Fuel Performance Improvement Program

Quarterly Progress Report
April - June 1978
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Work on this program is performed for the
UNITED STATES DEPARTMENT OF ENERGY
by
CONSUMERS POWER COMPANY and EXXON NUCLEAR COMPANY, INC.
Under Contract EY-76-C-02-4066
and by
PACIFIC NORTHWEST LABORATORY, Operated by BATTELLE MEMORIAL INSTITUTE,
Under Contract EY-76-C-06-1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy $_____; Microfiche $3.00

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FUEL PERFORMANCE IMPROVEMENT PROGRAM

Quarterly Progress Report
April - June 1978

Compiled by C. E. Crouthamel
Exxon Nuclear Company, Inc.
Richland, Washington 99352

July 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 EY-76-C-06-1830.

Approved:  
L. P. Bupp
Program Office

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SUMMARY


With the completion of the topical report titled, "State-of-the-Technology Review of Fuel-Cladding Interaction" (COO-4066-2/PNL-2488) and the inclusion of final comments and completion of the report titled, "Assessment of Fuel Concepts" (COO-4066-3/PNL-2490), activities associated with this task are considered to be completed.

Task 2 - Testing and Demonstration Program

The BRPR Series S-1 test matrix (Figure 3.1) has been expanded to include what is considered to be an optimized PCI-remedy fuel design, i.e., annular pellets with coated-cladding and prepressurization (4-6 atmos. of He) capable of achieving high burnup. Including the 16 additional non-chamfered "product" line rods that will receive equivalent characterization, the BRPR S-1 matrix now consists of 144 rods, 24 of which are segmented. After irradiation in BRPR, selected segmented rods or rodlets will be ramp tested in a suitable test reactor. Another optimized fuel design is being tested in this program, e.g., prepressurized-packed particle fuel. However, because of the greater impact in manufacturing and the more limited data base the development of this optimized concept lags that of the optimized pellet design. The word "optimized" is used in this report to refer to fuel designs where a number of improvement parameters are all placed in a fuel design together rather than a parametric study. The latter is considered to be too costly and time consuming in nuclear fuel development.

In addition, expansion of the program scope to include two (2) lead demonstration assemblies for Big Rock Point Reactor and four (4) lead assemblies irradiation in Oyster Creek Reactor is being considered and has been added to the program as Tasks 2G and 2H, respectively. As currently planned, the leads will incorporate the optimized PCI-remedy design and would be designed to achieve extended burnup, i.e., bundle average as high as 38 GWD/MTM, in order to demonstrate the commercial viability of the optimized design before proceeding on a commercial batch load scale.
Task 2A - Out-of-Reactor Studies

The major deficiency associated with the use of Dag 154 was the fact that the outgassed material was vulnerable to pellet abrasion. A search for a more tenacious graphite coating led to a dag containing alumina and silica additions which displayed increased durability. Evaluation of this material (designated as Dag '4) is in progress with the objective of qualifying the material for use in the BRPR Series S-1 demonstration irradiations.

The major problem encountered is that Dag 4 contains more residual water than Dag 154 after outgassing, and appears to absorb water at a higher rate than Dag 154.

Task 2B - In-Reactor Experiments

Fabrication of the twelve test rods, and six spare rods, for the HBWR H-1 and loading of the IFA-518 test rig was completed on schedule during the quarter. The eighteen test rods were shipped to Halden, Norway on April 30, 1978, and arrived on May 2, 1978. Final assembly of the IFA-518 test rig was completed during the quarter. All rig and rod instrumentation operated satisfactorily. The rig was loaded into Position 3-14 in the HBWR core in mid-June in preparation for startup during the second week of July.

Neutron radiographic examination of the finished rods was performed at the Hanford Engineering Development Laboratory. The quality of these radiographs was excellent and clearly showed the internal fuel geometry.

Task 2C - In-Reactor Demonstrations

Vented end caps were utilized to prevent porosity in the end closure welds due to the rise in the internal rod gas pressure during welding.

Chamfered pellets were prepared for BRPR Series S-1 fuel to avoid the pellet chipping which occurred during Halden test rod fabrication.

The design package, XN-NF-S30679, has been revised and issued.
Task 2E - Sphere-Pac Loading and Engineering Tests

Oak Ridge National Laboratory has agreed to prepare microspheres of UO₂ and general specifications have been established. A delivery schedule for 11% and 2.52% enriched spheres has been agreed upon.

Task 4 - Establishment of Technical Bases

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

Application of the thermal-mechanical technical bases to actual design evaluations for annular fuel is in progress.
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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 performance of the program involves the direct participation of Consumers Power Company (CPC), Exxon Nuclear Company (ENC), and Pacific Northwest Laboratory (PNL). The program is under prime contract to CPC from the U.S. Department of Energy (DOE). The majority of the work is under subcontract to ENC and to PNL. The functional arrangement of the program organization by task is shown in Figure 1.1.

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.

REFERENCES


FIGURE 1.1

FUEL PERFORMANCE IMPROVEMENT PROGRAM
PROGRAM ORGANIZATION

DOE

CPC PRIME CONTRACTOR
STEERING COMMITTEE

TASK 5
PROGRAM OFFICE
ENC

QA & LICENSING
ENC

TASK 1
ASSESS STATE-OF-THE-TECHNOLOGY AND POTENTIAL IMPROVED CONCEPTS
PNL

TASK 2
TESTING AND DEMONSTRATION COORDINATION
PNL

TASK 2A
OUT-OF-REACTOR EXPERIMENTS
PNL

TASK 2B
IN-REACTOR EXPERIMENTS
PNL

TASK 2C
IN-REACTOR DEMONSTRATIONS
ENC

TASK 2E
SPHERE-PAC ENGINEERING TESTS
ENC

TASK 2G
BRPR LEAD ASSEMBLIES
ENC

TASK 2H
OCR LEAD ASSEMBLIES
ENC

TASK 3
PERFORMANCE EVALUATION
PNL

TASK 4
TECHNICAL BASES
ENC
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 was to assess the state-of-the-technology of fuel-cladding interaction and to identify fuel concepts with potential for improved performance capabilities in order to provide direction and technical support for the Fuel Performance Improvement Program. The state-of-the-technology review presents a summarization 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 titled, "State-of-the-Technology Review of Fuel-Cladding Interaction" (C00-4066-2/PNL-2488) and the inclusion of final comments and completion of the report titled, "Assessment of Fuel Concepts" (C00-4066-3/PNL-2490), activities associated with this task are considered to be completed.
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 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 program includes Task 2A, Out-of-Reactor Studies; Task 2B, In-Reactor Experiments; Task 2C, In-Reactor Demonstrations; Task 2E, Sphere-Pac Engineering Tests; Task 2G, BRPR Lead Assemblies; and Task 2H, OCR Lead Assemblies.

Task 2A activities provide out-of-reactor supportive data needed for the initial Task 2B irradiation experiments in the Halden Boiling Water Reactor (HBWR) and the initial Task 2C demonstration irradiations in the Big Rock Point Reactor (BRPR). Task 2B involves an in-reactor testing program that consists of screening tests conducted in the HBWR followed by ramping of individual rods in the HBWR ramping rig and primary tests that consist of irradiations to significant burnups in Big Rock Point Reactor (BRPR) followed by ramping in a suitable test reactor. Task 2C activities involve the design, process development, and fabrication of the screening test rods for irradiation in HBWR and a significant number of fuel rods comprising the primary fuel concepts for demonstration irradiations in BRPR. Task 2E focuses on procuring sol-gel-derived microspheres and manufacturing sphere-pac fuel rods for irradiation in the HBWR and BRPR.

Coordination of sub-task activities is continuing in order to maintain scheduled progress. With the completion of the instrumented test rods for the Halden H-1 test, attention is being focused on the resolution of problems associated with producing the BRPR Series S-1 demonstration rods. Progress in addressing the critical items is being made.
<table>
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<tr>
<th>Fuel Form</th>
<th>Parameters</th>
<th>Full-Length Rods</th>
<th>Segmented Rods&lt;sup&gt;(b)&lt;/sup&gt;</th>
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<tr>
<td>Vipac</td>
<td>-- Yes&lt;sup&gt;(a)&lt;/sup&gt;</td>
<td>16</td>
<td>4 [4]&lt;sup&gt;(d)&lt;/sup&gt;</td>
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<tr>
<td>Annular</td>
<td>Yes Yes</td>
<td>24</td>
<td>4 [4]</td>
</tr>
<tr>
<td></td>
<td>Yes No</td>
<td>20</td>
<td>4 [4]</td>
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<td></td>
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<td>-</td>
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<td>No Yes</td>
<td>-</td>
<td>- [4]</td>
</tr>
<tr>
<td></td>
<td>No No</td>
<td>24&lt;sup&gt;(c)&lt;/sup&gt;</td>
<td>8 -</td>
</tr>
</tbody>
</table>

<sup>(a)</sup> Depending on process development results
<sup>(b)</sup> Number of segmented rods (each consisting of three rodlets) and the number of middle segment rodlets for ramp testing. Numbers in [ ] are lower segment rodlets and are considered to be spares. Top segment rodlets all contain reference pellets and primarily function as spacers.
<sup>(c)</sup> An additional 16 non-chamfered "product-line" rods will receive equivalent characterization. All other pellets are chamfered.
<sup>(d)</sup> Lower segment rodlets are non-pressurized.

