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Fuel Performance Improvement Program

Description and Characterization of HBWR Series H-2, H-3, and H-4 Test Rods

March 1980

Consumers
Power
Company

**EXXON NUCLEAR
COMPANY, Inc.**

Battelle

Pacific Northwest Laboratory

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UNITED STATES DEPARTMENT OF ENERGY

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FUEL PERFORMANCE IMPROVEMENT PROGRAM
DESCRIPTION AND CHARACTERIZATION OF
HBWR SERIES H-2, H-3, and H-4 TEST RODS

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SUMMARY

This report describes the fabrication process and as-built characteristics of the HBWR Series H-2 and H-3 test rods, as well as the three packed-particle (sphere-pac) rods in HBWR Series H-4. The HBWR Series H-2, H-3, and H-4 tests are part of the irradiation test program of the Fuel Performance Improvement Program. The HBWR Series H-4 test was a short-term experiment in conjunction with HBWR Series H-1 and is now completed. Irradiation of these test rods is being conducted in the Halden Boiling Water Reactor (HBWR), Halden, Norway. Fifteen rods were fabricated for the three test series. Rod designs include: (1) a reference dished pellet design incorporating chamfered edges, (2) a chamfered, annular pellet design combined with graphite-coated cladding, and (3) a sphere-pac design. Both the annular-coated and sphere-pac designs include internal pressurization using helium.

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CONVERSION TABLE FOR U.S. CUSTOMARY TO SI UNITS^(a,b)

	To convert from	to	Use this equation
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)	$\text{K} = ^{\circ}\text{C} + 273.15$
	To convert from	to	Multiply by
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	British thermal unit (Btu)	joule (J)	1.055×10^3
	calorie (cal)	joule (J)	4.187
	watt-second (W-s)	joule (J)	1.000
Linear Heat Rating	kilowatts/ft (kW/ft)	kilowatts/metre (kW/m)	3.281
Burnup	megawatt-day/metric ton of heavy metal ^(e) (Mwd/MTM)	gigajoule/kg of heavy metal ^(e) (GJ/kgM)	8.640×10^{-2}

(a) Conversions are based on ASTM Metric Practice Guide E380-74. The SI prefixes, SI symbols, and associated multiplication factors are:

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	$0.000\ 000\ 000\ 000\ 000\ 001 = 10^{-18}$

*To be avoided where possible.

(b) 10^6 Btu = 1.055 GJ = 0.17 barrels of oil^(c) = 100 kW-hr.^(d)

(c) One barrel of oil = 42 gallons.

(d) A conversion efficiency from heat to electricity of 0.33 is assumed.

(e) 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.

1.0 INTRODUCTION

The Fuel Performance Improvement Program (FPIP) is sponsored by the Department of Energy (DOE). The objectives of the FPIP are to identify and demonstrate fuel concepts with improved performance and to provide the supportive technical basis for developing commercial light water reactor (LWR) fuel designs capable of achieving high burnup and better utilization of uranium.

The objective of the testing and demonstration program, which forms the basis for the FPIP, is to conduct tests that will provide data needed to establish technical design bases for those fuel concepts that provide improved power-ramping capabilities. Activities associated with the testing and demonstration program have focused on identifying critical needs and activities within each task and assuring that the activities are performed in an integrated and mutually complementary manner.^(1,2) The activities in the testing and demonstration program include Task 2A, Out-of-Reactor Experiments; Task 2B, In-Reactor Experiments; and Task 2C, In-Reactor Demonstrations.

Task 2A activities concentrate on performing out-of-reactor experiments that will provide information needed to support 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). Coated cladding and the characteristics of packed-particle type fuel are specifically evaluated in Task 2A.

Task 2B activities concentrate on developing and implementing an optimized in-reactor testing program that is responsive to the objectives of the FPIP. Task 2B consists of both screening tests and primary tests. The first screening test (Series H-1) consisted of power-cycling highly instrumented test rods in the HBWR under quasi-steady-state irradiation conditions and will be followed by power ramping of individual rods in an HBWR ramping rig. HBWR Series H-2 and H-3 will also consist of irradiation in the HBWR followed by ramping in the same ramping rig, but the second and third series will not be power-cycled. Cladding elongation, fuel centerline temperatures, and internal gas pressure of the test rods will be monitored during quasi-steady-state irradiation in the HBWR.

For the Task 2B primary tests, segmented rods will undergo initial irradiation in BRPR and subsequently will be ramped in a suitable test reactor. These test results will allow a comparative evaluation of the fuel concepts being studied that have the potential for improved power-ramping capabilities.

Task 2C activities concentrate on design and process development of the primary fuel concepts [i.e., annular-coated-pressurized (ACP) and sphere-pac (SP)] that have been fabricated for the screening tests in HBWR and the demonstration irradiations in BRPR. Forty-eight of the 144 rods in BRPR Series S-1 and S-2 are segmented to facilitate ramp testing under Task 2B.

This report, which describes the fabrication and detailed characterization results for the rods used in Task 2B, is divided into four major sections: (1) experiment description, (2) process development required to fabricate the test rods, (3) methods and procedures used to fabricate and characterize the rods, and (4) a summary of the characterization results.

Detailed characterization results are presented in Appendices A through H and include:

- rod and pellet drawings
- physical and chemical characterization results for the cladding
- characterization results for graphite coating
- physical and chemical characterization results for the fuel
- physical and chemical characterization for the insulator pellets
- analytical results for the rod cover gas
- as-built rod characterization results, and
- physical and chemical characterization results for rod components.

2.0 EXPERIMENT DESCRIPTION

2.1 EXPERIMENT OBJECTIVES

The objective of the in-reactor experiments (Task 2B) is to conduct irradiation tests to study the detailed behavior characteristics and performance limits of fuel concepts with the potential for improved operating behavior in LWRs. Comparative parametric experiments are being performed with several fuel rod designs. The performance characteristics of the improved fuel concepts are being evaluated by means of screening tests that were originally planned to include three sequential groups of power-cycling and ramping irradiations in the HBWR test rig IFA-518. These three loadings in IFA-518 are designated HBWR Series H-1, H-2, and H-3. Irradiation of Series H-1⁽³⁾ was completed in January 1980. To permit an increase in burnup and burnup rate in the annular-coated-pressurized and sphere-pac rods, the power-cycling capability of the test rig was eliminated and the second loading in IFA-518 was changed to include two rods of Series H-1 and four rods of Series H-3, along with the rods of Series H-2. An additional irradiation test using HBWR test rig IFA-517 was designated HBWR Series H-4. This single loading in IFA-517 experienced quasi-steady-state irradiation from April 1979 to January 1980 to allow comparison of the temperature performance of the sphere-pac and reference designs.

The results of these comparative irradiations will be used to select the most promising fuel concept(s) for evaluation in the primary power-ramping experiments. The primary tests will utilize fuel rod segments that were pre-irradiated in the BRPR as part of Task 2C, In-Reactor Demonstrations.

2.2 DESCRIPTION OF HBWR SERIES H-2 AND H-3 RODS AND TEST RIG

The assessment of possible improved fuel rod concepts,⁽⁴⁾ which led to the selection of four fuel types for HBWR Series H-1, was the basis for the selection of fuel concepts in Series H-2 and H-3. The availability of sphere-pac fuel from Oak Ridge National Laboratory (ORNL) made it possible to substitute sphere-pac for vipac fuel in the Series H-2 and H-3 rods. The following fuel concepts are incorporated in rods that will be irradiated in HBWR Series H-2 and H-3:

- a reference design that uses a standard solid pellet with dished ends and chamfered edges (reference)
- a chamfered, annular pellet design combined with a graphite coating (Dag 4)^(a) on the inside surface of the cladding and pressurization with helium to ~455 kPa (~66 psia) (annular-coated-pressurized)
- a sphere-pac design pressurized with helium to ~455 kPa (~66 psia) (sphere-pac).

The HBWR test rig (IFA-518) for Series H-2 and H-3 test rods consists of two hexagonally arrayed clusters as depicted in Figure 2.1. The upper and lower clusters were alternately power-cycled in the first loading in IFA-518 using a movable, silver shield.⁽³⁾ However, the neutron absorber shield was removed from around IFA-518, which allows simultaneous peak rod linear heat generation rates of about 45.5 kW/m in both clusters in the second and third loadings of IFA-518.^(b) Table 2.1 lists the characteristics of the HBWR reactor. Instrumentation for the test rig includes:

- inlet and outlet flow meters and coolant thermocouples to determine total rig power;
- self-powered axial and radial neutron detectors to determine axial power variations and radial flux tilts; and,
- a failure detector to measure the presence of fission products in the coolant.

Test rod instrumentation for the Series H-2 and H-3 rods (Table 2.2) includes:

- linear variable differential transformer (LVDT) combination elongation/failure monitors (Figure 2.2) in the bottom of eight rods, and
- LVDT internal rod pressure monitors (Figure 2.3) in the bottom of four rods.

(a) Produced by Acheson Colloids Co., Port Huron, Michigan.

(b) Removal of the neutron absorber shield eliminated the power-cycling capabilities of the test rig but allows increased burnup and burnup rates.

FIGURE 2.1. Schematic of IFA-518 Test Rig

TABLE 2.1. HBWR Irradiation Conditions

Coolant Pressure	3.4 MPa (500 psi)
Coolant Temperature	240°C
Flow Mode	Natural Convection
Coolant	D ₂ O
Core Height	1.7 m
Axial Power Form Factor	1.2 - 1.3 (peak/avg.)
Reactor Power	12 MW
Thermal Neutron Flux	$2 - 4 \times 10^{17}$ neutron/m ² sec

TABLE 2.2. HBWR Series H-2, H-3 and H-4 Test Rod Instrumentation

Rod Type ^(a)	Rod Number	Instrumentation ^(b)
Reference	H2UCR023	E
	H2UCR024	P
	H3UCR025	E
	H3UCR026	P
Annular-Coated-Pressurized	H2UCG027	E
	H2UCG028	P
	H2UCG029	E
	H3UCG030	E
	H3UCG031	P
	H3UCG032	E
Sphere-Pac	H2UCS033	E
	H3UCS034	E
	H2SPS040	E
	H2XXS041	T,E
	H2XXS042	T,P

- (a) Reference = Solid pellet with dished and chamfered ends. Dish volume equals $\sim 1.0\%$ and chamfer volume equals $\sim 0.6\%$ of the volume of a solid cylindrical pellet.
 Annular-coated-pressurized = Pellet with 10 vol% central hole, chamfered edges equal to 0.6% of a solid pellet volume, graphite coating on the cladding inside surface, and a helium gas pressure of ~ 455 kPa (~ 66 psia).
 Sphere-pac = Spherical, packed-particle fuel made from a gel-derived process pressurized with a helium gas pressure of ~ 455 kPa (~ 66 psia).
 (b) T = Central fuel thermocouple
 E = Cladding elongation sensor
 P = Internal pressure sensor

FIGURE 2.2. Schematic of the Elongation/Failure Monitors Used in HBWR Series H-2, H-3 and H-4 Rods

FIGURE 2.3. Schematic of the Internal Rod Pressure Monitors for the HBWR Series H-2, H-3 and H-4 Rods

The design of the elongation and pressure monitors, which are incorporated in the lower end caps, was changed for Series H-2 and H-3. The outer contour of the upper end of the end cap was changed to improve weldability of the lower end cap to the lower end plug. The sensors are internally identical to the Series H-1 sensors, except for the level of pressurization in the bellows of the elongation/failure monitors for pressurized rods.

All test rod designs are based on a standard LWR fuel rod design. Drawings of the rods are shown in Appendix A. Plenum-to-fuel volume ratios in the fuel rod designs are larger than normal to accommodate the rod instrumentation. Porous frits have been included in the lower end plug assembly of all rods to prevent relocation of fuel particles into the lower instrumentation volume. The sphere-pac fuel rods also have an upper fuel retainer that prevents relocation of microspheres into the plenum region during handling. Both the porous frit and the upper fuel retainer allow gas to flow freely between the fueled region and the lower end cap and plenum, respectively. All test rods use an alumina (Al_2O_3) insulator pellet (disk) and low-enrichment (2.78% ^{235}U) UO_2 pellet at the ends of the fuel column. The low-enrichment UO_2 pellets were included in the fuel column to prevent power peaking in the adjacent high-enrichment (11% ^{235}U) fuel.

The peak, goal burnup for the Series H-2 and H-3 rods is $\sim 1380 \text{ GJ/kgM}^{(a)}$ ($\sim 16 \text{ MWd/kgM}$). Selected rods will be ramped in the IFA-517 ramping rig that

(a) See Conversion Table, p x.

will be used for ramping selected Series H-1 and H-4 rods. The ramp tests will be capable of producing rod powers up to ~ 65 kW/m in individual test rods.

2.3 DESCRIPTION OF HBWR SERIES H-4 RODS AND TEST RIG

The fuel rods in HBWR Series H-4 include three sphere-pac rods and one reference rod (H1LCR001) originally fabricated as a spare for HBWR Series H-1. The sphere-pac rods are identical in design to Series H-2 and H-3 sphere-pac rods, except for the inclusion of thermocouples. The reference rod used in Series H-4 was characterized along with the other Series H-1 rods.⁽³⁾ The Series H-4 test was devised to obtain sphere-pac fuel temperature, cladding elongation, and internal rod pressure data for comparison with the reference rod.

The Series H-4 test rig (IFA-517), which will also be used as a ramping rig, consists of four rods arranged in a square array (Figure 2.4). Instrumentation for this test rig includes:

FIGURE 2.4. Schematic of the IFA-517 Test Rig

- inlet and outlet flow meters and coolant thermocouples to determine total rig power;
- self-powered axial and radial neutron detectors to determine axial power variations and radial flux tilts;
- a centrally located cobalt neutron detector for detecting rapid changes in test rig power;
- a failure detector to measure the presence of fission products in the coolant; and
- a stainless steel coil that will be pressurized with ^3He during ramp tests to partly control power but was not used in the Series H-4 test.

Test rod instruments for the three sphere-pac fuel rods include elongation and pressure sensors, which are described in Section 2.2. In addition, two sphere-pac rods contain W-3%Re/W-25%Re fuel centerline thermocouples (Figure 2.5) in the upper portion of the fuel column. Test rod instrumentation for Series H-4 rods H2SPS040, H2XXS041 and H2XXS042 is summarized in Table 2.2. Although the pressure sensors are essentially the same in all of the HBWR tests, the Series H-4 sphere-pac rod with pressure sensor is placed in IFA-517 in such a manner that pressure changes are independent of changes in cladding elongation. Evaluation of internal pressure data for Series H-1, H-2, and H-3 rods requires the elongation data of a sibling rod to determine pressure variations.

The Series H-4 rod designs are also based on standard LWR fuel rod designs. The comments noted in Section 2.2 regarding plenum-to-fuel volume ratios, porous frits, upper fuel retainers, insulator pellets, and low-enrichment pellets also apply to Series H-4 sphere-pac rods. The sphere-pac rods with thermocouples also have a W-22%Re thermocouple well that is centered in the fuel rod. The thermocouple wells were centered with the aid of three W-25%Re wires of equal length that were welded perpendicular to the side of the well. Design data for the thermocouple wells, plenum springs, and zircaloy frits are in Appendix H.

After reaching an average burnup of ~ 604 GJ/kgM (7 MWd/kgM), quasi-steady-state testing of Series H-4 rods was completed. Three of the Series H-4 rods

FIGURE 2.5. Schematic of the Fuel Centerline Thermocouples
Used in the HBWR Series H-4 Sphere-pac Rods

will be power-ramp tested in IFA-517. Sphere-pac rod H2XSO42 will undergo postirradiation examination without having been ramped to determine the sphere-pac fuel structure resulting from normal operation.

2.4 EXPERIMENT OPERATION

All six rods from Series H-2, four from Series H-3 and two from Series H-1 were loaded into IFA-518 during the January-February 1980 shutdown. The two Series H-1 rods that were replaced into IFA-518 were subjected to interim visual, eddy-current and profilometry examinations. The silver shield was also removed from IFA-518 at this point, which resulted in the rig configuration shown in Figure 2.1. The positions of the sphere-pac (SP), annular-coated-pressurized (ACP), annular (A), and reference (R) rods are shown in Figures 2.6 and 2.7.

The third loading in IFA-518 will include all of the Series H-2 rods. The Series H-1 reference rod (H1UCR003) and annular-coated rod (H1LCG011), which are also in the second loading of IFA-518, will be replaced by a reference rod with pressure sensor (H3UCR026) and an annular-coated-pressurized rod with elongation sensor (H3UCG032). These Series H-3 rods will take the positions of the two rods removed from IFA-518.

Irradiation of HBWR Series H-4 was begun in April 1979 and testing was completed in January 1980. All rig and rod instrumentation operated satisfactorily during this period, except for a few short periods where electronic calibration adjustments were required. Elongation data was also affected for a short time by simultaneous energizing of three LVDTs; however, corrections have been identified for the elongation data affected by the simultaneous energizing. These rods were also removed for visual, eddy-current and profilometry examination. The loading for HBWR Series H-4 is shown in Figure 2.8.

FIGURE 2.6. Second Loading of IFA-518 Lower Cluster as Viewed from Above(a)

FIGURE 2.7. Second Loading of IFA-518 Upper Cluster as Viewed from Above(a)

- (a) See Table 2.1 for key to instrumentation.
 (b) Series H-1 rods are described in reference 3.

FIGURE 2.8. IFA-517 Loading Map for HBWR Series H-4 as Viewed from Above (b)

- (a) Series H-1 rods are described in reference 3.
(b) See Table 2.1 for key to instrumentation.

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3.0 PROCESS DEVELOPMENT FOR HBWR SERIES H-2, H-3, AND H-4 RODS

Process development was undertaken prior to the fabrication of HBWR Series H-2, H-3 and H-4 rods to improve pellet fabrication methods over those used for HBWR Series H-1 pellets, to allow the change from vipac to sphere-pac fuel, and to define the application techniques for the graphite coating (Dag 4) on the inside surface of the cladding.

3.1 PELLET FABRICATION PROCESS DEVELOPMENT

The 11% enriched UO_2 powder used to fabricate the HBWR Series H-1 pellets was very difficult to work with because of its variable ceramic properties.⁽³⁾ After re-evaluation of this material, it was decided to process the material in a hammer mill to obtain a more uniform pellet press feed material. The UO_2 powder was passed through a Bantam^(a) hammer mill in the following manner:

1st pass 14,000 rpm - no screen,
2nd pass 14,000 rpm - 0.69 mm (0.027 in.) herringbone screen

This material was then slugged on a Western Sintering press to $3.9 \pm 1 \text{ g/cm}^3$ and hand granulated through a 10-mesh screen. Sinterability tests of this

TABLE 3.1. Sinterability Test Results for UO_2 Pellet Powder^(b)

<u>Pellet Type</u>	<u>Green Density, g/cm^3</u>	<u>Sintering Temperature, $^\circ\text{C}$</u>	<u>Sintering Time, hr</u>	<u>Sintered Density, %TD</u>
Reference	5.40	1740	6.0	94.37
Reference	5.50	1740	6.0	94.45
Reference	5.62	1740	6.0	94.63
Annular	5.39	1740	6.0	94.54
Annular	5.48	1740	6.0	94.77
Annular	5.58	1740	6.0	94.90

(a) Manufactured by Bantam, Mikro-Pulverizer, Pulverizing Machinery Div. of MikroPul Corp., Summit, New Jersey.

(b) 0.2 wt% zinc stearate added.

powder provided very satisfactory results as summarized in Table 3.1. The results from these sinterability tests were used to set the process variables for pellet fabrication.

3.2 SPHERE-PAC PROCESS DEVELOPMENT

Spherical particle fuel was loaded into HBWR Series H-2, H-3, and H-4 sphere-pac test rods. Spherical particles were used instead of the angular particles used in HBWR Series H-1 vipac test rods because the former are expected to exhibit better performance. The improved fuel performance is due to an anticipated decrease in localized fuel-cladding mechanical interaction and, hence, lower stress on the cladding during irradiation.

