Fuel Performance Improvement Program

**Quarterly/Annual
Progress Report**

**October 1977 -
September 1978**

**Consumers
Power
Company**

**EXXON NUCLEAR
COMPANY, Inc.**

Pacific Northwest Laboratory

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FUEL PERFORMANCE IMPROVEMENT PROGRAM

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**October 1977 -
September 1978**

Compiled by C. E. Crouthamel

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

October 1978

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

SUMMARY

This quarterly/annual report reviews and summarizes the activities performed in support of the Fuel Performance Improvement Program (FPIP) during Fiscal Year 1978 with emphasis on those activities that transpired during the quarter ending September 30, 1978. As a result, some of the material has been reported in more detail in previous quarterly reports. However, this report is intended to provide an overall perspective of the FPIP activities during the year.

Significant progress has been made in achieving the primary objectives of the program, i.e., to demonstrate commercially viable fuel concepts with improved fuel — cladding interaction (FCI) behavior. This includes out-of-reactor experiments to support the fuel concepts being evaluated, initiation of instrumented test rod experiments in the Halden Boiling Water Reactor (HBWR), and fabrication of the first series of demonstration rods for irradiation in the Big Rock Point Reactor (BRPR). More summary details for each task are provided as follows:

Task 1 - Assess Fuel — Cladding Interaction (FCI) State-of-the-Technology and Potential Improved Concepts

Two topical reports were published: "State-of-the-Technology Review of Fuel — Cladding Interaction" and "Assessment of Fuel Concepts."

Task 2 - Testing and Demonstration Program

The FPIP activities are being focused on what is considered to be an optimized FCI-remedy fuel design capable of achieving high burnup, i.e., annular pellets with coated cladding and pressurization. The packed-particle (sphere-pac pressurized) fuel design (considered to be a back-up optimized design concept) is also being evaluated as part of this program.

In addition, an adjunct program involving the irradiation of lead demonstration assemblies in the Big Rock Point Reactor, a large BWR, and a large PWR is being considered as a supplement to the FPIP. The lead assemblies are currently planned to incorporate the optimized annular-coated-pressurized and sphere-pac designs and would be designed to achieve extended burnup, i.e.,

bundle average as high as 33 GJ/kg (38 GWd/MTM), in order to demonstrate the commercial viability of the optimized design before proceeding on a commercial reload scale. These lead assemblies will be part of a supplemental program with selected rods for ramping tests at high burnup being supplied by FPIP.

Task 2A - Out-of-Reactor Experiments

Activities have focused on evaluating and qualifying graphite coatings for the Halden test rods and the BRPR demonstration irradiations. The major concerns were reducing and controlling moisture content and pickup, abrasion and wear characteristics, and application techniques. Dag 154, which was used for coating the inside surface of the Halden cladding tubes, was replaced by Dag 4 for the BRPR demonstration rods because the latter exhibits significantly better abrasion and wear characteristics.

An evaluation was made to determine the feasibility of utilizing out-of-reactor tests to develop predictive capabilities which describe the in-reactor FCI performance of the different fuel designs.

Task 2B - In-Reactor Experiments

Fabrication of the twelve test rods and six spare rods for the HBWR Series H-1 loading of the IFA-518 test rig was completed and the rods were shipped to Halden, Norway on April 30, 1978. Irradiation of the instrumented rods is proceeding satisfactorily and peak burnups of 268 GJ/kg (3100 MWd/MTM) have been achieved. Central fuel temperatures in the different fuel types are being monitored as well as cladding elongation and internal rod pressure. After achieving about 860 GJ/kg (10000 MWd/MTM), the rods will be ramp tested in the HBWR.

Task 2C - In-Reactor Demonstrations

One hundred and forty-three rods (103 fuel-length, 24 segmented, and 16 fully characterized standard reference) of different types were fabricated for the BRPR Series S-1 demonstration irradiations. The rod designs included annular-coated-pressurized fuel rods, considered to be the optimized FCI-remedy design.

Task 2E - Sphere-Pac Loading and Engineering Tests

Oak Ridge National Laboratory is preparing UO_2 microspheres for the sphere-pac fuel that will be irradiated as part of the HBWR H-2 and BRPR S-2 irradiations.

Task 3 - Performance Evaluations

The preirradiation data requirements for the Task 2B Halden experiments and the Task 2C BRPR demonstration irradiations were finalized and included as part of the fabrication and characterization procedures.

The in-reactor instrumentation on the Halden test rods is providing comparative performance data on the different fuel types. Central fuel temperatures at comparable heat ratings show that, as expected, the temperatures are lowest in the annular pellet design and highest in the vipac fuel. Graphite coating on the inside cladding surface increases central fuel temperature by about 100°C at a linear heat rating of about 42 KW/m. Elongation sensors showed that FCI occurred during the initial startup of the vipac fuel rods and essentially disappeared on subsequent startups. Interaction has not yet occurred in any of the pellet fuel designs.

Task 4 - Establishment of Technical Bases

The automated performance file generation procedure has been applied on several fuel bundles previously irradiated in BRPR.

The thermal-mechanical technical bases are being applied to actual design evaluations for annular fuel.

CONTENTS

SUMMARY	iii
LIST OF FIGURES	ix
LIST OF TABLES	xii
GLOSSARY	xv
1.0 INTRODUCTION	1
1.1 Program Objectives	1
1.2 Background	1
1.3 Program Description	1
1.4 Program Organization	1
2.0 TASK 1 - ASSESS FUEL-CLADDING INTERACTION STATE-OF-THE- TECHNOLOGY AND POTENTIAL IMPROVED CONCEPTS	3
3.0 TASK 2 - TESTING AND DEMONSTRATION PROGRAM	5
3.1 Test Program Overview	5
4.0 TASK 2A - OUT-OF-REACTOR EXPERIMENTS	9
4.1 Coating Studies	9
4.2 Mechanistic Studies	28
5.0 TASK 2B - IN-REACTOR EXPERIMENTS	33
5.1 In-Reactor Experiment Summary	33
5.2 Summary Description of HBWR Series H-1 Screening Test	34
5.3 Design and Analysis - HBWR Series H-1	37
5.4 Process Development - HBWR Series H-1	52
5.5 Fabrication - HBWR Series H-1	64
5.6 Irradiation Status - HBWR Series H-1	71
5.7 Summary Description of Primary Ramping Tests	73
5.8 Performance Predictions	75
6.0 TASK 2C - IN-REACTOR DEMONSTRATIONS	81
6.1 Design and Analysis - BRPR Series S-1	81
6.2 Process Development - BRPR Series S-1	104
6.3 Fuel Rod Fabrication - BRPR Series S-1	107

7.0	TASK 2E - SPHERE-PAC LOADING AND ENGINEERING TESTS	115
8.0	TASK 3 - FUEL PERFORMANCE EVALUATIONS	121
8.1	General Activities	121
8.2	HBWR Series H-1 Performance	122
9.0	TASK 4 - ESTABLISHMENT OF TECHNICAL BASES	131
9.1	Technical Bases Documentation	131
9.2	Technical Bases Data	133
9.3	Performance Files	134
APPENDIX A	- CHARACTERIZATION REQUIREMENTS FOR HBWR SERIES H-1 FUEL RODS	135
APPENDIX B	- CHARACTERIZATION REQUIREMENTS FOR BRPR SERIES S-1 FULL-LENGTH CHARACTERIZED, DEMONSTRATION FUEL RODS AND SEGMENTED FUEL RODS	144
APPENDIX C	- CONVERSION TABLE FOR SI UNITS	153

LIST OF FIGURES

1.1	Program Organization of the Fuel Performance Improvement Program	2
4.1	SEM Micrographs Comparing the As-Deposited Surface of Dag 154 and Dag 4	11
4.2	Thermal Conductivity of Dags 4 and 154, over the Range of Interest	12
4.3	Schematic Diagram Showing Two Versions of the Flood Coater	13
4.4	Coating Thickness vs. Solids Content for Dag 154 and Dag 4	14
4.5	Measured Coating Thickness Profiles for Six Randomly Selected Coated Tubes for BRPR Series S-1	15
4.6	Calculated Diffusion of Carbon into Zirconium and Zircaloy-2 after 30,000 Hours at 400°C	20
4.7	(a) Zircaloy Control Sample and (b) Graphite-Coated Zircaloy Cladding, Both Heated to 600°C/37 Hours	22
4.8	Schematic Diagram of Friction Testing System	23
4.9	Plot Showing Results of 400°C Dry Inert Gas Push-Through Friction Tests	24
4.10	Schematic Representation of the Oxidation Cleavage of Polydimethylsiloxane	26
4.11	Conceptual Design of the FCI-Simulator	31
5.1	Reference Fuel Rod Assembly	41
5.2	Annular Pellet Fuel Rod Assembly	42
5.3	Annular-Coated Fuel Rod Assembly	43
5.4	Vipac Fuel Rod Assembly	44
5.5	Reference Fuel Rod Assembly (Thermocouple)	45
5.6	Annular Pellet Fuel Rod Assembly	46

5.7	Annular-Coated Fuel	47
5.8	Vipac Fuel Rod Assembly (Thermocouple)	48
5.9	Reference Fuel Pellet	49
5.10	Annular Fuel Pellet	50
5.11	Vipac Rod No. 16, Density vs. Length	56
5.12	Vipac Rod No. 17, Density vs. Length	57
5.13	Vipac Rod No. 18, Density vs. Length	58
5.14	Deformed Zircaloy Cladding for Test Rod Configuration	61
5.15	Hydride Layer in Deformed Region of Test Rod No. 29	61
5.16	Hydride Layer in Crack of Test Rod No. 29	63
5.17	Electrolytically Charged Hydride Layer on Zircaloy Cladding	63
5.18	Slight Evidence of Hydride Layer in Test Rod No. 12	64
5.19	IFA-518 Lower Cluster Loading Map, as Viewed from Above	74
5.20	IFA-518 Upper Cluster Loading Map, as Viewed from Above	74
6.1	Reference Fuel Pellet	83
6.2	Annular Fuel Pellet	84
6.3	Reference Fuel Demonstration Rod	88
6.4	Annular Pellet Demonstration Rod	89
6.5	Annular-Coated Demonstration Rod	90
6.6	Annular-Coated Pressurized Demonstration Rod	91
6.7	Vipac Pressurized Demonstration Rod	92
6.8	Reference and Coated Segmented Fuel Rod Assembly	95
6.9	Reference and Pressurized Segmented Fuel Rod Assembly	96

6.10	Annular Pellet Segmented Fuel Rod Assembly	97
6.11	Annular-Coated Segmented Fuel Rod Assembly	98
6.12	Annular-Coated-Pressurized Segmented Fuel Rod Assembly	99
6.13	Vipac Segmented Fuel Rod Assembly	100
6.14	BRPR Series S-1 Demonstration Fuel Assemblies. G-419 and G-420	102
6.15	BRPR Series S-1 Demonstration Fuel Assemblies. G-421 and G-422	103
7.1	Fuel Rod Loading Vibrator Assembly for Sphere Pac	120
8.1	Comparison of Fuel Centerline Temperatures in Pelletized Rods in IFA-518 During the Second Startup	124
8.2	Comparison of Fuel Centerline Temperatures in Vipac Rods in IFA-518 During Second Startup	125
8.3	Rod Elongation in Lower Cluster Rods of IFA-518 During Initial Startup	127
8.4	Comparison of Fuel Rod Elongation in Vipac Fuel Rods During Several Startups	129

LIST OF TABLES

3.1	Big Rock Point Reactor Series S-1 Matrix	7
4.1	Summary of Analytical Data for Dag 154 and Dag 4	10
4.2	Water and Calculated Hydrogen Contents of Dags Outgassed under Various Conditions	16
4.3	Water Contents of Outgassed Dags as a Function of Atmosphere Exposure	17
4.4	Water Contents of Dag 4 Exposed in Blanked Tubes	18
4.5	Effect of Short Air Exposures on Water Analysis Results, Dag 4	18
4.6	Calculated Diffusion Coefficients	19
4.7	Conditions and Results of Capsule Experiments	21
4.8	Thermodynamic Reaction Probability of Various Compounds with MoS ₂ at Room Temperature	28
5.1	HBWR Series H-1 Test Matrix and Rod Instrumentation	36
5.2	Characteristics of HBWR Series H-1 Test Rods	38
5.3	Pellet Sinterability Tests Using ORNL 11% Enriched Powder	54
5.4	HBWR Vipac Test Rod Process Development Parameters	55
5.5	Characteristics of the Test Rods Used to Evaluate the Effects of Moisture on Coated and Noncoated Cladding	60
5.6	Moisture/Dag-154 Coating Compatibility Test	62
5.7	HBWR Series H-1 Pellet Lot Designations	66
5.8	Description of Fuel Rods Fabricated for the HBWR Series H-1 Test	67
5.9	Summary of Rod Conditions as Observed Radiographically	69
5.10	Vipac Fuel Density Measurements for HBWR Series H-1 Rods	72

5.11	Design Parameters for the Fuel Types Analyzed	77
5.12	TRUMP Predictions of the Effect of the Presence of a Thermocouple on the Temperatures for the Four Fuel Types	78
5.13	GAPCON-THERMAL-3 Predictions of Centerline Temperatures in Reference and Vipac Fuel	79
6.1	Characteristics of BRPR Series S-1 Full-Length Demonstration Fuel Rods	85
6.2	Characteristics of BRPR Series S-1 Segmented Fuel Rods	93
6.3	BRPR Series S-1 Sinterability Test Data	105
6.4	BRPR Series S-1 Preproduction Sintering Data	106
6.5	BRPR Series S-1 Vipac Process Development Data	108
6.6	BRPR Series S-1 Demonstration Fuel Rods	110
6.7	BRPR Series S-1 Fuel Rod Serial Numbers	111
6.8	BRPR Series S-1 Vipac Rod Fabrication Parameters	112
7.1	UO ₂ Microsphere Size Fraction	115
7.2	Sphere-Pac Needs for FPIP	116
7.3	Density Comparison for Sphere-Pac Rods	118

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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 shrouds, 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.
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 concerns in both BWR and PWR light-water reactor fuel performance have been discussed in previous quarterly reports^(1.1, 1.2).

1.3 Program Description

The program description and history have been documented in the previous quarterly reports^(1.1, 1.2) 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). The U.S. Department of Energy's (DOE's) prime contractor for the program is CPC; 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 the performance of the research and development portion of the program and the scientific 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

REFERENCES

- 1.1 "Fuel Performance Improvement Program, Quarterly/Annual Progress Report, April-September 1977," C00-4066-4, November, 1977.
- 1.2 "Fuel Performance Improvement Program, Quarterly Progress Report, October-December 1977," C00-4066-5, January, 1978.

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 the Task 1 activity is 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. The state-of-the-technology review presents a summary of postulated fuel — cladding interaction mechanisms as reported in the open literature. Those concepts that will be investigated as part of this program and the technical bases which support their selection are presented in the assessment report.

With the completion of the topical report entitled, "State-of-the-Technology Review of Fuel — Cladding Interaction" (C00-4066-2/PNL-2488), and the inclusion of review comments and completion of the report entitled, "Assessment of Fuel Concepts" (C00-4066-3/PNL-2490), activities associated with this task are considered to be completed. The conclusions presented in these two reports were reported previously^(2.1).

REFERENCES

- 2.1 "Fuel Performance Improvement Program, Quarterly Progress Report, January-March 1978," C. E. Crouthamel, C00-4066-6, April, 1978.

3.0 TASK 2 - TESTING AND DEMONSTRATION PROGRAM

M. D. Freshley (Pacific Northwest Laboratory)

3.1 Test Program Overview

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 BRPR demonstration irradiations. Task 2B involves an in-reactor testing program that consists of screening tests conducted in the HBWR, which includes 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 sol-gel — derived microspheres and process development for the loading of sphere-pac fuel rods to be irradiated in the HBWR and BRPR.

Annular, coated-cladding and packed-particle fuel were selected for investigation as the basic fuel concepts deemed to have potential for improved power-maneuvering capability. Selection of these concepts for the first phase of the evaluations is based on the results from the Task 1 state-of-the-technology evaluation, concepts that do not represent a significant departure from commercial technology, and existence of an adequate data base to facilitate application.

The concepts included in the fuel designs for initial screening tests in the HBWR include a combination of the following fuel types:

- reference
- annular
- annular-coated
- packed-particle (vipac).

Pressurization has been reported to significantly benefit reduction of fuel — cladding interaction (FCI) effects and is not considered to be a major departure from current technology. Therefore, pressurization with 400-500 kPa of helium in combination with the annular-coated and reference fuel designs is being evaluated. Pressurization will be a standard part of the packed-particle design.

Currently, the annular-coated-pressurized design is designated as the optimized FCI-remedy fuel design and the Program's activities will focus on developing this design concept. Those parameters that are believed to provide significant improvement in fuel performance have been incorporated into this design concept. Because of the significant potential of the packed-particle fuel design and, in particular, the sphere-pac design as an FCI-remedy, this concept will be developed as a back-up optimized design as part of this program.

The BRPR S-1 test matrix (Table 3.1) was expanded to include the optimized FCI-remedy fuel design with the capability of achieving high burnup, i.e., annular-coated-pressurized. The BRPR S-1 matrix includes the 16 additional nonchamfered "product line" rods that will receive equivalent characterization; it consists of 143 rods, 24 of which are segmented. After irradiation in the BRPR, selected segmented rods or rodlets will be ramp tested in a suitable test reactor.

In addition, an adjunct program involving the irradiation of lead demonstration assemblies in the BRPR, a large BWR, and a large PWR is being considered as a supplement to the FPIP. As currently planned, the lead assemblies will consist of the optimized annular-coated-pressurized and

TABLE 3.1. Big Rock Point Reactor Series S-1 Matrix

Fuel Form	Parameters		Full-Length Rods	Segmented Rods ^(a)	
	Coated	Pressurized			
Vipac	No	Yes	15	4	[4] ^(c)
Annular	Yes	Yes	24	4	[4]
	Yes	No	20	4	[4]
	No	No	20	4	[4]
Reference	Yes	No	-	-	[4]
	No	Yes	-	-	[4]
	No	No	24 ^(b)	8	-
			103	24	[24]

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

(b) An additional 16 non-chamfered "product-line" rods received equivalent characterization. All other pellets are chamfered.

(c) Lower segment rodlets are nonpressurized.

sphere-pac FCI-remedy designs and would be designed to achieve extended burnup, i.e., bundle average as high as 33 GJ/kg (38 GWd/MTM), in order to demonstrate the commercial viability of the optimized design before proceeding on a commercial batch load scale. These lead assemblies will be part of a supplemental program with selected rods for ramping tests at high burnup being supplied by FPIP.

Coordination of subtask activities is continuing in order to maintain scheduled progress. With the completion of the instrumented test rods for the HBWR H-1 test, attention was focused on the fabrication of the BRPR S-1 demonstration rods. Now that that task has been completed, attention is being directed toward fabricating the instrumented rods for the HBWR H-2 and H-3 test series.

Because sol-gel spheres were not available for use in the initial packed-particle fuel rods for this program, high-density feed material was produced for vipac fuel by high energy pneumatic impaction (Dynapak).

Depleted UO_2 was dynapaked to investigate the effect of different processing parameters on particle shape. These parameters included different techniques to remove the compacted material from the cans, preslugging and granulation prior to compaction, and a modified loading technique of the cans. These techniques have resulted in the production of more regular-shaped particles with less lamination and a particle size distribution that is more suitable for vibrational compaction.

TABLE 3.1. Big Rock Point Reactor Series S-1 Matrix

Fuel Form	Parameters		Full-Length Rods	Segmented Rods ^(a)	
	Coated	Pressurized			
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	No	No	20	4	[4]
Reference	Yes	No	-	-	[4]
	No	Yes	-	-	[4]
	No	No	24 ^(b)	8	-
			103	24	[24]

- (a) Number of segmented rods (each consisting of three rodlets) and the number of middle segment rodlets for ramp testing. Numbers in brackets [ ] are lower segment rodlets and are considered to be spares. Top segment rodlets all contain reference pellets.
- (b) An additional 16 non-chamfered "product-line" rods received equivalent characterization. All other pellets are chamfered.
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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 minimize fuel — cladding interaction (FCI) failures, and improve fuel performance. During FY-1978, most of the effort was directed toward qualifying, characterizing, and providing process assistance to ENC for two types of graphite dag coating materials, one of which was used to coat the inside surface of cladding for the HBWR Series H-1 test rods and the other in the BRPR Series S-1 demonstration rods. Some laboratory work was also done on siloxane compounds as coating materials, as well as literature work on MoS_2 .

An analysis was completed of previously published data related to modeling of the case in which cladding is nonuniformly strained over pellet — pellet interfaces or cracked pellets. An apparatus was designed to simulate most of the in-reactor environment considered relevant to FCI, e.g., localized asymmetric mechanical loading and stress-corrodants.