FIGURE 3.1 Big Rock Point Reactor Series 1 (S-1) Matrix
The BRPR Series S-1 test matrix (Figure 3.1) has been expanded to include what is considered to be an optimized PCI-remedy fuel design, i.e., annular pellets with coated-cladding and pressurization (4-6 atmos. of He) capable of achieving high burnup. Including the 16 additional non-chamfered "product line" rods that will receive equivalent characterization, the BRPR Series S-1 matrix now consists of 144 rods, 24 of which are segmented. After irradiation in BRPR, selected segmented rods or rodlets will be ramp tested in a suitable test reactor.

In addition, expansion of the program scope to include two (2) lead demonstration assemblies for Big Rock Point Reactor and four (4) lead assemblies for irradiation in Oyster Creek Reactor is being considered and has been added to the program as Tasks 2G and 2H, respectively. As currently planned, the leads will incorporate the optimized PCI-remedy design and would be designed to achieve extended burnup, i.e., bundle average as high as 38 GWD/MTM, in order to demonstrate the commercial viability of the optimized design before proceeding on a commercial batch load scale.

Currently the annular-coated-pressurized design is designated as an optimized PCI-remedy fuel design. 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 a PCI-remedy, this concept will be developed as a back-up optimized design as part of this program.
4.0  TASK 2A - OUT-OF-REACTOR EXPERIMENTS

L. R. Bunnell and C. L. Mohr (Pacific Northwest Laboratory)

The purpose of this task is to conduct application-oriented out-of-reactor experiments in support of the development and demonstration of fuel concepts that will minimize fuel-cladding-interaction (FCI) failures, thereby improving fuel performance. During the past quarter, effort was concentrated on the characterization of an improved graphite coating for the inside surface of the cladding. This dag is more adherent and more resistant to pellet abrasion during pellet loading and shipping, and as a result, should display improved PCI behavior. Efforts are underway to qualify this material for use as the coating for the BRPR Series S-1 demonstration irradiations. The major problem with this material appears to be high moisture content. Whether or not this material will be used in BRPR Series S-1 depends on the outcome of experiments currently in progress. Some effort was also devoted to the characterization of siloxane coatings for the inside cladding surface. Modeling efforts of fuel-cladding-interaction continued and initial results are reported.

4.1  Evaluation of an Improved Graphite Coating

As mentioned in the previous quarterly report, the only major deficiency associated with the use of Dag 154 was the fact that the outgassed material was vulnerable to pellet abrasion; accordingly, pellet loading for HBWR Series H-1 was performed in a manner designed to minimize scratching through the coating to expose bare metal. A search for a more tenacious graphite coating led to a dag containing alumina and silica additions, which displayed increased durability. Evaluation of this material, designated as Dag 4, which was obtained from the same vendor as the previous dags, is in progress. The objective is to qualify the material for use in the BRPR Series S-1 demonstration irradiations. The major problem encountered is that Dag 4 contains

(a) Acheson Colloids, Port Huron, MI.
more residual water than Dag 154 after outgassing, and appears to absorb water at a higher rate than Dag 4 after outgassing. The current status of the evaluation of Dag 4 is summarized as follows:

4.1.1 General Characteristics

Dag 4 is water-based but contains no obviously hydrophilic material such as sodium silicate. The material contains alumina and silica which apparently results in increased adherence to the cladding inside surface and abrasion resistance. As-deposited Dag 4 has a density of 1.55 g/cc, as determined by mercury displacement. Impurities determined by emission spectroscopy are listed in Table 4.1. Because alumina and silica are both present in large quantities, they were analyzed by a different technique. Oxidizing the graphite at 700°C produced an ash containing mainly alumina and silica. This ash comprised 33.5% of the weight of the dried dag residue. The composition of this ash, as determined by x-ray fluorescence, was 47% SiO₂, 36% Al₂O₃, 2.5% Fe₂O₃, and 0.4% CaO, all in wt.%. Because the foregoing numbers do not add to 100%, they should be regarded as approximate. Hence, the dried solids from Dag 4 contain about 16% SiO₂, 12% Al₂O₃, 0.8% Fe₂O₃, and 0.1% CaO. X-ray diffraction of the oxide showed that it was completely amorphous. The halide content of the dag was determined to be 717 ppm Cl and 50 ppm F, both based on the solids weight after drying.

4.1.2 Application Methods Development

During the past quarter, an improved method for applying dags was developed. Figure 4.1 compares the improved method with the method used previously. The convenience of the new method substantially improves the coating of cladding for BRPR Series S-1 and would be applicable to virtually any coating applied as a liquid.
FIGURE 4.1. Comparison of Improved Applicator (MK 2) with Previous Applicator (MK 1)
TABLE 4.1. Spectrochemical Analysis of Dag 4

<table>
<thead>
<tr>
<th>Element</th>
<th>Content, ppm</th>
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</thead>
<tbody>
<tr>
<td>Al</td>
<td>50,000</td>
</tr>
<tr>
<td>Ba</td>
<td>50</td>
</tr>
<tr>
<td>Ca</td>
<td>500</td>
</tr>
<tr>
<td>Cr</td>
<td>&gt;1</td>
</tr>
<tr>
<td>Cu</td>
<td>1</td>
</tr>
<tr>
<td>Fe</td>
<td>200</td>
</tr>
<tr>
<td>Mg</td>
<td>50</td>
</tr>
<tr>
<td>Mn</td>
<td>50</td>
</tr>
<tr>
<td>Na</td>
<td>1,000</td>
</tr>
<tr>
<td>Si</td>
<td>30,000</td>
</tr>
<tr>
<td>Ti</td>
<td>&gt;1</td>
</tr>
<tr>
<td>V</td>
<td>50</td>
</tr>
<tr>
<td>Zn</td>
<td>&gt;1</td>
</tr>
<tr>
<td>Zr</td>
<td>1,000</td>
</tr>
</tbody>
</table>

4.1.3 Thermal Conductivity

The thermal conductivity of Dag 4 was calculated from the thermal diffusivity as determined by the laser pulse method, and is summarized in Table 4.2.

TABLE 4.2. Thermal Conductivity of Dag 4

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Thermal Conductivity, watt/m·°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>82</td>
<td>1.5</td>
</tr>
<tr>
<td>137</td>
<td>1.84</td>
</tr>
<tr>
<td>222</td>
<td>1.99</td>
</tr>
<tr>
<td>377</td>
<td>1.77</td>
</tr>
<tr>
<td>477</td>
<td>1.85</td>
</tr>
</tbody>
</table>
The conductivity of Dag 4 is substantially higher than Dag 154, i.e., by a factor of about 3. This is probably because the graphite platelets are aligned more randomly than with Dag 154. Alignment of the graphite basal planes parallel to the cladding surface, as is the case with Dag 154, exposes the low-conductivity directions to heat flow. A more random orientation produces higher conductivity by exposing more of the high-conductivity directions in the graphite crystal.

4.1.4 Thermogravimetric Analysis

The weight loss of Dag 4 was studied as a function of temperature and time-at-temperature, and compared with that for Dag 154 (Figure 4.2). The weight loss for Dag 4 is much lower than that for Dag 154, and stability at 450°C is more rapidly obtained. This is because Dag 154 contains an organic binder which decomposes relatively slowly, while Dag 4 contains no such binder.

4.1.5 Outgassing and Moisture Pickup

The outgassing of Dag 4 was performed under the same conditions used in the production of the Halden H-1 test rods. The outgassing conditions, which were established by their effect on cladding properties, were 425°C/24 hr at p < 1 x 10^{-2} Pa. After this treatment, analysis by the combustion technique used previously showed that Dag 4 contained more water than Dag 154 outgassed under the same conditions. Dag 4 was also shown to be more hygroscopic than Dag 154. (Table 4.3). It should be noted that the difference in the density of the two graphite coatings (0.95 g/cc for Dag 154, 1.55 g/cc for Dag 4) is partially responsible for the differences in moisture contents because it enters into the fuel-weight conversion. The exposures were performed on bulk dag specimens contained in pyrex ampoules with free access to the surrounding atmosphere. In order to obtain
FIGURE 4.2. TGA Plot Comparing Dag 4 and Dag 154
Heated in Zr-Gettered Ar
TABLE 4.3. Water Content of Outgassed Dags as a Function of Exposure

<table>
<thead>
<tr>
<th>Dag Type</th>
<th>Exposure Atmosphere</th>
<th>Time</th>
<th>Water Content Basis, ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>154</td>
<td>As-Outgassed, 425°C/24 hr, p&lt;1.3 x 10⁻³ Pa</td>
<td>--</td>
<td>1.4</td>
</tr>
<tr>
<td>154</td>
<td>N₂ glove box, 20 ppm H₂O</td>
<td>15 min</td>
<td>1.6</td>
</tr>
<tr>
<td>154</td>
<td>N₂ glove box, 20 ppm H₂O</td>
<td>1 hr</td>
<td>2.2</td>
</tr>
<tr>
<td>154</td>
<td>N₂ glove box, 20 ppm H₂O</td>
<td>24 hr</td>
<td>3.0</td>
</tr>
<tr>
<td>4</td>
<td>As-Outgassed, 425°C/24 hr, p&lt;1.3 x 10⁻³ Pa</td>
<td>--</td>
<td>4.4</td>
</tr>
<tr>
<td>4</td>
<td>N₂ glove box, 20 ppm H₂O</td>
<td>15 min</td>
<td>6.0</td>
</tr>
<tr>
<td>4</td>
<td>N₂ glove box, 20 ppm H₂O</td>
<td>1 hr</td>
<td>4.1</td>
</tr>
<tr>
<td>4</td>
<td>N₂ glove box, 20 ppm H₂O</td>
<td>24 hr</td>
<td>9.1</td>
</tr>
<tr>
<td>4</td>
<td>As-Outgassed, 425°C/24 hr, p&lt;1.3 x 10⁻³ Pa</td>
<td>--</td>
<td>5.3</td>
</tr>
<tr>
<td>4</td>
<td>He glove box, 50 ppm H₂O</td>
<td>15 min</td>
<td>8.1</td>
</tr>
<tr>
<td>4</td>
<td>Air, 52% relative humidity</td>
<td>1 min</td>
<td>8.5</td>
</tr>
<tr>
<td>4</td>
<td>Air, 52% relative humidity</td>
<td>5 min</td>
<td>9.2</td>
</tr>
</tbody>
</table>

more prototypic conditions, experiments are underway in which the dag specimens are placed in a length of Zircaloy cladding during outgassing and exposure.

