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Fuel Performance Improvement Program

Semiannual Progress Report

October 1979 - March 1980

April 1980

Consumers
Power
Company

EXXON NUCLEAR
COMPANY, Inc.

Battelle

Pacific Northwest Laboratory

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FUEL PERFORMANCE IMPROVEMENT PROGRAM

Semiannual Progress Report

October 1979 -
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April 1980

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ABSTRACT

Progress on the Fuel Performance Improvement Program's fuel design tests and demonstration irradiations for October 1979 through March 1980 is reported. Included are the results of out-of-reactor experiments with zircaloy cladding using a device that simulates the interaction between fuel and cladding. Also included are reports on the irradiation of the advanced LWR fuel designs in the Halden Boiling Water Reactor and in Consumers Power Company's Big Rock Point Reactor. The establishment of the technical bases and licensing requirements for the advanced fuel concepts are also described.

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SUMMARY

The Fuel Performance Improvement Program (FPIP) is being conducted for the Department of Energy by Consumers Power Company, Exxon Nuclear Company, Inc., and Pacific Northwest Laboratory^(a) to develop LWR fuels with improved performance. The program is designed to obtain data on and evaluate the irradiation and ramping behavior of improved fuel designs, and to review the licensing requirements and update the technical bases for the two advanced fuel concepts.

An annular-coated-pressurized design and a sphere-pac design are being evaluated by means of steady-state and ramping irradiations and their performance is being compared with a reference fuel design. Out-of-reactor experiments support the design bases and provide data that aids in the interpretation of the irradiation test results. Performance data obtained from the experiments in the Halden Boiling Water Reactor (HBWR) and the Big Rock Point Reactor (BRPR) are being used to support the technical bases for the improved fuel designs.

Results of out-of-reactor experiments obtained during this reporting period indicate that the strain-to-failure values for noncoated FPIP cladding specimens tested in an iodine atmosphere vary considerably and are unexpectedly high. FCI-simulator tests with zircaloy cladding of known susceptibility to iodine-SCC showed low strain-to-failure values with little scatter. Evidence of differential movement between the ceramic insert and the graphite-coated zircaloy test specimens indicates that the coating functions as a lubricant or parting layer. Examination of the fracture surfaces of FPIP cladding specimens shows the presence of high concentrations of Fe, Sn, and Cr, which suggests that they may be associated with the crack initiation mechanism.

The irradiation experiments being conducted in the HBWR are on schedule and performance of the instrumented rods is excellent. The centerline fuel temperatures of the two sphere-pac rods continued to operate more than 100°C lower than for the reference solid pellet rods. Based on these data and information reported in the literature, an interim thermal conductivity

(a) PNL is operated by Battelle Memorial Institute.

expression for sphere-pac fuel was developed. Collection, calibration, and analysis of data on the HBWR test rods were continued.

A revised ramping plan for the HBWR test rods was developed and operational modifications were implemented that will increase burnup rates in the test rods. The steady-state irradiation of ten of the twelve Series H-1 rods and the Series H-4 rods was completed. The IFA-518 test rig was reloaded with ten fresh Series H-2 and H-3 rods for irradiation. The IFA-517 ramping rig was reloaded with three irradiated rods from Series H-1 (two annular-coated and one vipac rod) and one irradiated rod from Series H-4 (sphere-pac).

An extended outage caused by mechanical problems in the BRPR in 1979 continued into the reporting period. The problems were corrected by early November, and the reactor is now operating at full power. Four fuel assemblies (instead of two) containing all 48 of the segmented demonstration rods were placed in the reactor, thus maintaining the primary ramping schedule intact for all the segmented rods.

The licensing requirements and the technical bases for the two advanced fuel concepts were reviewed. The Electric Power Research Institute fuel performance data base file system was reviewed for FPIP application and, with a few minor modifications, was found to be acceptable.

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DESCRIPTION OF THE VARIOUS FUEL ROD TYPES^(a)

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

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

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

1.0 INTRODUCTION

C. E. Crouthamel
(Exxon Nuclear Company)

1.1 PROGRAM OBJECTIVES

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

1.2 BACKGROUND

The FPIP focuses on improving the fuel-cladding interaction behavior of both BWR and PWR light-water reactor fuels during rapid power changes or ramping. Two advanced fuel designs are being tested and demonstrated. They are an annular-coated-pressurized design and a sphere-pac (helium pressurized) design. The program description and history have been documented in the previous quarterly reports.^(1.4,1.5) These reports also give the structures and descriptions of each task. There is a complete list of progress and topical reports published by FPIP at the end of this section.

1.3 PROGRAM ORGANIZATION

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

FIGURE 1.1. Organization of the Fuel Performance Improvement Program

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

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

1.4 FPIP PUBLICATIONS

- 1.1 "Fuel Performance Improvement Program, Quarterly Progress Report, April-June 1977," compiled by C. E. Crouthamel, C00-4066-1, July 1977.
- 1.2 W. J. Bailey, C. L. Wilson, L. J. MacGowan and P. J. Pankaskie, "State-of-the-Technology Review of Fuel Cladding Interaction," C00-4066-2, PNL-2488, December 1977.
- 1.3 W. J. Bailey and J. O. Barner, "Assessment of Fuel Concepts," C00-4066-3, PNL-2490, January 1978.

- 1.4 "Fuel Performance Improvement Program, Quarterly/Annual Progress Report, April-September 1977," compiled by C. E. Crouthamel, C00-4066-4, November 1977.
- 1.5 "Fuel Performance Improvement Program, Quarterly Progress Report, October-December 1977," compiled by C. E. Crouthamel, C00-4066-5, January 1978.
- 1.6 "Fuel Performance Improvement Program, Quarterly Progress Report, January-March 1978," compiled by C. E. Crouthamel, C00-4066-6, April 1977.
- 1.7 "Fuel Performance Improvement Program, Quarterly Progress Report, April-June 1978," compiled by C. E. Crouthamel, C00-4066-7, July 1978.
- 1.8 "Fuel Performance Improvement Program, Quarterly Progress Report, October 1977-September 1978," compiled by C. E. Crouthamel, C00-4066-8, October 1978.
- 1.9 "Fuel Performance Improvement Program, Quarterly Progress Report, October-December 1978," compiled by C. E. Crouthamel, C00-4066-9, January 1979.
- 1.10 "Fuel Performance Improvement Program, Quarterly Progress Report, January-March 1979," compiled by C. E. Crouthamel, C00-4066-10, April 1979.
- 1.11 F. W. Buckman, C. E. Crouthamel and M. D. Freshley, "FCI-Remedy Development for the Fuel Performance Improvement Program," Proceedings Light Water Reactor Fuel Performance, Portland, Oregon, April 29 to May 3, 1979, pp. 158-168.
- 1.12 S. R. Wagoner, J. O. Barner and R. K. Welty, "Fuel Performance Improvement Program, Description and Characterization of HBWR Series H-1 Test Rods," C00-4066-11, June 1979.
- 1.13 "Fuel Performance Improvement Program, Quarterly Progress Report, April-June 1979," compiled by C. E. Crouthamel, C00-4066-12, July 1979.
- 1.14 S. R. Wagoner, J. O. Barner and R. J. Guenther, "Comparative Performance of FCI-Remedy Fuel Designs," Trans. Am. Nucl. Soc. 33 (1979), pp. 271-272.
- 1.15 "Fuel Performance Improvement Program, Quarterly/Annual Progress Report, October 1978-September 1979," compiled by C. E. Crouthamel, C00-4066-13, October 1979.

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3.0 TASK 2--TESTING AND DEMONSTRATION PROGRAM

The objective of the testing and demonstration program is to provide data that supports the technical design bases for the fuel designs that have the potential for improved performance and are being developed as part of this program. The primary fuel designs being evaluated are an annular-coated-pressurized design and, at a more modest level, a sphere-pac design. Their performance is compared with a reference fuel design. The testing and demonstration program includes Task 2A, Out-of-Reactor Experiments; Task 2B, In-Reactor Experiments; and Task 2C, In-Reactor Demonstrations.

