190

DR 2428

COO-4066-9
UC-78

MASTER

4/16/79

Fuel Performance Improvement Program

Quarterly Progress Report
October - December 1978

Consumers
Power
Company

EXXON NUCLEAR
COMPANY, Inc.

Battelle

Pacific Northwest Laboratory

DISCLAIMER

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

DISCLAIMER

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

NOTICE

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

The views, opinions and conclusions contained in this report are those of the contractor and do not necessarily represent those of the United States Government or the United States Department of Energy.

Work on this program is performed for the
UNITED STATES DEPARTMENT OF ENERGY
by
CONSUMERS POWER COMPANY and EXXON NUCLEAR COMPANY, INC.
Under Contract EY-76-C-02-4066
and by
PACIFIC NORTHWEST LABORATORY, Operated by BATTELLE MEMORIAL INSTITUTE,
Under Contract EY-76-C-06-1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy \$ ____*; Microfiche \$3.00

*Pages	NTIS Selling Price
001-025	\$4.00
026-050	\$4.50
051-075	\$5.25
076-100	\$6.00
101-125	\$6.50
126-150	\$7.25
151-175	\$8.00
176-200	\$9.00
201-225	\$9.25
226-250	\$9.50
251-275	\$10.75
276-300	\$11.00

FUEL PERFORMANCE IMPROVEMENT PROGRAM

**Quarterly Progress Report
October - December 1978**

Compiled by C. E. Crouthamel

**Exxon Nuclear Company, Inc.
Richland, Washington 99352**

January 1979

This report was prepared for the U.S. Department of Energy by Consumers Power Company and Exxon Nuclear Company, Inc. under Contract EY-76-C-02-4066 and by Pacific Northwest Laboratory, operated by Battelle Memorial Institute, under Contract No. EY-76-C-06-1830.

Approved: _____

L. P. Bupp

L. P. Bupp
Program Office

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

SUMMARY

This report summarizes the activities of the Fuel Performance Improvement Program (FPIP) for the first quarter of fiscal year 1979, (October through December, 1978). An overall perspective of FPIP activities for fiscal year 1978 was given in the last quarterly/annual progress report, C00-4066-8.^(1.8)

Task 2 - Testing and Demonstration Program

Coordination of activities associated with the fabrication and qualification of the Halden test fuel for HBWR Series H-2, H-3, and H-4 and Big Rock Point Reactor (BRPR) demonstration fuel BRPR Series S-2 and S-3 continued. The program focuses on the chosen optimized PCI-remedy fuel design, i.e., annular-coated-pressurized. An alternate backup fuel being tested in parallel, but on a reduced level of effort, is a sphere-pac fuel design.

Task 2A - Out-of-Reactor Experiments

Studies are being conducted on control of the graphite coating thickness on the inside cladding surface.

A friction tester has been tested and calibrated for use with urania pellets and coated surfaces.

A design for a fuel-cladding interaction (FCI) simulator has been completed.

Task 2B - In-Reactor Experiments

The HBWR Series H-2, H-3, and H-4 tests include only the optimized annular-coated-pressurized design and the sphere-pac design in addition to reference rods. The HBWR H-4 test is designed to obtain fuel temperature, elongation, and internal pressure data on sphere-pac fuel rods. Fabrication of test fuel rods for HBWR H-2, H-3, and H-4 is in various stages of completion. The HBWR H-4 fuel will be completed first for shipment in January 1979.

The irradiation of twelve rods in the HBWR Series H-1 test continued to perform satisfactorily in the IFA-518 test rig. The first cycle was completed

in mid-October 1978 at a peak burnup of 268 GJ/kg (3100 MWd/MTM). After a routine shutdown, the reactor was restarted in late November 1978 and the irradiations have continued as planned.

Task 2C - In-Reactor Demonstrations

The one hundred and forty-three fuel rods (103 full length, 24 segmented, and 16 full-length characterized standard reference) for HBWR Series S-1 were assembled into bundles and shipped to the Big Rock Point Reactor. The assemblies will be loaded in BRPR in February 1979.

The microsphere fabrication for the Halden fuel was completed by Oak Ridge National Laboratory.

Task 3 - Performance Evaluations

The fuel performance evaluations this quarter were directed toward the HBWR Series H-1 and involved the following activities:

- determination of data plots required to analyze IFA-518 performance
- assessment of the validity of the IFA-supplied rig power and linear heat rating equations
- analysis of the apparent discrepancy in the power split between the upper and lower clusters of IFA-518.

CONTENTS

SUMMARY	iii
LIST OF FIGURES.	vii
LIST OF TABLES	viii
GLOSSARY OF TERMS	ix
1.0 INTRODUCTION	1
1.1 PROGRAM OBJECTIVES	1
1.2 BACKGROUND.	1
1.3 PROGRAM DESCRIPTION	1
1.4 PROGRAM ORGANIZATION	1
PREVIOUSLY PUBLISHED FPIP REPORTS	3
2.0 TASK 1 - ASSESS FUEL - CLADDING INTERACTION STATE-OF-THE-TECHNOLOGY AND POTENTIAL IMPROVED CONCEPTS	5
3.0 TASK 2 - TESTING AND DEMONSTRATION PROGRAM	7
3.1 PROGRAM OBJECTIVES	7
3.2 TESTING PROGRAM STATUS SUMMARY	7
4.0 TASK 2A - OUT-OF-REACTOR EXPERIMENTS	11
4.1 GRAPHITE COATING STUDIES	11
4.2 SILOXANE COATING STUDIES	13
4.3 FRICTION AND WEAR TESTING	15
4.4 FUEL-CLADDING INTERACTION SIMULATOR	16
5.0 TASK 2B - IN-REACTOR EXPERIMENTS	17
5.1 IN-REACTOR EXPERIMENT SUMMARY	17
5.2 SUMMARY DESCRIPTION OF HBWR SCREENING TESTS	18
5.3 DESIGN AND ANALYSIS - HBWR SERIES H-2, H-3, AND H-4 RODS	20
5.4 PROCESS DEVELOPMENT - HBWR SERIES H-2, H-3, AND H-4	20

5.5	FABRICATION - HBWR SERIES H-2, H-3, AND H-4	21
5.6	IRRADIATION STATUS - HBWR SERIES H-1	23
5.7	SUMMARY DESCRIPTION OF PRIMARY RAMPING TESTS	24
6.0	TASK 2C - IN-REACTOR DEMONSTRATIONS	27
7.0	TASK 2E - SPHERE-PAC LOADING AND ENGINEERING TESTS	43
8.0	TASK 3 - FUEL PERFORMANCE EVALUATIONS	45
8.1	PROGRAM OBJECTIVES	45
8.2	HBWR SERIES H-1 PERFORMANCE EVALUATION	45
APPENDIX A	CONVERSION TABLE FOR SI UNITS	55