4.1.6 Adherence and Abrasion Resistance

Pellet abrasion of the thin graphite coatings during pellet loading and during shipping is considered an important factor from the standpoint of PCI behavior during irradiation. The adherence of Dag 4, as determined by a tape stripping test after
outgassing, is comparable to that of Dag 154. However, abrasion resistance is vastly superior to that of outgassed Dag 154. Two-hundred pellets (groups of five with no special care used) loaded into a horizontally positioned tube produced no visible damage of Dag 4 coatings, whereas this treatment produced many scratches in Dag 154, some revealing base metal.

4.1.7 Coating Thickness Control

To obtain the specified coating thickness of $6.4 \mu m \pm 4 \mu m$ with Dag 4, the as-supplied concentration of 24% solids must be diluted. The concentration producing the desired thickness was determined experimentally by flood-coating 51-cm long tubes. Dag 4 does not recoat as well as Dag 154 because the second coat does not adhere well to the first and some of the first coat is removed, so a one-coat application approach is necessary. The average single-coat thickness as a function of solids content is shown in Figure 4.3. Similar data for Dag 154 are included in the figure. As shown, Dag 4 thickness is a fairly steep function of solids content and is not linear, so dilution must be carefully controlled. Thickness profiles obtained on 180 cm lengths of BRPR-sized tubing generally do not show substantial taper in spite of the single-coat application process. The top 10-20 cm of the tubing is slightly thinner but within the specified limits. In the two-coat application method used for Dag 154, the draining direction was reversed between coats in order to minimize thickness variations.

4.1.8 Microstructure

The microstructure of outgassed Dag 4 is characterized by larger particles than the microstructure of outgassed Dag 154 (Figure 4.4). Elemental analysis of the bright area (circled) in Figure 4.4 indicates a higher concentration of aluminum than in
FIGURE 4.3. Single-Application Coating Thickness as a Function of Solids Content. Points are averages; bars represent extremes.
FIGURE 4.4. SEM Micrographs Comparing the As-Deposited Surface of Dag 154 and Dag 4
the matrix. When the oxide residue was examined, similar aluminum concentrations were found. The origin of the localized variations in concentration is not understood.

4.1.9 Dag 4/Zircaloy Compatibility

The compatibility of the graphite coatings with the Zircaloy cladding is acceptable at normal operating temperatures, even including those likely to occur during a postulated LOCA. The alumina and silica additives in Dag 4 are thermodynamically capable of reacting with Zircaloy to form ZrO₂ and free metal. Thermodynamically, alumina could react at temperatures in excess of ~800°C, and silica could react at any temperature. In order to assess whether such reactions would actually occur, compatibility tests were performed using 10-cm long sections of sealed BRPR-sized cladding tubes coated with a 6 µm thick layer of Dag 4 and containing a He atmosphere. A UO₂ pellet was added to each capsule to provide stoichiometry control, and some capsules contained an excess of dag, i.e., ~10 times the normal amount. The capsules (one uncoated control, one coated, and one coated and containing an excess of graphite) were heated in a vacuum furnace. Two heat treatments were used; isothermal heating to 600°C/37 hr representing a severe operating situation, and a time-temperature exposure approximating a LOCA condition. The temperature versus time plot of the latter is shown in Figure 4.5. The high-temperature transient produced extensive ballooning of the capsules, but no failures. Results are summarized in Table 4.4 and pertinent micrographs are shown in Figures 4.6 and 4.7. There is no evidence of a reaction layer for either condition. Also, SEM elemental analysis of the coating/Zircaloy interface region showed no detectable Al or Si. Longer-term tests are being performed to make sure that there are no deleterious reactions between the graphite coating and the Zircaloy cladding.
FIGURE 4.5. Time-Temperature Plot for Transient
<table>
<thead>
<tr>
<th>Capsule Number</th>
<th>Contents</th>
<th>Heating Time, Temperature</th>
<th>External Appearance</th>
<th>Metallographic Results</th>
<th>SEM Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-4</td>
<td>Empty (control)</td>
<td>600°C/37 hr</td>
<td>No change</td>
<td>No reaction</td>
<td></td>
</tr>
<tr>
<td>D-4-7</td>
<td>Coated +UO₂ Pellet</td>
<td>600°C/37 hr</td>
<td>No change</td>
<td>No reaction</td>
<td>No Al or Si in the questioned area</td>
</tr>
<tr>
<td>D-4-8</td>
<td>Coated, UO₂ Pellet, 10x normal amount of Dag 4</td>
<td>600°C/37 hr</td>
<td>No change</td>
<td>No reaction</td>
<td></td>
</tr>
<tr>
<td>C-1</td>
<td>Non-Coated +UO₂ Pellet</td>
<td>1200°C/4 sec</td>
<td>Capsule intact but bulged from pressure, large grains</td>
<td>No reaction (not sectioned adjacent to UO₂)</td>
<td></td>
</tr>
<tr>
<td>D-4-16</td>
<td>Coated, +UO₂ Pellet</td>
<td>1200°C/4 sec</td>
<td>Capsule intact but bulged from pressure, large grains</td>
<td>No reaction layer (not sectioned adjacent to UO₂)</td>
<td>No Al or Si in the coating/cladding interface area examined.</td>
</tr>
<tr>
<td>D-4-17</td>
<td>Coated and UO₂ pellet, 10x normal amount of Dag 4</td>
<td>1200°C/4 sec</td>
<td>Capsule intact but bulged from pressure, large grains</td>
<td>No reaction layer (not sectioned adjacent to UO₂)</td>
<td></td>
</tr>
</tbody>
</table>
FIGURE 4.6. (a) Zircaloy Control Sample and (b) Graphite-Coated Zircaloy Cladding, Both Heated to 600°C/37 Hours.
FIGURE 4.7. (a) Zircaloy Control Sample and (b) Graphite-Coated Zircaloy Cladding, Both Heated to 1200°C for 4 sec.
4.2 **Siloxane Coating Development**

Siloxane compounds are promising as coatings for cladding to alleviate PCI. Investigators in Canada\(^{(4.2)}\) have used siloxanes for this purpose with considerable success, and the siloxane coating appears to be superior to graphite, at least on the basis of limited reported data. Silicone fluids as siloxane compounds and addition of 6-7% silica flour to these fluids increases the viscosity. These materials are commonly used as vacuum greases. The oxidation reaction shown in Figure 4.8 converts the siloxane to a more rigid lacquer containing only a minimal amount of hydrogen. The reaction must be carefully controlled to avoid the formation of only brittle silica on the cladding inside surface. TGA studies have been used to determine the approximate temperature for the reaction. Because oxidation cleavage would involve heating the siloxane-coated Zircaloy tubing in air, an upper temperature limit of \(\sim 350^\circ C\) is imposed. This reaction will require additional investigation, as will application techniques. If silicone fluid is used, the viscosity change with temperature would cause thinning to occur during heating, possibly uncontrollably. On the other hand, applying a uniform, \(\sim 6 \: \mu m\) thick of vacuum grease to the inside surface of a cladding tube is expected to be difficult. Attention is being given to these problems, and a prototype applicator was designed.

4.3 **Mechanistic Studies**

The studies of the PCI failure mechanisms have concentrated on evaluating the results of existing experimental stress-corrosion-cracking-related experiments. As part of this work, detailed finite element models have been prepared for the localized ductility specimens tested by Tomalin\(^{(4.3,4.4)}\) at General Electric, and for a model designed to describe pellet-cladding interaction. The objective of this study is to show the relationship of existing data to the type of data that is most representative of crack initiation and growth as it pertains to PCI fuel failure. An additional objective is to evaluate the feasibility of ex-reactor tests to investigate with statistical significance the existence of a stress or strain threshold that can be correlated with in-reactor data and with fuel performance analysis codes.
FIGURE 4.8. Schematic Representation of the Oxidation Cleavage of Polydimethylsiloxane
The analytical results have shown that significant bending moments are present in Tomalin's experiments \(^{(4.3)}\) and that these experimental results, when considered in the small strain regime required for crack initiation, show significant deviation from plane stress, plane strain, or simple tension conditions.

The pellet cladding interaction analysis model has not been completed; however, a similar analysis performed by Levy and Wilkinson \(^{(4.4)}\) has shown that a significant portion of the cladding is subjected to high bending stresses. The direction and location of the principal bending planes are related to the crack pattern and the frictional effects that are present. Their results show high tensile hoop stress on the cladding inside surface over the pellet-pellet interface region with high tensile axial stresses over the pellet mid-region.

The results of data analysis to date indicate that the testing conditions for crack initiation should include stress gradient conditions as well as environmental effects. The approximation of stress-corrosion-cracking conditions used for threshold evaluations should simulate as closely as possible the chemical, mechanical, and textural effects present in the cladding during PCI. The results that have been obtained to date form the basis for developing the test criteria and relating them to both in-reactor data and fuel performance analyses.