The substitution of sphere-pac for vipac fuel required the establishment of new fabrication techniques and modification of previous work areas. The process equipment for loading microspheres into tubes was installed in the glovebox previously used for vipac rod fabrication.⁽³⁾ The sphere-pac process equipment included a low-energy, pneumatic vibrator (instead of the Branford^(a) variable impactor used for vipac fuel) and three controlled feeders, one for each sphere size fraction. A shape plate was also set up to segregate broken spheres from any down-loaded fuel rods. Preliminary sphere-pac process loading tests, patterned on information received from ORNL, were performed to qualify procedures for production rod loading.

The axial density of four test rods containing depleted uranium microspheres loaded at ORNL were measured on a gamma densitometer (densigage) at Exxon Nuclear Co., Inc. (ENC).⁽¹⁾ The linear density measurements were uniform (86-88% TD) except at the top end (6.4 - 12.7 mm) of the fuel column where there was a slightly lower (approximately 84% TD) density region. This situation also existed in the initial trial loadings of depleted microspheres. Success in eliminating the decrease in density at the top of the rods during fabrication of Series H-2, H-3, and H-4 test rods was limited. Although it was not possible to completely eliminate the low density regions, none of the density values in these preproduction test rods were below 84% TD and all of the lower density regions were confined to the top 25 mm of the rods.

(a) A product of Branford Vibrator Co., New Britain, Conn.

3.3 COATED-CLADDING PROCESS DEVELOPMENT

Dag 4 was used in the HBWR Series H-2 and H-3 annular-coated-pressurized rods. The Dag 4 graphite coating contains alumina and silica and is preferred because of its improved abrasion resistance compared with Dag 154 that was used in the HBWR Series H-1 rods.⁽³⁾

Considerable difficulty was encountered in controlling the thickness of the graphite layer on the inside surface of the Series H-2 and H-3 tubes tested for preproduction process verification. As a result, a procedure was instituted that required frequent checks of the coating thickness and frequent adjustment of the solids content of the Dag 4 solution. Each day, one or two tubes were coated and the graphite thickness was measured before a batch of tubes was coated. Adjustments were then made to the Dag 4 solution to assure the desired thickness, and several more tubes were coated before another process check was made. This procedure resulted in a production yield of ~60% for the fabrication of graphite-coated tubes for Series H-2 and H-3. Later, considerable improvement was made during production of BRPR Series S-2 and S-3 rods: the production yield for the BRPR rods was greater than 90%.⁽²⁾

A separate and more detailed report on coating technology using graphite Dag 154 and Dag 4 was written by Bunnell and Welty.⁽⁵⁾

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4.0 FABRICATION AND CHARACTERIZATION PROCEDURES AND METHODS FOR HBWR SERIES H-2, H-3, AND H-4 FUEL RODS

The procedures and methods used to fabricate and characterize the HBWR Series H-2, H-3, and H-4 fuel and test rods are described below. The description of these procedures and methods will permit comparison of performance data from the HBWR Series H-2, H-3, and H-4 test rods with the HBWR Series H-1 results.

4.1 FABRICATION

The HBWR Series H-2, H-3, and H-4 test fuel rods were fabricated at Exxon Nuclear's Process Engineering Laboratory. A fuel loading station, graphite coating and outgassing facility, and fuel pellet processing laboratory were used.

The fuel loading station consisted of a stainless steel glovebox with a circulating helium gas atmosphere. The moisture content of the helium was controlled within a range of 2 to 5 ppm water using a Dri-train.^(a) Both microsphere and pellet fuel material were loaded into the fuel rods at this station. The microsphere material was fed into the rods using two controlled vibrators:^(b) one for the coarse and medium-coarse spheres and another vibrator for the fine spheres. The feed rate of each sphere size fraction was controlled with a separate weir gate in the trough for each sphere size. The sphere-pac rods were vibrated^(c) during loading to prevent segregation of the three sphere size fractions. After loading, the microspheres in the rods were compacted to required densities using a low-energy pneumatic vibrator.^(d)

(a) Dri-train is a gas purification system manufactured by Vacuum Atmospheres Co.

(b) VIBCO Vibrator Products, Model BB190.

(c) Syntron vibrator manufactured by the Syntron Co.

(d) A springless vibrator with a 25.4 mm dia piston, manufactured by Cleveland Vibrator Company.

The graphite coating was applied in the graphite coating and outgassing facility,^(3,5) which consisted of a mechanical coating device, a glovebox with a controlled atmosphere, and a vacuum furnace used for drying and outgassing the coated tubes.

The fuel pellet processing laboratory contained a 10-ton, single-die pellet press, a vacuum-hydrogen sintering furnace capable of achieving 1800°C, a centerless grinder, and a fuel outgassing retort.

Flow sheets for the reference, annular-coated-pressurized, and sphere-pac designs are shown in Figures 4.1, 4.2 and 4.3, respectively.

4.1.1 Fuel Preparation

4.1.1.1 Pellet Fuel Preparation

The reference and annular pellets for HBWR Series H-2 and H-3 were fabricated based on the results of preproduction testing as presented in Section 3.1. No chipping, cracking or other difficulties were encountered as they had been during fabrication of the H-1 pellets.⁽³⁾ The powder uniformity treatment discussed in Section 3.1 was successful in eliminating these problems. The quality of all the pellets was categorized "excellent." The pellet fabrication parameters and resinter test results are listed in Table 4.1.

TABLE 4.1. HBWR Series H-2 and H-3 Pellet Fabrication Results

Pellet Form	Green Density, g/cm ³	Sintering Temp., °C	Sintering Time, hr	Average Sintered Density, %TD	Standard Deviation, %TD	Range, %TD	
						High	Low
Reference	5.49	1720	3	94.38	0.10	94.73	94.01
Reference resinter	--	1700	24	94.44	0.07	94.56	94.29
Annular	5.49	1720	3	94.42	0.09	94.68	93.97
Annular resinter	--	1700	24	94.44	0.09	94.60	92.27

FIGURE 4.1. Fabrication and Inspection Steps for HBWR Series H-2 and H-3 Reference Fuel Rod Manufacture

FIGURE 4.3. Fabrication and Inspection Steps for HBWR Series H-2, H-3 and H-4 Sphere-Pac Fuel Rod Manufacture

Pellet fabrication was conducted using the following procedures:

- Powder Preparation - The as-received, blended FPIP-001 powder was milled using a Bantam hammer mill, slugged in a Western Sintering 10-ton press, and hand granulated through a 10-mesh screen as described in Section 3.1. The resulting powder was designated FPIP-002.
- Lubricant Blending - Milled urania powder and 0.2 w/o zinc stearate lubricant were poured into a twin-shell blender and mixed for 10 min prior to pellet pressing.
- Pellet Pressing - The pellets were pressed in a single-die hydraulic press in this way: as the feed shoe extended over the die, the shoe released powder to fill the die cavity; the top punch was lowered, pressing the pellet; the upper punch was retracted; and the pressed pellet was ejected from the die cavity. The finished pellet was scribed with a pellet number and transferred by hand to a molybdenum sintering boat.
- Pellet Sintering - The pellets were batch sintered at 1720°C for 3 hr in a vacuum/hydrogen sintering furnace. The pellets were loaded in the furnace; the furnace was closed and evacuated to less than 27 Pa by using a roughing pump; the diffusion pump was turned on and the system pressure further reduced to 0.013 Pa. Heatup was started and hydrogen process gas was introduced into the furnace. When sintering was complete, the furnace was cooled under a hydrogen atmosphere, purged with pure nitrogen gas, backfilled with air, and opened. The pellets were removed from the furnace and stored in air in the sintering boats.
- Pellet Grinding - The pellets were ground to size using a centerless grinder. The diamond grinding wheel was set to remove no more than 0.038 mm of pellet diameter per 25.4 mm of grinding wheel face width for each pass the pellet made through the grinder. The pellet feed rate was minimized to prevent the formation of a lobe on the pellets. The pellet diameters were checked and, if required, reground to the specified diameter.

- Pellet Outgassing - The pellets were placed in stainless steel trays and loaded into the vacuum outgassing furnace. The outgassing furnace was then evacuated to 0.013 Pa. Outgassing was performed at 450°C for at least 3.5 hr. The vacuum outgassing furnace was cooled under vacuum, and the pellets were transferred to the pellet handling glovebox where the pellets were stored in an inert atmosphere.

4.1.1.2 Microsphere Preparation

The 11% enriched microspheres were prepared at ORNL. Chemical analysis of the as-received material is contained in Appendix D. The microspheres were outgassed in the same manner as was the pellet fuel described above.

4.1.1.3 Low Enrichment Fuel Pellets

The 2.78% enriched fuel pellets used at the ends of the fuel stacks to prevent power peaking were prepared using standard ENC procedures. The low enrichment pellets were made during the Series H-1 fabrication campaign and no additional low enrichment pellets were fabricated for Series H-2, H-3, or H-4 fuel rods.

4.1.2 Cladding Surface Treatment - Cleaning

The fuel rod tubes were washed in a detergent for at least three minutes, rinsed in hot flowing water, and finally rinsed in deionized water. Transfer times between washing and rinsing were minimized to prevent the tube surface from drying. The tubes were blown dry with high-pressure nitrogen to prevent water staining. All tubes were visually inspected for cleanliness, moisture contamination, and surface scratches. The cleaned tubes were stored in plastic sleeves, which were sealed on both ends with tape.

Prior to welding, the ends of the tubes were wiped with a cotton swab to remove any dust or debris. The graphite-coated tubes were cleaned to a depth of approximately 10 mm with a swab soaked in ethyl alcohol.

Components, such as springs and noninstrumented end caps, were cleaned using a procedure similar to the procedure used for the tubes.

4.1.3 Coated-Cladding Preparation

The coating method was essentially the same as that used for HBWR Series H-1 tubes.⁽³⁾ A flood coating technique was used: a dispersion of graphite in water was drawn down through a vertical tube using a silastic plug. The tube was allowed to drain for a short time and then air dried by forcing $\sim 80^{\circ}\text{C}$ air up through the bottom. Only one coating of graphite was applied. Measurements were taken on the inside diameter of the tube with an air gage before and after coating to determine the graphite coating thickness. Acceptable tubes were then cured under vacuum at 425°C for 24-28 hr. After curing, and before welding, the tubes were handled only in a helium atmosphere glovebox where they were plugged on both ends with temporary end caps and stored.

The point-by-point coating thicknesses of the graphite-coated tubes used for the HBWR H-2 and H-3 fuel rods are listed in Appendix C. All of the tubes were essentially at "nominal" for the specification range of 5 to 8 μm (0.0002-0.0003 in.).

4.1.4 Fuel Rod Loading - Pellets

The Zircaloy-2 tubes, with lower end caps welded in place, were put into the protective atmosphere glovebox containing 90 to 95% He and <5 ppm water. The pellets to be loaded into the fuel rod were placed end to end on a loading tray and the fuel column length was measured with a caliper. Insulator disks were placed at each end of the fuel column, and the pellets were pushed carefully into the tubes in a horizontal position. The design of the loading tray was such that chips, dust, etc., were prevented from entering the fuel rod: such material dropped through parallel bars in the loading tray into a catch tray.

After the pellets were loaded into the tube, the plenum length was measured using a quality control standard. The plenum spring was inserted and a temporary cap placed on the rod for transfer to the welding station.

4.1.5 Fuel Rod Loading - Sphere-pac

Five sphere-pac rods were made for HBWR Series H-2, H-3, and H-4 fuel loadings. All of the sphere-pac rods were loaded as follows: the coarse and

medium-coarse microspheres were fed directly into the fuel rod from separate loading troughs, which were attached to a single vibrator. Simultaneously, the fine microspheres were fed from a third trough and vibrated using a second vibrator. This technique was used to control the particle mix and prevent particle size segregation as the microspheres were loaded into the tube. The following microsphere size distribution was used:

<u>Fraction</u>	<u>Size, μm</u>	<u>wt%</u>	<u>Microsphere Density, %TD</u>
Coarse	1150-1410	58	98.26
Medium coarse	280-320	20	98.17
Fine	≤ 45	22	---

A fuel rod was vibrated at very low amplitude (vibrator air pressure of 137 kPa) during loading of the microspheres. When the required amount of fuel was added to the tube, air pressure to the vibrators was increased to 276 kPa and a weighted^(b) follower rod was placed on top of the fuel column. The rod was then vibrated until the correct plenum length was obtained. One of the factors in achieving the specified smear density ($87 \pm 1\%$ TD) for the fuel column was controlling the feed rates of the microspheres as they entered the rod. Other major factors were the length of time the rods were vibrated and the type of vibration applied to the rods. The fabrication process parameters are listed in Table 4.2.

In addition to the calculated smear densities, point-by-point densigage readings were recorded for each rod. Plots of densigage readings are shown in Appendix G. All of the data show the same trend, i.e., there is scatter in localized density at the bottom of the fuel column, very uniform density in the middle portion of the rods, and a rapid decrease in density in the top 25 to 50 mm. However, none of the localized density values are below 84% TD. A solution to this problem was later found in process development of BRPR Series

(a) The analytical procedure was not capable of assessing the %TD of fine fraction.

(b) 800 g.

TABLE 4.2. HBWR Series H-2, H-3, and H-4 Sphere-Pac Fabrication Variables

Rod No.	Smear Density of fuel, %TD	Loading Time, sec	Loading Vibrator Air Pressure, kPa (psi)	Final Compaction Time, sec	Final Compaction Air Pressure, kPa (psi)
33	87.7	30	137 (20)	270	276 (40)
34	87.9	32	137 (20)	270	276 (40)
40	87.7	30	137 (20)	330	276 (40)
41	87.6	30	137 (20)	210-bottom ^(a) 17-top	276 (40)
42	87.0	30	137 (20)	195-bottom ^(a) 15-top	276 (40)

(a) Rods 41 and 42 have thermocouples in the top end of the fuel column. The tube was filled with microspheres until a predetermined level was reached. A thermocouple well was inserted, and then the rods were topped off with microspheres. This accounts for the two compaction times. Extreme care had to be taken so as not to damage the thermocouple well.

S-2 and S-3 rods; i.e., by overfilling and vibrating the rods, and then removing excess microspheres by aspiration down to the correct plenum length.⁽²⁾ The smear density in the Series H-2, H-3, and H-4 sphere-pac rods averaged 87.90 ± 0.95% TD.

4.1.6 Fuel Rod Welding

While awaiting delivery of the lower end caps that were made at Halden, the loaded annular-coated-pressurized and reference fuel rods were fitted with temporary end caps and stored in a helium-atmosphere glovebox. Control samples of both pellets and Dag 4 were also placed in the storage glovebox. Just prior to welding the permanent lower end caps to the rods, the samples were analyzed for water and hydrogen content. These results showed that the pellets contained <2 ppm water. The sample of graphite was found to contain 5190 ppm water^(a) (0.3 ppm H₂-fuel weight basis) in comparison to 4180 ppm water^(a) (0.24 ppm

(a) Average of five analyses.

H₂-fuel weight basis) observed just prior to storage. Thus, the fuel rods were judged to be acceptable for closure. In addition to the process control samples, analysis showed a 99.7% helium atmosphere in the glovebox storage area just before storage and 93.6% helium and 89.2% helium just after the rods were removed from the glovebox.

While the fuel rods were stored briefly, the lower end caps were machined to finish the weld preparation area. The weld design of the lower end cap was changed slightly from Series H-1 to reduce the possibility of voids. The weld lip was eliminated and the root of the weld was angled to $5^{\circ} \pm 2^{\circ}$. In addition, the outside diameter of the lower end plug was reduced slightly to 10.43 mm (0.4105 in.) from 10.48 mm (0.4125 in.) to provide a looser interference fit. As a result of the weld and end-plug changes, no bottom end cap welds were rejected in Series H-2, H-3, or H-4 fuel rods.

Pressurization of the sphere-pac rods required redetermination of the time required in the weld chamber to allow the rods to equalize under pressure. From previous experience with BRPR segmented vipac rods, it was determined that 20 min in the weld chamber was required for pressure equalization. A subsequent process development test was made using four HBWR sphere-pac rods. A calibrated pressure transducer was attached to the upper end of the fuel rod and the time required for the rod to pressurize was recorded. (The rods were pressurized from the lower end because of the upper end cap configurations.) The pressure level in the sphere-pac rods asymptotically approached the pressure level set at the lower end of the rod. Within two minutes, most of the test rods reached ~90% of the set pressure level. Five minutes were allowed to assure pressure equalization in the sphere-pac rods prior to welding in actual fabrication.

After the lower end caps were prepared, the tubes and components were loaded into the welding chamber. The chamber was evacuated to 0.13 Pa and backfilled with helium of a purity greater than 99.9%. The evacuation and backfill procedure was repeated to ensure that the atmosphere in the rod was similar to the atmosphere in the chamber. The helium pressure in Series H-2

and H-3 reference rods was brought up to 101 kPa (1 atm). The helium gas pressure was increased to 425 kPa (4.20 atm) in the sphere-pac and annular-coated-pressurized rods. Pressurization in the annular-coated-pressurized rods was essentially instantaneous while pressure equalization in the sphere-pac rods was allowed for about five minutes. The moisture level in the gas was kept well below 100 ppm. Gas samples were taken from the supply bottles (manifold) to assure that process specifications were met.

End plugs and end caps were welded to the fuel rod tubes using a programmed gas tungsten arc welder. The tubes were inserted into the fuel rod holding fixture and a rotating weld head was positioned over the weld zone. An end cap or an end plug assembly was inserted into the tube, locked into position, and welded, the latter taking around eight seconds. The weld chamber helium pressure was increased at a rate of 7 kPa (0.07 atm) per second during welding of the sphere-pac and annular-coated-pressurized rods to compensate for the effect of welding on the gas pressure inside the rod. Thus, the internal rod pressure in the annular-coated-pressurized and sphere-pac rods is between the initial pressure of 425 kPa (4.20 atm) and ~480 kPa (~4.74 atm) at the end of welding.

Two process control welding samples were made before and after every group of welds. These samples were inspected metallographically and their quality was determined to be excellent.

4.1.7 Fuel Rod Surface Treatment - Cleaning and Etching

The completed fuel rods were agitated continuously while being etched in a nitric-hydrofluoric acid solution. The etch time was determined by the rate at which the acid removed Zircaloy-2 from a test sample.

The fuel rods were then transferred from the acid bath to an aluminum nitrate stop bath solution and agitated to assure that the solution came in contact with all parts of the fuel rods.

The rods were then transferred to a hot flowing water bath, where they were rinsed free of aluminum nitrate, then given a final rinse in deionized water. The rods were removed from the final rinse, blown dry with compressed nitrogen gas and wiped with ethanol. The dried fuel rods were stored in clean transfer carts.

4.1.8 Miscellaneous Components

Both the lower end caps (combination elongation-failure sensors or internal pressure sensors), and the upper end caps with and without thermocouples were produced by the Institutt for Atomenergi, Halden, Norway. Prior to use, the upper end caps with thermocouples were outgassed under vacuum at $175 \pm 27^{\circ}\text{C}$ to remove any adsorbed water from the BeO thermocouple insulators.

The alumina insulator pellets and the 2.78%-enriched fuel pellets with holes for thermocouples were used in sphere-pac rods. The holes were drilled with solid diamond drills, and the coolant/lubricant used was distilled water. The pellets were then washed with distilled water and outgassed.

The Zircaloy-2 porous frits used in the lower end plugs to prevent fuel fragment relocation into the lower instrumented end cap regions were machined from 60% dense (40% porosity), sheets 4.27 mm (0.168 in.) thick. One lot of frits was produced for all the HBWR rods. The sheets were produced by cold-pressing and sintering Zircaloy-2 powder. The resultant pore size was estimated to be in the 10 to 15 μm range. No lubricants were used during machining, and care was taken to avoid marring the as-sintered surfaces. The porous frits were outgassed under vacuum at $175 \pm 25^{\circ}\text{C}$ to remove adsorbed water prior to insertion into the fuel rods.