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

Task 2A out-of-reactor study activities currently include FCI-simulator tests, which are being performed to provide comparative data on the effectiveness of graphite coating applied to the inside cladding surface to improve FCI behavior. The function of the coating, or the manner in which the coating improves performance is also being studied. These studies are described in Section 4.0.

Task 2B in-reactor experiments activities primarily involve data acquisition associated with the continued irradiation of HBWR Series H-1 and Series H-4 instrumented rods in HBWR. The current status of the in-reactor experiments is described in Section 5.0.

Task 2C in-reactor demonstration activities are now focused on following the progress of the irradiation of the four FPIP assemblies in BRPR. The status of the in-reactor demonstrations is described in Section 6.0.

4.0 TASK 2A--OUT-OF-REACTOR EXPERIMENTS

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(Pacific Northwest Laboratory)

The purpose of this task is to conduct out-of-reactor experiments that provide data to support the technical design bases and aid in the interpretation of the irradiation results. Specifically, current activities include comparative tests using the FCI-simulator to evaluate the effectiveness of graphite coatings to improve FCI behavior and coating function studies to determine the manner in which the coating improves performance. The status of these activities is described below.

4.1 FCI SIMULATOR TESTS

4.1.1. Test Descriptions and Results

A series of tests was performed with the FCI-simulator^(1.8) to compare the strain-to-failure of coated (Dag 4) and noncoated zircaloy cladding specimens exposed to different test conditions. Previously reported results^(1.8) (Figure 4.1) have shown that: 1) a factor-of-four change in strain rate does not have a large effect on strain-to-failure, 2) the addition of iodine decreases the strain-to-failure, and 3) graphite coatings increase the strain-to-failure in the presence of iodine. These were the first results obtained with the FCI-simulator when several iron-containing internal components were exposed to the test atmosphere. After removal of the iron-containing internal components, which could act as a catalyst for iodine-SCC,^(4.1) the test results with FPIP cladding exhibited variability of the strain-to-failure values.

Several tests were performed at 300°C at a constant strain rate of 2%/hr in order to determine the cause of the variability in the strain-to-failure. The results of a variety of tests, which include re-evaluated points for some of the data shown in Figure 4.1, are presented in Figure 4.2. It is shown that the distinction of strain-to-failure values between coated and noncoated cladding specimens disappears and, further, that even the difference between an iodine atmosphere and an iodine-free atmosphere is not large. Scrupulous care

FIGURE 4.1. Average Strain-to-Failure Versus Strain Rate for Different Test Conditions (early tests with iron present)

was taken with the iodine-free tests, so the strain-to-failure of 7 to 8% under these conditions is regarded as normal for a noncoated specimen. In some cases, the strain-to-failure for the iodine-containing tests is higher than

FIGURE 4.2. Summary of Average Strain-to-Failure Values Obtained with the FCI-Simulator for the Conditions Indicated (all tests performed at a strain rate of 2%/hr at 300°C)

the strain-to-failure in the absence of iodine. A possible explanation is that oxygen or water vapor was contaminating the atmosphere and maintained the protective zirconium-oxide layer on the specimen surfaces, thus retarding iodine-SCC crack initiation. However, an oxygen meter^(a) connected to the test section during one of the tests showed that the pre-test purge is adequate to reduce the oxygen concentration to <1 ppm, and furthermore that the purity of the gas remains at this level during the tests. Also, by use of a solid-state probe^(b) sensitive to I^- ions (Figure 4.3) to monitor the iodine concentration of the gas leaving the test section, it was shown that up to 40% of the iodine supplied remained in the test section, presumably by reacting with the zircaloy.

Reexamination of all previous FCI-simulator test data leads to the observations that: (1) the strains-to-failure being obtained with the FPIP Zircaloy-2 cladding are significantly higher than those reported in the literature, and (2) the scatter in results is large. Several changes were made to the system in an effort to determine the cause(s) of this behavior, as related above. In an attempt to eliminate the possibility of continuously introducing oxygen contamination into the test section, the system was converted from a flowing to a static system, as illustrated in Figure 4.4. With this modification, a fixed amount of iodine is added at the start of the test instead of being continuously supplied.

A series of identical tests was performed with the static system to evaluate the possible effects of the above changes. The results for FPIP cladding are shown in Figure 4.5. In all cases, the strain rate was 2%/hr, the test temperature was 300°C, and the initial static iodine concentration was $\sim 5 \text{ mg/cm}^2$ of cladding surface. Once again, the results for FPIP cladding show high values of strain-to-failure and significant scatter. SEM examination of the specimens shows that the fracture morphology is representative of classic stress-corrosion cracking (iodine-SCC), i.e., the fracture was predominately transgranular and fluting was noted. It was hypothesized that if strain-to-failure is affected by the presence of some type of surface defect, and if the

(a) Research Incorporated, Minneapolis, Minnesota, Model No. 648A

(b) Chemtrix, Inc., Hillsboro, Oregon

FIGURE 4.3. Illustration of the System Used for Monitoring the Iodine Content of the Gas Exiting the FCI-Simulator

FPIP cladding has a low areal density of such defects, high strain-to-failure values and high scatter can be expected.

In regards to the strain-to-failure results for the FPIP cladding, it should be noted that this cladding was the most resistant to iodine-SCC of the cladding types tested by Cubicciotti^(4.2) (Figure 4.6). The pressurized tube test results of Cubicciotti show that the FPIP cladding would survive 100 hr at a stress level that would cause the Supplier B cladding tested by Cubicciotti to fail within 1 hr.

In order to develop comparative test results for evaluation, zircaloy cladding, which has known poor iodine-SCC resistance (Lot 6719), was tested in the FCI-simulator. Results of FCI-simulator tests obtained with Lot 6719 cladding are shown in Figure 4.5. The test conditions were the same as for

A. FLOWING SYSTEM USED ON FIRST 50 SIMULATOR TESTS

B. SEALED SYSTEM USED IN PRESENT AND FUTURE TESTS

FIGURE 4.4. Illustration of the (a) Flowing and (b) Static Gas Environment Systems for the FCI-Simulator

FPIP cladding, i.e., a strain rate of 2%/hr at a test temperature of 300°C and an initial static iodine concentration of 5 mg/cm² of cladding surface. Compared with the FPIP cladding, the strain-to-failure values for the Lot 6719 cladding were low (average 1.0%) and exhibited very little scatter ($\sigma = 0.18\%$ for 12 tests). The data are consistent with the results of Cubicciotti and show that the FCI-simulator is a valid method for comparing the iodine-SCC susceptibility of zircaloy cladding.

4.1.2 Post-Test Examinations

Several specimens tested on the FCI-simulator were examined using the scanning electron microscope equipped with energy dispersive x-ray analysis (SEM-EDAX). The EDAX system permits detection of elements of atomic number

FIGURE 4.5. FCI-Simulator Data for Noncoated Lot 6719 Cladding Compared with Noncoated FPIP Cladding (all testing performed in iodine at 300°C, 2%/hr strain rate)

≥11 when present in concentrations >0.2 atomic percent. The electron beam penetrates to about 1 μm below the surface; consequently, some surface contaminants may not be detected.