REFERENCES


5.0 TASK 2B - IN-REACTOR EXPERIMENTS

J. O. Barner and S. R. Wagoner (Pacific Northwest Laboratory)

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 the potential for improved operating behavior in LWR's. Initial comparative parametric fuel rod experiments are being performed with 1) a reference, solid, dished-pellet design, 2) an annular-pellet design, 3) the annular-pellet design combined with a graphite coating on the inside surface of the cladding, and 4) vipac fuel designs. The performance characteristics of the improved concepts will be evaluated during the screening tests in which three sequential groups of power-cycling/ramping irradiations will be conducted 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 pre-irradiated in BRPR as part of the Task 2C in-reactor demonstrations. Details of the general testing criteria, the selection of the irradiation facilities, experiment schedule, and the detailed test descriptions were presented previously. (5.1, 5.2)

5.1 Screening Test Status

Fabrication of the twelve test rods, and six spare rods, for the HBWR H-1 loading of the IFA-518 test rig was completed on schedule during the quarter. A considerable amount of the Task 2B effort during the fuel rod fabrication was spent in support and audit activities. The general development of the fabrication equipment and techniques, and the detailed description of the fabrication of the test rods is summarized in Section 6 of this report. Table 5.1 illustrates the rod type matrix for the HBWR H-1 test and the instruments incorporated in each test rod. Originally, all six rods for the lower cluster were intended to contain a fuel thermocouple. However, the thermocouple intended for annular-coated Rod 10
TABLE 5.1. Halden H-1 Test Matrix and Rod Instrumentation

<table>
<thead>
<tr>
<th>Rod Type (a)</th>
<th>Rod No.</th>
<th>Instrumentation (b)</th>
<th>Lower Cluster</th>
<th>Upper Cluster</th>
<th>Spares</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>01</td>
<td></td>
<td>--</td>
<td>--</td>
<td>T, E</td>
</tr>
<tr>
<td></td>
<td>02</td>
<td>T, E</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td></td>
<td>03</td>
<td>--</td>
<td>E</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td></td>
<td>04</td>
<td>--</td>
<td>--</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td></td>
<td>05</td>
<td>--</td>
<td>P</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Annular</td>
<td>06</td>
<td>T, E</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td></td>
<td>07</td>
<td>--</td>
<td>E</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td></td>
<td>08</td>
<td>--</td>
<td>--</td>
<td>E</td>
<td></td>
</tr>
<tr>
<td>Annular-Coated</td>
<td>09</td>
<td>T, E</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>P</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>--</td>
<td>E</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>--</td>
<td>--</td>
<td>E</td>
<td></td>
</tr>
<tr>
<td>Vipac</td>
<td>13</td>
<td>T, E</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>T, P</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>--</td>
<td>--</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>--</td>
<td>--</td>
<td>E</td>
<td></td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>--</td>
<td>E</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>--</td>
<td>P</td>
<td>--</td>
<td></td>
</tr>
</tbody>
</table>

(a) Reference = Solid pellet with dished ends
Annular = Pellet with central 10 volume percent hole
Annular-Coated = Annular pellet combined with graphite coating on cladding inside surface
Vipac = Vibrationally compacted Dynapak feed particles

(b) T = Central fuel thermocouple
E = Cladding elongation sensor
P = Internal Pressure sensor
was broken during fabrication. In addition to all the standard characterization data recorded at ENC, neutron radiographic examination of the finished rods was performed at the Hanford Engineering Developmental Laboratory. The quality of these radiographs was excellent and clearly showed the internal fuel geometry, including the dishes and central holes in the pellet fuel, and individual large particles and some macro-density variations in the vipac fuel.

The eighteen test rods were shipped to Halden, Norway on April 30, 1978, and arrived on May 2, 1978. Rod diameters and rod bow were measured at 0° and 90° orientations using the linear profilometer at the Kjeller Laboratories. The quality of the profilometry was excellent. X-radiographic examination was also completed to inspect the rods for any shipping damage and no significant damage or fuel pellet chipping was observed.

Final assembly of the IFA-518 test rig was completed during the quarter. The rods were inserted into the rig and all instrumentation, including the movement of the absorber shield, was checked out at room temperature and in the hot water calibration loop. All rig and rod instrumentation operated satisfactorily. The rig was loaded into Position 3-14 in the HBWR core in mid-June in preparation for startup during the second week of July. Figures 5.1 and 5.2 illustrate the individual rod locations in the IFA-518 test rig.

An internal Institutt for Atomenergi experimental procedure for IFA-518 was prepared. This document describes the operation, calibration, and safety requirements for the test. In order to study any initial fuel-cladding interactions, the initial startup will proceed from approximately 10% of full power to full reactor power with no power holds for calibrations. The IFA-518 rig will then be power calibrated, using the inlet and outlet thermocouples and flowmeters and the reactor subcooled
FIGURE 5.1. IFA-518 Lower Cluster Loading Map, as Viewed from Above
FIGURE 5.2. IFA-518 Upper Cluster Loading Map, as Viewed from Above
moderator flow. Corrections to the total measured rig power for gamma heating and heat transfer to the external moderator will be made in order to determine the total rig fission power. The individual rod powers will be computed from the total fission power and the output signals from the eight neutron detectors positioned within the rig. These individual rod powers will be corrected for rod geometry, actual fuel weight and length, inclusion of thermocouples, spectral factors caused by the presence of the silver absorber shield, and the flux tilt.

Preparation of an as-built description report for the HBWR H-1 IFA-518 rods has been initiated. It is expected that it will take approximately five months to compile and publish the report.

5.2 Primary Test Status
The primary phase power-ramping tests are to utilize rodlets from the Task 2C Big Rock Point Reactor (BRPR) demonstration irradiations. During the quarter, the BRPR S-1 test matrix for the initial BRP loading was modified to include prepressurization as a test variable. As a result, the total number of variables and the total number of segmented rods for BRPR S-1 were increased. Figure 3.1 lists the modified matrix for BRPR S-1 segmented rods.

5.3 Performance Evaluation Status
Anticipated effects of the presence of fuel centerline thermocouples upon indicated fuel temperatures were reported previously. The effect reported for the reference fuel case is believed to be too large. Investigations into the cause for the discrepancy in the output from the TRUMP code have not identified the problem. Corrected values will be provided as soon as the problem is identified.

A literature search was conducted to obtain information concerning the thermal performance of packed-particle (vipac) fuel rods during irradiation. This effort was initiated to develop a thermal conductance and
restructuring model for packed-particle fuel. After the thermal model has been developed, a fuel-cladding mechanical model will be developed.

Preparations were initiated for the analysis of the data from the in-reactor instrumentation in IFA-518. An existing PDP-11/45 computer system will be used for data handling and a disk file has been ordered. A review of the existing computer programs at PNL used for data manipulations indicates that only minor modifications will be required. Most of these modifications will be required to determine individual rod heat ratings, the methods for allowing for the radial flux tilt and the axial heat generation with the absorber shield in place, and the methods for computing the internal fuel rod pressures. These modifications will be initiated as soon as the raw data logging formats are provided by the Institutt for Atomenergi.

REFERENCES


6.0 TASK 2C - IN-REACTOR DEMONSTRATIONS

R. K. Welty (Exxon Nuclear Company)

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

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

Fuel assemblies containing demonstration fuel rods will be inserted in the reactor with each of four 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. A limited number of fuel rods will be removed periodically (at intermediate burnup levels) from each series for destructive examination or power ramping in a test reactor.

6.1 Design and Analysis

6.1.1 Halden Series H-1

The design package, XN-NF-530679, Rev. 3, (parts list, drawings, and specifications) for Halden Series H-1 test rods which incorporated final design modifications arising during fabrication of the Halden test pins was revised and issued.

The following fuel rod assembly drawings which were included in the January-March, 1978 Quarterly Progress Report(6.1) were revised to include a vented end cap weld. The vented end caps were necessary to prevent porosity in the end closure welds due to the rise in the internal rod gas pressure during welding.
The hole in the vented end caps was sealed after end closure welding with a plug weld. A drawing of a typical end cap with revisions, 303-110-1, is shown in Figure 6.1.

303,115-1 Reference Fuel Rod Assembly w/Elongation Sensor
303,115-2 Reference Fuel Rod Assembly w/Pressure Sensor
303,116-1 Annular Fuel Rod Assembly w/Elongation Sensor
303,117-1 Annular Coated Fuel Rod Assembly w/Elongation Sensor
303,118-1 Packed-Powder Rod Assembly w/Elongation Sensor
303,118-2 Packed-Powder Rod Assembly w/Elongation Sensor
*303,122-1 Packed-Powder Rod Assembly w/Elongation Sensor and Thermocouple
303,122-2 Packed-Powder Rod Assembly w/Pressure Sensor and Thermocouple

*The lower end plug assembly was vented on these rod assemblies due to the presence of the thermocouple in the upper end cap.

6.1.2 Big Rock Point Reactor Series S-1

A revised parts list for Series S-1 Big Rock Point fuel rods, XN-NF-530,673, Rev. 1, was issued. This revision includes the latest designs incorporated into Series S-1 including pressurization of full length and segmented fuel rods.

Table 6.1, "BRPR Series S-1 Demonstration Fuel Rod Designations" summarizes the fuel characteristics of the full length rods and the various combinations of fuel in the segmented rods.

Tables 6.2 and 6.3 summarize the design characteristics of the full length and segmented rods. Fuel and cladding characteristics include reference (solid) fuel pellets, annular (hollow core) fuel pellets, packed-particle (vipac) fuel, graphite-coated cladding, and pressurized rods.