FIGURES

1.1	Program Organization of the Fuel Performance Improvement Program	2
4.1	Viscosity of Dag 4 as a Function of Shearing Speed	12
4.2	Sketch Showing Salient Features of the Friction Testing Apparatus	16
6.1	BRPR Series S-1 Assembly G4-19 Rod Loading Map	28
6.2	BRPR Series S-1 Assembly G4-20 Rod Loading Map	29
6.3	BRPR Series S-1 Assembly G4-21 Rod Loading Map	30
6.4	BRPR Series S-1 Assembly G4-22 Rod Loading Map	31
8.1	Measured Fuel Temperatures as a Function of Indicated Linear Heat Rating Before and After the Initial Power-Cycling Shield Shift for IFA-518	51

TABLES

3.1	HBWR Test Matrix	9
3.2	BRPR Series S-2 Matrix	10
3.3	BRPR Series S-3 Matrix	10
5.1	Sinterability Test Results	21
5.2	HBWR Series H-2 and H-3 Pellet Fabrication Results	22
6.1	BRPR Assembly G4-19	32
6.2	BRPR Assembly G4-20	34
6.3	BRPR Assembly G4-21	36
6.4	BRPR Assembly G4-22	39
8.1	Selection Criteria for Data Correlations	46
8.2	Requirements and Rationale for Data Correlations	47

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

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, chamfered-corner (except HBWR Series H-1) fuel pellet.
Annular	Cylindrical, flat-ended, chamfered-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

PREVIOUSLY PUBLISHED FPIP REPORTS

- 1.1 "Fuel Performance Improvement Program, Quaterly 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.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

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 and 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.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

3.0 TASK 2 - TESTING AND DEMONSTRATION PROGRAM

M. D. Freshley (Pacific Northwest Laboratory)

3.1 PROGRAM OBJECTIVES

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.

3.2 TESTING PROGRAM STATUS SUMMARY

Coordination of subtask activities is continuing in order to maintain scheduled progress. Attention is focused on laboratory studies to improve the ability to control the thickness of the graphite coatings; assembly and testing of the friction-and-wear testing apparatus; design and fabrication 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; design of the rods 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. Frequent status meetings are held to coordinate the activities, follow progress, identify problem areas, and assign responsibilities for timely solutions.

Task 2B, In-Reactor Experiments, now includes HBWR Series H-4, the designation given to the short-term irradiation of four rods (3 sphere-pac and 1 reference) in the IFA-517 test rig to obtain comparative fuel temperature, cladding elongation, and internal pressure behavior data on sphere-pac fuel. Irradiation of HBWR Series H-4 is expected to commence in March 1979.

Detailed program plans and estimated costs were developed for FPIP to facilitate long-range planning through CY-1984, the duration of the program. The program scenario focuses on the chosen optimized PCI-remedy design, namely the annular-coated-pressurized fuel design, with development of the sphere-pac fuel concept as an alternate optimized design on a lower level of effort compared with the annular-coated-pressurized concept. 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 is shown in Table 3.1. The matrices developed for BRPR Series S-2 and S-3 demonstration irradiations in BRPR as part of Task 2C are shown in Tables 3.2 and 3.3. The BRPR Series S-1 matrix was presented previously.^(1.8)

TABLE 3.1. HBWR Test Matrix

ROD TYPE	NO. RODS (NO. RODS TO BE RAMPED)	HBWR SERIES IDENTIFICATION				
		H-1-LC	H-1-UC H-2-LC	H-2-UC H-3-LC	H-3-UC	H-4
REFERENCE	8 (7)					
ANNULAR	2 (2)					
COATED (DAG 154)	3 (3)					
COATED (DAG 4)- PRESSURIZED	6 (6)					
VIPAC	4 (4)					
SPHERE-PAC- PRESSURIZED	5 (2)					

TEST IDENTIFICATION

H_ = SERIES NUMBER

LC = LOWER CLUSTER

UC = UPPER CLUSTER

INSTRUMENTATION IDENTIFICATION

E = ELONGATION SENSOR

P = PRESSURE SENSOR

T = FUEL THERMOCOUPLE

= A ROD WITH THE
INDICATED INSTRUMENTATION

TABLE 3.2. BRPR Series S-2 Matrix

Fuel Form	Parameters		Full-Length Rods	Segmented Rods(a)
	Coated	Pressurized		
Annular	Yes	Yes	56	8
	Yes	No	-	-
	No	No	-	-
Sphere pac	-	Yes	14	8
Reference	Yes	No	-	-
	No	Yes	-	-
	No	No	<u>14</u>	<u>8</u>
			84	24

(a) Number of segmented rods (each consisting of three rodlets) and the number of middle segment rodlets for ramp testing. Top and bottom rodlets all contain reference pellets and are considered to be spares.

TABLE 3.3. BRPR Series S-3 Matrix

Fuel Form	Parameters		Full-Length Rods
	Coated	Pressurized	
Annular	Yes	Yes	66
	Yes	No	-
	No	No	-
Sphere- pac	-	Yes	24
Reference	Yes	No	-
	No	Yes	-
	No	No	<u>18</u>
			108

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, friction and wear testing, and the development of an FCI simulator.

4.1 GRAPHITE COATING STUDIES

The graphite dag designated as Dag 4, which is produced by the Acheson Colloids Corp. of Port Huron, Michigan, has been or is being used as a coating material on all of the coated rods in HBWR Series H-2, H-3, and H-4 and the BRPR demonstration series fuel irradiations. Most of the development problems associated with the use of this material, in particular the control of moisture content, have been worked out. However, control of the coating thickness to a specification of $6.4 \pm 4 \mu\text{m}$ remains a persistent problem that has not been satisfactorily resolved despite considerable effort.

In order for the coating to be effective, the inner surface of the cladding must be completely covered to a thickness which provides a reasonable amount of graphite to function as a lubricant and/or barrier. The thickness specification ($6.4 \pm 4 \mu\text{m}$) is also important because of its relationship to the hydrogen inventory in the rod. Achieving predictable coating thickness on a routine basis has been difficult. Dag 4 contains additives (alumina and silica) which are in a gel form, and the material is being used at a solids content such that gelation occurs on a time scale of minutes.

The flood coating process, while basically simple, is one which depends heavily on the properties of the fluid, i.e., no precision-fit element is used to spread the coating to some defined thickness. Ovality and surface features of the cladding are on the same order as the intended coating thickness, effectively eliminating that approach. Once the inside of the

cladding is flood coated by the dag and left to drain, the viscosity of the dag becomes important in relationship to the coating thickness.

To date, solids content has been used as an index for controlling coating thickness; viscosity is perhaps more appropriate. The viscosity of Dag 4 as a function of shearing rate (viscometer spindle speed) is shown in Figure 4.1; also shown in the figure is the viscosity of a classical Newtonian

FIGURE 4.1. Viscosity of Dag 4 as a Function of Shearing Speed. (Solids Content of 12.8 wt%; the bars represent one standard deviation.)

fluid, which is a constant that is independent of spindle speed. Dag 4 exhibits thixotropy, i.e., it has a high viscosity at low shearing rates, which decreases as the shearing rate increases. The shearing rate during the draining of the dag is very low, so that viscosity should be determined at a low shear rate to be most meaningful. This approach, along with continuous agitation of the dag to retard gelation, is being pursued to improve coating thickness control.