An upper fuel retainer was also included in the sphere-pac fuel rod design. This thin, Zircaloy-2 disc prevents the relocation of microspheres from the fuel column into the plenum region during rod handling. A central hole in the upper fuel retainer allows an essentially unobstructed flow of gas to the plenum. The design and placement of this retainer above the insulator pellet at the top of the fuel column is shown in Appendix A. The upper fuel retainer was fabricated from Zircaloy-2 sheets using a single-die stamp.

4.1.9 Deviations from Process Specification

Fabrication of the HBWR Series H-2, H-3, and H-4 test rods proceeded essentially as planned because of the experience gained in fabricating HBWR Series H-1. If measurements or tests could not be performed, but were not critical to quality assurance; or if the results were not within specifications, but were judged to be innocuous to fuel performance, deviating material

reports (DMR) were written. There were only eight deviating reports issued during this fabrication effort. Table 4.3 provides a summary of these reports.

4.2 CHARACTERIZATION

Characterization procedures and methods used for the HBWR Series H-2, H-3, and H-4 fuel rods are summarized below.

4.2.1 Physical Characterization

The methods and techniques used to determine the dimensions and weights of the fuel pellets, UO_2 microspheres, cladding, graphite coating, and completed fuel rods are described below.

4.2.1.1 Pellet Measurements

The diameter and length of all reference and annular pellets were measured with a calibrated standard Vee (V) micrometer. The accuracy of this measurement was ± 0.005 mm. The pellets were weighed with a balance accurate to ± 0.001 g.

4.2.1.2 Cladding Dimensions

Cladding dimensions (outside diameter, inside diameter, wall thickness) were derived using an ultrasonic immersion technique. These measurements were made during the fabrication of the HBWR Series H-1 rods because all HBWR Series rods were from the same cladding lot. The cladding was simultaneously rotated and translated between diametrically opposed ultrasonic transducers that operated in the pulse-echo mode. The dimensions were obtained by measuring the time necessary for the ultrasonic signal to leave and return to the transducers from the outer and inner surfaces of the tubing, respectively.

The ultrasonic immersion technique was calibrated by measuring a standard and referencing succeeding measurements to that standard. Measurements were to the following precisions: ID = ± 0.0038 mm (± 0.00015 in.); OD = ± 0.0025 mm (± 0.00010 in.); wall thickness = ± 0.0019 mm (± 0.00007 in.).

TABLE 4.3. Deviating Material Reports for HBWR Series H-2, H-3, and H-4 Fuel Rods

Part Exhibiting Deviation	Deviation	Justification for Waiver
Hardware - Porous Frits	Dimensions	Slight deviations will not affect function of part.
Fuel - Instrumented Pellets	Center hole dimensions	Slight deviations will not affect function of part.
Fuel - Annular and Reference Pellets	N ₂ , O ₂ gas analysis	Equipment not available for analysis. This analysis is beyond normal QC requirements and waiver of the analysis will not impare performance. Sufficient pellets have been placed in protective archive containers for future analysis.
Fuel - Sphere-pac	Off-gas measurements	Off-gas measurements were affected by atmospheric contamination during analysis. Subsequent tests showed that the hydrogen levels were due primarily to handling during analysis. (See Appendix D)
Fuel - Sphere-pac	H ₂ analysis	H ₂ measurements were affected by atmospheric contamination, but further analysis attributed the moisture to handling procedures during analysis and not the fuel. Moisture analysis for 5 samples = 4, 2, 3, 3, and 4 ppm water. $\bar{X}$ = 3.2ppm, σ = 0.836 ppm, and upper 95:95 = 6.7 ppm water. Sphere-pac particles are of high density and have little porosity.
Fuel - Sphere-pac	Immersion density	Coarse = 98.16% TD; Medium coarse = 98.17% TD. Analytical procedure not capable of analyzing fines ($\leq 45 \mu\text{m}$).
Rods - Sphere-pac	Test equipment not available to check rod internal pressure.	Welding equipment was qualified using calibrated pressure transducer. See Section 4.1.6.
Rods - Sphere-pac	Small gaps (~1 mm) between lower insulator discs and end caps.	The insulator pellets were pushed slightly upward by small amounts of fuel during rod loading. These spheres are estimated to be at low-packing density (~65% TD), and will not provide much power or very high temperature.

4.2.1.3 Graphite Coating Thickness

Air gages were used to measure the graphite coating thickness on the inside surface of each tube. The accuracy of this measurement was ± 0.0025 mm. Measurements were made at five points along the tubes. The maximum and minimum inside diameters were recorded at each location. After coating, measurements were taken again at the same locations. The difference between the two measurements represents the average maximum and minimum circumferential graphite coating thickness along the length of the tube.

4.2.1.4 Rod Dimensions

The outside diameter and the length of each finished fuel rod were measured along with variations in rod diameter. The outside diameter was measured using a calibrated, standard micrometer. Measurements were taken at 0° and 90° at three equally spaced locations along the length of the rod. The locations were 178 mm, 356 mm, and 533 mm from the top of the upper end cap. Measurements of rod outside diameters were accurate to within ± 0.005 mm. Measurements of rod length were accurate to within ± 0.03 mm. Variations in rod diameter were also provided by profilometry traces taken at Kjeller, Norway.

4.2.2 Chemical Characterization

4.2.2.1 Fuel

Several techniques were used to determine the chemical composition and impurities in the starting UO_2 , the pellet fuel, and the UO_2 microspheres. The techniques used are discussed below.

- Isotopic Analysis - This analysis was performed by thermal ionization mass spectrometry. A triple filament, 90° sector, 15-in. radius instrument was used. Detection was by electron multiplier-VPE strip chart system. Multiplier correction factors were determined using National Bureau of Standards (NBS) standard reference materials.
- Percent Uranium and O/U Ratio - This data was obtained gravimetrically. The sample was oxidized in air at 900°C to produce stoichiometric U_3O_8 . The percent uranium and O/U ratio were determined

by the weight gain. The atomic weight of the uranium was calculated based on the isotopic analysis and corrections made for impurities.

- Fluoride and Chloride Analysis - Fluoride and chloride were separated from the sample by pyrohydrolysis at 900 to 1000°C. The separated acids were collected in a specific volume of buffered solution. The fluoride and chloride contents were then determined with specific ion electrodes.
- Carbon Analysis - The carbon content was determined using a LECO^(a) carbon analyzer. The sample was oxidized in oxygen. All carbon oxides were converted to CO₂, and a chromatograph was used to determine the CO₂ content.
- Nitrogen Analysis - The total nitrogen content was determined with a LECO nitrogen determinator. Ignition was made at temperatures greater than 2000°C and nitrogen contents was determined with a chromatograph.
- Hydrogen Analysis - Hydrogen content was determined by the inert gas fusion method using a LECO hydrogen analyzer. A chromatograph was used to detect the hydrogen. Appropriate traps were used to prevent interferences.
- Total Gas Analysis - Vacuum extraction was made of the gases that desorbed from the sample at 1650°C. The gas was pumped into a measured volume where the pressure was measured with either a capacitance manometer or a Baratron.^(b) The gas content per unit of fuel weight at standard temperature and pressure was calculated according to Boyle's Law. The gas was then analyzed by gas mass spectrometry to determine nitrogen and hydrogen in the offgas.
- Water Analysis - Water content in the sample was determined with a moisture analyzer. A nominal temperature of 800°C was used to remove

(a) A product of LECO Corp., St. Joseph, Michigan.

(b) A product of MKS Instrument, Inc.; Burlington, Massachusetts.

the water from the sample. Detection was by coulometry. Analyses were made in a controlled atmosphere glovebox. The sample was weighed after analysis to detect sorption of atmospheric moisture.

- Trace Metallic Impurity Analysis - Trace metallic impurities were determined by emission spectrometry. The analyses were divided into two groups: regular impurities, and rare earth and refractory elements. Methods used are as follows:
 - Regular Impurities - The sample was oxidized to U_3O_8 , mixed with either Ga_2O_3 , $AgCl-LiF$, or $RbCl$ carriers, and excited. Spectral detection was electronic. Ni, Fe, B and Cd were detected by this technique.
 - Rare Earth and Refractories - The sample was dissolved and uranium was separated from the impurities by tributyl phosphate solvent extraction. The aqueous phase containing the impurities was evaporated on graphite until dry. Yttrium was used as an internal standard. The residue and the graphite were mixed with a $AgCl-LiF(1:1)$ carrier and excited in a second oxygen atmosphere. The spectrum was recorded electronically.

4.2.2.2 Cladding

Chemical overcheck analyses of cladding were done as follows:

- Interstitial Gasses - Nitrogen and oxygen were determined simultaneously with an oxygen-nitrogen determinator, using a platinum flux. Hydrogen was determined with a hydrogen determinator, using a tin flux (see Section 4.2.2.1).
- Chemical Composition - The concentrations of tin, iron, nickel and chromium were determined by atomic absorption spectroscopy using a dissolved sample.
- Uranium in the sample was extracted into hexane, and the concentration was determined by fluorimetry.
- Chloride was determined by pyrohydrolysis (see Section 4.2.2.1).

- Carbon was determined using a carbon analyzer (see Section 4.2.2.1).
- Trace metal impurities were determined spectrometrically. The sample was oxidized and mixed with a AgCl-LiF(1:1) carrier and excited with a direct current arc. The spectrum was recorded electronically.

4.2.2.3 Coating

The graphite coating was analyzed for water, solids, and off-gasses.

- Water Content - The graphite coating was analyzed for water content using a phosphorus pentoxide cell. Because the water analysis involved heating the graphite to 800°C, any reaction between water and graphite would release free hydrogen that would not be detected. Therefore, a Cu-CuO combustor was placed downstream of the pentoxide cell to convert the hydrogen to water.
- Solids Content - The solids content of Dag 4 was used as a means of controlling coating thickness. The solids content was determined by weighing the dag in a sealed, tared container, then opening the container and drying the solids content overnight at 100°C to evaporate the water, then reweighing the container and solids.
- Off-Gas - The volume of gas that remained in the graphite coating after outgassing was determined by placing a weighed sample in a platinum container and heating to 1600°C in an evacuated glass system. The gases were then collected, the volume was measured at STP, the gases were drawn into an evacuated, sealed container, and were analyzed by mass spectroscopy.

4.2.2.4 Helium Gas Analysis

Impurities in the helium were analyzed chromatographically. A dual column instrument with dual thermal conductivity detectors, linear programming, and subambient control was used. Single-point calibration was used.

4.2.2.5 Alumina Insulator Pellet

Moisture and total gas in the alumina were analyzed by the same methods used to analyze the fuel described in Section 4.2.2.1.

4.2.3 Ceramographic Characterization

The milled urania powder (FPIP-002) used to fabricate pellets was characterized using a scanning electron microscope (SEM). Photographs of the powder were taken at 100X to 5000X magnifications. The microspheres received from ORNL were also examined using SEM. Several views of each microsphere size used in the sphere-pac fuel (FPIP-002 sphere-pac) are shown in Appendix D.

All fuel types were also analyzed by ceramographic techniques. Transverse and longitudinal sections of the reference and annular pellets were examined in the polished and etched conditions. Separate ceramographs were taken of etched samples of coarse, medium-coarse, and fine UO_2 microspheres. The ceramographs are shown in Appendix D.

4.2.4 Enrichment Verification - Passive Assay

The fuel rods were tested for enrichment uniformity using a ^{235}U gamma-ray passive assay system. The fuel rods were passed through the system at 330 mm/min. At this rate, the passive assay system was capable of detecting a relative enrichment nonuniformity of approximately $\pm 10\%$. A short length at each end of the rods was subject to geometric effects that resulted in reduced sensitivity. None of the traces had deflections that exceeded the reject level.

4.2.5 Sphere-pac Rod Smear Density Measurement

The smear densities of the sphere-pac rods were determined by measuring the attenuation of a collimated monoenergetic gamma beam as it passed diametrically through a rod. Density readings were averaged over small axial regions of the rod by translating the rod at ~ 1.3 mm/sec past a collimator window 4.95 mm long and 1.27 mm wide (the measurement period was ~ 10 sec). The collimator window was orientated with the length of the window parallel to and centered on the rod axis. A correction was made for the attenuation caused by the cladding thickness.

The densigage readings were calibrated by comparing the average of all uncalibrated readings for a rod with the calculated smear density of the loaded fuel.

4.2.6 Leak Check

Prior to etching, the fuel rods were tested for helium leaks in a horizontal, leak test station. No leaks were found in the test rods when compared to a standard leak of 1.0×10^{-8} cc (STP)/sec.

4.2.7 Radiography

Neutron and x-ray radiography were used to examine the condition of the fuel in the loaded rods.

The neutron radiographic facility at the 250 kW Triga Reactor, Hanford Engineering Development Laboratory, was used for the neutron radiographic examination. The examination was conducted to detect the location of any fuel pellets with fissile contents that varied from the design specification, to identify any internal fuel pellet flaws, and to identify any variations in the apparent density of the sphere-pac fuel column. The radiographic facility used a beam tube 6.10 m (20 ft) long. The tube tapered from a 432 mm x 1016 mm (17 in. x 40 in.) exposure area to a 25.4 mm x 25.4 mm (1 in. x 1 in.) source aperture located near the core periphery. The fuel rods were positioned between the exposure area and an evacuated film cassette during the 60 min exposure to thermal neutrons. The film cassette contained a gadolinium screen and Kodak Type SR[®] film that were exposed simultaneously. The rods were radiographed in both the 0° and 90° orientations and resulted in excellent quality radiographs.

The test rods were also radiographed using a 300 keV X-ray machine. Closure welds of all rods were radiographed in one position. The radiographic technique used is capable of detecting voids ≥ 0.25 mm in diameter. Full-length radiographs were also taken at three positions, 60° apart. Two axial exposures were required to obtain the full length of the fuel column.

Neutron and x-ray radiographs showed no anomalies in the fuel columns.

[®] A registered trademark of the Kodak Co; Rochester, New York.

4.2.8 Resinter Test

The pellets made for the HBWR Series H-2 and H-3 test rods were pressed to 5.49 g/cm³ using 0.2 wt% zinc stearate, and were sintered at 1720°C for 3.0 hr. Several pellets were checked for densification by sintering for an additional 24 hr at 1700°C. (See Table 4.1.)

4.2.9 Miscellaneous Characterization

End plugs were inspected, especially in weld joint areas, using standard micrometers and optical gages prior to fit-up and welding.

Special pellets with holes for thermocouples were inspected for concentricity of the holes. Dowel pins and run-out dial gages were used for this inspection.

Mechanical properties certification for the cladding was provided by Sandvik Special Metals, Inc., the supplier of tubing for the project.

5.0 SUMMARY OF CHARACTERIZATION RESULTS

Characterization results are the pertinent, detailed data that describe the HBWR Series H-2, H-3, and H-4 rods. The data are included in the Appendices listed below:

- Appendix A - Pellet and Rod Drawings
- Appendix B - Physical and Chemical Characterization Results for the Cladding
- Appendix C - Characterization Results for Graphite Coating
- Appendix D - Physical and Chemical Characterization Results for the Fuel
- Appendix E - Physical and Chemical Characterization Results for the Alumina Insulator Pellets
- Appendix F - Analytical Results for the Rod Cover Gas
- Appendix G - As-Built Rod Characterization Results
- Appendix H - Physical and Chemical Characterization Results for Rod Components

Table 5.1 summarizes the information presented in the appendices. Note: Although units used in the table are given in the metric system, measurement data were normally obtained in English units and converted to metric.

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TABLE 5.1. HBWR Series H-2, H-3, and H-4 Fuel Rod Characterization Summary

Rod Number	Rod Type	Thermo-couple	Pressure Transducer	Elongation Sensor	Rod Description			Void Volume, cm ³	Cladding		Tube Identity Number	Coating		Fuel					Cover Gas, % He
					Overall Length, mm (in.)	Length, (a) mm	Smear Density, %TD ^(b)		ID mm (in.)	OD mm (in.)		Maximum Thickness, m (in.)	Minimum Thickness, m (in.)	Average, mm (in.)	Range, mm (in.)	Average, mm (in.)	Fuel Weight, g 11%/2.78%	Fuel Length 11% 2.78%/2.78% mm (in.)	
H2UCR023	Reference			✓	715.289 (28.161)	547.42	88.9	6.86	10.51 (0.4138)	12.33 (0.4854)	115C	--	--	10.26 (0.4041)	0.003 (0.0001)	--	375.4/14.3	460.78/16.75 (18.141)/(0.6596)	99.96
H2UCR024	Reference		✓		715.239 (28.159)	547.54	88.8	6.87	10.52 (0.4140)	12.33 (0.4854)	58B	--	--	10.26 (0.4041)	0.005 (0.0002)	--	376.3/13.8	461.64/16.43 (18.175)/(0.6468)	99.96
H3UCR025	Reference			✓	715.315 (28.162)	547.88	88.7	6.84	10.52 (0.4140)	12.33 (0.4853)	58D	--	--	10.26 (0.4040)	0.004 (0.0001)	--	376.4/13.6	461.05/16.28 (18.187)/(0.6408)	99.96
H3UCR026	Reference		✓		715.188 (28.157)	547.16	88.7	6.53	10.52 (0.4141)	12.33 (0.4854)	58E	--	--	10.26 (0.4040)	0.004 (0.0002)	--	379.4/14.0	465.86/16.58 (18.341)/(0.6528)	99.96
H2UCG027	Annular-Coated-Pressurized			✓	715.442 (28.167)	548.19	80.5	9.99	10.52 (0.4143)	12.33 (0.4853)	66G	7.0 (0.00028)	6.4 (0.00025)	10.25 (0.4035)	0.006 (0.0002)	3.251 (0.128)	341.4/13.7	462.53/16.30 (18.210)/(0.6418)	99.96
H2UCG028	Annular-Coated-Pressurized		✓		715.620 (28.174)	547.19	80.6	10.28	10.52 (0.4141)	12.33 (0.4854)	5E	6.4 (0.00025)	5.1 (0.00020)	10.25 (0.4035)	0.004 (0.0002)	3.251 (0.128)	338.3/14.0	458.60/16.64 (18.055)/(0.6553)	99.96
H2UCG029	Annular-Coated-Pressurized			✓	715.061 (28.152)	548.70	80.7	9.57	10.51 (0.4138)	12.33 (0.4853)	170C	7.0 (0.00028)	6.4 (0.00025)	10.25 (0.4035)	0.003 (0.0002)	3.251 (0.128)	344.7/13.9	467.08/16.59 (18.389)/(0.6533)	99.96
H3UCG030	Annular-Coated-Pressurized			✓	715.162 (28.156)	547.73	80.6	9.76	10.51 (0.4138)	12.33 (0.4853)	170D	7.0 (0.00028)	5.7 (0.00023)	10.25 (0.4035)	0.004 (0.0001)	3.251 (0.128)	342.6/13.9	464.52/16.52 (18.288)/(0.6506)	99.96
H3UCG031	Annular-Coated-Pressurized		✓		715.061 (28.152)	548.15	80.6	10.12	10.52 (0.4140)	12.33 (0.4854)	66A	7.0 (0.00028)	5.1 (0.00020)	10.25 (0.4035)	0.006 (0.0002)	3.251 (0.128)	339.9/14.0	460.81/16.64 (18.142)/(0.6551)	99.96
H3UCG032	Annular-Coated-Pressurized			✓	715.086 (28.153)	548.46	80.4	9.75	10.52 (0.4142)	12.33 (0.4855)	5F	6.4 (0.00025)	5.1 (0.00020)	10.25 (0.4035)	0.005 (0.0002)	3.251 (0.128)	343.4/14.0	465.75/16.63 (18.337)/(0.6547)	99.96
H2UCS033	Sphere-pac			✓	715.721 (28.178)	547.85	87.7	9.00	10.52 (0.4141)	12.34 (0.4857)	58F	--	--	10.52 (0.4141)	--	--	372.8/13.9	462.84/16.47 (18.222)/(0.6484)	99.28
H3UCS034	Sphere-pac			✓	715.315 (28.162)	546.96	87.9	8.87	10.52 (0.4141)	12.33 (0.4856)	58G	--	--	10.52 (0.4141)	--	--	373.8/14.6	463.47/16.92 (18.247)/(0.6662)	99.28
H2SPS040	Sphere-pac			✓	715.620 (28.174)	--	87.5	8.86	10.51 (0.4138)	12.34 (0.4857)	115E	--	--	10.51 (0.4138)	--	--	373.6/14.5	465.46/16.60 (18.325)/(0.6536)	99.28
H2XXS041	Sphere-pac	✓		✓	715.442 (28.167)	--	87.8	9.01	10.51 (0.4138)	12.34 (0.4857)	115F	--	--	10.51 (0.4138)	--	--	369.4/13.0	463.07/16.64 (18.231)/(0.6550)	99.28
H2XXS042	Sphere-pac	✓	✓		715.315 (28.162)	--	86.9	9.16	10.52 (0.4140)	12.34 (0.4859)	58A	--	--	10.52 (0.4140)	--	--	368.4/13.3	465.99/16.62 (18.346)/(0.6545)	99.28

(a) The length, as measured by the Institutt for Atomenergi at Kjeller, Norway, is from V-notch to V-notch (see Appendix G).

