower for a given measured fuel temperature than when the shield was up. The error in reference fuel rods was estimated to be about 18%. A slightly smaller error in the linear heat generation rate was noted for annular-coated fuel and may be compared with reference fuel using Figures 7.1 and 7.2.

Analysis of special shield movement experiments and the basic data acquired during irradiation indicated that corrections to the power and linear heat generation rate equations were required for the following items:

- Neutron streaming at both ends of the absorber shield caused higher total power in the shielded rods than was indicated by the neutron detectors.
- Neutron streaming at the upper end of the shield caused a higher linear heat generation rate at the shielded thermocouple tip than at the nearby neutron detector which is shielded more completely than the thermocouple.
- Thermal flux depression adjacent to the absorber shield in the region of the neutron detectors is significantly greater than originally estimated.
- A step burnup correction was made in the original power equations at the time of the shield shift. This caused a 1.9% error in the calculated linear heat generation rates.

Incorporation of corrections for these items significantly reduced the observed 18% error in the linear heat generation rates at the thermocouples.

FIGURE 7.1. Comparison of the Temperature Changes in a Reference Rod During Several Power Ascensions

FIGURE 7.2. Comparison of the Temperature Changes in a Annular-Coated Rod During Several Power Ascensions

Figure 7.3 shows the results of incorporating the changes to the power equations for the lower cluster reference rod.

Several other modifications were made to the power equations to more correctly calculate the linear heat generation rates in the clusters and individual rods but which did not affect the observed error before and after the shield shift. These modifications were:

- Corrections for the power split between clusters and the power split between rods in a cluster were made based upon the differences in radial flux depression within rods for the different fuel designs, e.g., annular fuel versus reference fuel.
- Corrections were made for the power generated in the thermocouple regions of the reference and vipac rods.
- A correction was made to the linear heat generation rate equation at the thermocouple for the axial displacement between the thermocouple tip and the nearest adjacent neutron detector.

A detailed description of all the corrections for the IFA-518 power equations was previously documented.^(7.1)

7.1.2 HBWR Series H-1 Centerline Fuel Temperature Measurements

Preliminary comparisons between the measured centerline fuel temperatures for the four fuel types in the Series H-1 rods were reported previously.^(5.1) These comparisons were based upon linear heat generation rates calculated using the original power equations. Comparisons of fuel centerline temperatures during the initial experiment startup, which are based upon the modified power equations, are presented in Figure 7.4. The plotted temperatures represent the actual measured values. The linear heat generation rates plotted in Figure 7.4 have been corrected as described in Section 7.1.1 and are currently considered to be the best values available. As expected, because of the larger hole in the annular fuel, the annular fuel rods operated at significantly lower fuel temperatures than did the reference pellet fuel. The presence of the graphite coating did not have a significant effect on fuel temperatures compared with the noncoated annular fuel. As expected, the vipac rods had the highest fuel temperatures of the four fuel types.

FIGURE 7.3. Comparison of Corrected and Uncorrected Power Data Prior To and After the September 28, 1978 Shield Shift

FIGURE 7.4. Comparison of Measured Fuel Centerline Temperatures in Series H-1 Rods During the Initial Power Ascension

The measured temperature in the reference and vipac rods have not been corrected for the presence of the thermocouple hole, i.e., the fuel temperature at the same linear heat generation rates if there was no thermocouple present. At a linear heat generation rate of 40 kW/m, the fuel temperature correction factors for this effect are estimated to be 80°C and 180°C for the reference and vipac rods, respectively.

The effect of burnup on the fuel centerline temperatures is illustrated in Figure 7.5. The plots were developed by monitoring the fuel temperatures during power ascensions and decreases at linear heat generation rate values of 36 kW/m and 20 kW/m. The two values were selected in order to make comparisons 1) near the peak linear heat generation rates, and 2) at a level that permits continuous data sampling for a condition that is independent of whether or not the peak power is being suppressed by the absorber shield. The measured temperatures have not been corrected for decalibration of the thermocouples caused by transmutation of tungsten to rhenium. (Transmutation decalibration causes a decrease in the thermocouple output.) For the current burnup levels, the decalibration is expected to be small. The following observations were made:

- Operating temperatures of all four fuel types increased during the first 1.7 GJ/kgM (0.2 MWd/kgM) burnup. This increase is probably due to the effects of slight fuel densification and/or gas conductance degradation caused by off-gassing. Apparently fuel fragment relocation in the pellet fuel rods occurs rapidly, i.e., during the first startups, as evidenced by 1) lower measured temperatures than would be predicted based upon noncracked fuel, and 2) no significant measured decrease in fuel operating temperature with increasing burnup.
- The fuel temperature difference, about 90°C at 40 kW/m, between annular-coated and annular fuel that occurred early in life disappeared at a burnup of about 35 GJ/kgM (4 MWd/kgM).
- At 36 kW/m and after a burnup of 1.7 GJ/kgM, the fuel temperatures for the four fuel types were relatively constant with increasing

FIGURE 7.5. Fuel Centerline Temperatures in Series H-1 Rods Measured at Two Discrete LHGRs During Power Ascensions and Decreases as a Function of Burnup

burnup. Perhaps there is a slight tendency for a temperature decrease in the annular-coated and annular rods; this may be due to thermocouple decalibration or fuel relocation. Perhaps there is a slight tendency for a temperature increase in the reference rod; possibly due to higher fission gas release at the higher fuel temperatures in the reference fuel, when compared to annular fuel.

- The general increase in fuel temperatures at an indicated constant linear heat generation rate of 20 kW/m for the burnup range from 250 GJ/kgM (3 MWd/kgM) to 345 GJ/kgM (4 MWd/kgM) occurred while the IFA-518 absorber shield covered the rods. The burnup ranges before and after this period were for the shield-up conditions. The difference in temperatures between the shield-up and shield-down conditions may represent a small error in the calculations which are used to determine the power split between clusters.

7.1.3 HBWR Series H-1 Fuel Rod Elongation Behavior

Preliminary comparisons of the measured fuel rod elongations for the four types of Series H-1 rods were reported previously.^(5.1) Comparisons of fuel rod elongation during the initial experiment startup, which are based upon the modified power equations, are presented in Figure 7.6. The annular-coated, annular, and reference rods all exhibited free thermal expansion of the cladding up to an average LHGR of about 32 kW/m. No fuel-cladding mechanical interaction was indicated in these rods during continuous monitoring of the elongation sensors versus the natural cyclic reactor power variations (typically $\pm 3\%$) at the peak operating conditions. As expected, the cladding elongation of the vipac rod deviated significantly from a free expansion curve during the initial power ascension, indicating strong fuel cladding mechanical interaction. However, above an average linear heat generation rate of about 12 kW/m, the elongation curve for the vipac rod was roughly parallel to the expansion curves for the pellet-containing rods, indicating that relaxation in the fuel and/or cladding occurred at about the same rate that the increase in reactor power was causing additional interaction, i.e., there was a force equilibrium in the rod. After about three hours of steady-state operation at the peak power condition, sufficient relaxation had occurred in

FIGURE 7.6. Fuel Rod Elongation in Series H-1 Rods During Initial Power Ascensions

the vipac rod to permit the cladding to contract at the same rate as the pelletized rods during the following power decrease. This indicated that the interaction rapidly relaxed during steady-state operation. The vipac rod subsequently exhibited elongations during power ascensions that were similar to the pelletized rods up to the point that the previous peak linear heat generation rate was exceeded (Figure 7.7). However, continuous monitoring of the vipac rod elongation sensor as a function of the natural cyclic reactor power variations at peak average rod linear heat generation rates of about 32 kW/m indicated that the rod elongation continuously correlated with the reactor power, i.e., the fuel remains in soft contact with the cladding at the peak rod linear heat generation rates. This effect was always observed except for periods of extended operations at linear heat generation rates significantly below those previously attained by the vipac rod, e.g., after a power reduction due to the absorber shield shift.