Pressurization was added to the demonstration fuel assemblies in anticipation of its use in the proposed lead assemblies for
the next BRPR reload. Chamfered pellets were chosen to prevent the pellet chipping which occurred during the Halden test rod fabrication. Characterized standard pellet rods were added for comparison between the performance standard ENC G-4 unchamfered pellets and reference chamfered pellets.

The revised configuration of the four Series S-1 demonstration fuel assemblies is shown in Figures 6.2 and 6.3.

The Safety Analysis Report for Series S-1 Big Rock Point Reactor fuel assemblies, XN-NF-78-18, was issued in draft form. This document covers safety-related mechanical, thermal-hydraulic, neutronic and accident analysis aspects of the design of the four BRPR Series S-1 fuel assemblies.

The Irradiation Test Authorization, XN-NF-ITA-77-1, Rev. 1, was revised and issued. This document includes the latest FPIP design modifications for BRPR fuel assemblies.

PTA-235, "DOE FPIP Task 20 Series 1 BRPR Demonstration Fuel Rod Fabrication: was written, reviewed, and submitted for approval. This Process Test Authorization is similar to the document written for the Halden H-1 test rods and covers the fabrication and characterization of the 144 demonstration fuel rods.

6.2 Fuel Fabrication for the Halden H-1 Test Rods

Eighteen Halden fuel test pins were completed and shipped to the Hanford Engineering Development Laboratory (HEDL) on April 26, 1978, for neutron radiography. Neutron radiography was completed on April 27 and the fuel pins were sent to Seattle, Washington, for shipment to Halden, Norway.

The final shipment of the test pins was as planned except for pin No. 10 which was changed from an instrumented thermocouple to a standard end cap due to damage of the thermocouple during rework on the test pin.
A summary of the test pin design matrix is as follows:

<table>
<thead>
<tr>
<th>Test Pin Serial Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1LCR001</td>
<td>Reference pellet with thermocouple and elongation sensor</td>
</tr>
<tr>
<td>H1LCR002</td>
<td>Reference pellet with thermocouple and elongation sensor</td>
</tr>
<tr>
<td>H1UCR003</td>
<td>Reference pellet with elongation sensor</td>
</tr>
<tr>
<td>H1UCR004</td>
<td>Reference pellet with pressure transducer</td>
</tr>
<tr>
<td>H1LCR005</td>
<td>Reference pellet with pressure transducer</td>
</tr>
<tr>
<td>H1LCA006</td>
<td>Annular pellet with thermocouple and elongation sensor</td>
</tr>
<tr>
<td>H1LCA007</td>
<td>Annular pellet with elongation sensor</td>
</tr>
<tr>
<td>H1LCA008</td>
<td>Annular pellet with elongation sensor</td>
</tr>
<tr>
<td>H1LCG009</td>
<td>Annular pellet/graphite coating with thermocouple and elongation sensor</td>
</tr>
<tr>
<td>H1LCG010</td>
<td>Annular pellet/graphite coating with pressure transducer</td>
</tr>
<tr>
<td>H1LCG011</td>
<td>Annular pellet/graphite coating with elongation sensor</td>
</tr>
<tr>
<td>H1UCG012</td>
<td>Annular pellet/graphite coating with elongation sensor</td>
</tr>
<tr>
<td>H1LCP013</td>
<td>Vipac fuel with thermocouple and elongation sensor</td>
</tr>
<tr>
<td>H1LCP014</td>
<td>Vipac fuel with thermocouple and pressure sensor</td>
</tr>
<tr>
<td>H1LCP015</td>
<td>Vipac fuel with pressure transducer</td>
</tr>
<tr>
<td>H1LCP016</td>
<td>Vipac fuel with elongation sensor</td>
</tr>
<tr>
<td>H1UCP017</td>
<td>Vipac fuel with elongation sensor</td>
</tr>
<tr>
<td>H1UCP018</td>
<td>Vipac fuel with pressure transducer</td>
</tr>
</tbody>
</table>

Chipping of the annular pellets occurred during fabrication; this was attributed mainly to a temporary end cap which was used to protect the fuel from atmospheric moisture after loading and prior to final end cap welding. The temporary cap made a snug fit by drawing a cone-shaped metal plug up into a nylon sleeve; however, the fit was so tight that a slight tap on the cap was required to free the plug. This caused a "shock wave" to pass down through the pellet stack which produced chips in some of the pellets. The annular pellets appeared to be relatively more fragile than the reference pellets as demonstrated by cracking of
some of the annular pellets during outgassing. An evaluation of the chamfered pellets is underway to prevent or reduce pellet chipping for BRPR Series S-1 fuel.

The product specification for gas purity in finished fuel rods is 99.5% He. The maximum He content obtainable in the packed powder loading hood is 90-95% He. A technique of purging the packed-particle fuel rods with high purity helium after compaction to displace air entrained in the fuel column was used to bring the fuel pin atmosphere up to specification limits.

Due to the above noted loading box atmosphere, reference fuel rods were also purged after final closure welding by back filling with high purity helium and bleeding off the pressure repeatedly through a small hole drilled through the lower end plug. The small vent hole in the lower end plug was subsequently welded shut.

Packed-particle fuel rods for the Halden H-1 test were measured for axial density by a gamma ray attenuation method on the Densigauge. A new calibration based upon the mass absorption coefficient for UO₂ and for the zircaloy cladding gives improved agreement with the calculated density based upon measurement and weight of feed. Plots of typical data that have been reduced to density by this calibration appear in Figures 6.4, 6.5, and 6.6. Note that the entire rod was not scanned, rather readings at 0.5 in. increments represent an axial length of 0.2 in. of particle fuel.

Thirty-eight deviating material reports were issued during the fabrication of the Halden H-1 test rods. Nine were for hardware items (end caps, frits, insulator discs), five were for pellets (dimensions, impurities), four for packed-particle fuel (impurities), five for finished rods (surface finish, gas atmosphere, processing), and six for welds (voids, root defects).

The welding presented the most difficult problem because the butt joint weld design continued to exhibit voids and root defects. Weld integrity was more than adequate however, based on fatigue crack growth criteria. Leak testing revealed no leaks.
All of the Halden H-1 fuel pins were neutron radiographed at HEDL before shipment to Norway. A generalized comment of the condition of each rod is as follows:

<table>
<thead>
<tr>
<th>Rod Number</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. (Spare)</td>
<td>Little dust around lower insulator. No chips.</td>
</tr>
<tr>
<td>2. (LC)</td>
<td>No chips. Spoon lower end plug weld.</td>
</tr>
<tr>
<td>3. (UC)</td>
<td>No chips.</td>
</tr>
<tr>
<td>4. (Spare)</td>
<td>Dust around lower insulator. Spoon lower end plug weld. No chips.</td>
</tr>
<tr>
<td>5. (UC)</td>
<td>10x20 mil chip sitting on self of 19th 11% pellet from bottom, in gap of 20th. Spoon lower end plug weld.</td>
</tr>
<tr>
<td>6. (LC)</td>
<td>Spoons, upper weld and lower end plug weld. Dust around lower insulator, more than usual for pellet rod. No chips.</td>
</tr>
<tr>
<td>7. (UC)</td>
<td>No chips.</td>
</tr>
<tr>
<td>8. (Spare)</td>
<td>Dust around lower insulator. No chips.</td>
</tr>
<tr>
<td>9. (LC)</td>
<td>6x10 mil chip, 3rd 11% pellet from bottom. 4th 11% pellet has a major offset. Little dust around lower insulator. (Note rods 9 and 10 are mislead on lower two radiographs).</td>
</tr>
<tr>
<td>10. (LC)</td>
<td>Upper insulator has TC hole. 10 mil dia chip wedged in interface between 6th and 7th 11% pellet from bottom. 5x10 mil chip near lower end of 4th 11% pellet. Two or more large chips in lower 90 mils of gap of 1st 11% pellet from bottom.</td>
</tr>
<tr>
<td>11. (UC)</td>
<td>No chips.</td>
</tr>
<tr>
<td>12. (Spare)</td>
<td>Spoon lower end cap weld. No chips.</td>
</tr>
<tr>
<td>14. (LC)</td>
<td>Spoon upper weld. Dust around lower insulator. Dust is separated. Spoon in lower end plug weld.</td>
</tr>
<tr>
<td>15. (Spare)</td>
<td>Separated dust around lower insulator. Spoon lower end plug weld. Lack of fusion lower end cap weld.</td>
</tr>
<tr>
<td>16. (Spare)</td>
<td>Large separation in dust around lower insulator.</td>
</tr>
<tr>
<td>17. (UC)</td>
<td>Spoon lower end plug weld. Separated dust around lower insulator. Few large chips around upper insulator.</td>
</tr>
<tr>
<td>18. (UC)</td>
<td>Spoon lower end plug weld. Dust around lower insulator.</td>
</tr>
</tbody>
</table>
6.3 Fuel Process Development for BRPR Series S-1 Rods

6.3.1 Pellet Process Development

Preproduction tests were started on reference and annular pellet tooling. This tooling is chamfered to help reduce chipping of the annular pellets that was experienced during the fabrication of the Halden fuel.

The testing of the tooling and UO₂ powder will involve pressing, sintering, and outgassing. (Outgas processing of Halden fuel caused some pellet cracking.)

Production of the annular and reference pellets will start in July.

6.3.2 Packed-Particle Fuel Process Development

Thirty-six Kg of ENC UO₂ powder was dynapaked at PNL. The process conditions for producing acceptable particle feed stock were as follows:

A pilot Dynapak can (Can #32) of powder containing 44 grams of -100 mesh recycled scrap from an earlier 4 Kg batch of the same material and 3556 grams of virgin powder was Dynapaked at 1100°C and 975 psi fire pressure to a density of 98.3% TD. Three samples consisting of two approximately 10 gram fragments and about 5 grams of the largest selected particles from a -6 mesh screen size fraction of the Dynapaked material were sintered to an average density of 99.3% TD using the following sintering parameters:

- Heating rate-manually controlled at rapid rate to 500°C; 100°C/hr from 500° to 1750°C; soak time 12 hours at 1750°C; cooled to room temperature in 1-1/2 hours.