(b) Smear density of 11% enriched pellets assuming 100% TD equals 10.96 g/cm³.

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APPENDIX A

PELLET AND ROD DRAWINGS

PELLET AND ROD DRAWINGS

Appendix A contains drawings of reference fuel pellets (Figure A.1), annular fuel pellets (Figure A.2), standard rod designs, (Figures A.3-A.6), and the upper fuel retainer (Figure A.7). Both pellet drawings include the chamfered edge, which was not part of the HBWR Series H-1 pellet design. The sphere-pac rod designs incorporate the upper fuel retainer that was used to prevent the relocation of microspheres into the plenum and insulator pellet areas.

FIGURES

A.1	Reference Fuel Pellet	.	.	.	.	.	.	.	.	A-2
A.2	Annular Fuel Pellet	.	.	.	.	.	.	.	.	A-3
A.3	Reference Fuel Rod Design	.	.	.	.	.	.	.	.	A-4
A.4	Annular-Coated-Pressurized Fuel Rod Design	.	.	.	.	.	.	.	.	A-5
A.5	Sphere-pac Fuel Rod Design	.	.	.	.	.	.	.	.	A-6
A.6	Sphere-pac Fuel Rod Design with Thermocouple	.	.	.	.	.	.	.	.	A-7
A.7	Upper Fuel Retainer	.	.	.	.	.	.	.	.	A-8

FIGURE A.1. Reference Fuel Pellet

FIGURE A.3. Reference Fuel Rod Design

A-5

FIGURE A.4. Annular-Coated-Pressurized Fuel Rod Design

FIGURE A.5. Sphere-pac Fuel Rod Design

A-7

FIGURE A.6. Sphere-pac Fuel Rod Design With Thermocouple

FIGURE A.7. Upper Fuel Retainer

APPENDIX B

PHYSICAL AND CHEMICAL CHARACTERIZATION RESULTS FOR THE CLADDING

PHYSICAL AND CHEMICAL CHARACTERIZATION RESULTS FOR THE CLADDING

Appendix B contains characterization data for the tubing used for the cladding. Table B.1 lists mechanical and physical properties of the tubing. Table B.2 lists the chemical composition of the ingot from which the tubing was fabricated by Sandvik Special Metals Corporation. The results of the chemical overchecks on the cladding did not vary significantly from the ingot analysis and thus are not listed.

The inside tubing dimensions are listed separately in Table 5.1. The outside tubing measurements are listed in Tables 5.1 and G.3.

TABLES

B.1	Tubing Qualification Results	.	.	.	.	.	.	.	B-2
B.2	Chemical Analyses of Zircaloy Ingot	.	.	.	.	.	.	.	B-3

TABLE B.1. Tubing Qualification Results

Test	Results	
	Sample 1	Sample 2
<u>Tensile Properties, 20°C</u>		
Ultimate tensile strength, MPa (psi)	711.6 (103,200)	721.9 (104,700)
0.2% yield strength, MPa (psi)	515.1 (74,700)	522.6 (75,800)
Elongation, %	21	22
<u>Tensile Properties, 382°C</u>		
Ultimate tensile strength, MPa (psi)	413.7 (60,000)	423.4 (61,400)
0.2% yield strength, MPa (psi)	282.7 (41,000)	311.0 (45,100)
Elongation, %	25	28
<u>Burst Test Results</u>		
Hoop stress, MPa (psi)	881.2 (127,800)	884.6 (128,300)
Pressure, MPa (psi)	140.7 (20,400)	140.7 (20,400)
Circumferential elongation, %	20.8	18.7
Eccentricity, %	1.3	1.3
<u>Cladding Hydride Orientation (Fn Number)(a)</u>		
Outer diameter	0.05	0.02
Center	0.03	0.03
Inner diameter	0.01	0.02
<u>Cladding Grain Size(b)</u>		
Transverse	11	11
Longitudinal	11	11

(a) The Fn number is a measure of the number of hydride platelets oriented within 45° of the radial direction. A low Fn number indicates most of the hydride is tangentially oriented with respect to the cladding. A high Fn number indicates the hydride platelets are oriented in the radial direction.

(b) The grain size is a standard ASTM grain-size number.

TABLE B.2. Chemical Analyses of Zircaloy Ingot
(ENC Order Number A30704)

Element	Composition, wt%		
	Top	Middle	Bottom
Sn	1.50	1.60	1.49
Fe	0.14	0.16	0.16
Cr	0.10	0.10	0.10
Ni	0.05	0.05	0.05

Element	Composition, ppm		
	Top	Middle	Bottom
Al	36	40	35
B	<0.25	<0.25	<0.25
Cd	<0.25	<0.25	<0.25
Ca	<10	<10	<10
C	100	180	120
Cl	<5	<5	<5
Co	<10	<10	<10
Cu	17	17	16
Hf	63	80	65
H	<5	<5	<5
Pb	<25	<25	<25
Mg	<10	<10	<10
Mn	<25	<25	<25
N	39	49	42
Si	93	107	98
Ti	<25	<25	<25
W	<25	<25	<25
U	1.4	0.9	0.9
O	1220	1240	1230
Nb	<50	<50	<50
Mo	<10	<10	<10
Ta	<100	<100	<100
V	<25	<25	<25

APPENDIX C

CHARACTERIZATION RESULTS FOR GRAPHITE COATING

CHARACTERIZATION RESULTS FOR GRAPHITE COATING

The coating used on the inner surface of the cladding for HBWR Series H-2 and H-3 annular-coated-pressurized rods was designated Dag 4. The as-supplied Dag 4 uses a water vehicle and contains ~33.5 wt% solids. The dag was diluted to ~13 wt% solids with deionized water. Considerable difficulty was encountered in applying the graphite coating to the specified thickness. As a result, a procedure was instituted that required frequent checks of the coating thickness and frequent adjustments of the solids content in the dag. Fifteen coated tubes were prepared for HBWR Series H-2 and H-3.

The chemical analysis of impurities in the out-gassed Dag 4 is shown in Table C.1. Water content and total off-gas analyses for the off-gas are presented in Table C.2. The results of a mass spectrometric gas analysis for a control sample of Dag 4 taken during fabrication of the Series H-2 and H-3 annular-coated-pressurized rods are shown in Table C.3. A photomicrograph of a Dag 4 coating is shown in Figure C.1. Dag 4 was not buffed as in HBWR Series H-1 rods because the improved adhesion of Dag 4 eliminated the need for buffing in the annular-coated-pressurized rods. A summary of the measurements of coating thickness on the inside surface of the rods is presented in Table C.4.

FIGURE

C.1	Surface Appearance of Dag 4 Used in HBWR Series H-2 and H-3 Annular-Coated-Pressurized Rods		C-2
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TABLES

C.1	Chemical Analysis of Impurities in Out-Gassed Dag 4		C-3
C.2	Water Content and Total Off-Gas Content of Dag 4		C-4
C.3	Mass Spectrometric Gas Analysis for Off-Gas Sample from HBWR Series H-2 and H-3 Annular-Coated-Pressurized Rods		C-4
C.4	Summary of Coating Thickness Measurements		C-5

FIGURE C.1. Surface Appearance of Dag 4 Used in HBWR Series H-2 and H-3 Annular-Coated-Pressurized Rods

TABLE C.1. Chemical Analysis of Impurities
in Outgassed Dag 4

Element	Content, ppm(a)
A. Spectrochemical	
Al	48,000
Ba	50
Ca	12,000
Cr	10
Cu	5
Fe	8,000
Mg	100
Mn	100
Na	16,000
Si	110,300
Ti	<1
V	50
Zn	1(b)
Zr	1,000
B. Halide Analysis	
F	50(b)
Cl + other halides	717(b)

- (a) The content of the elements in Dag 4 are an average of four separate tests of as-received Dag 4 and Dag 4 used during rod fabrication, all from the same lot. Comparison is made on a weight basis. An earlier emission spectrometric analysis of Dag 4 showed 200 ppm Fe, 500 ppm Ca, and 1000 ppm Na. Analysis of Dag 4 during rod fabrication indicated about 12,000 ppm Fe, 8400 ppm Ca, and 2900 ppm Na. The four separate tests were done to verify the elemental contents in Dag 4. Based on a fuel-to-graphite weight ratio of 1:2000, the contents of Fe, Ca and Na are 4, 6 and 8 ppm on a fuel-weight basis. The ASTM-AISI fuel specification limits for Fe, Ca, and Na are 500, 200, and (no stated value), respectively.
- (b) Data obtained from original test results of outgassed Dag 4.

TABLE C.2. Water Content and Total Off-Gas Content of Dag 4

Sample	Water Content, (a)		Off-gas, (b) cm^3/g
	wt% (c)	ppm (d)	
1	0.38	1.9	39.0
2	0.44	2.2	36.1
3	0.51	2.6	39.9
4	0.42	2.1	35.7
5	0.34	1.7	34.7
Average	0.42	2.1	37.0
Standard deviation	0.06	0.3	2.25

(a) By combustion technique.

(b) By vacuum outgassing at 1600°C.

(c) Weight percent of Dag.

(d) On a fuel-weight basis.

TABLE C.3. Mass Spectrometric Gas Analysis of Graphite Off-Gas Samples Representative of HBWR Series H-2 and H-3 Annular-Coated-Pressurized Rods

Compound	Content, (a), Mole %
CO_2	5.26
Ar	0.22
O_2	2.60
N_2	17.8
CO	28.5
He	<0.01
H_2	43.1
CH_4	1.11

(a) Content is an average of two mass spectrometric analyses. The average offgas for the above samples was 15.3 cm^3/g at STP. Data was obtained for Dag 4 used in BRPR fuel rods coated with graphite from the same lot used for HBWR Series H-2 and H-3 Annular-Coated-Pressurized Rods.

TABLE C.4. Summary of Coating Thickness Measurements

Rod Number	Tube Number		Coating Thickness, μm (in.)				
			Position 1 ^(a)	Position 2	Position 3	Position 4	Position 5
H2UCG027	66G	Max. ^(b)	7.0 (0.00028)	7.0 (0.00028)	6.4 (0.00025)	6.4 (0.00025)	7.0 (0.00028)
		Min.	6.4 (0.00025)	6.4 (0.00025)	6.4 (0.00025)	6.4 (0.00025)	5.7 (0.00023)
H2UCG028	5E	Max.	6.4 (0.00025)	6.4 (0.00025)	6.4 (0.00025)	6.4 (0.00025)	5.1 (0.00020)
		Min.	5.7 (0.00023)	6.4 (0.00025)	5.1 (0.00020)	6.4 (0.00025)	5.7 (0.00023)
H2UCG029	170C	Max.	6.4 (0.00025)	7.0 (0.00028)	6.4 (0.00025)	7.0 (0.00028)	5.7 (0.00023)
		Min.	7.0 (0.00028)	5.7 (0.00023)	5.7 (0.00023)	6.4 (0.00025)	5.7 (0.00023)
H3UCG030	170D	Max.	5.7 (0.00023)	5.7 (0.00023)	7.0 (0.00028)	6.4 (0.00025)	5.7 (0.00023)
		Min.	7.0 (0.00028)	5.7 (0.00023)	7.0 (0.00028)	5.7 (0.00023)	5.7 (0.00023)
H3UCG031	66A	Max.	6.4 (0.00025)	5.7 (0.00023)	6.4 (0.00025)	6.4 (0.00025)	6.4 (0.00025)
		Min.	6.4 (0.00025)	7.0 (0.00028)	5.7 (0.00023)	6.4 (0.00025)	5.1 (0.00020)
H3UCG032	5F	Max.	6.4 (0.00025)	6.4 (0.00025)	5.7 (0.00023)	5.1 (0.00020)	5.7 (0.00023)
		Min.	6.4 (0.00025)	5.1 (0.00020)	6.4 (0.00025)	6.4 (0.00025)	6.4 (0.00025)

(a) The coating thickness was measured at 5 locations, 13.03 cm (5.13 in.), 19.38 cm (7.63 in.), 25.73 cm (10.13 in.), 32.21 cm (12.63 in.), 38.03 cm (15.13 in.), starting from the end of the tube with the identification number.

(b) Maximum and minimum refers to measurements at the maximum and minimum diameter of the tube at any given axial position.

APPENDIX D

PHYSICAL AND CHEMICAL CHARACTERIZATION RESULTS FOR THE FUEL

PHYSICAL AND CHEMICAL CHARACTERIZATION RESULTS FOR THE FUEL

Appendix D includes the analyses of the reference, annular and sphere-pac fuels that were loaded into the Series H-2, H-3, and H-4 rods. These analyses include the chemical characterization of the fuel and fuel offgas;^(a) dimensional characterization of the pellets; pellet loading information; and metallographic analyses of the various fuel types.

The grading of the "appearance" of pellets loaded into the reference and annular-coated-pressurized rods adheres to the same criteria used for Series H-1 rods.⁽³⁾ The condition of all 11% enriched pellets was classified "excellent," since the pellets were near perfect. The "average" insulator pellets were fabricated during the Series H-1 campaign. These pellets were classed in the "average" condition based on visual standards that allowed end chips (2 to 3% of land area), circumferential chips (0.2 to 0.5% of circumference), and cracks (1 to 2% of the average pellet diameter). No marginal pellets were loaded into Series H-2 or H-3 rods.

Appendix D contains SEM micrographs of the UO_2 powder and microspheres used in Series H-2, H-3, and H-4 fuel rods (Figures D.1 to D.4). Typical reference and annular pellets are shown in Figures D.5, D.8, and D.9. The microstructures of the reference and annular pellets and UO_2 microspheres are shown in Figures D.6 and D.7 and D.10 to D.12.

The chemical analysis of the fuel and offgas from pellet fuel are presented in Tables D.1 to D.4. Average density and resinter results for pellet fuel are contained in Table D.5. Pellet inspection data for 11% enriched,

(a) The analysis of offgas data for sphere-pac fuel encountered analytical problems similar to those problems that existed in Series H-1 vipac rods.⁽³⁾ Because of the analyzing technique, the particle fuel became contaminated with moisture from the atmosphere. Five analyses of sphere-pac fuel resulted in total offgas values of 0.001, 0.111, 0.246, 0.195, and 0.030 cm^3/g at STP. Water resorption tests at ENC indicated an approximate 100% increase in water due to handling. All H_2 values would pass quality control standards using this equivalent increase in H_2 due to water.

2.78% enriched, and drilled, 2.78% enriched pellets are tabulated in Tables D.6, D.7, and D.8, respectively. Pellet loading data for each pellet fuel rod is given in Tables D.9 to D.18.

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100 μm

100X

FIGURE D.1. SEM Micrographs of
As-Milled FFIP-002 UO_2 Powder

20 μm

500X

2 μm

5000X

500 μm

20X

FIGURE D.2. SEM Micrographs of FPIP-002
UO₂ Microspheres (coarse fraction)

10 μm

1000X

5 μm

2000X

500 μm

20X

FIGURE D.3. SEM Micrographs of FPIP-002
CO₂ Microspheres (medium-coarse fraction)

5 μm

2000X

2 μm

5000X

100 μ m

100X

10 μ m

1000X

2 μ m

5000X

FIGURE D.4. SEM Micrographs of FPIP-002
UO₂ Microspheres (fine fraction)

FIGURE D.5. Typical Reference Pellet with Dished Ends,
Chamfered Edges and Enrichment Symbol
Identification

Longitudinal

25X

Transverse

25X

FIGURE D.6. Microstructure of an FPIP-002, Reference Pellet typical of Those Used in HBWR Series H-2 and H-3 Rods (As Polished)

Transverse

33.3 μm

300X

Longitudinal

33.3 μm

300X

FIGURE D.7. Microstructure of an FPIP-002, Reference Pellet Typical of Those Used in HBWR Series H-2 and H-3 Rods (Etched)

FIGURE D.8. Typical Annular Pellet with Chamfered Edges and Enrichment Symbol Identification

FIGURE D.9. Axial Section of an Annular Pellet

Transverse

25X

Longitudinal

25X

FIGURE D.10. Microstructure of an FPIP-002 Annular Pellet
Typical of Those Used in HBWR Series H-2
and H-3 Rods (As Polished)

Longitudinal

33.3 μm

300X

Transverse

33.3 μm

300X

FIGURE D.11. Microstructure of an FPIP-002 Annular Pellet
Typical of Those Used in HBWR Series H-2 and
H-3 Rods (Etched)

Fine Fraction

33.3 μm

300X

FIGURE D.12. Microstructure of Coarse, Medium-Coarse, and Fine UO_2 Microspheres Typical of Those Used in HBWR Series H-2, H-3 and H-4 Rods (Etched)

Medium-Coarse
Fraction
33.3 μm

300X

Coarse Fraction

33.3 μm

300X

TABLE D.1. Chemical Analysis of Starting UO_2 Pellet Powder

Lot Number	FPIP-001 ^(a)
Uranium, wt%	87.308
O/M	2.125
Moisture, ppm	1428
Isotopic Composition, %	
^{234}U	NA
^{235}U	11.023
^{236}U	NA
^{238}U	Balance
Bulk density, g/cm^3	2.25

(a) FPIP-001 was a combination of ORNL powder lots 450630 and 450626. U-234 and U-236 isotopic composition in both of these lots were 0.07% and 0.06%, respectively. This lot was later milled and designated FPIP-002.

TABLE D.2. Trace Impurity Content in Pellet Fuel and UO₂ Microspheres for Sphere-pac Fuel

Element	Average Content, ppm	
	Pellet Lot FPIP-002 ^(a)	Sphere-pac Lot FPIP-002 ^(b)
Al	8.5	5.8
B	0.13	<0.12
Ba	1.	1.
Be	0.1	0.1
C	11.	6.
Ca	14.6	19.0
Cd	<0.10	<0.10
Co	<4.0	<4.0
Cr	6.8	4.8
Cu	5.	2.
Dy	<0.04	<0.07
Eu	<2.70	<5.32
F	5.	5.
Fe	37.	20.
Gd	<0.11	<0.21
Hf	<0.34	<0.68
Li	<1.00	1.14
Mg	<19.0	<19.0
Mn	3.0	2.0
Mo	1.8	24.3
N	5.	5.
Ni	3.6	2.2
P	<30.	<30.
Pb	<1.00	1.01
Si	47.	20.
Sm	<0.08	<0.17
Sn	2.9	<1.0
Ta	<4.8	4.7
Ti	4.1	4.7
V	<1.0	<1.0
W	0.28	0.55
Zn	<1.0	1.3
Zr	13.7	13.6

(a) Analysis of five pellet samples. ENC specimen 307Z, 308Z, 309Z, 310Z, 311Z.

(b) Sample was taken from an originally representative mixture of coarse, medium coarse, and fine fractions. Sample was probably deficient in fine fraction due to rapid separation of fines during sampling; however, analysis is not invalidated. Analysis was made using five samples: ENC numbers 312Z, 313Z, 314Z, 315Z and 316Z.

