FUEL PERFORMANCE IMPROVEMENT PROGRAM

**Quarterly Progress Report
January - March 1979**

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SUMMARY

This report summarizes the activities of the Fuel Performance Improvement Program (FPIP) for the second quarter of the fiscal year 1979, (January through March, 1979).

Task 2 - Testing and Demonstration Program

Coordination of subtask activities is continuing in order to maintain scheduled progress. Activities are currently focused on laboratory studies to improve graphite coating thickness control; friction and wear testing of different coating materials; stressed-ring tests to evaluate the effectiveness of different coating materials to inhibit SCC in zircaloy cladding; development of the FCI-simulator; data reduction and evaluation in connection with the irradiation of the HBWR Series H-1 experiment (IFA-518); process development and fabrication of the fuel rods for HBWR Series H-2, H-3, and H-4; process development for BRPR Series S-2 and S-3; and procurement of the UO_2 sol-gel microspheres needed for the irradiations in HBWR and BRPR.

The matrix developed for the HBWR Series H-1, H-2, H-3 and H-4 irradiation tests in HBWR as part of Task 2B and the matrices developed for BRPR Series S-2 and S-3 demonstration irradiations in BRPR as part of Task 2C were presented previously.^(1.9)

Task 2A - Out-of-Reactor Experiments

An alternate approach to obtaining graphite coatings within the specified thickness ($6.4 \pm 4 \mu m$) was tested on twenty cladding tubes. This method involved minimal drain times and rapid drying. However, although the coatings achieved by this technique were quite uniform, they were too thin.

The friction tester showed that for the coatings tested, there was no noticeable dependence of friction on the load or sliding speed within the ranges tested. Dag 4 had the lowest friction coefficient of the coatings tested, ranging from 0.02 to 0.08.

Stressed ring tests appear to fall short of the simple and definitive test for the effectiveness of coatings to prevent or retard iodine SCC.

An evaluation of the prototype FCI-simulator component parts has been completed and components have been selected for use in the test device.

Task 2B - In-Reactor Experiments

HBWR Series H-4 test rods have been fabricated and shipped to Halden for installation in test rig IFA-517.

The remaining HBWR test rods, Series H-2 and H-3 have been assembled up to the welding of the lower end cap (provided by Halden). The major changes in HBWR Series H-2 and H-3 rods compared to Series H-1 include a small edge chamfer of fuel pellets, pressurization of annular pellet and sphere-pac fuel rods to 455 kPa, an improved graphite coating material (Dag 4), and substitution of microspheres (sphere-pac) fuel for dynapaked, angular particle (vipac) fuel.

The irradiation of the twelve rods, which comprise HBWR Series H-1, continued satisfactorily in the IFA-518 test rig. The second cycle of operation was completed at the end of January 1979 after achieving a peak burnup of 372 GJ/kg (4300 MWd/MTM) in the lower cluster rods. The lower cluster rods operated during the period covered by the silver absorber shield to suppress power. As a result, the power in the lower cluster was maintained at about 29 kW/m during the second cycle after having been irradiated to a burnup of about 216 GJ/kg at 42 kW/m during the first cycle. Reconditioning is expected to have occurred during irradiation at the lower power.

The three sphere-pac rods for HBWR Series H-4 were neutron-radiographed at the Hanford Engineering Development Laboratory (HEDL) and shipped to Norway in February 1979. Profilometry was completed at the Kjeller Laboratory and the three sphere-pac rods and an extra reference rod from HBWR Series H-1 were loaded into the IFA-517 test rig. The rig was thermally and hydraulically calibrated out-of-reactor and inserted into the HBWR in preparation for the April 1979 startup.

Task 2C - In-Reactor Demonstrations

BRPR Series S-2 and S-3 fuel rods are being fabricated in a single campaign. BRPR S-2 and S-3 each consists of 108 fuel rods; however, only Series S-2 is to include 24 segmented fuel rods. Series S-2 and S-3 rods consist of three fuel types; reference, annular-coated-pressurized, and sphere-pac. The major changes proposed for Series S-2 and S-3 rods compared to Series S-1 include a reduction in the number of different rod types, substitution of sphere-pac, pressurized fuel rods for vipac rods, and placement of reference fuel in the lower as well as upper segment of all segmented rods.

Task 3 - Fuel Performance Evaluations

An apparent discrepancy was observed in the measured fuel temperatures in the lower cluster as a function of LHGR after the first shield shift. It was considered that neutron streaming into the shield might be the cause for the discrepancy. An experiment showed that neutron streaming was causing significantly higher power generation at the ends of the rods than if a normal axial power profile was assumed and was a significant contributor to the discrepancy. Indicated corrections have been programmed to the LHGR equations. An acceptable agreement with the temperature as a function of LHGR has been obtained.

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GLOSSARY OF TERMS FOR 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 graphite, except HBWR Series H-1 which utilizes Dag 154 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.

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. Program Organization of the Fuel Performance Improvement Program

1.5 PREVIOUSLY PUBLISHED FPIP REPORTS

- 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, 1978.
- 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-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.

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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" (COO-4066-2/PNL-2488) and "Assessment of Fuel Concepts" (COO-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 conduct a comprehensive, well balanced testing program to provide the data needed for establishing technical design bases for those fuel concepts with improved performance capabilities. The testing and demonstration program includes Task 2A, Out-of-Reactor Experiments; Task 2B, In-Reactor Experiments; Task 2C, In-Reactor Demonstrations; and Task 2E, Sphere-Pac Engineering Tests.

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 includes an in-reactor testing program that consists of screening tests conducted 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 burnups 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. Task 2E focuses on procurement of microspheres prepared by the sol-gel process and process development for the loading of sphere-pac fuel rods to be irradiated in the HBWR and BRPR.

3.1 TESTING PROGRAM STATUS SUMMARY

Coordination of subtask activities is continuing in order to maintain scheduled progress. Activities are currently focused on laboratory studies to improve graphite coating thickness control; friction and wear testing of different coating materials; stressed-ring tests to evaluate the effectiveness of different coating materials to inhibit SCC of zircaloy cladding; development of the FCI-simulator; data reduction and evaluation in connection with the irradiation of the HBWR Series H-1 experiment (IFA-518); process development and fabrication of the fuel rods for HBWR Series H-2, H-3, and H-4;

process development for BRPR Series S-2 and S-3; and procurement of the UO_2 sol-gel microspheres needed for the irradiations in HBWR and BPRP.