- Atmosphere - 50% H₂/50% argon; H₂ was passed over the top of a reservoir of water before reaching the common line where it was mixed with argon.
The packed powder loading hood was modified to accept six-foot BRPR rods. The plan is to test a vibratory feed system to load the UO₂ particles at a measured rate as a mix while vibrating the rod at low frequencies with auxiliary pneumatic vibrators; then compact the rod to final density using the Branford vibrator.

6.3.3 Graphite-Coated Cladding Process Development

Experimental work continued on water analysis for Dag-4 along with zircaloy compatibility with alumina and silica, which are contained in Dag-4. Samples will be exposed to typical pellet loading glove box atmospheres; additional samples will be further exposed to room air for one minute and 5 minute periods (to simulate entry into the weld chamber). Samples are then analyzed for moisture.

The specification for moisture contained in the graphite is 6.5 ppm (fuel weight basis) in order to meet the fuel specification of 1.5 ppm H₂ from all sources. (Pellet fuel averages ~0.5 ppm H₂.)

The equipment for applying graphite to six foot tubes by the improved flood coating technique described in Section 4.1.2 is being installed.

6.3.4 Welding Process Development

Process tests will be conducted on prepressurization of packed-particle fuel to determine the conditions required to evacuation of the fuel pin to prevent dusting and possible weld zone contamination. Permeability of the fuel column will also be studied to determine pressurization requirements.

REFERENCES

TABLE 6.1
BRPR SERIES 1 DEMONSTRATION FUEL ROD DESIGNATIONS

<table>
<thead>
<tr>
<th>Demo. Rod Designation</th>
<th>Quantity</th>
<th>Test Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24</td>
<td>2.52 Wt% U-235, reference pellet full length demonstration rod.</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>2.69 Wt% U-235, annular pellet full length demonstration fuel rod.</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>2.69 Wt% U-235, annular pellet/coated cladding full length demonstration fuel rod.</td>
</tr>
<tr>
<td>4</td>
<td>24</td>
<td>2.69 Wt% U-235, annular pellet/coated cladding/pressurized full length demonstration fuel rod.</td>
</tr>
<tr>
<td>5</td>
<td>16</td>
<td>2.52 Wt% U-235, packed powder-pressurized full length demonstration fuel rod.</td>
</tr>
<tr>
<td>6</td>
<td>16</td>
<td>2.52 Wt% U-235, standard G-4 medium enrichment pellet full length characterized rod.</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>Segmented fuel rod with rod type 1 configuration in upper and middle segments and type 1 configuration with coated cladding in lower segment.</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>Segmented fuel rod with rod type 1 configuration in upper and middle segments and type 1 configuration/pressurized in lower segment.</td>
</tr>
<tr>
<td>9</td>
<td>4</td>
<td>Segmented fuel rod with rod type 1 configuration in upper segment and type 2 configuration in middle and lower segment.</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>Segmented fuel rod with rod type 1 configuration in upper segment and type 3 configuration in middle and lower segment.</td>
</tr>
<tr>
<td>Demo. Rod Designation</td>
<td>Quantity</td>
<td>Test Requirements</td>
</tr>
<tr>
<td>-----------------------</td>
<td>----------</td>
<td>-------------------</td>
</tr>
<tr>
<td>11</td>
<td>4</td>
<td>Segmented fuel rod with type 1 configuration in upper segment and type 4 configuration in middle and lower segment.</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>Segmented fuel rod with type 1 configuration in upper segment and type 5 configuration in middle segment and type 5 unpressurized in lower segment.</td>
</tr>
</tbody>
</table>
TABLE 6.2
CHARACTERISTICS OF BRPR SERIES 1
FULL LENGTH DEMONSTRATION FUEL RODS

<table>
<thead>
<tr>
<th>Reference Fuel</th>
<th>Type</th>
<th>Solid Pellet (Edge Chamfer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>UO₂</td>
<td></td>
</tr>
<tr>
<td>Density (%)</td>
<td>93.5 ± 1.5</td>
<td>93.5 ± 1.5</td>
</tr>
<tr>
<td>Diameter, mm (in.)</td>
<td>9.436 ± .013 (0.3715 ± .0005)</td>
<td>9.436 ± .013 (0.3715 ± .0005)</td>
</tr>
<tr>
<td>Length, mm (in.)</td>
<td>7.62 ± .64 (0.300 ± .025)</td>
<td>7.62 ± .64 (0.300 ± .025)</td>
</tr>
<tr>
<td>Dish</td>
<td>Both ends</td>
<td>Both ends</td>
</tr>
<tr>
<td>Dish Volume (%)</td>
<td>2.0 ± 0.5 (0.25 Edge Chamfer)</td>
<td>2.0 ± 0.5 (0.25 Edge Chamfer)</td>
</tr>
<tr>
<td>Enrichment (w/o U235)</td>
<td>2.52 ± .05</td>
<td>2.52 ± .05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Annular Fuel</th>
<th>Type</th>
<th>Annular pellet (Edge Chamfer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>UO₂</td>
<td></td>
</tr>
<tr>
<td>Density (%)</td>
<td>93.5 ± 1.5</td>
<td>93.5 ± 1.5</td>
</tr>
<tr>
<td>Diameter, O.D., mm (in.)</td>
<td>9.436 ± .013 (0.3715 ± .0005)*</td>
<td>9.436 ± .013 (0.3715 ± .0005)*</td>
</tr>
<tr>
<td>I.D., mm (in.)</td>
<td>2.984 ± .127 (0.1175 ± .005)</td>
<td>2.984 ± .127 (0.1175 ± .005)</td>
</tr>
<tr>
<td>Length, mm (in.)</td>
<td>7.62 ± .64 (0.300 ± .025)</td>
<td>7.62 ± .64 (0.300 ± .025)</td>
</tr>
<tr>
<td>Dish</td>
<td>None (0.25 Edge Chamfer)</td>
<td>None (0.25 Edge Chamfer)</td>
</tr>
<tr>
<td>Enrichment</td>
<td>2.69 ± .05</td>
<td>2.69 ± .05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Packed Powder Fuel</th>
<th>Type</th>
<th>Vibratory compacted particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>UO₂</td>
<td></td>
</tr>
<tr>
<td>Density (%)</td>
<td>&gt;98</td>
<td>9.677 ± .038 (0.3810 ± .0015)**</td>
</tr>
<tr>
<td>Diameter (clad I.D., mm (in.))</td>
<td>9.677 ± .038 (0.3810 ± .0015)**</td>
<td>9.677 ± .038 (0.3810 ± .0015)**</td>
</tr>
<tr>
<td>Enrichment (w/o U235)</td>
<td>2.52 ± .05</td>
<td>2.52 ± .05</td>
</tr>
<tr>
<td>Smear Density (%)</td>
<td>87.0 ± 1.0</td>
<td>87.0 ± 1.0</td>
</tr>
<tr>
<td>TABLE 6.2 (Continued)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Standard Fuel Type</strong></td>
<td>Same as reference (without chamfer)</td>
<td></td>
</tr>
<tr>
<td><strong>Insulator Disks</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Alumina</td>
<td></td>
</tr>
<tr>
<td>Density (kg/m$^3$)</td>
<td>3890</td>
<td></td>
</tr>
<tr>
<td>Diameter, mm (in.)</td>
<td>9.195 (0.362)</td>
<td></td>
</tr>
<tr>
<td>Length, mm (in.)</td>
<td>5.1 (0.200)</td>
<td></td>
</tr>
<tr>
<td>Number, location</td>
<td>2, One at each end of fuel column</td>
<td></td>
</tr>
<tr>
<td><strong>Plenum Spring</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Inconel X-750</td>
<td></td>
</tr>
<tr>
<td>Spring force, nominal, N (lb)</td>
<td>49 (1)</td>
<td></td>
</tr>
<tr>
<td>Spring constant, nominal N/m (lb/in)</td>
<td>2100 (2)</td>
<td></td>
</tr>
<tr>
<td>Spring volume mm$^3$, (in$^3$)</td>
<td>628 (0.0383)</td>
<td></td>
</tr>
<tr>
<td><strong>Fill Gas</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>He</td>
<td></td>
</tr>
<tr>
<td>Purity (%)</td>
<td>99.9</td>
<td></td>
</tr>
<tr>
<td>Fill pressure, MPa (psia, nominal)</td>
<td>0.10 (14.7)</td>
<td></td>
</tr>
<tr>
<td>Pressurization fill pressure, MPa (psia)</td>
<td>$0.462 \pm 0.048 (67 + 7)$</td>
<td></td>
</tr>
<tr>
<td><strong>Cladding</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Zircaloy-2</td>
<td></td>
</tr>
<tr>
<td>Condition</td>
<td>CW-Stress relieved</td>
<td></td>
</tr>
<tr>
<td>O.D., mm (in.)</td>
<td>$11.455 \pm 0.038 (0.451 \pm 0.0015)^{**}$</td>
<td></td>
</tr>
<tr>
<td>I.D., mm (in.)</td>
<td>$9.677 \pm 0.038 (0.381 \pm 0.0015)^{**}$</td>
<td></td>
</tr>
<tr>
<td>Wall thickness, minimum, mm (in.)</td>
<td>0.831 (.0327)</td>
<td></td>
</tr>
<tr>
<td>Length, mm (in.)</td>
<td>$1902.18 \pm .38 (74.889 \pm .015)$</td>
<td></td>
</tr>
<tr>
<td>TABLE 6.2 (Continued)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Cladding (Continued)**

<table>
<thead>
<tr>
<th>Allowable bow, mm/m (in/ft)</th>
<th>1.25 (.015)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coating (present in some rods with annular fuel)</td>
<td>Graphite</td>
</tr>
<tr>
<td>Coating layer thickness, mm (in.)</td>
<td>0.0064 ± .0038 (0.00025 ± .00015)</td>
</tr>
</tbody>
</table>

**Fuel Rod**

<table>
<thead>
<tr>
<th>O.D., mm (in.)</th>
<th>11.405 ± .051 (0.449 ± .002)***</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plenum length, mm (in.)</td>
<td>99.08 (3.901)</td>
</tr>
<tr>
<td>Fuel column length, mm (in.)</td>
<td>1778.0 ± 6.4 (70.00 ± .25)</td>
</tr>
<tr>
<td>Allowable bow, mm/m (in/ft)</td>
<td>1.25 (.015)</td>
</tr>
</tbody>
</table>

---

* Pellet O.D. = 9.423 ± .013 mm (0.3710 ± .0005 in) in coated cladding rods.