4.1 Coating Studies

4.1.1 Dag Characterization

Two graphite dags were chosen for coating the inside surface of zircaloy cladding tubes used in the irradiation program. Both dags were produced by Acheson Colloids Corp., Port Huron, MI. The first of these, designated Dag 154, used an isopropanol vehicle and contained a thermoplastic resin binder. The only major problem encountered with this dag for this application was that in order to lower the hydrogen content to acceptable levels, the outgassing treatment ($425^\circ\text{C}/24 \text{ hr}$ at $P < 1.3 \times 10^{-2} \text{ Pa}$) carbonized the binder. This produced only a weak bond between the graphite flakes and the zircaloy cladding surface. Considerable care had to be exercised during pellet loading to avoid abrading portions of the coating. The improved dag, designated as Dag 4, utilizes a water vehicle. Dag 4 contains the alumina and silica in

gel form and forms a much more abrasion-resistant layer on the cladding. Table 4.1 summarizes analytical data pertaining to the two outgassed dags. Both materials are quite pure and do not contain quantities of halides that would be objectionable for reactor use. This is especially true considering the small quantities of material involved in the coatings (a full-length BRPR cladding coated with a 6 μm layer of Dag 4 would contain only 0.55 g of graphite).

TABLE 4.1. Summary of Analytical Data for Dag 154 and Dag 4

A. Spectrochemical

Element	Content, ppm	
	Dag 154	Dag 4
Al	5	>50,000
Ba	--	50
Ca	100	500
Cr	--	1
Cu	--	1
Fe	200	200
Mg	3	50
Mn	2	50
Na	100	1,000
Si	10	>30,000
Ti	--	1
V	--	50
Zn	--	1
Zr	--	1,000

B. Halide Analysis

F	9.5	50
Cl + other halides	62	717

The SEM photos (Figure 4.1) show the two dags in the as-outgassed condition. The graphite flakes in Dag 154 tend to lie parallel to the tubing surface, whereas the Dag 4 flakes are much larger and are more randomly

FIGURE 4.1. SEM Micrographs Comparing the As-Deposited Surface of Dag 154 and Dag 4. (The circled area is high in alumina.)

oriented. The alumina and silica in Dag 4 are amorphous as indicated by x-ray analysis and are apparently in a gel state.

A plot of thermal conductivity for the two dags, calculated from thermal diffusivity values as determined by the laser-pulse method, is shown in Figure 4.2. In both cases the conductivity is sufficiently high as to cause no significant increase in temperature drop across the fuel — cladding gap. The conductivity of Dag 4 is higher by a factor of ~ 3 , probably because of its higher density and the fact that the more random orientation of its crystallites exposes more of the high-conductivity directions of the crystallites with the heat flow path.

FIGURE 4.2. Thermal Conductivity of Dags 4 and 154, Over the Range of Interest

4.1.2 Application Techniques and Thickness Control

The basic method used to apply the graphite dags is flood coating, in which the inner tubing surface is thoroughly wetted by a dag supply retained above a silicone rubber dam, and then allowed to drain freely. By proper control of the dag's solids content, coatings can be applied to quite reproducible thicknesses. Figure 4.3 shows two modifications of the flood coating technique. The Mark 1 version was used on coatings for HBWR H-1 cladding tubes, while the Mark 2, using a magnetically coupled dam, was used for the BRPR S-1 cladding. The Dag 154 used for HBWR cladding was applied

MARK I DAG COATER

MARK II DAG COATER

FIGURE 4.3. Schematic Diagram Showing Two Versions of the Flood Coater

in two coats because it was felt that this technique would result in a better quality coating than a single application. The Dag 4 did not overcoat as well, so it was applied in a single pass. In both cases, the solids content necessary to produce the specified thickness ($6.4 \pm 4.0 \mu\text{m}$) was determined experimentally by coating tubes that were closely measured by air gauging, and then remeasuring them to determine coating thickness. Thickness/solids-content plots for the two dags are shown in Figure 4.4. Thickness, in the range of interest, is a fairly steep function of solids content in both cases, perhaps more so for Dag 4. Some difficulties in controlling thickness were experienced during the BRPR S-1 fabrication, e.g., coatings tended to be too thick when applied at a 14% solids level. The data for Dag 4 shown in Figure 4.4 are the result of a more recent determination; apparently the dag has aged in the 5 months since the original work was performed and its coating characteristics have changed. Thickness control problems will hopefully be remedied before the next fabrication campaign.

The thickness of the Dag 4 coatings produced was very consistent when applied within acceptable ranges. Thickness profiles for six rods

FIGURE 4.4. Coating Thickness vs. Solids Content for Dag 154 (two coats) and Dag 4 (one coat)

selected at random from a coating batch are shown in Figure 4.5. Both the end-to-end variation and scatter are considered small.

4.1.3 Outgas and Moisture Adsorption Studies

Because both of the graphite dags contain rather large quantities of hydrogen in the as-applied conditions, the coatings must be vacuum outgassed and must be kept in a dry environment during the subsequent handling operations to preclude resorption of water. To this end, a large amount of work was done to define the outgassing and handling procedures which would yield coatings with acceptably low moisture (hydrogen) contents. Table 4.2

FIGURE 4.5. Measured Coating Thickness Profiles for Six Randomly Selected Coated Tubes for BRPR Series S-1

summarizes the previous work performed on outgassing treatments. To avoid metallurgical modifications to the cladding during the outgassing treatment, the temperature was limited to $425^{\circ} \pm 25^{\circ}\text{C}$ for 24 hr at a pressure of $<1.3 \times 10^{-2}$ Pa. The experiments bracketed these conditions. Table 4.2 generally shows expected trends in water content versus temperature and pressure. In all cases, the water content was determined by a "combustion" technique, in which a standard P_2O_5 water analyzer was used and the sample was heated to 800°C . Because free hydrogen would be undetected by this method, a Cu-CuO reaction tube was placed between sample and P_2O_5 cell to convert all H_2 to H_2O . Thus, all hydrogen contents listed in Table 4.2 are computed from the water contents. Hydrogen content to 1600°C has been

TABLE 4.2. Water and Calculated Hydrogen Contents of Dags Outgassed under Various Conditions

Dag Type	Outgas Conditions			Fuel Weight Basis, ppm	
	Temperature, °C	Time, Hr	Pressure, Pa	H ₂	H ₂ O
A. Experimental					
154	450	24	1.3×10^{-3}	0.2	1.6
154	400	24	1.3×10^{-3}	0.4	3.5
154	450	24	1.3×10^{-1}	0.4	3.1
154	400	24	1.3×10^{-1}	0.5	4.8
154	450	4	5.2×10^{-3}	0.4	3.5
154	400	4	1.3×10^{-3}	0.3	2.5
4	425	24	1.3×10^{-3}	0.5	4.4
B. HBWR Series H-1					
154	425 $\pm$ 25	24	1.3×10^{-2}	0.4	3.1
154	425 $\pm$ 25	24	1.3×10^{-2}	0.4	3.4
4	425 $\pm$ 25	24	1.3×10^{-2}	0.4	3.8

determined by vacuum extraction; it is <10% of the hydrogen originating from the water. Water content determined to 800°C thus provides a satisfactory indication of total hydrogen.

After outgassing, the dag-coated tubes must be kept in a dry atmosphere or substantial water sorption will occur; this was especially true with Dag 4. Several experiments involving exposure of dags to known atmospheres were performed to evaluate the sorption characteristics, particularly because the fabrication process for BRPR fuel required exposing a coated tube to room air for a few seconds prior to welding. The results of these experiments, summarized in Table 4.3, indicate that rather high water contents can be attained in relatively short times. However, the results were biased high because the graphite samples used for analysis were exposed to atmospheric circulation; whereas a coated tube has a length/diameter ratio which precludes

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154	400	24	1.3×10^{-3}	0.4	3.5
154	450	24	1.3×10^{-1}	0.4	3.1
154	400	24	1.3×10^{-1}	0.5	4.8
154	450	4	5.2×10^{-3}	0.4	3.5
154	400	4	1.3×10^{-3}	0.3	2.5
4	425	24	1.3×10^{-3}	0.5	4.4
B. HBWR Series H-1					
154	425 $\pm$ 25	24	1.3×10^{-2}	0.4	3.1
154	425 $\pm$ 25	24	1.3×10^{-2}	0.4	3.4
4	425 $\pm$ 25	24	1.3×10^{-2}	0.4	3.8

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TABLE 4.3. Water Contents^(a) of Outgassed Dags as a Function of Atmosphere Exposure

Graphite Type	As-Outgassed	Glove Box @ 20 ppm H ₂ O			15 min in Glove Box @ 1 min air, 5 min air, 60 ppm H ₂ O 52% R.H. 52% R.H.		
		15 min	1 hr	24 hr			
Dag 154	1.4	1.6	2.2	3.0			
Dag 4	4.4	6.0	4.1	9.1	8.1	8.5	9.2

(a) All water contents are expressed in parts per million on a fuel weight basis. All dags outgassed 425°C/24 hr at $P < 1.3 \times 10^{-3}$ Pa.

rapid exposure to circulated air, especially when the density of the gas contained is the same as that of the surrounding gas. Accordingly, some tube segments containing -40 mesh graphite dag powder with an end cap welded on one end, were exposed to various atmospheres after outgassing. Table 4.4 summarizes results of the analyses that were obtained by using this more prototypic technique. These exposure conditions indicate much lower water content and were the basis for the technique used during the BRPR fabrication; short tube sections (46 cm) were used as carrier tubes for a -40 mesh analytical-control dag sample. The contents of one tube were analyzed in the as-outgassed condition to show that the outgassing treatment was satisfactory and another tube was capped and was carried along with the batch of coated tubes (ca. 20 tubes) through the fuel rod fabrication while being subjected to the same conditions. This dag was then analyzed to determine the in-process water pickup. The water analysis performed by the combustion method was originally done in a laboratory using a technique that involved a short (7 sec) reproducible air exposure during sample transfer. This resulted in a bias that did not create a problem with Dag 154 because of its low water sorption characteristics. However, Dag 4 was another matter, and the need for a 95/95 statistical basis required both low water contents and low standard deviations. Early analytical results for BRPR S-1 indicated that on a 95/95 basis, the water content in Dag 4 was rather marginal and, in some cases, unacceptable. The specified limits for BRPR S-1 permitted 1 ppm H₂O contained in the coating. At this time, an ENC water analysis facility was activated: it was totally enclosed and involved no open-air transfers.

TABLE 4.4. Water Contents of Dag 4 Exposed in Blanked Tubes

Exposure Conditions	Average Water Content, ppm	$\bar{x} + 4.2$, ppm ^(a)
As-outgassed, 425°C/24 hr at $P < 1.3 \times 10^{-2}$ Pa	3.8	7.1 ^(b)
15 min glove box ^(a) 20 ppm H ₂ O	3.6	5.6
Glove box exposure above +5 min air ^(a) 39% R.H.	3.8	5.6
Glove box exposure above +15 min air ^(a) 39% R.H.	3.6	5.4

(a) For a 95/95 statistical basis with quintuplicate samples, 4.2 times the standard deviation must be added to the average.

(b) High because of a single high data point which increased the standard deviation.

Table 4.5 summarizes some experimental results which indicate that the short air exposure caused a substantial bias. The ENC facility was used for all the BRPR S-1 analyses and results were well within specification.

TABLE 4.5. Effect of Short Air Exposures on Water Analysis Results, Dag 4(a)

Conditions	Water Content, ppm (fuel wt. basis)
Previous analytical source with 7 sec air exposure	4.2
ENC, no air exposure	1.9
ENC, 5-10 sec air exposure	3.0
ENC, 20 sec air exposure	8.8

(a) Outgassed 425°C/24 hr at $P < 1.3 \times 10^{-2}$ Pa.

4.1.4 Compatibility of Graphite with Zircaloy Cladding

Graphite coating materials would not be expected to diffuse significantly into zircaloy at the temperatures encountered during normal irradiation. However, because of the extended time--30,000 hr for four complete

cycles in BRPR at ca. 400°C--it was considered important to evaluate the compatibility of graphite coating with the zircaloy cladding. Available literature on carbon diffusion into zirconium and zircaloy^(4.1, 4.2) were collected. Extrapolation of the diffusion equation $D = D_0 e^{-Q/RT}$ (where both D_0 and Q have been experimentally determined for the range listed) to 400°C gives diffusion coefficients. These are summarized in Table 4.6.

TABLE 4.6. Calculated Diffusion Coefficients

Ref. No.	Temperature Range, °C	Diffusing Element	Solute	D_0 , cm ² /sec	Q , cal/mole	D , cm ² /sec (extrapolated to 400°C)
4.1	600-800	C ¹⁴	α-zirconium	3.5×10^{-5}	30,700	3.8×10^{-15}
4.2	600-850	C ¹⁴	α-zirconium	2×10^{-3}	36,200	3.5×10^{-15}
4.2	600-770	C ¹⁴	Zircaloy-2	1.4×10^{-3}	38,000	6.5×10^{-16}

By applying a standard Fick's law calculation, these values result in curves as shown in Figure 4.6. The values of C¹⁴ and C diffusion into α-zirconium from different sources are in excellent agreement. According to Reference 4.2, the slower diffusion in the zircaloy may be due to the stiffening of the zirconium lattice by the alloying elements. The results show that after 30,000 hours, the penetration depth of carbon in zircaloy to a concentration of ca. 100 ppm, is about 15 μm. The carbon content in zircaloy is normally ca. 100 ppm.

Carbon solubility (substitutional) in zirconium and its alloys is essentially nil because of the formation of ZrC (interstitial). Specifications for reactor-quality zircaloy tubing call for a maximum of 100 ppm C because C greatly reduces the corrosion resistance of zircaloy in hot acidic water. The presence of small amounts of carbon does not greatly influence the strength of zirconium and its alloys^(4.3, 4.4) and is not likely to cause a problem in this case.

In addition to the possibility of carbon diffusion, Dag 4 involves another potential compatibility problem caused by the possible reaction of the contained alumina and silica with the zircaloy. Thermodynamically,

FIGURE 4.6. Calculated Diffusion of Carbon into Zirconium and Zircaloy-2 After 30,000 Hours at 400°C

zirconium could reduce alumina at temperatures above ca. 800°C and silica at any temperature. The possibility of this reaction occurring at temperatures of interest (ca. 400°C) and at LOCA-type temperatures (ca. 1200°C) was examined experimentally. Results are summarized in Table 4.7. Figure 4.7 shows a pair of optical micrographs of control and graphite-coated specimens heated to 600°C/37 hr. No reaction zone is visible, and no aluminum or silicon was present as indicated by a thorough SEM-microprobe examination of the surface of the sample exposed at 1200°C. Apparently, kinetics are not sufficiently rapid to cause a significant reaction.

TABLE 4.7. Conditions and Results of Capsule Experiments

<u>Contents</u>	<u>Temperature/Time</u>	<u>External Appearance</u>	<u>Metallographic Results</u>	<u>SEM Results</u>
Empty (control)	600°C/37 hr	No change	No reaction	
Coated, UO ₂ pellet	600°C/37 hr	No change		No Al or Si in the area examined
Non-Coated, UO ₂ pellet	1200°C/4 sec	Capsule intact but bulged from pressure, large grains	No reaction layer (not sectioned adjacent to UO ₂)	
Coated, UO ₂ pellet	1200°C/4 sec	Capsule intact but bulged from pressure, large grains	No reaction layer (not sectioned adjacent to UO ₂)	No Al or Si in the coating/cladding interface area examined
Coated, UO ₂ pellet, 10 X normal amount of Dag 4	1200°C/4 sec	Capsule intact but bulged from pressure, large grains	No reaction layer (not sectioned adjacent to UO ₂)	
Empty (control)	485°C/100 hr	No change	No reaction	
Coated	485°C/100 hr	No change	No reaction	
Coated, 10 X normal amount of Dag 4	485°C/100 hr	No change	No reaction	

4.1.5 Friction and Wear of Graphite Coatings

Because reduction of pellet – cladding friction may be involved in the effectiveness of graphite coatings to improve FCI behavior, pellet – cladding frictional characteristics have been examined under fairly realistic and high load conditions using the apparatus shown in Figure 4.8. With this technique, the force required to push 25 μ m oversized pellets through a zircaloy tube was measured. Results of testing performed at 400°C with Dag 154 in a dry, Zr-gettered argon atmosphere are summarized in Figure 4.9. The coating decreased frictional forces, as well as preventing galling on the zircaloy surfaces. Dag 4 coated tubes produced equivalent results in room-temperature tests.

(a)

(b)

20 μ m

FIGURE 4.7. (a) Zircaloy Control Sample and (b) Graphite-Coated Zircaloy Cladding, Both Heated to 600°C/37 Hours

FIGURE 4.8. Schematic Diagram of Friction Testing System

Abrasion of the coating during pellet loading is a prime consideration with graphite coatings. Therefore, Dag 154 and Dag 4 were evaluated for durability by pushing 200 UO₂ pellets, five at a time, through outgassed tubes coated with one or the other type of dag. In the case of Dag 154, the coating was removed to bare metal in numerous locations as a result of this treatment, especially in the first 15 cm, before the train of pellets was properly aligned. The Dag 4 showed only a few scratches, none of them exposing bare metal, and no other visible damage. These results were one reason for selection of Dag 4 as the coating material.

A friction/wear testing apparatus was assembled which will be used to more quantitatively evaluate the two dags, as well as siloxanes. The apparatus is a fairly conventional pin-on-disc design, but is capable of testing to 400°C in vacuum or gettered inert atmospheres at high loads and low sliding speeds.

FIGURE 4.9. Plot Showing Results of 400°C Dry Inert Gas Push-Through Friction Tests. Both coated and uncoated tubes are shown. Shaded areas bounded all values measured, but each symbol refers to a separate tube and pellet.

4.1.6 Siloxane Coatings

Siloxane coatings applied to the inside surface of zircaloy cladding tubes have been shown by Canadian investigators^(4.5) to result in improved FCI behavior by preventing iodine SCC.

Siloxanes (polyorganosiloxanes) are a family of compounds based on a silicon-oxygen backbone with various organic radicals included via Si-C bonding. The family includes silicone fluids which may, in turn, be thickened into usable vacuum greases by the addition of extremely fine (100 Å) silica flour.

Siloxane compounds contain large quantities of hydrogen which must be removed to make the material useful as a coating on the inside surface of zircaloy cladding tubes. The original siloxane molecule must react with oxygen to eliminate the organic groups by oxidation cleavage. This process, as illustrated schematically in Figure 4.10, if allowed to proceed to completion at sufficiently high temperatures, yields only SiO_2 . The silica is brittle and the volume changes involved are sufficient to produce only a powdery residue instead of a coherent, protective coating. From a practical point of view, in order to prevent excessive oxidation of the zircaloy cladding that would interfere with the etching and autoclaving operations, siloxane oxidation temperatures are limited to the 300°-350°C region. A limited amount of laboratory work is proceeding on siloxane coatings derived from silicone fluids or vacuum greases. To date, the balance between processing conditions and final coating properties has been rather delicate; coatings achieved thus far are generally too soft or too brittle and nonadherent.

The incentive for further work is that Canadian experience with siloxanes continues to yield positive results^(4.6), with a growing base of irradiated fuel. A coating process developed by Dow Corning, Metal Surface Treatment, develops a protective, adherent film composed mainly of vitreous silica. This coating, which is applied at temperatures <200°C, is very resistant to abrasion and chloride corrosion when applied to aluminum, and also is reported to contain much less hydrogen. An initial evaluation of this material is being conducted.

4.1.7 Molybdenum Disulfide

Molybdenum disulfide was evaluated as a potential material for coating the inside surface of zircaloy cladding to improve FCI behavior. Considered strictly as a lubricant, MoS_2 will perform better than graphite in the dry atmosphere of a fuel pin^(4.7, 4.8) and MoS_2 is extremely stable.^(4.7) Free sulfur is not detected even when outgassing at 1000°C and free sulfur is not present in commercial MoS_2 . The element present in excess of stoichiometry is always Mo.