Continuous monitoring of the elongation sensors in the lower cluster rods as a function of the natural cyclic reactor power variations at peak rod linear heat generation rates and average rod burnups of about 370 GJ/kgM (4.3 MWd/kgM) indicated that soft fuel-cladding mechanical interaction was occurring in the reference and annular rods and a somewhat stronger interaction was occurring in the vipac rods. The annular-coated rod did not exhibit fuel-cladding mechanical interaction (Figure 7.8). These effects were first observed in the pelletized rods during the first power ascension after the extended period of operation at reduced power, i.e., after the first shield-induced power cycle. The occurrence of soft interaction in the reference, annular, and vipac rods and no interaction in the annular-coated rod has continued to the current average burnup level of approximately 622 GJ/kgM (7.2 MWd/kgM). Apparently, the graphite coating is performing as a lubricant between the fuel and cladding.

7.1.4 HBWR Series H-1 Fuel Rod Internal Pressure Behavior

Internal pressure sensors are included in four HBWR Series H-1 fuel rods: an annular-coated and a vipac rod in the lower cluster, and a reference and a vipac rod in the upper cluster. The pressure sensors in these rods are sensitive to both rod internal pressure and rod elongation. Therefore, rod

FIGURE 7.7. Fuel Rod Elongation in a Vipac Fuel Rod During Four Power Ascensions

FIGURE 7.8. Fuel Rod Elongation in Series H-1 Rods at 370 GJ/kgM (4.3 MWd/kgM) Burnup Compared to Reactor Power Oscillations

elongation measurements from sibling rods must be algebraically summed with the pressure sensor signal to determine rod internal pressure. The rod pressures were determined during the first few reactor startup periods in order to determine the amount of off-gassing in the different types of rods. During this initial operating period, the silver absorber shield was in the upper position. Consequently the power was higher in the lower cluster rods than in the upper cluster rods. The reactor operated for about two days at about 17% of fuel power and then underwent several power ascensions and power decreases for experimental and calibration purposes. Hold times were a few hours at the peak power conditions after each power ascension. The measured pressure increase in the rods caused by off-gassing are summarized in Table 7.1. Table 7.2 summarizes the calculated percentage releases of off-gas

TABLE 7.1. Internal Pressure Measurements from HBWR Series H-1 Fuel Rods

Rod Type (No.)	Cluster	Average LHGR After First Startup, kW/m	Increased Pressure at STP, kPa (psi)(1)			
			After 2-MW Operation	After First Startup	After Second Startup	After Third Startup
Reference (3)	Upper	22.8	0.0 (0.0)	0.7 (0.1)	3.5 (0.5)	1.4 (0.2)
Annular-Coated (10)	Lower	32.1	10.3 (1.5)	13.8 (2.0)	15.2 (2.2)	13.1 (1.9)
Vipac (14)	Lower	31.3	12.4 (1.8)(2)	0.0 (0.0)	5.5 (0.8)	8.3 (1.2)
Vipac (18)	Upper	21.7	42.0 (6.1)	15.9 (2.3)	20.7 (3.0)	26.9 (3.9)

(1) Reactor operated for approximately 2 days at 2 MW (17% of full power). Peak average LHGRs after the first and third startup were about the same. Peak average LHGRs after the second startup were ~21% higher in the lower cluster and ~9% lower in the upper cluster. Hold times at peak LHGR were less than 10 hr.

(2) Peak pressure, 49.0 kPa (7.1 psi), occurred during 2 MW operation.

TABLE 7.2. Calculated Releases from Different Sources Within the Rods

Rod Type (No.)	Basis for Release(1)	Percentage Release, %(2)			
		After 2 MW Operation	After First Startup	After Second Startup	After Third Startup
Reference (3)	Gas-Fuel	0	0.3	3.3	1.4
Annular-Coated (10)	Gas-Coating/ Gas-Fuel	83(3)	106(4)	118(4)	99(4)
Vipac (14)	Water-Fuel	76(5)	-	-	-
	Gas-Fuel	-	0	0.3	0.5
Vipac (18)	Water-Fuel	273	-	-	-
	Gas-Fuel	-	9.0	11.6	14.7

(1) Gas-Fuel = $0.023 \text{ cm}^3/\text{g}$ for reference, $0.008 \text{ cm}^3/\text{g}$ for annular, and $0.049 \text{ cm}^3/\text{g}$ for vipac.
 Water-fuel (Vipac) = 3 ppm.
 Gas-coating = $14.75 \text{ cm}^3/\text{g}$.