FIGURE 4.6. Iodine-SCC Data for a Variety of Cladding Using the Pressurized-Tube Method(4.2)

Failed FPIP cladding specimens were sectioned longitudinally to present a plan view of the surface. After examining the surface, the specimens were broken by propagating the original fracture, thus enabling examination of the crack morphology and determination of its original boundary as evidenced by the transition from a brittle to ductile fracture mode. The difference between ductile and brittle morphology in a noncoated specimen is illustrated in Figure 4.7. The dimpled, ductile fracture zone in Figure 4.7a is distinguishable from the brittle transgranular fracture mode in Figure 4.7b. Iodine was detectable in the brittle zone, but may have been deposited by gas flow after tube-wall penetration occurred. The brittle zone also contained Fe, Sn, and Cr evenly distributed over the fracture surface. The Fe may have come from the steel plunger which was not gold plated when this specimen was tested. The localized high concentrations of Sn and Cr are probably due to segregation of the alloying elements. The consistent presence of these elements at the failure sites suggests that they may be associated with the crack initiation mechanism as suggested by other investigators.^(4.2)

A typical interior surface of a noncoated FPIP cladding specimen after testing in iodine is shown in Figure 4.8. Alumina, which was used as a stand-in for UO_2 , has galled the surface and adheres in places. Areas between alumina fragments, where maximum strain occurred, contain numerous small cracks. The cracked areas in this specimen also contain increased I, Fe, and Sn concentrations. The smallest cracks are bridged by a very thin layer, thought to be zirconium-oxide, that is penetrated by the electron beam (Figure 4.9). A crack in the zirconium-oxide layer would permit iodine to contact the unprotected zircaloy and serve as an initiation site for iodine-SCC. Cox^(4.4) also observed a similar layer on zircaloy that had been exposed to iodine. In another specimen tested in the FCI-simulator, small cracks in the zirconium-oxide surface layer were also found adjacent to the main fracture crack (Figure 4.10). The specimen in this case was graphite coated, but the graphite was missing in the region of highest strain where there was no alumina pressing against it. This is an important observation because spalling of the graphite coating from the cladding surface ultimately limits any chemical barrier function that it may have. In areas where the alumina pressed against the graphite

a. Ductile Fracture Features in an Area Adjacent to an I₂-SCC Crack Site

b. Brittle Fracture Zone at the Main I₂SCC Crack Site

FIGURE 4.7. Scanning Electron Micrographs Showing Typical Fracture Surface Features in FPIP Cladding Specimens Tested with the FCI-Simulator

FIGURE 4.8. Interior Surface of a Non-coated FPIP Cladding Specimen Tested in the FCI-Simulator

FIGURE 4.9. Small Crack in a Noncoated FPIP Cladding Specimen Bridged by a Thin Zirconium-Oxide Layer Which is Also Cracked (the underlying metal appears to be undercut beyond the penetration of the thin oxide layer)

100 μm

FIGURE 4.10. Small Cracks, as in Figure 4.6, Adjacent to the Main Failure Crack. FPIP cladding specimen was originally coated (arrow) with graphite which did not adhere in the high-strain region.

coating, the coating remained in place even though it cracked occasionally (Figure 4.11). In these regions, the coating was compressed and then smeared by the differential movement of the alumina fragments. The observation of differential movement between the alumina and the cladding indicates that the graphite coating functioned as a lubricant or parting layer, thus preventing hard alumina-to-cladding engagement. The cracks in the coating contained I_2 , but there was no evidence of Fe or Sn.

2 μm

FIGURE 4.11. Graphite-Coated Cladding in an Area Where the Alumina Pressed Against the Coating

Iron-group inclusions present on the inside surface of zircaloy cladding and crystallographic texture have been regarded as defects that may act as nucleation sites for iodine-SCC.^(4.3) Examination of the inside surfaces of FPIP and Lot 6719 cladding has been performed using an electron beam microprobe operating as an SEM and equipped with a stepping motor to detect the small ($\sim 20 \mu\text{m}$) surface inclusions. The inclusions are recognizable because of their different rate of secondary electron generation, which make them appear bright against the zircaloy background. Using the electron beam microprobe in this way, about 6 cm^2 of FPIP cladding and about 3 cm^2 of Lot 6719 cladding was scanned without finding any iron-group inclusions. Assuming that the specimens were representative of those tested in the FCI-simulator, any iron-group

inclusions present must be sub-surface or at a very low areal density. Hence, the difference in iodine-SCC performance between the two cladding types must result from some other presently unidentified factor.

4.2 COATING FUNCTION STUDIES

As part of the coating function studies to study the manner in which the graphite coating improves performance, specimens of the zircaloy cladding being used in the Task 2B irradiations in HBWR were pulled in tension, in passive and aggressive (iodine) atmospheres. The pulling apparatus and specimen geometry have been described previously.^(1.8) The pulling method exposes the cladding surfaces to the test atmosphere without the uncertainties introduced by the more realistic but complex loading conditions characteristic of the FCI-simulator. Pre- and post-test characterization of the cladding surface by SEM and study by surface science techniques, such as Auger spectroscopy, are also more easily accomplished on this type of specimen.

The advantages of the specimen configuration being used are partially offset by the difficulty of defining a gauge length for the purpose of quantifying strain rate. The specimen was analyzed using the finite-element program ANSYS^(a) in an attempt to define the gauge length. The use of only the elastic version of ANSYS did not work; the main result was location of the stress concentrations as shown in Figure 4.12. The location of these stress concentrations agrees well with the usual failure mode, which is also shown in Figure 4.12. Thus, the results of the coating function studies will probably not be interpretable in terms of strain rate.

A series of identical specimens was pulled at 300°C in gettered helium over a wide range of crosshead speeds (0.013 to 13 mm/min) using an Instron^(b) machine. The area under the load curve, known as the work-of-fracture (WOF) was measured (Figure 4.13). The main body of data applies to as-received cladding and shows essentially no dependence of WOF on crosshead speed (strain rate), as would be expected for a nonaggressive environment.

(a) Property of Swanson Analysis Systems, Inc., Houston, Pennsylvania.

(b) Instron Corporation, Canton, Massachusetts.

FIGURE 4.12. Small Section of a D-Ring Test Specimen, as Analyzed (the points of high strain concentration are shown and the line represents the usual fracture path for specimens tested in an iodine-free atmosphere)

Also shown in Figure 4.13 are some test results that represent: 1) coated cladding (Dag 4) that had been exposed to the usual 425°C/24 hr vacuum outgassing cycle, and 2) noncoated cladding that had been exposed to the same temperature/time outgassing cycle. As shown, heat treatment or the presence of graphite coating has no significant effect on WOF.

The normal test temperature, 300°C, is on the low side of cladding temperature for some LWR fuel types, so the effect of temperature on the WOF was assessed. Figure 4.14 shows the effect of temperature over the range of 300 to 350°C on the WOF of specimens pulled at 1.3 mm/min in the iodine-free atmosphere. The effect of temperature on WOF was ~17%; a fairly minor dependence.

In order to make a valid analysis of coating effects, the environment must be free of spurious contaminants. Because structural requirements prevent making the loading fixtures and atmosphere chamber from zircaloy, several stainless steel or hardened steel parts were used. In order to avoid the possible effects of iron, internal parts contacted by the iodine atmosphere were coated with a 12 µm-thick layer of gold.

FIGURE 4.13. Work-of-Fracture as a Function of Crosshead Speed for As-Received, Coated-Outgassed, and Noncoated Zircaloy Cladding Specimens (all tests in an iodine-free atmosphere)

D-ring testing of FPIP cladding specimens was also performed in an iodine atmosphere, using gold-plated pulling hardware to prevent reaction between the components of the apparatus and the test atmosphere. The atmosphere was gettered helium containing 40 Pa of iodine pressure as supplied by a room-temperature saturator. As was done during the iodine-free tests, a wide variety of crosshead speeds was employed to examine for the strain-rate effects that are characteristic of stress-corrosion cracking.

Figure 4.15 shows the results for the iodine-atmosphere tests. For reference, a line drawn through the non-iodine data (regarding graphite-coated as no different than non-coated) is also shown. Strain rates were calculated on the basis of an assumed gauge length and are not expected to be closer than $\pm 50\%$. The other data on the plot are from the literature as well as a GAPCON-THERMAL-2^(4.5) calculation of strain rates. The lowest strain rates achieved thus far with the D-ring tests are much higher than those calculated by other

FIGURE 4.14. Work-of-Fracture as a Function of Temperature (all specimens pulled at 1.3 mm/min in an iodine-free atmosphere)

investigators, but the other strain-rate data are averaged circumferential strains, whereas the D-ring data represent peak strain rates. The peak strain rates on the circumferentially averaged specimens are probably within an order of magnitude of the D-ring data. The data show that iodine has no effect at high strain rates, i.e., above 500%/hr. At lower strain rates, the WOF decreased in an iodine atmosphere. SEM examination of the fracture surfaces showed that the high-rate specimens failed in a ductile manner, whereas the lower strain rates produced at least a partially brittle fracture with some evidence of ductile fracture as the crack propagated.