FIGURE 4.10. Schematic Representation of the Oxidation Cleavage of Polydimethylsiloxane

The effect of radiation on solid lubricants is difficult to assess due to the very difficult task of evaluating friction and characteristics under reactor conditions. Specimens friction tested under static conditions after exposure to radiation levels of $3 \times 10^{16} \text{ n/cm}^2$ ($E > 1.0 \text{ MeV}$) showed no discernable effects of radiation on either graphite or MoS_2 coatings. (4.9) In dynamic friction testing during radiation exposure, a mixed coating composed of both substances showed that high fluxes increased friction more than the equivalent fluence delivered at lower flux. (4.10)

Neutron irradiation to 3.66×10^{20} n/cm² in a noncharacterized reactor flux affected pellets of graphite and MoS₂ differently.^(4.11) X-ray powder patterns showed marked changes in the lattice spacings of graphite in an experiment where the specimen temperature reached 500°C. In contrast, MoS₂ having the same radiation exposure and thermal history showed barely perceptible changes in lattice spacings. This is the highest reported radiation exposure of MoS₂. The graphite results show excellent agreement with other reported graphite radiation experience.^(4.12) By use of the computer code ORIGEN^(4.13), only innocuous transmutation products were found to result from the irradiation of MoS₂ in a fuel rod.^(4.14)

One of the more attractive features of using MoS₂ is that a dense, adherent coating might be built up by burnishing MoS₂ into the zircaloy surface, possibly to a thickness of 5 μm.^(4.15) Thermodynamic calculations indicate that MoS₂ will react with various fission product species as summarized in Table 4.8. No data were available on complex reaction products such as molybdates or intermediate reaction products such as MoOS. MoS₂, like graphite, also forms intercalation compounds.^(4.16) Some intercalation compounds reported in the literature include:

There is no precedent for the use of MoS₂ as a pellet-cladding lubricant in a fuel rod. Even though the MoS₂ would be very dispersed, sulfide contaminants in a reactor coolant system could not be tolerated because of possible problems related to corrosiveness; especially in the case of Inconel components. Because of this consideration, MoS₂ will not be given further consideration for use in this program.

TABLE 4.8. Thermodynamic Reaction Probability of Various Compounds with MoS₂ at Room Temperature

<u>Species</u>	<u>Probability of Reaction</u>
CsO	Most likely
Zr	Very likely
CdO	Very likely
Cd	Very likely
Cs	Very likely
I	Possibly; literature contains wide range of opinions about possible formation of Mo iodides
CdI ₂	
CsI	
ZrO ₂	
ZrO ₂	Very unlikely
UO ₂	Very unlikely

4.2 Mechanistic Studies

Current studies of the FCI failure mechanisms, which have been performed at PNL, have concentrated on evaluating the results of existing experimental stress-corrosion-cracking (SCC) related experiments reported in the literature and, through stress analysis techniques, comparing them to mathematical models simulating pellet - cladding mechanical interaction. The objective of this effort is to determine how the reported ex-reactor mechanistic data relate to FCI loading conditions and to determine if these data are representative of crack initiation and growth behavior from LWR fuel failure analyses.^(4.17)

A secondary objective of this effort is to identify an out-of-reactor testing technique that could be used to evaluate, on a statistical basis, the existence of possible critical stress, strain, or strain rate thresholds for SCC. These thresholds would then be correlated with the in-reactor test results from this program and would provide a firm base for applying the FPIP data through fuel performance code analysis.

Finite element stress analysis models have been developed at PNL^(4.18) for the two experimental configurations reported by General Electric Company (GE)^(4.18, 4.20) and for two FCI configurations. The results of the analysis

of the GE experiments using plane strain specimens and simple tension specimens showed that significant bending moments were present that were not strictly typical of FCI conditions. Although bending is a major consideration, the bending gradients that were obtained in these tests were, in terms of the cladding/fuel geometry, generally in the opposite direction than what would be expected during FCI. These tests, however, were the most prototypic of fuel loading of any tests that were reviewed and provided the type of localized strain and a measure of the ductility that is close to that associated with cladding that lies over cracks that occur in the fuel. The PNL analysis also shows that the strain conditions that are found during the small initial strain period, which are characteristic of the crack initiation and growth phases, do not fall in either a plane strain or a plane stress category.

As a result of this analysis of the GE experiments, detailed finite element models of fuel-cladding interaction were developed to identify the major cladding deformation characteristics. A simple planar model was used initially while working on a comprehensive three-dimensional model that included pellet - pellet interaction loading. Both models included cracked fuel; the effects of friction, and typical thermal gradients.

The analytical results that were obtained indicated that circumferential strain ratios (cladding strain over cracked fuel regions divided by cladding strain over uncracked fuel regions) can be as much as 2.8 for coefficients of friction of 0.8. Through-wall normalized strain gradients, which are indicative of the degree of bending present, were as large as 1.2. The direction of the computed strain and stress gradients confirmed the aforementioned concerns about the GE experiments and indicate that, if texture and anisotropy are important during the crack initiation and growth phase, these parameters should be included in out-of-reactor simulations.

A similar analysis of fuel cladding deformation has been performed by Levy and Wilkinson.^(4.21) The stress/strain results that they reported are similar to those obtained in this study in terms of direction and distribution. They identified the existence of large bending gradients that are

related to the crack patterns and the frictional effects that are present. Their results showed high tensile hoop stresses on the cladding inside surface over the pellet-to-pellet interface regions with large axial tensile stresses over the pellet mid-regions.

The results of both the data analysis and analytical models indicate that the testing conditions for crack initiation should include the major stress gradients as well as environmental effects. The approximation of stress-corrosion-cracking (SCC) conditions used for threshold crack initiation evaluations should simulate as closely as possible the chemical, mechanical, and textural effects present in the cladding during FCI.

A detailed examination of finite element models and the experimental data indicate that an expanded-mandrel test of the type performed more recently at GE. (4.19,4.20) would provide a more representative stress state. However, the GE work is directed predominantly at evaluating the cracked-fuel pellet - cladding behavior at the pellet centerline, rather than over the pellet - pellet interface. Our analysis indicates that the most severe stress condition in the cladding is adjacent to the intersection of axial pellet cracks and pellet interfaces, which requires a different type of mandrel loading.

As a result of these evaluations, an alternate type of mandrel test has been conceptually designed that will permit the pellet - pellet interface loading to be modeled with cracked fuel. Figure 4.11 is a schematic of this concept. The apparatus makes it possible to identify the effects of coatings/barriers, atmosphere, fuel type, strain-rate, and cladding type, on SCC with an accurate read-out of pressure and strain. As shown in Figure 4.11, the cladding is loaded by a UO_2 annulus that becomes cracked as pressure is applied to the reusable tungsten segments. Provisions will be made to test at elevated temperature in the presence of iodine or cadmium and at relevant oxygen partial pressures. The FCI simulator will also be adaptable to accommodate sphere-pac fuel.

The tests with the FCI simulator will be focused at assessing the efficacy of the various FCI remedies being evaluated as part of this program. The

detailed out-of-reactor measurements possible with this apparatus should facilitate analysis of the in-reactor tests.

FIGURE 4.11. Conceptual Design of the FCI-Simulator.
(Axial loading can be added as an option.)

REFERENCES

- 4.1. A. I. Nakonechnikov and L. V. Pavlinov, "Diffusion of C in the Alpha Phases of Zirconium and Titanium," summarized in English in Diffusion Data, 6, 573 (1972).
- 4.2. R. P. Agarwala and A. R. Paul, "Diffusion of Carbon in Zirconium and Some of its Alloys," Journal of Nuclear Materials, 58, 25 (1975).
- 4.3. B. Lustman and F. Kerze, Jr., The Metallurgy of Zirconium, McGraw-Hill, p. 518 (1955).
- 4.4. Zirconium in Nuclear Applications, ASTM Special Technical Publication 551, 131 (1974).
- 4.5. A. S. Bain, J. C. Wood and C. E. Coleman, "Fuel Designs to Eliminate Defects on Power Increases," British Nuclear Soc., International Conference, October 15-19, 1973, London.
- 4.6. D. G. Hardy, J. C. Wood and A. S. Bain, "CANDU Fuel Performance and Development," presented at 18th Annual International Conference of the Canadian Nuclear Association, Ottawa, Canada, June 14, 1978.

- 4.7. W. O. Winer, "Molybdenum Disulfide as a Lubricant: A Review of the Fundamental Knowledge," Wear, 10, 422 (1967).
- 4.8. J. P. G. Farr, "Molybdenum Disulfide in Lubrication, A Review," Wear, 35, 1 (1975).
- 4.9. W. E. French, Radiation Effects on Lubricants for NERVA Application, TID/SNA-386 (5110-XLU07-W183-11), Aerojet-General (August 1970).
- 4.10. R. P. Jacobson, Dynamic Friction and Wear of a Solid Film Lubricant During Radiation Exposure in a Nuclear Reactor, NASA TN D-6940 (1972).
- 4.11. B. Daniel, Solid Film Lubricants for High Temperature Nuclear Environments, WADD TR 60-823, Part II (Sept. 1961).
- 4.12. E. R. Braithwaite, "Graphite and Molybdenum Disulfide," Nuclear Engineering, 2, 107 (1957).
- 4.13. M. J. Bell, ORIGEN, The ORNL Isotope Generation and Depletion Code, ORNL-4628 (1973).
- 4.14. C. E. Crouthamel, Fuel Performance Improvement Program, Quarterly Progress Report, Oct-Dec 1977, C00-4066-5 (Jan. 1978).
- 4.15. R. P. M. Johnston and A. J. W. Moore, "The Burnishing of Molybdenum Disulfide onto Metal Surfaces," Wear, 7, 498 (1964).
- 4.16. G. A. Tsigdinos, "The Properties and Structures of Inorganic Molybdenum-Sulfur Compounds," Bulletin Cab-17, Climax Molybdenum Co., Greenwich, CN.
- 4.17. D. S. Tomalin, "Localized Ductility of Irradiated Zircaloy-2 Cladding in Air and Iodine Environments," Zircaloy in the Nuclear Industry, A. L. Lowe and G. W. Parry (eds), ASTM STP 633 (August 1976).
- 4.18. P. J. Pankaskie, P. G. Heasler and C. L. Mohr, "PCI Fuel Failure Analysis," PNL 2755 (to be published).
- 4.19. H. S. Rosenbaum, "Demonstration of Fuel Resistant to Pellet-Cladding Interaction, First Semiannual Report, July-December 1977," GEAP-23773, February 1978.
- 4.20. D. S. Tomalin, R. B. Adamson and R. P. Gangloff, "The Performance of Irradiated Copper and Zirconium Barrier-Modified Zircaloy Cladding Under Simulated FCI Conditions," NEDO-12715, September 1978.
- 4.21. S. Levy and J. P. D. Wilkinson, "A Three-Dimensional Study of Nuclear Fuel Rod Behavior During Startup," Nuclear Engineering and Design, 29, (1974), pp. 157-166.

5.0 TASK 2B - IN-REACTOR EXPERIMENTS

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The objective of the in-reactor experiments task is to conduct irradiation tests to study the detailed behavioral characteristics and performance limits of those fuel concepts which have potential for improved operating behavior in LWR's. Comparative parametric fuel rod experiments are being performed with 1) a reference, solid, dished pellet design (reference), 2) an annular pellet design (annular), 3) the annular pellet design combined with a graphite coating on the inside surface of the cladding (annular-coated), and 4) packed-particle (vipac or sphere-pac) fuel designs. The performance characteristics of the improved concepts are being evaluated by means of screening tests which involve three sequential groups of power cycling/ramping irradiations in the Halden Boiling Water Reactor (HBWR). The results of these comparative irradiations will be utilized to select the most promising fuel concept for evaluation in the primary power-ramping experiments. The primary tests will utilize fuel rod segments that were 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 were presented in previous progress reports. (5.1,5.2) Summaries of the test descriptions and the status of the screening and primary test irradiations are presented below.

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 undished 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). Subsequent screening tests will incorporate a helium cover gas at an internal pressure of approximately 400 to 500 kPa in the annular-coated and packed-particle fuel designs; Dag-4 as the coating material for the annular-coated design; and sphere-pac fuel for the packed-particle design.

The initial BRPR Series S-1 demonstration irradiations include segmented rods or rodlets of (1) both the coated and noncoated reference designs, (2) both the pressurized and nonpressurized reference designs, (3) annular; annular-coated; and annular-coated-pressurized designs, and (4) both the pressurized and nonpressurized vipac designs. The coated rods in BRPR S-1 utilize Dag 4. The large number of combinations of the design parameters were included in BRPR S-1 in order to have available irradiated rodlets for the possible separation of the effects of individual and combined parameters, as may be required in the primary power-ramp tests. Subsequent demonstration irradiation series in BRPR will also include segmented rods for ramp testing. However, the number of individual designs will be reduced and sphere-pac fuel will be used in the packed-particle design.

5.2 Summary Description of HBWR Series H-1 Screening Test

The two 6-rod clusters in the HBWR test rig (IFA-518) will be 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 to 850 GJ/kg (8,000-10,000 MWd/MTM), the upper cluster will be moved to the lower position and six fresh rods will be inserted into the upper

position. After another two power cycles and accumulation of an additional 700 to 850 GJ/kg burnup, the lower cluster rods will be replaced by the upper rods, and six fresh rods will be inserted in the upper cluster position. This sequence will be repeated one more time. 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 to 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 to 1400 GJ/kg, and six rods will be ramped from the last upper cluster after 700 to 850 GJ/kg burnup for a total of 24 HBWR ramp tests.

Power control during cycling irradiation is being accomplished by movement of a silver absorber shield which alternates position 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 rod instrumentation for HBWR H-1 includes LVDT combination rod-elongation/failure monitors in the bottom of eight rods, fuel centerline thermocouples in five rods located in the lower cluster, and LVDT internal rod pressure monitors in four rods. The combination elongation/failure monitors and the internal pressure monitors will be operative during both the cycling and ramping portions of the tests. The thermocouples will be operative during only the cycling portion of the tests.

The test matrix for the HBWR H-1 screening test in IFA-518 is illustrated in Table 5.1. The table also shows the individual instrumentation included on each test rod.

TABLE 5.1. HBWR Series H-1 Test Matrix and Rod Instrumentation

Rod Type	Rod No.	(a) Instrumentation		
		Lower Cluster	Upper Cluster	Spares
Reference	01	--	--	T, E
	02	T, E	--	--
	03	--	E	--
	04	--	--	P
	05	--	P	--
Annular	06	T, E	--	--
	07	--	E	--
	08	--	--	E
Annular-Coated	09	T, E	--	--
	10	P	--	--
	11	--	E	--
	12	--	--	E
Vipac	13	T, E	--	--
	14	T, P	--	--
	15	--	--	P
	16	--	--	E
	17	--	E	--
	18	--	P	--

(a) T = Central fuel thermocouple
 E = Cladding elongation sensor
 P = Internal pressure sensor

5.2.1 HBWR Screening Test Status

During the year, the following items were completed for the HBWR Series H-1 screening test:

- The designs of the experimental rods and the test rig, IFA-518, were finalized
- The test rig and the instrumented end plugs for the fuel rods were fabricated by the Institute for Atomenergi
- The fuel rods were fabricated, inspected, and shipped to Halden, Norway
- The fuel rods were inserted into the IFA-518 test rig and all out-of-reactor calibrations were completed
- The HBWR H-1 experiment was initiated in IFA-518 with the first rise to full power on July 13, 1978

5.3 Design and Analysis - HBWR Series H-1

The conceptual designs for the HBWR Series H-1 test rods established the general requirements for detailed designs that were representative of commercial BWR fuel rods.

HBWR H-1 test fuel rods are approximately 711 mm (28 in.) long with an outer diameter of 12.3 mm (0.485 in.). The upper plenum is 28.4 mm (1.12 in.) long and was scaled to provide a void-to-fuel volume representative of commercial BWR fuel rods. General characteristics are summarized in Table 5.2. Representative fuel rod drawings are shown in Figures 5.1 through 5.8.

HBWR Series H-1 test rods consist of four different fuel designs: reference, annular, annular-coated, and vipac. Reference and annular fuel pellets are shown in Figures 5.9 and 5.10. The fuel columns have a single, low-enrichment fuel pellet at each end to reduce flux peaking at the ends of the rods. Additionally, the reference pellet rods instrumented with thermocouples, have a 2 mm (0.079 in.) diameter center hole in the upper end pellet and in the

TABLE 5.2. Characteristics of HBWR Series H-1 Test Rods

Reference Fuel

Type	Solid Pellet
Material	UO ₂
Density, %TD	94.0 ± 1.5
Diameter, mm (in.)	10.262 ± 0.013 (0.4040 ± 0.0005)
Length, mm (in.)	8.13 ± 0.64 (0.320 ± 0.025)
Dish	Both Ends
Dish volume, %	1.0 ± 0.3
Enrichment, wt% ²³⁵ U	11.0 ± 0.05

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 ± 0.05

Annular Fuel

Type	Annular pellet
Material	UO ₂
Density, %TD	94.0 ± 1.5
Diameter, O.D., mm (in.)	10.262 ± 0.013 (0.4040 ± 0.0005) ^(a)
Diameter, I.D., mm (in.)	3.25 ± 0.64 (0.128 ± 0.025)
Length, mm (in.)	8.13 ± 0.64 (0.320 ± 0.025)
Dish	None
Enrichment, wt% ²³⁵ U	11.0 ± 0.05

Vipac Fuel

Type	Vibrationally compacted particles
Material	UO ₂
Density (particles), %TD	>98
Diameter (cladding I.D.), mm (in.)	10.516 ± 0.051 (0.414 ± 0.002)

TABLE 5.2 (continued)

Vipac Fuel (cont'd)Enrichment, wt% ^{235}U 11.0 ± 0.05 Smear Density, %TD 87.0 ± 1.0 Insulator Disks

Material Alumina

Density, kg/m^3 3890

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 ± 0.51 (2.00 ± 0.020)Spring force, N (lb) 13.12 ± 1.33 (2.95 ± 0.30)

Spring constant, N/m (lb/in.) 590 (3.37)

Spring volume, mm^3 (in. ^{3}) 269 (0.0164)Cladding

Material Zircaloy-2

Condition Cold-worked and stress relieved

O.D., mm (in.) 12.370 ± 0.013 (0.487 ± 0.0005)I.D., mm (in.) 10.516 ± 0.013 (0.414 ± 0.0005)

Wall thickness, minimum, mm (in.) 0.841 (0.0331)

Length, mm (in.) 513.99 ± 0.13 (20.236 ± 0.005)

Allowable bow, mm/m (in./ft) 1.0 (0.012)

Coating (present in some rods with annular pellets) Graphite

Coating layer thickness, mm (in.) 0.0064 ± 0.0038 (0.00025 ± 0.00015)

TABLE 5.2 (continued)

End Caps

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

Fuel Rods

O.D., mm (in.)	12.32 ± 0.02 (0.485 ± 0.001)
Plenum length, mm (in.)	28.55 (1.124)
Fuel column length (including end pellets, mm (in.))	463.3 ± 4.1 (18.24 ± 0.16)
Allowable bow, mm/m (in./ft)	1.0 (0.012)

(a) Pellet O.D. = 10.249 ± 0.13 mm (0.4035 ± 0.0005 in.) in coated cladding rods

FIGURE 5.1. Reference Fuel Rod Assembly

42

FIGURE 5.2. Annular Pellet Fuel Rod Assembly

FIGURE 5.3. Annular-Coated Fuel Rod Assembly

FIGURE 5.4. Vipac Fuel Rod Assembly

FIGURE 5.5. Reference Fuel Rod Assembly (Thermocouple)

FIGURE 5.6. Annular Pellet Fuel Rod Assembly (Thermocouple)

FIGURE 5.7. Annular-Coated Fuel

FIGURE 5.8. Vipac Fuel Rod Assembly (Thermocouple).

FIGURE 5.9. Reference Fuel Pellet

FIGURE 5.10. Annular Fuel Pellet

ten "instrumented" pellets at the top of the fuel column to accept the thermocouple. Vipac fuel rods that are instrumented with a thermocouple contain a thin-walled tungsten-rhenium thermocouple well to provide a channel for introducing the thermocouple into the fuel column. Three, evenly spaced tungsten-rhenium spacers extend radially from the lower end of the well in order to maintain the position of the well in the center of the cladding tube.

The fuel column including the end pellets, is contained between a pair of insulator disks, one at each end. The upper insulator disk in the thermocouple fuel rods has a hole to accept the thermocouple. Fuel column position is maintained by a coil spring in the upper plenum.

The upper end caps consist of either solid Zircaloy-2, standard end caps, or instrumented thermocouple end caps that contain a bimetallic transition joint with zircaloy adjacent to the cladding. The lower end caps consist of a Zircaloy-2 body and either an elongation sensor or a pressure transducer (stainless steel bellows) assembly.

The lower end of the fuel rods contain a short Zircaloy-2 end plug between the cladding and the lower end cap. This plug contains a porous Zircaloy-2 frit to prevent fuel particles from interfering with the lower end cap instrument bellows while allowing gas communication between the fuel column and the instrumentation. Additionally, a small vent hole in the body of the end plug on the vipac rods allows for gas pressure relief during welding and provides a means for minimizing weld voids. The vent hole is welded shut after final end cap welding.

Coated-cladding fuel rods were produced using cladding that was coated with Dag 154. Dag 154 is a commercial designation for a colloidal graphite lubricant manufactured by the Acheson Colloids Company. Details of the coating technique are described in Section 4.

The parts list, drawings, and specifications for the Halden Series H-1 test rods are described in the design package XN-NF-530679, Rev. 3. Process Test Authorization No. 230 was written covering all the detailed instructions and responsibilities required to fabricate the HBWR H-1 fuel.