TABLE D.3. Chemical Analysis of Pellet Fuel and UO₂ Microspheres for Sphere-pac Fuel in Series H-2, H-3 and H-4 Rods

	<u>Pellet</u>	<u>Sphere-pac</u>
Uranium, wt%	88.048	88.041
O/M	2.011	2.013
Moisture, ppm	2.4	3.2 ^(a)
Isotopic composition, %		
²³⁴ U	0.072	0.073
²³⁵ U	11.001	10.984
²³⁶ U	0.062	0.062
²³⁸ U	88.865	88.881

(a) A deviating material report was written for the off-gas analysis of sphere-pac fuel. The test was shown to be high in hydrogen by about 0.5 ppm H. Average hydrogen content for the sphere-pac fuel was 1.42 ppm or 0.92 if adjusted for adsorption of atmospheric hydrogen during sample processing.

TABLE D.4. Off-Gas Analysis for Pellet Fuel

Total gas, cm ³ /g	0.002
H ₂ content, ppm	0.27
Mass spectrometric analysis, mole%	
CO ₂	0.95
Ar	0.06
O ₂	0.71
N ₂	6.4
CO	47.4
He	<0.01
H ₂	44.1
CH ₄	0.31

TABLE D.5. Average Density and Resinter Results for
FPIP-002 Reference and Annular Pellets

	<u>Reference</u>	<u>Annular</u>
Average density, (a) %TD(b)		
Mean value(c)	94.38	94.42
Standard deviation	0.10	0.09
Resintered density, (d) %TD		
Mean value(c)	94.44	94.44
Standard deviation	0.07	0.09

(a) Sintered at 1720°C for 3.0 hr

(b) TD = 10.96 g/cm³

(c) Sample of five pellets for each fuel type

(d) Resintering done at 1700°C for 24 hr.

TABLE D.6. Pellet Inspection Results for 11% Enriched
Reference and Annular Pellets^(a)

Data	Reference Pellet		Annular Pellet	
	Mean Value ^(b)	Standard Deviation	Mean Value ^(b)	Standard Deviation
Diameter, cm (in.)	1.0264 (0.4041)	0.0003 (0.0001)	1.0249 (0.4035)	0.0003 (0.0001)
Hole Diameter, ^(c) cm (in.)	---	---	0.325 (0.128)	0.0 (0.0)
Length, cm (in.)	0.8222 (0.3237)	0.0097 (0.0038)	0.8194 (0.3226)	0.0099 (0.0039)
Weight, g	6.948	0.292	6.271	0.077
Density, %TD ^(d)	94.39	0.09	94.41	0.09

(a) Reference and Annular pellets were both from the same powder lot and were produced under the same conditions.

(b) Mean value is calculated from the data for all pellets loaded into the fuel rods.

(c) Hole diameter was measured using a pin gage that indicated the minimum pellet inside diameter.

(d) TD = 10.96 g/cm³

TABLE D.7. Pellet Inspection Results for 2.78% Enriched Pellets

<u>Data</u>	<u>Mean Value(a)</u>	<u>Standard Deviation</u>
Diameter, cm (in.)		
Maximum	1.0262 (0.4040)	0.0003 (0.0001)
Minimum	1.0257 (0.4038)	0.0003 (0.0001)
Length, cm (in.)	0.8285 (0.3262)	0.0066 (0.0026)
Dish depth, cm (in.)		
Top	0.0147 (0.0058)	0.0010 (0.0004)
Bottom	0.0155 (0.0061)	0.0008 (0.0003)
Dish Diameter, cm (in.)		
Top	0.686 (0.270)	---
Bottom	0.686 (0.270)	---
Land width, cm (in.)		
Top	0.165 (0.065)	---
Bottom	0.165 (0.065)	---
Dish volume, %	0.87	0.04
Weight, g	7.043	0.060
Density, %TD(b)	94.63	0.15

(a) Sample consisted of 39 pellets fabricated for HBWR Series H-1 rods. Low enrichment pellets used in HBWR Series H-2, H-3 and H-4 rods were from the same lot (Lot No. 125-7-1).

(b) TD = 10.96 g/cm³

TABLE D.8. Pellet Inspection Results for Drilled,
2.78% Enriched Pellets

<u>Data</u>	<u>Mean Value(a)</u>	<u>Standard Deviation</u>
Hole diameter, cm (in.)		
Top	0.2660 (0.1047)	0.0074 (0.0029)
Bottom	0.2685 (0.1057)	0.0104 (0.0041)
Pin gage size of hole,(b)		
cm (in.)	0.2497 (0.0983)	0.0015 (0.0006)

-
- (a) Sample consisted of 15 pellets fabricated for HBWR Series H-1 rods. The drilled, low-enrichment pellets used in HBWR Series H-2, H-3 and H-4 rods were from the same lot.
- (b) Pellets were drilled from top and bottom. Pin gage size indicates maximum possible diameter available for insertion of thermocouples in the eccentric holes.

TABLE D.9. Pellet Loading Information for H2UCR023 (reference rod)

Loading Sequence	Pellet Diameter, cm (in.)	Pellet Length, cm (in.)	Appearance	Lot
Lower End				
1	1.0279 (0.4047)	0.8334 (0.3281)	Average	125-7-1
2	1.0264 (0.4041)	0.7981 (0.3142)	Excellent	FPIP-002
3	1.0264 (0.4041)	0.8044 (0.3167)	Excellent	FPIP-002
4	1.0267 (0.4042)	0.8341 (0.3284)	Excellent	FPIP-002
5	1.0264 (0.4041)	0.8346 (0.3286)	Excellent	FPIP-002
6	1.0264 (0.4041)	0.8499 (0.3246)	Excellent	FPIP-002
7	1.0264 (0.4041)	0.8247 (0.3247)	Excellent	FPIP-002
8	1.0264 (0.4041)	0.8245 (0.3246)	Excellent	FPIP-002
9	1.0264 (0.4041)	0.8164 (0.3214)	Excellent	FPIP-002
10	1.0264 (0.4041)	0.8352 (0.3287)	Excellent	FPIP-002
11	1.0264 (0.4041)	0.8260 (0.3252)	Excellent	FPIP-002
12	1.0264 (0.4041)	0.8197 (0.3227)	Excellent	FPIP-002
13	1.0264 (0.4041)	0.8098 (0.3188)	Excellent	FPIP-002
14	1.0267 (0.4042)	0.8222 (0.3237)	Excellent	FPIP-002
15	1.0264 (0.4041)	0.8108 (0.3192)	Excellent	FPIP-002
16	1.0262 (0.4040)	0.8024 (0.3159)	Excellent	FPIP-002
17	1.0264 (0.4041)	0.8001 (0.3150)	Excellent	FPIP-002
18	1.0264 (0.4041)	0.8166 (0.3215)	Excellent	FPIP-002
19	1.0267 (0.4042)	0.8214 (0.3234)	Excellent	FPIP-002
20	1.0264 (0.4041)	0.8052 (0.3170)	Excellent	FPIP-002
21	1.0267 (0.4042)	0.8087 (0.3184)	Excellent	FPIP-002
22	1.0264 (0.4041)	0.8082 (0.3182)	Excellent	FPIP-002
23	1.0264 (0.4041)	0.8110 (0.3193)	Excellent	FPIP-002
24	1.0267 (0.4042)	0.8153 (0.3210)	Excellent	FPIP-002
25	1.0257 (0.4038)	0.8222 (0.3237)	Excellent	FPIP-002
26	1.0264 (0.4041)	0.8288 (0.3263)	Excellent	FPIP-002
27	1.0264 (0.4041)	0.8222 (0.3237)	Excellent	FPIP-002
28	1.0264 (0.4041)	0.8169 (0.3216)	Excellent	FPIP-002
29	1.0267 (0.4042)	0.8283 (0.3261)	Excellent	FPIP-002
30	1.0267 (0.4042)	0.8214 (0.3234)	Excellent	FPIP-002
31	1.0267 (0.4042)	0.8179 (0.3220)	Excellent	FPIP-002
32	1.0267 (0.4042)	0.8237 (0.3243)	Excellent	FPIP-002
33	1.0264 (0.4041)	0.8552 (0.3367)	Excellent	FPIP-002
34	1.0267 (0.4042)	0.8321 (0.3276)	Excellent	FPIP-002
35	1.0267 (0.4042)	0.8255 (0.3250)	Excellent	FPIP-002
36	1.0267 (0.4042)	0.8298 (0.3267)	Excellent	FPIP-002
37	1.0264 (0.4041)	0.8179 (0.3220)	Excellent	FPIP-002
38	1.0267 (0.4042)	0.8410 (0.3311)	Excellent	FPIP-002
39	1.0264 (0.4041)	0.8346 (0.3286)	Excellent	FPIP-002
40	1.0267 (0.4042)	0.8217 (0.3235)	Excellent	FPIP-002
41	1.0264 (0.4041)	0.8237 (0.3243)	Excellent	FPIP-002
42	1.0257 (0.4038)	0.8207 (0.3231)	Excellent	FPIP-002
43	1.0262 (0.4040)	0.8412 (0.3312)	Excellent	FPIP-002
44	1.0262 (0.4040)	0.8369 (0.3295)	Excellent	FPIP-002
45	1.0262 (0.4040)	0.8090 (0.3185)	Excellent	FPIP-002
46	1.0267 (0.4042)	0.8237 (0.3243)	Excellent	FPIP-002
47	1.0267 (0.4042)	0.8219 (0.3236)	Excellent	FPIP-002
48	1.0262 (0.4040)	0.8194 (0.3226)	Excellent	FPIP-002
49	1.0267 (0.4042)	0.8204 (0.3230)	Excellent	FPIP-002
50	1.0262 (0.4040)	0.8232 (0.3241)	Excellent	FPIP-002
51	1.0267 (0.4042)	0.8313 (0.3273)	Excellent	FPIP-002
52	1.0267 (0.4042)	0.8407 (0.3310)	Excellent	FPIP-002
53	1.0267 (0.4042)	0.8275 (0.3258)	Excellent	FPIP-002
54	1.0262 (0.4040)	0.8204 (0.3230)	Excellent	FPIP-002
55	1.0262 (0.4040)	0.8318 (0.3275)	Excellent	FPIP-002
56	1.0272 (0.4044)	0.8420 (0.3315)	Average	125-7-1
Upper End				
Mean Value	1.0265 (0.4041)			
Standard deviation	0.0003 (0.0001)			

TABLE D.10. Pellet Loading Information for H2UCR024 (reference rod)

Loading Sequence	Pellet Diameter, cm (in.)	Pellet Length, cm (in.)	Appearance	Lot
Lower end				
1	1.0279 (0.4047)	0.8098 (0.3188)	Average	125-7-1
2	1.0267 (0.4042)	0.8301 (0.3268)	Excellent	FPIP-002
3	1.0262 (0.4040)	0.8313 (0.3273)	Excellent	FPIP-002
4	1.0267 (0.4042)	0.8265 (0.3254)	Excellent	FPIP-002
5	1.0267 (0.4042)	0.8260 (0.3252)	Excellent	FPIP-002
6	1.0262 (0.4040)	0.8301 (0.3268)	Excellent	FPIP-002
7	1.0267 (0.4042)	0.8260 (0.3252)	Excellent	FPIP-002
8	1.0267 (0.4042)	0.8285 (0.3262)	Excellent	FPIP-002
9	1.0267 (0.4042)	0.8143 (0.3206)	Excellent	FPIP-002
10	1.0269 (0.4043)	0.8209 (0.3232)	Excellent	FPIP-002
11	1.0267 (0.4042)	0.8268 (0.3255)	Excellent	FPIP-002
12	1.0262 (0.4040)	0.8400 (0.3307)	Excellent	FPIP-002
13	1.0267 (0.4042)	0.8240 (0.3244)	Excellent	FPIP-002
14	1.0267 (0.4042)	0.8141 (0.3205)	Excellent	FPIP-002
15	1.0267 (0.4042)	0.8352 (0.3228)	Excellent	FPIP-002
16	1.0257 (0.4038)	0.8316 (0.3274)	Excellent	FPIP-002
17	1.0259 (0.4039)	0.8339 (0.3283)	Excellent	FPIP-002
18	1.0262 (0.4040)	0.8181 (0.3221)	Excellent	FPIP-002
19	1.0269 (0.4043)	0.8204 (0.3230)	Excellent	FPIP-002
20	1.0269 (0.4043)	0.8255 (0.3250)	Excellent	FPIP-002
21	1.0267 (0.4042)	0.8306 (0.3270)	Excellent	FPIP-002
22	1.0267 (0.4042)	0.8176 (0.3219)	Excellent	FPIP-002
23	1.0267 (0.4042)	0.8235 (0.3242)	Excellent	FPIP-002
24	1.0267 (0.4042)	0.8438 (0.3322)	Excellent	FPIP-002
25	1.0267 (0.4042)	0.8331 (0.3280)	Excellent	FPIP-002
26	1.0267 (0.4042)	0.8313 (0.3273)	Excellent	FPIP-002
27	1.0254 (0.4037)	0.8237 (0.3243)	Excellent	FPIP-002
28	1.0267 (0.4042)	0.8280 (0.3260)	Excellent	FPIP-002
29	1.0264 (0.4041)	0.8232 (0.3241)	Excellent	FPIP-002
30	1.0264 (0.4041)	0.8171 (0.3217)	Excellent	FPIP-002
31	1.0267 (0.4042)	0.8385 (0.3301)	Excellent	FPIP-002
32	1.0262 (0.4040)	0.8059 (0.3173)	Excellent	FPIP-002
33	1.0262 (0.4040)	0.8250 (0.3248)	Excellent	FPIP-002
34	1.0262 (0.4040)	0.8288 (0.3263)	Excellent	FPIP-002
35	1.0267 (0.4042)	0.8260 (0.3252)	Excellent	FPIP-002
36	1.0264 (0.4041)	0.8237 (0.3243)	Excellent	FPIP-002
37	1.0264 (0.4041)	0.8230 (0.3240)	Excellent	FPIP-002
38	1.0267 (0.4042)	0.8280 (0.3260)	Excellent	FPIP-002
39	1.0267 (0.4042)	0.8242 (0.3245)	Excellent	FPIP-002
40	1.0262 (0.4040)	0.8179 (0.3220)	Excellent	FPIP-002
41	1.0262 (0.4040)	0.8164 (0.3214)	Excellent	FPIP-002
42	1.0262 (0.4040)	0.8169 (0.3216)	Excellent	FPIP-002
43	1.0267 (0.4042)	0.8344 (0.3285)	Excellent	FPIP-002
44	1.0269 (0.4043)	0.8214 (0.3234)	Excellent	FPIP-002
45	1.0257 (0.4038)	0.8123 (0.3198)	Excellent	FPIP-002
46	1.0269 (0.4043)	0.8199 (0.3228)	Excellent	FPIP-002
47	1.0262 (0.4040)	0.8171 (0.3217)	Excellent	FPIP-002
48	1.0251 (0.4036)	0.8285 (0.3262)	Excellent	FPIP-002
49	1.0262 (0.4040)	0.8255 (0.3250)	Excellent	FPIP-002
50	1.0264 (0.4041)	0.8029 (0.3161)	Excellent	FPIP-002
51	1.0267 (0.4042)	0.8204 (0.3230)	Excellent	FPIP-002
52	1.0267 (0.4042)	0.8285 (0.3262)	Excellent	FPIP-002
53	1.0257 (0.4038)	0.8192 (0.3225)	Excellent	FPIP-002
54	1.0267 (0.4042)	0.8377 (0.3298)	Excellent	FPIP-002
55	1.0257 (0.4038)	0.8197 (0.3227)	Excellent	FPIP-002
56	1.0267 (0.4042)	0.8331 (0.3280)	Average	125-7-1
Upper End				
Mean Value	1.0264 (0.4041)			
Standard deviation	0.0005 (0.0002)			

TABLE D.11. Pellet Loading Information for H3UCR025 (reference rod)

Loading Sequence	Pellet Diameter, cm (in.)	Pellet Length, cm (in.)	Appearance	Lot
Lower end				
1	1.0259 (0.4039)	0.8108 (0.3192)	Average	125-7-1
2	1.0262 (0.4040)	0.8156 (0.3211)	Excellent	FPIP-002
3	1.0259 (0.4039)	0.8255 (0.3250)	Excellent	FPIP-002
4	1.0262 (0.4040)	0.8212 (0.3233)	Excellent	FPIP-002
5	1.0262 (0.4040)	0.8270 (0.3256)	Excellent	FPIP-002
6	1.0262 (0.4040)	0.8207 (0.3231)	Excellent	FPIP-002
7	1.0267 (0.4042)	0.8230 (0.3240)	Excellent	FPIP-002
8	1.0262 (0.4040)	0.8283 (0.3261)	Excellent	FPIP-002
9	1.0267 (0.4042)	0.8242 (0.3245)	Excellent	FPIP-002
10	1.0267 (0.4042)	0.8324 (0.3277)	Excellent	FPIP-002
11	1.0267 (0.4042)	0.8349 (0.3287)	Excellent	FPIP-002
12	1.0267 (0.4042)	0.8283 (0.3261)	Excellent	FPIP-002
13	1.0267 (0.4042)	0.8263 (0.3253)	Excellent	FPIP-002
14	1.0257 (0.4038)	0.8245 (0.3246)	Excellent	FPIP-002
15	1.0257 (0.4038)	0.8148 (0.3208)	Excellent	FPIP-002
16	1.0257 (0.4038)	0.8138 (0.3204)	Excellent	FPIP-002
17	1.0257 (0.4038)	0.8219 (0.3236)	Excellent	FPIP-002
18	1.0262 (0.4040)	0.8420 (0.3315)	Excellent	FPIP-002
19	1.0262 (0.4040)	0.8367 (0.3294)	Excellent	FPIP-002
20	1.0262 (0.4040)	0.8364 (0.3293)	Excellent	FPIP-002
21	1.0262 (0.4040)	0.8189 (0.3224)	Excellent	FPIP-002
22	1.0264 (0.4041)	0.8131 (0.3201)	Excellent	FPIP-002
23	1.0264 (0.4041)	0.8395 (0.3305)	Excellent	FPIP-002
24	1.0267 (0.4042)	0.8252 (0.3249)	Excellent	FPIP-002
25	1.0267 (0.4042)	0.8324 (0.3277)	Excellent	FPIP-002
26	1.0267 (0.4042)	0.8352 (0.3288)	Excellent	FPIP-002
27	1.0259 (0.4039)	0.8316 (0.3274)	Excellent	FPIP-002
28	1.0262 (0.4040)	0.8349 (0.3287)	Excellent	FPIP-002
29	1.0262 (0.4040)	0.8283 (0.3261)	Excellent	FPIP-002
30	1.0262 (0.4040)	0.8385 (0.3301)	Excellent	FPIP-002
31	1.0262 (0.4040)	0.8120 (0.3197)	Excellent	FPIP-002
32	1.0259 (0.4039)	0.8197 (0.3227)	Excellent	FPIP-002
33	1.0259 (0.4039)	0.8171 (0.3217)	Excellent	FPIP-002
34	1.0262 (0.4040)	0.8075 (0.3179)	Excellent	FPIP-002
35	1.0259 (0.4039)	0.8377 (0.3298)	Excellent	FPIP-002
36	1.0267 (0.4042)	0.8400 (0.3307)	Excellent	FPIP-002
37	1.0267 (0.4042)	0.8301 (0.3268)	Excellent	FPIP-002
38	1.0267 (0.4042)	0.8151 (0.3209)	Excellent	FPIP-002
39	1.0262 (0.4040)	0.8321 (0.3276)	Excellent	FPIP-002
40	1.0267 (0.4042)	0.8176 (0.3219)	Excellent	FPIP-002
41	1.0267 (0.4042)	0.8202 (0.3229)	Excellent	FPIP-002
42	1.0267 (0.4042)	0.8296 (0.3266)	Excellent	FPIP-002
43	1.0257 (0.4038)	0.8285 (0.3262)	Excellent	FPIP-002
44	1.0257 (0.4038)	0.8240 (0.3244)	Excellent	FPIP-002
45	1.0262 (0.4040)	0.8194 (0.3226)	Excellent	FPIP-002
46	1.0259 (0.4039)	0.8336 (0.3282)	Excellent	FPIP-002
47	1.0259 (0.4039)	0.8156 (0.3211)	Excellent	FPIP-002
48	1.0262 (0.4040)	0.8219 (0.3236)	Excellent	FPIP-002
49	1.0262 (0.4040)	0.8156 (0.3211)	Excellent	FPIP-002
50	1.0262 (0.4040)	0.8204 (0.3230)	Excellent	FPIP-002
51	1.0267 (0.4042)	0.8255 (0.3250)	Excellent	FPIP-002
52	1.0264 (0.4041)	0.8232 (0.3241)	Excellent	FPIP-002
53	1.0267 (0.4042)	0.8265 (0.3254)	Excellent	FPIP-002
54	1.0267 (0.4042)	0.8227 (0.3239)	Excellent	FPIP-002
55	1.0269 (0.4043)	0.8171 (0.3217)	Excellent	FPIP-002
56	1.0262 (0.4040)	0.8169 (0.3216)	Average	125-7-1
Upper end				
Mean value	1.0262 (0.4040)			
Standard deviation	0.0004 (0.0001)			