The plot of Figure 4.15 also shows that, in the iodine atmosphere, the graphite coating apparently had no effect on WOF. This is caused at least

partially by the fact that the strain is sufficiently high to cause the graphite coating to crack and spall from the surface of the D-ring specimens. The high strain may be a result of the high iodine-SCC resistance of the FPIP cladding but the cracking and spalling of the graphite coating not only prevents it from being effective in this test but prevents close study to investigate any chemical gettering effects it may have for iodine. Because of this behavior, this study has been terminated.

4.3 REFERENCES

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5.0 TASK 2B - IN-REACTOR EXPERIMENTS

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The objective of the in-reactor experiments task is to conduct irradiation tests to study the behavior and performance limits of fuel designs which have potential for improved operating behavior in LWRs. Irradiation experiments are being performed with emphasis on the annular-coated-pressurized design and, at a more modest level, the sphere-pac design as a backup. The performance of both designs is compared with a reference fuel design. The performance characteristics of the improved designs are being evaluated in screening tests, which include the steady-state irradiation of three series of instrumented rods followed by ramping of the rods in the Halden Boiling Water Reactor (HBWR). The performance of the selected improved designs is also being evaluated in primary tests which include the ramp testing of rods that have been irradiated in the Big Rock Point Reactor (BRPR) as part of the Task 2C in-reactor demonstrations. Fuel performance data being obtained from the in-reactor experiments will be used to support the technical bases for the improved designs.

Details of the general testing criteria, the selection of the irradiation facilities, and the detailed test descriptions of irradiations currently in progress were presented in previous progress reports.^(1.8,1.15) The current status of these irradiations is described below.

5.1 SUMMARY DESCRIPTION OF HBWR TESTS

The steady-state irradiations for the screening tests are being performed in two test rigs in the HBWR. The IFA-518 test rig contains two six-rod clusters; whereas, the IFA-517 test rig contains a single cluster of four rods. Rod instrumentation in both rigs during steady-state irradiation includes fuel centerline thermocouples, cladding elongation sensors, and internal pressure

transducers. The rigs are instrumented with neutron detectors to measure power generation, and the peak linear heat generation rate (LHGR) for the rods is about 44.5 kW/m.

IFA-518 is being sequentially loaded with rods from HBWR Series H-1, H-2, and H-3. Four fuel forms were included in HBWR Series H-1 (IFA-518.1): reference, annular, annular-coated, and vipac. An axially movable neutron absorber shield covered one or the other of the six-rod clusters at any one time, allowing the power of the shielded cluster to be reduced approximately 40%. (This shield was removed from the test rig after irradiation of IFA-518.1.) A total of twenty-four rods are to be irradiated in IFA-518, the majority of which will be power ramped.

The four Series H-4 fuel rods irradiated in the HBWR assembly IFA-517 included three pressurized sphere-pac rods (two with fuel centerline thermocouples) and one reference rod with a fuel centerline thermocouple. Two of the sphere-pac rods and the reference rod are instrumented with elongation sensors; the other sphere-pac rod contains a pressure sensor. The rods are in a square array, with the midplane of the active fuel length aligned with the peak in the axial flux profile. Power-ramp testing of the test fuel rods will be conducted in the IFA-517 ramping rig.

5.2 HBWR IRRADIATION AND RAMPING PLAN MODIFICATIONS

The HBWR irradiation plan was modified to:

- a) increase the average burnup rate in HBWR Series H-2 and H-3 rods, resulting in a decreased irradiation period to obtain goal burnups,
- b) increase the number of annular-coated-pressurized rods, that will achieve a goal burnup of about 16 MWd/kgM, and
- c) provide more emphasis on annular-coated-pressurized and sphere-pac fuel rods, particularly for the ramping tests.

The modifications to the ramping plan are summarized in Table 5.1. Removal of the IFA-518 absorber shield and operation of the HBWR Series H-2 and H-3 rods at the same peak linear heat generation rate as the Series H-1 rods will

TABLE 5.1. HBWR Irradiation Plan

Rod No.	Rod Type (a)	Original Plan					Current Plan				
		Charging Date	Rig (b)	Cluster (c)	Peak Goal Burnup, MWd/kgM	Ramp Date	Charging Date	Rig (b)	Cluster (c)	Peak Goal Burnup, MWd/kgM	Ramp Date
H1LCR002	R	7-78	518	LC	8-10	7-80	7-78	518.1	LC	10.9	8-80
H1LCA006	A	7-78	518	LC	8-10	7-80	7-78	518.1	LC	10.9	8-80
H1LCG009	AC	7-78	518	LC	8-10	5-80	7-78	518.1	LC	10.9	4-80
H1LCG010	AC	7-78	518	LC	8-10	5-80	7-78	518.1	LC	10.9	4-80
H1LCP013	VP	7-78	518	LC	8-10	5-80	7-78	518.1	LC	10.9	4-80
H1LCP014	VP	7-78	518	LC	8-10	5-80	7-78	518.1	LC	10.9	NP ^(d)
H1UCR003	R	7-78	518	UC-LC	16	12-81	7-78	518.1, .2	UC	16	8-81
H1LCR005	R	7-78	518	UC-LC	16	12-81	7-78	518.1	UC	8.8	8-81
H1LCA007	A	7-78	518	UC-LC	16	12-81	7-78	518.1	UC	8.8	8-81
H1LCG011	AC	7-78	518	UC-LC	16	12-81	7-78	518.1, .2	UC	16	8-81
H1UCP017	VP	7-78	518	UC-LC	16	3-82	7-78	518.1	UC	8.8	NP
H1UCP018	VP	7-78	518	UC-LC	16	3-82	7-78	518.1	UC	8.8	NP
H1LCR001	R	4-79	517	NA ^(e)	7.5	NP	4-79	517.1	NA	7.1	8-80
H2SPS040	SP	4-79	517	NA	7.5	NP	4-79	517.1	NA	7.1	8-80
H2XSS041	SP	4-79	517	NA	7.5	NP	4-79	517.1	NA	7.1	4-80
H2XSS042	SP	4-79	517	NA	7.5	NP	4-79	517.1	NA	7.1	NP
H2UCR023	R	4-80	518	UC-LC	16	7-83	2-80	518.2, .3	LC	16	11-82
H2UCR024	R	4-80	518	UC-LC	16	10-83	2-80	518.2, .3	LC	16	2-83
H2UCG027	ACP	4-80	518	UC-LC	16	7-83	2-80	518.2, .3	LC	16	11-82
H2UCG028	ACP	4-80	518	UC-LC	16	7-83	2-80	518.2, .3	LC	16	11-82
H2UCG029	ACP	4-80	518	UC-LC	16	7-83	2-80	518.2, .3	LC	16	11-82
H2UCS033	SP	4-80	518	UC-LC	16	10-83	2-80	518.2, .3	LC	16	2-83
H3UCR025	R	10-81	518	UC	8	12-83	2-80	518.2, .3	UC	16	5-83
H3UCR026	R	10-81	518	UC	8	12-83	7-81	518.3	UC	8	5-83
H3UCG030	ACP	10-81	518	UC	8	10-83	2-80	518.2, .3	UC	16	2-83
H3UCG031	ACP	10-81	518	UC	8	10-83	2-80	518.2, .3	UC	16	2-83
H3UCG032	ACP	10-81	518	UC	8	12-83	7-81	518.3	UC	8	5-83
H3UCS034	SP	10-81	518	UC	8	12-83	2-80	518.2, .3	UC	16	5-83

(a) R = Reference

A = Annular

AC = Annular-coated (Dag 154)

VP = Vipac

SP = Sphere-pac

ACP = Annular-Coated (Dag 4)-Pressurized.

(b) 518 = IFA-518 (2 six-rod clusters)

517 = IFA-517 (1 four-rod cluster).

