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Precharacterization Report for Instrumented Fuel Assembly (IFA)-527

Prepared by M. E. Cunningham, E. R. Bradley, J. L. Daniel,
N. C. Davis, D. D. Lanning, R. E. Williford

Pacific Northwest Laboratory
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ABSTRACT

This report is a resource document covering the rationale, design, fabrication, and preirradiation characterization of instrumented fuel assembly (IFA)-527. This assembly is being irradiated in the Halden Boiling Water Reactor (HBWR) in Norway as part of the Experimental Support and Development of Single-Rod Fuel Codes Program conducted by Pacific Northwest Laboratory (PNL) and sponsored by the Fuel Behavior Research Branch of the U.S. Nuclear Regulatory Commission (NRC). Data from this assembly will be used to better understand light water reactor (LWR) fuel behavior under normal operating conditions.

SUMMARY

The six-rod instrumented fuel assembly (IFA)-527 is being irradiated in the Halden Boiling Water Reactor (HBWR) in Halden, Norway. This is the fourth and last test assembly to be irradiated under the U.S. Nuclear Regulatory Commission (NRC) Experimental Support and Development of Single-Rod Fuel Codes Program. The principal goal of this assembly is to provide data to improve the understanding of fuel cracking and relocation.

This report is a resource document covering the rationale, design, fabrication, and preirradiation characterization of IFA-527. This assembly is highly similar to the three previous assemblies irradiated under this program: IFA-431, -432, and -513. IFA-527 contains six rods, each instrumented with two fuel centerline thermocouples, a bellows-type internal gas pressure transducer, and a cladding axial elongation monitor. All rods are backfilled with 100% xenon to amplify the thermal effects due to fuel cracking and relocation. In addition, rods 1 through 5 are nominally identical so that data of a statistical nature may be obtained. Rod 6 has a small fuel-cladding gap and will provide data for evaluating the lower bound of gap conductance under known fuel-cladding contact conditions.

The fuel for IFA-527 was fabricated to be similar to the fuel used in IFA-431, -432, and -513; based on microstructural analysis, it is believed that the fuel in all four assemblies should behave similarly. Fuel thermal conductivity and thermal resintering tests were conducted on both IFA-527 and IFA-513 fuel, and the results are in agreement with previous tests.

CONTENTS

FIGURES

TABLES

INTRODUCTION

If a loss-of-coolant accident (LOCA) should occur in a light water reactor (LWR), the short-term thermal stored energy and long-term decay heat of the fuel rods become the driving forces for fuel damage. To assess the amount of energy that would be present in the core of a commercial LWR should a LOCA occur, the U.S. Nuclear Regulatory Commission (NRC) must rely on computer codes, which are designed to account for fuel type, fuel and cladding dimensions, coolant conditions, power level, operating history, and a host of other considerations. However, these codes are only as reliable as the data bases that are used to build them and to verify their results.

The Experimental Support and Development of Single-Rod Fuel Codes Program was primarily established to develop a well-characterized data base to assure such reliability. The program was begun at Pacific Northwest Laboratory (PNL)[a] in 1974 by the Fuel Behavior Research Branch of the NRC. The data generated from this program is now being used in the development and verification of the NRC audit codes GAPCON-THERMAL[1] and FRAPCON.[2]

To date, four instrumented fuel assemblies (IFAs) have been built and irradiated in the Halden Boiling Water Reactor (HBWR), Halden, Norway. The first of these assemblies, IFA-431, was irradiated from June 1975 to February 1976 and obtained an assembly average burnup of 389 GJ/kgU (4.5 GWd/MTM). The second assembly, IFA-432, is identical in design to IFA-431 and began irradiation in December 1975; it is still in the reactor and is providing data at high fuel burnup.[b] The design of the third assembly, IFA-513, is similar to the two previous assemblies with some differences--principally fuel length and initial fill gas composition and pressure. IFA-513 began irradiation in November 1978 and is still in-reactor.[c] The data obtained from all three of these assemblies has been consistent and useful for verifying existing models, developing new models, and developing new techniques for analysis of fuel rod data.

(a) Operated for the U.S. Department of Energy (DOE) by Battelle Memorial Institute.

(b) As of October 4, 1980, the assembly average burnup for IFA-432 was approximately 2335 GJ/kgU (27 GWd/MTM).

(c) As of October 4, 1980, the assembly average burnup for IFA-513 was 775 GJ/kgU (9 GWd/MTM).

To continue the work begun with IFA-431, -432, and -513, the fourth (and final) assembly was charged into the HBWR in June 1980. This assembly, designated IFA-527, is principally designed to provide additional data on the phenomena of fuel cracking and relocation. To emphasize the thermal effects of cracking and relocation, all six rods in IFA-527 have an initial fill gas of pure xenon at 1-atm pressure. In addition, because cracking and relocation are of a statistical nature, five of the six rods are nominally identical; the sixth rod has a smaller initial fuel-cladding gap.

This report is a repository of information on the objective, design, and fabrication of IFA-527. Since this assembly shares some design features and materials with the previous assemblies, their precharacterization reports[a] are referenced when appropriate. The information included in this report is organized as follows:

- Test Objectives
- IFA-527 Design and Assembly Fabrication
- Fuel Fabrication and Characterization
- Assembly Operation
- Appendices.

(a) Precharacterization report for IFA-431 and -432 hereafter referred to as BNWL-1988;[3] precharacterization report for IFA-513 hereafter referred to as PNL-3156.[4]

TEST OBJECTIVES

A principal objective of the NRC/PNL Experimental Support and Development of Single-Rod Fuel Codes Program has continually been to obtain well-characterized thermal-mechanical fuel rod data over the spectrum of normal LWR operation. By varying the density, stability, and dimensions of the fuel and the composition and initial pressure of the fill gas, thermal and mechanical data has been obtained under a variety of known conditions. By using replicate rods filled with xenon gas, data from IFA-527 will be used for:

- analysis of fuel cracking and relocation
- definition of the lower boundary for fuel-cladding contact conductance
- insight into the possible statistical variation in behavior that can occur between nominally identical rods
- further insight into the question of enhanced fission gas release with increasing burnup.

ANALYSIS OF FUEL CRACKING AND RELOCATION

Thermal stresses in UO_2 fuel pellets that arise from radial temperature gradients are sufficient to cause cracking of the pellets. Subsequently, the resulting pellet fragments may undergo some limited movement relative to their original positions (relocation). Fuel cracking and relocation can have several effects in a fuel rod:

- increased gap conductance due to decreased fuel-cladding gap width
- decreased effective fuel thermal conductivity due to the presence of cracks
- decreased elastic modulus of UO_2 due to the presence of cracks.

The action of fuel cracking and relocation is reflected through temperatures and cladding deformation (radial and axial). A model has been developed that uses measured fuel centerline temperature and total cladding elastic elongation data to deduce gap conductance, effective fuel thermal conductivity, and elastic moduli (radial and axial).[5]

Because the analysis of relocation is dependent upon measured temperatures, slight shifts in temperature can indicate changes in fuel condition. By using xenon as a fill gas (it has the lowest thermal conductivity of the noble gases), the temperature effect of fuel changes is magnified as compared to helium fill gas. Thus, it may be possible to observe fuel changes that are not as easily observed with helium fill gas.

FUEL-CLADDING CONTACT CONDUCTANCE

The conductance of heat from the fuel to the cladding is principally dependent upon the thermal conductivity of the gas occupying the volume between the fuel and cladding, the distance between the fuel and cladding, and any contact that occurs between the fuel and cladding. Previous assemblies provided data on helium-filled rods with large gaps and closed gaps; the rods in this assembly will provide data on xenon-filled rods with initial gaps of both normal (230 μm) and small size (50 μm). In particular, rod 6, which has a small gap, will have fuel-cladding contact when brought to power; thus, a lower bound on gap conductance under known contact conditions will be established. The uncertainty in fill gas thermal conductivity as a function of burnup is also minimized by using xenon fill gas. Thus, solid conductance may be estimated at higher burnups where fuel swelling and relocation may cause gap closure of the normal gap size rods.

STATISTICAL VARIATIONS

Although fuel rods may be built to the same design specifications and may meet specified tolerances, there will be local variations in dimensions and material properties. The combination of these variations and differences in operating conditions (neutron flux, coolant conditions) may result in different behavior from nominally identical rods. The question may then arise as to whether the observed variation is significant; and in particular, how much difference is there between the observed variation and the anticipated uncertainty in fuel rod performance or predictions of fuel rod performance.

Rods 1 through 5 of IFA-527 are nominally identical; there will be a variation in operating conditions because of an expected radial neutron flux tilt across the assembly (IFA-527 is located at the edge of the core in a low-power region to avoid extreme fuel temperatures caused by the xenon fill gas reducing gap conductance). A comparison of behavior between these rods will provide an estimate of the variation that can be expected between nominally identical rods. Comparison to uncertainties associated with fuel performance code predictions may also prove useful in evaluating uncertainty assessment techniques.[6]

BURNUP-ENHANCED FISSION GAS RELEASE

The increased rate of fission gas release from the fuel matrix as a function of increasing burnup is a concern in fuel rod design. Fission gas release is highly temperature dependent and involves a thermal feedback loop for helium-filled rods: fission gas release degrades fill gas thermal conductivity, which decreases gap conductance, which leads to higher fuel temperatures and thus to more fission gas release. This process can obscure an increasing rate of fission gas release due to burnup effects.

Because IFA-527 fuel rods were initially filled with xenon, temperatures cannot increase due to the above described thermal feedback effect because the release of additional xenon (fission gas) has little effect on heat transfer. Thus, if a near constant power/temperature history is maintained while the rate of fission gas release increases (as indicated by gas pressure measurements), the increase can be attributed to burnup-related effects (i.e., burnup-induced microstructrual changes).

INSTRUMENTED FUEL ASSEMBLY (IFA)-527 DESIGN AND ASSEMBLY FABRICATION

The design of IFA-527 is very similar to that of IFA-431, -432, and -513 and is discussed in this section in three parts: individual rod design, overall assembly design,[a] and fuel rod fabrication. Associated instrumentation will be discussed where appropriate throughout the report.

ROD DESIGN

Five of the six rods in IFA-527 are nominally identical, and rod 6 is similar but with a smaller fuel-cladding gap size. The cladding is annealed seamless Zircaloy-2, and the fuel is compacted and sintered UO_2 of $\sim$95% theoretical density (TD) enriched to 9.90 weight percent (wt%) uranium-235. To reduce flux peaking at the ends of the fuel columns, a poison pellet consisting of 95% natural UO_2 and 5% Dy_2O_3 is located at each end. Table 1 lists rod design parameters, and Table 2 summarizes the as-built dimensions and variations. A general rod design schematic is shown in Figure 1. The pellet stacking order for each rod is presented in Appendix A.

The instrumentation for each rod consists of two fuel centerline thermocouples and a bellows-type pressure transducer. Because the thermocouples (W-3% Re/W-25% Re with BeO insulators) are located in both the lower (near the neutron flux peak) and upper ends of the fuel rods (see Figure 1), they provide temperature measurements at two power levels. The power level at the upper thermocouple is approximately 75% of the power at the lower thermocouple. The pressure transducer is connected to the plenum and automatically provides continuous pressure measurements.

Assumed measurement uncertainty for the fuel thermocouples is $\pm$3% for temperatures less than 2473K.[7] This includes calibration, instrumentation, and some irradiation effects at low burnup. The uncertainty will increase with burnup due to decalibration caused by neutron irradiation. The pressure transducers are quoted by Halden to have an uncertainty of $\pm$1.5% at 0.2 MPa.

(a) Halden has supplied PNL with copies of the design drawings for the fuel rods, instrumentation, and supporting hardware.

TABLE 1. Instrumented Fuel Assembly (IFA)-527 Rod Design Parameters

Cladding:[a]	Material	Zircaloy-2
	Outer Diameter	12.789 mm
	Inner Diameter	10.909 mm
Fuel:	Material	UO_2
	Enrichment	9.90 wt% ^{235}U
	Density	95% theoretical
	Diameter	10.681 mm (rods 1 through 5) 10.833 mm (rod 6)
	Pellet Length	12.7 mm
Poison Pellets:	Material	95% natural UO_2, 5% Dy_2O_3
	Diameter	10.2 mm
	Length	7.0 mm
Fill Gas:	100% Xe at 0.1 MPa	

(a) See Appendix A of BNWL-1988 for cladding certification.

TABLE 2. As-Fabricated Dimensions and Variances for Instrumented Fuel Assembly (IFA)-527

Rod No.	Pellet Length, mm ±1σ	Pellet Diameter, mm ±1σ	Theoretical Density,[a] % ±1σ
1	12.609 ±0.088	10.681 ±0.004	95.04 ±0.154
2	12.616 ±0.083	10.683 ±0.004	95.04 ±0.209
3	12.680 ±0.068	10.681 ±0.003	94.93 ±0.199
4	12.718 ±0.083	10.683 ±0.004	94.82 ±0.121
5	12.662 ±0.136	10.683 ±0.003	94.89 ±0.147
6	12.852 ±0.112	10.864 ±0.002	95.35 ±0.095

Rod No.	Enriched Fuel Weight,[b] g	Enriched Fuel Length,[b] mm	Total Fuel Length,[c] mm	Plenum Length,[d] mm
1	717.5	776.2	792.9	32.3
2	715.5	773.7	792.2	32.4
3	716.5	775.5	793.0	32.2
4	717.5	777.4	792.5	33.1
5	719.0	777.6	793.0	31.8
6	739.5	770.3	790.0	33.3

(a) Geometric density.
(b) Reported by Halden, excludes poison pellets.
(c) Reported by Halden, includes poison pellets.
(d) Top of fuel stack to end of cladding (accuracy is 0.1 to 0.2 mm).

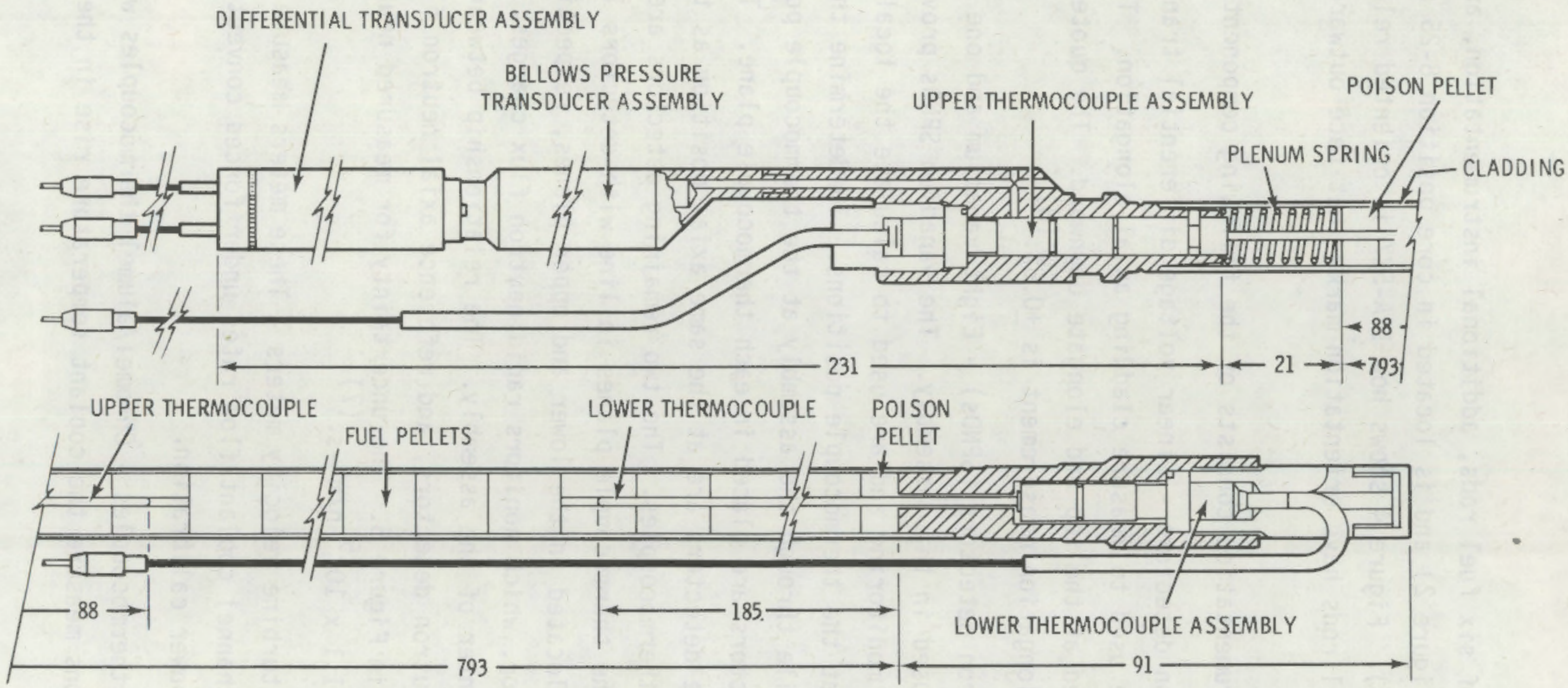


FIGURE 1. Schematic Arrangement of Fuel Rod for Instrumented Fuel Assembly (IFA)-527 (fabricated dimensions are in mm)

ASSEMBLY DESIGN

IFA-527 consists of six fuel rods, additional instrumentation, and supporting hardware (see Figure 2) and is located in core position 8-25 of the HBWR core (see Figure 3). Figure 4 shows how IFA-527 is oriented relative to the core centerline; all rods have orientation marks that face outward from the assembly center.

The assembly instrumentation consists of the following components:

- cladding elongation detectors - Linear voltage differential transducers (LVDTs) are used to measure cladding axial elongation. The fuel rods are fixed at the top and elongate downward. The quoted uncertainty for elongation measurement is $\pm 0.6\%$.[8]

- self-powered neutron detectors (SPNDs) - Eight vanadium and one cobalt SPNDs are used in this assembly. The vanadium SPNDs provide steady-state flux monitoring and are used to calculate the local linear heat rate at the thermocouple positions. To determine the neutron flux profile through the assembly at the thermocouple positions, three detectors are placed in each thermocouple plane. The centerlines of the detectors are at the same axial position as the junctions of the thermocouples. The two remaining detectors are located between the thermocouple planes in line with detectors 1 and 6, which are located in the lower and upper planes, respectively. The cobalt detector, which monitors rapid neutron flux changes, is located in the center of the assembly. The relationship between the thermocouples, neutron detectors, and reference axial neutron flux profile is shown in Figure 5. The uncertainty for measured neutron flux is $\pm 3.0\%$ at 1.1×10^{15} n/m^2-s.[7]

- inlet and outlet turbine velocity meters - These meters measure inlet and outlet fuel channel coolant flow rates under forced convection during assembly power calibration.

- inlet and outlet thermocouples - Chromel/alumel thermocouples with insulated junctions measure the coolant temperature rise in the fuel channel.

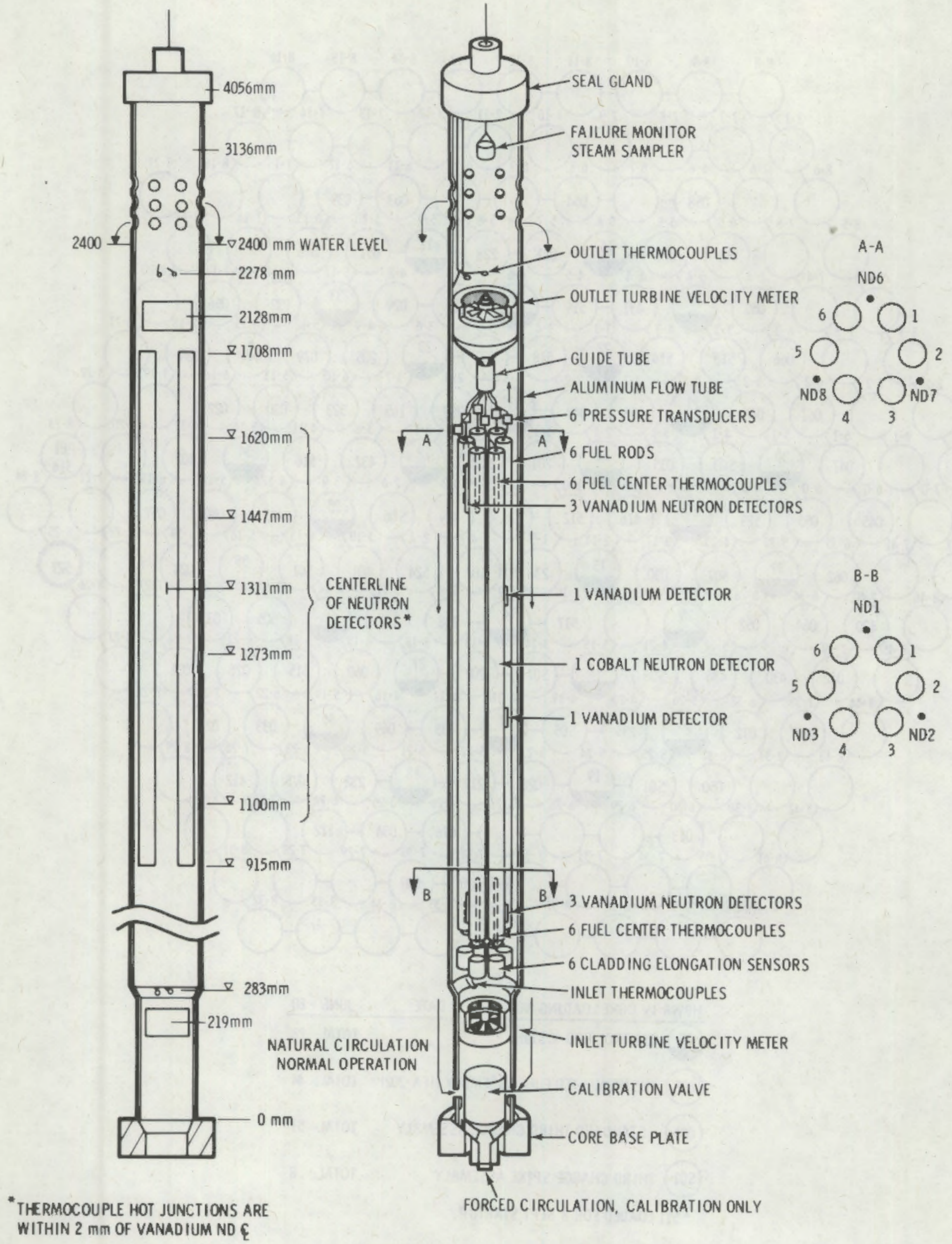


FIGURE 2. Schematic of Instrumented Fuel Assembly (IFA)-527 (neutron detectors 4 and 5 are in line with detectors 1 and 6; not drawn to scale)

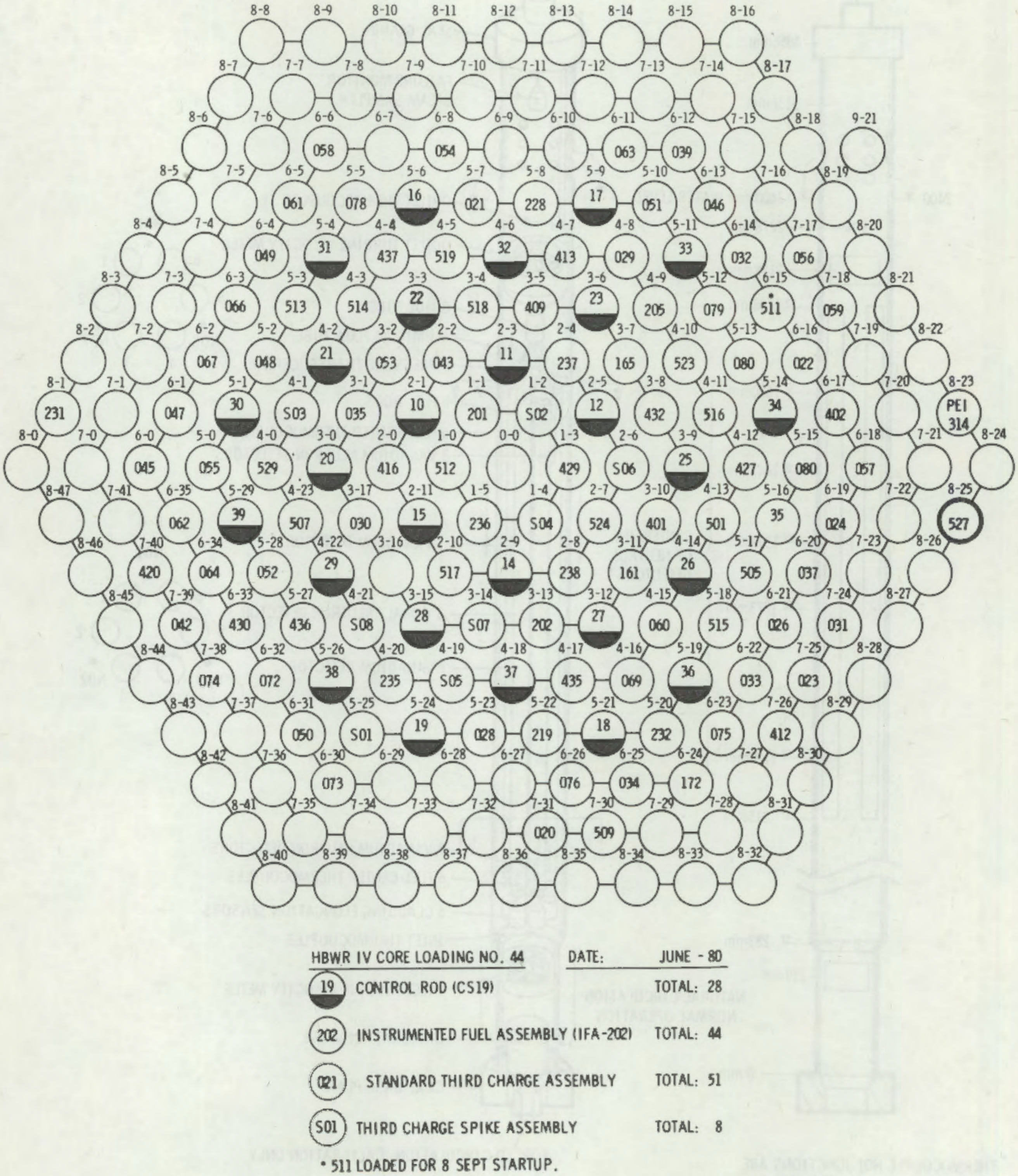


FIGURE 3. HBWR Core Loading No. 44, June 1980

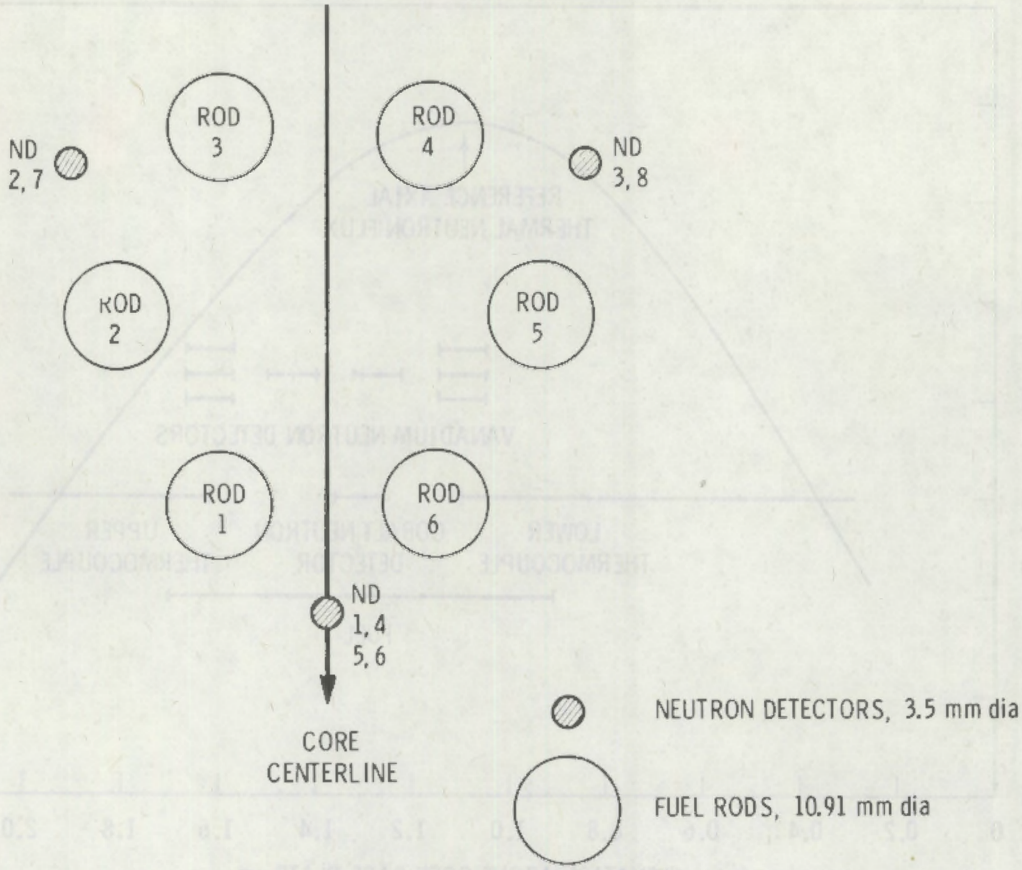


FIGURE 4. Orientation of Instrumented Fuel Assembly (IFA)-527 Relative to Core Centerline

The four photographs in Figure 6 were taken after IFA-527 was fabricated. The designations on the photographs are defined below:

- 527-X - X designates which fuel rod is pictured
- PF-X and TRAFO - fuel rod internal gas pressure bellows and rod pressure LVDTs, respectively (operate as one unit)
- TF-X - fuel thermocouple assembly
- ND-7 - vanadium neutron detector 7, located at top of assembly
- EC-X - LVDT for measuring cladding axial elongation.