(2) Reactor operated for approximately 2 days at 2 MW (17% of full power). Peak average LHGRs are listed in Table 7.1. Hold times at peak LHGR were less than 10 hr.

(3) Based on coating off-gas.

(4) Based on coating off-gas + 1.4% release from fuel.

(5) Peak pressure occurred during the 2 MW operation at a water release equivalent to 304%.

based upon known amounts of absorbed gas as determined by analysis of fuel samples. The calculations are based upon pressure indications at reduced power, i.e., before and after the reactor power was cycled. After the first and second power cycle, the reactor only returned to about 15 to 20% of full power. The effects of fuel temperature on gas pressure at reduced power have been estimated. However, the best comparisons were made after 2 MW of operation and after the third cycle when the reactor was at zero power. The following observations and conclusions were made by comparing the off-gas results:

- Reference Rod No. 3 - In the reference rod, which initially operated at lower linear heat generation rates than the lower cluster rods, very low off-gassing occurred during initial operation. Based upon as-fabricated absorbed gas measurements,

only 1 to 3% of the gases were released. The pressure decrease after the third startup indicates that about one-half of the released gases are chemically stable, e.g., helium or nitrogen, while the other one-half reacts with the fuel and/or the cladding, e.g., water, hydrogen or oxygen.

- Annular-Coated Rod No. 10 - In the annular-coated rod, which operated in the lower cluster at high power, the off-gassing primarily occurred concurrent with the low power (2 MW) operation. The amount of gas release corresponds to essentially 100% of that released from coating control samples. The pressure in the annular-coated rod remained relatively stable after each power cycle, indicating that the released gas is chemically stable, e.g., helium or nitrogen.
- Vipac Rods No. 14 and 18 - In the vipac rods, one each in the upper and lower clusters, significant off-gassing occurred during the low power (2 MW) operation. In the higher-power rod (V14), off-gassing occurred during the initial heatup and decreased during the low power (2 MW) operating period and the first power cycle. In the lower-power rod (V18), off-gassing occurred throughout the low power (2 MW) operating period and decreased during the first power cycle. Additional off-gassing occurred in both vipac rods during the second (very high power) and third power cycles. The initial releases, combined with subsequent pressure decreases, indicate that these gases are chemically reactive with the fuel or, more probably, the cladding. Due to analytical difficulties, the off-gas results for the as-fabricated vipac fuel have a large uncertainty. Therefore, comparisons of the results to water releases, as listed in Table 7.2, are probably not completely valid. However, the significant releases at low power (2 MW) indicate that the gases are probably water combined with hydrogen and/or oxygen. The later releases at high

power are apparently more stable, e.g., helium or nitrogen. The large difference in indicated off-gassing between the two vipac rods is apparently real, although differences in elongation between rod No. 18 and its sibling rod with an elongation sensor could account for the calculated pressure differences. It is not possible to definitely check the differences in elongation.

The off-gas results indicate that initial degradation of the conductivity of contained gas in pellet and coated rods due to dilution of the helium fill gas by lower conductivity gases is not significant.

7.2 HBWR SERIES H-4 PERFORMANCE EVALUATION

7.2.1 HBWR Series H-4 Power Equations

The Series H-4 fuel rods under irradiation in the HBWR assembly IFA-517 include three pressurized sphere-pac rods, two with fuel centerline thermocouples and one reference rod with a fuel centerline thermocouple. Two of the sphere-pac rods and the reference rod are instrumented with elongation sensors; the other sphere-pac rod has a pressure sensor (Figure 3.1). The rods are geometrically arranged in a square array with the midplane of the active fuel length aligned with the expected peak in the axial flux profile. The four vanadium neutron detectors located at the midplane of the rod are also positioned in a square array. Assuming that the flux tilt across the assembly can be described by a plane, the average of the signals of the two neutron detectors adjacent to any fuel rod represents the flux at the midplane of the fueled length of the rod. An axial array of three neutron detectors, including the detector in the horizontal array at the fuel midplane, are used to describe the axial flux profile. The average linear heat generation rate in a specified rod is calculated from the average flux computed from the neutron detector readings, the fissile mass ratios in the fuel rods, and a calibration factor from the heat balance in the assembly. Linear heat generation rates at the thermocouple locations are determined in a similar manner by computing the equivalent neutron detector signal at the axial location of the thermocouple and adjusting the radial power distribution for the presence

of the thermocouple hole. The power calculations are corrected for the estimated gamma heating contribution in the test rig structural materials and burnup (fissile depletion) in the individual fuel rods.