4.2 SILOXANE COATING STUDIES

Siloxane coatings have been reported by Canadian investigators^(a) to prevent stress corrosion cracking involving iodine. Efforts to produce a protective siloxane coating during this quarter have proceeded in two areas; these are discussed below.

4.2.1 Thinned High Vacuum Grease

Uniform thin coatings of siloxane high vacuum grease (Catalog No. 971V, Dow Corning Corp., Midland, Michigan) are difficult to apply due to the sticky nature of the grease. Thinning the grease with a solvent and dipping the part to be coated results in a coating that is both smooth and easy to apply. Xylene and toluene thin vacuum grease effectively; but they occasionally result in rippled coatings due to uneven flow during evaporation of the vehicle. Heptane appeared to perform well as a thinner, but considerable settling occurred in the makeup reservoirs. Although halogenated solvents are usually avoided, trichloroethane proved to be the best thinning vehicle. Trichloroethane blends rapidly with vacuum grease, coatings dry evenly, and there is little separation of thinner and grease with setting times up to 1000 hr. Analysis of a baked (310°C/20 hr) trichloroethane-thinned, vacuum grease coating for halides showed only 50 ppm Cl and <2 ppm F.

Dipping 6 cm-long zircaloy cladding sections in a coating liquid of 1 part high vacuum grease to 5 parts trichloroethane and baking at 310°C/20 hrs in air resulted in a coating 6-7 μ m thick with a smooth appearance.

(a) A. S. Bain, J. C. Wood, C. E. Coleman, "Fuel Designs to Eliminate Defects on Power Increases," British Nuclear Soc., International Conference, October 15-19, 1973, London.

Scanning electron microscope (SEM) examination of the coating at 100X to 3000X, however, revealed many undesirable agglomerate particles (0.5-5 μm), probably silica flour, in an otherwise uniform coating.

As reported previously,^(1.8) siloxane coatings contain excessive amounts of hydrogen. The hydrogen content before baking was calculated to be 7.5 wt% based on the formula 93% polydimethyl siloxane + 7% SiO_2 , i.e., 93% $[(\text{CH}_3)_2\text{SiO}]_n + 7\%\text{SiO}_2$. Oxidation at ca 300°C removed some of the hydrogen. The optimum baking temperature of 310°C was determined by the fact that although most of the hydrogen is removed at a temperature of 450°C in air, the resulting coating is nonadherent and brittle after baking at the higher temperature. In addition, another major consideration is the fact that zircaloy oxidizes to a significant degree in air at temperatures greater than 310°C. After baking at 310°C, the coatings remain adherent and soft, but the amount of hydrogen contained is 3 to 4 wt%, as determined by 800°C extraction with zircaloy in an evacuated silica capsule and then analysis of the metal for hydrogen. (One wt% hydrogen contained in a 6 μm -thick siloxane coating on the inside surface of a BRPR fuel rod cladding is equivalent to ca 51 ppm water in the fuel or ca 23 ppm hydrogen in the cladding if it were all released and reacted uniformly.) This amount of hydrogen, which is available for reaction with the zircaloy cladding either uniformly or locally, is presently considered to be unacceptably high for LWR fuel service application.

4.2.2 Dow Corning Resin X96502

A resin that contains less hydrogen than the vacuum grease-derived material has been received from Dow Corning Corporation for evaluation as a coating material. Because of company proprietary considerations, the exact composition of the resin is unavailable, but it could be regarded as being pyrolyzed to a gel containing less than one methyl radical $[(\text{CH}_3)_{0.1}\text{SiO}]_n$.

The coating is easily applied by dipping the substrate into the liquid and curing at 150°C/3 min. Dipping results in a coating that is about 4 μm thick on a zirconium sheet, but is <2 μm thick when applied to the inside surface of cladding, apparently because drying is faster in free air circulation than on the inside surface of the tubing. Gentle blow-drying of the dipped

cladding results in a coating of 5-7 μm average thickness. However, variations occurring in the coating thickness indicate the need for further work. The coating is smooth, shiny, adherent, and retains some plasticity. Halide analysis of the coating showed 114 ppm Cl and <2 ppm F. Hydrogen analysis by reaction with the zircaloy at 800°C showed that the cladding contained approximately 2.5 wt%. For a coating thickness of 6 μm on a BRPR fuel rod, this would result in a maximum of ca 0.015g H_2 which is equivalent to ca 57 ppm H_2 in the cladding if it reacts uniformly. This hydrogen level is regarded as excessive and it appears that the baking treatment required to reduce the hydrogen concentration to an acceptable level will degrade the coating and/or cladding excessively. This high hydrogen content currently remains an obstacle to possible use of the Dow Corning resin for this application.

4.3 FRICTION AND WEAR TESTING

One possible reason the graphite coating improves PCI performance is that it functions as a lubricant between the pellets and the cladding, thus reducing the stress levels at pellet-pellet interfaces during power increases. A friction tester was constructed to evaluate the lubricating effectiveness of the graphite coating and other coating materials. Figure 4.2 illustrates the main features of the apparatus. The tester is of a standard pin-on-disc configuration: the zircaloy sample disc, A, turns while the UO_2 rider, B, bears upon it. The rider is mounted on an arm which is provided with strain gauges to measure the tractive force f_t . Division of the tractive force by the normal force f_n (provided by weights) enables calculation of the sliding friction coefficient. The machine was designed for testing at sliding speeds ranging from 0.2 to 100 cm/min, at temperatures ranging from room temperature to 400°C, and in vacuum or any desired atmosphere.

The friction tester has been debugged and calibrated and will soon be used with UO_2 . The test procedure is designed to provide accurate friction coefficient data (small sliding distance, low sliding speed, low to intermediate loads) as well as data on comparative durability or wear resistance of different coating materials (long distances, high speed, high loads).

FIGURE 4.2. Sketch Showing Salient Features of the Friction Testing Apparatus

4.4 FUEL-CLADDING INTERACTION SIMULATOR

The conceptual design for the Fuel-Cladding Interaction (FCI) simulator has been completed. This design provides loading conditions in the cladding that are representative of FCI and facilitates relative measurements of the effectiveness of selected fuel design options. Thus, it will be possible to investigate how coatings, fuel types, cladding changes, and chemical environment affect FCI behavior.

The design for the FCI simulator utilizes a UO_2 annulus with tungsten-copper segments loaded by means of an enclosed silicone rubber plug that is pressurized by externally actuated hydraulic rams. Radial expansion loads as well as axial force and pellet-to-pellet interface conditions can be simulated with this system. Pellet-to-cladding frictional effects are simulated by the UO_2 annulus; and the number of cracks can be varied by changing the number of tungsten segments.

Preliminary scoping tests are currently being performed to determine the feasibility of using various individual components specified in the design. The results of these tests indicate that the method of applying pressure to the silicone plug is workable. This method which utilizes hydraulic rams is the simplest of three options considered.