The matrix developed for the HBWR Series H-1, H-2, H-3 and H-4 irradiation tests in HBWR as part of Task 2B and the matrices developed for BRPR Series S-2 and S-3 demonstration irradiations in BRPR as part of Task 2C were presented previously.^(1.9)

4.0 TASK 2A - OUT-OF-REACTOR EXPERIMENTS

L. R. Bunnell, C. L. Mohr, and K. M. Olson (Pacific Northwest Laboratory)

The purpose of this task is to conduct application-oriented out-of-reactor studies in support of the development and demonstration of fuel concepts that will improve fuel performance by minimizing failures involving fuel-cladding interaction (FCI). Current activities include studies of the characteristics of graphite and siloxane coatings applied to the inside surface of the zircaloy cladding, stressed-ring testing, friction and wear testing, and the development of an FCI simulator.

4.1 GRAPHITE COATING STUDIES

As discussed previously,^(1.9) the graphite dispersion (Dag 4)* being used to coat the inside surface of cladding has fluid properties which make it difficult to produce coatings of $6.4 \pm 1.3 \mu\text{m}$ average thickness on a routine basis. The addition of continuous agitation, which eliminated the tendency toward gelation of the dag, was not completely successful in decreasing the coating thickness variation. This variability had, during BRPR Series S-1 fabrication, produced reject rates of about 50%. One reason for this variability appears to be that the long drain time after flood coating (15 min) and the slow drying (15 min) allowed too much time for the coating to set up which resulted in excessive thickness variations.

An alternate approach being evaluated is to use minimal drain times (2 min) and dry the coating more rapidly (5 min), thus allowing less time for the dag properties to determine the resulting coating thickness. Changing these parameters required a decrease in the solids content of the dag because less thinning of the coating occurred during draining. By determining the weight of dag remaining on the cladding surface and knowing the solids content of the dag, a real-time assessment of the average coating thickness is made. This modification has been tried on a small but significant (20-tube) batch of cladding; initial results were disappointing in that thin coatings were produced ($3.8 \mu\text{m}$). The highest average thickness per tube was $4.3 \mu\text{m}$ and the

* Acheson Colloids, Port Huron, MI.

thinnest was 3.0 μm ; the standard deviation of all measurements was 0.8 μm . However, these results represent a significant improvement in coating thickness uniformity. The approach will be refined and will probably be used on coated cladding for BRPR Series S-2 and S-3.

4.2 SILOXANE COATINGS

As reported previously,^(1.9) two different forms of siloxane coatings were examined; thinned silicone vacuum grease and Dow Corning Resin X96502. High residual hydrogen was an immutable characteristic of siloxane-derived coatings from either source, given the 425°C curing temperature limit necessary to avoid degradation of the properties of the zircaloy cladding on which the coating was applied. Table 4.1 is a summary of analytical results obtained by coating cladding with a known mass of the X96502 resin, performing the indicated thermal curing cycle, heating the cladding and coating to 800°C in an evacuated fused silica ampoule, and analyzing the cladding for hydrogen. The Dow Corning resin was about a factor of two lower in hydrogen than siloxane coatings derived from vacuum grease. The amount of hydrogen, e.g., 2.5 wt% hydrogen in the siloxane coating (equivalent to 128 ppm H_2O in the fuel or 57 ppm hydrogen in BRPR cladding if reacted uniformly), is regarded as unacceptable according to present specifications, so further work on siloxane coatings will be discontinued. The friction and wear performance of the X96502 resin was also disappointing (see section 4.3).

TABLE 4.1. Percent H_2 in Dow Corning Resin X96502 Coatings After Various Curing Cycles

Time, hr	Temperature ($^{\circ}\text{K}$) and Atmosphere					
	523, Air	573, Air	623, Air	673, Air	698, Vacuum	773, Air
1	--	3.0 ^(a)	3.1	2.2	--	1.1
20	--	3.4	2.3	1.9	2.1	0.7
65	1.9	2.1	1.8	1.6	--	1.0

(a) Reported as wt% hydrogen in the siloxane.

4.3 FRICTION AND WEAR TESTING OF COATINGS

Because reduction of pellet-cladding friction may be involved in the effectiveness of graphite coatings to improve FCI behavior, a pin-on-disc type friction apparatus is being used to evaluate the friction of round-tipped (1.3 cm radius) UO_2 pellets riding on coated and noncoated zircaloy discs. A friction coefficient of 0.2 was arbitrarily chosen as an indication of coating failure.

The results obtained to date are tabulated in Table 4.2 and plotted in Fig. 4.1. There was no noticeable dependence of friction on load or sliding speed within the ranges tested. These initial room temperature results indicate that Dag 4 had the lowest friction coefficient of the coatings tested, ranging from 0.02 to 0.08. The life of Dag 4 coating has not yet been established in the tests conducted to date, but there have been no failures.

The Dag 154 coating began with similarly low friction, but the coefficient of friction rose rapidly to the levels of noncoated zircaloy.

TABLE 4.2. Results of Friction Tests with UO_2 Pellets Sliding on Coated and Noncoated Zircaloy Discs. (Tests conducted in air at room temperature.)

Coating	Load, kg	Sliding Speed, cm/min	Coefficient of Friction, f
None	3.3-10	2	0.16-0.27
None	3.3-10	12-188	0.16-0.37
None	3.3-6.8	6	0.12-0.28
Dag 4	3.3-10	12-188	0.06
Dag 4	3.3-10	12-188	0.02-0.07
Dag 4	3.3-10	1	0.06-0.08
Dag 154	3.3-13.2	3-94	0.05-0.32 ^(a)
X96502	3.3	2	0.35-0.45
Siloxane Resin			

(a) This test was run in vacuum, $P = 6.7 \times 10^{-3}$ Pa.

FIGURE 4.1. Friction Coefficient as a Function of Sliding Distance.
(Tests conducted in air at room temperature. Loads are indicated on the appropriate lines.)

Under the conditions of this test (related tests indicate that results would be similar in air), this coating was apparently swept aside without forming a lubricated wear track, probably as a result of poorer bonding of the coating to the zircaloy.