7.2.2 HBWR Series H-4 Fuel Centerline Temperature Measurements

At any equivalent linear heat generation rate during the initial startup period, the measured fuel temperatures in the sphere-pac rods were significantly lower than the measured fuel temperatures in the reference rod in IFA-517. The difference in fuel temperature, shown in Figure 7.9, is about 130°C at 40 kW/m. Also shown is a comparison of the fuel temperature in the reference rods from IFA-517 and IFA-518. The measured actual temperatures have not been corrected for the presence of the thermocouple hole, i.e., the fuel temperature at the same linear heat generation rate if there was no thermocouple present. If differential temperatures in the sphere-pac fuel rod resulting from the presence of the thermocouple hole are proportional to the differential temperatures in vipac fuel, the correction factor for this effect in sphere-pac fuel is estimated to be about 120°C at 40 kW/m (Section 7.1.2). The correction factor at 40 kW/m for the reference fuel is estimated to be about 80°C. Using these values, the estimated fuel centerline temperatures for pressurized sphere-pac fuel and the IFA-517 reference fuel both operating at 40 kW/m with no thermocouples present would be 1330°C and 1420°C, respectively.

Comparison of the fuel temperatures in vipac (Figure 7.4) and pressurized sphere-pac rods shows that the sphere-pac fuel operates at considerably lower temperatures than the vipac fuel. The major part of this difference is currently attributed to the effect of helium pressurization in the sphere-pac rods, although there may also be a generic difference in the effective conductivity of vipac and sphere-pac type fuel at a given level of pressurization.

7.2.3 HBWR Series H-4 Fuel Rod Elongation Behavior

Hardwiring of the rod elongation sensors to obtain simultaneous comparative data for the rod types resulted in difficulties in obtaining elongation data during the first cycle of irradiation in IFA-517 (Sections 5.5.1

FIGURE 7.9. Comparison of Measured Fuel Centerline Temperatures in Sphere-pac and Reference Fuel Rods

and 5.5.2). Therefore, comparisons of the magnitude of the differences in elongation between the sphere-pac and reference rods cannot currently be made. However, a relative comparison of the elongation curves for vipac fuel from IFA-518 and sphere-pac fuel from IFA-517 indicates that the curve shapes are similar. The sphere-pac fuel rod also exhibited fuel-cladding mechanical interaction during the first power ascension, relaxation during the last part of the power ascension and during the hold period at peak power, and elongations similar to the free expansion of the cladding on subsequent startups, as long as the previous peak power was not significantly exceeded. Continuous monitoring of the elongation as a function of the normal cyclic power variation of the reactor at fuel power indicates that the fuel in the sphere-pac rods is also in soft contact with the cladding after relaxation has occurred.

Due to the axial centering of the rods in the peak flux, the maximum average LHGRs in IFA-517 are about 42 kW/m at fuel reactor power, i.e., about 30% higher than in the unshielded cluster of IFA-518. However, the peak LHGRs occurring in the rods in the two test rigs are about the same. The reference rod underwent fuel-cladding mechanical interaction during the initial power ascension, possibly due to the higher average linear heat generation rates in IFA-517 than in IFA-518. (The reference rod in IFA-518 did not undergo FCI during the initial startup.) A slight interaction was indicated in the Series H-4 reference rod by both the TFDR elongation data taken every 15 min and continuous monitoring of the elongation sensor as a function of the cyclic power variation of the reactor. Elongation in the reference rod during subsequent startups in the first cycle of operation was similar to the free expansion of the cladding. Because the reference rod in IFA-517 was known to have had at least one small fuel chip in the fuel-cladding gap, the mechanical interaction may have been caused by wedging of a fuel chip between the fuel and the cladding.