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 groups of power cycling/ramping irradiations and a special fuel temperature test on sphere-pac fuel in the HBWR. The results of these comparative irradiations will be utilized to select the most promising fuel concept and test conditions for evaluation in the primary power-ramping experiments on rod segments that are to be preirradiated in the Big Rock Point Reactor (BRPR) as part of the Task 2C in-reactor demonstrations.

5.1 IN-REACTOR EXPERIMENT SUMMARY

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. (1.4, 1.6, 1.8) Regarding the initial irradiations which are in progress, the emphasis for HBWR Series H-1 was placed upon evaluating the effects of the individual design differences. Development activities are now focused on evaluating an optimized annular-coated-pressurized design and the sphere-pac design as a back-up.

The screening tests will evaluate (and the primary tests will have available for evaluation), rods or rodlets incorporating the following design parameters:

1. a reference fuel design utilizing a standard solid, dished pellet;

2. an annular pellet design with a central hole volume that is equivalent to 10% of a solid, nondished pellet;
3. the annular pellet design combined with graphite coating on the inside surface of the cladding;
4. a packed-particle (vipac or sphere-pac) fuel design, and
5. internal pressurization.

In the initial HBWR Series H-1 screening tests, all the rod types contain a cover gas of helium at one atmosphere pressure, the annular-coated design utilizes Dag 154 for the coating material, and the packed-particle design utilizes vibrationally compacted, angular fuel particles (vipac). In subsequent tests in HBWR (Series H-2, H-3 and H-4), only the optimized annular-coated-pressurized design, the backup sphere-pac design, and the reference design will be evaluated. The HBWR Series H-4 test consisting of three sphere-pac and one reference rod, will be irradiated to about 400 GJ/kg burnup. This test was added to the original matrix in order to obtain fuel temperature as well as elongation and internal pressure data on sphere-pac fuel. All the rods from HBWR Series H-1, H-2, and H-3 will be power-ramp tested. Current plans do not include ramp testing of HBWR Series H-4 rods.

Several types of rodlets are included in the initial BRPR Series S-1 demonstration irradiations which will be available for later ramp testing. These include 1.) both coated and noncoated reference rods; 2.) both pressurized and nonpressurized reference rods; 3.) annular, annular-coated, and annular-coated-pressurized rods, and 4.) both pressurized and nonpressurized vipac rods. The coated rods in the BRPR Series S-1 utilize Dag 4. The BRPR Series S-2 will have only rodlets of the optimized annular-coated-pressurized design, the backup sphere-pac design, and the reference design. During subsequent power ramp testing, emphasis will be placed on the optimized designs.

5.2 SUMMARY DESCRIPTION OF HBWR SCREENING TESTS

The two 6-rod clusters in the HBWR test rig (IFA-518) are being alternately power cycled between a peak conditioning power of 44.5 kW/m and a peak reconditioning power of 29.0 kW/m. After two power cycles and accumulation

of a peak burnup of 700-850 GJ/kg (8,000-10,000 MWd/MTM) on HBWR H-1, the upper cluster will be moved to the lower position and six fresh rods (HBWR H-2) will be inserted into the upper position. After another two power cycles and accumulation of an additional 700-850 GJ/kg burnup, the lower cluster rods will be replaced by the upper rods, and six fresh rods (HBWR H-3) will be inserted in the upper cluster position. This power cycling sequence will be repeated one more time with HBWR H-3. The rods will be individually power ramped in a ramping rig in HBWR. Thus, six rods will be ramped from the original lower cluster after 700-850 GJ/kg burnup, twelve rods will be ramped after cycling irradiation in both the upper and lower cluster positions after a peak burnup of about 1200-1400 GJ/kg, and six rods will be ramped from the last upper cluster after 700-850 GJ/kg burnup: a total of 24 HBWR ramp tests.

Power control during cycling irradiation is being accomplished by moving a silver absorber shield which alternates between the two six-rod clusters. Power during ramping will be controlled through combining adjustment of the ³He pressure in coils surrounding the test rod and reactor power. The tests have been designed to achieve peak ramping powers as high as 65 kW/m in rods that have accumulated 1700 GJ/kg burnup.

The IFA-518 test rig instrumentation includes inlet and outlet flowmeters and thermocouples to determine total rig power, self-powered axial and radial neutron detectors to determine axial power variations and radial flux tilts and a failure detector to measure the presence of fission products in the coolant.

The test matrix for the HBWR screening tests is illustrated in Table 3.1. The HBWR Series H-1, H-2, and H-3 are being irradiated during their power cycling irradiation in test rig IFA-518. The HBWR Series H-4, the special sphere-pac fuel temperature measurement experiment, will be irradiated in a rig designated IFA-517. The HBWR test rod instrumentation includes various combinations of rod-elongation/failure and pressure monitors in the lower end cap of all the test rods. Fuel centerline thermocouples are included in five of the HBWR Series H-1 lower cluster rods and three of the four rods in the HBWR Series H-4. The combination elongation/failure monitors and the internal rod pressure monitors will be operative during both the cycling and ramping

portions of the HBWR Series H-1, H-2, and H-3 tests. The thermocouples will be operative during only the preramping cycling portion of the irradiation in IFA-518 and during the steady-state irradiation in IFA-517.

Actual fabrication of the HBWR Series H-2, H-3, and H-4 rods will take place during the next quarter. Irradiation of the HBWR Series H-4 is scheduled to start in March 1979. Irradiation of the HBWR Series H-2 will start approximately January 1980 and the irradiation of HBWR Series H-3 about April 1981.

A draft of essentially all of the HBWR Series H-1 rod characterization report has been written. The sections are currently being reviewed for continuity and completeness.

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

The parts list (XN-NF-PL-14) and product drawings for the HBWR Series H-2, H-3, and H-4 were prepared and routed for approval.

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

5.4.1 Pellet Process Development

A re-evaluation of the ceramic properties of the 11% enriched UO_2 powder supplied by ORNL was performed. This powder presented difficulties during the fabrication of the HBWR Series H-1 pellets because of its variability. In order to obtain a more uniform feed material, the 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

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 5.1.

5.4.2 Coated-Cladding Process Development

The as-received graphite dag (Dag 4) for coating tubes contained 12.5 wt% solids. Considerable difficulty was encountered in controlling the

TABLE 5.1. Sinterability Test Results^(a)

Pellet Type	Green Density, g/cm ³	Sintering Temperature, °C	Sintering Time, Hr	Sintered Density, %TD
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.

thickness of the graphite layer on the inside surface of the tubes. 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.

5.4.3 Sphere-Pac Process Development

Process equipment for loading microspheres into tubes was installed in the glovebox 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. A shape plate was also set up to segregate broken spheres from down-loaded fuel rods.

As reported previously,^(1.8) the axial density of four test rods containing depleted uranium microspheres which were loaded at ORNL was measured on the densigauge. The linear density measurements were very uniform (86-88% TD) except at the top end (0.64-1.27 cm) of the rods where there was a slightly lower (approximately 84% TD) density region. This situation also existed in the initial trial loadings of depleted microspheres at ENC.