TABLE D.12. Pellet Loading Information for H2UCR026 (reference rod)

Loading Sequence	Pellet Diameter, cm (in.)	Pellet Length, cm (in.)	Appearance	Lot
Lower end				
1	1.0274 (0.4045)	0.8280 (0.3260)	Average	125-7-1
2	1.0262 (0.4040)	0.8225 (0.3238)	Excellent	FPIP-002
3	1.0262 (0.4040)	0.8067 (0.3176)	Excellent	FPIP-002
4	1.0259 (0.4039)	0.8166 (0.3215)	Excellent	FPIP-002
5	1.0259 (0.4039)	0.8118 (0.3196)	Excellent	FPIP-002
6	1.0259 (0.4039)	0.8237 (0.3243)	Excellent	FPIP-002
7	1.0259 (0.4039)	0.8199 (0.3228)	Excellent	FPIP-002
8	1.0259 (0.4039)	0.8252 (0.3249)	Excellent	FPIP-002
9	1.0262 (0.4040)	0.8181 (0.3221)	Excellent	FPIP-002
10	1.0259 (0.4039)	0.8153 (0.3210)	Excellent	FPIP-002
11	1.0262 (0.4040)	0.8072 (0.3178)	Excellent	FPIP-002
12	1.0264 (0.4041)	0.8326 (0.3278)	Excellent	FPIP-002
13	1.0264 (0.4041)	0.8273 (0.3257)	Excellent	FPIP-002
14	1.0267 (0.4042)	0.8184 (0.3222)	Excellent	FPIP-002
15	1.0267 (0.4042)	0.8075 (0.3179)	Excellent	FPIP-002
16	1.0257 (0.4038)	0.8054 (0.3171)	Excellent	FPIP-002
17	1.0257 (0.4038)	0.8273 (0.3257)	Excellent	FPIP-002
18	1.0254 (0.4037)	0.8080 (0.3181)	Excellent	FPIP-002
19	1.0257 (0.4038)	0.8326 (0.3278)	Excellent	FPIP-002
20	1.0251 (0.4036)	0.8166 (0.3215)	Excellent	FPIP-002
21	1.0264 (0.4041)	0.8105 (0.3191)	Excellent	FPIP-002
22	1.0262 (0.4040)	0.8230 (0.3240)	Excellent	FPIP-002
23	1.0262 (0.4040)	0.8214 (0.3234)	Excellent	FPIP-002
24	1.0267 (0.4042)	0.8339 (0.3283)	Excellent	FPIP-002
25	1.0267 (0.4042)	0.8232 (0.3241)	Excellent	FPIP-002
26	1.0267 (0.4042)	0.8174 (0.3218)	Excellent	FPIP-002
27	1.0269 (0.4043)	0.8001 (0.3150)	Excellent	FPIP-002
28	1.0267 (0.4042)	0.8113 (0.3194)	Excellent	FPIP-002
29	1.0262 (0.4040)	0.8321 (0.3276)	Excellent	FPIP-002
30	1.0267 (0.4042)	0.8156 (0.3211)	Excellent	FPIP-002
31	1.0257 (0.4038)	0.8075 (0.3179)	Excellent	FPIP-002
32	1.0262 (0.4040)	0.8143 (0.3206)	Excellent	FPIP-002
33	1.0267 (0.4042)	0.8169 (0.3216)	Excellent	FPIP-002
34	1.0262 (0.4040)	0.8158 (0.3212)	Excellent	FPIP-002
35	1.0264 (0.4041)	0.8130 (0.3201)	Excellent	FPIP-002
36	1.0262 (0.4040)	0.8067 (0.3176)	Excellent	FPIP-002
37	1.0257 (0.4038)	0.8242 (0.3245)	Excellent	FPIP-002
38	1.0264 (0.4041)	0.8186 (0.3223)	Excellent	FPIP-002
39	1.0267 (0.4042)	0.8204 (0.3230)	Excellent	FPIP-002
40	1.0267 (0.4042)	0.8194 (0.3226)	Excellent	FPIP-002
41	1.0269 (0.4043)	0.8174 (0.3210)	Excellent	FPIP-002
42	1.0267 (0.4042)	0.7920 (0.3118)	Excellent	FPIP-002
43	1.0267 (0.4042)	0.8186 (0.3223)	Excellent	FPIP-002
44	1.0264 (0.4041)	0.8217 (0.3235)	Excellent	FPIP-002
45	1.0262 (0.4040)	0.8232 (0.3241)	Excellent	FPIP-002
46	1.0264 (0.4041)	0.8263 (0.3253)	Excellent	FPIP-002
47	1.0264 (0.4041)	0.8192 (0.3225)	Excellent	FPIP-002
48	1.0267 (0.4042)	0.8179 (0.3220)	Excellent	FPIP-002
49	1.0264 (0.4041)	0.8004 (0.3151)	Excellent	FPIP-002
50	1.0264 (0.4041)	0.8092 (0.3186)	Excellent	FPIP-002
51	1.0269 (0.4043)	0.8141 (0.3205)	Excellent	FPIP-002
52	1.0257 (0.4038)	0.8184 (0.3222)	Excellent	FPIP-002
53	1.0264 (0.4041)	0.8176 (0.3219)	Excellent	FPIP-002
54	1.0264 (0.4041)	0.8095 (0.3187)	Excellent	FPIP-002
55	1.0262 (0.4040)	0.8247 (0.3247)	Excellent	FPIP-002
56	1.0267 (0.4042)	0.8105 (0.3191)	Excellent	FPIP-002
57	1.0262 (0.4040)	0.8301 (0.3268)	Average	125-7-1
Upper end				
Mean value	1.0263 (0.4040)			
Standard deviation	0.0004 (0.0002)			

**TABLE D.13. Pellet Loading Information for H2UCG027
(annular-coated-pressurized rod)**

<u>Loading Sequence</u>	<u>Pellet Diameter, cm (in.)</u>	<u>Pellet Length, cm (in.)</u>	<u>Appearance</u>	<u>Lot</u>
Lower end				
1	1.0277 (0.4046)	0.8075 (0.3179)	Average	125-7-1
2	1.0246 (0.4034)	0.8169 (0.3216)	Excellent	FPIP-002
3	1.0244 (0.4033)	0.8331 (0.3280)	Excellent	FPIP-002
4	1.0249 (0.4035)	0.8169 (0.3216)	Excellent	FPIP-002
5	1.0251 (0.4036)	0.8344 (0.3285)	Excellent	FPIP-002
6	1.0249 (0.4035)	0.8265 (0.3254)	Excellent	FPIP-002
7	1.0249 (0.4035)	0.8278 (0.3259)	Excellent	FPIP-002
8	1.0251 (0.4036)	0.8423 (0.3316)	Excellent	FPIP-002
9	1.0249 (0.4035)	0.8123 (0.3198)	Excellent	FPIP-002
10	1.0239 (0.4031)	0.8313 (0.3273)	Excellent	FPIP-002
11	1.0244 (0.4033)	0.8194 (0.3226)	Excellent	FPIP-002
12	1.0241 (0.4032)	0.8387 (0.3302)	Excellent	FPIP-002
13	1.0241 (0.4032)	0.8192 (0.3225)	Excellent	FPIP-002
14	1.0249 (0.4035)	0.8392 (0.3304)	Excellent	FPIP-002
15	1.0244 (0.4033)	0.8313 (0.3273)	Excellent	FPIP-002
16	1.0239 (0.4031)	0.8197 (0.3227)	Excellent	FPIP-002
17	1.0244 (0.4033)	0.8344 (0.3285)	Excellent	FPIP-002
18	1.0244 (0.4033)	0.8349 (0.3387)	Excellent	FPIP-002
19	1.0244 (0.4033)	0.8331 (0.3280)	Excellent	FPIP-002
20	1.0244 (0.4033)	0.8275 (0.3258)	Excellent	FPIP-002
21	1.0246 (0.4034)	0.8273 (0.3257)	Excellent	FPIP-002
22	1.0246 (0.4034)	0.8336 (0.3282)	Excellent	FPIP-002
23	1.0246 (0.4034)	0.8451 (0.3327)	Excellent	FPIP-002
24	1.0246 (0.4034)	0.8318 (0.3275)	Excellent	FPIP-002
25	1.0249 (0.4035)	0.8138 (0.3304)	Excellent	FPIP-002
26	1.0249 (0.4035)	0.8268 (0.3255)	Excellent	FPIP-002
27	1.0246 (0.4034)	0.8298 (0.3267)	Excellent	FPIP-002
28	1.0251 (0.4036)	0.8293 (0.3265)	Excellent	FPIP-002
29	1.0249 (0.4035)	0.8301 (0.3268)	Excellent	FPIP-002
30	1.0249 (0.4035)	0.8270 (0.3256)	Excellent	FPIP-002
31	1.0249 (0.4035)	0.8237 (0.3243)	Excellent	FPIP-002
32	1.0249 (0.4035)	0.8217 (0.3235)	Excellent	FPIP-002
33	1.0251 (0.4036)	0.8346 (0.3286)	Excellent	FPIP-002
34	1.0249 (0.4035)	0.8359 (0.3291)	Excellent	FPIP-002
35	1.0251 (0.4036)	0.8268 (0.3255)	Excellent	FPIP-002
36	1.0251 (0.4036)	0.8217 (0.3235)	Excellent	FPIP-002
37	1.0254 (0.4037)	0.8194 (0.3226)	Excellent	FPIP-002
38	1.0249 (0.4035)	0.8235 (0.3242)	Excellent	FPIP-002
39	1.0249 (0.4035)	0.8138 (0.3204)	Excellent	FPIP-002
40	1.0249 (0.4035)	0.8316 (0.3274)	Excellent	FPIP-002
41	1.0249 (0.4035)	0.8138 (0.3204)	Excellent	FPIP-002
42	1.0249 (0.4035)	0.8247 (0.3247)	Excellent	FPIP-002
43	1.0249 (0.4035)	0.8217 (0.3235)	Excellent	FPIP-002
44	1.0251 (0.4036)	0.8181 (0.3221)	Excellent	FPIP-002
45	1.0251 (0.4036)	0.8242 (0.3245)	Excellent	FPIP-002
46	1.0251 (0.4036)	0.8214 (0.3234)	Excellent	FPIP-002
47	1.0249 (0.4035)	0.8252 (0.3249)	Excellent	FPIP-002
48	1.0249 (0.4035)	0.8156 (0.3211)	Excellent	FPIP-002
49	1.0254 (0.4037)	0.8212 (0.3233)	Excellent	FPIP-002
50	1.0254 (0.4037)	0.8125 (0.3199)	Excellent	FPIP-002
51	1.0254 (0.4037)	0.8344 (0.3285)	Excellent	FPIP-002
52	1.0249 (0.4035)	0.8199 (0.3228)	Excellent	FPIP-002
53	1.0249 (0.4035)	0.8227 (0.3239)	Excellent	FPIP-002
54	1.0249 (0.4035)	0.8174 (0.3218)	Excellent	FPIP-002
55	1.0254 (0.4037)	0.8184 (0.3222)	Excellent	FPIP-002
56	1.0274 (0.4045)	0.8227 (0.3239)	Average	125-7-1
Upper end				
Mean value	1.0249 (0.4035)			
Standard deviation	0.0006 (0.0002)			

**TABLE D.14. Pellet Loading Information for H2UCG028
(annular-coated-pressurized rod)**

Loading Sequence	Pellet Diameter, cm (in.)	Pellet Length, cm (in.)	Appearance	Lot
Lower end				
1	1.0269 (0.4043)	0.8298 (0.3267)	Average	125-7-1
2	1.0251 (0.4036)	0.8296 (0.3266)	Excellent	FPIP-002
3	1.0251 (0.4036)	0.8080 (0.3181)	Excellent	FPIP-002
4	1.0249 (0.4035)	0.8105 (0.3191)	Excellent	FPIP-002
5	1.0249 (0.4035)	0.8219 (0.3236)	Excellent	FPIP-002
6	1.0249 (0.4035)	0.8176 (0.3219)	Excellent	FPIP-002
7	1.0249 (0.4035)	0.8364 (0.3293)	Excellent	FPIP-002
8	1.0249 (0.4035)	0.8273 (0.3257)	Excellent	FPIP-002
9	1.0251 (0.4036)	0.8308 (0.3271)	Excellent	FPIP-002
10	1.0251 (0.4036)	0.8179 (0.3220)	Excellent	FPIP-002
11	1.0249 (0.4035)	0.8171 (0.3217)	Excellent	FPIP-002
12	1.0246 (0.4034)	0.8197 (0.3227)	Excellent	FPIP-002
13	1.0251 (0.4036)	0.7988 (0.3145)	Excellent	FPIP-002
14	1.0249 (0.4035)	0.8006 (0.3152)	Excellent	FPIP-002
15	1.0249 (0.4035)	0.8146 (0.3207)	Excellent	FPIP-002
16	1.0249 (0.4035)	0.8339 (0.3283)	Excellent	FPIP-002
17	1.0251 (0.4036)	0.8095 (0.3187)	Excellent	FPIP-002
18	1.0249 (0.4035)	0.8237 (0.3243)	Excellent	FPIP-002
19	1.0249 (0.4035)	0.8113 (0.3194)	Excellent	FPIP-002
20	1.0249 (0.4035)	0.8362 (0.3292)	Excellent	FPIP-002
21	1.0251 (0.4036)	0.8123 (0.3198)	Excellent	FPIP-002
22	1.0249 (0.4035)	0.8202 (0.3229)	Excellent	FPIP-002
23	1.0249 (0.4035)	0.7958 (0.3133)	Excellent	FPIP-002
24	1.0249 (0.4035)	0.8298 (0.3267)	Excellent	FPIP-002
25	1.0251 (0.4036)	0.8313 (0.3273)	Excellent	FPIP-002
26	1.0251 (0.4036)	0.8186 (0.3223)	Excellent	FPIP-002
27	1.0249 (0.4035)	0.8222 (0.3237)	Excellent	FPIP-002
28	1.0249 (0.4035)	0.8319 (0.3275)	Excellent	FPIP-002
29	1.0249 (0.4035)	0.8321 (0.3276)	Excellent	FPIP-002
30	1.0249 (0.4035)	0.8298 (0.3267)	Excellent	FPIP-002
31	1.0249 (0.4035)	0.8118 (0.3196)	Excellent	FPIP-002
32	1.0251 (0.4036)	0.8433 (0.3320)	Excellent	FPIP-002
33	1.0249 (0.4035)	0.8138 (0.3204)	Excellent	FPIP-002
34	1.0249 (0.4035)	0.8049 (0.3169)	Excellent	FPIP-002
35	1.0241 (0.4032)	0.8082 (0.3182)	Excellent	FPIP-002
36	1.0249 (0.4035)	0.8258 (0.3251)	Excellent	FPIP-002
37	1.0249 (0.4035)	0.8189 (0.3224)	Excellent	FPIP-002
38	1.0251 (0.4036)	0.8031 (0.3162)	Excellent	FPIP-002
39	1.0249 (0.4035)	0.8065 (0.3175)	Excellent	FPIP-002
40	1.0249 (0.4035)	0.8227 (0.3239)	Excellent	FPIP-002
41	1.0251 (0.4036)	0.8115 (0.3195)	Excellent	FPIP-002
42	1.0251 (0.4036)	0.8113 (0.3194)	Excellent	FPIP-002
43	1.0251 (0.4036)	0.8169 (0.3216)	Excellent	FPIP-002
44	1.0244 (0.4033)	0.8105 (0.3191)	Excellent	FPIP-002
45	1.0251 (0.4036)	0.8222 (0.3237)	Excellent	FPIP-002
46	1.0246 (0.4034)	0.8166 (0.3215)	Excellent	FPIP-002
47	1.0249 (0.4035)	0.8118 (0.3196)	Excellent	FPIP-002
48	1.0249 (0.4035)	0.8072 (0.3178)	Excellent	FPIP-002
49	1.0249 (0.4035)	0.8237 (0.3243)	Excellent	FPIP-002
50	1.0249 (0.4035)	0.8136 (0.3203)	Excellent	FPIP-002
51	1.0249 (0.4035)	0.8197 (0.3227)	Excellent	FPIP-002
52	1.0246 (0.4034)	0.8174 (0.3218)	Excellent	FPIP-002
53	1.0249 (0.4035)	0.8242 (0.3245)	Excellent	FPIP-002
54	1.0244 (0.4033)	0.8184 (0.3222)	Excellent	FPIP-002
55	1.0246 (0.4034)	0.8222 (0.3237)	Excellent	FPIP-002
56	1.0267 (0.4042)	0.8346 (0.3286)	Average	125-7-1
Upper end				
Mean value	1.0250 (0.4035)			
Standard deviation	0.0004 (0.0002)			