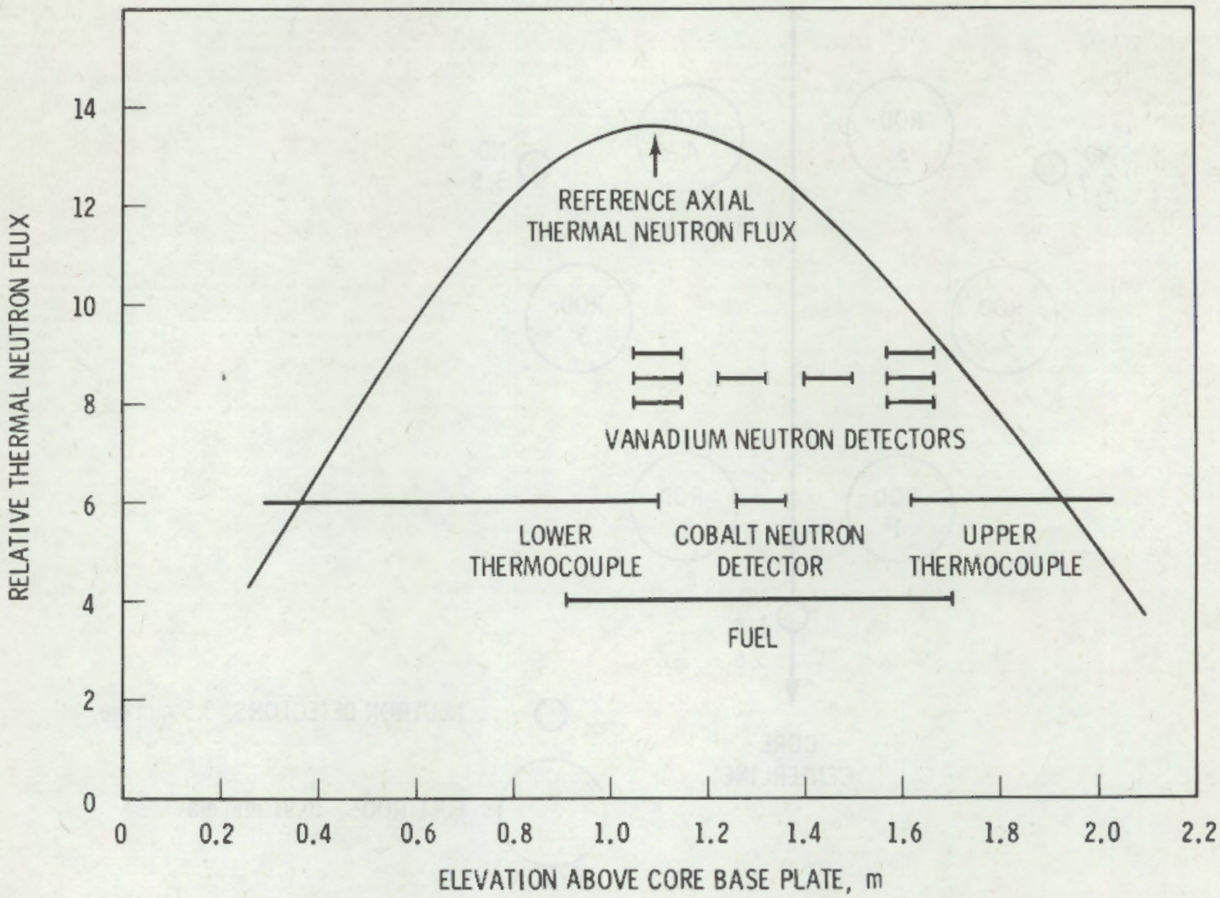
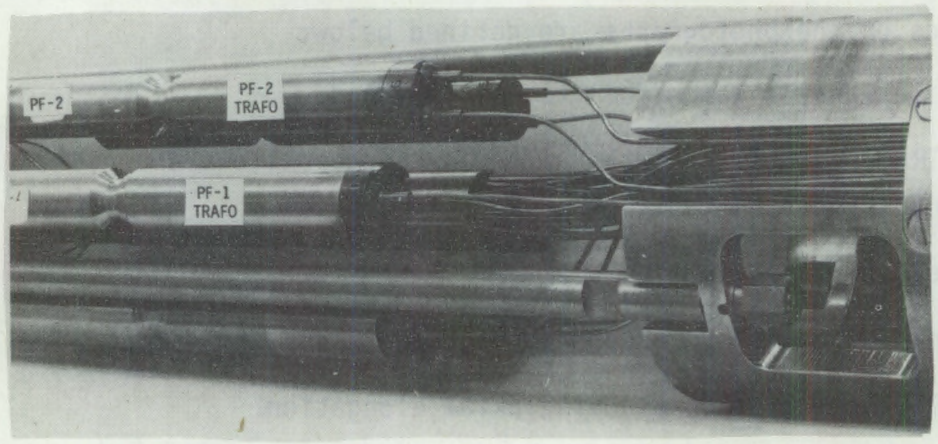
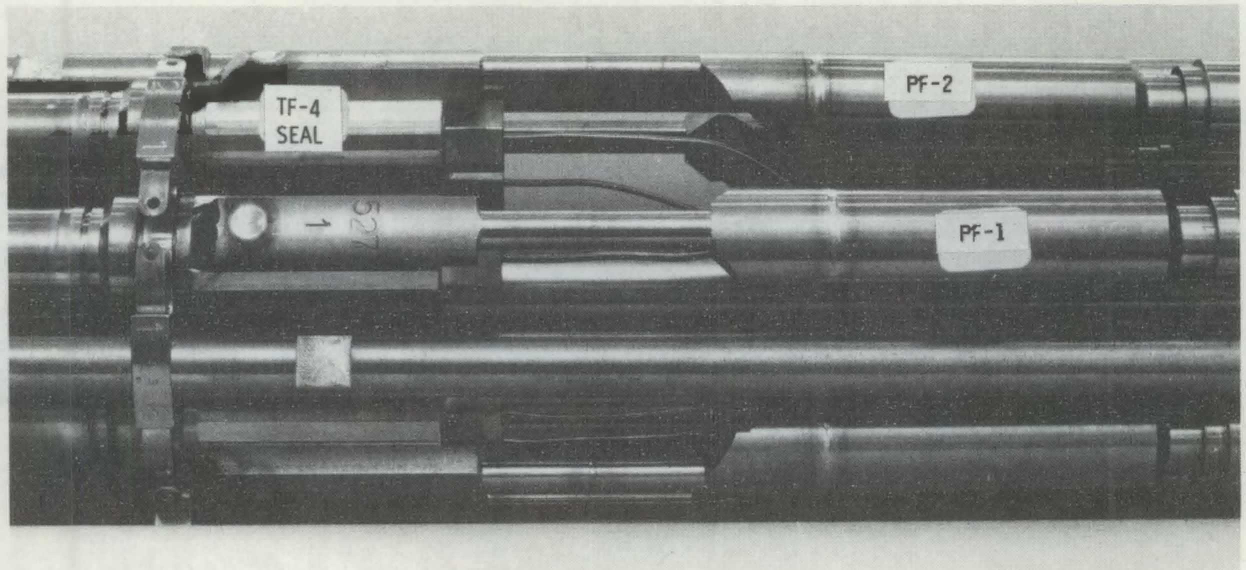


FIGURE 5. Arrangement of Fuel and Instruments Relative to Reference Axial Thermal Flux Profile

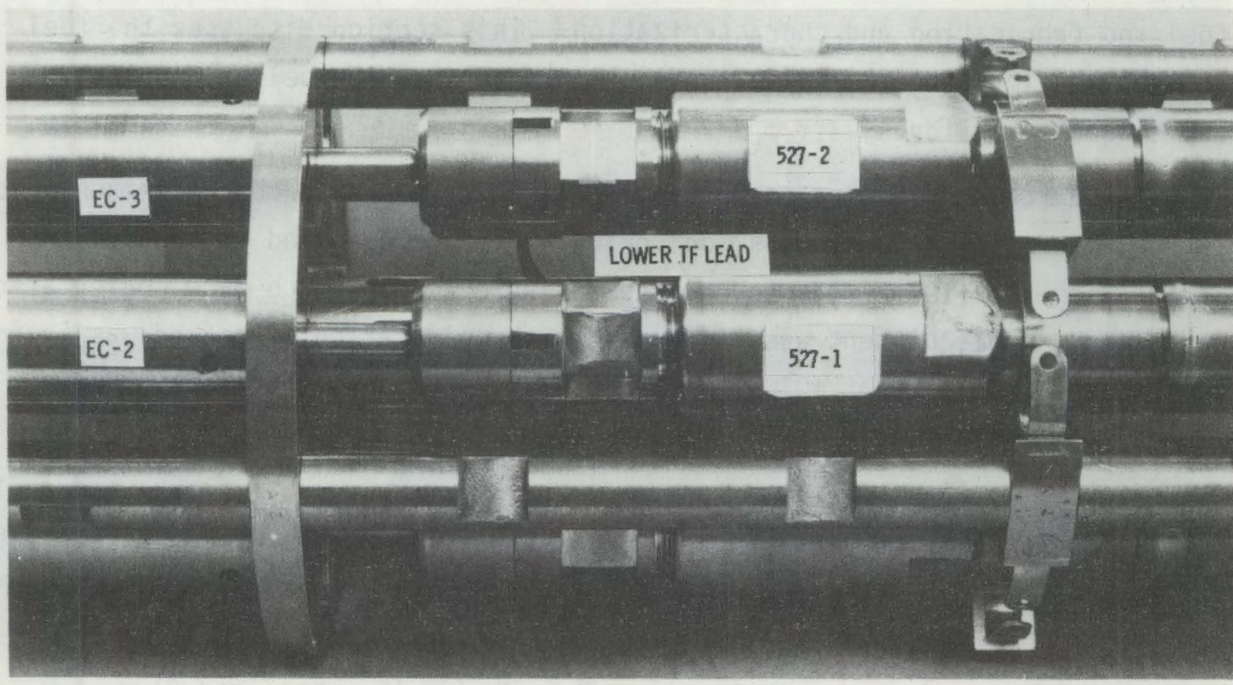


(a) Upper end of assembly showing gas pressure bellows and differential transducer assemblies

FIGURE 6. Completed Instrumented Fuel Assembly (IFA)-527

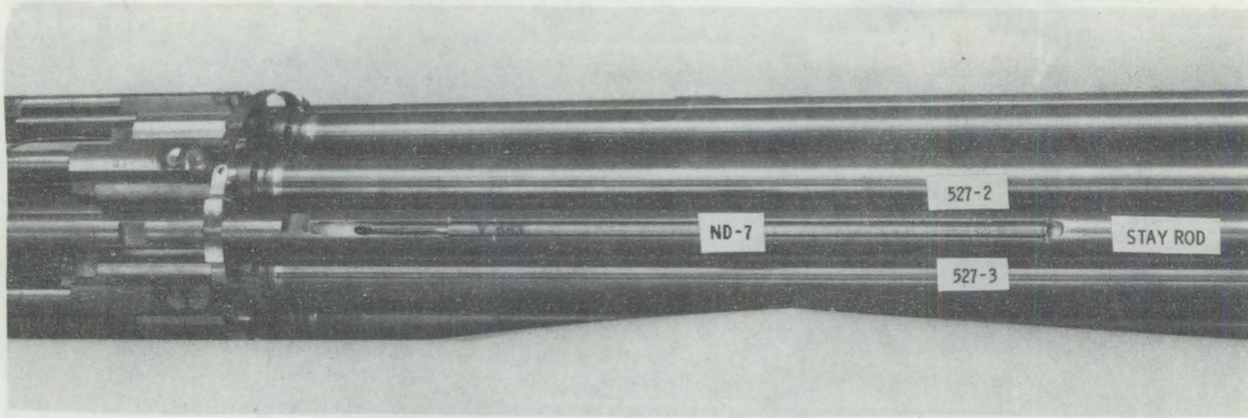


(b) Upper end of assembly showing upper ends of rods



(c) Lower end of assembly showing lower ends of rods and elongation sensors

FIGURE 6. (Contd)



(d) Vanadium neutron detector and fuel rods

FIGURE 6. (contd)

FUEL ROD FABRICATION

The fuel pellets were fabricated and characterized at PNL and were then shipped to the Institutt for Atomenergi's laboratory in Kjeller, Norway, for fuel rod fabrication and characterization. This section discusses the fuel rod fabrication, and the following section describes the pellet fabrication and characterization.

The Zircaloy-2 tubing to be used as cladding was also characterized prior to fuel loading. A continuous monitoring air gauge was used to measure the inside diameter (ID) of the tubes, and a single linear trace at 0° orientation was taken. The equipment was calibrated with calibration rings and was found to have a sensitivity of ±0.002 mm. Appendix B contains the profilometry traces of the cladding.

The first step in the fuel rod fabrication process was to clean the fuel pellets with alcohol and then dry them in vacuum at 623K for 1 h. Assembly of the fuel rods began with the loading of the fuel and the thermocouples. During loading, the lower thermocouple tips were positioned 185 mm above the lower end plug; the upper thermocouple tips, 88 mm below the upper end plug.

After welding the lower end plug to the cladding, the plenum length was measured (see Table 2); and the plenum spring (Figure 7) and bearing disk were inserted. Next, the upper end plug and bellows pressure transducer assembly were welded to the fuel rod. The free volume within the fuel rod was then measured by a method using a silicon oil manometer with the following results:

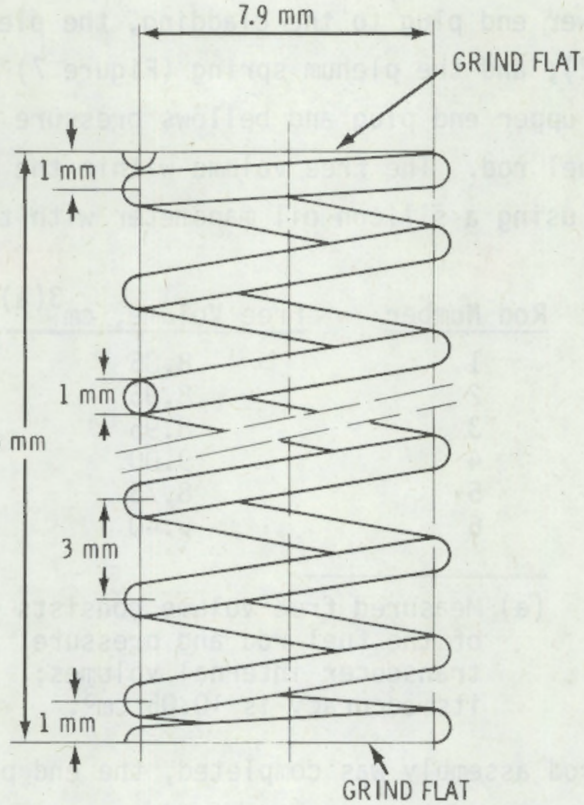
Rod Number	Free Volume, cm^3 [a]
1	8.85
2	8.95
3	8.95
4	9.00
5	8.75
6	6.40

(a) Measured free volume consists of the fuel rod and pressure transducer internal volumes; its accuracy is $\pm 0.05\ cm^3$.

After the fuel rod assembly was completed, the end plugs, seal welds, and the active fuel length were x-ray inspected; no faults were found. As a final check for fuel rod integrity, a helium mass spectrometer with a sensitivity of $2 \times 10^{-10}\ cm^3/s$ at standard temperature and pressure (STP) was used to measure helium leakage; no leakage was found.

To complete the assembly of the fuel rods, the rods were evacuated and refilled with xenon and the vent holes in the end plugs were welded shut. The nominal gas composition in volume percent (vol%) for xenon fill gas was:

Fill Gas Components	Volume Percent
Xenon	99.99
Krypton	0.01
Nitrogen	0.002
Oxygen and Argon	0.0003
Hydrogen	0.0001
Hydrocarbons	0.0002
H_2O	0.0002



TO BE HARDENED:
650°C FOR 4 HOURS
THEN COOLING IN AIR

VOLUME = 0.156 cm^3

MATERIAL = INCONEL x 750, COLD DRAWN

NUMBER OF TURNS = 8

FIGURE 7. Details of Plenum Spring

Electron beam welding in a vacuum (1.3 x 10^{-2} Pa) was used for all welds except for those at the vent holes in the end plugs, which were closed by tungsten inert gas (TIG) welding. Prior to welding, all surfaces were cleaned with xylol[(a)] and alcohol.

(a) Xylol is the Norwegian equivalent of xylene (C_8H_{10}).

FUEL FABRICATION AND CHARACTERIZATION

The pellet fabrication process for IFA-527 included acquisition of the UO_2 powder, sinterability tests, pellet fabrication, pellet certification, and pellet physical measurements. Microstructural characterization of porosity and grain size and out-of-reactor thermal conductivity measurements were also conducted.

FUEL FABRICATION

The fuel pellets for IFA-527 and -513 were fabricated from enriched UO_2 ceramic-grade powder obtained from Oak Ridge National Laboratory (ORNL). This powder was obtained under PNL Purchase Order 10990-AY and originated from ORNL Mfg. Batch No. 30-2785. When the powder was received, the containers were inspected and net weights were confirmed. It was then sampled and analyzed, and the data provided by ORNL was confirmed. After the analytical data was reviewed, a UO_2 Powder Certification of Compliance Quality Control Release was approved and the powder was released for pellet production. Appendix C of PNL-3156 contains details of the UO_2 powder acquisition.

One preproduction sinterability test was performed prior to pellet production runs to evaluate the ability of the furnace to successfully sinter a 4-kg batch of pellets made with depleted UO_2 powder. Pellets of the 10% enriched powder used for Halden test pellets were also included in the test; these 24 pellets determined IFA-527 production parameters. This test was successful and cleared the way for the production of pellets for IFA-527. The test plan, data, and conclusions may be found in Appendix C along with the pellet production process parameters, sintering data, and chemical analysis of the completed fuel pellets.

Specifications for IFA-527 pellets and their required characterization are presented in Table 3, and the following list outlines the procedure used to manufacture the fuel pellets:

- powder reduced to -100 mesh
- powder slugged to 4.3 $\pm$0.1 g/cm^3 density
- powder granulated to -20 mesh

- powder blended with 0.3 ±0.1 wt% sterotex
- powder pressed to pellets of 5.15 ±0.05 g/cm^3 density (5.45 g/cm^3 for larger pellets)
- pellets identified by numbering while in green condition
- pellets sintered in a hydrogen atmosphere from room temperature (RT) to 1173K and in half hydrogen and half argon for remainder of sintering (1173-1973K, 1973K for 8 h)
- pellets preinspected
- pellets centerless ground to specified diameter of 0.4205 or 0.4275 ±0.0005 in.[(a)]
- final chemical analysis of the pellets was made (Table 4).

Before the pellets were given final cleaning and shipped to Halden, they were inspected and dimensional measurements were taken. All pellets were checked in the following manner, and the data was recorded.

- visual defects - The PNL visual standard for UO_2 fuel pellets (shown in Figure 8) was used to inspect for chips and cracks.
- diameter - Measurements to the nearest 0.0001 in. were made at three positions: near each end and at the center. All pellets used in IFA-527 met the specified tolerance of ±0.0005 in.
- length - Each pellet was measured to the nearest 0.0001 in. at two locations.
- weight - Each pellet was weighed to the nearest 0.001 g.
- density - The geometric density for all pellets was determined from the measured weight and average length and diameter for each pellet. The density of the archive pellets was also determined by a liquid immersion technique: water was used as the suspension medium.[(b)] Geometric densities are lower than immersion densities because the measured volume is not reduced to account for surface roughness and chips and is therefore greater than the true volume.

(a) Dimensions are as specified in inches.
(b) The immersion density technique is described on pages 7-2 and 7-4 of BNWL-1988

TABLE 3. Pellet Specifications and Required Characterization for Instrumented Fuel Assembly (IFA)-527

SPECIFICATIONS

Pellet Diameter	0.4275 ±0.0005 or 0.4205 ±0.0005 in.[(a)]
Pellet Length	0.500 ±0.015 in.
Pellet Density	95 ±0.5 %TD (stable structure)
ID of Thermocouple Hole	0.067 to 0.071 in.
Pellet Geometry	Flat ended
Enrichment	Nominal 10% ^{235}U
Powder	ASTM standard specification for nuclear-grade, sinterable uranium dioxide powder (C753-73)
Pellet Defects and Cleanliness	PNL visual standard, ultrasonic plus forced air dry

PELLET CHARACTERIZATION

Dimension	Technique Used	Precision	Frequency, %
Outer Diameter	Cross ends and center	0.0001 in.	100
Inner Diameter	Go/no-go	--	100
Length	Two locations 180° apart	0.0001 in.	100
Density - Geometric			
Weight	Analytical balance	0.001 g	100
Density	Calculated	±0.01 g/cm^3[(b)]	100
Density - Immersion		±0.01 g/cm^3[(b)]	100[(c)]

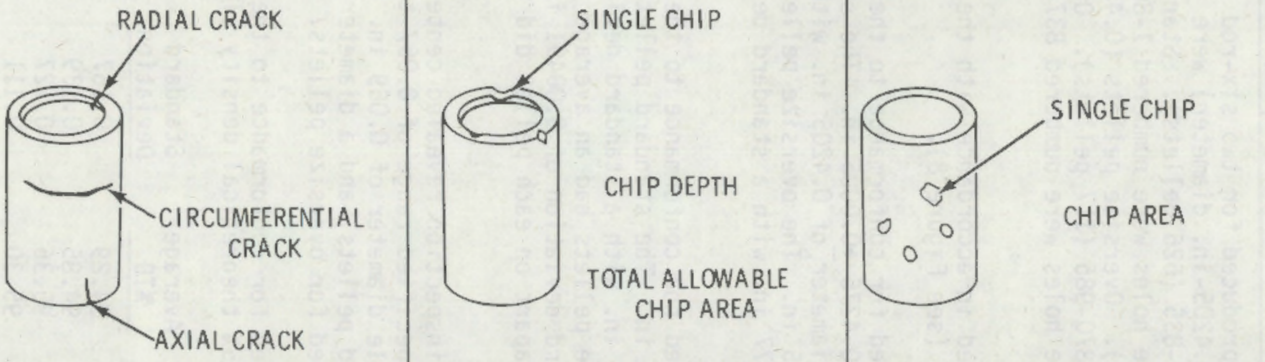
(a) Units are reported as measured.
(b) Reported to three significant figures.
(c) Archive pellets.