5.5 FABRICATION - HBWR SERIES H-2, H-3 AND H-4

5.5.1 Pellet Fabrication

The pellets (reference and annular) for HBWR Series H-2 and H-3 have been fabricated. The pellet production process was based on the results

of preproduction testing as presented in Section 5.4.1. No difficulties were encountered in fabricating these pellets and their quality was excellent. The processing variables and densities are listed in Table 5.2.

TABLE 5.2. HBWR Series H-2 and H-3 Pellet Fabrication Results

Pellet Form	Green Density, g/cm ³	Sintering Temperature, °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

5.5.2 Coated-Cladding Fabrication

Fifteen coated tubes were prepared for HBWR Series H-2 and H-3. A yield of only 63% was achieved. All of the out-of-specification coated tubes had thin coatings. The satisfactory tubes will now be cured.

5.5.3 Sphere-Pac Fabrication

The enriched microspheres prepared at ORNL were received and chemical overchecks were completed on the as-received material. The results were:

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

Fabrication of the HBWR Series H-2, H-3, and H-4 sphere-pac rods is scheduled for late January, 1979.

5.6 IRRADIATION STATUS - HBWR SERIES H-1

The irradiation of the twelve rods, which comprise the HBWR Series H-1, continued with satisfactory operation in the IFA-518 test rig during the quarter. The first cycle of operation was completed in mid-October at a peak burnup of approximately 268 GJ/kg (3100 MWd/MTM). After a routine maintenance and experiment exchange shutdown of about six weeks, the reactor was restarted; it has operated since as-planned.

Data from the in-reactor instrumentation from the test rods and the IFA-518 test rig are recorded using three systems: 1.) the Test Fuel Data Report (TFDR) system; 2.) the CALIB system; and 3.) a multichannel strip chart recorder. The TFDR and the CALIB systems record the outputs from the rod instrumentation (fuel thermocouples, elongation sensors, and pressure sensors) and the rig instrumentation (flowmeters, neutron detectors, inlet and outlet thermocouples, and adjacent control rod locations). The TFDR automatically samples all instruments every 15 min during reactor operation and records the data on magnetic computer tape. The CALIB system samples all the instruments at time intervals specified by the experimenter, normally in the range of 1 to 5 min; it is usually utilized during periods of reactor power change, i.e., during reactor startups and shutdowns after a shield shift. The CALIB data output form is currently punched computer cards. Both the TFDR and CALIB data also include preliminary values of linear heat rating for each test rod. These linear heat rating values are calculated based upon 1.) a calibration factor which was determined from the measured total rig power and is corrected for an estimated gamma heating contribution, and 2.) the neutron detector signals with an assumed linear axial power form. The calculated linear heat ratings are also corrected for the different amounts of fissile material in the two clusters, the radial flux tilt as indicated by the neutron detectors, and a spectral factor for those rods which are covered by the silver adsorber shield. The multi-channel strip chart recorder is used periodically on selected instrumentation to provide continuous data logging, e.g., cladding elongation versus the naturally

cyclic variation in reactor power as indicated by a cobalt detector in an adjacent test rig position.

The following have been received for analysis: TFDR data tapes for the first cycle of operation; the CALIB cards for the first few power ascensions; and selected multichannel strip charts taken during the first few days of operation of IFA-518. TFDR data tapes for the initial portion of the second irradiation cycle, CALIB data for the shield shift which occurred near the end of the second cycle, and selected multi-channel strip chart records for the shield shift have not as yet been received from IFA. The normal time delay for data processing at IFA is from 20 to 60 days depending upon the work load at the reactor facility.

Several modifications were made to existing data handling computer codes to allow the IFA-518 TFDR tapes and CALIB cards to be transferred to storage on disc for the PDP 11/45 computer system and to facilitate plotting. All the necessary systems are now in place to permit plotting of elongation or temperature versus time, burnup, or calculated linear heat rating. Burnup and linear heat rating values currently used for plotting are those provided on the TFDR or CALIB outputs. Refinements in the linear heat rating values are expected based upon analyses which will be performed as part of the Task 3 (Section 8.0) activities.

The thermocouple in vipac rod No. 13 continues to indicate a decreasing temperature at constant power. It is not known whether this behavior is due to a fuel-related phenomenon taking place within the rod or to instrumentation malfunction. The elongation sensor signal from annular-coated rod No. 9 gave erratic signals during the last several days of the first cycle of operation due to a signal conditioner malfunction. The conditioner has been repaired and the instrumentation is now performing normally.

5.7 SUMMARY DESCRIPTION OF PRIMARY RAMPING TESTS

Rodlets comprising the fuel concept or concepts with the most potential for improved FCI behavior will be selected for ramp testing based upon the results of the screening tests in HBWR. These rodlets will be chosen from the segmented rods irradiated in BRPR as part of the Task 2C in-reactor

demonstrations. The test reactor to be used for the primary ramp tests has not been selected, but the rodlets have been designed so that they can be ramped in any of the available high-flux reactors. Only the central rodlet from the three-segment, segmented rods will be used for the primary ramp tests; however, rodlets from the lower portion of the segmented rods can serve as backups for the primary ramping tests.

The BRPR Series S-1 demonstrations include 24 segmented rods with several rod types.^(1.8) The BRPR Series S-2 will have 24 segmented rods with eight of the optimized annular-coated-pressurized design, eight of the backup sphere-pac design, and eight rods of the reference design. No segmented rods are currently planned for BRPR Series S3.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

6.0 TASK 2C - IN-REACTOR DEMONSTRATIONS

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

The rod loading maps for the four BRPR Series S-1 demonstration fuel assemblies are shown in Figures 6.1, 6.2, 6.3, and 6.4.

Rod identifications are shown in Tables 6.1, 6.2, 6.3, and 6.4. Fuel rod No. 9K in Assembly G4-19, Figure 6.1, was originally intended to be a full-length vipac fuel rod. However, it was replaced by a standard G-4 rod after the vipac fuel rod was destructively examined to verify a slight cross-contamination of HBWR Series H-1 feed material (11% enriched) and the BRPR Series S-1 feed material (2.52% enriched).^(1.8)

	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			KL33 0002	K06 00012	KR3 00017	KP33 0004	KE3 00538	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 6.2. 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	K063 0002	K06 00021								KN6 00007	K063 0004
10			KR3 00019						KM6 00006		
11			KN63 0002	K06 00008	KE3 00170	KM63 0003	KR3 00020	K06 00013	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
		KE3	K06	KR3	KP3	KE3	KM6	KN6		
		00581	00007	00012	00010	00582	00009	00014		
		KM6						KR3		
		00010						00011		
KP3	KN6								K06	KM6
00007	00012								00017	00013
KR3										KN6
00007										00013
K06										KP3
00008										00011
KE3										KE3
00586										00587
KP3										K06
00006										00009
KN6										KR3
00010										00009
KM6	K06								KN6	KP3
00014	00006								00011	00012
		KR3						KM6		
		00010						00012		
		KN6	KM6	KE3	KP3	KR3	K06	KE3		
		00009	00011	00585	00008	00008	00010	00584		

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.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

7.0 TASK 2E - SPHERE-PAC LOADING AND ENGINEERING TESTS

M. H. Campbell (Exxon Nuclear Company)

The procurement of microspheres and equipment adaptation for fabrication of the sphere-pac rods have been completed. Further process development is reported as applicable under Tasks 2B and 2C.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

8.0 TASK 3 - FUEL PERFORMANCE EVALUATIONS

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

8.1 PROGRAM OBJECTIVES

This task serves as a focal point for the integration and evaluation of data developed from the 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 HBWR.