** Cladding to be selected to fall within a range of ± .025 mm (+ .001 in.) if possible.

*** Rods to be selectively etched to fall within a range of ± .0015 inch.
### TABLE 6.3

**CHARACTERISTICS OF BRPR.SERIES 1**

**SEGMENTED FUEL RODS**

<table>
<thead>
<tr>
<th>Component</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reference Fuel</strong></td>
<td>Same as demonstration rods.</td>
</tr>
<tr>
<td><strong>Annular Fuel</strong></td>
<td>Same as demonstration rods.</td>
</tr>
<tr>
<td><strong>Packed Powder Fuel</strong></td>
<td>Same as demonstration rods.</td>
</tr>
<tr>
<td><strong>Insulator Disks (each segment)</strong></td>
<td>Same as demonstration rods.</td>
</tr>
<tr>
<td><strong>Upper Plenum Spring (upper segment only)</strong></td>
<td>Same as demonstration rods.</td>
</tr>
<tr>
<td><strong>Fill Gas</strong></td>
<td>Same as demonstration rods.</td>
</tr>
<tr>
<td><strong>Mid and Lower Segment Plenum Spring</strong></td>
<td>Material: Inconel X-750</td>
</tr>
<tr>
<td></td>
<td>Wire diameter, mm (in.): 0.805 (.0317)</td>
</tr>
<tr>
<td></td>
<td>Coil O.D., at working length, mm (in.): 8.64 ± .38 (.340 ± .015)</td>
</tr>
<tr>
<td></td>
<td>Free length, mm (in.): 56.90 ± .76 (2.240 ± .030)</td>
</tr>
<tr>
<td></td>
<td>Spring force, N (lb): 9.34 (2.10)</td>
</tr>
<tr>
<td></td>
<td>Spring constant, N/m (lb/in): 394 (2.23)</td>
</tr>
<tr>
<td></td>
<td>Spring volume, mm$^3$ (in$^3$): 304 (0.0185)</td>
</tr>
</tbody>
</table>

* Pellet O.D. = 9.423 ± 0.013 mm (0.3710 ± 0.0005 in) in coated cladding rods.
<table>
<thead>
<tr>
<th>Cladding</th>
<th>Same as demonstration rods.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Same as demonstration rods.</td>
</tr>
<tr>
<td>Condition</td>
<td>Same as demonstration rods.</td>
</tr>
<tr>
<td>O.D.</td>
<td>Same as demonstration rods.</td>
</tr>
<tr>
<td>I.D.</td>
<td>Same as demonstration rods.</td>
</tr>
<tr>
<td>Wall Thickness</td>
<td>Same as demonstration rods.</td>
</tr>
<tr>
<td>Coating (present in some segments with reference or annual fuel)</td>
<td>Same as demonstration rods.</td>
</tr>
<tr>
<td>Coating thickness (mm)</td>
<td>Same as demonstration rods.</td>
</tr>
<tr>
<td>Length, upper segment, mm (in.)</td>
<td>666.24 ± .13 (26.230 ± .005)</td>
</tr>
<tr>
<td>Length, mid and lower segment, mm (in.)</td>
<td>600.18 ± .13 (23.629 ± .005)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel Rod</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of segments</td>
<td>3</td>
</tr>
<tr>
<td>O.D.</td>
<td>Same as demonstration rods.</td>
</tr>
<tr>
<td>Allowable bow</td>
<td>Same as demonstration rods.</td>
</tr>
<tr>
<td>Plenum length, upper plenum</td>
<td>Same as demonstration rods.</td>
</tr>
<tr>
<td>Plenum, mid and lower plenum, mm (in.)</td>
<td>33 (1.300)</td>
</tr>
<tr>
<td>Fuel column length, upper segment, mm (in.)</td>
<td>544.45 ± 4.06 (21.435 ± .16)</td>
</tr>
<tr>
<td>Fuel column length, middle segment, mm (in.)</td>
<td>546.84 ± 2.03 (21.529 ± .08)</td>
</tr>
<tr>
<td>Fuel column length, lower segment, mm (in.)</td>
<td>544.45 ± 2.03 (21.435 ± .08)</td>
</tr>
<tr>
<td>Axial distance between fuel columns, mm (in.)</td>
<td>71.12 (2.800)</td>
</tr>
<tr>
<td>Fuel configuration, upper and mid segments</td>
<td>Reference fuel</td>
</tr>
<tr>
<td>Fuel configuration, mid and lower segments</td>
<td>Reference fuel-pressurized **</td>
</tr>
<tr>
<td></td>
<td>Reference fuel-coated cladding **</td>
</tr>
<tr>
<td></td>
<td>Annular fuel</td>
</tr>
<tr>
<td></td>
<td>Annular fuel - coated cladding</td>
</tr>
<tr>
<td></td>
<td>Annular fuel - coated cladding - Pressurized</td>
</tr>
<tr>
<td></td>
<td>Packed powder fuel **</td>
</tr>
<tr>
<td></td>
<td>Packed powder-pressurized</td>
</tr>
</tbody>
</table>

** Lower segment only.
SECTION 'B-B'

FIGURE 6.1

STANDARD
UPPER END CAP

XN-NF-303,110
FIGURE 6.2  SERIES 1 DEMONSTRATION FUEL
ASSEMBLY NOS. 1 & 2.

LEGEND

- 3.82 WT. % U-235, UO₂
- 1.2 WT. % GADOLINIA IN
- 3.82 WT. % U-235, UO₂
- 2.52 WT. % U-235, UO₂
- 1.50 WT. % U-235, UO₂
- 2.52 WT. % U-235, REFERENCE PELLET
- 2.69 WT. % U-235, ANNULAR PELLET
- 2.69 WT. % U-235, ANNULAR PELLET-
- COATED CLADDING
- 2.69 WT. % U-235, ANNULAR PELLET-
- COATED CLADDING - PRESSURIZED
- 2.52 WT. % U-235, PACKED POWDER-
- PRESSURIZED
- 3.82 WT. % U-235, UO₂

○ TIE ROD
○ SPACER CAPTURE ROD

X INERT ROD
FIGURE 6.3 SERIES 1 DEMONSTRATION FUEL ASSEMBLY NOS. 3 & 4

LEGEND

- TIE ROD
- SPACER CAPTURE ROD
- 2.52 WT. % U-235, REFERENCE & REFERENCE - COATED SEGMENTED ROD
- 2.52 WT. % U-235, REFERENCE & REFERENCE - PRESSURIZED SEGMENTED ROD
- 2.69 WT. % U-235, ANNUAL SEGMENTED ROD
- 2.69 WT. % U-235, ANNUAL - COATED CLADDING SEGMENTED ROD
- 2.52 WT. % U-235, PACKED POWDER & PACKED POWDER PRESSURIZED SEGMENTED ROD

- 3.82 WT. % U-235, UO₂
- 1.2 WT. % GADOLINIA IN 3.82 WT. % U-235, UO₂
- 2.52 WT. % U-235, UO₂
- 1.50 WT. % U-235, UO₂
- 2.52 WT. % U-235, REFERENCE PELLET
- 2.69 WT. % U-235, ANNULAR PELLET
- 2.69 WT. % U-235, ANNULAR PELLET - COATED CLADDING
- 2.69 WT. % U-235, ANNULAR PELLET - COATED CLADDING - PRESSURIZED
- 2.52 WT. % U-235, PACKED POWDER - PRESSURIZED
- INERT ROD
Calculated Density = 86.43
Mean Density = 87.45
ρ = 1.47
FIGURE 6.5  ROD NO. 17, DENSITY VS. LENGTH

Calculated Density = 86.66
Mean Density = 87.07
p = 1.98
Calculated Density = 86.40
Mean Density = 87.02
p = 1.50

FIGURE 6.6 ROD NO. 18, DENSITY VS. LENGTH
The objective of this task is to conduct tests on packing and handling of microspheres in a commercial environment with industry QA-QC on full length BRPR rods. These tests will cuminate in proof-of-fabrication of the sphere pac rods. Oak Ridge National Laboratory (ORNL) is preparing microspheres that meet the specifications shown in Table 7.1.

A material fabrication and delivery schedule was established as shown below so that ORNL could coordinate their scheduling with the FPIP program timing.