(c) LC = Lower Cluster

UC = Upper Cluster

UC-LC = Upper Cluster for First Half - Lower Cluster for Second Half of the Irradiation Period.

(d) NP = Not Planned.

(e) NA = Not Applicable.

reduce the irradiation time needed to achieve the goal burnups by about 20%. Fewer vipac fuel rods in the test matrix, reduction of the goal burnup for the Series H-1 upper cluster annular and sibling reference rods, and elimination of cluster inversions permit loading of two annular-coated-pressurized, one sphere-pac, and one reference rod sooner than originally planned. As a result, a higher burnup will be achieved prior to ramping these annular-coated-pressurized, sphere-pac, and sibling reference rods. Elimination of most of the vipac rods from steady-state irradiation and ramping tests, together with the faster, higher burnup to be achieved in the annular-coated-pressurized and sphere-pac rods, permits more emphasis on the rod designs of primary interest. The benefits of higher burnup and a shorter irradiation time are significant, because the results of the screening tests from HBWR obtained under these conditions can be used as criteria for selecting test parameters in subsequent tests, i.e., the last 10 (out of 15 total) primary power-ramp tests on the segmented rods irradiated in the BRPR.

5.3 FABRICATION--HBWR SERIES H-1, H-2, H-3 AND H-4 RODS

Fabrication of the 28 instrumented rods to be irradiated in HBWR Series H-1, H-2, H-3, and H-4 was completed. The HBWR Series H-1 characterization report, C00-4066-11, was distributed.^(5.1) A draft of a similar report for the Series H-2, H-3, and H-4 rods was completed and distributed for review. These reports are working documents and provide as-built data describing the rods. The major topics included in the reports are:

- experiment description
- process development
- fabrication and characterization procedures and methods
- physical, chemical, and ceramographic characterization data.

5.4 HBWR STEADY-STATE IRRADIATION STATUS

5.4.1 IFA-518 Irradiation

The steady-state irradiation of the 12 rods, which comprise HBWR Series H-1, started in July 1978 in the IFA-518 test rig. The irradiation was completed on January 7, 1980, after five HBWR reactor cycles of exposure. (In

order to clearly identify this irradiation from subsequent loadings of IFA-518, the experiment has been redesignated IFA-518.1.) The cluster average burnups for IFA-518.1 are 845 GJ/kgM (9.8 MWd/kgM) in the lower cluster rods and 677 GJ/kgM (7.8 MWd/kgM) in the upper cluster rods. The average of the rod peak burnups is about 946 GJ/kgM (10.9 MWd/kgM) and 759 GJ/kgM (8.8 MWd/kgM) for the lower and upper clusters, respectively. During the irradiation of IFA-518.1, an axially movable silver absorber shield was used to alternately cycle the power between the upper and lower clusters. (The shield will not be used during subsequent operation of IFA-518 in order to increase the burnup rate in the test rods. See Section 5.2.) During the irradiation of IFA-518.1, the shield position suppressed the power in the lower cluster during two operating periods, i.e., during the period from cluster average burnups of 240 GJ/kgM (2.8 MWd/kgM) to about 390 GJ/kgM (4.5 MWd/kgM) and during the period from about 690 GJ/kgM (8.0 MWd/kgM) to about 745 GJ/kgM (8.6 MWd/kgM). During the alternate periods, the power in the lower cluster was not suppressed. The powers in the upper cluster were correspondingly the opposite. Peak LHGRs in IFA-518.1 were in the range from 38 to 45 kW/m for the nonshielded cluster and 25 to 30 kW/m for the shielded cluster.

During the January/March shutdown, IFA-518.1 was removed from the reactor, and the rods were removed from the test rig and inspected. Inspection of the IFA-518.1 rods consisted of visual examination, profilometry, and an eddy-current test. Two of the rods, H1LCA006 (A6) and H1LCP014 (V14), had a patch of fluffy white oxide on the exterior surface of the cladding near the top of the fuel column. This material was easily removed by contact with the manipulator and is believed to have had no significant effect on the operation of the fuel rods. With the exception of the patch of fluffy oxide, the extent of oxidation on the surface of all the rods appeared to be slight. Eddy-current examination of the rods indicated a slight, but not as yet quantified, defect in the cladding of H1UCR003 (R3). This reference rod was irradiated in the upper cluster of IFA-518.1 and will be returned to the reactor for further steady-state irradiation. The status of the possible defect indication will be monitored for evidence of possible change. Profilometry results are not yet available.

The silver shield was removed from IFA-518 and the lower turbine flow-meter, which was stuck, was replaced. The IFA-518 test rig was reconstituted as IFA-518.2 and returned to the reactor. The lower cluster of IFA-518.2 was loaded with three unirradiated annular-coated-pressurized rods, two reference rods and one sphere-pac rod (Table 5.1). The upper cluster of IFA-518.2 was loaded with two unirradiated annular-coated-pressurized rods, one reference rod, and one sphere-pac rod, along with two previously irradiated Series H-1 rods, i.e., an annular-coated rod and a reference rod (Table 5.1). Operation of IFA-518.2 was started in HBWR in mid-March. Heat balance calibration has been completed.

5.4.2 IFA-517 Irradiation

Irradiation of the four HBWR Series H-4 rods, three sphere-pac rods and one reference rod, started in April 1979 in the IFA-517 test rig. The irradiation of IFA-517.1 was completed on January 7, 1980 after accumulating a cluster average burnup of 579 GJ/kgM (6.7 MWd/kgM) with the average of the rod peak burnups at 596 GJ/kgM (6.9 MWd/kgM). Peak linear heat generation rates in the Series H-4 rods were in the range from 40 to 45 kW/m.

During the January/March shutdown, the four rods were examined visually, measured with the profilometer, and given an eddy-current examination. The rods appeared to be in excellent condition. The lower turbine flowmeter in IFA-517, which was stuck, was replaced and an orifice flow plate was also installed to permit heat balance calibration when individual test rods are power-ramped in the rig. The IFA-517 test rig was reconstituted as IFA-517.2 with the irradiated rods to be power-ramped and returned to the reactor.

5.5 HBWR POWER-RAMP TESTING

IFA-517.2 was loaded for ramp testing with two annular-coated rods (H1LCG009 (AC9) and H1LCG010 (AC10)) and one vipac rod (H1LCP013 (V13)) from Series H-1 and one sphere-pac rod (H2XXS041 (S41)) from Series H-4. In order to achieve sufficient power during ramping, the rods will be ramped individually. This requires movement of the individual rods into and out of the reactor core with hydraulic pistons. During pre-operational checkout of the test

rig, it was determined that one of hydraulic pistons could not be withdrawn. Therefore, the test rig was removed from the reactor for inspection. In the event that the piston cannot be made operational, it will be necessary to utilize only the three operational positions in IFA-517. A contingency plan was developed for the possibility that only three test spaces are available in IFA-517. This plan utilizes two sequential loadings of three rods in IFA-517 with the loading of two rods in another ramp rig to be tested at the time of ramping the second IFA-517 loading. The initial power-ramp testing has been rescheduled for mid-May 1980.

5.6 HBWR DATA ACQUISITION AND PROCESSING

5.6.1 IFA-518.1

Test Fuel Data Report (TFDR) magnetic tapes containing the recorded measurements from all five cycles of the steady-state irradiation of IFA-518.1 were received. Known correction factors have been applied to the data, the linear heat generation rate values have been calculated, and the data were stored on a disc file.

The elongation data for the third irradiation cycle of IFA-518.1 required correction, because of magnetic interaction between the linear variable differential transformer elongation sensors when they were simultaneously energized. The sensors had been simultaneously energized, in different combinations for different time periods, in order to obtain rapid (7 times per second) data collection during reactor power ascensions. The rapid data collection permits comparison of simultaneous rod elongation behavior for the different fuel rod types as a function of the natural cyclic variation of the reactor power. As a result of the magnetic coupling, two kinds of corrections were required: 1) a correction for shift in the elongation sensor signals at zero reactor power (the zero shift), and 2) a correction for the sensitivity of the elongation sensors to rod elongations. Both corrections were required for each individual sensor and for each combination of sensors that were simultaneously energized.