Dow Corning X96502 siloxane resin coating exhibited higher friction than noncoated zircaloy, and the coating failed catastrophically during initial contact with the UO_2 . Tests will now be performed at elevated temperatures, and extended wear data will be collected for Dag 4.

4.4 STRESSED-RING TESTS

In order to examine the effectiveness of various coatings in retarding iodine SCC, a simple screening test was desired. The stressed-ring test used by Wood^(a) appeared to meet most of the requirements despite some shortcomings such as a continuous decrease of applied stress due to creep. In this type of test, a short (1.3 cm) length of cladding is slit longitudinally and wedged open by zircaloy shims, which place the inner surface under tension. Figure 4.2 illustrates the configuration. The specimens are sealed in an evacuated Pyrex capsule containing a known amount of iodine with iron added as a "catalyst." Wood^(a) reported that SCC did not occur without the presence of iron.

Sections of BRPR cladding (tube-reduced and stress-relieved) were exposed to conditions which were reported^(a) to produce failures within one hour in susceptible cladding, i.e., stress 552 MPa, I_2 concentration $3 \times 10^{-3} \text{ g/cm}^2$ zircaloy, temperature 300°C , and iron added. In tests lasting to 1000 hr, none of the four specimens tested failed. Wood reported^(a) that a single batch of cold-drawn cladding was most susceptible to SCC. Some similar material was obtained and testing was performed. SCC failures occurred on four specimens of this type of cladding at times between 6 and 70 hours, but in no case was there a failure in tests lasting to 200 hr unless the ampoule

(a) J. C. Wood, Interactions Between Stressed Zirconium Alloys and Iodine at 300°C , Nuclear Technology, 23, 63-79, July 1974.

FIGURE 4.2 Schematic Representation of the Stressed-Ring Test

also contained niobium. (For in-reactor tests conducted at GE^(a), failures were produced only when niobium was added to the fuel rod the niobium acts as an oxygen getter.)

The stressed-ring test appears to fall short of the intended simple and definitive test of different coatings to prevent or retard iodine SCC. Results to date exhibit some variability which might be attributed to the condition of the surface oxide on the cladding. The stressed-ring test relies on visual detection of failure at each time interval which makes accurate determination of the failure time imprecise and the test procedure awkward. Further, the cladding is subjected to continuously decreasing stress levels as creep relaxation occurs prior to the test, i.e., not while in the presence of iodine. Other techniques for achieving a simple comparative evaluation of the effectiveness of different coating materials to prevent or retard SCC on zircaloy cladding will be evaluated.

(a) J. H. Davies et al., Irradiation Tests to Characterize the PCI Failure Mechanism, NEDO-21551 (Feb. 1977).

4.5 FUEL-CLADDING INTERACTION SIMULATOR

An evaluation of the prototype FCI simulator component parts has been completed. As a result of this effort, components have been selected for use in the test device.

Results of initial tests have shown that pellet-pellet interface interaction strains of 10% can be obtained. Loading is accomplished by using a section of copper tubing filled with silicone rubber. Two groups of split segments 9.52 mm (0.375 in.) long are used to simulate the pellet-pellet interface. The total test section is 19.1 mm (0.75 in.) long and uses a total of eight segments, four in each group.

An alternate loading mechanism using graphite in a stainless steel bladder was also evaluated. This type of loading proved to be more efficient in terms of transmitting the applied load to the specimen than the copper tubing method. Experimental difficulties with compression of the graphite still need to be resolved before this method can be used effectively.

A loading fixture is currently being assembled that will provide axial as well as hoop loads on the cladding specimens. The fixture utilizes hydraulic cylinders for compression of the copper-rubber segments and an additional cylinder for providing axial loading. Strain measurement will be obtained by measuring the oil flow to the specimen load train. More sensitive strain measurements can also be made by the use of strain gages or LVDT clip gages. Force measurement will be made by measuring oil pressure for the pellet-pellet load and a load cell will be used for measuring axial cladding loads. An aggressive atmosphere such as iodine will be provided and monitored as well as the isothermal temperature conditions. Figure 4.3 is a schematic representation of the system.

The next series of tests will be performed in the test fixture at typical fuel rod operating temperatures using an Al_2O_3 annulus as a standin for UO_2 .

FIGURE 4.3. Schematic Representation of the FCI Simulator Loading and Measurement System.

5.0 TASK 2B - IN-REACTOR EXPERIMENTS

J. O. Barner, R. J. Guenther and S. R. Wagoner (Pacific Northwest Laboratory)
R. K. Welty and P. G. Sarafian (Exxon Nuclear Company)

The objective of the in-reactor experiments task is to conduct irradiation tests to study the detailed behavioral characteristics and performance limits of those fuel concepts which have potential for improved operating behavior in LWRs. Comparative parametric fuel rod experiments are being performed with emphasis on the annular-coated-pressurized design and, at a more modest level, the sphere-pac design as a back-up. 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/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 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 tests are being irradiated in the Big Rock Point Reactor (BRPR) as 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.^(1.8, 1.9) Regarding the initial irradiations which are in progress, the emphasis for HBWR Series H-1 was placed upon evaluating the individual effects of design differences such as reference, annular, annular-coated, and vipac.

5.1 SUMMARY DESCRIPTION OF HBWR TESTS

The screening tests are being irradiated 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 shifting a silver absorber shield over the two clusters. The IFA-517 test rig contains a single cluster of four rods. The peak operating linear heat generation rate in both assemblies is 44.5 kW/m.

Rod instrumentation in both assemblies includes fuel centerline thermocouples, elongation sensors, and internal pressure sensors. 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 of 1200 to 1400 GJ/kg (14 to 16 MWd/kg).

The HBWR Series H-4 rods will be irradiated in IFA-517 for two reactor cycles to peak burnups of about 430 GJ/kg (5 MWd/kg). The IFA-517 rig will also be used later for the power-ramping tests.

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

The test matrix for the HBWR Series H-2, H-3 and H-4 is shown in Table 5.1. HBWR H-2, H-3 and H-4 rods are being fabricated in a single campaign although irradiation of HBWR H-3 rods will not occur until 1980. HBWR H-4 rods are being irradiated in 1979 to obtain centerline temperature measurements for sphere-pac rods.