7.3 REFERENCES

- 7.1 "Fuel Performance Improvement Program, Quarterly Progress Report, April-June 1979," compiled by C. E. Crouthamel, C00-4066-12, July 1979.

8.0 TASK 4 - ESTABLISHMENT OF TECHNICAL BASES

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8.1 TASK OBJECTIVES

The objective of this task is to establish technical bases for design and design criteria of the candidate fuel concepts through transfer of program results and from information available on these fuel concepts in the open literature.

8.2 SUMMARY OF TASK ACCOMPLISHMENTS

The initial phase of the FPIP demonstration fuel irradiations required establishing the data requirements for an adequate technical bases for the fuel rod designs. A performance file structure was developed to assure that appropriate information would be collected and that a convenient method would be available for collecting and transferring such data. A detailed description of the recommended performance file contents was prepared and the procedures for generating the irradiation histories for the Big Rock Point Reactor (BRPR) fuel irradiations were developed. Analyses for following the neutronics history of the BRPR core were used as the data source to generate the rod power histories for the FPIP demonstration irradiations. (8.1)

During the collection of the information for the technical bases, data and technology from the literature were reviewed. A reference file system was developed to facilitate the collection, assessment and dissemination of the reference material. The reference file contains keywords, titles, authors, reference source, and comments of reviewers. The source material has been collected as part of the normal technical review process and the file editing has evolved through use. Keyword searches, editing of input format, and outputs in formats suitable for documents are all presently available. Over 200 references specifically related to the primary FPIP fuel designs being evaluated and their performance evaluation have been accumulated in this file.

The initial draft of the technical bases is being modified to apply more to the fuel concepts of current interest; i.e., annular-coated-pressurized and

sphere-pac. Determination of the effective thermal conductivity of the sphere-pac type fuel was considered to be of primary importance, and a major effort was made to establish a suitable technical bases. This effort resulted in adaptation of a unit cell calculational model that utilizes a three size component bed of spherical oxide particles in a pressurized gaseous environment of either helium or helium mixed with gaseous fission products. This model has been applied to the design parameters of the sphere-pac fuel design and checked against the out-of-reactor thermal conductivity tests performed at ORNL.^(8.2) The description of the unit cell model, its application to design and operational variables and its correlation to the ORNL data were developed.^(8.3) Besides the sphere-pac thermal conductivity model, the material modeling needs for sphere-pac fuel have been assessed, and a mechanical model adjustment procedure for annular fuel has been developed.

8.3 PERFORMANCE FILE DEVELOPMENT

Because a project report^(8.1) which describes details of the performance file contents and power history generation procedures for fuel rods irradiated in the BRPR was written, only the recently completed developments are reviewed. A change of computer systems required some code conversion. Conversion was necessary because all future fuel management analyses will be done on the new system and these analyses are the source data for the power history generation. During the code conversion, some data handling procedures were updated to facilitate power history generation for the FPIP fuel rods. Rods of different designs are included in each of the FPIP bundles in the BRPR. One bundle history is used to generate the power histories for the rods in a bundle and only a few of the input parameters are altered for each rod. Coding and input modifications were made to facilitate this type of evaluation. Different versions of power history generation codes were used for the standard BWR control rod configurations and the configuration used in the BRPR. In other applications of these codes for the plants with standard control rod configurations, improvement in the analyses would be made that would not automatically be incorporated into the BRPR version. After the coding conversion to be used for FPIP was generated, a combined version that works with both types of BWR

configurations was developed, so that future improvements also would be incorporated into the analyses used for the FPIP. This unification updated the generation of the hydraulics and fast flux state specification and the ability to run multiple bundle history generations for the same fuel rod position within bundles having similar rod configurations. Besides the general performance file card image definition and compatible history generation procedures, the computer handling procedure using the UPDATE file handling procedures for program or file libraries has been developed. Irradiation behavior results from the HBWR and BRPR are being accumulated for the data base of the technical bases.

8.4 REFERENCE SOURCE MATERIAL

Technical bases are developed from an accumulation of performance data, information collected from the technical literature, and analyses of the significance of these data to the process or operation to be defined. The reference material that is reviewed and collected during the conduct of the FPIP is handled with a computerized data file system with keywords identified as a possible aid for future searching.