The correction for the initial zero shift was made by equating the zero power elongation sensor signals during the first and second cycles of

irradiation to the zero power signal at the beginning of the third cycle. For subsequent corrections during the third cycle when sensors were energized in different combinations, the zero power signal to be corrected was equated to the last corrected zero power signal with the prior set of energized sensors. Thus, zero power corrections were always algebraically additive to prior known signals.

Sensitivity, or sensor calibration, corrections were made by comparing rod elongation behavior during power ascensions. Elongation data during power ascensions in the first and second cycles (the unaffected data) were compared to elongation data obtained during the third cycle (the affected data). Only data that showed no evidence of fuel-cladding mechanical interaction in the rods were used. Multiplication factors equating the slope of the unaffected data were determined. Comparisons were made for each combination of sensors that were simultaneously energized.

Standard plots of temperature, elongation, internal rod pressure, and linear heat generation rate as functions of time and burnup for each rod have been prepared. Plots of individual measurements as a function of linear heat generation rate have also been prepared. These plots will be used for performance evaluation in Task 3.

5.6.2 IFA-517.1

TFDR magnetic tapes for all three cycles of IFA-517.1 were received, corrected, and stored on disc file. The elongation and pressure sensor signals have been corrected for the simultaneous energizing during the first cycle of operation (see Section 5.6.1). The types of plots discussed in Section 5.6.1 have also been produced for the IFA-517.1 data.

5.7 PRIMARY RAMPING TEST STATUS

Central segments from the segmented rods in BRPR Series S-1 and S-2 will be utilized for the primary ramp tests after completion of steady-state irradiations in the BRPR. The 48 segmented rods are currently undergoing irradiation

in BRPR. Status of the BRPR is described in Section 6.0. Initial primary power-ramp tests on BRPR segmented rods are tentatively planned for April 1982.

5.8 REFERENCES

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6.0 TASK 2C--IN-REACTOR DEMONSTRATIONS

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The objective of this task is to demonstrate the commercial acceptability of the improved fuel concepts through irradiation of a significant sample of rods that were fabricated in accordance with commercial processes and quality control procedures.

A total of 359 rods, comprising the fuel concepts being evaluated as part of the Fuel Performance Improvement Program, will be irradiated in the BRPR. Four fuel assemblies containing demonstration fuel rods were inserted in BRPR during the spring of 1979 and the remaining six assemblies will be inserted around January 1981. Each assembly will remain in the reactor for four years, and will be subjected to the maximum power levels and power-ramping cycles that are consistent with normal operations. Selected fuel rods will be removed periodically (at intermediate burnup levels) from each series for destructive examination or power-ramping in a test reactor.

As reported previously, the fabrication of all the test and demonstration fuel rods has been completed.^(1.15) Four FPIP fuel assemblies containing 96 full-length and all of the 48 segmented rods are currently undergoing irradiation in the BRPR. The final demonstration series contains only full-length rods (199) and will be placed in BRPR during the next refueling outage. At this time, the FPIP assemblies have been in BRPR for about five full-power months and have accumulated an assembly-average burnup of about 277 GJ/kgM (3.22 MWd/kgM).

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7.0 TASK 3 - FUEL PERFORMANCE EVALUATIONS

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The objective of this task is to integrate and evaluate fuel performance using data developed in the Fuel Performance Improvement Program (FPIP), as well as the results of other FCI-related programs as they may pertain to the FPIP. The task activities will provide the data needed for establishing technical bases for fuel design.

7.1 HBWR SERIES H-4 FUEL CENTERLINE TEMPERATURE MEASUREMENTS

The Series H-4 fuel rods irradiated in the HBWR assembly IFA-517.1 included three pressurized sphere-pac rods (two with fuel centerline thermocouples) and one reference rod with a fuel centerline thermocouple. Two of the sphere-pac rods and the reference rod were instrumented with cladding elongation sensors; the other sphere-pac rod contained an internal pressure sensor. The rods were arranged in a square array, with the midplane of the active fuel length aligned with the peak in the axial flux profile.

From the beginning of the irradiation to the rod-average burnup of about 575 GJ/kgM (6.6 MWd/kgM), the measured fuel temperatures in the two pressurized (400-500 kPa helium) sphere-pac rods were consistently lower than the measured temperatures in the reference pellet rod. In addition, the two sphere-pac rods indicated essentially the same temperatures at equivalent linear heat generation rates (LHGRs). These observations are summarized in Figure 7.1 and Table 7.1. Based upon the relatively higher fuel temperatures measured in the nonpressurized vipac fuel rods irradiated in IFA-518.1, the lower operating temperatures in the pressurized sphere-pac fuel rods were somewhat unexpected, although helium pressurization had been expected to reduce the operating temperature due to Knudsen conduction in the gas space between spheres. The following discussion is intended to explain in a qualitative way, the lower sphere-pac fuel temperatures and to provide an interim quantitative expression for the effective thermal conductivity of pressurized LWR sphere-pac fuel.

FIGURE 7.1. Comparison of Measured Fuel Centerline Temperatures in Sphere-Pac and Reference Fuel Rods During Initial Startup.

7.1.1 Experimental Considerations

Several experimental considerations could affect the comparison of reference and sphere-pac operating fuel temperatures. Among these are erroneous thermocouple signals, neutronic effects, and thermocouple relocation. These are discussed below.

The temperature response as a function of LHGR for two reference rods, one during irradiation in IFA-517.1 and the other in IFA-518.1, is illustrated in Figure 7.1. Because of positioning in the core, the axial power profile in the

TABLE 7.1. Comparison of Fuel Centerline Temperatures in Sphere-Pac and Reference Fuels at 35 kW/m as a Function of Burnup

Fuel Type	Rod No.	Fuel Centerline Temperature, °C				
		0 GJ/kgM	22 GJ/kgM	311 GJ/kgM	435 GJ/kgM	575 GJ/kgM ^(a)
Reference	R1	1190	1240	1310	1340	1400
Sphere-Pac	S41	1065	1125	1170	1265	1260
	S42	1060	1125	1170	1265	1280

(a) Because of a rapid shutdown at the highest burnup value, interpolation between the recorded temperatures during the power decension could not be made at the 35 kW/m level. The listed values are based upon steady-state data and the temperatures at last known 35 kW/m point.

two rods was significantly different, i.e., the peak LHGR/fuel-temperature in the IFA-517.1 reference rod occurred at the midplane of the rod, whereas the peak LHGR/fuel-temperature in the IFA-518.1 reference rod occurred at the top of the rod. Considering these differences, the similarity in behavior of the temperature response in the two rods as a function of LHGR indicates that the methods of calculating local LHGRs at the location of the thermocouples in the rods are valid. Therefore, no significant bias or error for the calculated LHGR is indicated that would affect the temperature comparisons between the reference and sphere-pac rods in IFA-517.1.

The similarity of temperature response as a function of LHGR in the two sphere-pac rods indicates that the thermocouples are providing reliable signals and that the measured temperature response is reproducible (Figure 7.1).

The actual smear densities of the fuel in the sphere-pac rods at the locations of the thermocouple tips is not accurately known. The presence of the thermocouple well and the thermocouple prevented reliable gamma densitometer measurements of smear density at this location on the as-fabricated rods. Neutron radiographs of the rods showed that some segregation of small and large spheres had occurred in the region of the thermocouple well. Thus, it is suspected that fuel regions with a smear density lower than the nominal 87% TD occurred along the length of the thermocouple well. In particular, in the

regions adjacent to the thermocouple tips, a lower density region was observed in one quadrant of the fuel in each sphere-pac rod; i.e., there was a lower fissile density indicated between the cladding and the thermocouple well on one side in one of two neutron radiographs that were taken 90° apart. The degree to which the density was decreased in the effected quadrant cannot be quantified from the radiographs. However, a lower fuel density in the region of the thermocouple tip would be expected to reduce the calculated LHGR and also reduce the effective thermal conductivity of the sphere-pac fuel. These two effects would tend to be off-setting with respect to the temperature response of the sphere-pac fuel. An attempt to quantify the density variation at the tip of the thermocouple in sphere-pac rod number H2XXS042(S42) will be made during the postirradiation examination.