8.2 HBWR SERIES H-1 PERFORMANCE EVALUATION

Fuel performance evaluations during the quarter were directed towards three areas:

- 1) determination of the routine data plots required to analyze IFA-518 performance;
- 2) an assessment of the validity of the IFA-supplied rig power and linear heat rating equations; and
- 3) analysis of the apparent discrepancy in the power split between the upper and lower clusters of IFA-518.

The data from the in-reactor instrumentation in the IFA-518 test rig is recorded on magnetic tape and punched computer cards (see Section 5.6). In order to define trends and perform preliminary evaluations of the large amount of test data, a set of standard graphical data plots is utilized. These plots can be produced by a PDP 45/11 computer using current modified plotting routines. Table 8.1 lists the selection criteria for the standard and general types of correlations. Table 8.2 lists specific data correlations and their time spans. The plots are being produced as each data tape is received. These standard correlations will be used as the basis for evaluating fuel performance. Additional graphical representations will be prepared as required.

TABLE 8.1. Selection Criteria for Data Correlations

Type of Fuel	Properties of Interest	Corresponding Data Plots Needed
Annular	<ul style="list-style-type: none"> Fuel temperature: expected to be lower than that of the reference fuel General cladding stresses and localized stresses at pellet-pellet interfaces: expected to be lower than those of the reference fuel Releases of fission product: expected to be lower than those of the reference fuel 	<ul style="list-style-type: none"> (a) Fuel temperature versus time (b) Fuel temperature versus linear heat rate (c) Elongation versus time (d) Elongation versus burnup (e) Elongation versus linear heat rate (f) Pressure versus time (g) Pressure versus burnup
Annular-Coated	<ul style="list-style-type: none"> Fuel temperature and mechanical stresses as compared to those of the pellet fuels Releases of fission product: expected to be intermediate (between reference and annular fuels). 	<ul style="list-style-type: none"> (a), (b), (c), (d), (e) (f), (g)
Vipac	<ul style="list-style-type: none"> Fuel temperature: expected to be higher than that of the sintered pellets Localized stresses and strain concentrations: expected to be lower than those of the sintered pellets Releases of fission product: expected to be higher than those of the sintered pellets because of the higher fuel temperature and larger surface area 	<ul style="list-style-type: none"> (a), (b) (c), (d), (e) (f), (g)
Reference	<ul style="list-style-type: none"> Comparison to other fuel types 	<ul style="list-style-type: none"> (a), (b), (c), (d), (e), (f), (g)

TABLE 8.2. Requirements and Rationale for Data Correlations

Selected Data Plots		
Type	Time Span	Rationale
A. Temperature (measured at thermocouples)		
• Temperature versus time for		• To obtain a description of the history of thermal behavior
(i) Annular, annular-coated and reference fuels in lower cluster	(a) Time period recorded on one entire tape (b) One cycle (c) One month	• To check the functioning of thermocouples
(ii) Vipac and reference fuels in lower cluster	(a), (b), (c)	
• Temperature versus time at constant assembly power (sampled on reactor power increases) for (i), (ii)	(d) From time = 0 to latest date	• To obtain information on thermal properties, which is helpful to the understanding of PCI phenomenon (e.g., thermal conductivity changes and gap closure)
• Temperature versus linear heat rating for (i), (ii)	(e) Every full (upward + downward) power ramp	
B. Elongation		
• Elongation versus time for (i), (ii)	(a), (b), (c)	• To obtain a description of the history of mechanical behavior
(iii) Annular, annular-coated and reference fuels in upper cluster	(a), (b), (c)	• To check the functioning of elongation sensors
(iv) Vipac and reference fuels in upper cluster	(a), (b), (c)	
• Elongation versus time at constant assembly power (sampled on reactor power increases) for (i), (ii), (iii), (iv)	(d)	• To obtain information on mechanical properties, which is helpful to the understanding of PCI phenomenon (e.g., relocation, restructuring, onset and extent of PCI)
• Elongation versus burnup at constant assembly power (sampled on reactor power increases) for (i), (ii), (iii), (iv)	(d)	
• Elongation versus linear heat rating for (i), (ii), (iii), (iv)	(e)	
C. Pressure		
• Pressure versus time for		• To check the functioning of pressure sensors
(v) Annular-coated and vipac fuels in lower cluster	(a), (b), (c)	• To obtain information of fission product release in the fuel
(vi) Reference and vipac fuels in upper cluster	(a), (b), (c)	
• Pressure versus burnup for (v), (vi)	(a), (b), (c)	
• Pressure versus linear heat rating for (v), (vi)	(a), (b), (c)	

An assessment was made of the IFA-supplied IFA-518 rig power and linear heat rating equations in order to ascertain whether or not all the currently identifiable terms are being taken into account. The equation used to calculate the total rig power is:

$$QA = Kg \left[C_{DL} \cdot SP_L \left(\frac{I_1 + I_4}{2} \right) \left(\frac{I_1 + I_2 + I_3}{3I_1} \right) + C_{DU} \cdot SP_U \cdot MR \left(\frac{I_5 + I_8}{2} \right) \left(\frac{I_5 + I_6 + I_7}{3I_5} \right) \right] \quad (1)$$

where

QA = total rig fission power, kW

Kg = calibration constant corrected for gamma heating, kW/
nanoamp (1.128 for shield up, 1.120 for shield down)

C_{DL} , C_{DU} = depletion factors for lower and upper clusters, respectively

SP_L , SP_U = spectral factors for lower and upper clusters (1.00 for
uncovered cluster, 1.10 for covered cluster), respectively

MR = mass ratio between upper and lower cluster (1.02)

I_j = current from jth neutron detector, nanoamps.

The two major terms within the brackets of Equation 1, multiplied by Kg, represent the total fission power in the lower and upper clusters. The neutron detectors which provide the I_1 , I_4 , I_5 and I_8 signals, are positioned in line axially in the test rig with the first two adjacent to the lower cluster and the last two adjacent to the upper cluster. The neutron detectors which provide the signals I_2 and I_3 are at the axial location of the I_1 detector and the three detectors are azimuthally oriented 120° apart. The same geometry applies for the detectors that provide the signals for I_5 , I_6 , and I_7 . The calibration constant Kg is determined calorimetrically during forced flow operation. A spectral factor of 1.10 is required to adjust the power for the cluster under the shield because of hardening of the neutron spectrum by the shield with the resultant decrease in efficiency of the neutron detectors.