An extensive fuel material property evaluation was performed as part of the DOE-sponsored Fuel Refabrication and Development Program (FRAD) and references were collected using the format proposed for the FPIP.^(8.4) Part of the FRAD effort included modifying and updating this file editing and search system. A significant part of the general fuel material property assessment was for packed-particle fuel; hence, much of the assessment was directly applicable to FPIP interests. The applicable references included in this review and assessment, particularly those related to general design considerations and the references on the annular and coated-cladding technology, have been combined in the FPIP Technical Bases Reference File. All the techniques developed for file editing and searching are applicable to the FPIP file. The FPIP Technical Bases Reference File system is currently being used and the source reference material is continually being expanded.

8.5 TECHNICAL BASES DOCUMENTATION

The primary fuel concepts being evaluated by the FPIP are annular-coated-pressurized and sphere-pac, and an objective of this program is to establish technical bases pertaining to the design and design criteria for these fuel types. The fuel performance or behavior data being obtained by this program that will contribute to the data base for the annular-coated-pressurized fuel design include fuel temperature, fuel deformation, cladding stress/strain, fission product (gas) release and migration, axial fuel relocation, coating stability, and coating function to improve PCI performance. Behavior data being obtained for sphere-pac fuel includes fuel temperature, fuel deformation, cladding stress/strain, fission product (gas) release and migration, and fuel restructuring and relocation. The supporting data is being obtained by means of steady state and quasi-steady state irradiations of instrumented and non-instrumented rods, ramping irradiations, and postirradiation examinations.

Fabrication and design parameters are being established and technical bases to support the sphere-pac fuel design are being developed. An effective thermal conductivity evaluation procedure dependent upon fill gas pressure, microsphere packing density, particle sizes, fission gas content, and restructuring is needed to establish the technical bases for this fuel concept. Design and licensing calculations require such bases for the thermal conductivity, because the performance and safety evaluations are most strongly influenced by this fuel property. Adaptation and expansion of an existing sphere-pac fuel thermal conductivity model^(8.5) was performed for the specific FPIP sphere-pac design parameters.^(8.3) The extension of the existing model used a fuel bed composed of three sizes of UO_2 microspheres. To provide the needed design correlations, the sphere sizes and packing fractions of the FPIP fuel loaded into BRPR were used. Thermal conductivity as a function of temperature, fill gas pressure, fraction of fill gas composed of gaseous fission products, and neck-to-radius ratio formed between particles during restructuring were used as parameters in the evaluations with the expanded model. The basic unit cell models are schematically represented in Figure 8.1.

The basis of the calculational procedure for sphere-pac thermal conductivity is to develop an effective conductivity for the small sphere size

- (a) Fine fraction surrounded by fill gas.
- (b) Medium fraction surrounded by fine fraction and gas.
- (c) Coarse fraction surrounded by fine and coarse fractions and fill gas.

FIGURE 8.1. Schematic Representative of a Sphere-Pac Unit Cell

fraction using a finite difference representation of two spheres in contact. The Knudsen gas conductance domain in the region of closely contacting spherical surfaces takes into account fill gas pressurization effects. The regions of small sphere exclusion and the effective thermal conductivity of the small size fraction are treated in the medium and large sphere models. The effective thermal conductivity of the mixed sphere size is treated in the large sphere model. The relationships between sphere-pac effective thermal conductivity and fill-gas composition, fuel pressure and temperature and gas composition, and fuel temperature and neck ratios between particles, as with the model for the FPIP fuel design parameters, are shown in Figures 8.2, 8.3, and 8.4.

While development of sphere-pac thermal conductivity model was in preparation, out-of-reactor experimental results were obtained from tests conducted at ORNL on thermal conductivity as a function of fill gas pressure and free temperature.^(8.2) The FPIP model was applied to simulate the test fuel bed and experimental conditions. The comparison of calculations and test results with no model adjustments are shown in Figure 8.5. Model applicability seems justified based on these initial comparisons. A systematic deviation of the pressure effect can be noted in these results. This general deviation follows the thermal conductivity/pressure dependence for the small size spheres.