5.4 Process Development - HBWR Series H-1

Process development in support of the fabrication of the HBWR H-1 rods is summarized in the following subsections:

5.4.1 Pellet Process Development

The UO_2 used for the Halden H-1 fuel was prepared at ORNL. The material was received in three sublots of slightly different enrichments.

<u>ORNL Lot No.</u>	<u>Net Wt.</u>	<u>Enrichment</u>
450626	15 kg UO_2	10.86% ^{235}U
450627	15 kg UO_2	10.95% ^{235}U
450630	15 kg UO_2	11.15% ^{235}U

Each lot was contained in five bottles, each of which contained 3 kg of material.

It was originally intended to take advantage of the enrichment differences by assigning the lowest enrichment (10.86%) for reference pellets (highest smear density), the middle enrichment (10.95%) for vipac fuel, and the highest enrichment (11.15%) for annular pellets (lowest smear density). This was done to balance the linear heat rating among the rods in the irradiation test rig.

It was discovered, however, that there were significant differences in ceramic properties between each of the 3 kg bottles within each lot.

Pellet sinterability tests were performed for the various lots of UO_2 powder and are listed in Table 5.3.

A preproduction test (Section 5.5.1) was based on the results of Test No. 6. The reference pellets were accepted through QC release with no difficulties, but the first lot of annular pellets experienced a high frequency of cracking during outgassing.

The unexplained cracking of the pellets, along with the lot variabilities, led to the decision to make the master blend FPIP-001 from ORNL Lots 450626 and 450630. (Lot 450627 had already been committed for vipac fuel

preparation.) The resultant blended enrichment was 11.023% ^{235}U . A sinterability test was performed on this blended material. The conditions were the same as for sintering Test No. 6 in Table 5.3. Average pellet densities obtained from this test were 93.9%TD for the annular pellets and 94.1%TD for the reference pellets. The results of this test were used for subsequent pre-production testing.

5.4.2 Vipac Process Development

Results of the initial experiments with depleted UO_2 showed that the size distribution of the pneumatically-impacted (Dynapak) particles after removal from the impaction container was approximately 15% +6 mesh, 35% -6 +10 mesh and 50% -10 mesh. Removal of the UO_2 without the usual pressing action to deform the container was attempted in an effort to obtain larger UO_2 particles. Repeated tapping and pounding with a hammer proved to be a satisfactory technique for removing the UO_2 in view of the relatively small number of impaction billets to be processed. In both techniques, one end of the impacted billet was first removed by machining in a lathe. The size distribution of ORNL-supplied depleted UO_2 removed from the Dynapak billet by this technique was 80% +6 mesh, 8% -6 mesh, and 12% -10 mesh.

The particle density of the Dynapak feed material for the Halden vipac rods (ORNL Lot 450627, 10.95 ^{235}U) was low (97.9%TD) and a post-Dynapak sintering operation did not increase the density (perhaps due to heating the material too rapidly). This resulted in low (85-86%TD) vipac fuel densities. Consequently, after adding sufficient hyper-stoichiometric UO_2 to assure adequacy of the mechanical properties, the material was re-Dynapaked. The resultant material, after sintering, achieved particle densities in excess of 99%TD. A vipac test with this material resulted in an acceptable smear density of 86-87%TD.

Initially, 79 depleted vipac fuel rods were prepared in developing loading techniques to achieve uniform and satisfactory smear densities. The most successful technique was a continuous particle feed at low vibrational

TABLE 5.3. Pellet Sinterability Tests Using
ORNL 11% Enriched Powder

Test No.	Powder Lot No.	Lubricant, wt%	Green Density, Mg/m ³	Sintering Time, hr	Sintering Temp, °C	Average Pellet Density, %TD
1	450630	0.03 Sterotex	5.45	5.5	1550	91.7
2	450626	0.03 Sterotex	5.40	5.5	1550	91.5
3	450630	0.01 Zinc Stearate	5.70, 5.85, 6.00	5.5	1650	94.4
4	450630	0.02 Zinc Stearate	5.70, 5.85, 6.00	5.5	1750	93.2
5	450630	0.03 Sterotex	5.45	5.5	1650	92.1
6	450630	0.01 Zinc Stearate	5.45, 5.55, 5.60	5.5	1700	94.2
7	450630	0.01 Zinc Stearate	5.60, 5.70	5.5	1625	93.8

energies, followed by a brief vibrational period at high energies with a follower rod. A Branford variable impact pneumatic vibrator was utilized.

Typical parameters developed for the Halden test rods are listed in Table 5.4.

Cladding strain measurements were taken during test compaction of two vipac fuel rods. The results of the tests were used to establish a limit for the fatigue stress amplitude of 82 MPa (based upon a cladding thickness of 80% of nominal) with a conservative safety factor of 20 times the maximum number of cycles allowed during compaction of the fuel rods. No cracks occurred in the cladding, end caps, or weld areas during the tests.

A Densigauge using gamma ray attenuation was set up and calibrated to measure axial density of HBWR H-1 fuel rods. An error analysis for the Densigauge calibration was completed and it was concluded that the systematic

TABLE 5.4. HBWR Vipac Test Rod Process Development Parameters

Development Fuel Rod No.	Loading Time, sec	Compaction Time, sec. (a)		Calculated Density, %TD
		Initial Compaction with Rod Follower	Final Compaction with 9kg Weight	
66	-	77	60	85.3
67	30	31	120	86.4
68	10	105	150	85.6
69	30	45	165	86.1
74 (b)	-	60	15	87.6

(a) Branford vibrator operated at 5 cycles/sec. Particle size distribution in all tests was: 50 wt% 2000 - 3360 μm

50 wt% minus 2000 μm

(b) Fuel rod with thermocouple well

error was small with a standard deviation of $\pm 2\%$ of the nominal density. Plots of typical density measurements using the Densigauge are shown in Figures 5.11 through 5.13. The entire rod was not scanned; rather, readings at 12.7 mm (0.5 in.) increments were taken over a 5 mm (0.2 in.) axial length of the vipac fuel.

5.4.3 Coated-Cladding Process Development

Several tests were performed with Dag 154 to determine the possible effect of the graphite coating on cladding integrity.

One test investigated the possible effects on the Zircaloy-2, when heated to 450°C during outgassing of the graphite. Six samples from the same Zircaloy-2 tube were heated at 450° $\pm 10^\circ\text{C}$ for 2, 4, 18, 27, and 51 hr and then tensile tested.

FIGURE 5.11. Vipac Rod No. 16, Density vs. Length

FIGURE 5.12. Vipac Rod No. 17, Density vs. Length

FIGURE 5.13. Vipac Rod No. 18, Density vs. Length

The results were as follows:

Heat Time, hr	0.2% Yield Strength, MPa	Ultimate Tensile Strength, MPa	Elongation, %
0	523	712	22.2
2	528	712	22.2
4	526	714	21.7
18	528	707	22.7
27	523	701	23.2
51	515	691	23.7
Specifications Require	>414	>483	>16.0

After 51 hr, there was only a few percent drop in both yield and ultimate strength, and an increase in elongation. Ovality measurements indicated no measurable changes in ovality of any of the heated tubes. From these results, it was concluded that an outgassing treatment of 24 hr at $425^{\circ} \pm 25^{\circ}\text{C}$ for the graphite will have no harmful effect on the mechanical properties of the Zircaloy-2 cladding.

A comprehensive test was run to evaluate the possible effect of graphite coating moisture levels on cladding performance. Short-length test fuel rods were fabricated with either graphite-coated cladding (Dag 154) or standard, uncoated cladding. They were loaded with glass ampules containing various amounts of moisture (Table 5.5). The rods were heated to 450°C for 24 hr and then pinched against two mandrels to deform the cladding and rupture the internal zirconium oxide film (Figure 5.14). The test rods were reheated to 450°C for over 100 hr to determine if hydriding of the cladding would occur.

Hydriding was observed (Table 5.6) on only the two test rods with the highest moisture contents (Figures 5.15 through 5.18). These rods contained over 100 ppm moisture on a fuel weight basis. A test rod with about 15 ppm moisture (50% above current specification limits) showed no evidence of

TABLE 5.5. Characteristics of the Test Rods Used to Evaluate the Effects of Moisture on Coated and Noncoated Cladding

Developmental Test Rod No.	Coating Thickness, μm	Water Added, mg	Fuel Weight, gm	Void Volume, cm^3
<u>Dag 154 Coated</u>				
14	10-13	--	117.7	1.964
16	11-12	0.58	118.7	1.581
13	10-13	0.63	123.0	1.151
21	14-16.5	2.83	122.2	1.484
9	19-20	14.37	117.9	1.554
12	15.5-19	14.51	112.7	1.108
<u>Noncoated</u>				
14	--	--	120.4	1.169
27	--	0.81	118.6	1.688
30	--	0.87	119.7	1.553
28	--	3.17	124.4	1.250
29	--	15.67	121.8	2.207
22	--	15.87	118.4	1.696

FIGURE 5.14 Deformed Zircaloy Cladding for Test Rod Configuration (Rod No. 29)

FIGURE 5.15 Hydride Layer in Deformed Region of Test Rod No. 29

TABLE 5.6. Moisture/Dag-154 Coating Compatibility Test

Test Rod Number	Rod Moisture Content, (a) mg/cm ³	Equivalent Fuel Moisture Content, ppm	Hydride Indications
<u>Dag 154 Coated</u>			
14	0.62	10.3	None ^(b)
16	1.14	15.2	None ^(b)
13	1.62	15.2	None ^(b)
21	2.73	33.2	None ^(b)
9	10.03	132.3	None
12	14.19	139.5	Slight
<u>Noncoated</u>			
19	<0.21	<2.0	None ^(b)
27	0.62	8.8	None ^(b)
30	0.71	9.3	None ^(b)
28	2.74	27.5	None ^(b)
29	7.21	130.7	Extensive
22	10.08	144.4	Leaked after deformation

(a) Based upon cold void volume. Values include residual moisture in fuel plus added moisture.

(b) May have failed mechanically during deformation, allowing hydrogen to escape.

FIGURE 5.16 Hydride Layer in Crack of Test Rod No. 29

FIGURE 5.17 Electrolytically Charged Hydride Layer on Zircaloy Cladding (6 hr at 100 mA/cm² in 0.1N H₂SO₄)

FIGURE 5.18. Slight Evidence of Hydride Layer
in Test Rod No. 12

hydriding. Other test rods were not hydrided, but may have failed mechanically during the pinching operation and, thus, released the contained hydrogen. Through-wall cracks were apparent in some instances.

Section 4.0 describes the process technology for applying the graphite coating to the cladding. A flood coating technique was used and has proven to be very satisfactory.

Several preproduction tests were conducted to adapt the coating techniques to the production facility. An air-gauging system was also set up in the same area to measure the coating thickness.

5.5 Fabrication - HBWR Series H-1

HBWR Series H-1 fuel rod fabrication is summarized in the following subsections.

5.5.1 Pellet Fabrication

Preproduction sintering tests were made on the 11% enriched UO_2 and were based on the results of sinterability testing (Section 5.4.1). The

first preproduction test was made on ORNL Powder Lots 450626 and 450630 using the parameters listed in sinterability test No. 6 (Table 5.3). Average sintered densities from this test were 93.5%TD for annular pellets and 92.5%TD for reference pellets. These pellets were checked for densification by sintering for an additional 5.5 hr at 1700°C. The annular pellets increased in density to 94.0%TD and the reference pellets to 93.1%TD.

These pellets exhibited a high degree of cracking during the outgassing treatment, so a master blend was made of Lots 450626 and 450630. This new material was identified as Lot FPIP-001.

A preproduction sinterability test was run on Lot FPIP-001 using the same sintering conditions as described above. Sintered results were 93.3%TD for annular pellets and 93.1%TD for reference pellets. The resinter results were 93.4%TD for the annular and 93.1%TD for the reference pellets.

Cracking of the annular pellets still occurred during outgassing. As a result the sintering time was increased to 11.0 hr at 1700°C to anneal any residual stresses remaining in the annular pellets after pressing. The first production lot (FPIP-001, Revision 0) was made using these conditions. There was a decrease in pellet cracking in this lot. However, because there were insufficient pellets left for rod loading, it was necessary to use some of the preproduction pellets. In order to treat the latter pellets in a manner similar to Lot FPIP-001, Rev. 0, the preproduction pellets were given an additional 11.0 hr of sintering time, for a total of 16.5 hr. This lot was designated FPIP-001, Revision 1. Using this process, there was a marked decrease in pellet cracking so an additional lot was made (FPIP-001, Revision 2) and sintered using the two-step sintering cycle as per the Rev. 1 lot. No pellets in this lot cracked during outgassing.

The final pellet rod designations used for HBWR Series H-1 rod fabrication are summarized in Table 5.7.

TABLE 5.7. HBWR Series H-1 Pellet Lot Designations

<u>Lot Number</u>	<u>Pellet Type and Diameter, mm</u>	
FPIP-001, Revision 0	Annular	10.3 (0.4040 in.)
	Annular	10.2 (0.4035 in.)
	Reference	10.3 (0.4040 in.)
	Instrumented	10.3 (0.4040 in.)
FPIP-001, Revision 1	Annular	10.3 (0.4040 in.)
	Annular	10.2 (0.4035 in.)
	Reference	10.3 (0.4040 in.)
FPIP-001, Revision 2	Annular	10.3 (0.4040 in.)
	Annular	10.2 (0.4035 in.)

5.5.2 Fuel Rod Fabrication

Eighteen test fuel rods were fabricated for HBWR Series H-1. Figures 5.1 through 5.10 are representative of fuel rod and pellet drawings for the HBWR H-1 fuel rods and pellets. The rod types and serial numbers are listed in Table 5.8.

The fuel rods were shipped to Hanford Engineering Development Laboratory (HEDL) on April 26, 1978, for neutron radiography. From HEDL, the fuel rods were sent to Seattle, Washington, for shipment to Norway.

The final shipment of the test pins was performed according to plan except for Pin No. 10 which was changed from a rod with a thermocouple to a rod with a standard end cap. This was necessitated because of damage to the thermocouple during rework on the test rod.

TABLE 5.8. Description of Fuel Rods Fabricated for
the HBWR Series H-1 Test

<u>Test Rod Serial No.</u>	<u>Fuel Type</u>	<u>Rod</u>	<u>Special Instrumentation</u>
H1LCR001	Reference		Thermocouple, Elongation Sensor
H1LCR002	Reference		Thermocouple, Elongation Sensor
H1UCR003	Reference		Elongation Sensor
H1UCR004	Reference		Pressure Transducer
H1LCR005	Reference		Pressure Transducer
H1LCA006	Annular		Thermocouple, Elongation Sensor
H1LCA007	Annular		Thermocouple, Elongation Sensor
H1LCA008	Annular		Elongation Sensor
H1LCG009	Annular	Coated	Thermocouple, Elongation Sensor
H1LCG010	Annular	Coated	Pressure Transducer
H1LCG011	Annular	Coated	Elongation Sensor
H1UCG012	Annular	Coated	Elongation Sensor
H1LCP013	Vipac		Thermocouple, Elongation Sensor
H1LCP014	Vipac		Thermocouple, Pressure Transducer
H1LCP015	Vipac		Pressure Transducer
H1LCP016	Vipac		Elongation Sensor
H1LCP017	Vipac		Elongation Sensor
H1UCP018	Vipac		Pressure Transducer

Table 5.9 lists summary comments on the condition of each rod as evidenced by x-ray and neutron radiographic examination. X-ray radiography after closure welding of the initial loading showed that several rods contained badly chipped pellets. (This was a separate problem from the pellet "cracking" phenomenon discussed in Section 5.5.1). The problem eventually was traced to a faulty design in the temporary end plugs used to seal the rods during the transfer and handling that occurred prior to closure welding. These rods were down-loaded, the most severely chipped pellets removed, replacement pellets added and the fuel reloaded into new cladding tubes. (During evaluation of the chipping problem, it was decided to modify the pellet design to include a shallow edge chamfer for BRPR Series S-1 fuel rods. This design was shown to reduce significantly the tendency of pellets to chip during handling.)

During fabrication of the HBWR Series H-1 rods, some of the reference pellet fuel rods were seal-welded without weld chamber evacuation and backfill with helium. Thus, it was suspected that the rod atmosphere might not meet the required helium purity. To correct the situation, the rods were repeatedly pressurized and depressurized with helium through a small vent hole drilled into the lower end plug. The vent holes were then welded shut in the weld chamber.

The vipac fuel rods were loaded in a glovebox atmosphere containing between 90-95% helium. Because this atmosphere was below the specified atmosphere purity in finished fuel rods, the vipac rods were purged with high purity helium until gas samples collected at the vent end of the rod indicated >99% helium.

Difficulty was encountered with end-cap welding of HBWR H-1 fuel rods. The butt-weld type of joint between end-caps and cladding resulted in a high incidence of weld voids. Rods were X-rayed in two orientations, 0° and 90°, and the defects were characterized. Some of the rods were reworked by removing the defects by grinding and rewelding. Those defects that remained and could not be reworked were evaluated on the basis of upper bound fatigue crack growth calculations. Spherical voids that exist in HBWR H-1 rod welds

TABLE 5.9. Summary of Rod Conditions as Observed Radiographically

<u>Rod Number</u>	<u>Location</u>	<u>Comments</u>
H1LCR001	Spare	Little dust around lower insulator. No chips.
H1LCR002	Lower Cluster	No chips. Spoon-shaped defect in lower end-plug weld.
H1LCR003	Upper Cluster	No chips.
H1LCR004	Spare	Dust around lower insulator. Spoon-shaped defect in lower end-plug weld. No chips.
H1LCR005	Upper Cluster	250 x 500 μ m chip sitting on shelf formed by 19th 11% pellet from bottom and in gap of 20th pellet.
H1LCR006	Lower Cluster	Spoon-shaped defects in upper weld and lower end-plug weld. Dust around lower insulator, more than usual for pellet rod. No chips.
H1LCR007	Upper Cluster	No chips.
H1LCR008	Spare	Dust around lower insulator. No chips.
H1LCR009	Lower Cluster	150 x 250 μ m chip, 3rd 11% pellet from bottom. 4th 11% pellet has a major offset. Little dust around lower insulator.
H1LCR010	Lower Cluster	Upper insulator has thermocouple hole. 250 μ m dia. chip wedged in interface between 6th and 7th 11% pellet from bottom. 125 x 250 μ m chip near lower end of 4th 11% pellet. Two or more large chips in lower 2300 μ m of pellet-cladding gap 11% pellet from bottom.
H1LCR011	Upper Cluster	No chips.
H1LCR012	Spare	Spoon-shaped defect in lower end-cap weld. No chips.
H1LCR013	Lower Cluster	Spoon-shaped defect in upper weld. Dust around upper and lower insulator. Upper insulator cocked by pellet chip. Spoon-shaped defect in lower end-plug weld.

Table 5.9 (cont.)

<u>Rod Number</u>	<u>Location</u>	<u>Comments</u>
H1LCR014	Lower Cluster	Spoon-shaped defect in upper weld. Dust around lower insulator. Dust is separated. Spoon-shaped defect in lower end-plug weld.
H1CCR015	Spare	Separated dust around lower insulator. Spoon-shaped defect in lower end-plug weld. Lack of fusion in lower end-cap weld.
H1LCR016	Spare	Large separation in dust around lower insulator.
H1LCR017	Upper Cluster	Spoon-shaped defect in lower end-plug weld. Separated dust around lower insulator. Few large chips around upper insulator.
H1LCR018	Upper Cluster	Spoon-shaped defect in lower end-plug weld. Dust around lower insulator.

are isolated voids less than 0.381 mm (0.015 in.) diameter. Calculations indicate no fatigue failures will be induced by such flaws. In the future, it is expected that improved equipment will permit more effective control of the welding process to eliminate weld voids.

The vipac fuel rods for the HBWR Series H-1 test were measured for axial density variations by a gamma ray attenuation method (Densigauge). A calibration based upon the mass absorption coefficient for UO_2 and the zircaloy cladding gave good agreement with the calculated density based upon volume measurement and weight of UO_2 in the rod. The data for all the fuel rods are summarized in Table 5.10. The entire rod was not scanned; rather readings at 12.7 mm (0.5 in.) increments were taken over an axial length of 5 mm (0.2 in.) of particle fuel. At the 254 mm (10 in.) point, the rod was rotated and readings were taken at 90° increments.

Thirty-eight Deviating Material Reports (DMR) were issued during the fabrication of the HBWR Series H-1 test rods. Nine were for hardware items (end caps, frits, insulator discs), nine were for pellets (dimensions, impurities), five were for UO_2 powder (isotopic, impurities), four for vipac fuel (impurities), five for finished rods (surface finish, gas atmosphere, processing), and six for welds (voids, root defects).

The production pellets and rods for HBWR Series H-1 were characterized as per the requirements listed in Appendix A.

Preparation of an as-built description and characterization report for the HBWR Series H-1 rods is continuing. Tables summarizing the characterization data have been prepared and are being typed; however, preparation of the text describing the methods of measurement of individual fuel rod characteristics was delayed due to the BRPR Series S-1 fabrication effort.