TABLE 4. Summary of Chemical Analysis for Instrumented Fuel Assembly (IFA)-527

Fuel Makeup	Requirement[(a)]	Results for Sample DB-122
Uranium-235, %	10.0 ±0.2	9.84 ±0.05
Uranium, %	87.7 wt% minimum	88.08
Oxygen/Uranium Ratio	1.99/2.02	2.004
EBC[(b)]	4	3.8
Gas Content	0.05 cm^3/gU maximum	0.007
Aluminum	250	<50
Carbon	100	33
Calcium + Magnesium	200	100 + <10
Chlorine	25	<10
Chromium	250	30
Cobalt	100	0.2
Fluorine	15	<5
Hydrogen[(c)]	2	<5
Iron	500	100
Nickel	250	50
Nitrogen	75	<10
Silicon	250	<60
Thorium	10	40

(a) Except for % ^{235}U requirements are based on ASTM specification C753-73. Units are maximum allowable µg/gU, except where noted.
(b) Equivalent boron content.
(c) Including H_2O.

Table 5 summarizes inspection results; Appendix A contains the measured data for all pellets and the immersion density results for the archive pellets.



SURFACE CRACKS SHALL NOT EXCEED THE FOLLOWING LIMITS	END CHIPS SHALL NOT EXCEED THE FOLLOWING LIMITS (SAME LIMITS ON NON-DISHED PELLETS)	CIRCUMFERENTIAL CHIPS SHALL NOT EXCEED THE FOLLOWING LIMITS
1. END RADIAL CRACKS $\geq$ 25% OF DIAMETER	1. SINGLE CHIP $\leq$ 10% OF LAND AREA	1. SINGLE CHIPS SHALL NOT EXCEED 3% OF SURFACE AREA
2. CIRCUMFERENTIAL CRACKS 180^0	2. TOTAL CHIPPING < 25% OF LAND AREA	2. TOTAL SURFACE OF CHIPS SHALL NOT EXCEED 10% OF SURFACE AREA
3. AXIAL CRACKS SHALL NOT EXCEED 25% OF PELLET LENGTH	3. CHIP DEPTH SHALL NOT EXCEED 0.020 in.	3. DEPTH 0.020 in.
4. MICRO CRACKING IS ACCEPTABLE		

INSPECTION SHALL REJECT ANY "BORDER-LINE" QUESTIONABLE PELLET

FIGURE 8. PNL Visual Standards for UO_2 Fuel Pellets

TABLE 5. Summary of Fuel Pellet Specifications and Inspection Results for Instrumented Fuel Assembly (IFA)-527

Pellet Characteristic or Attribute	Quality Control Specification[a] and Inspection Results
Summary	Sufficient pellets were produced for two six-rod assemblies. Standard-size pellets (0.4205-in. diameter) were numbered 81-319, 400-640, and 690-835 (626 pellets). Standard-size pellets with thermocouple holes were numbered 1-80, 320-399, and 641-689 (209 pellets). Oversize pellets (0.4275-in. diameter) were numbered 870-986 (117 pellets). Oversize pellets with thermocouple holes were numbered 837-869 (33 pellets).
Visual Inspection of Chips and Cracks	All pellets were inspected in accordance with the applicable PNL visual standard (see Figure 8).
Pellet Diameter	All pellets were inspected for conformance to the specifications of 0.4205 and 0.4275 ±0.0005 in. The standard pellets had an average diameter of 0.4205 in. with a standard deviation of 0.00015 in. The oversize pellets had an average diameter of 0.4277 in. with a standard deviation of 0.00012.
Pellet Length	All pellets were inspected for conformance to the specification of 0.500 ±0.015 in. The standard pellets had an average length of 0.4985 in. with a standard deviation of 0.00384 in. The oversize pellets had an average length of 0.5008 in. with a standard deviation of 0.00491 in. Two measurements taken 180° apart on each pellet did not vary more than 0.001 in.
Pellet Centerline Hole	100% attribute go/no-go inspection revealed centerline holes to be within the specified range of 0.067 to 0.071 in. An average hole diameter of 0.069 in. has been assumed for standard pellets, and a diameter of 0.070 in. has been assumed for oversize pellets.
Pellet Geometric Calculated Density	All pellets were inspected for conformance to the specification of 95% ±0.5% theoretical density (TD).

Pellet Type	Average %TD	Standard Deviation
Standard without hole	94.29	0.167
Standard with hole	94.85	0.139
Oversize without hole	95.36	0.127
Oversize with hole	95.30	0.111

Pellet Characteristic or Attribute	Quality Control Specification[a] and Inspection Results
Pellet Water Immersion Density	All archive pellets were immersion density checked. The average density for the standard pellets was 95.59% TD, and the average density for the oversize pellets was 96.25% TD.

(a) Dimensions are repeated here as specified and measured.

FUEL CHARACTERIZATION

Since the experimental data to be obtained from IFA-527 will be correlated with data from IFA-431, -432, and 513, it is important to understand the microstructural characteristics of the fuel. The fuel for IFA-527 was specified to be similar to the 95% TD stable UO_2 fuel of IFA-432 and was made from the same powder as IFA-513. The characterization plan was therefore mainly aimed at comparing the key microstructural characteristics (pore volume, pore size distribution, and grain size) of the 95% TD stable UO_2 used in IFA-527 to that used in IFA-431, -432, and -513. Checks on thermal resintering and thermal conductivity were also conducted to confirm the assumption of similarity to IFA-431 and -432.

Experimental Procedure

The methods and procedures used to characterize the IFA-527 fuel pellets followed the same philosophy used for IFA-431 and -432 and reported in BNWL-1988. Measurements were taken to determine pore size and volume distribution as well as average grain size as a function of radial location.

Based on experience with the fuel used in IFA-431 and -432, minor changes were made in testing and measurement procedures. Rather than providing a complete data reference base, these data are intended primarily as verification that the fuel pellets met their design criteria. Three pellets whose bulk density measurements were approximately the average value for the pellets loaded in the assembly were selected from the assembly fuel lot. Each pellet was sectioned transversely at its midpoint, encapsulated in epoxy resin, and polished by the procedure described in BNWL-1988. Special care was taken to minimize physical pullout of grains or UO_2 particles. Light microscopy was used to examine the as-polished surfaces for pores larger than 2 μm. Carefully controlled vacuum cathodic etching removed surface debris from submicron porosity; smaller pores were examined by scanning electron microscopy at the same sites on the polished surfaces. Grain sizes were recorded on the same surfaces after etching more vigorously (using H_2O_2-H_2SO_4) to reveal grain boundaries clearly.

The microscopy, porosity measurements, computation of porosity characteristics, and determination of grain size were all conducted as reported in BNWL-1988. The following sites were specified for porosity study on each of the pellet sections: two peripheral, two midradius, and one center radial location. Data from all three pellets (15 sites) was combined to obtain "average" properties. Grain size data was obtained from measurements made with photomicrographs taken at a peripheral, midradius, and central area on each pellet.

Porosity Evaluation

The general pore size and volume distributions for IFA-527 (as sintered) are similar to those of IFA-431, -432, and -513. The general nature of the porosity may be seen in the typical microstructures shown in Figure 9.

Table 6 and Figure 10 provide an overall summary of the microstructures; the porosity normally varied randomly throughout the pellets within the ranges shown.

Although the fuel for IFA-527 is generally similar to that for IFA-431 and -432, there is a significant difference (see Figure 10). A well-defined small volume component of porosity occurs centered at about 1-μm diameter, while the large-diameter porosity peak (>10 μm) tends to broaden toward larger pore sizes. The overall effect on pore volume is small, however, as shown by the data in Table 6. The increase in the submicron porosity component is small and would not be expected to have a significant effect on fuel behavior. The influence of porosity on the behavior of all four IFAs is expected to be similar.

The pellets for IFA-527 and -513 were fabricated from the powder shown in Figure 11. Pretreatment of the as-received powder resulted in rounded agglomerated particles averaging approximately 25 to 50 μm in diameter (upper photos in Figure 11). Close examination of the large particle structure reveals that they are composed of close-packed, randomly shaped particles approximately 0.1-0.2 μm in diameter (lower photos in Figure 11). This combination of agglomerated particles permitted sintering to high density with some control over retained porosity. No IFA-431 or -432 powder samples were available for comparison.

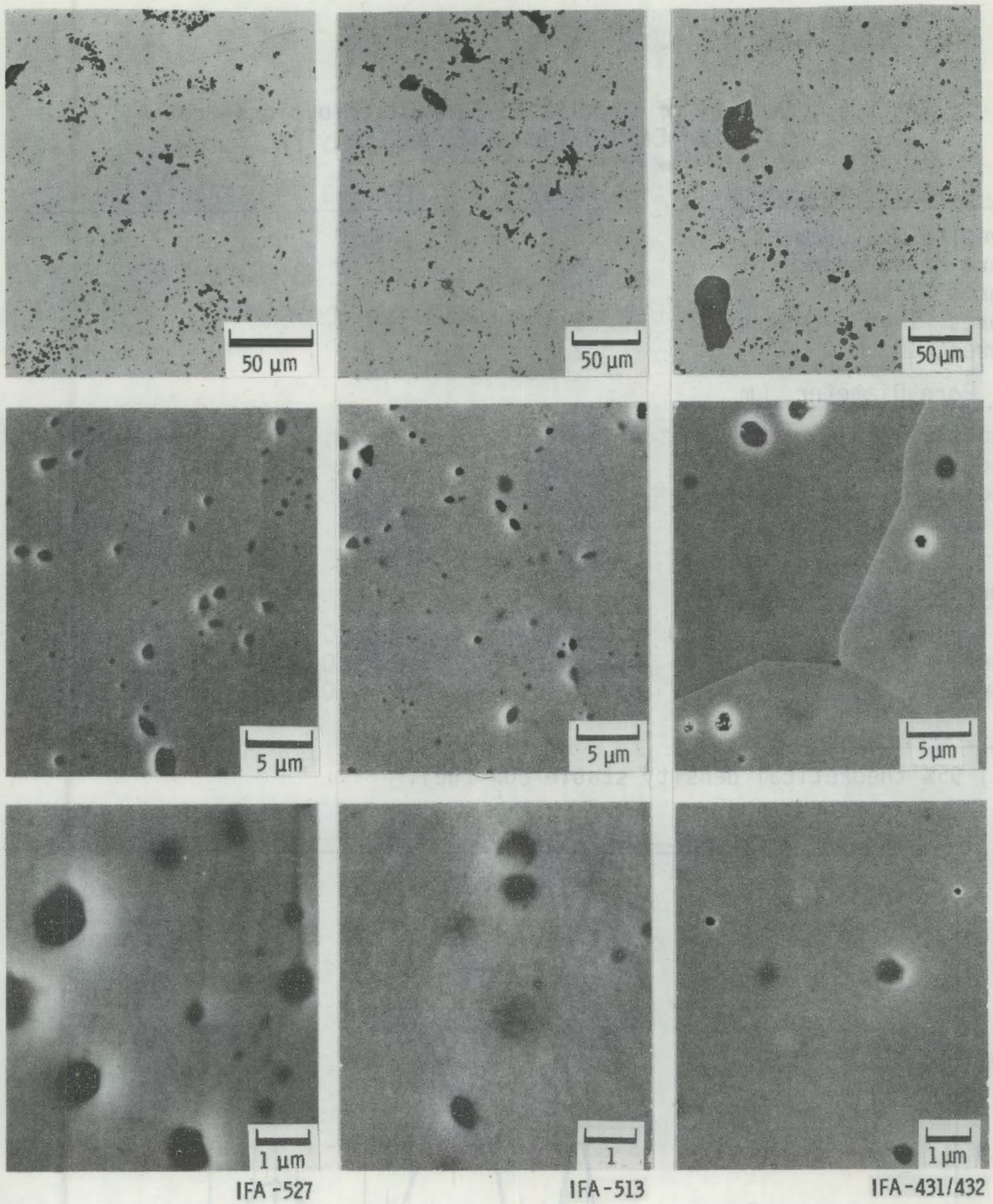
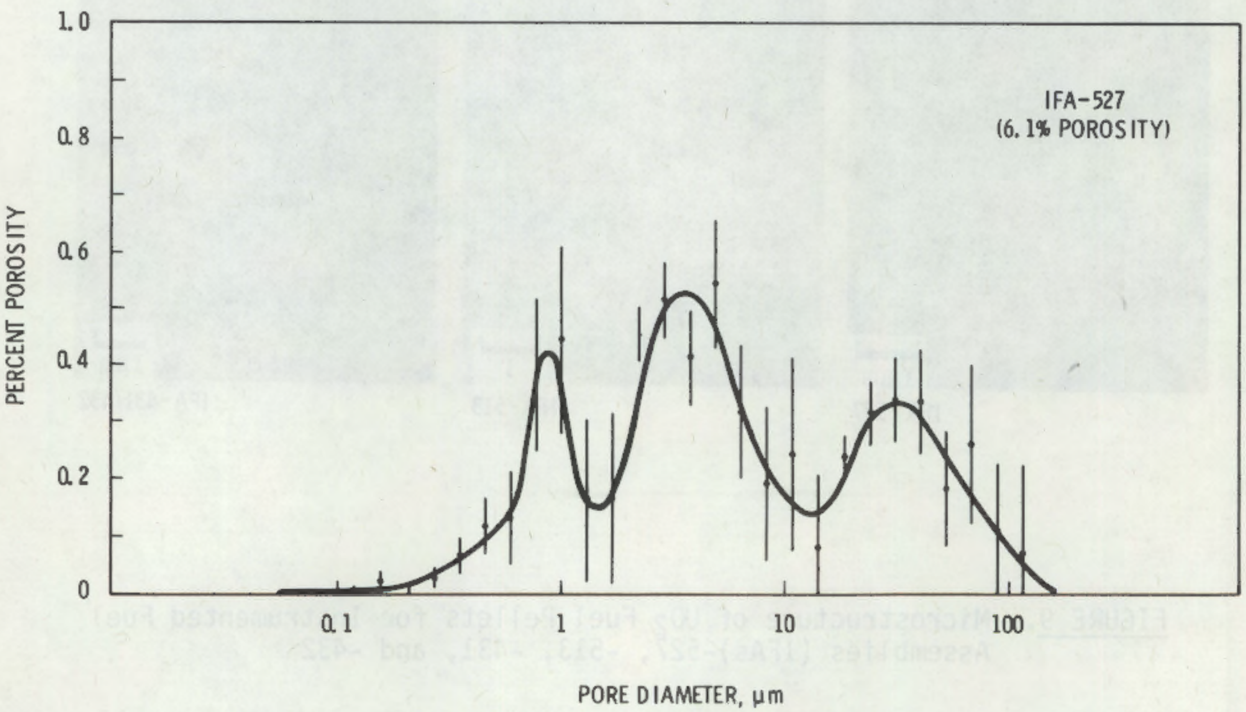


FIGURE 9. Microstructure of UO_2 Fuel Pellets for Instrumented Fuel Assemblies (IFAs)-527, -513, -431, and -432

TABLE 6. Summary of Calculated Pore Distributions from All Data for Each Halden Fuel Assembly[a]

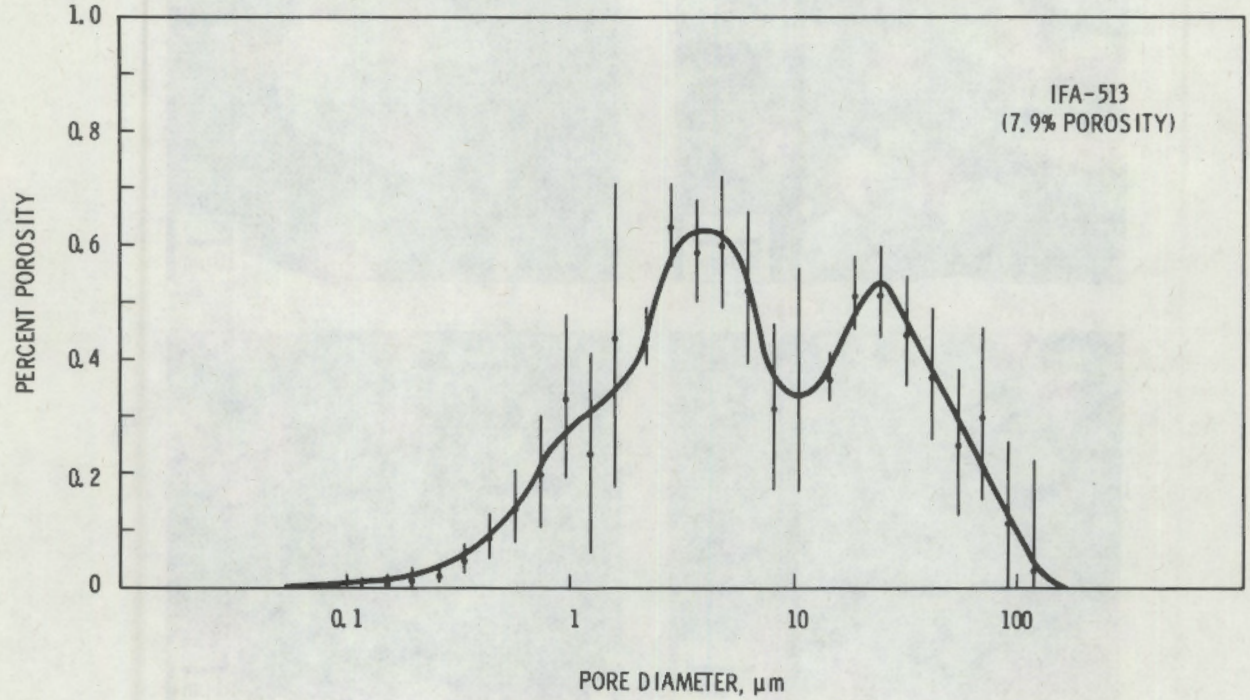
Porosity Volume, %	IFA-527	IFA-513	IFA-431 and -432
Density Measurement	5.1	5.0	4.4
Pore Measurement	6.1	7.9	6.7
Pores < 1 μm	0.7	0.6	0.6
Pores >1 μm	5.4	7.3	6.1
Pores >10 μm	2.2	3.3	1.8
Pore Diameter, μm			
Median, Total	5.6	7.3	5.1
Median, <1 μm	0.7	0.7	0.6
Median, >1 μm	5.6	7.3	5.1
Median, >10 μm	36	28	32
Maximum	114	119	101
Pore Population, No./cm^3			
All Pores	3.3×10^{11}	2.4×10^{11}	2.4×10^{11}
Pores >1 μm	7.8×10^9	7.6×10^9	6.3×10^9
Pores >10 μm	5.0×10^6	8.3×10^6	4.5×10^6

(a) 95% theoretical density stable UO_2 fuel.

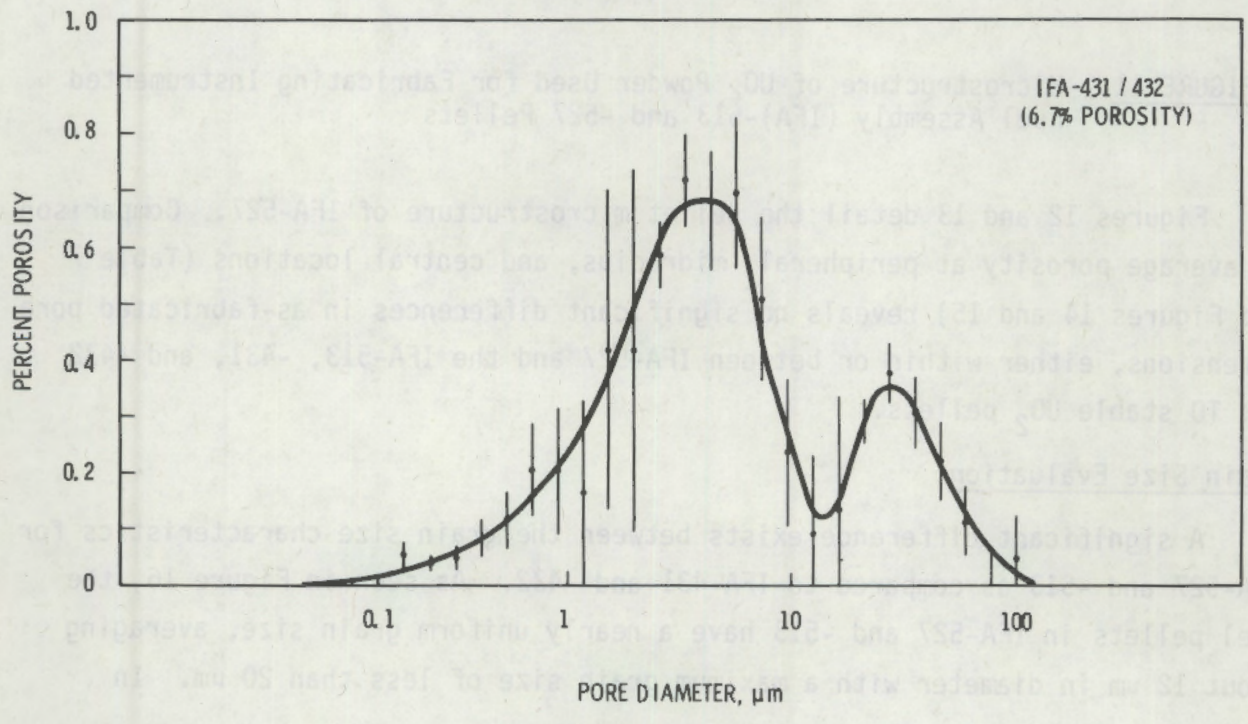


a) IFA-527

FIGURE 10. Pore Size and Volume Distribution for 95% TD Stable UO_2 Fuel Used in IFA-527, -513, -431, and -432 (vertical lines indicate 2σ confidence limits at midpoint of each size range)



b) IFA-513



c) IFA-431/432

FIGURE 10. (contd)

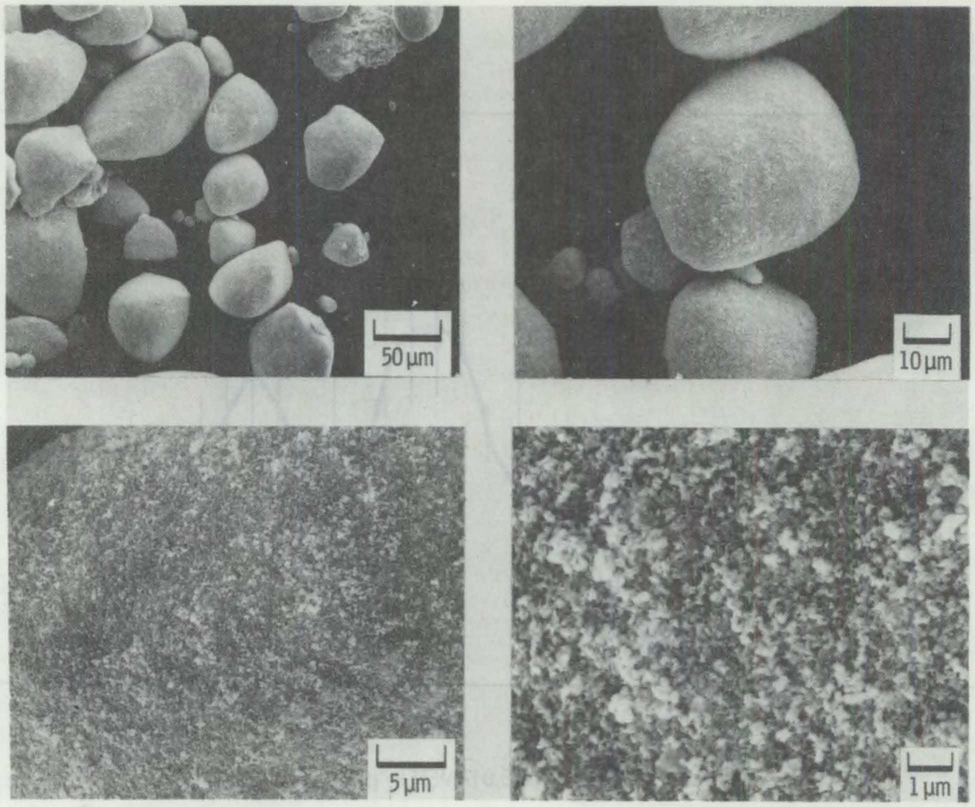
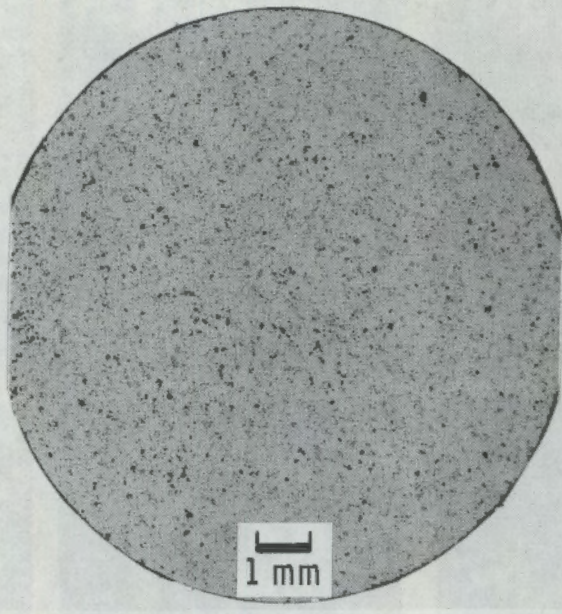


FIGURE 11. Microstructure of UO_2 Powder Used for Fabricating Instrumented Fuel Assembly (IFA)-513 and -527 Pellets

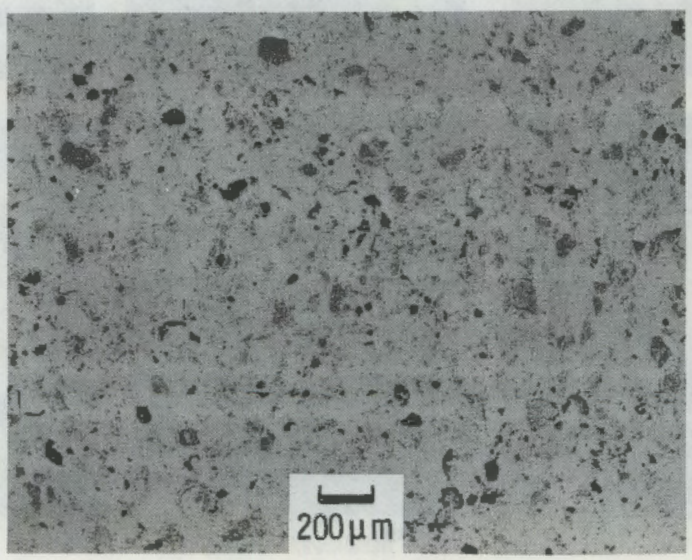
Figures 12 and 13 detail the pellet microstructure of IFA-527. Comparison of average porosity at peripheral, midradius, and central locations (Table 7 and Figures 14 and 15) reveals no significant differences in as-fabricated pore dimensions, either within or between IFA-527 and the IFA-513, -431, and -432 95% TD stable UO_2 pellets.