**TABLE D.15. Pellet Loading Information for H2UCG029
(annular-coated-pressurized rod)**

<u>Loading Sequence</u>	<u>Pellet Diameter, cm (in.)</u>	<u>Pellet Length, cm (in.)</u>	<u>Appearance</u>	<u>Lot</u>
Lower end				
1	1.0274 (0.4045)	0.8364 (0.3293)	Average	125-7-1
2	1.0249 (0.4035)	0.8161 (0.3213)	Excellent	FPIP-002
3	1.0251 (0.4036)	0.8400 (0.3307)	Excellent	FPIP-002
4	1.0249 (0.4035)	0.8103 (0.3190)	Excellent	FPIP-002
5	1.0249 (0.4035)	0.8245 (0.3246)	Excellent	FPIP-002
6	1.0249 (0.4035)	0.8029 (0.3161)	Excellent	FPIP-002
7	1.0249 (0.4035)	0.8108 (0.3192)	Excellent	FPIP-002
8	1.0251 (0.4036)	0.8164 (0.3214)	Excellent	FPIP-002
9	1.0246 (0.4034)	0.8260 (0.3252)	Excellent	FPIP-002
10	1.0249 (0.4035)	0.8113 (0.3194)	Excellent	FPIP-002
11	1.0249 (0.4035)	0.8039 (0.3165)	Excellent	FPIP-002
12	1.0251 (0.4036)	0.8082 (0.3182)	Excellent	FPIP-002
13	1.0254 (0.4037)	0.8301 (0.3268)	Excellent	FPIP-002
14	1.0251 (0.4036)	0.8031 (0.3162)	Excellent	FPIP-002
15	1.0244 (0.4033)	0.8204 (0.3230)	Excellent	FPIP-002
16	1.0249 (0.4035)	0.8136 (0.3203)	Excellent	FPIP-002
17	1.0249 (0.4035)	0.8230 (0.3240)	Excellent	FPIP-002
18	1.0249 (0.4035)	0.8321 (0.3276)	Excellent	FPIP-002
19	1.0251 (0.4036)	0.8270 (0.3256)	Excellent	FPIP-002
20	1.0246 (0.4034)	0.8245 (0.3246)	Excellent	FPIP-002
21	1.0246 (0.4034)	0.8115 (0.3195)	Excellent	FPIP-002
22	1.0249 (0.4035)	0.7973 (0.3139)	Excellent	FPIP-002
23	1.0249 (0.4035)	0.8146 (0.3207)	Excellent	FPIP-002
24	1.0249 (0.4035)	0.8067 (0.3176)	Excellent	FPIP-002
25	1.0249 (0.4035)	0.8252 (0.3249)	Excellent	FPIP-002
26	1.0246 (0.4034)	0.8341 (0.3284)	Excellent	FPIP-002
27	1.0249 (0.4035)	0.8252 (0.3249)	Excellent	FPIP-002
28	1.0246 (0.4034)	0.8288 (0.3263)	Excellent	FPIP-002
29	1.0251 (0.4036)	0.8212 (0.3233)	Excellent	FPIP-002
30	1.0249 (0.4035)	0.8272 (0.3257)	Excellent	FPIP-002
31	1.0249 (0.4035)	0.8362 (0.3292)	Excellent	FPIP-002
32	1.0249 (0.4035)	0.8235 (0.3242)	Excellent	FPIP-002
33	1.0249 (0.4035)	0.8064 (0.3175)	Excellent	FPIP-002
34	1.0249 (0.4035)	0.8308 (0.3271)	Excellent	FPIP-002
35	1.0249 (0.4035)	0.8235 (0.3242)	Excellent	FPIP-002
36	1.0249 (0.4035)	0.8166 (0.3215)	Excellent	FPIP-002
37	1.0249 (0.4035)	0.8318 (0.3275)	Excellent	FPIP-002
38	1.0249 (0.4035)	0.8225 (0.3238)	Excellent	FPIP-002
39	1.0249 (0.4035)	0.7935 (0.3124)	Excellent	FPIP-002
40	1.0249 (0.4035)	0.8311 (0.3272)	Excellent	FPIP-002
41	1.0246 (0.4034)	0.8232 (0.3241)	Excellent	FPIP-002
42	1.0249 (0.4035)	0.8217 (0.3236)	Excellent	FPIP-002
43	1.0249 (0.4035)	0.8237 (0.3243)	Excellent	FPIP-002
44	1.0249 (0.4035)	0.8072 (0.3178)	Excellent	FPIP-002
45	1.0246 (0.4034)	0.8311 (0.3272)	Excellent	FPIP-002
46	1.0246 (0.4034)	0.8095 (0.3187)	Excellent	FPIP-002
47	1.0249 (0.4035)	0.8118 (0.3196)	Excellent	FPIP-002
48	1.0249 (0.4035)	0.8245 (0.3246)	Excellent	FPIP-002
49	1.0249 (0.4035)	0.8278 (0.3259)	Excellent	FPIP-002
50	1.0246 (0.4034)	0.8263 (0.3253)	Excellent	FPIP-002
51	1.0246 (0.4034)	0.8085 (0.3183)	Excellent	FPIP-002
52	1.0251 (0.4036)	0.8283 (0.3261)	Excellent	FPIP-002
53	1.0251 (0.4036)	0.8110 (0.3193)	Excellent	FPIP-002
54	1.0246 (0.4034)	0.8151 (0.3209)	Excellent	FPIP-002
55	1.0249 (0.4035)	0.8207 (0.3231)	Excellent	FPIP-002
56	1.0249 (0.4035)	0.8052 (0.3170)	Excellent	FPIP-002
57	1.0254 (0.4037)	0.8230 (0.3240)	Average	125-7-1
Upper end				
Mean value	1.0249 (0.4035)			
Standard deviation	0.0003 (0.0002)			

TABLE D.16. Pellet Loading Information for H3UCG030
(annular-coated-pressurized rod)

Loading Sequence	Pellet Diameter, cm (in.)	Pellet Length, cm (in.)	Appearance	Lot
Lower end				
1	1.0272 (0.4044)	0.8161 (0.3213)	Average	125-7-1
2	1.0249 (0.4035)	0.8082 (0.3182)	Excellent	FPIP-002
3	1.0246 (0.4034)	0.8103 (0.3190)	Excellent	FPIP-002
4	1.0246 (0.4034)	0.8136 (0.3203)	Excellent	FPIP-002
5	1.0246 (0.4034)	0.8202 (0.3229)	Excellent	FPIP-002
6	1.0246 (0.4034)	0.8224 (0.3238)	Excellent	FPIP-002
7	1.0249 (0.4035)	0.8219 (0.3236)	Excellent	FPIP-002
8	1.0246 (0.4034)	0.8095 (0.3187)	Excellent	FPIP-002
9	1.0249 (0.4035)	0.8044 (0.3167)	Excellent	FPIP-002
10	1.0246 (0.4034)	0.8192 (0.3225)	Excellent	FPIP-002
11	1.0249 (0.4035)	0.8075 (0.3179)	Excellent	FPIP-002
12	1.0249 (0.4035)	0.8153 (0.3210)	Excellent	FPIP-002
13	1.0249 (0.4035)	0.8247 (0.3247)	Excellent	FPIP-002
14	1.0251 (0.4036)	0.8174 (0.3218)	Excellent	FPIP-002
15	1.0251 (0.4036)	0.8161 (0.3213)	Excellent	FPIP-002
16	1.0249 (0.4035)	0.8034 (0.3163)	Excellent	FPIP-002
17	1.0251 (0.4036)	0.8227 (0.3239)	Excellent	FPIP-002
18	1.0249 (0.4035)	0.8120 (0.3197)	Excellent	FPIP-002
19	1.0249 (0.4035)	0.7983 (0.3143)	Excellent	FPIP-002
20	1.0249 (0.4035)	0.8108 (0.3192)	Excellent	FPIP-002
21	1.0249 (0.4035)	0.8153 (0.3210)	Excellent	FPIP-002
22	1.0244 (0.4033)	0.8077 (0.3180)	Excellent	FPIP-002
23	1.0246 (0.4034)	0.8219 (0.3236)	Excellent	FPIP-002
24	1.0244 (0.4033)	0.8004 (0.3151)	Excellent	FPIP-002
25	1.0249 (0.4035)	0.8209 (0.3232)	Excellent	FPIP-002
26	1.0249 (0.4035)	0.8100 (0.3189)	Excellent	FPIP-002
27	1.0246 (0.4034)	0.8138 (0.3204)	Excellent	FPIP-002
28	1.0249 (0.4035)	0.8062 (0.3174)	Excellent	FPIP-002
29	1.0249 (0.4035)	0.8026 (0.3160)	Excellent	FPIP-002
30	1.0249 (0.4035)	0.8240 (0.3244)	Excellent	FPIP-002
31	1.0246 (0.4034)	0.8283 (0.3261)	Excellent	FPIP-002
32	1.0251 (0.4036)	0.8158 (0.3212)	Excellent	FPIP-002
33	1.0244 (0.4033)	0.8133 (0.3202)	Excellent	FPIP-002
34	1.0249 (0.4035)	0.8095 (0.3187)	Excellent	FPIP-002
35	1.0249 (0.4035)	0.8113 (0.3194)	Excellent	FPIP-002
36	1.0246 (0.4034)	0.8072 (0.3178)	Excellent	FPIP-002
37	1.0251 (0.4036)	0.8263 (0.3253)	Excellent	FPIP-002
38	1.0246 (0.4034)	0.8192 (0.3225)	Excellent	FPIP-002
39	1.0246 (0.4034)	0.8192 (0.3225)	Excellent	FPIP-002
40	1.0249 (0.4035)	0.7963 (0.3135)	Excellent	FPIP-002
41	1.0246 (0.4034)	0.7993 (0.3147)	Excellent	FPIP-002
42	1.0246 (0.4034)	0.8283 (0.3261)	Excellent	FPIP-002
43	1.0264 (0.4034)	0.8141 (0.3205)	Excellent	FPIP-002
44	1.0249 (0.4035)	0.8098 (0.3188)	Excellent	FPIP-002
45	1.0249 (0.4035)	0.8169 (0.3216)	Excellent	FPIP-002
46	1.0249 (0.4035)	0.8219 (0.3236)	Excellent	FPIP-002
47	1.0249 (0.4035)	0.8263 (0.3253)	Excellent	FPIP-002
48	1.0251 (0.4036)	0.8296 (0.3266)	Excellent	FPIP-002
49	1.0249 (0.4035)	0.8087 (0.3184)	Excellent	FPIP-002
50	1.0246 (0.4034)	0.8247 (0.3247)	Excellent	FPIP-002
51	1.0249 (0.4035)	0.8092 (0.3186)	Excellent	FPIP-002
52	1.0246 (0.4034)	0.8133 (0.3202)	Excellent	FPIP-002
53	1.0246 (0.4034)	0.8207 (0.3231)	Excellent	FPIP-002
54	1.0246 (0.4034)	0.8189 (0.3224)	Excellent	FPIP-002
55	1.0244 (0.4033)	0.8136 (0.3203)	Excellent	FPIP-002
56	1.0249 (0.4035)	0.8166 (0.3215)	Excellent	FPIP-002
57	1.0254 (0.4037)	0.8364 (0.3293)	Average	125-7-1
Upper end				
Mean value	1.0248 (0.4035)			
Standard deviation	0.0004 (0.0001)			

**TABLE D.17. Pellet Loading Information for H3UCG031
(annular-coated-pressurized rod)**

<u>Loading Sequence</u>	<u>Pellet Diameter, cm (in.)</u>	<u>Pellet Length, cm (in.)</u>	<u>Appearance</u>	<u>Lot</u>
Lower end				
1	1.0277 (0.4046)	0.8240 (0.3244)	Average	125-7-1
2	1.0244 (0.4033)	0.8105 (0.3191)	Excellent	FPIP-002
3	1.0246 (0.4034)	0.8156 (0.3211)	Excellent	FPIP-002
4	1.0246 (0.4034)	0.8331 (0.3280)	Excellent	FPIP-002
5	1.0246 (0.4034)	0.8118 (0.3196)	Excellent	FPIP-002
6	1.0249 (0.4035)	0.8143 (0.3206)	Excellent	FPIP-002
7	1.0249 (0.4035)	0.8263 (0.3253)	Excellent	FPIP-002
8	1.0249 (0.4035)	0.8278 (0.3259)	Excellent	FPIP-002
9	1.0241 (0.4032)	0.8197 (0.3227)	Excellent	FPIP-002
10	1.0249 (0.4035)	0.8270 (0.3256)	Excellent	FPIP-002
11	1.0249 (0.4035)	0.8270 (0.3256)	Excellent	FPIP-002
12	1.0246 (0.4034)	0.8324 (0.3277)	Excellent	FPIP-002
13	1.0246 (0.4034)	0.8222 (0.3237)	Excellent	FPIP-002
14	1.0244 (0.4033)	0.8141 (0.3205)	Excellent	FPIP-002
15	1.0246 (0.4034)	0.8273 (0.3257)	Excellent	FPIP-002
16	1.0249 (0.4035)	0.8219 (0.3236)	Excellent	FPIP-002
17	1.0246 (0.4034)	0.8186 (0.3223)	Excellent	FPIP-002
18	1.0249 (0.4035)	0.8192 (0.3225)	Excellent	FPIP-002
19	1.0249 (0.4035)	0.8219 (0.3236)	Excellent	FPIP-002
20	1.0251 (0.4036)	0.8291 (0.3264)	Excellent	FPIP-002
21	1.0249 (0.4035)	0.8301 (0.3268)	Excellent	FPIP-002
22	1.0249 (0.4035)	0.8372 (0.3296)	Excellent	FPIP-002
23	1.0249 (0.4035)	0.8306 (0.3270)	Excellent	FPIP-002
24	1.0246 (0.4034)	0.8364 (0.3293)	Excellent	FPIP-002
25	1.0251 (0.4036)	0.8197 (0.3227)	Excellent	FPIP-002
26	1.0249 (0.4035)	0.8156 (0.3211)	Excellent	FPIP-002
27	1.0246 (0.4034)	0.8214 (0.3234)	Excellent	FPIP-002
28	1.0249 (0.4035)	0.8212 (0.3233)	Excellent	FPIP-002
29	1.0249 (0.4035)	0.8237 (0.3243)	Excellent	FPIP-002
30	1.0249 (0.4035)	0.8156 (0.3211)	Excellent	FPIP-002
31	1.0246 (0.4034)	0.8133 (0.3202)	Excellent	FPIP-002
32	1.0249 (0.4035)	0.8247 (0.3247)	Excellent	FPIP-002
33	1.0246 (0.4034)	0.8169 (0.3216)	Excellent	FPIP-002
34	1.0246 (0.4034)	0.8240 (0.3244)	Excellent	FPIP-002
35	1.0249 (0.4035)	0.8065 (0.3175)	Excellent	FPIP-002
36	1.0246 (0.4034)	0.8301 (0.3268)	Excellent	FPIP-002
37	1.0246 (0.4034)	0.8214 (0.3234)	Excellent	FPIP-002
38	1.0249 (0.4035)	0.8247 (0.3247)	Excellent	FPIP-002
39	1.0246 (0.4034)	0.8247 (0.3247)	Excellent	FPIP-002
40	1.0244 (0.4033)	0.8255 (0.3250)	Excellent	FPIP-002
41	1.0246 (0.4034)	0.8258 (0.3251)	Excellent	FPIP-002
42	1.0246 (0.4034)	0.8207 (0.3231)	Excellent	FPIP-002
43	1.0249 (0.4035)	0.8181 (0.3221)	Excellent	FPIP-002
44	1.0249 (0.4035)	0.8369 (0.3295)	Excellent	FPIP-002
45	1.0246 (0.4034)	0.8158 (0.3212)	Excellent	FPIP-002
46	1.0251 (0.4036)	0.8192 (0.3225)	Excellent	FPIP-002
47	1.0249 (0.4035)	0.8265 (0.3254)	Excellent	FPIP-002
48	1.0246 (0.4034)	0.8324 (0.3277)	Excellent	FPIP-002
49	1.0249 (0.4035)	0.8141 (0.3205)	Excellent	FPIP-002
50	1.0249 (0.4035)	0.8171 (0.3217)	Excellent	FPIP-002
51	1.0249 (0.4035)	0.8186 (0.3223)	Excellent	FPIP-002
52	1.0249 (0.4035)	0.8222 (0.3237)	Excellent	FPIP-002
53	1.0251 (0.4036)	0.8174 (0.3218)	Excellent	FPIP-002
54	1.0249 (0.4035)	0.8283 (0.3261)	Excellent	FPIP-002
55	1.0244 (0.4033)	0.8214 (0.3234)	Excellent	FPIP-002
56	1.0277 (0.4046)	0.8400 (0.3307)	Average	125-7-1
Upper end				
Mean value	1.0249 (0.4035)			
Standard deviation	0.0006 (0.0002)			

**TABLE D.18. Pellet Loading Information for H3UCG032
(annular-coated-pressurized rod)**

<u>Loading Sequence</u>	<u>Pellet Diameter, cm (in.)</u>	<u>Pellet Length, cm (in.)</u>	<u>Appearance</u>	<u>Lot</u>
Lower end				
1	1.0264 (0.4041)	0.8321 (0.3276)	Average	125-7-1
2	1.0246 (0.4034)	0.8153 (0.3210)	Excellent	FPIP-002
3	1.0246 (0.4034)	0.8100 (0.3189)	Excellent	FPIP-002
4	1.0249 (0.4035)	0.8164 (0.3214)	Excellent	FPIP-002
5	1.0246 (0.4034)	0.8275 (0.3258)	Excellent	FPIP-002
6	1.0249 (0.4035)	0.8057 (0.3172)	Excellent	FPIP-002
7	1.0249 (0.4035)	0.8275 (0.3258)	Excellent	FPIP-002
8	1.0246 (0.4034)	0.8131 (0.3201)	Excellent	FPIP-002
9	1.0249 (0.4035)	0.8110 (0.3193)	Excellent	FPIP-002
10	1.0246 (0.4034)	0.8268 (0.3255)	Excellent	FPIP-002
11	1.0249 (0.4035)	0.8242 (0.3245)	Excellent	FPIP-002
12	1.0246 (0.4034)	0.8301 (0.3268)	Excellent	FPIP-002
13	1.0246 (0.4034)	0.8265 (0.3254)	Excellent	FPIP-002
14	1.0246 (0.4034)	0.8301 (0.3268)	Excellent	FPIP-002
15	1.0249 (0.4035)	0.8189 (0.3224)	Excellent	FPIP-002
16	1.0251 (0.4036)	0.8252 (0.3244)	Excellent	FPIP-002
17	1.0249 (0.4035)	0.8179 (0.3220)	Excellent	FPIP-002
18	1.0246 (0.4034)	0.8250 (0.3248)	Excellent	FPIP-002
19	1.0246 (0.4034)	0.8352 (0.3288)	Excellent	FPIP-002
20	1.0249 (0.4035)	0.8313 (0.3273)	Excellent	FPIP-002
21	1.0249 (0.4035)	0.8164 (0.3214)	Excellent	FPIP-002
22	1.0249 (0.4035)	0.8110 (0.3193)	Excellent	FPIP-002
23	1.0249 (0.4035)	0.8184 (0.3222)	Excellent	FPIP-002
24	1.0244 (0.4033)	0.8158 (0.3212)	Excellent	FPIP-002
25	1.0249 (0.4035)	0.8181 (0.3221)	Excellent	FPIP-002
26	1.0249 (0.4035)	0.8209 (0.3232)	Excellent	FPIP-002
27	1.0244 (0.4033)	0.7978 (0.3141)	Excellent	FPIP-002
28	1.0246 (0.4034)	0.8136 (0.3203)	Excellent	FPIP-002
29	1.0244 (0.4033)	0.8151 (0.3209)	Excellent	FPIP-002
30	1.0249 (0.4035)	0.8146 (0.3207)	Excellent	FPIP-002
31	1.0249 (0.4035)	0.8199 (0.3228)	Excellent	FPIP-002
32	1.0246 (0.4034)	0.8189 (0.3224)	Excellent	FPIP-002
33	1.0244 (0.4033)	0.8090 (0.3185)	Excellent	FPIP-002
34	1.0251 (0.4036)	0.8169 (0.3216)	Excellent	FPIP-002
35	1.0249 (0.4035)	0.8049 (0.3169)	Excellent	FPIP-002
36	1.0249 (0.4035)	0.8237 (0.3243)	Excellent	FPIP-002
37	1.0244 (0.4033)	0.8057 (0.3172)	Excellent	FPIP-002
38	1.0246 (0.4034)	0.8186 (0.3223)	Excellent	FPIP-002
39	1.0249 (0.4035)	0.8026 (0.3160)	Excellent	FPIP-002
40	1.0246 (0.4034)	0.8001 (0.3150)	Excellent	FPIP-002
41	1.0246 (0.4034)	0.8052 (0.3170)	Excellent	FPIP-002
42	1.0249 (0.4035)	0.7955 (0.3132)	Excellent	FPIP-002
43	1.0246 (0.4034)	0.8029 (0.3161)	Excellent	FPIP-002
44	1.0246 (0.4034)	0.8024 (0.3159)	Excellent	FPIP-002
45	1.0249 (0.4035)	0.8268 (0.3255)	Excellent	FPIP-002
46	1.0249 (0.4035)	0.8174 (0.3218)	Excellent	FPIP-002
47	1.0246 (0.4034)	0.8077 (0.3180)	Excellent	FPIP-002
48	1.0249 (0.4035)	0.8151 (0.3209)	Excellent	FPIP-002
49	1.0251 (0.4036)	0.8037 (0.3164)	Excellent	FPIP-002
50	1.0246 (0.4034)	0.8174 (0.3218)	Excellent	FPIP-002
51	1.0246 (0.4034)	0.8110 (0.3193)	Excellent	FPIP-002
52	1.0246 (0.4034)	0.8438 (0.3322)	Excellent	FPIP-002
53	1.0249 (0.4035)	0.8237 (0.3243)	Excellent	FPIP-002
54	1.0246 (0.4034)	0.8265 (0.3254)	Excellent	FPIP-002
55	1.0246 (0.4034)	0.7973 (0.3139)	Excellent	FPIP-002
56	1.0246 (0.4034)	0.8354 (0.3289)	Excellent	FPIP-002
57	1.0282 (0.4048)	0.8308 (0.3271)	Average	125-7-1
Upper end				
Mean value	1.0248 (0.4035)			
Standard deviation	0.0005 (0.0002)			

APPENDIX E

PHYSICAL AND CHEMICAL CHARACTERIZATION RESULTS FOR THE ALUMINA INSULATOR PELLETS

PHYSICAL AND CHEMICAL CHARACTERIZATION RESULTS
FOR THE ALUMINA INSULATOR PELLETS

Chemical analysis (Table E.1), density (Table E.2) and dimensional measurement results (Table E.3) from typical alumina (Al_2O_3) insulator pellets are contained in Appendix E.