5.6 Irradiation Status - HBWR Series H-1

The HBWR Series H-1 test irradiations began in IFA-518 on July 13, 1978. All rig and rod instrumentation in IFA-518 have operated satisfactorily. The axially moveable absorber shield was designed to reduce the linear power of

**TABLE 5.10. Vipac Fuel Density (%TD) Measurements
for HBWR Series H-1 Rods**

X mm (in.)	Axial Location, X + Column Heading Value									
	0.0 Rod 13*	12.7	25.4	38.1	50.8	63.5	76.2	88.9	101.6	114.3
0 (0)	91.18	89.38	88.28	86.16	88.06	88.90	87.28	87.46	88.38	85.18
127 (5)	86.95	86.24	86.12	95.39	88.09	86.07	84.68	86.09	85.68	86.64
254 (10)	87.35	89.69	87.79	87.36	88.57	87.72	88.88	89.99	84.04	76.25
381 (15)	75.52 ^(a)	73.66 ^(a)	74.28 ^(a)	74.21 ^(a)	71.04 ^(a)	75.68 ^(a)	NA			
254 (10) ^(b)	89.54	87.67	89.22	87.51						
Rod 14										
0 (0)	91.65	87.88	90.00	89.74	87.53	88.66	87.40	87.51	89.34	88.65
127 (5)	87.90	87.97	86.91	86.57	85.38	88.23	88.34	87.04	86.33	88.01 ^(a)
254 (10)	86.56 ^(a)	88.39	88.24	88.06	85.32	84.45	85.58	86.82 ^(a)	85.77	80.17 ^(a)
381 (15)	78.35 ^(a)	79.35 ^(a)	75.37 ^(a)	78.39 ^(a)	78.90 ^(a)	82.67 ^(a)	88.39 ^(a)	86.54 ^(a)		
254 (10) ^(b)	86.54	86.47	86.89	86.88						
Rod 15										
0 (0)	91.26	86.67	86.40	88.47	88.27	90.15	86.26	89.76	86.52	89.46
127 (5)	83.35	85.42	88.47	88.69	87.88	87.84	88.02	88.17	83.23	84.70
254 (10)	89.39	86.87	89.15	84.73	90.13	83.86	85.57	87.94	89.74	89.22
381 (15)	85.12	86.72	85.83	88.76	82.72	53.49	33.11			
254 (10) ^(b)	84.07	82.54	34.62	31.91						
Rod 16										
0 (0)	87.63	88.47	87.92	85.69	86.94	85.99	87.07	87.90	86.73	88.18
127 (5)	89.06	85.30	88.80	88.01	83.24	88.36	84.92	89.18	87.26	86.59
254 (10)	84.47	88.11	98.05	84.63	98.84	86.94	87.38	89.77	88.40	87.94
381 (15)	89.13	85.42	88.81	89.28	85.60	64.90	38.38			
254 (10) ^(b)	87.29	85.61	84.38	85.55						
Rod 17										
0 (0)	90.95	89.86	86.15	87.48	88.44	82.28	84.53	83.45	86.61	87.34
127 (5)	85.37	85.50	86.89	86.05	84.48	85.56	87.74	89.14	87.60	83.71
254 (10)	86.99	88.29	88.19	87.41	88.16	90.08	89.15	87.59	88.54	88.98
381 (15)	87.65	86.33	85.27	90.46	89.38	66.39	29.44			
254 (10) ^(b)	84.02	86.28	86.94	84.86						
Rod 18										
0 (0)	91.08	86.76	87.83	87.15	88.43	87.01	85.02	85.84	84.24	88.93
127 (5)	88.90	88.55	87.33	83.38	86.37	85.59	86.48	84.72	85.26	88.22
254 (10)	87.35	86.36	87.12	88.35	87.83	89.66	85.80	89.12	87.42	86.05
381 (15)	86.79	86.50	87.03	88.07	88.44	76.60	26.56			
254 (10) ^(b)	86.37	87.09	87.55	86.13						

(a) Values measured in region of thermocouple
(b) Values obtained by rotating the rod 90°

the rods enclosed by the shield to 65% of the nonshielded value. Preliminary analysis indicates that with the shield located in the upper position, the power is reduced to 63% of the non-shielded power.

Power balancing of the various types of rods with differing smear densities was accomplished by placing the low smear density rods closer to the center of the core. As a result, the annular pellet designs which have the lowest smear density, are operating at powers only about 3% lower than the high smear density reference and vipac designs. Figures 5.19 and 5.20 show the fuel rod positions in the test rig.

Peak operating powers in the IFA-518 rods have varied with the operating power range of the reactor. Preliminary analysis indicates that peak linear heat ratings as high as 46.5 kW/m (105% of the design peak power) were achieved with the majority of the peak operating powers being in the range of 40-42 kW/m (90-95% of the design peak power).

The initial power cycle, which was achieved by moving the shield between the upper and lower cluster rods, was accomplished on September 25, 1978 at a calculated average burnup of 216 GJ/kg (2500 MWd/MTM) on the lower cluster rods. Peak burnup on the lower cluster rods at the end of the fiscal year was approximately 252 GJ/kg (2900 MWd/MTM).

The initial data tapes for the experiment instrumentation were received recently and processing was initiated. The tape information includes data from pressure transducers, elongation sensors, thermocouples, and neutron detectors, as well as the calculated heat ratings for each fuel rod. The information on the data tape is now being transferred from the tape to storage on disc on the PDP 11/45 computer system. As of October, the data should be ready for analysis. Initial results and preliminary evaluations are presented in Section 8.0 of this report.

5.7 Summary Description of Primary Ramping Tests

Based upon the results of the screening tests in HBWR, rodlets comprising the fuel concept or concepts with the most potential for improved FCI behavior will be selected from the segmented rods irradiated in BRPR as part of the

FIGURE 5.19. IFA-518 Lower Cluster Loading Map, as Viewed from Above

FIGURE 5.20. IFA-518 Upper Cluster Loading Map, as Viewed from Above

Task 2C In-Reactor Demonstrations for subsequent ramp testing. The test reactor to be used for the primary ramp tests has not been selected. Only the central rodlet from the three-segment, segmented rods will be utilized for the primary ramp tests; however, rodlets from the lower portion of the segmented rods will serve as backups for the primary ramping tests.

A number of items related to the segmented rodlets that will receive steady-state irradiation in BRPR as part of the Task 2C In-Reactor Demonstrations prior to ramp testing, were completed during the year. These include:

- Finalizing the design of the segmented rods and rodlets
- Determining the matrix of rod types for BRPR Series S-1 (See Section 6.0)
- Fabricating and inspecting the BRPR Series S-1 segmented and full-length, rods in preparation for shipment to BRPR (See Section 6.0 for fabrication details)

The first rodlets from BRPR Series S-1 for primary ramp testing will be removed from BRPR after two, approximately one-year long, reactor cycles.

5.8 Performance Predictions

The presence of thermocouples in the fueled region of selected test rods will cause localized perturbations in peak fuel temperatures when compared with rods without thermocouples. A computer study was conducted to determine the magnitude of these perturbations, i.e., gamma heating in the thermocouple, axial heat conduction up the thermocouple, and removal of fissile material in the reference and vipac fuel, on the indicated temperatures.

The code used for the first two analyses was the three-dimensional asymmetric heat transfer code TRUMP.^(5.3) To determine the effect of gamma heating and axial conduction on the fuel centerline temperature, a series of calculations were made for each fuel type. For the reference, annular, annular-coated, and vipac fuel types, each of the following cases was evaluated:

1. Fuel without a thermocouple (for reference and vipac rods the fuel was modeled both with and without a thermocouple hole);
2. Fuel with a thermocouple; and
3. Fuel with a thermocouple and gamma heating.

The rods were modeled starting from the top of the Al_2O_3 insulator pellet to the bottom of the thermocouple. The model included the low enrichment (2.78% ^{235}U) pellet located at the top of the fuel stack. The model without a thermocouple in the fuel stack assumed the top boundary of the Al_2O_3 insulator pellet to be adiabatic.

Input data used to model the fuel rods were obtained from several sources. The radial gap size was matched to the gap sizes calculated by GAPCON-THERMAL-3 and the flux depression was calculated from equations used in the GAPCON-THERMAL-3 code.^(5.4) The thermal conductivity values for the UO_2 were obtained from characterization of other Halden experiments,^(5.5) and from the work of Calza-Bini.^(5.6) Thermal conductivity of the insulator pellets and the thermocouple materials was taken from Touloukian.^(5.7) Gamma heating values in the thermocouple and thermocouple well were assumed to be 0.86 kW/kg. Due to the expected relative flatness of the axial flux profile in the region of the thermocouple during the experiment, a constant linear power of 43.6 kW/m was used over the fuel length containing the thermocouple. The design parameters used in the model of the fuel are summarized in Table 5.11.

Using the above information, the temperature distributions in the rods were calculated. The calculated changes in indicated temperature at the thermocouple are shown in Table 5.12.

The calculations predict that axial heat conduction along the thermocouple does not cause any significant temperature perturbation at the thermocouple junction. However, the addition of the thermocouple slightly decreases the fuel temperatures near the top of the fuel stack.

TABLE 5.11. Design Parameters for the Fuel Types Analyzed

	Reference	Reference with Thermo- couple Hole	Annular	Annular- Coated	Vipac	Vipac with Thermocouple Hole
Clad ID, mm	10.52	10.52	10.52	10.52	10.52	10.52
Clad OD, mm	12.29	12.29	12.29	12.29	12.29	12.29
Fuel OD (cold), mm	10.26	10.26	10.26	10.25	10.52	10.52
Fuel OD (hot), mm	10.43	10.43	10.39	10.38	10.52	10.52
Center Hole Diameter, mm	--	2.04	3.26	3.26	--	2.36
Coating Thickness, mm	--	--	--	0.0064	--	--
Nodes in Fuel	16	14	13	13	16	14
Nodes in Cladding	3	3	3	3	3	3
Nodes in Gap	1	1	1	1	0	0
Nodes in Coating	--	--	--	1	--	--
Axial Segments	10	10	10	10	10	10
Length of Axial Segments in Fuel, mm	8.12	8.12	8.12	8.12	8.12	8.12
Length in Axial Segments in Al_2O_3 , mm	5.08	5.08	5.08	5.08	5.08	5.08
Coolant Temperature, $^{\circ}C$	245	245	245	245	245	245
Thermocouple Hole Length, mm	--	78.23	--	--	--	78.23
Fill Gas	He	He	He	He	He	He

The thermocouple was modeled with the following design parameters: Nodes in sheath - 1; sheath material - W-Re; sheath OD, mm - 1.58; sheath ID, mm - 1.07; insulator materials - BeO; nodes in insulator - 2.

TABLE 5.12. TRUMP Predictions of the Effect of the Presence of a Thermocouple on the Temperatures for the Four Fuel Types

Cases	Fuel Centerline Temperature, °C
Predicted change in indicated temperature due to axial conduction up thermocouple	
Reference	0
Annular	0
Annular-Coated	-2
Vipac	-1
Predicted change in indicated temperature caused by gamma heating (at thermocouple junction)	
Reference	+4
Annular	+2
Annular-Coated	+1
Vipac	+4

The results also predict that gamma heating in the thermocouple will not cause a significant effect. The heat generation from gamma heating causes only a small increase in the centerline temperature calculated at the thermocouple junction.

Several GAPCON-THERMAL-3^(5.4) calculations were performed to analyze the effect on temperature of adding a thermocouple hole to the vipac and the reference fuel designs. The calculations were made at a power of 44.3 kW/m. The calculated effect of the central hole is summarized in Table 5.13.

TABLE 5.13. GAPCON-THERMAL-3 Predictions of
Centerline Temperatures in
Reference and Vipac Fuel

<u>Case</u>	<u>Reduction in Centerline Temperature Due to Addition of Thermocouple Hole, °C</u>
Reference	87
Vipac	198

REFERENCES

- 5.1 Fuel Performance Improvement Program, Quarterly/Annual Progress Report, April-September, 1977, C00-4066-4, November, 1977.
- 5.2 Fuel Performance Improvement Program, Quarterly Progress Report, October-December, 1977, C00-4066-6, January, 1978.
- 5.3 A. L. Edwards, TRUMP: A Computer Program for Transient and Steady State Temperature Distributions in Multidimensional Systems. UCRL-14754, Rev. 3, Lawrence Livermore Laboratory, Livermore, CA 94550, September 1, 1972.
- 5.4 D. D. Lanning, C. L. Mohr, F. E. Panisko, and K. B. Stewart, GAPCON-THERMAL-3 Code Description, PNL-2434, January 1978.
- 5.5 C. R. Hann, Test Design, Pre-Characterization and Fuel Assembly Fabrication for Instrumented Fuel Assemblies IFA-431 and IFA-432. BNWL-1988, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, November 1977.
- 5.6 A. Calza-Bini, G. Cosoli, G. Filacchioni, M. Lanchi, A. Nobili, U. V. Rocca, P. L. Rotoloni, B. Marsico and G. Trezza, "Thermal Behavior of Fuel Pins for Power Reactors," Nuclear Fuel Performance, International Conference, London, October 15-19, 1973.
- 5.7 Y. S. Touloukian, Thermal Properties of High Temperature Solid Materials, Volume 1 and 4, MacMillan Co., New York, NY, 1967.

6.0 TASK 2C - IN-REACTOR DEMONSTRATIONS

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

This task is structured as a series of fuel irradiations followed by examination at selected fuel burnups. A total of approximately 400 rods of the selected fuel concepts will be irradiated in the Consumers Power Company's Big Rock Point Reactor (BRPR).

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

6.1 Design and Analysis - BRPR Series S-1

The BRPR Series S-1 demonstration fuel rods, which are included in the G-4 reload batch for the BRPR, incorporate most of the fuel design concepts used in the HBWR Series H-1 test rods. BRPR S-1 rods consist of both full-length demonstration rods, which have the same rod, plenum, and fuel stack envelope as BRPR reload G-4 rods, and segmented fuel rods. Each of the latter consists of three short-length fuel rods (segments) that are joined end-to-end by solid zircaloy connectors.

Certain design changes were incorporated into the BRPR Series S-1 demonstration rod subsequent to the HBWR Series H-1 test rod fabrication. Reference and annular pellets were redesigned to include a small (0.117 mm or 0.007 in.

maximum axial) edge chamfer for purposes of reducing pellet chipping. Reference and annular pellet designs are shown in Figures 6.1 and 6.2. Because of this minor modification, sixteen standard BRPR reload G-4 fuel rods with nonchamfered pellets were added to the matrix and characterized in order to compare their performance with that of the chamfered-pellet demonstration rods. Additionally, some annular-coated and vipac fuel rods were pressurized to 455 kPa with helium to study pressurization effects. Rods with annular pellets and annular-coated nonpressurized rods were also fabricated in order to permit evaluation of the separate effects of the graphite coating and pressurization.

The graphite coating material for BRPR Series S-1 was changed from Dag 154, which was used in HBWR Series H-1, to an improved graphite material designated Dag 4. Dag 4 is a designation for one variation of a colloidal graphite lubricant manufactured by Acheson Colloids Company. This material differs from the Dag 154 in that it does not contain organic binder or alcohol as the suspension vehicle. Dag 4 is water based, and contains alumina and silica. The pellet loading abrasion characteristics of Dag 4 are significantly better than Dag 154. Full-length demonstration rods in BRPR Series S-1 include standard characterized G-4 rods; reference rods, annular pellet rods; annular-coated rods; annular-coated-pressurized rods; and vipac-pressurized rods. Characteristics of the BRPR Series S-1 full-length rods are summarized in Table 6.1 and Figures 6.3 through 6.7.

Segmented rods were incorporated into the BRPR Series S-1 fuel in order to provide rodlets for subsequent ramping tests as part of Task 2B. After irradiation in BRPR, segmented rods will be selected for removal from the parent fuel assembly and subsequently separated into individual segments. Some of these segments will then be sent to a test reactor for power-ramp testing. Each of the lower two rod segments contains an upper plenum and plenum spring that are one-third the length of the corresponding component of full-length rods. Characteristics of segmented rods are summarized in Table 6.2 and Figures 6.8 through 6.13.

FIGURE 6.1. Reference Fuel Pellet

FIGURE 6.2. Annular Fuel Pellet

TABLE 6.1. Characteristics of BRPR Series S-1
Full-Length Demonstration Fuel Rods

Reference Fuel

Type	Solid Pellet (Edge Chamfer)
Material	UO ₂
Density, %TD	93.5 ± 1.5
Diameter, mm (in.)	9.436 ± 0.013 (0.3715 ± 0.0005)
Length, mm (in.)	7.62 ± 0.64 (0.300 ± 0.025)
Dish	Both ends
Dish Volume	2.0 ± 0.5 (0.25 Edge Chamfer)
Enrichment, wt% ²³⁵ U	2.52 ± 0.05

Annular Fuel

Type	Annular pellet (Edge Chamfer)
Material	UO ₂
Density, %TD	93.5 ± 1.5
Diameter, O.D., mm (in.)	9.436 ± 0.013 (0.3715 ± 0.0005) ^(a)
I.D., mm (in.)	2.984 ± 0.127 (0.1175 ± 0.005)
Length, mm (in.)	7.62 ± 0.64 (0.300 ± 0.025)
Dish	None (0.025 Edge Chamfer)
Enrichment	2.69 ± 0.05

Vipac Fuel

Type	Vibrationally-compacted particles
Material	UO ₂
Density (particles) %TD	>98
Diameter (cladding I.D.) mm (in.)	9.677 ± 0.038 (0.3810 ± 0.0015) ^(b)
Enrichment, wt% ²³⁵ U	2.52 ± 0.05
Smear Density, %TD	87.0 ± 1.0

TABLE 6.1 (Continued)

<u>Standard Fuel</u>	
Type	Same as reference (without chamfer)
<u>Insulator Disks</u>	
Material	Alumina
Density, Mg/m 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
<u>Plenum Spring</u>	
Material	Inconel X-750
Spring force, nominal, N (lb)	49 (1)
Spring constant, nominal N/m (lb/in)	2100 (2)
Spring volume mm ³ , (in ³ ,)	628 (0.0383)
<u>Fill Gas</u>	
Material	He
Purity, %	99.9
Fill pressure, MPa (psia, nominal)	0.10 (14.7)
Pressurization fill pressure, MPa (psia)	0.462 $\pm$ 0.048 (67 $\pm$ 7)
<u>Cladding</u>	
Material	Zircaloy-2
Condition	Cold-Worked/Stress-Relieved
O.D., mm (in.)	11.455 $\pm$ 0.038 (0.451 $\pm$ 0.0015) ^(b)
I.D., mm (in.)	9.677 $\pm$ 0.038 (0.381 $\pm$ 0.0015)
Wall Thickness, minimum, mm (in.)	0.831 (0.0327)
Length, mm (in.)	1902.18 $\pm$ 0.38 (74.889 $\pm$ 0.015)

TABLE 6.1 (Continued)

Cladding (Continued)

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 ± 0.0038 (0.00025 ± 0.00015)

Fuel Rod

O.D., mm (in.)	11.405 ± 0.051 (0.449 ± 0.002) ^(c)
Plenum length, mm (in.)	99.08 (3.901)
Fuel column length, mm (in.)	1778.0 ± 6.4 (70.00 ± 0.25)
Allowable bow, mm/m (in/ft)	1.25 (0.015)

(a) Pellet O.D. = 9.423 ± 0.013 mm (0.3710 ± 0.0005 in.) in coated-cladding rods.

(b) Cladding selected to fall within a range of ± 0.025 mm (± 0.001 in.)

(c) Rods selectively etched to fall within a range of ± 0.038 mm (± 0.0015 in.)

FIGURE 6.3. Reference Fuel Demonstration Rod

FIGURE 6.4. Annular Pellet Demonstration Rod

FIGURE 6.5. Annular-Coated Demonstration Rod

FIGURE 6.6. Annular-Coated Pressurized Demonstration Rod

FIGURE 6.7. Vipac Pressurized Demonstration Rod

TABLE 6.2. Characteristics of BRPR Series S-1
Segmented Fuel Rods

Reference Fuel

Same as demonstration rods. (a)

Annular Fuel

Same as demonstration rods. (a)

Vipac 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 ± 0.38 (0.340 ± 0.015)

Free length, mm (in.)

56.90 ± 0.76 (2.240 ± 0.030)

Spring force, N (lb)

9.34 (2.10)

Spring Constant, N/m (lb/in)

394 (2.23)

Spring volume, mm³ (in.³)

304 (0.0185)

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 annual fuel

Coating thickness, mm

Length, upper segment, mm (in.)

Length, mid and lower segment, mm (in.)

Fuel Rod

Number of segments

O.D.

Allowable bow

Plenum length, upper plenum

Plenum, mid and lower plenum, mm (in.)