Grain Size Evaluation

A significant difference exists between the grain size characteristics for IFA-527 and -513 as compared to IFA-431 and -432. As seen in Figure 16, the fuel pellets in IFA-527 and -513 have a nearly uniform grain size, averaging about 12 µm in diameter with a maximum grain size of less than 20 µm. In



TRANSVERSE SECTION NEAR PELLET CENTER



TYPICAL AREA OF TRANSVERSE SECTION

FIGURE 12. General Porosity Characteristics of 95% TD Stable UO_2 Pellets Used in Instrumented Fuel Assembly (IFA)-527

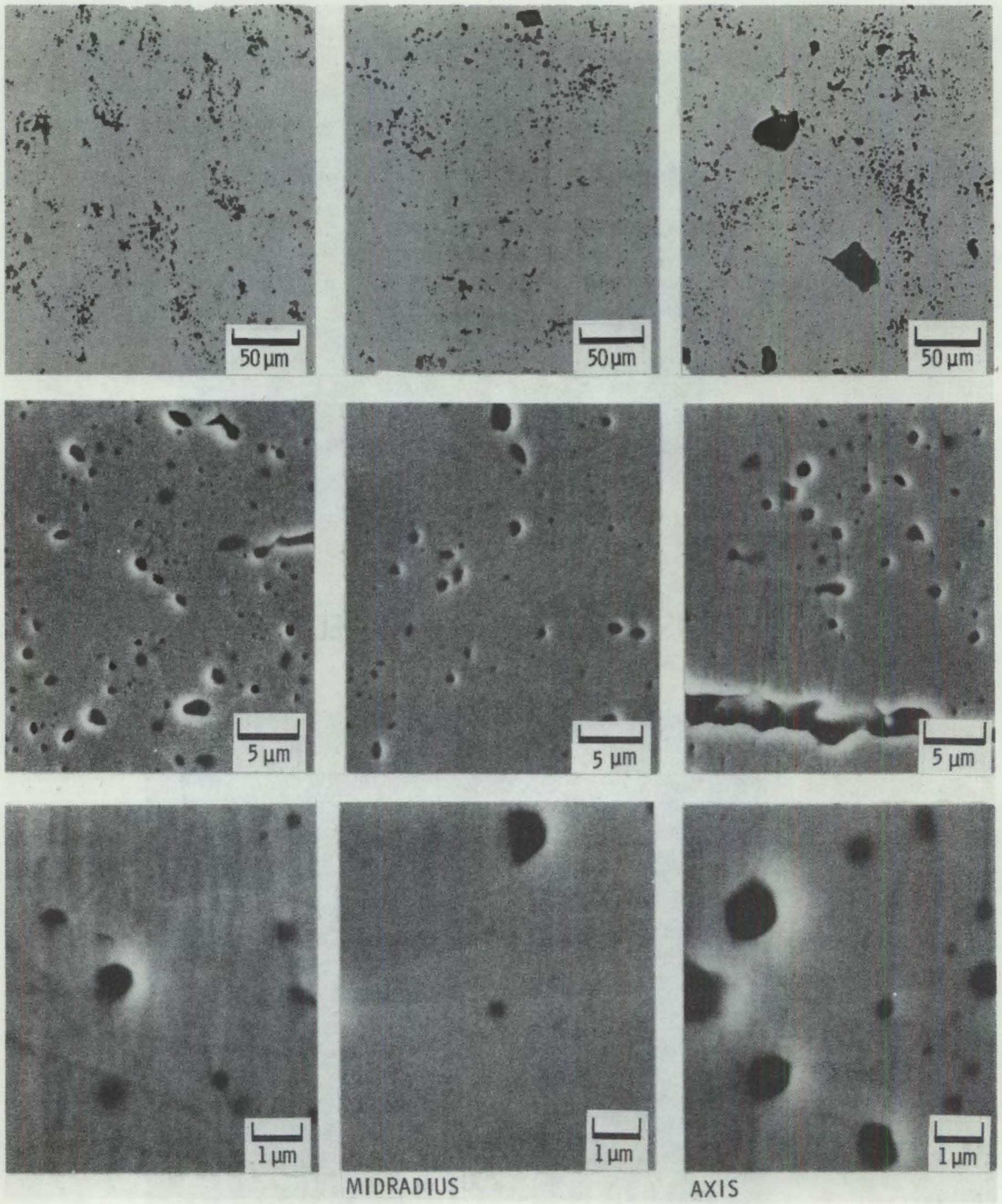
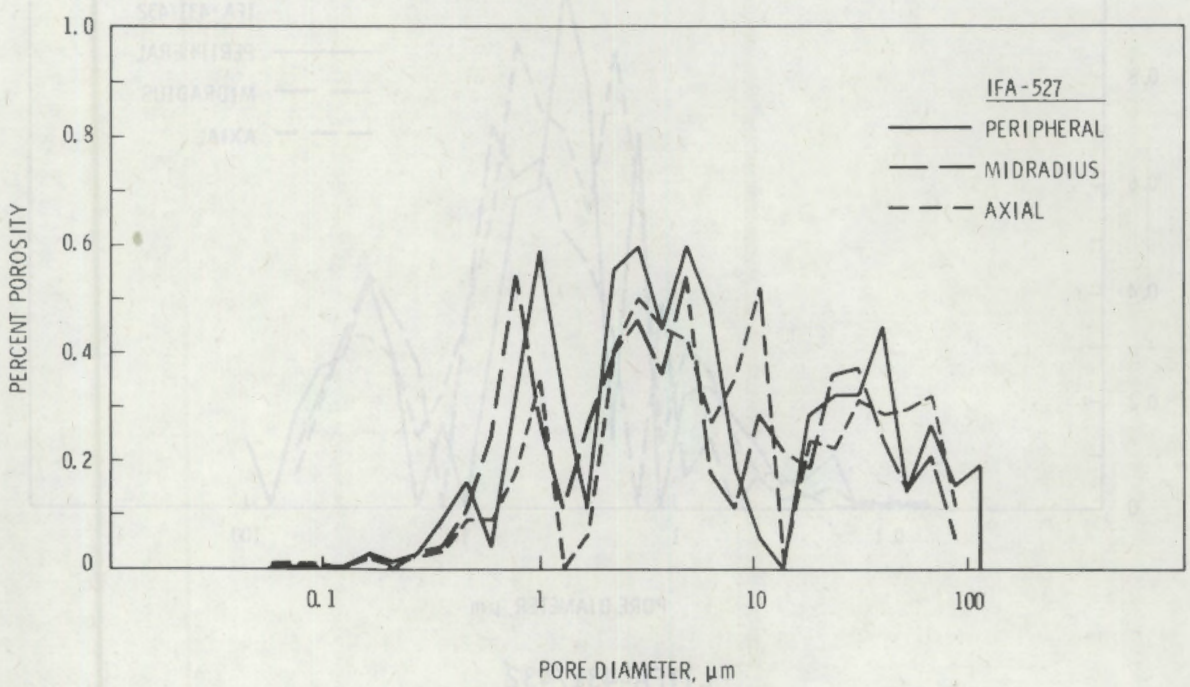


FIGURE 13. Typical Porosity Characteristics of UO_2 Pellets Used for Instrumented Fuel Assembly (IFA)-527. No discernible difference exists as a function of radial position in the pellets.

TABLE 7. Pore Distributions for Instrumented Fuel Assembly (IFA)-527[a]

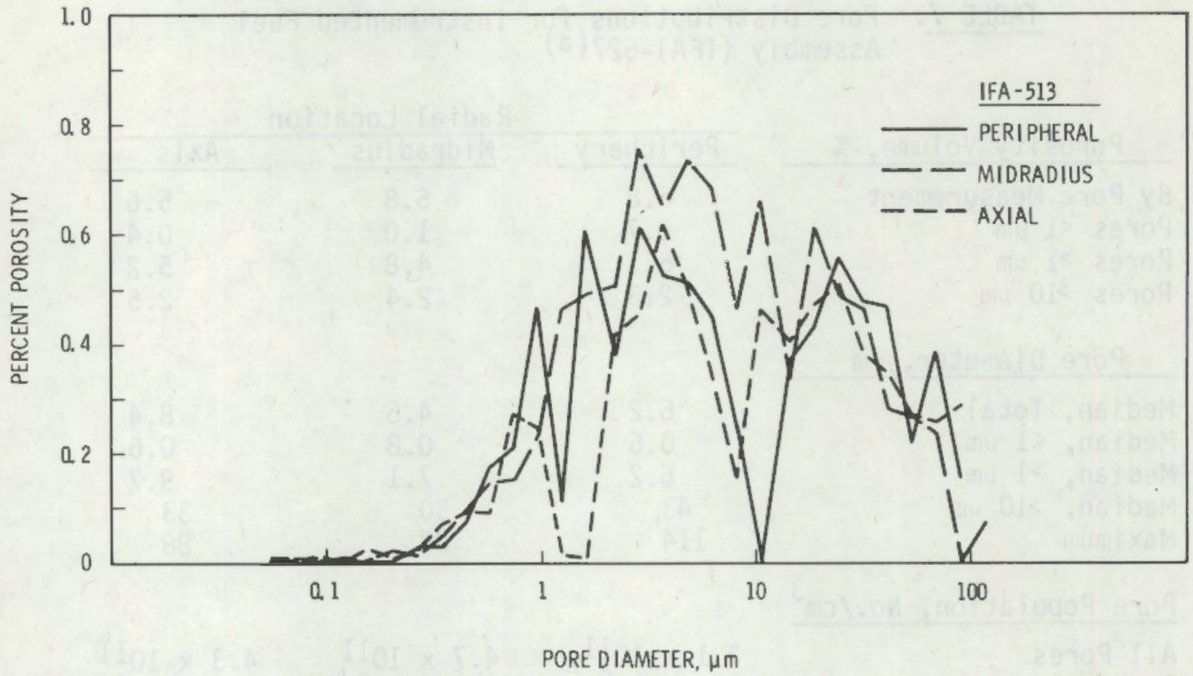
Porosity Volume, %	Periphery	Midradius	Axis
By Pore Measurement	6.8	5.8	5.6
Pores <1 μm	0.7	1.0	0.4
Pores >1 μm	6.1	4.8	5.2
Pores >10 μm	2.3	2.4	2.5
Pore Diameter, μm			
Median, Total	5.2	4.5	8.4
Median, <1 μm	0.6	0.8	0.6
Median, >1 μm	6.2	7.1	9.7
Median, >10 μm	43	30	33
Maximum	114	88	88
Pore Population, No./cm^3			
All Pores	3.1×10^{11}	4.7×10^{11}	4.3×10^{11}
Pores >1 μm	11×10^{9}	5.5×10^{9}	5.3×10^{9}
Pores >10 μm	2.8×10^{6}	5.5×10^{6}	8.6×10^{6}

(a) 95% theoretical density stable UO_2 fuel.

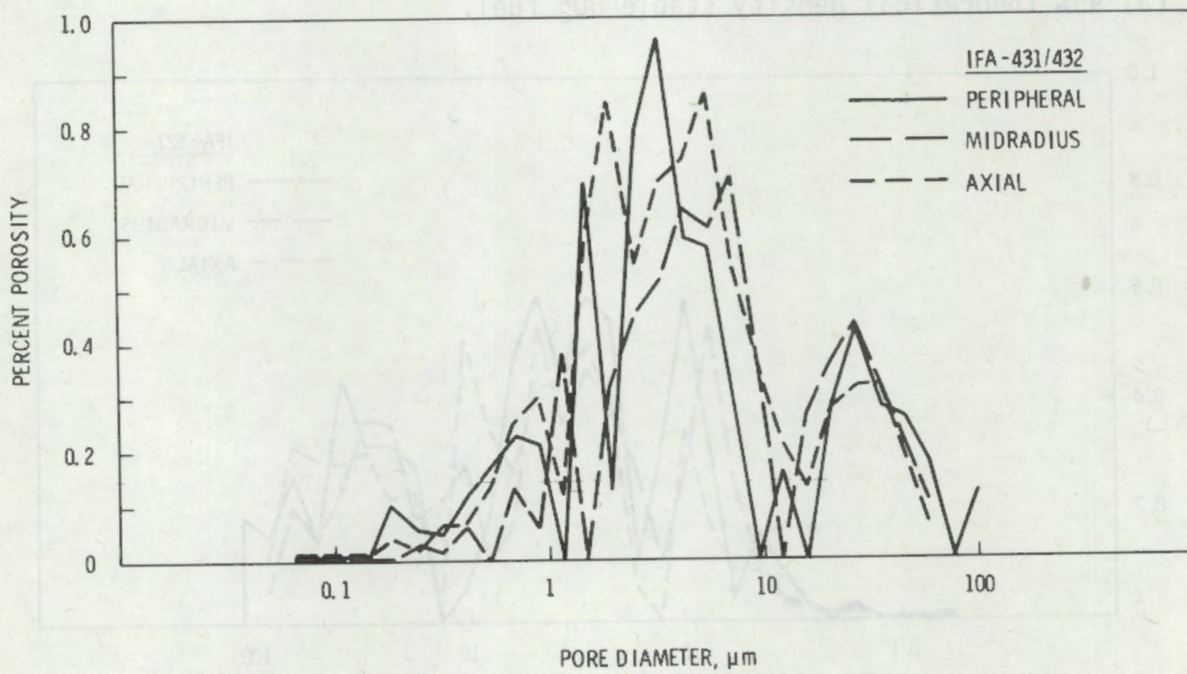


a) IFA-527

FIGURE 14. Summary of Radial Distribution of Pore Size and Volume (line segments join peak values of midpoint of successive size ranges)

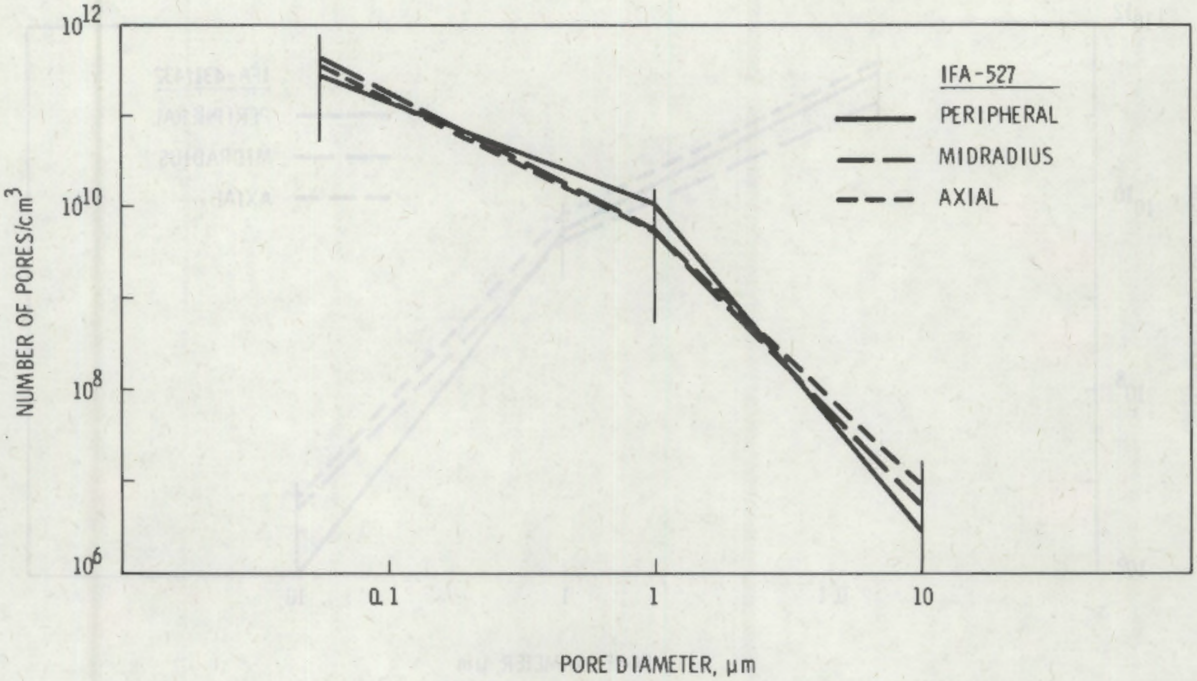


b) IFA-513

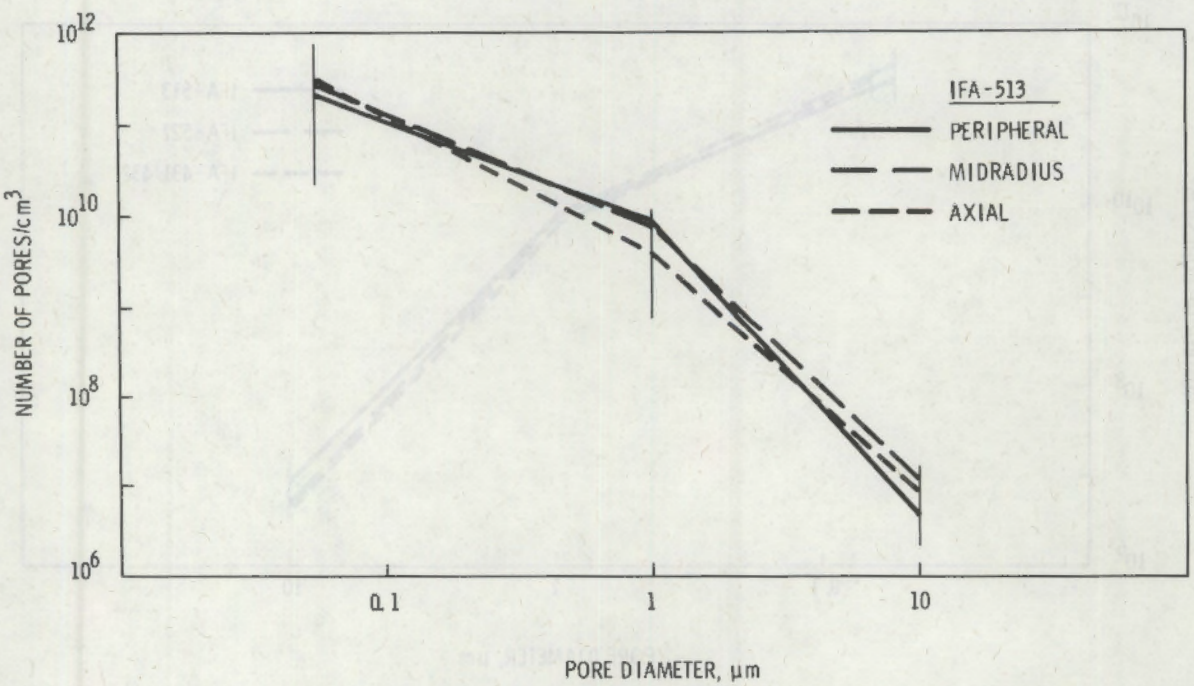


c) IFA-431/432

FIGURE 14. (contd)

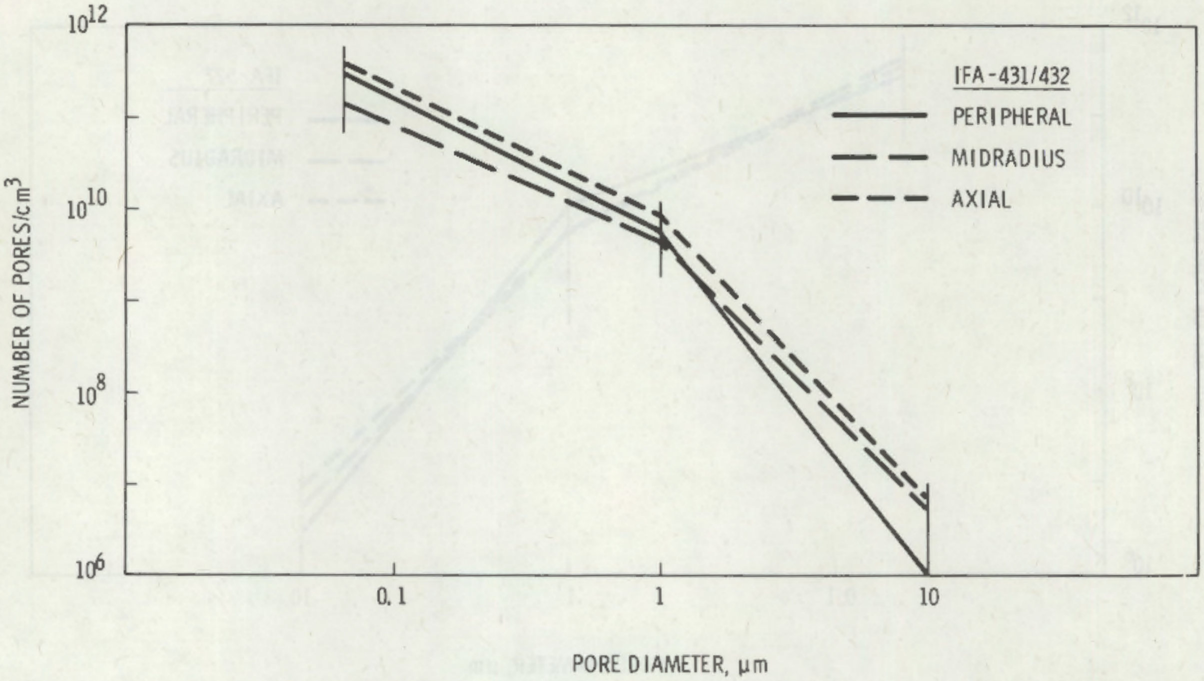


a) IFA-527

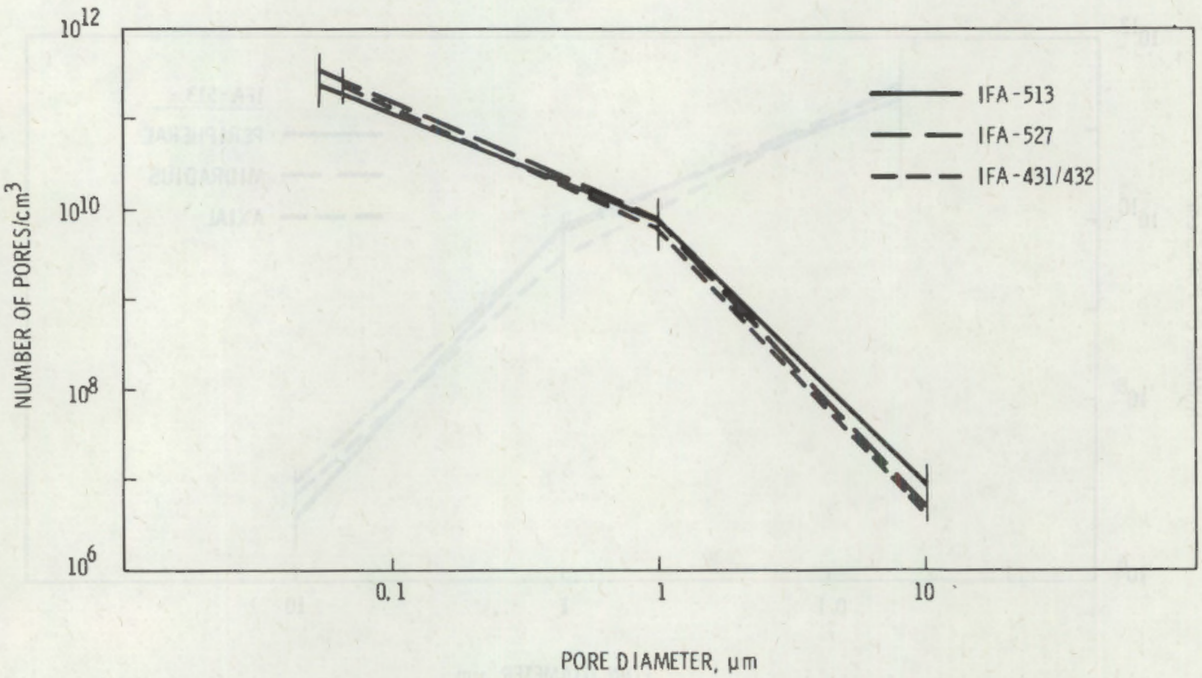


b) IFA-513

FIGURE 15. Radial Distribution of Pore Population as a Function of Pore Size (cumulative total number of pores larger than the corresponding pore size)



c)IFA-431/432



d)Comparison of IFA-527, -513, and -431/432

FIGURE 15. (contd)