HBWR H-2 and H-3 consist of three fuel types: reference, annular-coated-pressurized, and sphere-pac. Characteristics of the HBWR Series H-2, H-3, and H-4 fuel rods are shown in Table 5.2. The reference fuel rods are essentially the same configuration as the HBWR Series H-1 rods^(1.8). The end cap configuration has been changed to improve weldability.

The major innovations in HBWR Series H-2, H-3, and H-4 rods compared to HBWR H-1 include a small edge chamfer on the fuel pellets, pressurization of the annular pellet and packed-particle fuel rods to 455 kPa (66 psia), an improved graphite coating material (Dag 4), and substitution of sol-gel microsphere (sphere-pac) fuel for dynapaked, angular particle (vipac) fuel.

The sphere-pac fuel rods are designed with a thin zircaloy disk placed between the plenum spring and the upper insulator disk (Figures 5.1 and 5.2). This upper fuel retainer disk contains a center hole to permit gas communication between the fuel column and the upper gas plenum. The retainer disc fits snugly against the cladding to prevent fuel microspheres from relocating into the plenum region during horizontal handling and shipping of the rods (Figure 5.3).

TABLE 5.1 HBWR Series H-2, H-3, and H-4 Test Rod Matrix

<u>ROD TYPE</u>	<u>SERIES PREFIX</u>	
	<u>H2UC</u>	<u>H3UC</u>
REFERENCE
ANNULAR-COATED-PRESSURIZED
SPHERE-PAC
	<u>H4</u>	
REFERENCE
SPHERE-PAC

TEST IDENTIFICATION:

H = TEST PHASE

UC = UPPER

INSTRUMENTATION ID:

TC = THERMOCOUPLE

P = PRESSURE TRANSDUCER

E = ELONGATION SENSOR

=A ROD WITH TEST INSTRUMENTATION
AS INDICATED

TABLE 5.2. Characteristics of HBWR Series H-2
and H-3 Test Rods

Reference Fuel

Type	Solid pellet
Material	UO ₂
Density, %TD	94.0
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
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 5.2 (Continued)

Packed-Particle Fuel

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 5.2 (Continued)

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)	1.0 (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, Thermcouple sensor
Lower end caps	Elongation sensor, 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)	1.0 (0.012)

The Parts List (list of components, drawings and specifications) for the HBWR Series H-2, H-3, and H-4 test rods, XN-NF-PL-14, was issued in January 1979 and reissued as Revision 1 in February 1979.

FIGURE 5.1 Packed-Particle/Pressurized Fuel Rod Assembly

FIGURE 5.2 Packed-Particle/Pressurized Fuel Rod Assembly - Thermocouple

FIGURE 5.3 Upper Fuel Retainer

5.3 FABRICATION - HBWR SERIES H-2, H-3, and H-4 RODS

5.3.1 Pellet Rod Fabrication

The reference and annular-coated-pressurized fuel rods for HBWR Series H-2 and H-3 were assembled up to the welding of the lower end cap. The loaded rods are being stored using a temporary lower end cap (the upper end caps are welded in place) until the instrumented lower end caps become available. The lower end caps were received from Halden towards the latter part of March and submitted to the machine shop for finishing of the weld area. The fuel rods are being stored in a helium atmosphere glove box along with pellet and graphite (Dag 4) process control samples. These samples will be analyzed for H_2O and H_2 just prior to lower end closure of the fuel rods. Completion of the HBWR Series H-2 and H-3 fuel pins is scheduled for April. A description of these fuel rods is:

- 2 - reference with elongation sensors
- 2 - reference with pressure transducers
- 1 - reference (spare)
- 1 - reference (archive)
- 4 - annular-coated-pressurized with elongation sensors
- 2 - annular-coated-pressurized with pressure transducers
- 1 - annular-coated-pressurized (spare)
- 1 - annular-coated-pressurized (archive)

5.3.2 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 BRPR Series S-1 coatings, so little improvement was made in controlling the graphite film thickness. (The tubes can be recycled by washing the graphite out and re-coating.)

The coating method is essentially the same as that used for BRPR Series S-1 tubes. A flood coating technique is used where a dispersion of graphite in water is drawn down through a vertical tube by using a silastic plug. The tube is allowed to drain for a short time and then air dried by forcing hot air up through the tube. Both before and after cooling,

measurements are taken on the inside diameter of the tube with an air gage to determine the graphite coating thickness. Accepted tubes are then cured at 425°C between 24-28 hr under vacuum. After curing, the tubes are plugged on both ends with temporary end caps and stored in a helium atmosphere glove box.

The point-by-point film thickness and average thickness for the coated tubes used for the HBWR H-2 and H-3 fuel rods are listed in Table 5.3. All of these tubes are essentially at "nominal" for the specification range of 5 to 8 μm (0.0002-0.0003 in.).

TABLE 5.3. Graphite Coating Thickness Measurements

Tube No.	Fuel Rod Serial No.	Thickness at Position					Average Thickness,	Tube Average, mm
		$\frac{\text{max}}{\text{min}} \times 10^{-3} \text{ mm}$					$\frac{\text{max}}{\text{min}} \times 10^{-3}$	
		1	2	3	4	5	mm	
66G	27	6.98	6.98	6.35	6.35	6.98	6.73	0.00648
		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	0.00597
		6.71	0.35	5.08	6.35	5.71	5.84	
170C	29	6.35	6.98	6.35	6.98	5.71	6.47	0.00629
		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	0.00616
		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	0.00616
		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	0.00597
		6.35	5.08	6.35	6.35	6.35	6.09	

* Measurements made at approximately 7.6 mm (3 in.) spacing.

5.3.3 Sphere-Pac Fabrication

Five sphere-pac rods were made for HBWR Series H-2, H-3 and H-4 fuel loadings. A sixth sphere-pac rod with a graphite coating on the inside surface was attempted but the graphite was eroded off the tube wall during vibratory compaction, so this fuel rod was eliminated from the program.