The average linear heat generation rate for each individual rod is calculated by the equation:

$$ALHR_i = SP \left(\frac{M_i}{M} \right) \left(\frac{1}{L_i} \right) C_D \cdot Kg \left(\frac{I_{1,5} + I_{4,8}}{2I_{1,5}} \right) (0.757I_n + 0.333I_m - 0.091I_f) \quad (2)$$

where

SP, C_D , Kg = appropriate factors as per Equation 1

L_i = length of fueled region, m

M_i = mass of fissile atoms in the i th rod, g

M = mass of fissile atoms in the appropriate cluster, g

I_n = current from nearest neutron detector in the 3-detector array, nanoamp

I_m = current from next nearest detector in the 3-detector array, nanoamp

I_f = current from farthest detector in the 3-detector array, nanoamps.

The linear heat rating at the thermocouple in a particular rod is calculated by assuming that the signal from the neutron detector located nearest the thermocouple, i.e., I_4 , is typical of the power generated at the thermocouple. The equation substitutes the terms $\left(\frac{I_4}{I_1} \right)$ for $\left(\frac{I_1 + I_4}{2I_1} \right)$ and C_{DTF} for C_D in Equation 2, where C_{DTF} is the depletion factor at the thermocouple.

The equations assume a linear power distribution in the rods. As a first approximation, this is a reasonable estimate, especially for the noncovered rods.

The initial evaluation of the equations indicates that at least the following corrections should be made in order to better define the individual rod heat ratings:

1. The nonlinear decrease in generated heat due to fuel removal at the thermocouple should be taken into account,
2. the delay constant of approximately 5.5 min for the vanadium neutron detectors should be taken into account during nonsteady-state operation, and
3. the axial midplane of the neutron detector which provides the I_4 signal, is not located at the same plane as the tip of the thermocouple. This

should be taken into account geometrically after a better refinement on the axial power distribution has been obtained.

The instrumentation signals and calculated heat ratings from Equations 1 and 2 have been used in the preliminary evaluation of the test results. It is not planned to use the values calculated from Equations 1 and 2 in the final evaluations of the data. A computer code will be written to process the TFDR and CALIB signals based upon the above observations and any other refinements that are deemed necessary.

An apparent discrepancy was observed in the measured fuel temperature as a function of linear heat rating after the first power-cycling shield shift on September 26, 1978. It appeared that, at constant indicated power, the fuel temperatures were higher in all the rods after the shift than before the shift. The differences are illustrated in Figure 8.1. For comparison, a single reactor power increase with the shield down that was made on July 15-16, 1978 during the calibration of IFA-518 is also shown.

Because all the thermocouples indicated the same behavior after the initial power-cycling shield shift, the observed temperatures are believed to be correct and the calculated linear heat ratings are believed to be incorrect. These observations indicate the possibility that the power split between the upper and lower clusters was not correct or that some unknown phenomenon had not been taken into account when calculating the linear heat ratings.^(a) Several possible causes for the apparent discrepancy were assessed.

The positions of adjacent control rods before and after the shift were checked and no correlation between their position and the apparent discrepancy was found.

The position of the silver absorber shield in the adjacent assembly IFA-507 was correlated with the data before and after the shift. There was no

(a) The omissions from the calculated linear heat ratings mentioned above are essentially all linearly scalable and would not account for the apparent discrepancy, e.g., the inclusion of the 5.5 neutron detector delay constant merely shifts the curves.

FIGURE 8.1. Measured Fuel Temperatures as a Function of Indicated Linear Heat Rating Before and After the Initial Power-Cycling Shield Shift for IFA-518

apparent relationship; however, data for all the combinations of shield positions for IFA-507 and IFA-518 were not available.

The ratio of I_4/I_1 as a function of time was evaluated to determine if there was a significant change in the indicated axial linear heat generation distribution before and after the shield shift. This, in conjunction with the aforementioned observation that the axial center of the neutron detector, I_4 , is not aligned with the tip of the thermocouple (as assumed in the heat generation calculation), accounts for only a 4 to 5% decrease in the difference in the temperature response before and after the shield shift. This would not, itself, account for the apparent discrepancy.

The Institutt for Atomenergi recommended a new set of K_g and SP values, in combination with a zero shift in the linear heat rating, to bring the curves together. The new values were obtained by using the data from power changes made immediately before and after the shield shift, and forcing the two curves to overlap. Several other reactor power ascensions were compared at PNL using the suggested values for K_g and SP . Indeed the slopes were the same, but a large variation in the zero shift was required to make the curves overlap. Although usable as an interim measure, this method is not preferred because the independent variable (temperature) and the dependent variable (linear heat generation rate) are not truly independent. It is preferred to account for the proper calculation of linear heat rating from first principles, with temperature observations to perhaps help identify the principles.

There is a possible explanation for the apparent discrepancy: the neutron flux as indicated by signal I_4 is not truly indicative of the flux at the tip of the thermocouples. This is because: 1.) the two are not at precisely the same axial location, i.e., the neutron detector midplane is 67 mm lower in the shield than the thermocouple; 2.) the silver shield is approximately the same length as the fuel stack, e.g., not an infinitely long shield from a calculational standpoint, and 3.) the neutron detector is very close to the shield and partially shielded by the adjacent fuel rods such that neutron

streaming into the upper region's inside absorber shield may result in a higher flux at the thermocouple than mid-position on the neutron detector. This possibility and any resultant changes in axial power profile in the rods covered by the shield will be evaluated.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX A

CONVERSION TABLE FOR SI UNITS

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

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.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

DISTRIBUTION

No. of Copies

No. of Copies

OFFSITE

2 A. A. Churm
DOE Patent Division
9800 S. Cass Avenue
Argonne, IL 60439

DOE, NASAP Control Office
Mail Stop B-107
Germantown, MD 20767

192 T. Abernathy
DOE, Technical Information Center
P.O. Box 62
Oak Ridge, TN 22161

4 S. J. Nowicki
U.S. Nuclear Regulatory Commission, Division of Operating Reactors
Mail Stop 542
Washington, D.C. 20555

D. L. Ziemann
(Docket No.: 50-55, License DPR-6, Big Rock Point Plant)
U.S. Nuclear Regulatory Commission, Division of Operating Reactors
Mail Stop 542
Washington, D.C. 20555

Dr. W. V. Johnston
Chief, Fuel Behavior Research Branch
Division of Reactor Safety Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Director
U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation
Washington, D.C. 20555