Whereas the reference rods do not have thermocouple wells, the W-22%Re thermocouple wells in the sphere-pac rods would tend to depress the neutron flux and power in the center region of these rods. Based upon a comparison of the macroscopic cross-sections of the materials located adjacent to the thermocouples in the two types of rods, the presence of the additional material in the sphere-pac rods would be expected to reduce the flux and power in these rods less than one percent compared to the reference rods. More detailed neutronic calculations are being performed to confirm this value and evaluate its effect on LHGR and fuel temperature.

Even though neutron radiography showed that the thermocouples were centered in the sphere-pac rods at the completion of fabrication, the possibility exists that the thermocouples have since moved off-center. Thus, if this occurred, the thermocouples would measure a lower temperature than the maximum temperature occurring in the center of the fuel rods. The temperature response as a function of LHGR during the first few startups of the sphere-pac rods was essentially the same. Therefore, this indicates that it is unlikely that the thermocouples have relocated radially within the rods. However, the possibility that movement has occurred will be checked by neutron radiography during post-irradiation examination.

In summary, none of the possible experimental causes for lower fuel temperatures in the sphere-pac rods that have been evaluated are expected to account for the lower indicated fuel temperature in sphere-pac rods compared with reference rods.

7.1.2 Out-of-Reactor Studies of Sphere-Pac Fuel Conductivity

The effective thermal conductivity of sphere-pac fuel has been measured out-of-reactor^(7.1) and has been estimated from theoretical considerations.^(7.2) These studies are discussed below.

The effective thermal conductivity of sphere-pac fuel with a smear density of 87% TD was measured as a function of helium fill-gas pressure at relatively low temperatures, i.e., a maximum of 600°C at pressures of 304 and 608 kPa, by investigators at Oak Ridge National Laboratory (ORNL).^(7.1) Any reasonable extrapolation of this data into the temperature range of interest for an operating fuel rod results in effective thermal conductivity values that are significantly lower than required to explain the in-reactor measurements. The out-of-reactor measurements were made using a radial heat flow method and included the fuel-to-"cladding" gap. The apparatus utilized a central heater for obtaining a temperature gradient through the sphere-pac bed, a stainless steel shell for containing the sphere-pac bed, and an exterior heater for control of the ambient temperature. The fuel was loaded into the shell and compacted at room temperature. There was no method for applying axial restraint on the sphere-pac fuel column in the apparatus during the measurements.

Upon heating to the test temperature, the stainless steel shell tended to expand more than the sphere-pac fuel bed. This is the opposite of what occurs in a fuel rod, where the fuel expands more than the cladding whether during heating to a hot standby or a power producing condition. Thus, in the out-of-reactor measurement apparatus, the contact pressure, contact area, and hence, the heat transfer between spheres and from the sphere-pac bed to the container wall were lower than what normally occurs in an operating zircaloy-clad fuel rod, while heat transfer through the interstitial gas spaces remained essentially unaffected or slightly reduced. Therefore, the effective thermal

conductivity values for the sphere-pac fuel that were measured out-of-reactor are probably lower than the actual values for sphere-pac rods during irradiation.

Out-of-reactor measurements of the effective thermal conductivity of vipac fuel over the temperature range of interest tend to be lower than values derived from in-reactor temperature measurements.^(7.3) Perhaps there are problems, e.g., the sphere-pac-to-container differential expansion, that are generic to the out-of-reactor measurement of the effective thermal conductivity of packed-particle beds.

Ades has estimated the effective thermal conductivity of sphere-pac fuel as functions of helium fill-gas pressure and the degree of fuel restructuring, i.e., neck growth between spheres.^(7.2) These estimates were based upon the geometric characteristics and physical properties of the spheres and the helium fill gas. For the sphere-pac fuel with a smear density of 87% TD, about 450 kPa internal pressure, and no restructuring, the estimated values for effective thermal conductivity of the bed were about 80% of the out-of-reactor values as determined by ORNL.^(7.1) Increasing the amount of restructuring increased the estimated effective conductivity. However, for any reasonable amount of restructuring, the estimated values are still not high enough to explain the measured in-reactor fuel temperatures.

In summary, the out-of-reactor measurements of effective thermal conductivity of sphere-pac fuel appear to be biased low compared with values derived from irradiation experiments. Theoretical estimates of sphere-pac effective thermal conductivity have not been benchmarked to in-reactor data.

7.1.3 In-Reactor Measurements of Sphere-Pac Fuel Conductivity

The two sphere-pac rods in IFA-517.1 were the first two pressurized LWR sphere-pac rods to be irradiated with fuel centerline thermocouples. Therefore, a comparison of in-reactor results can be made only with nonpressurized LWR and fast reactor type sphere-pac rods.

ORNL has reviewed the performance of sphere-pac fuel irradiated in thermal reactors and thermal reactor irradiations of fast reactor sphere-pac fuel.^(7.4) These irradiations were performed by the Netherlands Energy Research Foundation (ECN); Riso National Laboratory, Denmark; Kerforschungsanlage (KFA) at Julich,

FRG; Comitato Nazionale per l'Energie Nucleaire (CNEN), Italy; and ORNL. Results from the ORNL review that are pertinent to this discussion are:

- The restructured region in urania-plutonia sphere-pac fuel rods that operated at high LHGRs (60 kW/m), was smaller in a pressurized fuel rod than in a nonpressurized rod. This observation indicates that the effective thermal conductivity of a pressurized sphere-pac fuel rod is higher than for a nonpressurized rod.
- The LHGR required to produce a fuel temperature of 2000°C in a two-size fraction, urania-plutonia sphere-pac rod with a smear density of 81% TD was 52.5 kW/m. The LHGR required to produce a fuel temperature of 2000°C in a pellet rod with a smear density of 82% TD (83.5% theoretical density pellet with a 0.066 mm diametral gap) was 47.5 kW/m. These results indicate that the effective thermal conductivities of sphere-pac and pelletized fuel rods are comparable.
- The gap conductance derived for a two-size fraction, urania-plutonia sphere-pac rod with a smear density of 81% TD during irradiation was high, i.e., 19.3 kW/m²-°C. The value is about three times higher than the value derived for a small gap, i.e., 0.066 mm cold diametral gap, pelletized rod.

In addition to the above observations, Calza-Bini^(7.5) derived expressions for the effective thermal conductivities for fast reactor-type sphere-pac and pelletized fuel rod designs. The derived effective thermal conductivity during the initial irradiation of the two-size fraction (UO₂-PuO₂ large spheres and UO₂ fine spheres), nonpressurized sphere-pac fuel rod with a smear density of 83% TD was about 95% of the value required to explain the measured values for the HBWR Series H-4 pressurized sphere-pac rods if a high gap conductance is assumed for the Series H-4 rods. The effective thermal conductivity of the sphere-pac fuel derived by Calza-Bini is similar to the conductivity of pellet fuel over the temperature range of interest, being about 30% lower at 500°C and equivalent at 1500°C.

In summary, results based on measurements made on irradiated sphere-pac and pellet fuels indicate 1) increased effective thermal conductivity in

pressurized sphere-pac rods compared with nonpressurized rods, 2) a high fuel-to-cladding gap conductance in sphere-pac rods and, 3) comparable effective thermal conductivities for pellet and sphere-pac fuel rods.

7.1.4 Evaluation of Fuel Temperatures in Reference and Sphere-Pac Rods and Development of the Rationale for an Interim Sphere-Pac Thermal Conductivity Expression

In both reference pellet and pressurized sphere-pac fuel rods, the measured fuel centerline temperatures at equivalent LHGRs are dependent upon the thermal conductivity of the fuel and the fuel-cladding gap conductance. For low LHGRs and fuel temperatures that do not result in significant restructuring in either fuel type, i.e., operating LHGRs typical of LWRs, the thermal conductivity of the reference solid pellet fuel is typical of about 94% dense urania. Under similar operating conditions, the effective thermal conductivity of the sphere-pac bed is determined by the combined effects of the thermal conductivity of 99% dense urania spheres and the conductivity of the fill gas. Thermal conduction across the gap in a pellet rod is dependent upon the conductivity of the fill gas and the width of the fuel-to-cladding gap which, in turn, is determined by the extent of pellet fragmentation and outward relocation of the fragments. Conduction across the gap in a sphere-pac fuel rod is determined by a combination of the contact conductance between the spheres and the cladding and the conductance of the fill gas.