A description of the five sphere-pac fuel rods which were fabricated follows:

<u>Series</u>	<u>No. Rods</u>	<u>Description</u>
H-2	1	Sphere-pac with elongation sensor
H-3	1	Sphere-pac with elongation sensor
H-4	1	Sphere-pac with thermocouple and elongation sensor
H-4	1	Sphere-pac with thermocouple and pressure transducer
H-4	1	Sphere-pac with elongation sensor

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

<u>Fraction</u>	<u>Size</u>	<u>Wt%</u>
Coarse	1150-1410 μm	58
Medium coarse	280-320 μm	20
Fine	45 μm	22

The fuel rod is vibrated at very low amplitude (vibrator air pressure of 13.7×10^4 Pa) during loading of the microspheres. When the calculated fuel loading has been added to the tube, air pressure to the vibrators is increased to 27.6×10^4 Pa and a weighted (800 grams) follower rod is placed

on top of the fuel column. The rod is then vibrated until the correct plenum depth is obtained. Controlling the microsphere feed rates results in the specified smear density ($87 \pm 1\%$ TD) for the fuel column. The fabrication process variables are listed in Table 5.4.

TABLE 5.4. 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, Pa x 10 ⁴ (psi)	Final Compaction Time, sec	Final Compaction Air Pressure, Pa x 10 ⁴ (psi)
33	87.7	30	13.7 (20)	270	27.6 (40)
34	87.9	32	13.7 (20)	300	27.6 (40)
40	87.7	30	13.7 (20)	330	27.6 (40)
41	87.6	30	13.7 (20)	210-bottom* 17-top	27.6 (40)
42	87.0	30	13.7 (20)	195 bottom* 15-top	27.6 (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.

In addition to the calculated smear densities, point-by-point densi-gage 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 is 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 25-50 mm); however, none of the localized density values are below 84% TD. Overall standard deviations are quite good; averaging approximately $\pm 0.95\%$ TD for the five rods.

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. 42 (density versus length)

5.4 IRRADIATION STATUS - HBWR TESTS

5.4.1 IFA-518 Irradiation

The irradiation of the twelve rods, which comprise HBWR Series H-1, continued satisfactorily in the IFA-518 test rig. The second cycle of operation was completed at the end of January 1979, after achieving a peak burnup of 372 GJ/kg (4300 MWd/MTM) in the lower cluster rods. The lower cluster rods were covered by the silver absorber shield during the irradiation period to suppress power. As a result, the linear heat generation rate (LHGR) in the lower cluster was maintained at about 29 kW/m during the second cycle after having been irradiated to a burnup of about 216 GJ/kg at a peak LHGR of 42 kW/m during the first cycle. Reconditioning is expected to have occurred during irradiation at the lower power. The next shield shift, which will uncover the lower cluster rods, is scheduled to occur shortly after the next reactor cycle startup in early April 1979.

The Test Fuel Data Report (TFDR) data for operation of IFA-518 during the second cycle of operation, October 1978 through January 1979, was received and placed on disc storage. The TFDR system samples and records all the rig and rod instrumentation every 15 min. A plot of the data indicated that the thermocouple signals from vipac rod No. 13 were erratic and generally continued their steady decline. This thermocouple apparently continues to yield unreliable signals. All other rod and rig instrumentation is operating satisfactorily.

CALIB data cards for transient operation on September 26, December 14 and 18, 1978 and January 4 and 22, 1979 were received and transferred to disc storage. The CALIB data acquisition system samples and records all the rig and rod instrumentation every 3 to 5 min. Because future CALIB data will be transmitted on tape, new data handling programs are being prepared.

In addition to TFDR and CALIB, it is expected that future transient operation will be monitored by the FAST-SCAN data acquisition system. This system samples selected instrumentation about seven times per second.

5.4.2 IFA-517 Irradiation

The three sphere-pac rods for HBWR Series H-4 were neutron-radiographed at the Hanford Engineering Development Laboratory (HEDL) and shipped to Norway in February 1979. Profilometry was completed at the Kjeller Laboratory and three sphere-pac rods and an extra reference rod from HBWR H-1 were loaded into the IFA-517 test rig. The rig was thermally and hydraulically calibrated out-of-reactor and inserted into the HBWR in preparation for the April 1978 startup. Two of the three sphere-pac rods in HBWR H-4 have centerline thermocouples in order to monitor fuel temperatures during irradiation and to compare with the temperature in the reference rod. Two of the sphere-pac rods contain cladding elongation sensors to measure fuel-cladding mechanical interaction. The third sphere-pac rod contains a pressure transducer to measure the fission gas release. The loading map and rod instrumentation for HBWR Series H-4 is shown in Figure 5.9.

Radiography of the sphere-pac fuel column showed that fuel density variations were present in the region of the thermocouple well, i.e., the uppermost 89 mm (3.5 in.) of the fuel column. Such density variations can be expected to produce localized perturbations in power and/or thermal conductance. Fortunately, it appears that these variations were a minimum in the region of the thermocouple tip, i.e., 64 mm (2.5 in.) into the sphere-pac fuel column.

In preparation for processing the data from the in-reactor instrumentation in IFA-517, disk storage assignments were made and the axial relationships between the thermocouple tips and the neutron detectors were determined. The midplane of the highest neutron detector is very close to the axial plane of the thermocouple tips, i.e., only 26 mm below the tips. This close proximity is expected to reduce the local power uncertainties in IFA-517 in comparison to the uncertainties encountered in IFA-518.

KEY:

SPH-PAC = SPHERE-PAC ROD
 REF = REFERENCE ROD
 T = FUEL THERMOCOUPLE
 E = ROD ELONGATION SENSOR
 P = ROD PRESSURE SENSOR

FIGURE 5.9. IFA-517 Loading Map
 (as viewed from above).

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6.0 TASK 2C - IN-REACTOR DEMONSTRATIONS

R. K. Welty and P. G. Sarafian (Exxon Nuclear Company)

6.1 DESIGN AND ANALYSIS

The remaining demonstration fuel rods to be fabricated and irradiated in Big Rock Point Reactor are designated as BRPR Series S-2 and S-3. Both BRPR S-2 and S-3 fuel rods are being fabricated in a single campaign. BRPR S-2 rods will be irradiated in BRPR reload batch H-1 fuel assemblies (not to be confused with Halden Series H-1 test rods) being loaded into BRPR in Cycle 17, and BRPR S-3 will be irradiated in reload batch H-2 fuel assemblies being loaded into BRPR in Cycle 18. The demonstration fuel rods and fuel assembly matrix is shown in Table 6.1.