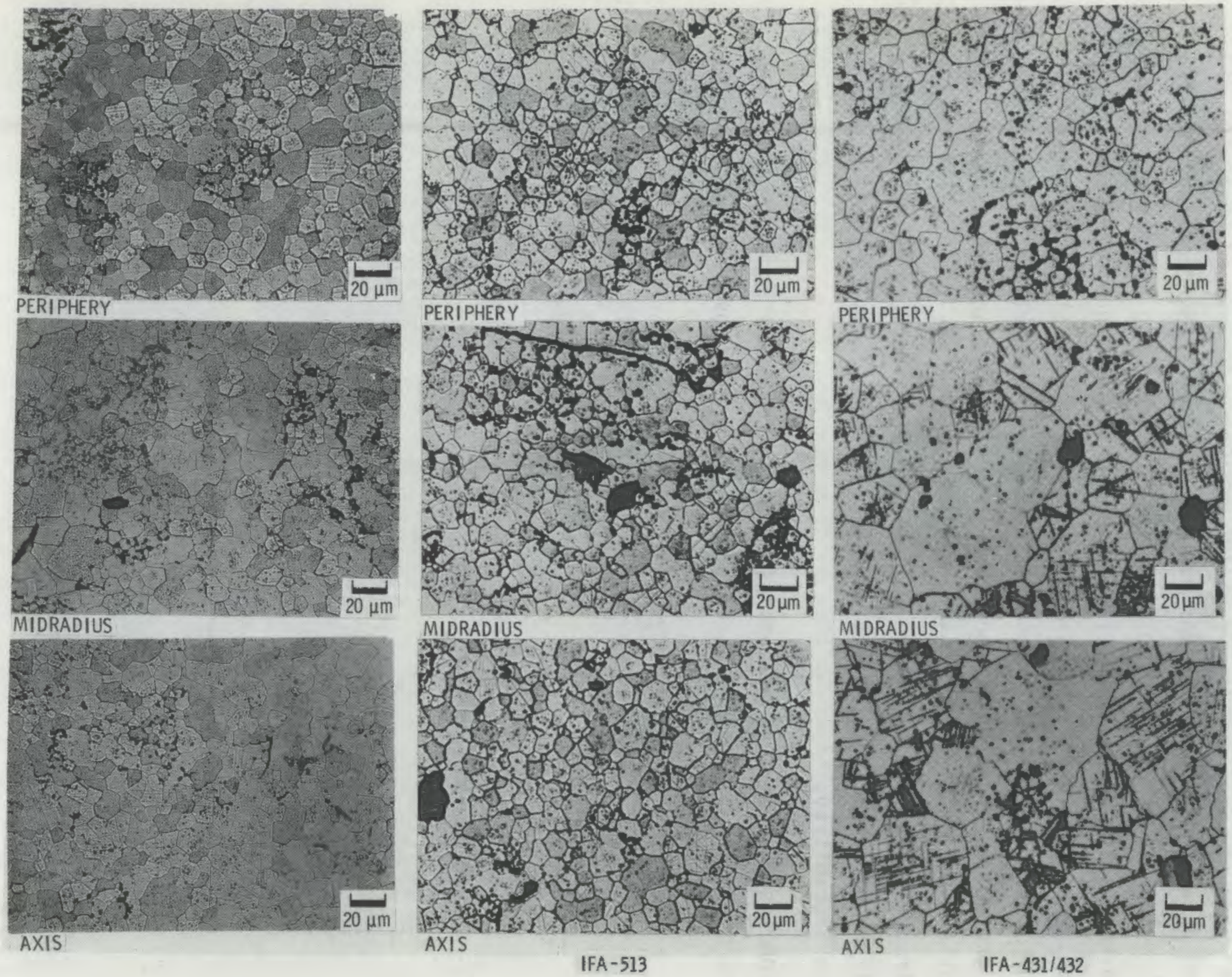


FIGURE 16. Variation in Grain Size for 95% TD Stable UO_2 Pellets Used in Instrumented Fuel Assemblies (IFA)-527, -513, -431, and -432

contrast, IFA-431 and -432 have a marked radial gradient in grain size, from an average diameter of 22 μm at the pellet periphery to over 70 μm at the mid-radius and axial positions. The maximum grain diameter observed for IFA-431 and -432 fuel was over 80 μm. The differences between the assemblies are further illustrated in Figure 17 and Table 8. The observed grain size differences can probably be explained by the various combinations of starting powder, furnace, and sintering conditions used for fabricating the pellets. The clusters of small grain-boundary porosity observed in IFA-527 are scattered randomly throughout the pellet and are probably responsible for the 1-μm peak in the pore distribution curve (see Figure 10). The grain size for IFA-527, while much smaller than those for IFA-431 and -432, is not likely to cause any densification instability.[9]

In conclusion, the fuel pellets used in all four fuel assemblies are similar in microstructure. The greatest similarity is in porosity characteristics

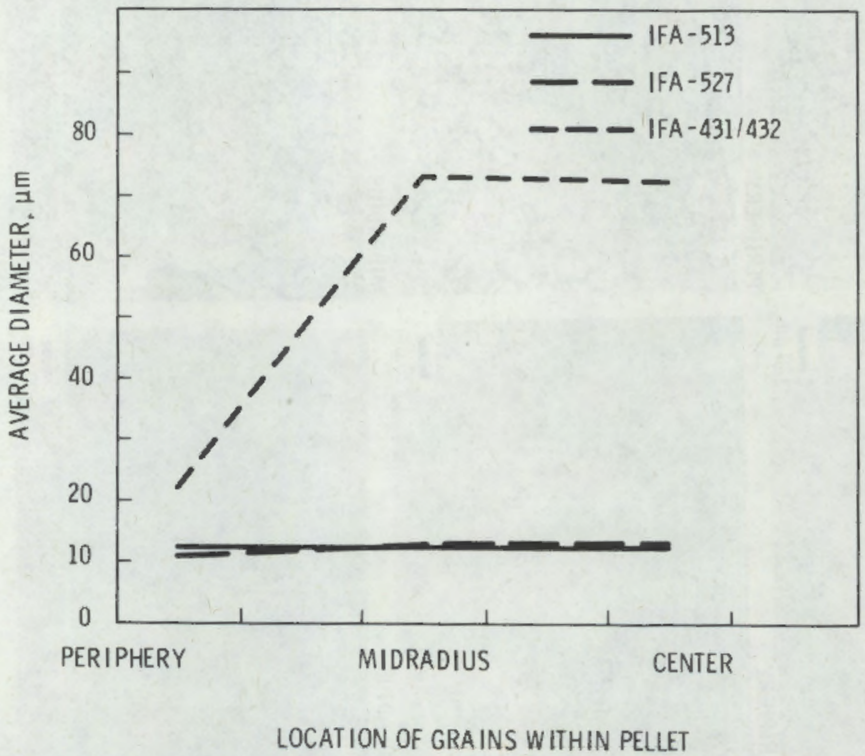


FIGURE 17. Summary of Radial Variation in Grain Size for IFA-527 and -513 and IFA-431 and -432

TABLE 8. Grain Size of As-Sintered Pellets[a]

Position	Average Diameter, μm		
	IFA-527[b]	IFA-513[b]	IFA-431 and -432[c]
Peripheral	11 ±1	12 ±2	22
Midradius	13 ±1	12 ±2	73
Axial	13 ±2	12 ±1	72

(a) 95% theoretical density stable fuel.
(b) Averages from transverse sections of three pellets.
(c) Averages of transverse and longitudinal sections of two pellets.

although IFA-527 contains a small component of 1-μm porosity not present in the others. The greatest difference is in grain size; the grain sizes of IFA-431 and -432 are two to five times larger than those in IFA-527 and -513. Based on the densification studies by Freshley et al.,[9] the combination of characteristics in both fuel batches (few pores smaller than 1-μm diameter, total porosity of 5 to 7%, and grain size greater than 10-μm diameter) is expected to result in similar microstructural behavior (including densification stability).

Thermal Resintering

At the time the IFA-513 precharacterization report (PNL-3156) was published, no thermal resintering tests had been performed on the fuel. Because the microstructure of the IFA-513 fuel was similar to that of IFA-432, it was concluded that there would be little densification of the IFA-513 fuel. A thermal resintering test has now been performed on three IFA-513 pellets and one IFA-527 pellet.

The pellets were resintered in a refractory metal-cold wall furnace with a tungsten element. The atmosphere was 50% Ar/50% He flowing at 283 l/h (10 ft^3/h). The furnace heating rate was 150K/h to 723K; then 300K/h, to 1973K. The pellets were held at 1973K for 24 h and then cooled at 400K/h.

Table 9 presents the as-sintered characterization of the four pellets. Table 10 presents the same measurements after the resintering test. It can be seen that the average increase in immersion density was approximately 0.32% TD. The average density increase for the 95% TD stable fuel used in IFA-431 and

TABLE 9. As-Sintered Characterization of Pellets to Be Resintered

Parameter[a]	IFA-527 Pellet 835	Pellet 151	IFA-513 Pellet 321	Pellet 368
Diameter, in.	0.4209	0.4202	0.4207	0.4209
Length, in.	0.4975	0.4965	0.5025	0.4985
Weight, g	11.801	11.720	11.867	11.783
Geometrical Density,				
g/cm^3	10.40	10.39	10.37	10.38
%TD	94.9	94.8	94.6	94.7
Immersion Density,				
g/cm^3	10.48	10.48	10.44	10.47
%TD	95.6	95.6	95.3	95.5

(a) Presented in as-measured units.

TABLE 10. Resintered Characterization of Pellets

Parameter(a)	IFA-527 Pellet 835	Pellet 151	IFA-513 Pellet 321	Pellet 368
Diameter, in.	0.4205	0.4199	0.4203	0.4203
Length, in.	0.4970	0.4960	0.5020	0.4975
Weight, g	11.799	11.718	11.861	11.778
Geometrical Density,				
g/cm^3	10.43	10.41	10.39	10.41
%TD	95.2	95.0	94.8	95.0
Immersion Density,				
g/cm^3	10.51	10.51	10.48	10.51
%TD	95.9	95.9	95.6	95.9

(a) Presented in as-measured units.

-432 was approximately 0.25% TD. Therefore, the thermal resintering behavior for the IFA-513 and -527 fuel is very similar to that of the previous fuel.

Thermal Conductivity

In addition to the thermal resintering tests, thermal conductivity measurements were also made on IFA-513 and -527 pellets using the same technique as for IFA-431/432. That is, a laser "flash" technique was used to measure the thermal diffusivity, from which the thermal conductivity was then calculated.

Thermal conductivity is calculated from

$$\lambda = \alpha \rho C_p$$

where λ = thermal conductivity, W/m-K

α = measured thermal diffusivity, m^2/s

ρ = density, kg/m^3

C_p = heat capacity, J/kg-K.

Density was assumed to be temperature dependent and determined by

$$\rho = \frac{\rho_o}{\left(1 + \frac{\Delta L}{L_o}\right)^3}$$

Appendix D tabulates α and λ as a function of temperature. Table 11 lists the resulting polynomial fits for thermal conductivity and the equations for $\Delta L/L_o$ and C_p. Figure 18 compares the IFA-513 and -527 fuel thermal conductivities to those of IFA-431 and -432 (BNW-1988), Lyons,[10] and MATPRO-10.[11] The measured thermal conductivities of IFA-527 and IFA-513 are sufficiently similar to appear as a single curve in the figure. In addition, the expressions by Lyons and MATPRO-10 are in good agreement with the IFA-527/513 measurements. The measured thermal conductivity for the 95% TD fuel used in IFA-431/432 is higher than that measured for IFA-527/513, which has been partially attributed to an improved technique when the IFA-527/513 measurements were made.

TABLE 11. Thermal Conductivity Expressions[(a)]

IFA-527:

$$\lambda(T) = 8.657 - 1.990 \times 10^{-2} T + 4.605 \times 10^{-5} T^2 - 7.474 \times 10^{-8} T^3 + 7.190 \times 10^{-11} T^4 - 3.664 \times 10^{-14} T^5 + 7.587 \times 10^{-18} T^6$$

IFA-513:

$$\lambda(T) = 7.495 - 9.153 \times 10^{-3} T + 3.637 \times 10^{-6} T^2 + 8.075 \times 10^{-9} T^3 - 1.293 \times 10^{-11} T^4 + 7.214 \times 10^{-15} T^5 - 1.441 \times 10^{-18} T^6$$

IFA-431/432:

$$\lambda(T) = \frac{1}{(11.7 + 1.50 \times 10^{-2} T + 4.50 \times 10^{-6} T^2)}$$

Lyons:[(10)]

$$\lambda(T) = \frac{38.24}{402.4 + T} + 6.1256 \times 10^{-13} (T + 273)^3$$

MATPRO-10:[(11)]

$$\lambda(T) = \frac{40.4}{464 + T} + 1.216 \times 10^{-4} \exp(1.867 \times 10^{-3} T)$$

Density:[(b)(12)]

$$\frac{\Delta L}{L} = -2.0701 \times 10^{-4} + 8.4051 \times 10^{-6} T + 1.6502 \times 10^{-9} T^2 + 2.6128 \times 10^{-13} T^3$$

Heat Capacity:[(b)]

$$C_p = 2.2882 \times 10^2 + 3.8723 \times 10^{-1} T - 8.3260 \times 10^{-4} T^2 + 1.0706 \times 10^{-6} T^3 - 7.7784 \times 10^{-10} T^4 + 2.8913 \times 10^{-13} T^5 - 4.0804 \times 10^{-17} T^6$$

(a) T in °C rather than K; $\lambda(T)$ in W/m-°C; C_p in J/kg-°C.
(b) For calculating thermal conductivity from thermal diffusivity.

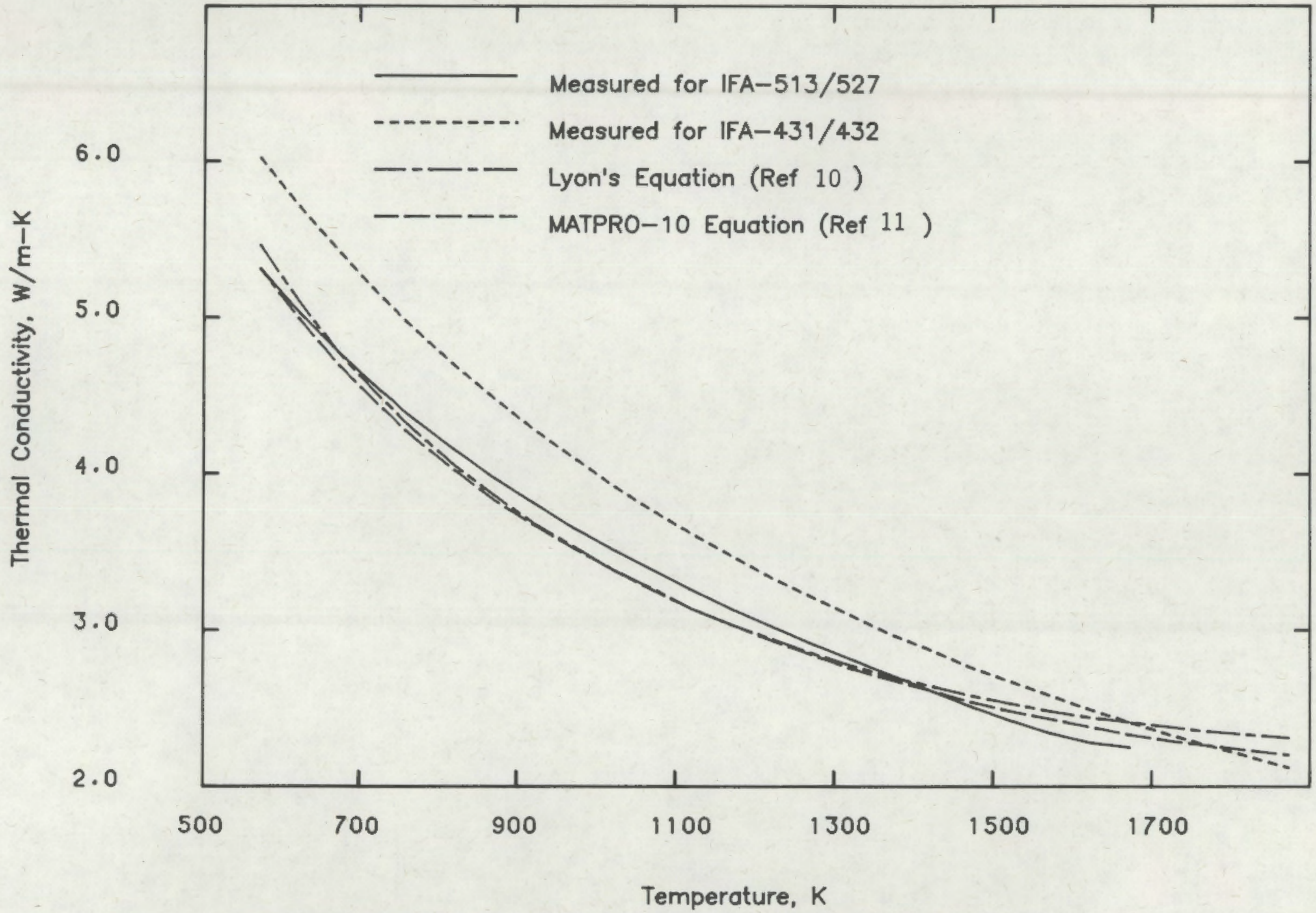


FIGURE 18. Comparison of IFA-513 and -527 Fuel Thermal Conductivity with IFA-431 and -432 Thermal Conductivity and Selected Expressions

ASSEMBLY OPERATION

During its irradiation, IFA-527 will be subjected to two operating conditions: normal, steady-state HBWR operations and PNL-requested special operations. During the normal steady-state operation, the fuel rods will be exposed to operating conditions that provide a standard data set of steady-state fuel centerline temperatures, local linear heat rates, cladding axial elongation, and fuel rod internal gas pressure. The normal HBWR operating cycle consists of running at nearly full power for approximately 2 months followed by shutdown for fuel assembly changes, maintenance, and other necessary work. PNL-requested special procedures consist of transient operations that take place within normal power ranges. They are designed to provide additional data for the evaluation of fuel rod conditions.

STEADY-STATE OPERATION

To satisfactorily meet the goals of this fuel assembly, it will be necessary to obtain reliable thermocouple response throughout the irradiation. This will require reduced linear heat rates (relative to helium-filled rods) to prevent exposure of the thermocouples to possibly damaging temperatures. Experience at Halden has indicated a threshold temperature for thermocouple failure (for extended periods of operation) of 1900 to 1950K. The recommended peak temperature for IFA-527 of 1575K prevents both thermocouple failure and fuel restructuring, which could begin at 1675K.

The appropriate linear heat rate necessary to prevent exceeding 1575K may be determined from two sources: experimental data and computer code predictions. IFA-431 and -432 each contained a fuel rod that had an initial fill gas of xenon at 1-atm pressure. However, these rods had special designs (oversize pellets to restrain specific fuel regions) that are believed to have affected the thermal performance of the rods.[13] In turn, no code has yet been developed that adequately models all situations.

Examination of the beginning-of-life (BOL) data for rod 4 of IFA-431 and IFA-432 has shown that a centerline temperature of 1575K occurred at the following powers:

IFA-431:	concentric region	16.0 kW/m
	eccentric region	20.0 kW/m
IFA-432:	concentric region	12.0 kW/m
	eccentric region	15.0 kW/m

GAPCON-THERMAL-3[1] predictions have been:

no fuel relocation	11.0 kW/m
in-code relocation	12.0 kW/m
30% initial relocation,[a] no in-code relocation	15.5 kW/m

An initial relocation of approximately 30% has been consistently concluded for both IFA-431 and -432. Another factor to consider is that rod 4 of both IFA-431 and -432 experienced an increase in thermal resistance after the initial startup. That increase in resistance was equivalent to a 60K increase in centerline temperature at the same linear heat rate.

The recommended maximum linear heat rate for IFA-527 is 14.0 kW/m at BOL, which will result in maximum centerline temperatures of less than 1575K, even after the expected thermal resistance increase. This maximum linear heat rate will occur at the lower thermocouples, which are positioned at the peak of the axial thermal neutron flux profile (see Figure 5). The fuel in the region of the upper thermocouples will be at approximately 75% of full power or 10.5 kW/m.

Data from IFA-431 and -432 has also shown that after a burnup of 45 GJ/kgU the thermal resistance for xenon-filled rods will begin decreasing; which will allow the linear heat rate to be increased without exceeding the 1575K temperature limit. After 85 GJ/kgU of burnup, it is expected that an increase of peak linear heat rate to 18.0 to 20.0 kW/m will be possible. If the allowable maximum temperature is raised to 1675K at this point, the corresponding maximum linear heat rate will be 23.0 to 24.0 kW/m.

(a) Reduction in the initial cold fuel-cladding gap of 30%.

Data is collected every 15 minutes during steady-state operation and is handled automatically by an IBM-1800 process computer. This data is stored on disk for 24 h and then transferred to magnetic tape for permanent storage.

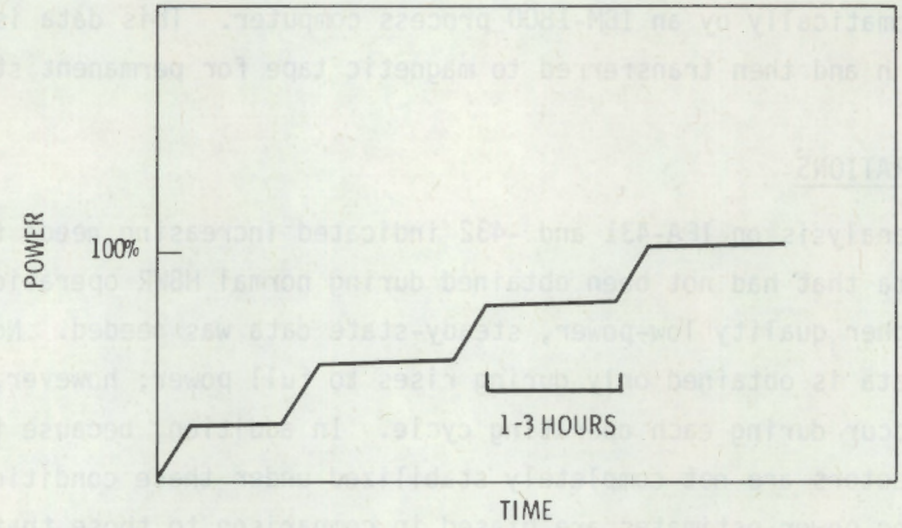
SPECIAL OPERATIONS

Early analysis on IFA-431 and -432 indicated increasing needs for two types of data that had not been obtained during normal HBWR operation. First, more and higher quality low-power, steady-state data was needed. Normally, low-power data is obtained only during rises to full power; however, only a few rises occur during each operating cycle. In addition, because the vanadium neutron detectors are not completely stabilized under these conditions,[a] the resulting power estimates are biased in comparison to those that would be obtained under true steady-state conditions. The solution to this problem has been to use a "staircase" approach to power as illustrated in Figure 19a. By holding at intermediate power levels for 1 to 3 h, both the amount and quality of low-power, steady-state data are improved.

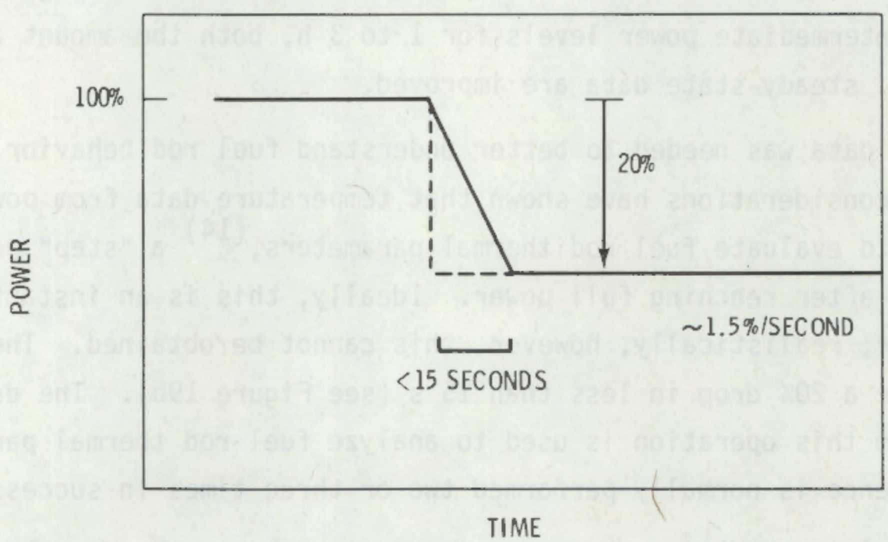
Second, data was needed to better understand fuel rod behavior. Since theoretical considerations have shown that temperature data from power drops can be used to evaluate fuel rod thermal parameters,[14] a "step" power drop is performed after reaching full power. Ideally, this is an instantaneous 20% drop in power; realistically, however, this cannot be obtained. The requirements are for a 20% drop in less than 15 s (see Figure 19b). The data obtained from this operation is used to analyze fuel rod thermal parameters, and the sequence is normally performed two or three times in succession.

By performing a staircase power rise just prior to the power drops, an improved correlation may be made between the steady-state data and the transient analysis. Preferably, the combined staircase and power-drop operations would be carried out once per month, depending on the reactor operations schedule. However, this sequence is particularly important during the initial startup of the assembly and during subsequent startups following extended shutdowns.

(a) The time constant for the vanadium neutron detectors is 5.4 minutes.



a) Staircase approach to power



b) Step power drop (actual operation)

FIGURE 19. Special Operational Procedures for Instrumental Fuel Assembly (IFA)-527

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*Available for purchase from the NRC/GPO Sales Program, U.S. Nuclear Regulatory Commission, Washington, DC 20555, and/or the National Technical Information Service, Springfield, VA 22161.

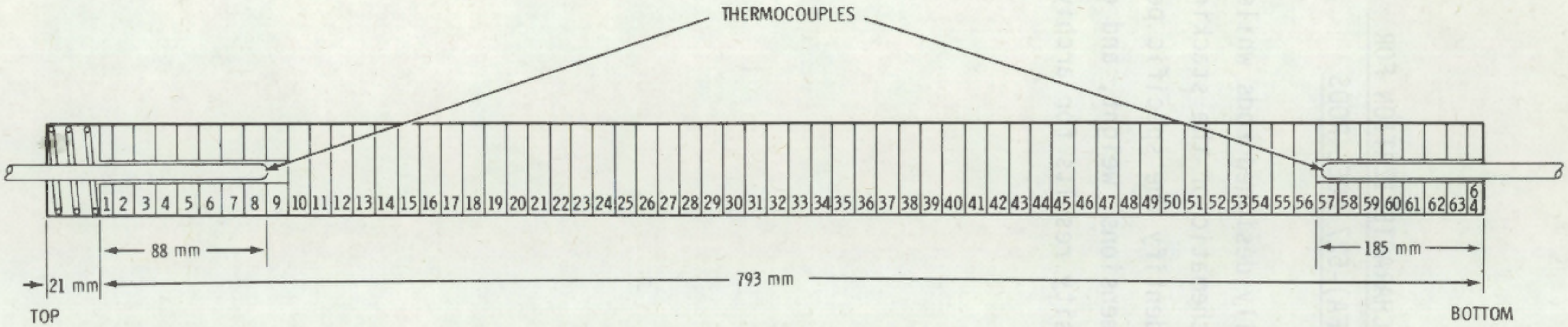
APPENDIX A

STACKING ARRANGEMENT AND PELLET CHARACTERIZATION FOR INSTRUMENTED FUEL ASSEMBLY (IFA)-527 FUEL RODS

APPENDIX A

STACKING ARRANGEMENT AND PELLET CHARACTERIZATION FOR INSTRUMENTED FUEL ASSEMBLY (IFA)-527 FUEL RODS

Rods 1 through 5 of IFA-527 are identically designed rods while rod 6 has fuel of a larger diameter. Figure A.1 is a schematic of the stacking arrangement for the rods. Tables A.1 through A.6 identify the specific pellets loaded into each rod and their as-measured dimensions, weight, and geometrical density; and Table A.7 provides immersion density results for archive fuel pellets.