<table>
<thead>
<tr>
<th>Material</th>
<th>Purpose</th>
<th>Amount</th>
<th>Delivery Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>UO$_2$, Depleted</td>
<td>Trial Loading</td>
<td>10 kg</td>
<td>Aug. 20, 1978</td>
</tr>
<tr>
<td>UO$_2$, 11% U-235 Enriched</td>
<td>Halden Rods</td>
<td>5 kg</td>
<td>Nov. 1, 1978</td>
</tr>
<tr>
<td>UO$_2$, 2.52% U-235 Enriched</td>
<td>BRPR Rods</td>
<td>50 kg</td>
<td>Apr. 2, 1979</td>
</tr>
</tbody>
</table>

Based upon this schedule, the following feed material, already obtained for the FPIP program, have been provided to ORNL for sphere preparation.

- 10 kg 11% U-235 enriched
- 100 kg 2.52% U-235 enriched

The 11% enriched material was converted from UO$_2$ to U$_3$O$_8$ since the feed material for microsphere preparation is an acid deficient uranyl nitrate solution. ORNL will convert the 2.52% enriched material from UO$_2$ to U$_3$O$_8$. (Nitric acid dissolution of the U$_3$O$_8$ is performed at ORNL to obtain an acid deficient solution.)

On June 27 and 28, M. H. Campbell and R. K. Welty (ENC) and J. O. Barner (PNL) visited ORNL to observe the microsphere preparation process and see a demonstration of sphere pac fuel fabrication. The highlights of the demonstration are noted below.
A two-foot rod was loaded by infiltration. Vibratory feeders were used to add the coarse (1200\mu m) and medium coarse (300\mu m) fractions simultaneously. A funnel with a screen on the bottom was then rested on top of the fuel column and aliquots of the fine particles were added to the funnel; a follower rod with an 850 g weight was placed on the fines; and a syntron vibrator was used to infiltrate the fines into the coarse spheres. The process of making additions of fines and vibrating required about 20 minutes. The smear density of the finished rod was 86.5\% TD. The syntron vibration was quite mild compared to the vipac vibrator.

A six-foot rod was prepared by adding all three fractions simultaneously so that a complete rod loading was added with the desired particle size distribution. Without vibration to pack during the loading, there were still some of the spheres in the funnel stem. A short vibration burst settled the column of fuel so that the funnel could be removed and the follower rod implaced. The loading operation required about four minutes using the same syntron feeder devices mentioned earlier. The rod was vibrated for eight minutes with a follower rod in place. The smear density achieved was 87.0\% TD. Down loading was achieved by merely pouring the spheres from the rod. A modest 1\% breakage of the large spheres, which comprise 58\% of the loading, was observed. There was an attendant increase in the medium coarse fraction indicating that fracture was probably due to existing cracks in the large spheres and not due entirely to the vibrating action.

The vibratory assembly for the simultaneous loading was quite unique and simple. The six-foot rod was clamped into the vee of a stainless steel angle iron. Two air vibrators were 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).

ORNL is still developing a gamma densitometer so they have not compared the axial fuel density of rods prepared by the above two loading operations. Since selection of the best loading technique is dependent in part on this parameter, a comparative test will be performed. ORNL will load four six-
foot rods with depleted uranium microspheres that are scheduled for delivery to ENC in August, 1978. Two of the rods will have been loaded by infiltration, and two by simultaneous addition of all three fractions. Scans will be made with the ENC Densiguage to assess the axial uniformity.
TABLE 7.1

UO₂ MICROSPHERE SPECIFICATIONS

Size - - - - Each lot will comprise three size fractions: coarse, medium, and fine. The nominal fraction size and amount for each lot will be:

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Sphere Diameter (μm)</th>
<th>Amount (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>1150-1410</td>
<td>56</td>
</tr>
<tr>
<td>Medium</td>
<td>280-320</td>
<td>27</td>
</tr>
<tr>
<td>Fine</td>
<td>25-40</td>
<td>17</td>
</tr>
</tbody>
</table>

The exact fraction sizes and size distributions will be left open at this time to take advantage of ongoing ORNL sphere-pac development. A detailed size specification will be developed to provide sphere blends which pack as well as or better than the stated nominal sizes.

Shape - - - - All material will be in the form of spheres. A detailed shape specification will be developed to assure maximum loading and packing efficiency for all material supplied.

Density - - - - The target sphere density will be >99% of theoretical.

Chemical and Nuclear - - - The trial loading material will be nominally UO₂, with ThO₂ as a backup in the event preparation of UO₂ would delay the delivery schedule. No impurity specification will be applied to the trial loading material.

The enriched UO₂ will conform to ANSI/ASTM C-776-76, Standard Specification for Sintered Uranium Dioxide Pellets.
8.0 TASKS 2G AND 2H - LEAD ASSEMBLIES

C. E. Crouthamel (Exxon Nuclear Company)

The objective of this task is to evaluate the performance of an optimized PCI-remedy fuel design concept by irradiating two lead assemblies in the Big Rock Point Reactor (BRPR) and four lead assemblies in Oyster Creek Reactor (OCR). Although these lead assembly tasks have been proposed for consideration as part of the FPIP and formal approval has not been obtained at this time, planning and scheduling activities have started on these assemblies.

This task provides prototype demonstration of an optimized PCI-remedy fuel concept before introduction into a reactor on a commercial reload batch scale. The results of these irradiations will contribute to commercialization of an optimized PCI-remedy fuel design that is capable of safe operation in both BWR's and PWR's to extended burnups and under reactor operating modes which provide more efficient uranium resource utilization. The optimized design is considered to be the annular pellet, coated cladding, pressurized concept.

8.1 Big Rock Point Reactor Lead Assemblies

The lead assembly work scope covers the design, process definition, and fabrication of two (2) assemblies for BRPR, under the commercial quality assurance practices of ENG.

The design of the lead fuel assemblies and the enrichment levels will permit a discharge exposure of 32 to 33 GWD/MTM (five cycles) with the option to drive the assemblies an extra cycle to ~38 GWD/MTU.

9.1 Oyster Creek Reactor Lead Assemblies

The lead assembly work scope covers the design, process definition, and fabrication of four (4) assemblies for OCR, under the commercial quality assurance practices of ENC, followed by irradiation and NDT in a prototypic BWR environment to extended burnup.
The design of the lead fuel assemblies and the enrichment levels will permit a discharge exposure of 32 to 33 GWD/MTU (five cycles) with the option to drive the assemblies an extra cycle to ~38 GWD/MTU.
9.0 TASK 3 - FUEL PERFORMANCE EVALUATION
M. D. Freshley (Pacific Northwest Laboratory)

Work was initiated on developing a coordinated program plan for the Fuel Performance Improvement Program; however, because of the possible modification of the program plan to include an evaluation of an optimized fuel design concept that is considered to have the most potential as an FCI-remedy, work on the coordinated program plan for each of the primary fuel concepts was temporarily suspended.
10.0 TASK 4 - ESTABLISHMENT OF TECHNICAL BASES

K. R. Merckx (Exxon Nuclear Company)

The automated performance file generation system has been used and the technical bases for annular pellet fuel have been used to make design evaluations.

8.1 Data Requirements

The automated performance file generation procedure has been applied on several fuel bundles previously irradiated in Big Rock Point Reactor. Several minor coding errors have been discovered and removed from the system. All the stages of data accumulation for the FPIP Performance File generation are being checked by accumulating and using the data from a few sample fuel rods.

8.2 Fuel Performance Code

Application of the thermal-mechanical technical bases to actual design evaluations for annular pellet fuel is in progress. The thermal evaluations for stored energy have been performed with existing calculational procedures. The thermal-mechanical evaluations yielded results that indicated the flexibility concept applied for solid fuel underestimates the flexibilities of fuel regions near the central hole which results in the initial contact pressures being too high and causes too much central hole closure. A new technical bases for the displacement-contact pressure relation for the annular pellet fuel thermal-mechanical evaluations has been developed.
APPENDIX A

SI UNIT CONVERSION TABLE
CONVERSION TABLE FOR SI UNITS

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

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

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<th>Multiplication Factors</th>
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<tr>
<td>tera</td>
<td>T</td>
<td>1 000 000 000 000 = 10^12</td>
</tr>
<tr>
<td>giga</td>
<td>G</td>
<td>1 000 000 000 = 10^9</td>
</tr>
<tr>
<td>mega</td>
<td>M</td>
<td>1 000 000 = 10^6</td>
</tr>
<tr>
<td>kilo</td>
<td>k</td>
<td>1 000 = 10^3</td>
</tr>
<tr>
<td>hecto*</td>
<td>h</td>
<td>100 = 10^2</td>
</tr>
<tr>
<td>deka*</td>
<td>da</td>
<td>10 = 10^1</td>
</tr>
<tr>
<td>deci*</td>
<td>d</td>
<td>0.1 = 10^-1</td>
</tr>
<tr>
<td>centi*</td>
<td>c</td>
<td>0.01 = 10^-2</td>
</tr>
<tr>
<td>milli</td>
<td>m</td>
<td>0.001 = 10^-3</td>
</tr>
<tr>
<td>micro</td>
<td>µ</td>
<td>0.000 001 = 10^-6</td>
</tr>
<tr>
<td>nano</td>
<td>n</td>
<td>0.000 000 001 = 10^-9</td>
</tr>
<tr>
<td>pico</td>
<td>p</td>
<td>0.000 000 000 001 = 10^-12</td>
</tr>
<tr>
<td>femto</td>
<td>f</td>
<td>0.000 000 000 000 001 = 10^-15</td>
</tr>
<tr>
<td>atto</td>
<td>a</td>
<td>0.000 000 000 000 000 001 = 10^-18</td>
</tr>
</tbody>
</table>

(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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