For the combinations of fuel and gap conductance discussed above for pellet and sphere-pac fuel rods, some of the determining factors can be estimated and quantified. The thermal conductivity of 94% dense urania is well known as a function of temperature (Figure 7.2).^(7.6) By applying a generally accepted correction for density,^(7.7) the thermal conductivity of 99% TD urania is estimated to be about 14% higher than for 94% dense fuel. The gap conductance in three-fraction sphere-pac fuel is expected to be higher than for fragmented pellet fuel because there is a significantly larger fraction of the surface of sphere-pac fuel in contact with the cladding, whereas there is probably a small fraction of the pellet fragment surface in contact early in the irradiation. The in-reactor measurements at ORNL also indicate a high gap conductance value for sphere-pac fuel.^(7.4) Because the temperature drop across the fuel-cladding gap is not highly sensitive to gap conductance at high gap conductance

FIGURE 7.2. Comparison of Effective Thermal Conductivity Values for Sphere-Pac Fuel

values and because an LWR sphere-pac fuel rod with a smear density of 87% TD probably has a larger area of fuel in contact with the cladding than the ORNL two-fraction sphere-pac fuel with a smear density of 81% TD, a gap conductance value slightly higher than the ORNL value appears justified for typical LWR sphere-pac fuel. A value of $28.4 \text{ kW/m}^2\text{-}^\circ\text{C}$ ($5000 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F}$) was selected.

Using the conductivity values for 94% dense urania and the Zircaloy-2 cladding, the flux depression in 11% enriched fuel, the geometry of the fuel and fuel rod in the HBWR Series H-4 reference rod, and the measured fuel centerline temperature at 40 kW/m in the reference rod, a calculation of the temperature distribution across the rod was made using GAPCON-THERMAL-2^(7.8) (Figure 7.3). A temperature drop across the fuel-cladding gap of approximately 200°C is indicated. Also shown in Figure 7.3 is the predicted radial temperature profile at 40 kW/m in the portion of the fuel where the thermocouples are absent.

FIGURE 7.3. Calculated HBWR Reference Pellet Fuel Startup Temperatures at 40 kW/m

Comparison of the thermal conductivity curves for sphere-pac fuel as a function of temperature as predicted by Ades^(7.3) and as measured by Calza-Bini^(7.3) reveal a difference in magnitude but similar shapes (Figure 7.2). (The theoretical predictions of Ades have not been benchmarked against measured data.) Also shown in Figure 7.2 is an extrapolation of the ORNL out-of-reactor data with a shape similar to the Ades and Calza-Bini curves. The results of a GAPCON-THERMAL-2 calculation using the extrapolated ORNL thermal conductivity data, a gap conductance of $28.4 \text{ kW/m}^2\text{-}^\circ\text{C}$, and an LHGR of 40 kW/m indicate a center fuel temperature that is approximately 450°C higher than the value that was measured for the Series H-4 sphere-pac rods (Figure 7.4). Thus, ignoring the

FIGURE 7.4. Calculated HBWR Sphere-Pac Startup Temperatures at 40 kW/m

improbable causes for a lower measured temperature discussed in Section 7.1.1, the ORNL out-of-reactor effective thermal conductivity data appears to be too low.

In order to provide an interim effective thermal conductivity for sphere--pac fuel, it is assumed that Ades' predictions, Calza-Bini's measurements, and the ORNL measurements (at low temperature) define the shape of the conductivity versus temperature curve. The interim value then is determined by applying an appropriate multiplication factor to the extrapolated ORNL curve that makes the calculated and measured center fuel temperatures coincide at a LHGR of 40 kW/m. Using a gap conductance of $28.4 \text{ kW/m}^2\text{-}^\circ\text{C}$ and a modified version of GAPCON-THERMAL-2, a multiplying factor of 1.48 was determined. The resultant

effective thermal conductivity curve as a function of temperature is also shown in Figure 7.2. Over the temperature range from 400°C to 1800°C, the following expression describes the effective thermal conductivity of sphere-pac fuel with a smear density of 87% TD,

$$k = 4.313 - 2.210 \times 10^{-3}(T) + 6.905 \times 10^{-7}(T)^2 ,$$

where the temperature is expressed in degrees Celsius and the thermal conductivity in W/m-°C. This effective thermal conductivity will be used until additional data provide reason to modify it. Calculated radial temperature profiles for the HBWR Series H-4 sphere-pac fuel rods operating at 40 kW/m with and without a thermocouple hole and based on this effective thermal conductivity are also illustrated in Figure 7.4. A comparison of the calculated radial temperature profiles of Series H-4 reference and sphere-pac fuel rods at 40 kW/m are shown in Figure 7.5. For the case of a sphere-pac fuel rod with no thermocouple hole operating at 40 kW/m, the center fuel temperature is approximately 150°C lower than for the reference, solid pellet rod. The major cause of the higher temperature in the reference fuel rod is primarily due to the effect of the lower fuel cladding gap.

7.2 HBWR DATA REDUCTION

Program SAMPL, which compresses the extensive HBWR performance data to approximately four percent of the original file, is now functional. This program follows the power history of single rods and makes linear approximations to power ascensions, power descensions, and steady-state operation. The program logic accounts for spurious data points, short periods of steady-state operation, scrams, and missing data points. Engineering data is extracted for the sampled power points and is stored for output in a format compatible with the EPRI fuel rod performance format.^(7.9) Engineering data extracted for each rod at each power point includes; average LHGR, LHGR at the thermocouple, fuel centerline temperature, rod elongation, rod pressure, burnup, shield position (IFA-518.1 only), time, and date. Examples of original and sampled LHGR data are shown in Figures 7.6 and 7.7.

FIGURE 7.5. Comparison of Calculated Temperatures in HBWR Reference and Sphere-Pac Rods at Initial Startup at 40 kW/m

FIGURE 7.6. Comparison of Actual LHGR Data and Reduced LHGR Data from SAMPL for Reference Rod HILCR002 from the Lower Cluster of IFA-518.1

FIGURE 7.7. Comparison of Actual LHGR Data and Reduced LHGR Data from SAMPL for Reference Rod H1LCR005 from the Upper Cluster of IFA-518.1

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8.0 TASK 4--ESTABLISHMENT OF TECHNICAL BASES

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The objective of this task is to establish technical bases for design and design criteria for the improved fuel designs from program results and from information on these designs that may be available in the open literature.

8.1 TECHNICAL BASES

The updating of initial technical bases has been preceded by a general review of the licensing requirements for the fuel system. For alterations in fuel designs, only those responses altered by the new design need be developed in detail. The sphere-pac fuel design would require a much more extensive licensing submittal than an annular design because of the number of fuel responses that could be altered by this change in form. The expected licensing requirements for the annular-coated-pressurized and the sphere-pac fuel designs were prepared as a guide to identify those technical bases requirements that must be established.

8.2 PERFORMANCE FILE DEVELOPMENT

The EPRI Fuel Performance Data Base was reviewed for application to the establishment of the FPIP technical data base. The data content of the file system was adequate, except for the characterization of the sphere-pac fuel. A few minor modifications would permit application of the EPRI format and no difficulties are foreseen for its adaption. The characterization data from the HBWR Series H-1 test rods were compiled into a card image file in the EPRI format. The next stage is to reduce the irradiation history data tapes for the rods undergoing irradiation in HBWR.

APPENDIX A

CONVERSION TABLE FOR SI UNITS

CONVERSION TABLE FOR SI UNITS(a)

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

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

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

(h) 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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