TOTAL NUMBER OF PELLETS IN EACH STACK	=	64
NUMBER OF SOLID FUEL PELLETS	=	40
NUMBER OF DRILLED FUEL PELLETS	=	22
NUMBER OF POISON PELLETS	=	2

FUEL PELLET LENGTH = 12.700 ± 0.381 mm (0.500 ± 0.015 in.)

FUEL PELLET DIAMETER = 10.681 ± 0.013 mm (0.4205 ± 0.005 in.), RODS 1 THROUGH 5

10.859 ± 0.013 mm (0.4275 ± 0.005 in.), ROD 6

CENTRAL HOLE DIAMETER = 1.702 - 1.803 mm (0.067 - 0.071 in.)

POISON PELLET LENGTH = 7.0 mm (SUPPLIED BY HALDEN)

FIGURE A.1. Stacking Arrangement for Instrumented Fuel Assembly (IFA)-527, Design Dimensions

TABLE A.1. Pellet Data for Rod 1 of Instrumented Fuel Assembly (IFA)-527

PELLET POSITION	PELLET NUMBER	DIAMETER (INCHES) D-1	D-2	D-3	LENGTH (INCHES) L-1	L-2	VOID DIAMETER (INCHES)	WEIGHT (G)	DENSITY (G/CC)	DENSITY (% TD)
1	1	.4205	.4205	.4204	.4990	.4990	.0690	11.500	10.41	94.97
2	2	.4205	.4205	.4205	.5060	.5060	.0690	11.665	10.41	94.98
3	3	.4206	.4206	.4205	.4970	.4970	.0690	11.459	10.41	94.97
4	4	.4205	.4206	.4205	.4950	.4950	.0690	11.418	10.41	95.02
5	5	.4204	.4204	.4205	.4970	.4970	.0690	11.449	10.41	94.95
6	6	.4205	.4205	.4204	.4950	.4940	.0690	11.403	10.41	95.03
7	7	.4205	.4205	.4204	.4930	.4930	.0690	11.342	10.39	94.81
8	81	.4202	.4202	.4202	.4990	.4990	0.0000	11.802	10.41	94.96
9	82	.4205	.4205	.4204	.4950	.4940	0.0000	11.732	10.43	95.14
10	83	.4204	.4204	.4204	.4980	.4970	0.0000	11.771	10.40	94.91
11	84	.4205	.4204	.4204	.4990	.4980	0.0000	11.810	10.41	95.01
12	85	.4204	.4204	.4204	.4990	.4980	0.0000	11.803	10.41	94.97
13	86	.4205	.4205	.4205	.5020	.5020	0.0000	11.898	10.41	95.02
14	87	.4209	.4208	.4207	.5020	.5010	0.0000	11.912	10.42	95.10
15	88	.4208	.4208	.4208	.5000	.5000	0.0000	11.859	10.41	94.96
16	89	.4205	.4205	.4205	.5010	.5010	0.0000	11.884	10.42	95.10
17	90	.4204	.4205	.4205	.5010	.5020	0.0000	11.849	10.38	94.74
18	91	.4205	.4205	.4205	.4940	.4950	0.0000	11.751	10.44	95.27
19	92	.4206	.4205	.4205	.4950	.4950	0.0000	11.737	10.42	95.05
20	93	.4205	.4205	.4205	.4970	.4970	0.0000	11.809	10.44	95.26
21	94	.4205	.4205	.4205	.5010	.5000	0.0000	11.859	10.41	95.00
22	95	.4205	.4205	.4204	.4960	.4960	0.0000	11.773	10.43	95.18
23	96	.4205	.4205	.4205	.4960	.4970	0.0000	11.746	10.40	94.85
24	97	.4206	.4205	.4204	.4990	.4990	0.0000	11.835	10.42	95.09
25	98	.4206	.4206	.4206	.4960	.4970	0.0000	11.746	10.39	94.80
26	99	.4206	.4206	.4205	.5010	.5000	0.0000	11.890	10.44	95.22
27	100	.4206	.4205	.4205	.4920	.4920	0.0000	11.668	10.42	95.07
28	101	.4209	.4208	.4207	.4980	.4980	0.0000	11.786	10.38	94.75
29	102	.4205	.4205	.4205	.4980	.4990	0.0000	11.787	10.39	94.80
30	103	.4205	.4205	.4205	.4910	.4920	0.0000	11.650	10.42	95.03
31	104	.4205	.4205	.4204	.4930	.4940	0.0000	11.723	10.44	95.25
32	105	.4205	.4206	.4206	.4960	.4960	0.0000	11.788	10.44	95.25
33	106	.4205	.4205	.4205	.4990	.5000	0.0000	11.873	10.44	95.30
34	107	.4204	.4204	.4204	.4920	.4930	0.0000	11.707	10.45	95.35
35	108	.4208	.4209	.4209	.4980	.4980	0.0000	11.838	10.43	95.14
36	109	.4205	.4205	.4205	.4950	.4960	0.0000	11.750	10.42	95.07
37	110	.4205	.4205	.4205	.4900	.4910	0.0000	11.652	10.44	95.24
38	111	.4208	.4208	.4207	.4920	.4920	0.0000	11.715	10.45	95.34
39	112	.4202	.4202	.4202	.4940	.4940	0.0000	11.710	10.43	95.17
40	113	.4205	.4205	.4205	.4960	.4950	0.0000	11.778	10.44	95.30
41	114	.4205	.4205	.4205	.4920	.4920	0.0000	11.686	10.44	95.23
42	115	.4209	.4209	.4209	.4960	.4960	0.0000	11.782	10.42	95.06
43	116	.4204	.4204	.4204	.4910	.4910	0.0000	11.648	10.43	95.16
44	117	.4205	.4204	.4204	.4880	.4880	0.0000	11.579	10.43	95.16
45	118	.4204	.4204	.4204	.4920	.4920	0.0000	11.677	10.43	95.20
46	119	.4207	.4207	.4207	.4950	.4950	0.0000	11.760	10.43	95.16
47	120	.4205	.4205	.4204	.4940	.4950	0.0000	11.720	10.42	95.04
48	8	.4206	.4206	.4205	.4960	.4950	.0690	11.417	10.40	94.90
49	9	.4204	.4204	.4203	.4920	.4910	.0690	11.320	10.41	94.96
50	10	.4204	.4205	.4205	.4930	.4940	.0690	11.370	10.41	94.94
51	11	.4204	.4204	.4204	.4960	.4950	.0690	11.422	10.41	95.02
52	12	.4206	.4206	.4206	.4940	.4940	.0690	11.396	10.41	95.00
53	13	.4209	.4209	.4208	.4950	.4950	.0690	11.432	10.41	94.99
54	14	.4205	.4205	.4205	.4950	.4940	.0690	11.395	10.41	94.94
55	15	.4204	.4205	.4205	.4990	.5000	.0690	11.493	10.39	94.82
56	16	.4204	.4204	.4204	.4990	.5000	.0690	11.508	10.41	94.97
57	17	.4204	.4205	.4205	.5000	.5000	.0690	11.502	10.39	94.80
58	18	.4204	.4205	.4205	.5000	.5010	.0690	11.514	10.39	94.80
59	19	.4204	.4204	.4204	.5020	.5020	.0690	11.560	10.40	94.93
60	20	.4206	.4206	.4206	.4950	.4950	.0690	11.414	10.41	94.96
61	21	.4205	.4205	.4204	.4960	.4960	.0690	11.443	10.42	95.07

AVERAGE DIAMETER IS .4205 INCHES WITH A STD DEV OF .00014
AVERAGE LENGTH IS .4964 INCHES WITH A STD DEV OF .00346
AVERAGE WEIGHT IS 11.658 GRAMS WITH A STD DEV OF .17021
AVERAGE DENSITY IS 10.42 G/CC WITH A STD DEV OF .01683
AVERAGE THEORETICAL DENSITY IS 95.04 PERCENT WITH A STD DEV OF .15357

TOTAL FUEL LENGTH IS 30.2785 INCHES
TOTAL UO2 WEIGHT IS 711.165 GRAMS

PELLET 22 PLACED IN POSITION 62, ADJUSTED LENGTH = .2876 INCH, ADJUSTED WEIGHT= 6.640 GRAM

TABLE A.2. Pellet Data for Rod 2 of Instrumented Fuel Assembly (IFA)-527

PELLET POSITION	PELLET NUMBER	DIAMETER (INCHES) D-1	D-2	D-3	LENGTH (INCHES) L-1	L-2	VOID DIAMETER (INCHES)	WEIGHT (G)	DENSITY (G/CC)	DENSITY (% TD)
1	23	.4205	.4205	.4205	.4950	.4950	.0690	11.403	10.40	94.91
2	24	.4204	.4205	.4205	.5010	.5010	.0690	11.502	10.37	94.61
3	25	.4205	.4204	.4205	.5000	.5000	.0690	11.524	10.41	94.98
4	26	.4204	.4205	.4205	.5000	.5010	.0690	11.492	10.37	94.62
5	27	.4206	.4205	.4205	.4980	.4990	.0690	11.475	10.39	94.83
6	28	.4204	.4204	.4203	.5000	.5000	.0690	11.491	10.38	94.75
7	29	.4205	.4204	.4205	.4990	.5000	.0690	11.488	10.39	94.78
8	121	.4205	.4205	.4204	.4960	.4970	0.0000	11.788	10.43	95.20
9	122	.4206	.4206	.4205	.4940	.4950	0.0000	11.748	10.44	95.22
10	123	.4209	.4209	.4208	.4950	.4950	0.0000	11.773	10.43	95.19
11	124	.4205	.4205	.4205	.4940	.4940	0.0000	11.725	10.43	95.16
12	125	.4208	.4209	.4209	.4950	.4950	0.0000	11.760	10.42	95.08
13	126	.4207	.4206	.4206	.4970	.4970	0.0000	11.818	10.44	95.27
14	127	.4205	.4205	.4205	.4930	.4930	0.0000	11.723	10.45	95.34
15	128	.4206	.4206	.4207	.4920	.4930	0.0000	11.695	10.43	95.14
16	129	.4209	.4209	.4208	.4940	.4950	0.0000	11.747	10.42	95.08
17	130	.4208	.4208	.4208	.4930	.4940	0.0000	11.728	10.43	95.14
18	131	.4208	.4208	.4208	.4950	.4950	0.0000	11.770	10.43	95.20
19	132	.4204	.4204	.4204	.4900	.4900	0.0000	11.637	10.44	95.26
20	133	.4205	.4205	.4205	.4920	.4920	0.0000	11.704	10.45	95.38
21	134	.4206	.4206	.4206	.4920	.4920	0.0000	11.706	10.45	95.35
22	135	.4205	.4206	.4206	.4920	.4930	0.0000	11.708	10.44	95.28
23	136	.4205	.4205	.4205	.4950	.4940	0.0000	11.738	10.43	95.17
24	137	.4209	.4209	.4209	.4970	.4970	0.0000	11.824	10.43	95.20
25	138	.4206	.4206	.4206	.4980	.4980	0.0000	11.833	10.44	95.22
26	139	.4205	.4204	.4204	.4970	.4970	0.0000	11.792	10.43	95.16
27	140	.4206	.4206	.4206	.4930	.4930	0.0000	11.717	10.44	95.24
28	141	.4204	.4204	.4205	.4950	.4950	0.0000	11.748	10.43	95.18
29	142	.4205	.4204	.4204	.4950	.4950	0.0000	11.761	10.44	95.29
30	143	.4206	.4206	.4205	.4970	.4970	0.0000	11.805	10.43	95.20
31	144	.4209	.4209	.4209	.4920	.4930	0.0000	11.682	10.40	94.92
32	145	.4208	.4208	.4208	.4950	.4950	0.0000	11.778	10.44	95.26
33	146	.4205	.4205	.4206	.4950	.4950	0.0000	11.749	10.43	95.15
34	147	.4209	.4209	.4209	.4940	.4940	0.0000	11.746	10.43	95.15
35	148	.4205	.4205	.4206	.4990	.4990	0.0000	11.862	10.44	95.29
36	149	.4205	.4205	.4205	.4970	.4980	0.0000	11.796	10.42	95.06
37	150	.4210	.4210	.4210	.4910	.4900	0.0000	11.601	10.37	94.60
38	151	.4208	.4208	.4208	.4980	.4990	0.0000	11.831	10.41	95.02
39	152	.4205	.4205	.4205	.4980	.4990	0.0000	11.791	10.39	94.83
40	153	.4206	.4207	.4207	.4940	.4930	0.0000	11.711	10.42	95.07
41	154	.4206	.4205	.4205	.4930	.4940	0.0000	11.681	10.40	94.88
42	155	.4205	.4206	.4206	.4950	.4950	0.0000	11.728	10.41	94.96
43	156	.4206	.4205	.4205	.4980	.4980	0.0000	11.816	10.42	95.11
44	157	.4206	.4206	.4206	.4950	.4960	0.0000	11.771	10.43	95.20
45	158	.4207	.4207	.4206	.5010	.5000	0.0000	11.875	10.42	95.05
46	159	.4207	.4207	.4207	.4960	.4970	0.0000	11.773	10.41	94.98
47	160	.4205	.4205	.4206	.4990	.4990	0.0000	11.828	10.41	95.02
48	30	.4205	.4205	.4204	.4990	.4990	.0690	11.484	10.39	94.84
49	31	.4205	.4205	.4205	.4990	.4990	.0690	11.511	10.42	95.05
50	32	.4205	.4205	.4204	.5020	.5030	.0690	11.524	10.36	94.51
51	33	.4204	.4204	.4204	.4990	.4990	.0690	11.489	10.40	94.91
52	34	.4205	.4205	.4204	.5020	.5010	.0690	11.586	10.43	95.20
53	35	.4204	.4204	.4204	.4980	.4980	.0690	11.464	10.40	94.89
54	36	.4203	.4203	.4203	.5040	.5030	.0690	11.592	10.41	94.95
55	37	.4205	.4205	.4205	.5040	.5040	.0690	11.629	10.42	95.07
56	38	.4204	.4204	.4204	.5010	.5010	.0690	11.514	10.38	94.74
57	39	.4206	.4205	.4205	.4970	.4980	.0690	11.451	10.39	94.82
58	40	.4206	.4206	.4206	.4930	.4930	.0690	11.355	10.40	94.85
59	41	.4205	.4205	.4204	.5020	.5030	.0690	11.574	10.40	94.92
60	42	.4205	.4204	.4204	.4980	.4990	.0690	11.443	10.37	94.61
61	43	.4205	.4205	.4205	.4980	.4990	.0690	11.482	10.40	94.90

AVERAGE DIAMETER IS .4206 INCHES WITH A STD DEV OF .00016
AVERAGE LENGTH IS .4967 INCHES WITH A STD DEV OF .00326
AVERAGE WEIGHT IS 11.668 GRAMS WITH A STD DEV OF .13589
AVERAGE DENSITY IS 10.42 G/CC WITH A STD DEV OF .02292
AVERAGE THEORETICAL DENSITY IS 95.04 PERCENT WITH A STD DEV OF .20911

TOTAL FUEL LENGTH IS 30.2975 INCHES
TOTAL UO2 WEIGHT IS 711.740 GRAMS

PELLET 44 PLACED IN POSITION 62, ADJUSTED LENGTH = .1823 INCH, ADJUSTED WEIGHT= 4.199 GRAM

TABLE A.3. Pellet Data for Rod 3 of Instrumented Fuel Assembly (IFA)-527

PELLET POSITION	PELLET NUMBER	DIAMETER (INCHES) D-1	D-2	D-3	LENGTH (INCHES) L-1	L-2	VOID DIAMETER (INCHES)	WEIGHT (G)	DENSITY (G/CC)	DENSITY (% TD)
1	45	.4205	.4205	.4204	.5000	.5000	.0690	11.511	10.40	94.87
2	46	.4204	.4204	.4204	.4980	.4980	.0690	11.444	10.38	94.73
3	47	.4204	.4204	.4204	.4990	.4980	.0690	11.475	10.40	94.89
4	48	.4205	.4205	.4205	.5010	.5010	.0690	11.543	10.40	94.93
5	49	.4205	.4205	.4204	.5010	.5020	.0690	11.508	10.36	94.56
6	50	.4204	.4204	.4204	.4980	.4990	.0690	11.456	10.38	94.73
7	51	.4206	.4205	.4205	.4980	.4980	.0690	11.452	10.38	94.73
8	161	.4206	.4207	.4208	.4970	.4980	0.0000	11.820	10.43	95.17
9	163	.4204	.4204	.4204	.4970	.4970	0.0000	11.779	10.42	95.07
10	164	.4205	.4205	.4206	.4950	.4950	0.0000	11.757	10.44	95.21
11	165	.4206	.4206	.4207	.5000	.5000	0.0000	11.871	10.43	95.13
12	166	.4206	.4206	.4206	.4990	.4990	0.0000	11.846	10.43	95.13
13	167	.4205	.4205	.4205	.5000	.5000	0.0000	11.856	10.42	95.07
14	168	.4206	.4206	.4207	.4990	.4990	0.0000	11.862	10.44	95.25
15	169	.4208	.4208	.4208	.5000	.5000	0.0000	11.896	10.44	95.25
16	170	.4206	.4206	.4205	.4990	.4980	0.0000	11.808	10.41	94.94
17	171	.4207	.4207	.4207	.4980	.4990	0.0000	11.815	10.40	94.93
18	172	.4207	.4207	.4206	.5000	.5010	0.0000	11.880	10.42	95.09
19	173	.4209	.4209	.4208	.4990	.4980	0.0000	11.827	10.41	94.96
20	174	.4205	.4205	.4205	.4970	.4970	0.0000	11.782	10.42	95.04
21	175	.4207	.4207	.4206	.4970	.4960	0.0000	11.778	10.42	95.03
22	176	.4205	.4205	.4205	.4990	.4980	0.0000	11.821	10.42	95.07
23	177	.4207	.4207	.4206	.4990	.4990	0.0000	11.852	10.43	95.15
24	178	.4205	.4205	.4204	.4960	.4970	0.0000	11.788	10.43	95.20
25	179	.4205	.4205	.4204	.4970	.4980	0.0000	11.818	10.44	95.25
26	180	.4205	.4205	.4205	.4970	.4960	0.0000	11.780	10.43	95.12
27	181	.4205	.4205	.4205	.4950	.4960	0.0000	11.756	10.43	95.12
28	182	.4208	.4209	.4209	.4950	.4940	0.0000	11.761	10.43	95.19
29	183	.4208	.4209	.4209	.5050	.5050	0.0000	11.965	10.39	94.83
30	184	.4206	.4206	.4206	.5010	.5020	0.0000	11.885	10.41	94.97
31	185	.4205	.4205	.4205	.5040	.5050	0.0000	11.947	10.41	94.94
32	186	.4208	.4209	.4209	.5000	.5010	0.0000	11.852	10.39	94.78
33	187	.4207	.4206	.4206	.5020	.5020	0.0000	11.877	10.39	94.80
34	188	.4205	.4206	.4206	.5030	.5040	0.0000	11.896	10.38	94.70
35	189	.4204	.4205	.4205	.5010	.5010	0.0000	11.845	10.39	94.81
36	190	.4204	.4205	.4206	.5030	.5020	0.0000	11.886	10.39	94.83
37	191	.4206	.4207	.4207	.5030	.5030	0.0000	11.902	10.39	94.79
38	193	.4205	.4205	.4206	.5010	.5020	0.0000	11.857	10.39	94.78
39	194	.4206	.4206	.4206	.5040	.5040	0.0000	11.924	10.39	94.81
40	195	.4205	.4206	.4206	.5010	.5020	0.0000	11.863	10.39	94.81
41	196	.4207	.4206	.4206	.5040	.5040	0.0000	11.916	10.38	94.73
42	197	.4204	.4205	.4205	.5010	.5010	0.0000	11.825	10.37	94.65
43	198	.4204	.4204	.4203	.5020	.5020	0.0000	11.842	10.37	94.64
44	199	.4206	.4207	.4207	.5040	.5040	0.0000	11.911	10.38	94.68
45	200	.4205	.4205	.4206	.5000	.5000	0.0000	11.810	10.38	94.68
46	201	.4206	.4206	.4205	.5010	.5010	0.0000	11.841	10.38	94.73
47	202	.4207	.4207	.4206	.5020	.5020	0.0000	11.861	10.37	94.65
48	52	.4204	.4204	.4204	.4990	.5000	.0690	11.508	10.41	94.97
49	53	.4205	.4205	.4205	.4970	.4980	.0690	11.412	10.36	94.51
50	54	.4205	.4204	.4204	.4960	.4970	.0690	11.457	10.42	95.11
51	55	.4204	.4204	.4204	.4990	.5000	.0690	11.536	10.43	95.20
52	56	.4205	.4204	.4204	.4970	.4980	.0690	11.472	10.42	95.04
53	57	.4205	.4205	.4204	.4970	.4960	.0690	11.453	10.42	95.06
54	58	.4204	.4204	.4205	.4940	.4950	.0690	11.404	10.42	95.05
55	59	.4205	.4205	.4205	.4990	.4980	.0690	11.493	10.41	94.99
56	60	.4205	.4205	.4205	.4960	.4970	.0690	11.451	10.41	95.03
57	61	.4204	.4204	.4204	.4970	.4970	.0690	11.404	10.37	94.59
58	62	.4205	.4205	.4205	.4950	.4960	.0690	11.449	10.43	95.20
59	63	.4204	.4204	.4204	.4960	.4960	.0690	11.442	10.42	95.09
60	64	.4205	.4205	.4205	.4960	.4970	.0690	11.438	10.40	94.92
61	65	.4204	.4204	.4204	.4970	.4970	.0690	11.421	10.38	94.73

AVERAGE DIAMETER IS .4205 INCHES WITH A STD DEV OF .00013
AVERAGE LENGTH IS .4992 INCHES WITH A STD DEV OF .00267
AVERAGE WEIGHT IS 11.715 GRAMS WITH A STD DEV OF .18816
AVERAGE DENSITY IS 10.40 G/CC WITH A STD DEV OF .02177
AVERAGE THEORETICAL DENSITY IS 94.93 PERCENT WITH A STD DEV OF .19863

TOTAL FUEL LENGTH IS 30.4535 INCHES
TOTAL UO2 WEIGHT IS 714.587 GRAMS

PELLET 66 PLACED IN POSITION 62, ADJUSTED LENGTH = .3578 INCH, ADJUSTED WEIGHT= 8.245 GRAM

TABLE A.4. Pellet Data for Rod 4 of Instrumented Fuel Assembly (IFA)-527

PELLET POSITION	PELLET NUMBER	DIAMETER (INCHES) D=1	D=2	D=3	LENGTH (INCHES) L=1	L=2	VOID DIAMETER (INCHES)	WEIGHT (G)	DENSITY (G/CC)	DENSITY (% TD)
1	67	.4204	.4204	.4204	.4990	.4980	.0690	11.505	10.43	95.14
2	68	.4205	.4205	.4205	.4950	.4950	.0690	11.418	10.42	95.04
3	69	.4209	.4209	.4209	.4990	.4980	.0690	11.531	10.43	95.12
4	70	.4204	.4203	.4203	.4960	.4950	.0690	11.432	10.43	95.14
5	71	.4206	.4206	.4206	.4980	.4980	.0690	11.466	10.39	94.82
6	72	.4204	.4204	.4205	.5000	.5000	.0690	11.488	10.38	94.70
7	73	.4204	.4205	.4205	.4970	.4970	.0690	11.426	10.38	94.74
8	74	.4206	.4205	.4205	.5020	.5020	.0690	11.587	10.42	95.09
9	203	.4205	.4205	.4205	.5000	.5000	0.0000	11.820	10.39	94.78
10	204	.4201	.4201	.4201	.5030	.5030	0.0000	11.858	10.38	94.70
11	205	.4206	.4206	.4206	.5070	.5070	0.0000	11.990	10.39	94.77
12	206	.4205	.4206	.4207	.5050	.5050	0.0000	11.933	10.38	94.69
13	207	.4206	.4206	.4206	.5030	.5030	0.0000	11.888	10.38	94.71
14	208	.4206	.4206	.4206	.5030	.5030	0.0000	11.894	10.39	94.76
15	209	.4206	.4206	.4207	.5030	.5020	0.0000	11.866	10.37	94.61
16	211	.4204	.4204	.4204	.5050	.5060	0.0000	11.952	10.39	94.84
17	212	.4207	.4207	.4207	.4980	.4980	0.0000	11.800	10.40	94.91
18	213	.4202	.4202	.4202	.4990	.4990	0.0000	11.789	10.40	94.86
19	214	.4209	.4208	.4208	.4990	.4990	0.0000	11.830	10.40	94.90
20	215	.4205	.4206	.4206	.4970	.4980	0.0000	11.772	10.39	94.84
21	216	.4209	.4209	.4208	.5010	.5010	0.0000	11.872	10.39	94.84
22	217	.4207	.4207	.4206	.4980	.4990	0.0000	11.794	10.39	94.78
23	218	.4207	.4207	.4207	.4990	.4990	0.0000	11.834	10.41	94.99
24	219	.4205	.4205	.4205	.4990	.4980	0.0000	11.783	10.39	94.77
25	220	.4205	.4205	.4205	.5020	.5020	0.0000	11.870	10.39	94.80
26	221	.4206	.4206	.4206	.5040	.5040	0.0000	11.923	10.39	94.80
27	222	.4207	.4206	.4206	.4990	.5000	0.0000	11.823	10.39	94.84
28	223	.4206	.4206	.4206	.5020	.5010	0.0000	11.866	10.39	94.82
29	224	.4206	.4206	.4206	.4980	.4980	0.0000	11.784	10.39	94.83
30	226	.4206	.4206	.4206	.4990	.4990	0.0000	11.804	10.39	94.80
31	227	.4205	.4206	.4206	.5020	.5020	0.0000	11.901	10.41	95.02
32	228	.4207	.4207	.4206	.5020	.5020	0.0000	11.893	10.40	94.91
33	229	.4208	.4208	.4209	.5020	.5020	0.0000	11.882	10.38	94.75
34	230	.4207	.4206	.4206	.5080	.5080	0.0000	12.014	10.39	94.76
35	231	.4205	.4205	.4205	.5000	.5000	0.0000	11.826	10.39	94.83
36	232	.4208	.4209	.4209	.5020	.5020	0.0000	11.887	10.39	94.77
37	233	.4206	.4206	.4206	.5030	.5030	0.0000	11.905	10.40	94.85
38	234	.4205	.4206	.4206	.4980	.4980	0.0000	11.785	10.40	94.85
39	235	.4206	.4206	.4206	.4990	.4990	0.0000	11.802	10.39	94.78
40	236	.4206	.4207	.4207	.4970	.4970	0.0000	11.765	10.39	94.83
41	237	.4206	.4207	.4207	.5000	.5000	0.0000	11.834	10.39	94.82
42	238	.4206	.4206	.4206	.5050	.5050	0.0000	11.965	10.41	94.95
43	239	.4206	.4206	.4207	.4970	.4970	0.0000	11.761	10.39	94.82
44	240	.4209	.4209	.4209	.5040	.5040	0.0000	11.957	10.41	94.94
45	241	.4205	.4205	.4205	.5020	.5010	0.0000	11.863	10.39	94.84
46	242	.4205	.4206	.4206	.4980	.4980	0.0000	11.763	10.38	94.67
47	243	.4206	.4206	.4206	.4980	.4980	0.0000	11.767	10.38	94.69
48	75	.4205	.4205	.4205	.5010	.5020	.0690	11.528	10.38	94.71
49	76	.4204	.4205	.4205	.4970	.4970	.0690	11.447	10.40	94.91
50	77	.4204	.4204	.4204	.4960	.4960	.0690	11.410	10.39	94.83
51	78	.4205	.4205	.4205	.4920	.4930	.0690	11.328	10.39	94.77
52	79	.4205	.4205	.4205	.5010	.5020	.0690	11.552	10.40	94.91
53	80	.4205	.4205	.4205	.5010	.5020	.0690	11.521	10.37	94.65
54	320	.4205	.4204	.4204	.4990	.4990	.0690	11.453	10.37	94.60
55	321	.4207	.4207	.4207	.5020	.5020	.0690	11.560	10.39	94.79
56	322	.4205	.4205	.4204	.5050	.5040	.0690	11.581	10.37	94.60
57	323	.4205	.4205	.4205	.5070	.5060	.0690	11.654	10.39	94.80
58	325	.4205	.4205	.4205	.5070	.5070	.0690	11.663	10.39	94.78
59	327	.4204	.4204	.4204	.5060	.5070	.0690	11.653	10.39	94.84
60	328	.4205	.4205	.4205	.5040	.5030	.0690	11.573	10.38	94.70