TABLES

E.1	Chemical Analysis of Alumina Insulator Pellets		E-2
E.2	Density of Randomly Sampled Alumina Insulator Pellets		E-3
E.3	Dimensional Measurement Results for Sampled Alumina Insulator Pellets		E-3

TABLE E.1. Chemical Analysis of Alumina Insulator Pellets

<u>Trace Element</u>	<u>Content, ppm</u>
C	60
Ca	375
Cd	50
Cl	10
F	10
Fe	1600
Li	10
Mg	2600
Mn	35
N ₂	22
Na	1000
S	10
Si	1000
Ti	50
Moisture	3

<u>Equivalent Oxides</u>	<u>Content, %</u>
MgO	0.28
SiO ₂	0.038
Fe ₂ O ₃	0.092
Al ₂ O ₃	99.3

TABLE E.2. Density^(a) of Randomly Sampled Alumina Insulator Pellets

<u>Sample No.</u>	<u>Density</u>	
	<u>g/cm³</u>	<u>%TD</u>
1	3.98	99.8
2	3.93	98.6
3	3.93	98.6
4	3.94	98.6
5	3.93	98.6
Mean value	3.94	98.8
Standard deviation	0.02	0.6

(a) Density measured by immersion method.

TABLE E.3. Dimensional Measurement Results for Sample Alumina Insulator Pellets

<u>Sample No.</u>	<u>Diameter, cm (in.)</u>	<u>Length, cm (in.)</u>
1	0.9959 (0.3921)	0.5304 (0.2088)
2	0.9964 (0.3923)	0.5311 (0.2091)
3	0.9939 (0.3913)	0.5316 (0.2093)
4	0.9964 (0.3923)	0.5331 (0.2099)
5	0.9964 (0.3923)	0.5342 (0.2103)
Mean value	0.9958 (0.3921)	0.5321 (0.2095)
Standard deviation	0.0011 (0.0004)	0.0015 (0.0006)

APPENDIX F

ANALYTICAL RESULTS FOR THE ROD COVER GAS

ANALYTICAL RESULTS FOR THE ROD COVER GAS

The cover gas in the welding box that was present during welding of the reference and annular-coated-pressurized rods was tested for composition. The gas in the loading box was also analyzed to determine the gas composition in the sphere-pac rods. The results for the pellet rods and sphere-pac rods are shown in Tables F.1 and F.2, respectively.

TABLES

F.1	Cover Gas Analysis for Reference and Annular-Coated-Pressurized Rods	F-2
F.2	Cover Gas Analysis for Sphere-pac Rods in HBWR Series H-2, H-3 and H-4	F-2

TABLE F.1. Cover Gas Analysis for Reference and Annular-Coated-Pressurized Rods

<u>Gas</u>	<u>Content</u>
He	99.96 vol%
Ne	<25 ppm
H ₂	<200 ppm
N ₂	55 ppm
O ₂	45 ppm
Ar	<25 ppm
CO	<25 ppm
CH ₄	<25 ppm
CO ₂	<25 ppm

TABLE F.2. Cover Gas Analysis for Sphere-pac Rods in HBWR Series H-2, H-3 and H-4

<u>Gas</u>	<u>Content</u>
He	99.28 vol%
Ne	<25 ppm
H ₂	<200 ppm
N ₂	0.44 vol%
O ₂	0.25 vol%
Ar	<25 ppm
CO	<25 ppm
CH ₄	<25 ppm
CO ₂	35 ppm

APPENDIX G

AS-BUILT ROD CHARACTERIZATION RESULTS

AS-BUILT ROD CHARACTERIZATION RESULTS

Appendix G contains neutron radiographs of selected rods from HBWR Series H-2, H-3, and H-4 test rods. Measurement of the smear fuel density in the sphere-pac rods, profilometry data, and as-built rod measurements are also included in this appendix.

Neutron radiographs of typical reference, annular-coated-pressurized and sphere-pac fuel rods in the HBWR Series H-2, H-3 and H-4 are shown in Figures G.1 through G.3. The sphere-pac fuel type is shown with thermocouple and without thermocouple in Figure G.3. The two radiographs in Figure G.3 were taken at different times which caused the slight difference in film densities. Areas of interest have been enlarged in each figure.

The smear density variation along the fuel column length in each sphere-pac rod is shown in Figure G.4 and G.5. The average smear density measured is tabulated in Table G.1.

The profilometry traces shown in Figures G.6-G.17 were made using V-notches as references on the end caps that were machined at Kjeller, Norway. Profilometry traces start about 3 mm below the lower V-notch and end approximately 3 mm above the upper V-notch. The V-notches used for profilometry measurements are located 5.5 mm below the lower edge of the square notch on the lower end cap in Figures A.3, A.4 and A.5 and 4.0 mm above the upper edge of the upper square notch on the upper end cap. V-notches were not machined on the sphere-pac rods shown in Figures G.18-G.20 because of the thermocouple leads in the instrumented upper end cap.

Angles for profilometry measurements are referenced to a scribe mark made on the upper end cap prior to profilometry measurements at Kjeller, Norway. The 0° orientation corresponds to the scribe mark and measures the rod diameter at the scribe mark. The 90° orientation is obtained by viewing from above the top end of the rod and rotating the rod clockwise.

Additional information on rod bow (Table G.2), rod diameters (Table G.3), and other as-built data (Table G.4), such as rod smear densities, void volumes, rod lengths and fuel column lengths, are also included in this appendix.

FIGURES

G.1	Full-Scale Neutron Radiographs of Reference Rods H2UCR023 and H3UCR025 with 2X Enlargement of Selected Areas	G- 5
G.2	Full-Scale Neutron Radiographs of Annular-Coated-Pressurized Rods H2UCG027 and H3UCG030 with 2X Enlargement of Selected Areas	G- 7
G.3	Full-Scale Neutron Radiographs of Sphere-pac Rods H3UCS034 and H2XXS041 with 2X Enlargement of Selected Areas	G- 9
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G.7	Profilometry Traces at 0° and 90° for Rod H2UCR024	G-13
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FIGURE G.1. Full-Scale Neutron Radiographs of Reference Rods H2UCR023 and H3UCR025 with 2X Enlargement of Selected Areas

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FIGURE G.2. Full-Scale Neutron Radiographs of Annular-Coated Rods
H2UCG027 and H3UCG030 with 2X Enlargement of Selected Areas

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FIGURE G.3. Full-Scale Neutron Radiographs of Sphere-pac Rods H3UCS034 and H2XXS041 with 2X Enlargements of Selected Areas

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FIGURE G.4. Measured Density in Sphere-Pac Rods H2UCS033 and H3UCS034 (normalized to overall bulk smear density)

FIGURE G.5. Measured Density in Sphere-Pac Rods H2SPS040, H2XXS041 and H2XXS042 (normalized to overall bulk smear density)

FIGURE G.6. Profilometry Traces at 0° and 90° for Rod H2UCR023 (measured from lower notch)

FIGURE G.7. Profilometry Traces at 0° and 90° for Rod H2UCR024 (measured from lower notch)

FIGURE G.8. Profilometry Traces at 0° and 90° for Rod H3UCR025 (measured from lower notch)

FIGURE G.9. Profilometry Traces at 0° and 90° for Rod H3UCR026 (measured from lower notch)

FIGURE G.10. Profilometry Traces at 0° and 90° for Rod H2UCG027 (measured from lower notch)

FIGURE G.11. Profilometry Traces at 0° and 90° for Rod H2UCG028 (measured from lower notch)

FIGURE G.12. Profilometry Traces at 0° and 90° for Rod H2UCG029 (measured from lower notch)

FIGURE G.13. Profilometry Traces at 0° and 90° for Rod H3UCG030 (measured from lower notch)

FIGURE G.14. Profilometry Traces at 0° and 90° for Rod H3UCG031 (measured from lower notch)

FIGURE G.15. Profilometry Traces at 0° and 90° for Rod H3UCG032 (measured from lower notch)

FIGURE G.16. Profilometry Traces at 0° and 90° for Rod H2UCS033 (measured from lower notch)

FIGURE G.17. Profilometry Traces at 0° and 90° for Rod H3UCS034 (measured from lower notch)

FIGURE G.18. Profilometry Traces at 0° and 90° for Rod H2SPS040
(measured from bottom end)

FIGURE G.19. Profilometry Traces at 0° and 90° for Rod H2XXS041
(measured from bottom end)

FIGURE G.20. Profilometry Traces at 0° and 90° for Rod H2XXS042 (measured from bottom end)

TABLE G.1. Average Smear Density in Sphere-Pac Rods

Rod Number	Average Smear Density,	Standard Deviation,
	%TD	%TD
H2UCS033	87.6	1.1
H3UCS034	88.0	0.9
H2SPS040	87.9	0.95
H2XXS041	87.7 ^(b)	0.91
H2XXS042	88.5 ^(b)	0.89

(a) 100% TD = 10.96 g/cm³.

(b) In the region below the thermocouple well.

TABLE G.2. Measured and Calculated Bow of the HBWR Series H-2, H-3 and H-4 Rods

Rod Number	Measured Maximum ^(a) Bow and Location				Calculated ^(b) Maximum Bow		
	0°		90°				Angle
	Bow, mm	Location, mm	Bow, mm	Location, mm	Bow, mm	Location, mm	
H2UCR023	0.038	465	0.045	153	0.052	438	50
H2UCR024	-0.115	324	0.102	372	0.151	340	138
H3UCR025	0.128	335	0.031	376	0.131	343	13
H3UCR026	0.031	139	-0.184	302	0.184	302	270
H2UCG027	-0.094	276	0.108	178	0.131	216	128
H2UCG028	-0.139	290	0.231	226	0.265	253	120
H2UCG029	-0.057	303	0.092	202	0.105	279	122
H3UCG030	-0.053	293	0.030	92	0.053	292	177
H3UCG031	0.014	110	-0.111	246	0.111	246	270
H3UCG032	-0.098	280	-0.138	313	0.168	300	235
H2UCS033	0.092	155	0.036	145	0.099	156	21
H3UCS034	0.124	228	0.046	159	0.129	210	16
H2SPS040	0.066	262	0.013	499	0.067	263	354
H2XXS041	0.121	264	-0.060	224	0.135	259	333
H2XXS042	-0.037	189	0.069	213	0.077	201	117

(a) The maximum curve found in the rods between the notches (V-notches located in the end caps of H-2 and H-3 rods). The angle is measured from a scribe mark on the upper end cap that was marked at Kjeller, Norway. Location is measured from lower notch in rod. The 0° orientation measures rod bow and rod diameters in a direction parallel to a line drawn through the scribe mark and diametrically across the fuel rod. The 90° orientation is obtained by rotating the rod 90° clockwise when looking down on the top of the rod.

(b) Calculated maximum bow is the analytically determined peak bow and angle as determined from the 0° and 90° data. These values were all supplied by Kjeller, Norway.

TABLE G.3. Fuel Rod Diameters

Rod Number	Position	Diameter-Top, cm (in.)	Diameter-Middle, cm (in.)	Diameter-Bottom, cm (in.)	Average Diameter, cm (in.)	Standard Deviation, cm (in.)
H2UCR023	0°	1.2329 (0.4854)	1.2327 (0.4853)	1.2327 (0.4853)	1.2329 (0.4854)	0.0004 (0.0002)
	90°	1.2334 (0.4856)	1.2324 (0.4852)	1.2334 (0.4856)		
H2UCR024	0°	1.2329 (0.4854)	1.2324 (0.4852)	1.2332 (0.4855)	1.2330 (0.4854)	0.0004 (0.0001)
	90°	1.2332 (0.4855)	1.2334 (0.4856)	1.2332 (0.4855)		
H3UCR025	0°	1.2324 (0.4852)	1.2327 (0.4853)	1.2327 (0.4853)	1.2326 (0.4853)	0.0002 (0.0001)
	90°	1.2329 (0.4854)	1.2324 (0.4852)	1.2327 (0.4853)		
H3UCR026	0°	1.2339 (0.4858)	1.2329 (0.4854)	1.2327 (0.4853)	1.2328 (0.4854)	0.0007 (0.0003)
	90°	1.2324 (0.4852)	1.2329 (0.4854)	1.2319 (0.4850)		
H2UCG027	0°	1.2329 (0.4854)	1.2332 (0.4855)	1.2332 (0.4855)	1.2327 (0.4853)	0.0005 (0.0002)
	90°	1.2319 (0.4850)	1.2327 (0.4853)	1.2327 (0.4853)		
H2UCG028	0°	1.2337 (0.4857)	1.2327 (0.4853)	1.2329 (0.4854)	1.2330 (0.4854)	0.0004 (0.0002)
	90°	1.2327 (0.4853)	1.2334 (0.4856)	1.2329 (0.4854)		
H2UCG029	0°	1.2327 (0.4853)	1.2324 (0.4852)	1.2327 (0.4853)	1.2327 (0.4853)	0.0003 (0.0001)
	90°	1.2329 (0.4854)	1.2327 (0.4853)	1.2332 (0.4855)		
H3UCG030	0°	1.2324 (0.4852)	1.2327 (0.4853)	1.2329 (0.4854)	1.2327 (0.4853)	0.0002 (0.0001)
	90°	1.2329 (0.4854)	1.2327 (0.4853)	1.2324 (0.4852)		
H3UCG031	0°	1.2324 (0.4852)	1.2324 (0.4852)	1.2332 (0.4855)	1.2329 (0.4854)	0.0006 (0.0002)
	90°	1.2329 (0.4854)	1.2327 (0.4853)	1.2339 (0.4858)		
H3UCG032	0°	1.2332 (0.4855)	1.2334 (0.4856)	1.2334 (0.4856)	1.2332 (0.4855)	0.0003 (0.0001)
	90°	1.2332 (0.4855)	1.2332 (0.4855)	1.2327 (0.4853)		
H2UCS033	0°	1.2334 (0.4856)	1.2344 (0.4860)	1.2342 (0.4859)	1.2336 (0.4857)	0.0009 (0.0004)
	90°	1.2339 (0.4858)	1.2342 (0.4859)	1.2342 (0.4859)		
H3UCS034	0°	1.2339 (0.4858)	1.2332 (0.4855)	1.2337 (0.4857)	1.2334 (0.4856)	0.0003 (0.0001)
	90°	1.2332 (0.4855)	1.2334 (0.4856)	1.2332 (0.4855)		
H2SPS040	0°	1.2334 (0.4856)	1.2337 (0.4857)	1.2342 (0.4859)	1.2336 (0.4857)	0.0003 (0.0001)
	90°	1.2337 (0.4857)	1.2334 (0.4856)	1.2334 (0.4856)		
H2XXS041	0°	1.2342 (0.4859)	1.2332 (0.4855)	1.2342 (0.4859)	1.2336 (0.4857)	0.0005 (0.0002)
	90°	1.2339 (0.4858)	1.2332 (0.4855)	1.2332 (0.4855)		
H2XXS042	0°	1.2342 (0.4859)	1.2339 (0.4858)	1.2344 (0.4860)	1.2342 (0.4859)	0.0002 (0.0001)
	90°	1.2344 (0.4860)	1.2339 (0.4858)	1.2344 (0.4860)		

TABLE G.4. As-Built Rod Data for HBWR Series H-2, H-3 and H-4 Rods

Rod Number	Rod Length		Smear Density, %TD ^(c)	Void Volume, cm ³	Fuel Weight ^(d) 11%/2.78%, gm	Fuel Length ^(d) 11% + 2.78%/2.78%, gm
	Overall, ^(a) mm	Notch to ^(b) Notch, mm				
H2UCR023	715.289	547.42	88.9	6.86	375.4/14.3	460.78/16.75
H2UCR024	715.239	547.54	88.8	6.87	376.2/13.8	461.64/16.43
H3UCR025	715.315	547.88	88.7	6.84	376.3/13.6	461.95/16.28
H3UCR026	715.188	547.16	88.7	6.53	379.4/14.0	465.86/16.58
H2UCG027	715.442	548.19	80.5	9.99	341.2/13.7	462.28/16.30
H2UCG028	715.620	547.19	80.6	10.28	344.7/14.0	458.60/16.64
H2UCG029	715.061	548.70	80.7	9.57	344.7/13.9	467.08/16.59
H3UCG030	715.162	547.73	80.6	9.76	342.6/13.9	464.52/16.52
H3UCG031	715.061	548.15	80.6	10.12	339.8/14.0	460.81/16.64
H3UCG032	715.086	548.46	80.4	9.75	343.4/14.0	457.71/16.63
H2UCS033	715.721	547.85	87.7	9.00	372.8/13.9	462.84/16.47
H3UCS034	715.315	545.96	87.9	8.87	373.8/14.6	463.47/16.92
H2SPS040	715.620	NA	87.5	8.86	373.6/14.5	465.46/16.60
H2XXS041	715.442	NA	87.8	9.01	369.4/13.0	463.07/16.64
H2XXS042	715.315	NA	86.9	9.16	368.4/13.3	465.99/16.62

(a) Distance from lower end to bottom of upper end cap shoulder as measured at ENC.

(b) Distance between V-notches in upper and lower end caps as measured by the Institutt for Atomenergi at Kjeller, Norway. Rods H2SPS040, H2XXS041 and H2XXS042 did not have notches available for notch-to-notch measurements.

(c) TD = 10.96 g/cm³.

(d) Weight and Length of 11% ²³⁵U-enriched fuel and 2.78% ²³⁵U-enriched end pellets.

APPENDIX H

PHYSICAL AND CHEMICAL CHARACTERIZATION RESULTS FOR ROD COMPONENTS

PHYSICAL AND CHEMICAL CHARACTERIZATION RESULTS FOR ROD COMPONENTS

This appendix characterizes the Zircaloy-2 frit used in the lower end plug assembly (Figure H.1 and Tables H.1 and H.2), the plenum spring (Table H.3), and the thermocouple wells used in rods H2XXS041 and H2XXS042 (Table H.4).

FIGURE

H.1 Flow Rate of Helium Through Frit Material at Varying Pressures . H-2

TABLES

H.1	Chemical Analysis of Zircaloy Frits (BNW Order Number 56259AW)		H-2
H.2	Physical Characteristics of Zircaloy Frits		H-2
H.3	Plenum Spring Characterization		H-3
H.4	Physical Characteristics of Thermocouple Wells		H-3

FIGURE H.1. Flow Rate of Helium Through Frit Material at Varying Pressures

TABLE H.1. Chemical Analysis of Zircaloy Frits (BNW Order Number 56259AW)

<u>Element</u>	<u>Result</u>
Zr	94 wt%
Sn	1.39 wt%
Ni	490 ppm
Cr	1020 ppm
Fe	2820 ppm

TABLE H.2. Physical Characteristics of Zircaloy Frits

Thickness, cm (in.)	0.427 (0.168)
Porosity, %	40

TABLE H.3. Plenum Spring Characterizations

Material	Inconel X-750
Wire diameter, mm (in.)	0.89 (0.035)
Coil O.D., at working length, mm (in.)	9.6 (0.38)
Free length, mm (in.)	50.80 $\pm$ 0.51 (2.00 $\pm$ 0.020)
Spring force, N (lb)	13.12 $\pm$ 1.33 (2.95 $\pm$ 0.30)
Spring constant, N/m (lb/in.)	590 (3.37)
Spring volume, mm ³ (in. ³)	269 (0.0164)

TABLE H.4. Physical Characteristics of Thermocouple Wells

Material	W-22% Re
Inside Diameter, cm(in.)	0.191 $\pm$ 0.005 (0.075 $\pm$ 0.002)
Outside Diameter, cm (in.)	0.236 $\pm$ 0.005 (0.093 $\pm$ 0.002)
Spacer Wire Material	W-26% Re
Spacer Wire Diameter, cm (in.)	0.051 (0.020)

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