FIGURE 8.2. Effective Conductivity of Ternary Mixture versus Fill Gas Pressure and Composition at $1000^{\circ}C$ ($x/r = 0$)

FIGURE 8.3. Effective Conductivity of Ternary Mixture (Fine, Medium, and Coarse Fractions) versus Temperature for Various Contents of Fission Gas in Fill Gas at 5 Atmospheres ($x/r = 0$)

FIGURE 8.4. Effective Conductivity of Ternary Mixture versus Temperature for Various Neck Ratios (x/r)

FIGURE 8.5. Effective Conductivity of Ternary Mixture versus Temperature for ORNL Tests ($x/r = 0$)

8.7 REFERENCES

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- 8.3 M. H. Ades, "Thermal Conductivity of Sphere-Pac Fuel." XN-NF-79-96, to be published.
- 8.4 K. R. Merckx and R. E. Felt, "Fuel Properties Study - Fuel Refabrication and Development Program - Volume I." XN-RT-19, September 1979.
- 8.5 M. J. Ades, "Modeling of the Thermal Behavior of Irradiated Sphere-Pac Mixed Carbide Fuel." OSU-NE-7902, February 1979.

APPENDIX A

CONVERSION TABLE FOR SI UNITS

CONVERSION TABLE FOR SI UNITS^(a)

	To convert from	to	Use equation or multiply by
Temperature	degree Fahrenheit (°F)	degree Celsius (°C)	$^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$
	degree Fahrenheit (°F)	kelvin (K)	$\text{K} = (^{\circ}\text{F} + 459.67)/1.8$
	degree Celsius (°C)	kelvin (K)	$\text{K} = ^{\circ}\text{C} + 273.15$
Time	hour (hr)	second (s)	3.600×10^3
	day (d or day)	second (s)	8.640×10^4
Length	inch (in.)	metre (m)	2.540×10^{-2}
Area	inch ² (in. ²)	metre ² (m ²)	6.452×10^{-4}
Volume	inch ³ (in. ³)	metre ³ (m ³)	1.639×10^{-5}
Pound-Mass	lbm	kilogram (kg)	4.536×10^{-1}
Pound-Force	lbf	newton (N)	4.448
Pressure or stress	psi (lbf/in. ²)	pascal (Pa)	6.895×10^3
Energy ^(b)	British thermal unit (Btu)	joule (J)	1.055×10^3
	calorie (cal)	joule (J)	4.187
	watt-second (W-s)	joule (J)	1.000
Linear Heat Rating	kilowatts/ft (kW/ft)	kilowatts/metre (kW/m)	3.281
Burnup	megawatt-day/metric ton of	gigajoule/kg of heavy	8.640×10^{-2}
	heavy metal ^(c) (MWd/MTM)	metal ^(c) (GJ/kgM)	

(a) Conversions are based on ASTM Metric Practice Guide E380-74. Four of the prefixes (*) are to be avoided where possible.

Prefix	SI Symbol	Multiplication Factors
tera	T	$1\,000\,000\,000\,000 = 10^{12}$
giga	G	$1\,000\,000\,000 = 10^9$
mega	M	$1\,000\,000 = 10^6$
kilo	k	$1\,000 = 10^3$
hecto*	h	$100 = 10^2$
deka*	da	$10 = 10^1$
deci*	d	$0.1 = 10^{-1}$
centi*	c	$0.01 = 10^{-2}$
milli	m	$0.001 = 10^{-3}$
micro	μ	$0.000\,001 = 10^{-6}$
nano	n	$0.000\,000\,001 = 10^{-9}$
pico	p	$0.000\,000\,000\,001 = 10^{-12}$
femto	f	$0.000\,000\,000\,000\,001 = 10^{-15}$
atto	a	$0.000\,000\,000\,000\,000\,001 = 10^{-18}$

(b) 10^6 Btu = 1.055 GJ = 0.17 barrels of oil = 100 kW-hr, assuming one barrel of oil = 42 gallons and the conversion efficiency from heat to electricity is 0.33.

(c) M is normally the SI symbol for mega; an exception in this report is the additional use of M in burnup units to denote heavy metal.

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