AVERAGE DIAMETER IS .4206 INCHES WITH A STD DEV OF .00015
AVERAGE LENGTH IS .5007 INCHES WITH A STD DEV OF .00328
AVERAGE WEIGHT IS 11.735 GRAMS WITH A STD DEV OF .17891
AVERAGE DENSITY IS 10.39 G/CC WITH A STD DEV OF .01331
AVERAGE THEORETICAL DENSITY IS 94.82 PERCENT WITH A STD DEV OF .12140

TOTAL FUEL LENGTH IS 30.0435 INCHES
TOTAL UO2 WEIGHT IS 704.091 GRAMS

PELLET 329 PLACED IN POSITION 61, ADJUSTED LENGTH = .2823 INCH, ADJUSTED WEIGHT= 6.493 GRAM

TABLE A.5. Pellet Data for Rod 5 of Instrumented Fuel Assembly (IFA)-527

PELLET POSITION	PELLET NUMBER	DIAMETER (INCHES) D-1	D-2	D-3	LENGTH (INCHES) L-1	L-2	VOID DIAMETER (INCHES)	WEIGHT (G)	DENSITY (G/CC)	DENSITY (%TD)
1	330	.4204	.4204	.4203	.5080	.5080	.0690	11.667	10.38	94.69
2	331	.4205	.4206	.4206	.4950	.4960	.0690	11.407	10.39	94.82
3	332	.4204	.4204	.4205	.5030	.5040	.0690	11.578	10.39	94.78
4	333	.4205	.4205	.4206	.5050	.5060	.0690	11.641	10.40	94.87
5	334	.4205	.4205	.4205	.5000	.5010	.0690	11.532	10.40	94.93
6	335	.4204	.4204	.4205	.4980	.4980	.0690	11.485	10.42	95.05
7	336	.4206	.4205	.4205	.5010	.5010	.0690	11.564	10.42	95.09
8	337	.4207	.4207	.4206	.4990	.4990	.0690	11.497	10.40	94.85
9	244	.4205	.4205	.4206	.5020	.5020	0.0000	11.854	10.37	94.66
10	245	.4205	.4205	.4206	.4990	.4990	0.0000	11.815	10.40	94.91
11	246	.4206	.4206	.4206	.5040	.5040	0.0000	11.929	10.40	94.85
12	247	.4205	.4205	.4205	.5020	.5030	0.0000	11.893	10.40	94.89
13	248	.4206	.4206	.4206	.5000	.5000	0.0000	11.824	10.39	94.77
14	249	.4206	.4205	.4205	.5020	.5010	0.0000	11.882	10.41	94.98
15	250	.4205	.4205	.4205	.5040	.5040	0.0000	11.941	10.41	94.99
16	251	.4205	.4205	.4206	.5040	.5040	0.0000	11.940	10.41	94.97
17	252	.4206	.4206	.4206	.5000	.5000	0.0000	11.823	10.39	94.76
18	253	.4205	.4205	.4206	.4990	.4990	0.0000	11.794	10.38	94.75
19	254	.4206	.4206	.4206	.5070	.5070	0.0000	12.004	10.40	94.88
20	256	.4205	.4206	.4206	.4940	.4940	0.0000	11.683	10.39	94.79
21	257	.4206	.4205	.4205	.4990	.5000	0.0000	11.807	10.39	94.75
22	258	.4209	.4208	.4208	.5000	.5010	0.0000	11.869	10.40	94.93
23	259	.4206	.4206	.4205	.5000	.5000	0.0000	11.843	10.40	94.93
24	260	.4206	.4206	.4206	.5080	.5080	0.0000	12.000	10.37	94.66
25	261	.4206	.4205	.4205	.4970	.4970	0.0000	11.744	10.38	94.72
26	262	.4205	.4205	.4205	.5030	.5030	0.0000	11.893	10.39	94.80
27	263	.4205	.4205	.4205	.4870	.4870	0.0000	11.519	10.39	94.83
28	264	.4206	.4206	.4206	.4910	.4910	0.0000	11.596	10.37	94.64
29	265	.4205	.4205	.4204	.4970	.4970	0.0000	11.744	10.38	94.75
30	466	.4205	.4205	.4204	.4980	.4980	0.0000	11.767	10.38	94.75
31	267	.4205	.4205	.4205	.4990	.4990	0.0000	11.822	10.41	94.99
32	268	.4208	.4208	.4209	.4990	.4990	0.0000	11.804	10.38	94.69
33	269	.4206	.4206	.4206	.4990	.4990	0.0000	11.787	10.37	94.66
34	270	.4208	.4208	.4209	.5020	.5010	0.0000	11.916	10.42	95.11
35	271	.4204	.4204	.4204	.5010	.5010	0.0000	11.830	10.38	94.72
36	272	.4205	.4205	.4205	.5000	.5010	0.0000	11.824	10.38	94.72
37	273	.4206	.4206	.4206	.4980	.4980	0.0000	11.796	10.40	94.92
38	274	.4206	.4206	.4206	.4950	.4960	0.0000	11.778	10.44	95.25
39	275	.4209	.4209	.4209	.5050	.5060	0.0000	12.008	10.42	95.06
40	276	.4206	.4206	.4206	.5060	.5060	0.0000	12.001	10.42	95.04
41	277	.4206	.4206	.4206	.5000	.5000	0.0000	11.868	10.43	95.12
42	278	.4206	.4206	.4206	.5050	.5050	0.0000	11.980	10.42	95.07
43	279	.4206	.4206	.4206	.4870	.4870	0.0000	11.564	10.43	95.16
44	280	.4206	.4206	.4206	.4860	.4860	0.0000	11.538	10.43	95.14
45	281	.4206	.4206	.4206	.4880	.4880	0.0000	11.590	10.43	95.18
46	282	.4205	.4205	.4205	.4960	.4960	0.0000	11.761	10.42	95.07
47	283	.4204	.4204	.4204	.4860	.4860	0.0000	11.521	10.42	95.09
48	338	.4205	.4205	.4206	.5020	.5030	.0690	11.585	10.41	94.98
49	339	.4204	.4204	.4204	.4980	.4990	.0690	11.476	10.40	94.90
50	340	.4206	.4207	.4207	.5020	.5030	.0690	11.590	10.41	94.95
51	341	.4205	.4205	.4206	.5000	.5000	.0690	11.505	10.39	94.79
52	342	.4205	.4205	.4205	.4990	.5000	.0690	11.522	10.42	95.04
53	343	.4205	.4205	.4205	.4990	.4980	.0690	11.488	10.41	94.95
54	344	.4206	.4206	.4205	.4980	.4980	.0690	11.468	10.40	94.85
55	345	.4206	.4206	.4206	.4940	.4940	.0690	11.378	10.40	94.85
56	346	.4206	.4207	.4207	.4910	.4910	.0690	11.308	10.39	94.81
57	347	.4204	.4204	.4204	.4910	.4910	.0690	11.292	10.39	94.80
58	348	.4204	.4204	.4204	.4930	.4940	.0690	11.362	10.40	94.91
59	349	.4204	.4204	.4204	.4940	.4940	.0690	11.383	10.41	94.99
60	350	.4205	.4205	.4205	.4920	.4910	.0690	11.319	10.40	94.89
61	351	.4204	.4204	.4203	.4950	.4950	.0690	11.388	10.40	94.85

AVERAGE DIAMETER IS .4206 INCHES WITH A STD DEV OF .00011
AVERAGE LENGTH IS .4985 INCHES WITH A STD DEV OF .00534
AVERAGE WEIGHT IS 11.688 GRAMS WITH A STD DEV OF .20307
AVERAGE DENSITY IS 10.40 G/CC WITH A STD DEV OF .01615
AVERAGE THEORETICAL DENSITY IS 94.89 PERCENT WITH A STD DEV OF .14734

TOTAL FUEL LENGTH IS 30.4115 INCHES
TOTAL UO2 WEIGHT IS 712.987 GRAMS

PELLET 352 PLACED IN POSITION 62, ADJUSTED LENGTH = .2415 INCH, ADJUSTED WEIGHT= 5.559 GRAM

TABLE A.6. Pellet Data for Rod 6 of Instrumented Fuel Assembly (IFA)-527

PELLET POSITION	PELLET NUMBER	DIAMETER (INCHES) D-1	D-2	D-3	LENGTH (INCHES) L-1	L-2	VOID DIAMETER (INCHES)	WEIGHT (G)	DENSITY (G/CC)	DENSITY (%TD)
1	836	.4277	.4276	.4276	.5060	.5070	.0700	12.135	10.46	95.44
2	837	.4277	.4276	.4276	.5060	.5070	.0700	12.135	10.46	95.44
3	838	.4278	.4278	.4277	.5060	.5070	.0700	12.117	10.44	95.23
4	839	.4276	.4277	.4277	.5070	.5080	.0700	12.147	10.45	95.33
5	840	.4277	.4278	.4278	.5100	.5110	.0700	12.217	10.44	95.27
6	841	.4276	.4276	.4275	.5070	.5080	.0700	12.123	10.43	95.18
7	842	.4277	.4277	.4276	.5050	.5060	.0700	12.069	10.42	95.09
8	870	.4278	.4278	.4278	.5040	.5050	0.0000	12.420	10.45	95.36
9	871	.4278	.4278	.4278	.5060	.5070	0.0000	12.461	10.44	95.30
10	872	.4277	.4278	.4278	.5080	.5090	0.0000	12.516	10.45	95.36
11	873	.4277	.4276	.4276	.5090	.5100	0.0000	12.526	10.45	95.31
12	874	.4276	.4276	.4276	.5090	.5100	0.0000	12.534	10.45	95.38
13	875	.4277	.4277	.4276	.5090	.5100	0.0000	12.543	10.46	95.42
14	876	.4278	.4278	.4277	.5040	.5050	0.0000	12.432	10.46	95.47
15	877	.4277	.4278	.4278	.5060	.5070	0.0000	12.473	10.46	95.41
16	878	.4277	.4277	.4277	.5060	.5070	0.0000	12.438	10.43	95.17
17	879	.4277	.4277	.4278	.5040	.5050	0.0000	12.426	10.46	95.44
18	880	.4276	.4277	.4277	.5070	.5080	0.0000	12.502	10.47	95.48
19	882	.4276	.4276	.4277	.5080	.5090	0.0000	12.501	10.45	95.30
20	883	.4277	.4277	.4277	.5100	.5110	0.0000	12.541	10.43	95.20
21	884	.4278	.4278	.4277	.5060	.5070	0.0000	12.451	10.44	95.24
22	885	.4277	.4277	.4278	.5090	.5100	0.0000	12.546	10.46	95.41
23	886	.4277	.4277	.4276	.5090	.5100	0.0000	12.541	10.46	95.41
24	887	.4276	.4276	.4277	.5080	.5090	0.0000	12.514	10.46	95.40
25	888	.4277	.4277	.4276	.5090	.5100	0.0000	12.527	10.44	95.30
26	889	.4277	.4277	.4277	.5110	.5120	0.0000	12.577	10.44	95.29
27	890	.4277	.4278	.4278	.5080	.5090	0.0000	12.513	10.45	95.34
28	893	.4278	.4278	.4277	.5100	.5110	0.0000	12.582	10.47	95.49
29	894	.4276	.4277	.4277	.5100	.5110	0.0000	12.554	10.45	95.32
30	895	.4277	.4276	.4276	.5110	.5120	0.0000	12.593	10.46	95.44
31	896	.4278	.4278	.4278	.5080	.5090	0.0000	12.515	10.45	95.34
32	899	.4276	.4277	.4277	.5040	.5040	0.0000	12.400	10.45	95.36
33	901	.4278	.4277	.4276	.5010	.5020	0.0000	12.343	10.45	95.38
34	902	.4278	.4278	.4278	.4980	.4990	0.0000	12.285	10.46	95.46
35	904	.4276	.4276	.4277	.4980	.4990	0.0000	12.260	10.45	95.34
36	905	.4278	.4278	.4278	.4960	.4970	0.0000	12.214	10.44	95.29
37	906	.4278	.4278	.4277	.5060	.5070	0.0000	12.460	10.45	95.31
38	907	.4277	.4278	.4277	.4960	.4970	0.0000	12.210	10.44	95.29
39	908	.4278	.4278	.4277	.5030	.5040	0.0000	12.401	10.46	95.42
40	909	.4276	.4277	.4277	.5080	.5090	0.0000	12.521	10.46	95.44
41	910	.4277	.4277	.4277	.4980	.4990	0.0000	12.282	10.46	95.48
42	911	.4277	.4278	.4278	.4940	.4950	0.0000	12.182	10.46	95.44
43	912	.4278	.4278	.4277	.4950	.4960	0.0000	12.209	10.46	95.46
44	913	.4277	.4277	.4278	.4950	.4960	0.0000	12.197	10.45	95.38
45	914	.4278	.4277	.4278	.4980	.4990	0.0000	12.252	10.44	95.22
46	843	.4276	.4276	.4276	.5050	.5050	.0700	12.088	10.45	95.36
47	844	.4276	.4276	.4276	.5050	.5060	.0700	12.106	10.46	95.41
48	845	.4277	.4277	.4277	.5080	.5090	.0700	12.184	10.46	95.41
49	846	.4277	.4277	.4278	.5050	.5060	.0700	12.098	10.44	95.29
50	847	.4276	.4276	.4277	.5090	.5100	.0700	12.199	10.45	95.37
51	848	.4276	.4276	.4277	.5080	.5090	.0700	12.154	10.43	95.21
52	849	.4276	.4276	.4276	.5060	.5070	.0700	12.137	10.46	95.47
53	850	.4279	.4279	.4278	.5050	.5060	.0700	12.111	10.45	95.33
54	851	.4278	.4278	.4277	.5100	.5110	.0700	12.240	10.46	95.45
55	852	.4277	.4277	.4276	.5110	.5120	.0700	12.210	10.42	95.07
56	853	.4276	.4277	.4277	.5080	.5090	.0700	12.163	10.44	95.26
57	854	.4276	.4277	.4277	.5050	.5060	.0700	12.118	10.46	95.48
58	855	.4278	.4277	.4276	.5070	.5080	.0700	12.152	10.45	95.35
59	856	.4276	.4276	.4276	.5060	.5070	.0700	12.123	10.45	95.36
60	856	.4276	.4276	.4276	.5060	.5070	.0700	12.123	10.45	95.36

AVERAGE DIAMETER IS .4277 INCHES WITH A STD DEV OF .00008
AVERAGE LENGTH IS .5060 INCHES WITH A STD DEV OF .00439
AVERAGE WEIGHT IS 12.327 GRAMS WITH A STD DEV OF .17316
AVERAGE DENSITY IS 10.45 G/CC WITH A STD DEV OF .01046
AVERAGE THEORETICAL DENSITY IS 95.35 PERCENT WITH A STD DEV OF .00546

TOTAL FUEL LENGTH IS 30.3590 INCHES
TOTAL UO2 WEIGHT IS 739.591 GRAMS

ONLY 60 PELLETS USED IN ROD 6

TABLE A.7. Immersion Densities of Archive Instrumented Fuel Assembly (IFA)-527 Fuel Pellets

Pellet Batch and Number	Geometric Density, %TD	Immersion Density, % TD	
		First Test[a]	Second Test[b]
2-210	--	95.36	95.43
2-300	--	95.81	95.80
3-470	94.72	95.53	95.46
3-633	--	95.53	95.48
4-677	94.84	95.44	95.51
4-688	94.59	95.47	95.55
4-822	95.07	95.36	95.35
4-835	95.01	95.65	95.68
4-978	95.30	96.29	96.29
4-984	95.39	96.18	96.25

(a) July 5, 1978.
(b) July 6, 1978.

APPENDIX B

CLADDING CHARACTERIZATION

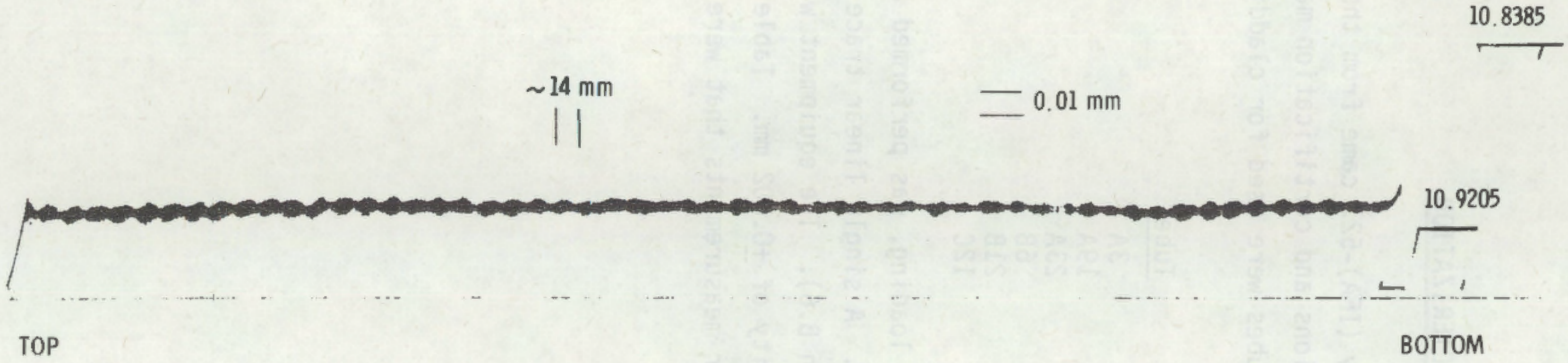
APPENDIX B

CLADDING CHARACTERIZATION

Tubing for instrumented fuel assembly (IFA)-527 came from the same batch obtained for IFA-431 and -432; specifications and certification may be found in BNWL-1988. The following Zircaloy-2 tubes were used for cladding:

Rod Number	Tube
1	3A
2	19A
3	23A
4	6B
5	21B
6	12C

Internal profilometry, prior to fuel loading, was performed by Kjeller. A continuous recording air gauge was used. A single linear trace at 0° was made for each rod (see Figures B.1 through B.6). The equipment was calibrated with calibration rings and has a sensitivity of ±0.002 mm. Table B.1 contains discrete cladding outer and inner diameter measurements that were taken manually.



ID MEASUREMENT WITH CONTINUOUS RECORDING AIR GAUGE

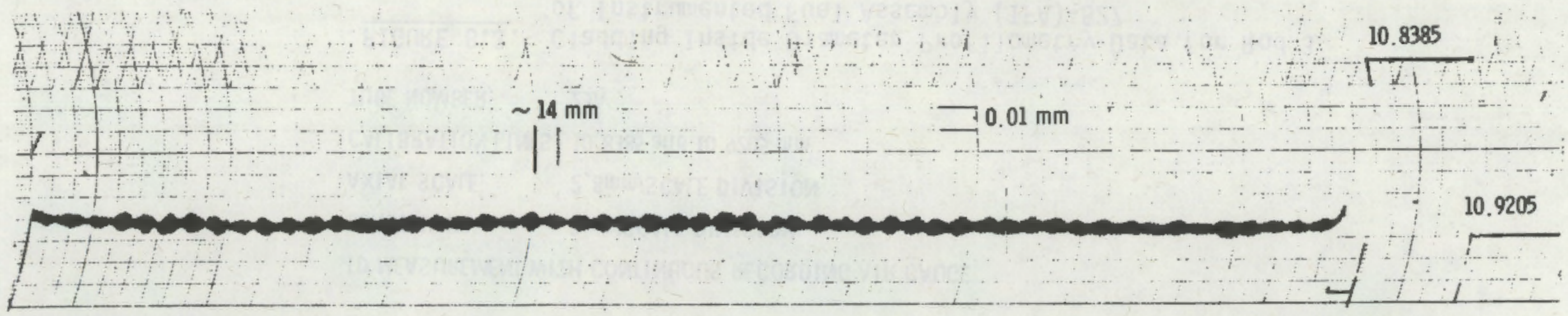
SENSITIVITY: 2 μm/SCALE DIVISION

AXIAL SCALE: 2.8mm/SCALE DIVISION

CALIBRATION LINES: 10.8385 and 10.9205 mm

TUBE NUMBER: 3A

FIGURE B.1. Cladding Inside Diameter Profilometry Data for Rod 1 of Instrumented Fuel Assembly (IFA)-527



ID MEASUREMENT WITH CONTINUOUS RECORDING AIR GAUGE

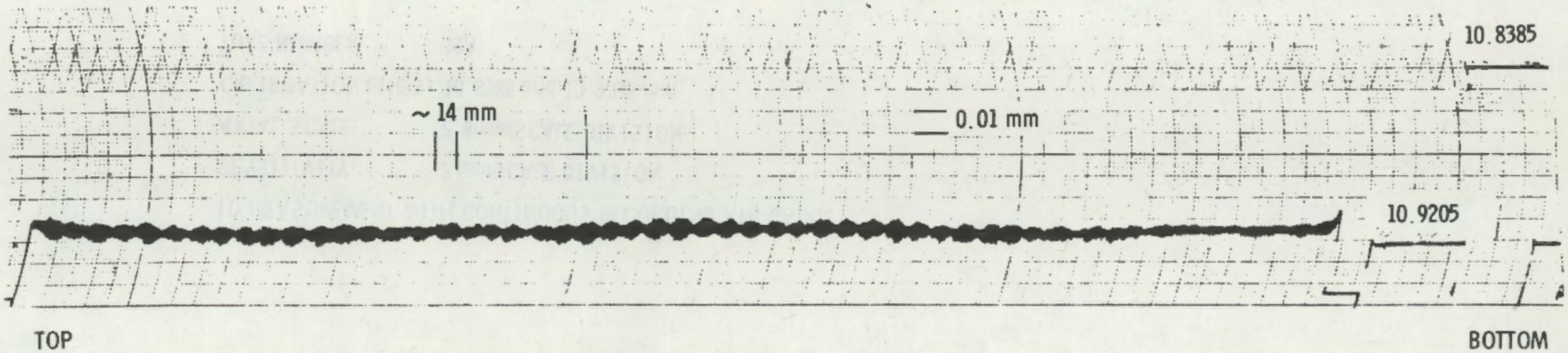
SENSITIVITY: 2 µm/SCALE DIVISION

AXIAL SCALE: 2.8mm/SCALE DIVISION

CALIBRATION LINES: 10.8385 and 10.9205 mm

TUBE NUMBER: 19A

FIGURE B.2. Cladding Inside Diameter Profilometry Data for Rod 2 of Instrumented Fuel Assembly (IFA)-527