Fuel column length, upper segment, mm (in.)

Fuel column length, middle segment, mm (in.)

Fuel column length, lower segment, mm (in.)

Axial distance between fuel columns, mm (in.)

Fuel configuration, upper and mid segments

Fuel configuration, mid and lower segments

Same as demonstration rods

Same as demonstration rods

666.24 ± 0.13 (26.230 ± 0.005)

600.18 ± 0.13 (23.629 ± 0.005)

3

Same as demonstration rods

Same as demonstration rods

Same as demonstration rods

33 (1.300)

544.45 ± 4.06 (21.435 ± 0.16)

546.84 ± 2.03 (21.529 ± 0.08)

544.45 ± 2.03 (21.435 ± 0.08)

71.12 (2.800)

Reference

Reference-pressurized^(b)

Reference-coated

Annular

Annular-coated-pressurized

Vipac^(b)

Vipac-pressurized^(b)

(a) Pellet O.D. = 9.423 ± 0.013 mm (0.3710 ± 0.0005 in.) in rods with coated-cladding

(b) Lower segment only

FIGURE 6.8. Reference and Coated Segmented Fuel Rod Assembly

FIGURE 6.9. Reference and Pressurized Segmented Fuel Rod Assembly

FIGURE 6.10. Annular Pellet Segmented Fuel Rod Assembly

FIGURE 6.11. Annular-Coated Segmented Fuel Rod Assembly

FIGURE 6.12. Annular-Coated-Pressurized Segmented Fuel Rod Assembly

FIGURE 6.13. Vipac Segmented Fuel Rod Assembly

All upper segments were fabricated from reference fuel because the skewed power profile at the top of the BRPR core renders these segments of little value for power ramping. Segment connectors at the top of nonpressurized segments were vented to relieve gas pressure buildup during end cap welding. The vents were subsequently welded shut. Due to equipment limitations, only the center segments of the vipac rods were pressurized.

BRPR Series S-1 demonstration fuel rods are distributed around the periphery and first inner row of four fuel assemblies (Figures 6.14 and 6.15). The corresponding bundle serial numbers in the G-4 reload batch are G-419, 420, 421, and 422. The first two assemblies, Figure 6.14, are identical except for one vipac rod that was omitted from assembly G-419 (see Section 6.3.2) and contain only full-length demonstration rods. The other two assemblies, Figure 6.15 are identical and contain both full-length and segmented rods.

Each pair of fuel assemblies are to be loaded into BRPR in symmetrical core locations. Each pair will be rotationally oriented 90° apart with respect to the adjacent control blade. This will provide a comparison between four different rod designs having nearly identical operating power histories.

The addition of annular and vipac fuel rods and segmented fuel rods to BRPR fuel assemblies was analyzed for licensing implications.^(6.1) Thermal hydraulic licensing limits required a minor (less than 1%) reduction of peak fuel assembly power compared to standard G-4 fuel assemblies. Results were based on the expected increase in localized rod powers due to the presence of nonfueled regions in the segmented rods. Sensitivity studies also were performed to determine the impact of the FPIP rods on LOCA analysis. Results showed little change in peak cladding temperatures; temperatures were lower at beginning of life and slightly higher at end of life compared to G-4 fuel assemblies.

Process Test Authorization 235 was written covering all the detailed instructions and responsibilities required to fabricate the BRPR Series S-1 fuel.

SERIAL NO. LOCATION

LEGEND

(H)	3.82 WT. % ^{235}U , UO_2		TIE ROD
(HG)	1.2 WT. % GADOLINIA IN 3.82 WT. % ^{235}U , UO_2		SPACER CAPTURE ROD
(6)	(M)	2.52 WT. % ^{235}U , UO_2	
(L)	1.50 WT. % ^{235}U , UO_2		
(1)	2.52 WT. % ^{235}U , REFERENCE		
(2)	2.69 WT. % ^{235}U , ANNULAR		
(3)	2.69 WT. % ^{235}U , ANNULAR-COATED		
(4)	2.69 WT. % ^{235}U , ANNULAR-COATED-PRESSURIZED		
(5)	2.52 WT. % ^{235}U , VIPAC-PRESSURIZED		
(X)	INERT ROD		

(a) VIPAC ROD IN THIS POSITION IN G-419 REPLACED WITH STANDARD ROD.

FIGURE 6.14. BRPR Series S-1 Demonstration Fuel Assemblies. G-419 and G-420

SERIAL NO. LOCATION

LEGEND

(H)	3.82 WT. % ^{235}U , UO_2	(TIE ROD)	TIE ROD
(HG)	1.2 WT. % GADOLINIA IN 3.82 WT. % ^{235}U , UO_2	(SPACER CAPTURE ROD)	SPACER CAPTURE ROD
(6) (M)	2.52 WT. % ^{235}U , UO_2	(7)	2.52 WT. % ^{235}U , REFERENCE & REFERENCE - COATED SEGMENTED
(L)	1.50 WT. % ^{235}U , UO_2		2.52 WT. % ^{235}U , REFERENCE & REFERENCE - PRESSURIZED SEGMENTED
(1)	2.52 WT. % ^{235}U , REFERENCE	(8)	2.69 WT. % ^{235}U , ANNULAR SEGMENTED
(2)	2.69 WT. % ^{235}U , ANNULAR	(9)	2.69 WT. % ^{235}U , ANNULAR - COATED SEGMENTED
(3)	2.69 WT. % ^{235}U , ANNULAR-COATED	(10)	2.69 WT. % ^{235}U , ANNULAR - COATED SEGMENTED
(4)	2.69 WT. % ^{235}U , ANNULAR-COATED- PRESSURIZED	(11)	2.69 WT. % ^{235}U , ANNULAR - COATED - PRESSURIZED SEGMENTED
(5)	2.52 WT. % ^{235}U , VIPAC- PRESSURIZED AND SEGMENTED	(12)	2.52 WT. % ^{235}U , VIPAC & VIPAC- PRESSURIZED AND SEGMENTED
(X)	INERT ROD		

FIGURE 6.15. BRPR Series S-1 Demonstration Fuel Assemblies. G-421 and G-422

6.2 Process Development - BRPR Series S-1

6.2.1 BRPR Pellet Process Development

The UO_2 used for the BRPR Series S-1 fuel was produced at Exxon Nuclear Company. The material was sinterability tested using standard practices. Data from the sinterability tests are summarized in Table 6.3.

Preproduction sintering tests were made based on the sinterability test results. The preproduction test data are summarized in Table 6.4.

6.2.2 BRPR Vipac Process Development

The source of the UO_2 used for vipac feed material was ENC powder Lot No. 127-3. The material was densified by the high-energy, pneumatic impaction (Dynapak) process.

The particle size distribution of the feed material for vipac process development studies was essentially the same as that used for the HBWR Series H-1 test rods, except that material less than 1190 μm was carefully screened to determine the particle size fractions that were present. All of the development and test rods were loaded with the following mixture:

50 wt%	1190-3360 μm
17.5 wt%	250-1190 μm
10 wt%	105-250 μm
2.5 wt%	74-105 μm
10 wt%	44-74 μm
10 wt%	minus 44 μm

The process equipment was the same as that used for the HBWR Series H-1 rods except that three small pneumatic vibrators were used during the continuous loading of the particle fuel material to more efficiently pack the particles inside the cladding. It was determined that the use of pneumatic vibrators during loading produced a more optimum dispersion of the particles. The Branford vibrator was then used sparingly to achieve final density.

TABLE 6.3. BRPR Series S-1 Sinterability Test Data

Lot Number	Lubricant, wt%	Green Density, mg/m ³	Sintering Time, hr	Sintering Temp., °C	Average Pellet Density, %TD	Resinter Pellet Density, %TD
SR-48-1 ^(a)	0.3 Sterotex	5.48	2.8	1650	94.02	95.03
"	0.3 Sterotex	5.48	2.8	1750	94.08	94.87
"	0.2 Zinc Stearate	5.46	2.8	1650	95.26	96.65
"	0.2 Zinc Stearate	5.46	2.8	1750	95.76	96.60
"	0.3 Zinc Stearate	5.46	2.8	1650	95.46	96.70
"	0.3 Zinc Stearate	5.46	2.8	1750	95.79	96.62
133-2/ SR54-3 ^(b)	0.2 Zinc Stearate	5.85	3.9	1780	92.96	(c)

(a) Powder Lot SR-48-1 was 2.69% enriched in ²³⁵U and was used for the annular pellets.

(b) Powder Lot 133-2/SR54-3 was 2.52% enriched in ²³⁵U and was used for the reference pellets.

(c) No resinter test was performed on powder Lot 133-2/SR54-3 because it was very inactive and would not resinter over 0.5%TD.

TABLE 6.4. BRPR Series S-1 Preproduction Sintering Data

Lot Number	Lubricant, wt%	Green Density, mg/m ³	Sintering Time, hr	Sintering Temp., °C	Average Pellet Density, %TD	Resinter Pellet Density, %TD
SR-48-1	0.3 Sterotex	5.45	2.8	1650	94.47	95.39
"	0.3 Sterotex	5.45	2.8	1700	94.78	95.53
"	0.3 Sterotex	5.45	2.8	1600	93.61	95.19
"	0.5 Sterotex	5.45	2.8	1700	94.00	94.87
"	0.5 Sterotex	5.45	2.8	1650	93.51	94.79
"	0.5 Sterotex plus 0.1 Zinc Stearate	5.45	2.8	1700	93.20	-
133-2/ SR54-2	0.2 Zinc Stearate	5.85	3.9	1780	92.96	(a)

(a) No resinter test was performed on powder Lot 133-2/SR54-3 because it was inactive and would not resinter over 0.5%TD.

Little difficulty was encountered in vibrationally compacting the BRPR Series S-1 test rods. Techniques and experience gained from the HBWR Series H-1 rods were utilized to produce the longer rods for BRPR.

Results of the process development parameter studies are summarized in Table 6.5.

6.2.3 BRPR Graphite Coating Process Development

A decision was made to switch from Dag 154 which was used on the HBWR Series H-1 fuel rods to Dag 4 for the BRPR Series S-1 rods. The use of Dag 4 was preferred because of its superior adhesion and wear resistance properties as compared to Dag 154.

The graphite coating techniques developed for DAG-154 did not change as a result of changing to Dag. 4. Most of the process development activities concentrated on verifying the compatibility of Dag 4 with the zircaloy cladding tubes and residual water associated with outgassed Dag 4 as well as the water sorption characteristics of Dag 4 on exposure to various atmospheres.

6.3 Fuel Rod Fabrication - BRPR Series S-1

6.3.1 BRPR Pellet Fabrication

The pellets for BRPR Series S-1 fuel were made based on the parameters developed from preproduction testing.

The annular-chamfered pellets were made from powder Lot SR4S-1 (2.69% enriched) with 0.5 wt% sterotex and 0.1 wt% zinc stearate used as the lubricant. The pellets were pressed to a green density of 5.45 mg/m^3 and fired at 1730°C for 2.8 hours at temperature. Average final densities were 93.60%TD (Std. Dev. = 0.31%TD). Resinter test data were 94.25%TD (Std. Dev. = 0.32%TD).

The reference dished chamfered pellets were made from powder Lot 133-2/SR54-2 (2.52% enriched). Two-tenths weight percent zinc stearate was used as the lubricant. The pellets were pressed to a green density of

TABLE 6.5. BRPR Series S-1 Vipac Process Development Data

Test No.	UO_2 Loading Time, min	Pneumatic Vibration Time, min	Branford Vibration Time, sec ^(a)	Smear Density, % TD
1	4.0	5.0	20	86.2
2	2.75	4.0	30	86.3
3	2.75	3.25	20	86.8
4(b)	3.25	4.25	30	86.8
5	0.75	1.75	10	88.2
6	1.75	2.75	25	86.7
7	1.25	2.25	45	86.5
8	1.25	2.75	50	86.6
9(c)	1.0	1.50	30	86.2
10(c)	1.0	2.0	--	87.0

(a) Branford operated at 5 cycles/sec for all tests

(b) Cladding strain test rod

(c) Segmented test rod

5.85 mg/m³ and fired for a total of 11.2 hours at 1780°C. Average final densities were 93.86%TD (Std. Dev. = 0.10%TD). Resinter test results were 94.36%TD (Std. Dev. = 0.13%TD).

6.3.2 BRPR Fuel Rod Fabrication

One hundred forty-three demonstration fuel rods were fabricated for BRPR Series S-1.

The rod types and quantities are listed in Table 6.6. Examples of the serial numbers are shown in Table 6.7. Vipac process parameters for all the vipac fuel rods are listed in Table 6.8. The fuel rods were completed on October 4, 1978, and shipped to BRPR on October 13, 1978.

The final shipment of the demonstration rods was as-planned except for fuel rod No. KP300009 (vipac fuel rod). This rod was sectioned and down-loaded at selected axial locations in order to determine the source of a few bright-appearing particles that showed on the neutron radiographs of the vipac rods. The fuel from the selected sections was spread on flat plates and neutron radiographed. From these neutron radiographs, suspect particles were selected for isotopic analysis and determined to be 11% enriched fuel. No other foreign materials were found in the fuel. The particles, which were few in number, were evidently 11% ²³⁵U material which had inadvertently been introduced into the 2.52% ²³⁵U material from cross (6.2) contamination of the processing equipment which was used mutually in the HBWR Series H-1 and BRPR Series S-1 fabrication campaigns. An analysis was performed which showed that because of the small size of the particles, the enrichment, and the few number of 11% enriched particles present, no deleterious operational effects are expected in BRPR. This experience indicates a need for strict enrichment cleanout procedures to be accomplished after each fabrication of packed-particle fuel. Additionally, commercial fabrication of this fuel type would require equipment designs that facilitate thorough cleanout.

Density uniformity for the vipac fuel rods was measured with the Densigauge. The 5 mm wide x 1.5 mm high slit traversed a 12.7 mm segment of the axial length in 10 seconds and the signals were cumulated over that time,

TABLE 6.6. BRPR Series S-1 Demonstration Fuel Rods

Demonstration Rod ^(a)	Type	Quantity	Rod Type
1		24	2.52 wt% ²³⁵ U, reference, full-length demonstration rod.
2		20	2.69 wt% ²³⁵ U, annular, full-length demonstration fuel rod.
3		20	2.69 wt% ²³⁵ U, annular-coated, full-length demonstration fuel rod.
4		24	2.69 wt% ²³⁵ U annular-coated-pressurized, full-length demonstration fuel rod.
5		15	2.52 wt% ²³⁵ U, vipac-pressurized, full-length demonstration fuel rod.
6		16	2.52 wt% ²³⁵ U, standard G-4 medium-enrichment, pellet, full-length characterized rod.
7		4	Segmented fuel rod with rod Type 1 configuration in upper and middle segments and Type 1 configuration with coated cladding in lower segment.
8		4	Segmented fuel rod with rod Type 1 configuration in upper and middle segments and pressurized Type 1 configuration in lower segment.
9		4	Segmented fuel rod with rod Type 1 configuration in upper segment and Type 2 configuration in middle and lower segments.
10		4	Segmented fuel rod with rod Type 1 configuration in upper segment and Type 3 configuration in middle and lower segments.
11		4	Segmented fuel rod with Type 1 configuration in upper segment and Type 4 configuration in middle and lower segments.
12		4	Segmented fuel rod with Type 1 configuration in upper segment and Type 5 configuration in middle segment and unpressurized Type 5 in lower segment.

(a) Keyed to Figures 6.13 and 6.14.

TABLE 6.7. BRPR Series S-1 Fuel Rod Serial Numbers

<u>Rod Type</u>	<u>Serial Numbers (Example)</u>
1. Reference, full-length demonstration rod	KR300001
2. Reference, upper segment rodlet	KR310001
3. Reference, middle segment rodlet	KR320001
4. Reference-pressurized, lower-segment rodlet	KR330001
5. Reference-coated, lower-segment rodlet	KL330001
6. Annular, full-length demonstration rod	KM600001
7. Annular, middle-segment rodlet	KM620001
8. Annular, lower-segment rodlet	KM630001
9. Annular-coated, full-length demonstration rod	KN600001
10. Annular-coated, middle-segment rodlet	KN620001
11. Annular-coated, lower-segment rodlet	KO630001
12. Annular-coated-pressurized, full-length demonstration rod	KO600001
13. Annular-coated-pressurized, middle-segment rodlet	KO620001
14. Annular-coated-pressurized, lower-segment rodlet	KO630001
15. Vipac-pressurized, full-length demonstration rod	KP300001
16. Vipac-pressurized, middle-segment rodlet	KP320001
17. Vipac, lower-segment rodlet	KP330001
18. Standard pellet rod	KE300001

KEY:

K Big Rock Point Reactor G-4
 E Series 1 fuel form
 3 Enrichment
 0 Type of rod or rodlet
 001, 002, etc. - Pin serial number

CODE:

Fuel Form:

R Reference or reference-pressurized
 L Reference-coated
 M Annular
 N Annular-coated
 O Annular-coated-pressurized
 P Vipac
 E Standard Pellet

Type of Rod/Rodlet

0 Full length demonstration rod
 1 Upper segment rodlet
 2 Middle segment rodlet
 3 Lower segment rodlet

Enrichment:

3 - 2.52 wt% ²³⁵U
 6 - 2.69 wt% ²³⁵U

TABLE 6.8. BRPR Series S-1 Vipac Rod Fabrication Parameters

<u>Fuel Serial Number</u>	<u>Material Loading Time, Min.</u>	<u>Pneumatic Vibrator Time, Min.</u>	<u>Branford Vibrator Time, sec</u>	<u>Smear Density, %TD</u>
KP300001	2.0	40	45	86.3
KP300002	2.0	4	25	86.1
KP300003	1.5	10	40	86.9
KP300004	1.5	20	15	86.7
KP300005	3.75	10	10	87.5
KP300006	3.0	30	24	87.1
KP300007	2.3	15	30	86.9
KP300008	1.3	30	75	86.9
KP300009	1.0	55	35	86.1
KP300010	1.6	60	45	86.1
KP300011	2.0	40	7	86.8
KP300012	2.0	10	10	86.9
KP300013	2.25	40	20	87.1
KP300014	1.25	45	90	87.4
KP300015	2.1	50	60	87.2
KP300016	2.0	40	30	86.5
KP320001	1.9	5	20	86.9
KP320002	1.25	6	30	87.1
KP320003	0.75	10	30	86.1
KP320004	1.1	10	15	87.3
KP330001	1.1	7	30	86.5
KP330002	1.5	7	35	87.4
KP330003	0.6	4	10	87.6
KP330004	1.1	5	15	87.3

Branford operated at 5 cycles/sec.

Particle size distribution in all rods and segments was:

50 wt%	1190-3360 μm
17.5 wt%	250-1190 μm
10 wt%	105-250 μm
2.5 wt%	74-105 μm
10 wt%	44-74 μm
10 wt%	minus 44 μm

thus providing an average density for each segment. Some localized density variations were found in the lower segments of some of the full-length rods. Ten of the sixteen full-length rods showed several discrete locations near the lower end of the rod with a density less than 84%TD. (Rods with a localized density significantly below the specified range in high power locations of the rod were rebuilt.) Centerline temperature calculations for the low density regions near the lower ends of the rods were deemed acceptable with respect to BRPR fuel performance because of the expected low heat rating in these regions. None of the segmented rods had any localized density variation below 83%TD.^(6.3)

Eleven Deviating Material Reports (DMR's) were issued for the BRPR Series 1 demonstration fuel. Seven DMR's were for finished fuel rods (overall length, nuclear assay standard, non-seated lower insulator disc, localized variations in density in vipac rods, and cross-contamination of 11% vipac material). Two DMR's were for welds, (small void, weld cover) one DMR was for pellets (process control sample for the outgas run) and one DMR was for vipac fuel (total gas content).

The production pellets and rods for BRPR Series S-1 were characterized as per the requirements listed in Appendix B. A characterization report will be written detailing all the measurements taken on this fuel.

REFERENCES

- 6.1 "Safety Analysis Report for Big Rock Point DOE Fuel Performance Improvement Program Series 1 Demonstration Fuel Assemblies", XN-NF-78-18, Exxon Nuclear Company, Inc., Richland, WA, July 1978.
- 6.2 "BRPR Vipac Particle Analysis", S. R. Wagoner, DMR 07805, Pacific Northwest Laboratory, Richland, WA, September 21, 1978.
- 6.3 "Localized Density Variations in Vipac Rods", DMR 07770, P. G. Sarafian, Exxon Nuclear Company, Inc., Richland, WA, September 14, 1978.

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

M. H. Campbell (Exxon Nuclear Company)

Packed-particle fuel was selected as one of the concepts for evaluation as a part of the Fuel Performance Improvement Program because localized cladding deformation is expected to be virtually absent with this type of fuel. Initially, fuel shards made from UO_2 densified by the Dynapak process were loaded into fuel rods using the vipac technique to achieve rod density. Because in comparison to fuel shards, spherical particles would be expected to provide a more uniform axial density, less cladding strain during loading, potentially better performance characteristics, and a process more potentially adaptable to production line operation, sphere-pac fuel is the preferred option and is being developed as a part of this program.