BRPR Series S-2 and S-3 each are to consist of 108 fuel rods; however, only BRPR S-2 is to include segmented fuel rods (Table 6.1). BRPR 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. Characteristics of the BRPR S-2 and S-3 rods are summarized in Tables 6.2 and 6.3. The reference and annular-coated-pressurized full-length demonstration rods are to be identical to the Series S-1 rods.^(1.8)

The major changes incorporated in the Series S-2 and S-3 rods, when compared to 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 6.7).

BRPR S-2 and S-3 sphere-pac rods are being designed with a thin, zircaloy fuel retainer disk at the top and bottom of the fuel columns, similar to the retainer disk in the Halden rods (Figure 5.3). The lower fuel retainer disk is located just above the lower insulator disk and will prevent the lower insulator disk from levitating during fuel compaction. Levitation permits fuel particles to infiltrate underneath the insulator disk. The upper fuel retainer disk is located between the plenum spring and upper insulator disk and prevents small microspheres

from spilling into the upper plenum region during horizontal handling and shipping of the rods. Optimization and testing of the fuel retainer disk design is continuing.

Series S-2 fuel rods are to be loaded into three fuel assemblies in BRPR reload batch H-1. One Series S-2 assembly will contain only full length demonstration rods (Table 6.7 and Figure 6.1). The remaining two Series S-2 fuel assemblies will contain both full-length and segmented rods (Table 6.7 and Figure 6.2). The Series S-2 fuel rods will occupy the same peripheral rod locations in the fuel assemblies as the Series S-1 rods occupied in their respective fuel assemblies. The number of segmented rods per assembly will also remain the same.

It is anticipated that the Series S-3 assembly design also will consist of three (identical) fuel assemblies, each containing 36 Series S-3 rods in the same peripheral rod locations as the Series S-2 assemblies (Table 6.1).

6.1.1 Errata

Appendix B carries corrections to Figures 6.1, 6.2, 6.3, and 6.4 and the accompanying Tables 6.1, 6.2, 6.3, and 6.4 that appeared in C00-4066-9 (Ref. 1.9).

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

6.2.1 BRPR Pellet Process Development

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

2.52%	SR-67-2	Rev. 1
2.69%	SR-48-1	Rev. 1

A summary of the chemical analysis of these two lots is summarized in Table 6.4.

Preproduction sinterability tests were performed on both of these lots which were prepared via the following steps:

- 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.)(50.8 mm - 2.00 in. for lot SR-48-1) through a 10 mesh (2.0 mm) screen,
- 3) Re-roll compacting at 76.2 mm clearance (3.0 in.) through a 10 mesh screen.

Results of the preproduction sinterability tests are listed in Table 6.5.

The production press tooling will be delivered in late April, and pressing of the production pellets is scheduled for May-June.

6.2.2 BRPR Sphere-Pac Process Development

Five, six-foot long BRPR sphere-pac development rods were loaded with depleted UO_2 microspheres to determine the extent of the low density regions in the top of the rods and to address the problem of the non-seated lower insulator disc.

Levitation of the lower insulator disc during vibratory compaction is caused by the migration of microspheres under the insulator disc. This would permit fuel particles to come in contact with the zircaloy end cap. Calculations show that the power is only less than about 6 kW/m in the lower end of the rod which results in an insignificant temperature rise in the lower end cap. However, a solution was sought to prevent the insulator disc from levitating. This was accomplished by using a thin zircaloy retainer disc to hold the insulator disc against the lower end cap during vibration of the sphere-pac rods. 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 0.01 mm.

Additional tests are to be run to determine if the zircaloy retainer discs will chemically react or seize against the cladding when the fuel rod is heated in an internal oxidizing atmosphere.

The top of the sphere-pac fuel columns have 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 over

which the density variation occurs is within 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 is 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. To date, no successful method has been developed to consistently prevent this minor separation of particles at the very top of the rod. Three tubes were loaded with microspheres (Table 6.6) with slightly lower than normal ratios of coarse spheres to fine spheres. As a result, the overall rod smear densities decreased slightly and there was no significant improvement density variability in the top of the fuel columns.

Rod No. D-1 (Table 6.6) represents 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 fed into the tube from another, independently controlled, vibrator. The time required to feed all the microspheres into a 1.8 m tube is 90 seconds. Small pneumatic vibrators attached to the tube are operated at low energy input during this period. 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 only 60 seconds to achieve the specified density of 87 ± 1 %TD.

Rod density uniformity is quite good (except at the very top) over the full-length, with the standard deviation ranging from 0.8 to 1.0%. There were no well-defined localized (over a 5 mm length) densities as low as 84 %TD which is a marked improvement over the vipac fuel.

6.2.3 BRPR Graphite Coating Process Development

Process development activities have continued on graphite coating techniques in an attempt to obtain a more consistent coating thickness control.

Presently, 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 changes have been made in an attempt to achieve improved coating thickness control. The Dag 4 is currently 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, has been reduced from 15 minutes to two minutes to prevent excess Dag 4 from dripping out of the tube, and the air velocity during drying has been increased to achieve faster drying.

Twenty tubes were coated to test the new process innovations, but all the coating thicknesses, while quite uniform, were too thin (less than the 0.005 mm specification minimum). A slightly thicker Dag 4 solution will be used to produce coatings within the 5-8 μm specification limits. The coating thickness problem does not prevent coating of production tubes, and 150 tubes have been withdrawn from storage for measurement (ID) with an air gauge in preparation for coating.

TABLE 6.1. 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	1	Reference	6	
		Annular-coated-pressurized	24	
		Sphere-pac	6	
	2	Reference	4	4
		Annular-coated-pressurized	16	4
		Sphere-pac	4	4
	3	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 each</u>	
		SUBTOTAL	36	
		TOTAL FOR THREE ASSEMBLIES		108

TABLE 6.2. Characteristics of 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 particles
Material	UO ₂
Density (particles), %TD	>96.5
Diameter (cladding I.D.), mm (in.)	9.677 (0.3810)
Enrichment, wt% ²³⁵ U	2.52
Smear Density, %TD	87.0

Table 6.2 (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 6.2 (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 6.3. Characteristics of BRPR Series S-2 and S-3
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 6.3 (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 6.3 (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 6.4. Chemical Analysis - Lot Average

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

TABLE 6.5. Preproduction Sinterability Tests
(BRPR S-2 and S-3)