H. Sobel
American Electric Power Service Corporation
2 Broadway
New York, NY 10004

W. Lipinski
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

O. Cypret
Arkansas Power and Light Company
9th and Louisiana
Little Rock, AR 72203

J. S. Tulenko
Babcock and Wilcox Company
Nuclear Power Generation Division
P.O. Box 120
Lynchburg, VA 24505

Technical Files
Battelle Memorial Institute
505 King Avenue
Columbus, OH 43201

B. A. Pasternak
Booz-Allen Applied Research
4330 East-West Highway
Bethesda, MD 20014

R. N. Duncan
Combustion Engineering, Inc.
1000 Prospect Hill Road
Windsor, CT 06095

W. M. Kiefer
Commonwealth Edison Company
P.O. Box 767
Chicago, IL 60690

D. R. O'Boyle
Commonwealth Edison Company
P.O. Box 767
Chicago, IL 60690

M. L. Lee
Consolidated Edison Company of New York
4 Irving Place
New York, NY 10003

No. of
Copies

D. B. Wehmeyer
Detroit Edison Company
2000 Second Avenue
Detroit, MI 48226

J. Korthever
Duke Power Company
P.O. Box 2178
Charlotte, NC 28342

T. Snead
Duke Power Company
P.O. Box 2178
Charlotte, NC 28342

F. E. Gelhaus
Electric Power Research Institute
P.O. Box 10412
Palo Alto, CA 94303

J. T. A. Roberts
Electric Power Research Institute
P.O. Box 10412
Palo Alto, CA 94303

G. R. Thomas
Electric Power Research Institute
P.O. Box 10412
Palo Alto, CA 94303

R. Williams
Electric Power Research Institute
P.O. Box 10412
Palo Alto, CA 94303

R. Christensen
Entropy Limited
South Great Road
Lincoln, MA 01773

C. Rau
Failure Analysis Associates
750 Welch Road, #116
Palo Alto, CA 94304

J. R. Tomonto
Florida Power and Light Company
P.O. Box 013100
Miami, FL 33101

No. of
Copies

S. Armijo
General Electric Company
175 Curtner Avenue
San Jose, CA 95125

P. Bray
General Electric Company
175 Curtner Avenue
San Jose, CA 95125

H. E. Stone
General Electric Company
175 Curtner Avenue
San Jose, CA 95125

R. A. Proebstle
General Electric Company
175 Curtner Avenue
San Jose, CA 95125

H. S. Rosenbaum
General Electric Company
175 Curtner Avenue
San Jose, CA 95125

R. Hanneman
General Electric Company
P.O. Box 8
Schenectady, NY 13201

G. Bond
General Public Utilities Service
Corporation (GPU)
260 Cherry Hill Road
Parsippany, NJ 07054

M. Zukor
General Public Utilities Service
Corporation (GPU)
260 Cherry Hill Road
Parsippany, NJ 07054

Knolls Atomic Power Laboratory
Technical Library
Box 1072
Schenectady, NY 12301

No. of
Copies

R. Ballinger
Massachusetts Institute of Tech-
nology (MIT)
Building 8, Room 139
Cambridge, MA 01239

J. E. Meyer
Massachusetts Institute of
Technology (MIT)
Department of Nuclear Engineering
77 Massachusetts Avenue
Cambridge, MA 01239

J. A. Gorman
MPR Associates
1140 Connecticut Avenue
Washington, D.C. 20036

S. W. Wilczek, Jr.
Niagara Mohawk Power Corporation
300 Erie Boulevard West
Syracuse, NY 13202

J. P. Cagnetta
Northeast Utilities Service Co.
P.O. Box 270
Hartford, CT 06101

J. Hallam
Nuclear Services Corporation
1700 Dell Avenue
Campbell, CA 95008

A. L. Lotts
Oak Ridge National Laboratory (ORNL)
P.O. Box X
Oak Ridge, TN 37830

T. Row
Oak Ridge National Laboratory (ORNL)
P.O. Box X
Oak Ridge, TN 37830

I. Spiwak
Oak Ridge National Laboratory (ORNL)
P.O. Box X
Oak Ridge, TN 37830

No. of
Copies

G. F. Deabeler
Philadelphia Electric Company
2301 Market Street
P.O. Box 8699
Philadelphia, PA 19101

K. Mahna
Public Service Electric and Gas
Company
80 Park Place
Newark, NJ 07101

R. R. O'Laughlin
Public Service Indiana
1000 East Main Street
Plainfield, IN 46168

W. R. Harris
Rand Corporation
1700 Main Street
Santa Monica, CA 90406

J. A. Lindberg
Sandvik Special Metals Corporation
P.O. Box 6027
Kennewick, WA 99336

P. Morris
Scandpower, Inc.
Suite B2
Triangle Towers
4853 Cordell Avenue
Bethesda, MD 20014

E. T. Rumble
Science Applications, Inc.
2680 Hanover Street
Palo Alto, CA 94304

E. Straker
Science Applications, Inc.
8400 Westpark Drive
McLean, VA 22101

D. Cubicciotti
Stanford Research Institute
333 Ravenswood Avenue
Menlo Park, CA 94025

No. of
Copies

No. of
Copies

A. Miller
Stanford University
Building 500
Stanford, CA 94305

D. Bell
Tennessee Valley Authority
1300 Commerce Union Bldg
Chattanooga, TN 37401

R. J. Mullin
Tennessee Valley Authority
1410 Commerce Union Bank Bldg
Chattanooga, TN 37401

J. D. Robertson
Tennessee Valley Authority
403 Power Building
Chattanooga, TN 37401

D. R. Olander
University of California, Berkeley
College of Engineering, Department
of Nuclear Engineering
Berkeley, CA 94720

D. R. Edwards
University of Missouri, Rolla
Building T-4
Rolla, MO 65401

H. M. Ferrari
Westinghouse Electric Corporation
Box 355
Pittsburgh, PA 15230

W. Jacobi
Westinghouse Electric Corporation
Box 355
Pittsburgh, PA 15230

R. S. Miller
Westinghouse Electric Corporation
Box 355
Pittsburgh, PA 15230

R. M. Grube
Yankee Atomic Electric Company
20 Turnpike Road
Westboro, MA 01581

DOE Richland Operations Office

H. E. Ransom

Hanford Engineering Development
Laboratory

R. Omberg

Washington Public Power Supply
System

D. L. Larkin
D. L. Renberger

INTERNAL

3 Consumers Power Company

W. J. Beckius
D. P. Blanchard
F. W. Buckman
R. B. DeWitt
G. F. Pratt (2)
Library
Records File

35 Exxon Nuclear Company, Inc.

L. P. Bupp
G. J. Busselman
M. H. Campbell
D. L. Cornell
C. E. Crouthamel (10)
P. L. Farnsworth
J. W. Fredericks
K. P. Galbraith
W. L. Hampson
O. L. Kruger
K. R. Merckx
W. S. Nechodom
R. Nilson
J. F. Patterson
R. K. Robinson
P. G. Sarafian
G. A. Sofer
L. Van Swam
R. C. Vogel

No. of
Copies

R. K. Welty
H. E. Williamson
K. E. Willis
K. N. Woods
Records File
Library

28 Pacific Northwest Laboratory

W. J. Bailey
J. O. Barner
D. W. Brite
L. R. Bunnell
T. D. Chikalla
E. L. Courtright
M. D. Freshley (5)
R. J. Guenther
C. R. Hann
P. E. Hart
R. P. Marshall
C. L. Mohr
F. E. Panisko
P. J. Pankaskie
R. E. Schreiber
S. R. Wagoner
R. D. Widrig
Publishing Coordination (2)
Technical Information Files (5)