Oak Ridge National Laboratories (ORNL) is producing the UO_2 microspheres for the HBWR Series H-2 and the BRPR Series S-2 rods. Three size fractions of microspheres were recommended by ORNL for fabricating rods that would have an average smear density of $87 \pm 1\%TD$. The size of each of the three fractions and the percent of each fraction required in a rod is listed in the following table.

TABLE 7.1. UO_2 Microsphere Size Fraction

<u>Size Fraction</u>	<u>Sphere Diameter, μm</u>	<u>Amount, %</u>
Coarse	1150-1410	56
Medium	280-320	27
Fine	24-40	17

In addition to the particle diameters in Table 7.1, the following specifications were tentatively established for the particles:

Shape:	All material will be in the form of spheres.
Density:	The target sphere density will be $>99\%TD$.
Chemical and Nuclear:	Conform to "ANSI/ASTM C-766-76 Standard Specification for Sintered Uranium Dioxide Pellets"

An initial 10 Kg batch of depleted UO_2 microspheres was prepared for rod loading tests. Following that, 11% enriched UO_2 sphere-pac material is needed for the HBWR Series H-2 and 2.52% enriched UO_2 sphere-pac material is required for the BRPR Series S-2. The sphere-pac needs for the FPIP program are summarized in Table 7.2.

TABLE 7.2. Sphere-Pac Needs for FPIP

<u>Material</u>	<u>Use</u>	<u>Amount</u>
UO_2 , Depleted	Trial Loading	10 Kg
UO_2 , 11% ^{235}U	Halden H-2	5 Kg
UO_2 , 2.52% ^{235}U	BRPR S-2	50 Kg

A visit was made to ORNL to observe sphere-pac fuel fabrication techniques and establish equipment requirements for this operation. Two rod loading techniques, infiltration and simultaneous addition (all three fractions at once), are being evaluated by ORNL. These techniques are described below.

- Infiltration

A 0.6 meter (two-foot) long rod is loaded by infiltration. Vibratory feeders are used to add the coarse (1200 μm) and medium coarse (300 μm) fractions simultaneously. A funnel with a screen on the bottom is then rested on top of the fuel column and aliquots of the fine particles are added to the funnel; a follower rod with an 850 g weight is placed on the fines; and a syntron vibrator is used to infiltrate the fines into the bed of coarse spheres. The process of making additions of fines and vibrating requires about 20 minutes. The smear density of the finished rod is 86.5%TD. The syntron vibration is quite mild compared to the vipac vibrator.

- Simultaneous Addition

A 1.83 meter (six-foot) long rod is loaded by adding all three fractions simultaneously so that a complete rod loading is added with the desired particle size distribution. After loading and

prior to vibration, an excess amount of spheres remains in the funnel stem. A short duration vibration settles the column of fuel so that the funnel can be removed and the follower rod placed on top of the fuel column.

The loading operation requires about four minutes using the same syntron feeder devices mentioned above. The rod is vibrated for eight minutes with a follower rod in place to a smear density of about 87.0%TD. Down-loading is achieved by merely pouring the spheres from the rod. A modest 1% breakage of the large spheres, which comprise 58% of the loading, occurs during the loading process. There is an attendant increase in the medium coarse fraction indicating that fracture of some of the large spheres occurs.

The vibrator assembly for the simultaneous addition technique is quite unique and simple and is shown in Figure 7.1. The 1.83 meter long rod is clamped into the vee of a stainless steel angle iron. Two air-driven vibrators are attached to the outer surface of the angle iron; one at 1/3 height and the other, on the opposite side, at 2/3 height. When in operation, the air vibrator creates a medium amplitude vibration (as compared to the syntron and the Branford used for vipac).

In order that the two loading techniques could be compared, ORNL loaded four 1.83 meter long fuel rods with the depleted UO_2 microspheres. Two of the rods were prepared by infiltration and two by simultaneous addition. These rods were neutron radiographed and the axial density was measured in the Densigauge. The neutron radiograph showed a distribution which was more uniform than that observed for the shards loaded by the vipac technique. There were easily identified, low density regions at the top of the rods prepared by the simultaneous addition technique. The neutron radiographs clearly showed the presence of the coarse fraction of spheres and a lack of fine spheres in this region. Gamma densitometry (Densigauge) confirmed the neutron radiography results by showing low densities in the upper 2-3 mm and very constant densities in the 86-88%TD range

all along the rest of the rods. The lack of small spheres in the upper region of the two rods loaded by the simultaneous addition technique indicates a need for careful formulation and control of the particle size fractions. The overall cumulative densities measured by the Densigauge are compared with the ORNL calculated densities in Table 7.3.

TABLE 7.3. Density Comparison for Sphere-Pac Rods

<u>Characteristic</u>	<u>Test Rod - 1.83 m (6') Nominal</u>			
	<u>E-1</u> ^(a)	<u>E-2</u> ^(a)	<u>E-3</u> ^(b)	<u>E-4</u> ^(b)
Size Fraction, g				
Coarse	748.2	742.2	698.8	701.7
Medium	243.6	249.8	236.5	237.5
Fines	198.5	208.1	252.9	254.0
Calculated Density,%TD	86.3	87.1	86.2	86.6
Average Axial Density (Densigauge),%TD	86.1	86.3	86.1	86.5

(a) Infiltration

(b) Simultaneous addition

Agreement was excellent except for Rod E-2. There is no immediate explanation of this difference; however, it is anticipated that a small increase in the fine fraction will adequately compensate.

Chemical analyses of the individual fractions showed few differences between fractions. One exception was the chlorine value (12 ppm) found in the fine fraction compared to the less-than-detection (<5 ppm) values found for the coarse and medium fractions. Even so, the chlorine value is within the specification value. The reason for the positive value is probably due to the washing procedure for the fine spheres after formation. Attention is being given this possibility at ORNL.

The ORNL sol-gel process for sphere formation is provided below to give a full perspective of the processes involved in preparation of UO₂ microspheres.

Coarse and medium spheres are prepared by mixing an amine gellation agent with acid deficient uranyl nitrate. This mixture (broth) is maintained at $<0^{\circ}\text{C}$ until it is formed into droplets discharged into a trichloroethylene carrier solution which is held at $60-70^{\circ}\text{C}$. The internal gellation process is nearly instantaneous at this temperature and the resulting spheres are suspended in the carrier due to their similarity in density. The carrier is pumped over a screen that collects the spheres which are subsequently washed with $1.5\text{M NH}_4\text{OH}$.

The fines are prepared in a similar manner; however, the process requires a surfactant and these spheres are prepared on a batchwise basis. There is a clumping problem that lowers the yield markedly. The ORNL staff is actively seeking to improve this segment of the preparation process.

The washed spheres are dried in an oven. Early attempts to air dry produced a different color product (yellow vs. orange) that had a much lower density and smaller grain size. Calcination is conducted in a 4% H-96% Ar atmosphere at 450°C . Sintering is carried out at 1700°C in a hydrogen atmosphere. The sphere shrinkage is eight-fold from drying through sintering. Sintered spheres are sieved and sorted on a shape table.

FIGURE 7.1. Fuel Rod Loading Vibrator Assembly for Sphere Pac

8.0 TASK 3 - FUEL PERFORMANCE EVALUATIONS

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8.1 General Activities

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. The task activities are intended to provide the basic resources from which technical bases for fuel design can be established.

Performance evaluation involves establishing the data requirements as they relate to preirradiation characterization, postirradiation evaluations, and data analysis. Evaluation of the fuel concepts under study will utilize the information developed in the various testing phases of this program as well as results obtained from ongoing FCI-related programs supported by DOE, EPRI, and other organizations. Performance evaluation necessitates thorough characterization of the fuel rods prior to irradiation in order to permit detailed preirradiation and postirradiation data comparisons. The pre-irradiation information or data requirements for the Task 2B Halden experimental rods and the Task 2C BRPR demonstration rods were finalized and are presented in Appendixes A and B. This listing involves extensive data gathering to fully characterize the rods in order to form the basis for performance evaluation and data analysis.

Careful attention to an evaluation of the conditions to which the experiments are exposed in the reactor during irradiation is essential in order to develop technical bases. Activities were initiated to define irradiation history data requirements for the Halden Boiling Water Reactor (HBWR) and the Big Rock Point Reactor (BRPR). It is planned to supplement the existing computerized data system at BRPR with additional data that will most likely have to be obtained by reviewing the operational records and expanding the normal fuel management calculations. The additional information being considered may include such things as:

- Once a week for thermal power if plant is operating at essentially constant power.

- Up ramps of power reported according to category of slow, moderate, or fast ramp rate, unless they exceed 3%/hour, in which case actual rates are required.
- Down ramps of power, including scrams, reported according to category of slow, moderate, or fast.
- Core flux maps at least weekly, if feasible.
- Offgas activity increase reported in terms of number of estimated rods with pin hole defects, if possible.
- Coolant flow and temperature data for FPIP channels reported at least as frequently as axial flux profiles (core maps).
- Water chemistry and coolant activity reported at least twice a week if offgas indicates suspected defects; once a week if no defects.
- Report any abnormal occurrences affecting core operation.

Interim and end-of-life basin examinations will be supplemented by the destructive examination of selected rods in hot-cell facilities to evaluate the effects of the test parameters on fuel-cladding interactions and reactions. The requirements for these examinations is being assessed.

A program report file was established and a computerized data file system for use in evaluating program results and developing bases for commercial fuel design analysis will be established and maintained. These activities have been initiated.

8.2 HBWR Series H-1 Performance

As described in Section 5.1.2, irradiation of HBWR Series H-1 was started in the HBWR during the last quarter of the year. Data tapes for the initial operation were received recently, however, sufficient time has not been available to adequately analyze the results. However, observations in two areas, temperature response and rod elongation, were considered noteworthy enough to provide preliminary evaluations at this time.

8.2.1 Fuel Temperatures

Fuel central temperatures in the annular-pellet fuel rod design are expected to be lower than in the reference dished-pellet design for equivalent operating heat ratings.^(8.1,8.2) The measured fuel centerline temperatures in the annular, annular-coated, and reference fuel rods during the second startup of IFA-518 are shown in Figure 8.1. The second startup was selected because the highest linear heat ratings achieved in IFA-518 were obtained during this power ascension. No significant differences in measured temperature trends occurred between the first and second power ascensions. At linear heat ratings in excess of 42 kW/m, the measured central fuel temperature of the annular rod is approximately 200°C lower than the measured temperature in the reference rod. Also shown in Figure 8.1 are the predicted central fuel temperatures at startup for a linear heat rating of 42.2 kW/m in the annular and reference fuel rods operating in the HBWR (including a 73°C correction for the presence of the thermocouple in the reference fuel). The temperature predictions were based upon calculations using the GAPCON-THERMAL-3 code^(8.3) which has a fuel fragment relocation model that is both power and burnup dependent. The measured central fuel temperature in the HBWR Series H-1 rods were less than predicted. This is expected because GAPCON-THERMAL-3 is designed to give conservatively high beginning-of-life fuel temperatures. As expected, due to the small decrease in gap conductance caused by the graphite coating on the inside cladding surface, the central fuel temperatures in the annular-coated rod were intermediate between those in the annular and reference rod.

After a burnup of approximately 20 GJ/kg, the central fuel temperatures in the reference, annular, and annular-coated rods have increased approximately 55°C, 45°C, and 20°C, respectively. The increases are tentatively attributed to a reduction in gas conductivity in the fuel-cladding gap regions caused by fission gas dilution of the helium fill gas.

Measured central fuel temperatures in the two vipac rods containing thermocouples are compared with temperatures in the reference fuel in Figure 8.2. Again the second startup of IFA-518 was selected for the comparison. The predicted value at a linear heat rating of 42.2 kW/m

FIGURE 8.1. Comparison of Fuel Centerline Temperatures in Pelletized Rods in IFA-518 During the Second Startup

FIGURE 8.2. Comparison of Fuel Centerline Temperatures in Vipac Rods in IFA-518 During Second Startup

determined by using the vipac thermal conductivity data of Calza-Bini^(8.4) and a fuel-cladding heat transfer coefficient of $8500 \text{ W/m}^2\text{-}^\circ\text{C}$ is also shown in Figure 8.2. Although a significant difference in central temperature between two vipac rods might be expected due to localized variations in fuel density, the difference between the two measurements is probably higher than would be expected. During subsequent operation to a burnup of approximately 200 GJ/kg, the fuel temperature in Rod 14 has increased approximately 55°C (consistent with the pelletized rods), while the indicated temperature in Rod 13 has decreased about 150°C . The general behavior of the indicated fuel temperature from Rod 13 is unusual and it is possible that the thermocouple is providing unreliable signals. Examination of the preirradiation neutron radiographs of Rods 13 and 14 indicate nothing unusual in the region of the thermocouple junction. The indicated temperature behavior of vipac Rods 13 and 14 will continue to be closely monitored.

8.2.2 Rod Elongation

Cladding elongation behavior during irradiation of the test rods in IFA-518 is considered to be the primary means of evaluating the comparative fuel-cladding mechanical interaction behavior of the different fuel types. The elongation of the four lower cluster rods equipped with the elongation sensors during the initial power ascension is shown in Figure 8.3. Fuel-cladding mechanical interaction (FCI) was expected to occur in the vipac rod, while no pellet-cladding interaction (FCI), except possibly at peak powers, was expected to occur in any of the pelletized rods. FCI would have been expected in the pelletized rods at high power, only if fuel fragmentation and relocation caused wedging and hard interaction of the fragments within the cladding tube. The expansion curves of the pelletized rods indicate that no significant FCI occurred during the initial startup. A rough calculation indicated that the observed increase in length was representative of the free thermal expansion of the Zircaloy-2 cladding. The average of the free expansion of the pelletized rods is illustrated as a dotted line (Figure 8.3). It is offset from the actual data in order to better compare the slopes of the curves, i.e., the offset itself does not imply FCI.

FIGURE 8.3. Rod Elongation in Lower Cluster Rods of IFA-518 During Initial Startup

The elongation of the vipac rod during the initial startup deviated significantly from what would be the free expansion curve for the cladding as the power was increased. The deviation of the slope of the cladding elongation curve from the cladding thermal expansion curve decreased until, on the average, the slope of the two curves was approximately the same over the average rod heat rating range of 16 to 32 kW/m. However, a significant offset from what would be a free thermal expansion curve for the cladding existed. The above observations are tentatively interpreted to indicate that significant fuel-cladding interaction occurs immediately as the power is increased during the first startup. This is followed by a nearly constant degree of interaction with further power increase. Perhaps an equilibrium stress state between the fuel and cladding at high power during the initial power ascension is indicated. After steady state operation for approximately two hours at the peak power condition, most of the rod elongation attributed to fuel-cladding interaction in the vipac rod recovered by fuel and/or cladding relaxation. Minor readjustment of particle positions, fuel and cladding creep, and/or in-reactor sintering of the vipac fuel particles is indicated. During the first reduction from full power, the rod length decrease nearly followed the cladding free contraction curve.

Rod elongation in vipac Rod 13 during three subsequent power ascensions, as well as the initial ascension, is shown in Figure 8.4. The degree of interaction, especially at low and intermediate powers, becomes less as irradiation continued. The elongation curve for the second power ascension illustrates that the vipac rod was "conditioned" during the first short operating periods because essentially no fuel-cladding interaction occurred at heat ratings below 14 kW/m and only moderate interaction occurred between 14 and 26 kW/m. Only when the operating power approached and exceeded the heat rating achieved during the initial ascension did fuel-cladding interaction increase significantly. Subsequent power increases have been limited to powers below the second ascension. Therefore, fuel-cladding interaction has only been minor.

FIGURE 8.4. Comparison of Fuel Rod Elongation in Vipac Fuel Rods During Several Startups

REFERENCES

- 8.1 Fuel Performance Improvement Program, Quarterly Progress Report, October-December, 1977, C. E. Crouthamel, COO-4066-5, January, 1978.
- 8.2 W. J. Bailey and J. O. Barner, Assessment of Fuel Concepts, COO-4066-3/PNL-2490, January, 1978.
- 8.3 D. D. Lanning, C. L. Mohr, F. E. Panisko, and K. B. Stewart, GAPCON-THERMAL-3 Code Description, PNL-2434, January, 1978.
- 8.4 A. Calza-Bini, G. Cosoli, G. Filacchioni, M. Lanchi, A. Nobili, U. V. Rocca, P. L. Rotoloni, B. Marsico and G. Trezza, "Thermal Behavior of Fuel Pins for Power Reactors," Nuclear Fuel Performance, International Conference, London, October 15-19, 1973.

9.0 TASK 4 - ESTABLISHMENT OF TECHNICAL BASES

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The objective of Task 4 is to interpret program results to facilitate commercial application by establishing technical bases for design and design criteria. Technical bases for design provide the foundation and best state-of-the-art for product design. They include technology which has been established through research and development studies, from operating experience and from licensing requirements. They also include the analytical methods, behavior models, and calculational procedures for computer codes which have been accepted for design use.

The establishment of technical bases in this program is concerned with the development of an appropriate data base, the selection of analytical procedures which are applicable for use in the design of fuel with improved power cycling capability, and the assessment of performance of the new fuel concepts as they would be used in a commercial power reactor.

The technical bases task produces technical bases documentation, technical bases data and performance files, and a final assessment interpreting the performance data and special material data in terms of commercial LWR performance.

9.1 Technical Bases Documentation

The technical bases documentation is an integral part of the design package documentation that supports the technical adequacy of each fuel design. The technical bases documentation being written and evaluated to support the special fuel designs of FPIP consists of:

- Fuel Rod Performance Design Criteria
- Thermal-Hydraulic Compliance
- Mechanical Performance
- Fuel Material Compositional Requirements
- Fuel Pellet Physical Characteristics
- Packed-Particle Characteristics
- Graphite-Coated Characteristics

The Fuel Rod Performance Design Criteria Bases is organized into the following five sections:

1. General Rod Design Criteria
2. Fuel Requirements
3. Fuel Pellets
4. Packed-Particle Fuel
5. Graphite-Coated Cladding

All the other Bases are organized into the general format of:

1. Criteria
2. Methods and Codes
3. Technical Bases
4. Behavior Models and Property Descriptions
5. References

The initial development of the bases was for the reference fuel. The technical bases were derived from existing literature documentation and were reviewed. After this initial review, a revised format was developed and another version was written that included sections on annular fuel, packed-particle characteristics, and graphite coating characteristics. This version was then circulated for further review. The technical bases for the annular and packed-particle fuel were weak in several areas and developments were required to strengthen thermal-mechanical design evaluations. Additional work was completed on the bases for the mechanical modeling of the annular fuel and the thermal-mechanical modeling of the packed-particle fuel. These special developments have also been circulated for general FPIP comments and have been incorporated into the design evaluation procedures for the BRPR fuel irradiation design evaluations.

The mechanical evaluation procedure for the annular pellets includes consideration of fuel movement into the central hole. A multideformational mechanism model including plastically deforming fuel ring, an elastic-creeping annular ring and an outer annular ring of cracked fuel undergoing creep compression has been developed. This model predicted greatly reduced pellet-cladding interaction pressures than those that were predicted for solid pellets under similar operational conditions.

The thermal-mechanical models for the packed-particle fuel have been extended to include the theoretical concepts used in modeling packed-particle beds and soils. These models were needed to extend the empirically based thermal models to account for pressurization, changing fill gas conductivity and varying packed-particle densities. These developments have also helped define data needs for the technical bases for packed-particle fuel.

The technical bases documentation has been developed to form a design bases documentation that includes data and criteria for the newer fuel concepts. The bases are continually being updated as new material is obtained from the laboratory tests and design studies for the new FPIP fuel concepts.

9.2 Technical Bases Data

Data bases for the Technical Bases are being established in a computer compatible form. A performance file format based on the LWR fuel performance file used for the FRAP-S verification studies has been modified to include data on the new fuel concepts, power and flow histories records compatible with those generated for the BRPR, and specific fuel fabrication data of significance to detailed performance assessment. The procedures for generating the power histories for the BRPR demonstration rods have been described in the report, System Description for Generating Operational Power Histories for Big Rock Point Fuel Rods. This report has been sent to the FPIP Program Office for project use. All file treatment programs described in this report are operational and have been used to generate histories of previously irradiated BRPR fuel rods. These histories were generated in a performance file compatible form and have been used in establishing design histories for the fuel to be tested in BRPR. The performance file not only helps to establish design histories, but it also provides defined minimal data requirements for performance assessment of the FPIP irradiated fuel rods.

As the technical bases for the new fuel concepts and the performance data base from previously irradiated rods of design similar to the FPIP fuel concepts are developed, references are collected into a computer

compatible reference file. This file includes key word indexing, cross referencing information, the documentation source information, and editing comments. An extensive reference file has been developed using this system and is kept in a file whose current contents can be readily obtained by anyone in the program.