<u>Lot Number</u>	<u>Tooling Used</u>	<u>Lubricant and Pore Former, wt%</u>	<u>Press. Density, gm/cc</u>	<u>Sinter- ing Temp., °C</u>	<u>Sinter- ing Time, hr.</u>	<u>Sintered Density, %TD</u>
SR-67-2	11.6 mm chamfered & dished	0.7 zinc	5.21	1770	2.85	94.79
		Sterate	5.35	"	"	94.91
		0.2 Sterotex	5.51	"	"	95.08
SR-67-2	11.6 mm chamfered & dished	0.1 zinc	5.08	1770	2.85	93.89
		Sterate	5.29	"	"	94.15
		0.4 Sterotex	5.51	"	"	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
		Sterate	5.18	"	"	94.15
		0.2 Sterotex	5.40	"	"	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
		Sterate	5.19	"	"	93.33
		0.4 Sterotex	5.41	"	"	93.68

Target sintered density = 93.5 ± 1.5 %TD

TABLE 6.6. BRPR Series S-2 and S-3 Sphere-pac Process Development

Test No.	Average Fill Density, %TD	Loading Time, sec.	Loading Vibrator Air Pressure, Pa x 10 ⁴ (psi)	Pre Compaction Vibrator Time, Sec.	Final Compaction Time, Sec.	Final Compaction Air Pressure, Pa x 10 ⁴ (psi)
D-1	87.6	90	13.7 (20)	30	60	55.2 (80)
D-2	87.4	90	13.7 (20)	60	60	55.2 (80)
D-3	86.9	90	13.7 (20)	30	60	55.2 (80)

Microsphere Particle Size Distribution

Test No.	Coarse (1150-1410 μ m), wt%	Medium (280-320 μ m), wt%	Fine (<45 μ m), wt%	Average Smear Density, %TD
D-1	58	20	22	87.6
D-2	56	21.5	22.5	87.4
D-3	55	22	23	86.9

TABLE 6.7. 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.

Spacer Serial No.
Orientation

FIGURE 6.1. BRPR Series S-2 Assembly No. 1

(6 each)	①	2.52 wt% ^{235}U , UO_2
Reference Demonstration Rod
(24 each)	②	2.69 wt% ^{235}U , UO_2
Annular-Coated-Pressurized
Demonstration Rod
6 each)	③	2.52 wt% ^{235}U , UO_2
Sphere-pac Demonstration Rod

FIGURE 6.2. BRPR Series S-2 Fuel Assemblies Nos. 2 and 3

(4 each)	①	2.52 wt% ^{235}U , UO_2
Reference Demonstration Rod	(4 each)	④	Reference,
Segmented Rod
(16 each)	②	2.69 wt% ^{235}U , UO_2
Annular-Coated-Pressurized
Demonstration Rod	(4 each)	⑤	Annular-Coated-Pressurized,
Segmented Rod
(4 each)	③	2.52 wt% ^{235}U , UO_2
Sphere-pac Demonstration Rod	(4 each)	⑥	Sphere-pac
Segmented Rod

7.0 TASK 3 - FUEL PERFORMANCE EVALUATIONS

M. D. Freshley, J. O. Barner, R. J. Guenther, D. D. Lanning, and S. R. Wagoner
(Pacific Northwest Laboratory)

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. At the present time, most of the activities in this task are related to the evaluation of the performance of the instrumented assembly (IFA-518) undergoing irradiation in the Halden Boiling Water Reactor (HBWR).

7.1 HBWR SERIES H-1 PERFORMANCE EVALUATION

Several corrections to the linear heat generation rate (LHGR) equation for the HBWR Series H-1 were identified and described previously.^(1.9) In addition, an apparent discrepancy was observed in the measured fuel temperatures in the lower cluster as a function of LHGR after the first shield shift. This corresponded to a LHGR discrepancy of about 18% at any particular LHGR. It was considered that neutron streaming into the shield might be the cause for the discrepancy. As a result, an experiment was performed in HBWR in late January 1979 to identify the source of the discrepancy. While the HBWR was operating at about 50% of full power, the silver absorber shield was slowly moved upwards. This movement more fully shielded the fuel adjacent to the thermocouple tip and the adjacent neutron detector. The thermocouple tip is located 63 mm below the top of the shield and the midplane of the adjacent neutron detector is positioned 67 mm farther down into the shield. The thermocouple signals immediately began to decrease as the shield was moved upwards. After 100 mm of shield movement, no further decrease in temperature occurred. During the shield movement, the neutron detector signal did not change. This test showed that neutron streaming was causing significantly higher power generation at the ends of the rods than if a normal axial power profile was assumed and was a significant contributor to the discrepancy.

The results of corrections that have been applied to the IFA-518 power equations are summarized in Table 7.1. A summary discussion of each correction is provided below in the order that they appear in the table. The effect of the correction on the apparent LHGR discrepancy is noted in the table.

Previous power calculations were based upon the fissile or mass ($MR, Mi/M$) ratios between the rods. Power splits between the clusters and the individual rods are based upon power ratios. Removal of material from the central or low specific power region of the fuel does not change the LHGR by the fraction of material removed. Therefore, annular fuel and the regions of the reference and vipac fuel which contain thermocouples produced more power than calculated based upon mass (fissile) ratios.

The axial displacement (AX) of the thermocouple tip from the midplane of the vanadium neutron detector in the axial flux gradient causes a 2.5% correction in the LHGR at the thermocouple when compared to the equation previously used, where the neutron detector signal was assumed to be representative of the power generated at the tip of the thermocouple.

By applying the corrections, the calibration factor, kg, between the measured heat generated in IFA-518 and the average neutron detector signals was changed from 1.128 to 1.085.

During transient operation, the calculated LHGR must be corrected for the delay constant of the vanadium neutron detectors. Two approaches to this correction are being considered. The first, which has been programmed for the TFDR data system, utilizes a 5.4 min linear proportionality between the data point of interest and the data point for the next time step. The resultant neutron detector signal is assigned to the point of interest. The second method, which has been programmed for the CALIB data system, involves 1) using several data points on each side of the point of interest, 2) determining a curve fit for a fourth order equation through the points, and 3) determining the appropriate neutron detector signal for the point of interest plus the 5.4 min. delay constant. One method may be more appropriate for different data sampling times.