9.3 Performance Files

Since no FPIP-supported irradiations were completed during this year, no performance assessments were made. Several requirements in developing the technical bases and supporting design evaluations did provide needed capabilities for future performance assessment. The use of the performance file in developing a design history demonstrated that the power history generation procedure will be operative for future performance assessments and that the performance file contains sufficient input information for performance evaluation. The development of thermal-mechanical models for the annular and packed-particle fuel required for design evaluation will also be required for the performance assessment evaluations. Thus, the general information flow is being organized to facilitate the performance assessment once measurements of irradiated fuel performance become available. Some definition of required basin and post-irradiation measurements for performance assessments has been supplied by the technical bases task. Much of this guidance has been based on results from other projects where such performance assessments have been made. This type of guidance has been built into the performance measurement data fields defined within the existing data formats. Since detailed work in this area is presently in progress in other programs, the advances from these programs are being factored into the general performance file data requirements.

APPENDIX A

CHARACTERIZATION REQUIREMENTS FOR
HBWR SERIES H-1 FUEL RODS

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APPENDIX A

CHARACTERIZATION REQUIREMENTS FOR HBWR H-1 FUEL RODS

<u>Characteristic</u>	<u>Requirement</u> ^(a)	<u>Form of Information</u>	<u>Responsible</u> ^(b) <u>Organization</u>
1. Rod Identification	Rod no. on end plug and cladding tube serial no.	Provide inspection sheets.	QC ^(c)
2. Rod Type	Refer to as reference, annular, packed-particle, annular-coated, thermocouple, elongation sensor and pressure sensor rods.	Provide inspection sheet relating type of rod to identification number on end plug.	QC & MPE
3. Rod			
a. length	Precision ± 0.05 mm (± 0.002 in.) corrected to 20°C	Provide data sheet	QC
b. Weight	Precision ± 0.1 gram	Provide data sheet	MPE
c. Diameter	ENC: Hand micrometer, 3 locations with 2 orientations, 0 and 90° precisions ± 2.5 μ m (± 0.0001 in.) Halden: Nominal axial profilometer traces, 45° apart, axial, circumference reference on rod precision 2.5 μ m (0.0001 in.)	Provide data sheet	PNL (After shipping)
d. Component Location	Three full-length (including end caps) radiographs, 60° apart (overlapping segments). Include in the x-rays a stepped wedge of width dimensions measured to ± 2.5 μ m (± 0.001 in.) The stepped bar shall be centered along the rod length to provide an axial reference point for the two overlapping x-rays along the rod	Provide radiographs. Verify instrumented end cap internal arrangement.	QC ME & PNL

APPENDIX A (Continued)

<u>Characteristic</u>	<u>Requirement^(a)</u>	<u>Form of Information</u>	<u>Responsible^(b) Organization</u>
	length. Resolution capability should be sufficient to detect a large, out-of-place chip of fuel, $\sim 75\mu\text{m}$ (± 0.030 in.) (viewed edgewise), and roughly 3.8 mm ($\pm .150$ in.) the other dimensions.		
e. Fuel Enrichment Identification	Pellet identification mark or powder identification card noted on loading inspection sheet.	Record and retain inspection sheet (2 signatures).	QC
	Passive assay	Provide passive assay data.	MPE
f. Fuel Column Density	Packed-particle and pellet axial density variation.	Provide gamma densitometer traces (neutron radiography optional).	MPE
	Packed-particle average column density	Provide powder fuel weight and column length and calculated density.	MPE
g. Weld Conditions	Radiograph, voids plus inclusions, no greater than $25\mu\text{m}$ (0.010 in.)	Provide radiographs. One orientation.	QC
h. Instrumentation	Verify thermocouple rods in working order with electrical continuity after autoclaving. (Seal with epoxy after checks.)	Provide test results for continuity and resistance	MPE
i. Fill Gas	Certify >99.9% He of purchased fill gas.	Provide data sheet containing gas analysis.	QC
	Verify prototypic rod sample atmosphere $\geq 99.9\%$ He (at least 50 ml. free volume).	Provide analysis result.	QC

APPENDIX A (Continued)

<u>Characteristic</u>	<u>Requirement</u> ^(a)	<u>Form of Information</u>	<u>Responsible</u> ^(b) <u>Organization</u>
j. Loading Procedure	General description of technique	Description (non-proprietary).	MPE
k. Surface Treatment	General description: cleaning, etching, autoclaving.	Description (non-proprietary).	MPE
4. Cladding			
a. Purchase Order	Reference.	On file at ENC	MP
b. Fabricator Certs	Records of ingot, trex, tube, as available.	Provide copies of records.	QC
c. Overcheck Results	As available.	Provide data sheets	QC
d. Surface Treatment	Describe and characterize result: routine treatment of inner and outer surfaces, also special preparation in vicinity of welds, especially with coated cladding.	Provide description (non-proprietary)	MPE
e. Lot Identity	Lot identification.	Retain tubing lot identification.	QC
f. Tube Identity	Tubes identified with respect to section in original tube.	Identification mark on tube. Provide inspection sheet showing location and orientation.	QC & MPE
g. Dimensions	ID, OD, wall to precision $\pm 5\mu\text{m}$ (± 0.0002 in.)	Retain charts.	MPE
h. Coating Process	Summarize process procedures. Measure average thickness on each cladding. Characterize thickness variability on samples.	Provide summary, data sheets, photos.	MPE

APPENDIX A (Continued)

<u>Characteristic</u>	<u>Requirement (a)</u>	<u>Form of Information</u>	<u>Responsible (b) Organization</u>
i. Coating Morphology	Characterize particle orientation and coating density (%TD). Characterize defects before and after loading.		PNL
j. Coating Chemistry	Measure oxide layer thickness. Measure H pickup in clad after bake-out. Chemically analyze coating after bake-out.		QC & MPE
5. Fuel (Both Enrichments)			
a. Material Purchase Order	Reference.	On file at ENC	MP
b. Processing Procedure	General description of technique.	Describe (non-proprietary)	MPE
c. Pellet Location in Rod	Follow behavior of each pellet.	Provide loading record with identity of each pellet and its location in each rod.	MPE
d. Dimension	Each pellet, diameter and length to precision $\pm 2.5 \mu\text{m} (\pm 0.0001 \text{ in.})$	Provide data sheets.	MPE
	On a 70 pellet/lot basis measure end squareness chamber, dish, land, taper, etc., as applicable.	Provide data sheets. 70 pellets/lot (each pellet of low enrichment).	QC
	On a 70 pellet/lot basis measure the min.-max. diameter difference (circumferentially) to $\pm 2.5 \mu\text{m} (\pm 0.0001 \text{ in.})$ precision.	Provide data sheets. 70 pellets/lot (each pellet of low enrichment).	QC

APPENDIX A (Continued)

<u>Characteristic</u>	<u>Requirement^(a)</u>	<u>Form of Information</u>	<u>Responsible^(b) Organization</u>
	On a 70 pellet/lot basis measure the annular pellet hole diameter (top & bottom) to $\pm 2.5\mu\text{m}$ (± 0.0001) in. precision.	Provide data sheets. 70 pellets/lot (each pellet of low enrichment).	QC
	Photograph packed-particle on SEM for surface condition and size distribution.	Provide photos.	MPE & QC
e. Chemical Content Before Out-Gas	Analyze 5 pellet/lot or fine 7g samples of powder fuel for total U, N, Fe, F, Cl, B, Cd, others as feasible. Perform isotopic analysis of U for masses 234, 235, 236, 238 on 2 pellet/lot or 2 7g samples of particle fuel. Results to be standard precision.	Provide copies of analysis results (from records if low enrichment).	QC
f. Metallographic Analysis	Photos of 5 pellets/lot or 5 (coarse mesh) particle fuel samples/lot adequate to determine grain size, porosity size and distribution and the presence of second phases, 50X-250X-500X, as-polished and as-etched.	Provide photos with proper identification	QC
g. Resinter Test for Densification Properties	Standard 5 pellets/lot.	Provide data sheets (from records if low enrichment).	QC & MPE
h. Absorbed Gas and Water Vapor After Out-Gas	Analyze 5 pellets/lot for N_2 , O_2 , H_2O , total H, and total gas, standard precision. O/U and U.	Provide data sheets (from records if low enrichment).	QC

APPENDIX A (Continued)

Characteristic	Requirement ^(a)	Form of Information	Responsible ^(b) Organization
i. Batch Identification	Each rod.	Reference in inspection records.	MPE
j. Fuel Density	Immersion density, 10 pellets/lot or 3 samples (+6 mesh) particle/lot.	Provide data sheet (from records if low enrichment).	QC
	Geometric density, 70 pellets/lot.	Provide data sheet (from records if low enrichment).	QC
k. Fuel Weight	±0.1 gram each rod.	Provide data sheet.	MPE
l. Pellet Defects	Categorize defects on cylindrical surface and defects that may produce small chips.	Provide photos of pellets representing marginal appearance, average, excellent, appearance. Record of marginal, average or excellent on loading sheets for each pellet.	QC MPE
6. Insulator Disks			
a. Dimensions	Diameter to ±13 μm (+0.0005 in.) length to ±25 μm (0.001 in.), 5 disks	Provide data sheet	MPE
b. Material	General chemical analysis, 1 pellet.	Provide data sheet	QC
c. Absorbed Gas	Moisture and total gas, 1 pellet.	Provide data sheet.	QC
d. Density	Typical immersion density, 5 pellets.	Provide data sheet.	QC
7. Zircaloy Frits	Moisture and total gas, 3 samples (after bake-out and 24 hrs. storage).	Provide data sheet.	QC

APPENDIX A (Continued)

<u>Characteristic</u>	<u>Requirement^(a)</u>	<u>Form of Information</u>	<u>Responsible^(b) Organization</u>
8. Miscellaneous			
a. Springs	Surface cleanliness.	Describe cleaning (non-proprietary).	MPE
b. Instrumentation Checkout	Inspect end caps for damage.	Radiograph, single orientation.	QC & MPE
c. Welding Procedure	General description of assembly procedure	Describe (non-proprietary).	MPE
9. Archives			
a. Cladding	One 0.30 m(12. in.) sample from each tube used for fuel rods, half as coated and baked out and half uncoated.	Retain	MPE collect
b. Fuel	Five pellets from each batch or 40 g packed-particle fuel.	Retain	MPE collect
c. End Pellets	Five end pellets from each pellet lot.	Retain	MPE collect
d. End Plug Material	Six'in. of bar stock from each lot.	Retain	MPE collect
e. Springs	One from each wire lot.	Retain	MPE collect
f. Rods	One of each fuel form with non-instrumented end caps.	Retain	MPE collect

APPENDIX A (Continued)

FOOTNOTES

- a. Quantity of samples is minimum recommended
- b. Responsibility organization indicates organization with primary responsibility
- c. PNL = Battelle, Pacific Northwest Laboratory
ME = ENC Mechanical Engineering
MP = ENC Materials & Purchasing
MPE = ENC Materials & Process Engineering
PO = ENC FPIP Program Office
QC = ENC Quality Control

APPENDIX B

CHARACTERIZATION REQUIREMENTS FOR BRPR SERIES S-1 FULL-LENGTH CHARACTERIZED, DEMONSTRATION FUEL RODS AND SEGMENTED FUEL RODS

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APPENDIX B

CHARACTERIZATION REQUIREMENTS FOR BRPR SERIES S-1 FULL LENGTH CHARACTERIZED, DEMONSTRATION FUEL RODS

AND

SEGMENTED FUEL RODS

<u>Characteristic</u>	<u>Requirement^(a)</u>	<u>Form of Information</u>	<u>Responsible^(b) Organization</u>
1. Rod & Rodlet Identification	Mark on end plug	Provide inspection records.	QC ⁽³⁾
2. Rod & Rodlet Type	Refer to as reference, annular, packed-particle, annular-coated, reference coated, or characterized.	Provide inspection record relating type of rod to identification number on end plug.	QC & MPE
3. Rod & Rodlet			
a. Length (end to end)	Precision $\pm 51\mu\text{m}$ (± 0.002 in.) corrected to 20°C.		QC
b. Diameter	Precision $\pm 2.5\mu\text{m}$ (± 0.0001 in.) spiral profilometry 3D tester, ID&OD). Axial profilometry @ 0° & 90° with respect to reference mark on end plug(OD).		QC & FP
c. Leak Check	$< 10^{-8}$ std. atm cc/sec criterion.	Provide statement that criterion was met.	QC
d. Component Locations	Three full length radiographs, 60° apart (overlapping segments). Include in the x-rays a stepped wedge with dimensions measured to $\pm 25\mu\text{m}$ (± 0.001 in.)	Retain radiographs.	QC

APPENDIX B (Continued)

<u>Characteristic</u>	<u>Requirement^(a)</u>	<u>Form of Information</u>	<u>Responsible^(b) Organization</u>
3. Rod & Rodlet (continued)			
d. Component Locations (continued)	Resolution capability should be sufficient to detect a large, out-of-place chip of fuel, $\sim 76\mu\text{m}$ (0.030 in.) thick viewed edgewise) and roughly 3.8 mm (0.150 in.) in the other dimensions.		
e. Fuel Enrichment	Passive, non-destructive assay technique	Provide charts, calibrations	QC
f. Fuel Column Density	Packed particle axial density variation.	Provide gamma densitometer traces.	MPE
g. Weld Conditions	Radiograph, voids, inclusions to greater than 0.25 mm (0.010 in.)	Retain radiographs.	QC
h. Fill Gas	Purity >99.9% He. (Particle fuel amended per product spec.)	Provide weld chamber or gas bottle analysis results.	QC
	Rod internal pressure ± 1.8 Pa (± 2 psi), corrected to 21°C.	Provide data	MPE
i. Loading Procedure	General description of technique.	Description (non-proprietary).	MPE
j. Surface Treatment	General description: cleaning, abrading, etching, autoclaving.	Description (non-proprietary).	MPE

APPENDIX B (Continued)

<u>Characteristic</u>	<u>Requirement^(a)</u>	<u>Form of Information</u>	<u>Responsible^(b) Organization</u>
k. Neutron Radiography	16-particle fuel rods 24-segmented rods	Provide films	HEDL/MPE
4. Cladding			
a. Purchase Order	Reference.	On file at ENC	MP
b. Fabricator Certs	Records of ingot, trex, tube, as available.	Provide copies of records.	QC
c. Overcheck Results	As available.	Provide data	QC
d. Coating Process	Summarize process procedures; measure average thickness on each cladding. Characterize thickness variability on samples.	Provide summary, data, photos.	MPE
e. Coating Chemistry	Measure oxide layer thickness. Measure H pickup in clad after bakeout. Chemically analyze coating after bakeout.	Provide results.	QC & MPE
5. Fuel			
a. Processing Procedure	General description of technique.	Describe (non-proprietary).	MPE
* b. Dimensions			
Rodlets	O.D. $\pm 2.5\mu\text{m}$ (± 0.0001 in.) of each pellet in middle and bottom segments. Labeled so locations in the pellet stack are known.	Provide record showing identity of each pellet and its location in each rodlet.	MPE

*50 pellets/lot acceptable for standard fuel only.

APPENDIX B (Continued)

<u>Characteristic</u>	<u>Requirement^(a)</u>	<u>Form of Information</u>	<u>Responsible^(b) Organization</u>
5. Fuel (Continued)			
b. Dimensions (Continued)			
Rods & Rodlets	On a 70 pellet/lot* basis, measure diameter and length to precision $\pm 2.5\mu\text{m}$ ($\pm 0.0001\text{in.}$)	Provide data sheets or charts.	QC
"	On a 70 pellet/lot basis measure end squareness, dish, land, taper, etc., as applicable.		
"	On a 70 pellet/lot basis measure min.-max diameter difference to $\pm 2.5\mu\text{m}$ ($\pm 0.0001\text{ in.}$) precision.		
"	On a 70 pellet/lot basis measure annular pellet hold diameter (top & bottom) to $\pm 2.5\mu\text{m}$ ($\pm 0.0001\text{ in.}$) precision.		
c. Chemical Content	Analyze 35 pellets/lot or 35 7g samples of particle fuel/lot for total U, N, Fe, F, Cl, B, Cd, others as commercial practice dictates. Perform isotopic analysis of U for masses 234, 235, 236, 238 on two pellets or two 7g samples of particle fuel/lot.	Provide copies of analysis results.	QC
d. Metallo- graphic Analysis	Photos adequate to deter- mine grain size, porosity size and distribution, second phases, 50X, 100X, and 300X, as-polished and as-etched on one sample before resinter (plus one more after resinter, if applicable).	Provide photos with proper identification	QC

*A lot is defined as powder which is uniform in isotopic, chemical and physical characteristics and which has been processed to assure uniformity. UO_2 power is lot blended after conversion to assure uniformity.

APPENDIX B (Continued)

<u>Characteristic</u>	<u>Requirement^(a)</u>	<u>Form of Information</u>	<u>Responsible^(b) Organization</u>
5. Fuel (continued)			
d. Metallographic Analysis (continued)			
	Photograph powder fuel by SEM for surface condition and size distribution.	Provide photos	MPE
e. Resinter Test for Densification Properties	Standard test, 5 pellets/lot.	Provide data.	QC & MPE
f. Absorbed Gas & Water Vapor, etc.	Analyze 5 pellets or 5 7g samples of particle fuel/lot for N ₂ and O ₂ . Analyze 34 pellets or particle fuel samples/lot for H ₂ O, total H, O/U, U, and total gas. Standard precision.	Provide data. N ₂ and O ₂ for information only.	QC/HEDL
g. Lot or Sublot Identification	Each rod.	Reference in inspection records.	QC & MPE
h. Fuel Density	Immersion density 10 pellets or 3 samples of +6 mesh particle fuel/lot. Geometric density of 70 pellets/lot.	Provide data.	QC
i. Fuel Weight	± 0.1 g each rod.	Provide data.	QC & MPE

APPENDIX B (Continued)

<u>Characteristic</u>	<u>Requirement^(a)</u>	<u>Form of Information</u>	<u>Responsible^(b) Organization</u>
j. Pellet Defects	Categorize defects on cylindrical surface and defects that may produce small chips. On segmented rods, middle and lower segment only.	Provide photos of pellets representing marginal, average, and excellent appearance. Provide loading records.	QC
6. Insulator Disks			
a. Dimensions	Diameter to $\pm 13\mu\text{m}$ (± 0.0005 in.) length to $\pm 25\mu\text{m}$ (± 0.001 in.), 5 disks.	Provide data.	QC
b. Material	General chemical analysis, 1 disk.	Provide data.	QC
c. Absorbed Gas	Typical gases and values, 1 disk.	Provide data.	QC
d. Density	Typical immersion, 5 disks.	Provide data.	QC
7. Miscellaneous			
a. Springs	Surface cleanliness.	Describe (non-proprietary).	MPE
b. End Plugs	Contribution to internal volume.	Provide drawings.	ME
c. Welding Procedure	General description of assembly procedure.	Describe (non-proprietary).	MPE
8. Archives			
a. Cladding			
Rods	Standard ENC practice plus as-coated and baked samples.	Retain.	MP

APPENDIX B (Continued)

<u>Characteristic</u>	<u>Requirement^(a)</u>	<u>Form of Information</u>	<u>Responsible^(b) Organization</u>
8. Archives (continued)			
a. Cladding (continued)			
Rodlets	One sample of each length used in segmented rods plus coated and baked samples.	retain.	MP
b. Fuel	Five pellets from each lot, 40 g packed-particle fuel.	Retain	QC
c. Insulator Disks	Five disks/lot.	Retain	MP
d. End Plug Material			
Rods	Six inches/lot of rod stock (if available).	Retain	MP
Rodlets	Six inches/lot of rod stock (if available)	Retain if different lot than end cap lot for full length rods.	MP
e. Springs			
Rods	One from each wire lot.	Retain	MP
Rodlets	One segment plenum spring from each wire lot.	Retain	MP
f. Rods	One of each type (full length not necessary)	Retain	QC
9. Drawings			
Assembly and Details	Complete information on dimensions, specifications, procedures should be available as needed on each rod type.	Provide drawings.	ME

APPENDIX B (Continued)

FOOTNOTES:

- a. Quantity of samples is minimum recommended. Where a requirement is common to both full length and segmented rods, it need only be satisfied once and not duplicated for both types (e.g., fuel chemistry for pellet lot used in both rod types).
- b. Responsible organization indicates organization with primary responsibility.
- c. PNL = Battelle, Pacific Northwest Laboratory
ME = ENC Mechanical Engineering
MP = ENC Materials & Purchasing
MPE = ENC Materials & Processing Engineering
QC = ENC Quality Control
FP = ENC Fuel Performance

APPENDIX C

CONVERSION TABLE FOR SI UNITS

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CONVERSION TABLE FOR SI UNITS^(a)

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

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

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

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

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

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