TABLE 7.1. Corrections in IFA-518 Power Equations

Variable or Constant Affected	Variable or Constant Name	Cause of Discrepancy	Effect of Correction	Reduction In Observed 18% Error
MR	Mass Ratio (Cluster)	Power split between the upper and lower cluster is based on a mass ratio. The percentage of mass removed is higher than the percentage of power lost for annular rods and thermocouple holes.	Calculated power in the lower cluster will be an increased proportion of the total assembly power.	None
Mi/M	Mass Ratio (Rod)	Power to each rod is based on the rod's contribution to the total cluster fuel mass. This underpredicts the power in annular fuel regions.	Average LHGR and LHGR at the thermocouple will be higher for annular rods and lower for both vipac and reference rods.	None
AX	Axial Displacement Factor	The thermocouple tips are 67 mm above the ND4 midplane which underpredicts the LHGR at the thermocouples.	Will cause the LHGR at the thermocouple to increase about 2.5% for both shielded and nonshielded conditions.	None
kg	Calibration Constant	kg was calculated from the original power equations and subcooled power data. New equations require a new kg.	The current value of 1.128 will decrease to 1.085.	None
LHGR	Transient LHGR	The vanadium neutron detector half life of 3.755 minutes causes the LHGR readings to lag the temperature response by about 5.4 minutes.	Proper correction will eliminate the underprediction of LHGR during power ascensions and the overprediction of LHGR during power decreases.	None
CDTF	Burnup Depletion Factor at the Thermocouple	The CDTF was 1.0 prior to the September 26, 1978 but the CDTF was 0.981 immediately after shield movement and acted like a step function. The burnups just before and after the September 26, 1978 shield shift are essentially the same.	Increases the LHGR values at the thermocouple for the shielded condition in comparison with the nonshielded LHGR values at the thermocouple.	1.9%
TE	Thermocouple End Effect Factor	Neutron streaming at the shield ends allows higher flux at the thermocouple tips than at the neutron detector (ND4).	LHGR values at the thermocouple will be higher than previously calculated for the shielded cluster.	5.3%
SE	Integral End Effect Factor	Neutron streaming at both shield ends causes higher power in the fuel rods than indicated by the neutron detectors.	Distributes a greater portion of the total assembly power to the shielded cluster.	3.7%
R	Radial Flux Factor	Thermal flux depression at ND4 caused by absorptions in the close proximity of the silver shield.	Will bring the shielded and nonshielded plots of temperature versus LHGR at the thermocouple closer together.	~6.0%

For the initial shield shift, a burnup correction (CDTF) was applied to the original TFDR data immediately after the shield shift, but not before the shift. This resulted in an error of 1.9% in the calculated LHGR after the shield shift.

The neutron streaming effect described above caused two corrections; a thermocouple end effect (TE) and an integral end effect (SE). The thermocouple end effect results in a shielded LHGR at the thermocouple which is 5.3% higher than if a normal power profile is assumed. This is a measured effect. The higher power generated at the ends of the shielded rods is equivalent to an increase of 3.7% in the cluster power. This was estimated from the measured thermocouple end effect. An appropriate decrease in the upper cluster power was determined by changing the rig calibration factor.

The radial flux factor (R) is the result of a radial flux gradient within the shielded cluster. It is probably due to the close proximity of the vanadium neutron detector to the silver absorber shield.

The above corrections have been programmed into the LHGR equations. A comparison of the corrected data to the noncorrected data for the HBWR Series H-1 reference rod for the period before and after the September 26, 1978 shield shift is illustrated in Figure 7.1. Acceptable agreement in the temperature as a function of LHGR has been obtained.

FIGURE 7.1. Comparison of Corrected and Noncorrected Fuel Centerline Temperatures as a Function of Linear Heat Generation Rate Before and After the First Shield Shift (IFA-518).

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8.0 TASK 4 - ESTABLISHMENT OF TECHNICAL BASES

K. R. Merckx (Exxon Nuclear Company)

The reference file system used for the FPIP Technical Bases References has been extended. The file on fuel material properties has been extended to over four hundred entries with many of these entries on packed-particle fuel data sources. In collecting data sources for the fuel material candidates and property assessment methods, an extensive data source applicable to uranium fuel and property assessment has been collected. The file treatment procedure has been extended to include edit checks on key words, file numbering, card type and file editors. A new University Computing Center (UCC) interactive file editing procedure has been adapted to expedite fuel updating and perform edits directly from corrected copies of selected search outputs. Thus, besides expanding the reference contents, the basic file system has been augmented with editing procedures for extracting information by subject, author, file editor, and type of data content. All of these capabilities have been found to be of value in a project type of data accumulation effort and have been developed through actual working requirements.

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 heavy metal ^(c) (MWD/MTM)	gigajoule/kg of heavy metal ^(c) (GJ/kgM)	8.640×10^{-2}

(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.

APPENDIX B

ERRATA

Appendix B carries corrections to Figures 6.1, 6.2, 6.3, and 6.4 and the accompanying Tables 6.1, 6.2, 6.3, and 6.4 that appeared in C00-4066-9 (Ref. 1.9).

	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 00581	K06 00007	KR3 00012	KP3 00010	KE3 00582	KM6 00009	KN6 00014		
2			KM6 00010						KR3 00011		
3	KP3 00007	KN6 00012								K06 00017	KM6 00013
4	KR3 00007										KN6 00013
5	K06 00008										KP3 00011
6	KE3 00586										KE3 00587
7	KP3 00006										K06 00009
8	KN6 00010										KR3 00009
9	KM6 00014	K06 00006								KN6 00011	KP3 00012
10			KR3 00010						KM6 00012		
11			KN6 00009	KM6 00011	KE3 00585	KP3 00008	KR3 00008	K06 00010	KE3 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. BRPR Assembly G4-19 (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. BRPR Assembly G4-20 (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. BRPR Assembly G4-21 (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	KM600006
11C	Segmented*; Annular-coated	KR310010 KN620002 KN630002
11D	Full-length; Annular pellet	KM600008
11E	Full-length; Standard pellet	KE300170
11F	Segmented*; Annular pellet	KR310007 KM620003 KM630003

TABLE 6.3. BRPR Assembly G4-21 (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. BRPR Assembly G4-22 (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	KM600002
11C	Segmented*; Annular-coated	KR310011 KN620003 KN630003

TABLE 6.4. BRPR Assembly G4-22 (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.

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