ID MEASUREMENT WITH CONTINUOUS RECORDING AIR GAUGE

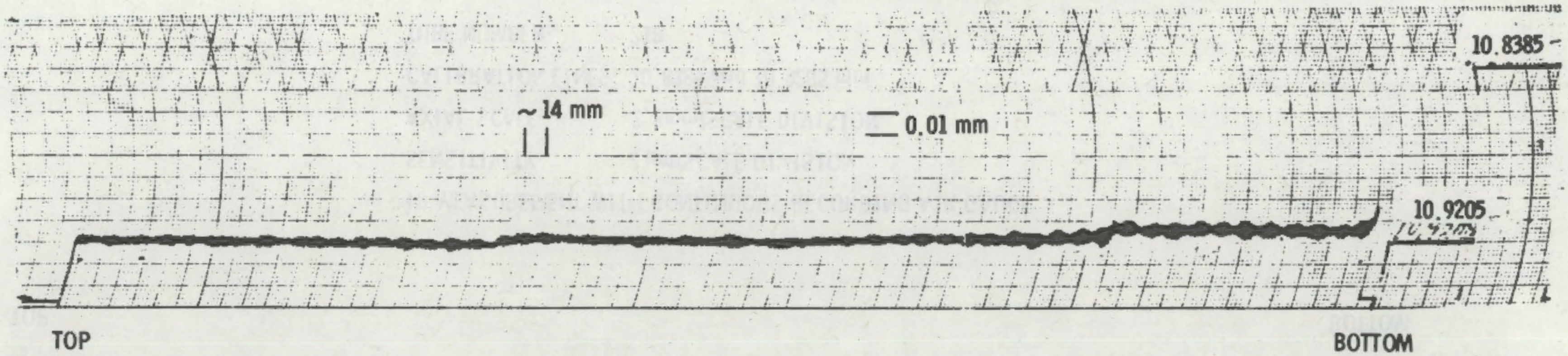
SENSITIVITY: 2 μm/SCALE DIVISION

AXIAL SCALE: 2.8mm/SCALE DIVISION

CALIBRATION LINES: 10.8385 and 10.9205 mm

TUBE NUMBER: 23A

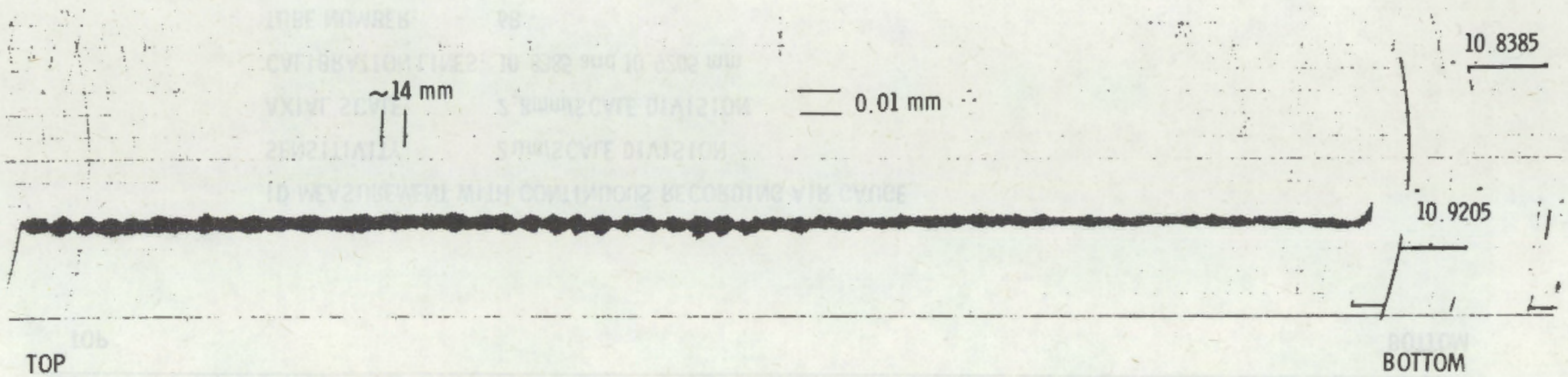
FIGURE B.3. Cladding Inside Diameter Profilometry Data for Rod 3 of Instrumented Fuel Assembly (IFA)-527



ID MEASUREMENT WITH CONTINUOUS RECORDING AIR GAUGE

SENSITIVITY:	2 µm/SCALE DIVISION
AXIAL SCALE:	2.8mm/SCALE DIVISION
CALIBRATION LINES:	10.8385 and 10.9205 mm
TUBE NUMBER:	6B

FIGURE B.4. Cladding Inside Diameter Profilometry Data for Rod 4 of Instrumented Fuel Assembly (IFA)-527



ID MEASUREMENT WITH CONTINUOUS RECORDING AIR GAUGE

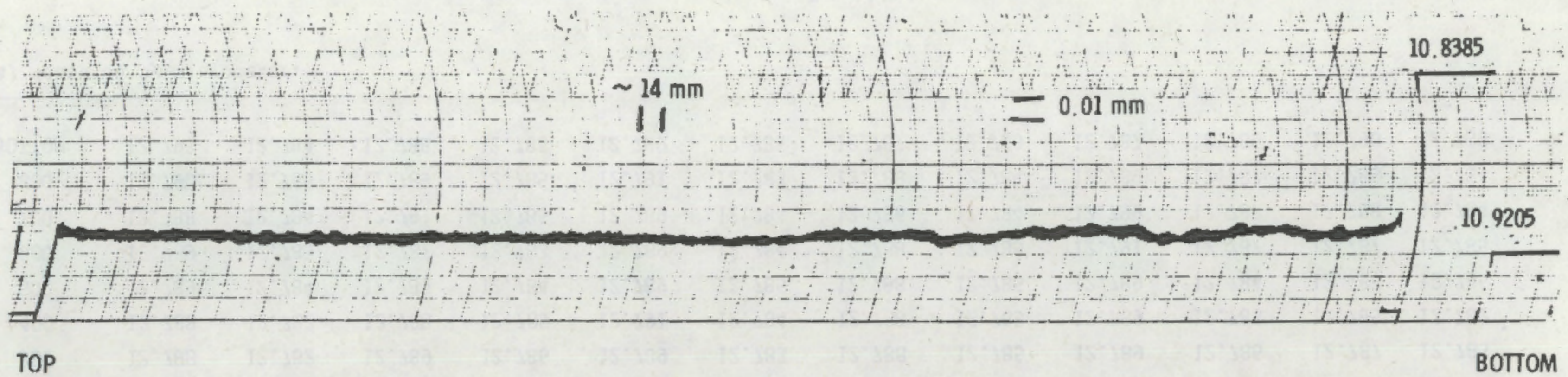
SENSITIVITY: 2 μm/SCALE DIVISION

AXIAL SCALE: 2.8mm/SCALE DIVISION

CALIBRATION LINES: 10.8385 and 10.9205 mm

TUBE NUMBER: 21B

FIGURE B.5. Cladding Inside Diameter Profilometry Data for Rod 5 of Instrumented Fuel Assembly (IFA)-527



ID MEASUREMENT WITH CONTINUOUS RECORDING AIR GAUGE

SENSITIVITY: 2 μm/SCALE DIVISION

AXIAL SCALE: 2.8mm/SCALE DIVISION

CALIBRATION LINES: 10.8385 and 10.9205 mm

TUBE NUMBER: 12C

FIGURE B.6. Cladding Inside Diameter Profilometry Data for Rod 6 of Instrumented Fuel Assembly (IFA)-527

TABLE B.1. Cladding Outer Diameter Measurements

Distance from Top of Rod, mm	Cladding Outer Diameter,[a] mm											
	Rod 1		Rod 2		Rod 3		Rod 4		Rod 5		Rod 6	
	max	min	max	min	max	min	max	min	max	min	max	min
TOP	12.789	12.785	12.791	12.787	12.788	12.784	12.789	12.784	12.790	12.787	12.784	12.779
100	12.788	12.783	12.789	12.784	12.790	12.785	12.788	12.785	12.789	12.787	12.787	12.785
200	12.789	12.785	12.788	12.784	12.789	12.785	12.790	12.785	12.790	12.788	12.788	12.783
300	12.788	12.782	12.789	12.786	12.789	12.783	12.788	12.785	12.789	12.786	12.787	12.783
400	12.788	12.782	12.788	12.785	12.791	12.784	12.788	12.785	12.789	12.785	12.785	12.782
500	12.789	12.784	12.789	12.784	12.789	12.785	12.788	12.785	12.789	12.784	12.788	12.785
600	12.789	12.783	12.787	12.783	12.789	12.784	12.788	12.785	12.791	12.787	12.787	12.785
700	12.788	12.784	12.791	12.785	12.789	12.784	12.786	12.784	12.789	12.787	12.788	12.784
800	12.790	12.785	12.789	12.785	12.791	12.783	12.788	12.784	12.789	12.787	12.788	12.784
BOTTOM	12.793	12.784	12.788	12.785	12.789	12.785	12.787	12.783	12.787	12.786	12.790	12.785

(a) Measured by micrometer.

APPENDIX C

FUEL FABRICATION

APPENDIX C

FUEL FABRICATION

ADDITIONAL PELLETS FOR HALDEN ASSEMBLIES[(a)]

Preproduction Sinterability Test Plan

1. Purpose of Test

The purpose of this test is to qualify a cold wall refractory metal furnace to successfully sinter a 4-kg batch of pellets made with depleted powder. Approximately 24 pellets of Halden material will be included to establish parameters for the production of Halden pellets.

2. Modifications to Molybdenum Boats

The molybdenum boats used to load material into the furnace need to have randomly spaced holes of approximately 1/8-in. diameter drilled in the bottom. This should increase the circulation of the H_2 over the pellets.

3. Special Instructions for Handling Halden Material

- granulate "as-received" UO_2 to pass through a 100-mesh screen
- run tap density
- slug 300 g of powder in three 100-g increments, using the 2-in. die and approximately 5-ton pressure; record slug size and density
- granulate the slugs to 20 mesh
- blend 0.4% sterotex in the combined 300-g lot
- press pellets (approximately 12 g each) with existing pellet die (normal 0.541-in. diameter pellets with flat ends) using a pressure range from 3 to 5 tons; target density range should be 5.2 ± 0.1 g/cm^3; record pressure, dimensions, and weight and calculate the green pellet density; bubble test for integrity and identify each pellet.

(a) Prepared by J. E. Spasoff; reviewed by N. C. Davis.

- drill three of the green pellets with a No. 43 tungsten carbide drill 0.089 in.

4. Sintering Parameters

- heating rate approximately 100°C/h
- soak 8 h at 1700°C $\pm$20°C
- furnace cool approximately 400°C/h
- furnace operating data supplied by circular chart.

5. Final Test Evaluation

- record the as-sintered weight of pellets
- record minimum diameter of each pellet
- grind pellets to cleanup diameter
- measure, weigh, and calculate density
- break a pellet to inspect microstructure visually
- record results and recommendations for production
- prepare production process parameter sheet for approval.

6. Preparation of Depleted UO_2 Powder

- 4 kg of depleted UO_2 powder will be handled in the same manner as the Halden powder.

Note: If this sinterability test proves successful for both the performance of the furnace and the Halden material, production of the 10% pellets could be started.

Sinterability Test

Date: ______

Powder Identification and Preparation:

Oak Ridge Powder Lot 30-2785

Same as released for IFA-513 pellets

Slug Data: Quantity ~300 grams

Diameter	Length	Weight	Density
2.010	0.443	101.60	~4.4
2.010	0.465	99.75	~4.15
2.010	0.460	100.7	~4.22

Sintered Run Number BREW #31

Sintered Pellet ______

Green Pellet

Green Diameter 0.5407 Dish V.V. ______ Sintered V.V. ______

Calculation Factor ______ Calculation Factor ______

Green Weight 194 net Sintered Weight 190 net

X = Cored

Pellet Number	Length "inches"	Weight grams	Volume cm^3	Density g/cm^3	Sinter Diameter	Ground Diameter	Length "inches"	Weight	g/cm^3 Density
10-1	0.673	12.809		5.06	0.423	0.4202	0.525	12.373	10.3705
-2	0.872	16.528		5.09	0.422	0.4186	0.680	15.913	10.3769
-3	0.562	10.837		5.12	0.4255	0.4237	0.440	10.542	10.3699
-4	0.498	9.670		5.16	0.4255	0.4237	0.392	9.394	10.3723
-5	0.498	9.764		5.21	0.427	0.4237	0.393	9.420	10.3746
-6	0.499	9.745		5.19	0.427	0.4237	0.392	9.408	10.3878
X -7	0.490	9.642		5.23	0.428	0.4237	0.387	8.999	
X -8	0.490	9.671		5.24	0.428	0.4237	0.388	9.034	
-9	0.492	9.677		5.23	0.428	0.4237	0.388	9.300	10.3744
-10	0.493	9.724		5.24	0.428	0.4237	0.390	9.341	10.3667
-11	0.481	9.758		5.39	0.4315	0.4298	0.384	9.496	10.4013
-12	0.479	9.724		5.39	0.4315	0.4298	0.382	9.453	10.4084
X -13	0.468	9.827		5.58	0.4365	0.4298	0.377	9.037	
X -14	0.468	9.712		5.51	0.436	0.4298	0.373	8.978	
-15	0.467	9.750		5.55	0.435	0.4298	0.374	9.308	10.4680
-16	0.466	9.700		5.53	0.4345	0.4298	0.375	9.308	10.4401
-17	0.464	9.640		5.52	0.434	0.4298	0.372	9.242	10.4497
X -18	0.456	9.713		5.66	0.4385	0.4352	0.367	9.088	
X -19	0.454	9.621		5.63	0.4385	0.4352	0.364	9.023	

EVALUATION OF SINTERABILITY-PREPRODUCTION TEST 31

Preproduction test 31 (10% enriched UO_2) confirmed the previous satisfactory results on the same powder lot, processed as IFA-513, Batch 1. The 4-kg batch of depleted pellets sintered in this run was completely satisfactory, qualifying the furnace for production. Density and dimensional results provide assurance that parameters can be established to fabricate the additional Halden pellets. The following observations and comments are based on the test results and the proposed parameters for processing:

- A visual inspection of the pellets indicated good physical integrity. The cross section appearance of a fractured pellet showed uniform microstructure.
- The new molybdenum boats, with the perforations for gas distribution shall be used, with 100% H_2 flowing through water until the temperature is greater than 900°C. From 900 to 1700°C, gas may be 50% H_2 and 50% Ar, with the H_2 continuous through the water.
- The only powder pretreatment necessary is to reduce it to pass a 100-mesh screen prior to slugging.
- The press tooling previously used is satisfactory. Pellets pressed to 5.15 $\pm$0.05 g/cm^3 will yield the required 0.4205-in. diameter with minimum grinding. Pellets (136 quantity) that require a finished diameter of 0.4275 in. should be pressed to a green density of 5.45 g/cm^3. This should be reconfirmed with a sample in the first production batch of the smaller pellets.
- The pressed length should be held to 0.636 $\pm$0.010 in. to maintain the specified sintered length of 0.500 in. High green density pellets should be checked since they will reduce less.
- The drill used for thermocouple hole 43 produced a final inside diameter of 0.069 to 0.070 in., which is within the specifications.

- Extremely uniform distribution of the sterotex will be necessary to maintain the 95% ±0.5% density.
- The process parameter sheet and density control charts are being prepared for approval and release for production.

Date 5-1-78

Rev. 1 - 6-22-78

Pellet Fabrication Process Parameters*
Oak Ridge Batch 30-2785

Project Halden W026209 Powder Lot No. -- Enrichment 10% Release 2

Pellet Specifications: Reference Previous Halden IFA-513 Release

Application	Quantity	Density ± 0.75%	Diameter ± 0.0005"	Length ± 0.010"	Dish Dimensions Spherical R. ± 0.02	Depth ± 0.002
(Additional Halden IFA-513 Pellets)	835	95.0%	0.4205	0.500	Flat ends Drill 25% or 209 with #43 drill	
	136	95.0%	0.4275	0.500	Flat ends Drill 25% or 34 each with #43 drill	

Powder Preparation: Maximum Batch Size: 560 grams see CSS-306-1.3

Powder Blending Time: all -100M homogenous

Slug Density 4.3 ± 0.1 Slug Size ~100 g Control Chart Plot ~10%

Granulate -20 Mesh: Lubricant 0.3 ± 0.1 Weight %

Special Instructions: Process in 3 pellet batch - Batch 2, 3 and 4 (Batch 1 was original IFA 513 pellets) ~324 pellets per batch with Batch 4 including the 136 pellet to be ground 0.4275" diameter

Pellet Pressing and Sintering

Green Density 5.15 ± 0.05 *1 gm/cm^3 Length ~0.635 Control Chart ~10% *2

Press Tooling Use flat face punch and die that yields 0.541" gram pellet

Sintering Heating Rate 100°/h to 1000°C 200°/h to 1700°C Maximum Temperature 1700 °C: Time 8 Hours

Cooling Rate 400 H_2 Flow *100% to 900°C & 50-50% H_2-AR to 1700 Purge Argon

Special Instructions: H_2 Flow - through water bubbler 100% H_2 to > 900°C 50% H_2 - 50% AR from ~900 to 1700°C 8 hr.

Grind pellets in accordance with above diameter specification, clean in Ultrasonic Alcohol Bath and dry 100°C ± 10°C for one hour. Inspection in accordance with Batch Inspection sample plan.

Comments: *1 5.15 g/cm^3 for all the 0.4205 dia pellets, increase green density to 5.45 for the larger 0.4275 pellets

*2 Number all pellets plot ~5 to 10 pellets at start of pressing or any re-start ~10% during pressing

Prepared by: JE Spasoff & NC Davis Date: 6-22-78 Approved by: Date:

*Process parameters as listed are based on final sinterability or pre-production Test Results. (Attached)

Pellet Fabrication Follower Data Sheet

Date 5/2/78

Project Halden w/o 26209 Lot Number Oak Ridge Batch #2 30-2785 Enrichment 9.9% Release 2

Powder Preparation: (Control chart attached)

Slug Density 4.3 ± 0.1 Slug Size ~100 grams

Granulate 4000 -20 + 100 mesh NA -100 mesh NA Re-slug

Lubricant 0.3% w/o sterotex 12 grams 4000+12=4012 grams UO_2

Blend 10 Min. Operator

Comments Had 107 g. left from sinterability test, which had 0.4% sterotex added. Ball milled 4012 grams for 5 min. Then added the 107 grams with 0.4% sterotex and blended 5 min. more. Total wt. UO_2 powder = 4118 grams.

Pellet Pressing: Batch No. 2 Identification Each pellet numbered

Green Density ~5.15 Green Length .636 Quantity 3904

(See control chart attached)

Pellet Sintering: Furnace Run No. Brew #32 Date 5/3/78

Time 8 hours Temperature 1700° C Pyrometer -

Average Pellet Diameter 0.425 Batch Weight 3859

Operator NCD/JEL/JES

Pellet Grinding: Specified Diameter Grind 319 pellets to 0.4205 ± .0005

Batch Weight 3802 grams

Operator JEL

Pellet Cleaning & Drying: Cleaned with ethyl alcohol in ultrasonic cleaner. Dried for 2 hrs. at 80-85° C Operator JES

Batch Inspection 100% Diameter .4205±.0005 Length .500±0.01 Dish - Dens.

100% Visual 100% Chips & Cracks

Analytical DB-122 Composite X Isotopic X Chemical X Oxygen/Uranium X Uranium

Comments Pellet #162

Pellet Fabrication Follower Data Sheet

Oak Ridge Batch #3 — Date 5/3/78

Project Halden w/o 26209 Lot Number 30-2785 Enrichment 9.9% Release 2

Powder Preparation: (Control chart attached)

Slug Density 4.3 ± 0.1 Slug Size ~100 grams

Granulate 4200 -20 + 100 mesh NA -100 mesh NA Re-slug

Lubricant 0.3% w/o sterotex 12.6 grams 4200+12.6=4212.6 grams UO_2

Blend 10 Min. Operator JES

Comments Blended in ball mill for 10 minutes. Total UO_2 weight 4212.6

Pellet Pressing: Batch No. 3 Identification Each pellet numbered

Green Density ~5.15 Green Length .636 Quantity 4205

(See control chart attached)

Pellet Sintering: Furnace Run No. Brew #33 Date 5/8/78

Time 8 hours Temperature 1700° C Pyrometer -

Average Pellet Diameter 0.425 Batch Weight 3932

Operator JEL/NCD/JES

Pellet Grinding: Specified Diameter Grind 320 pellets to 0.4205 ± .0005

Batch Weight 3820 grams

Operator JEL

Pellet Cleaning & Drying: Cleaned with ethyl alcohol in ultrasonic cleaner. Dried for 2 hrs. at 80-85° C. 3724 grams net Operator JES

Batch Inspection 100% Diameter .4205±.0005 Length .500±0.01 Dish - Dens.

100% Visual 100% Chips & Cracks

Analytical DB-122 Composite X Isotopic X Chemical

S Oxygen/Uranium S Uranium

Comments Pellet #418

Pellet Fabrication Follower Data Sheet

Date 5/5/78

Project Halden w/o 26209 Lot Number Oak Ridge Batch #4 30-2785 Enrichment 9.9% Release 2

Powder Preparation: (Control chart attached)

Slug Density 4.3 ± 0.1 Slug Size ~100 grams

Granulate 4009 -20 + 100 mesh NA -100 mesh NA Re-slug

Lubricant 0.3% w/o sterotex 12.03 grams 4009+12.03=4021.03 grams UO_2

Blend 10 Min. Operator JES

Comments Blended in ball mill for 10 minutes. Added ~380 grams powder left over from batch #3 pressing operation. Blended an additional 3 minutes.

Pellet Pressing: Batch No. 4 Identification Each pellet numbered

Green Density ~5.15 & 5.45 Green Length ~.636 Quantity 4399

(See control chart attached)

Pellet Sintering: Furnace Run No. Brew #34 Date 5/11/78

Time 8 hrs. Temperature 1700° C Pyrometer -

Average Pellet Diameter 0.425 and 0.434 Batch Weight 4369

Operator JEL/NCD/JES

Pellet Grinding: Specified Diameter Grind 195 pellets to .4205 ± .0005 and

Batch Weight 4293 grams 150 pellets to .4295 ± .0005

Operator JES

Pellet Cleaning & Drying: Cleaned with ethyl alcohol in ultrasonic cleaner. Dried for 10 minutes at 80-85° C Operator JES

Batch Inspection 100% Diameter .4205 ± .0005 .4295 ± .0005 Length .500 + .010 Dish - Dens.

100% Visual 100% Chips & Cracks

Analytical DB-122 Composite X Isotopic X Chemical

X Oxygen/Uranium X Uranium

Comments Pellet #977. Pellet # 791 thru 799 were inadvertently numbered 781 to 789 A line was scribed under number to indicate the 790 series.

BREW FURNACE NO. 3 SINTERING DATA

Date 5/3/78

Heating Rate 100° to 1000° then 200 to 1700 /hr.

Sintering Temperature 1700 °C

Sintering Time 8 hours

Cooling Rate 400 °/hr

H_2 Humidifier ______ Dry Cylinder Gas

H_2 passes ______ over X through water

______ volts ______ K. amp at temp.

Gas Flow Atmosphere

H_2 100% 20 / 10 SCFH Argon 0 — / 10 — above 900°C SCFH

Run Number 32

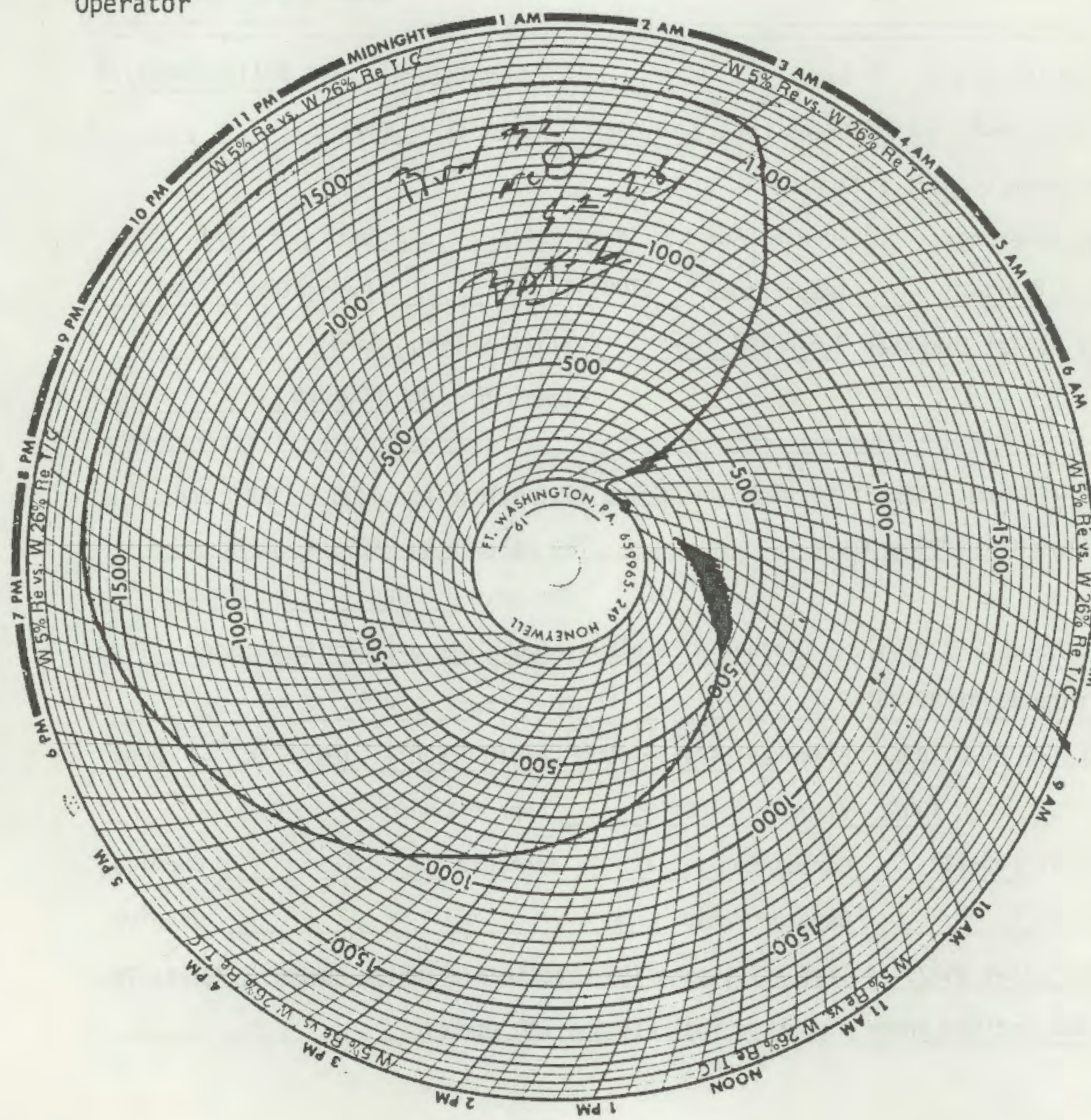
Furnace Content 3904 grams - 9.9%

HALDEN PELLETS BATCH 2

Remarks 100% H_2 to > 900°C — Converted to 50/50 H_2 + Ar at 970°C — at 3:50 pm — NCD —

N C Davis + J E Loston

Operator



BREW FURNACE NO. 3 SINTERING DATA

Date 5/8/78

Heating Rate 100° to 1000 then 200° to 1700°/hr.

Sintering Temperature 1700 °C

Sintering Time 8 hours

Cooling Rate 400 °/hr

H_2 Humidifier ______ Dry Cylinder Gas

H_2 passes ______ over X through water

______ volts ______ K. amp at temp.

Gas Flow Atmosphere

H_2 100 / 20 / 10 SCFH Argon 0 / 10 chans SCFH

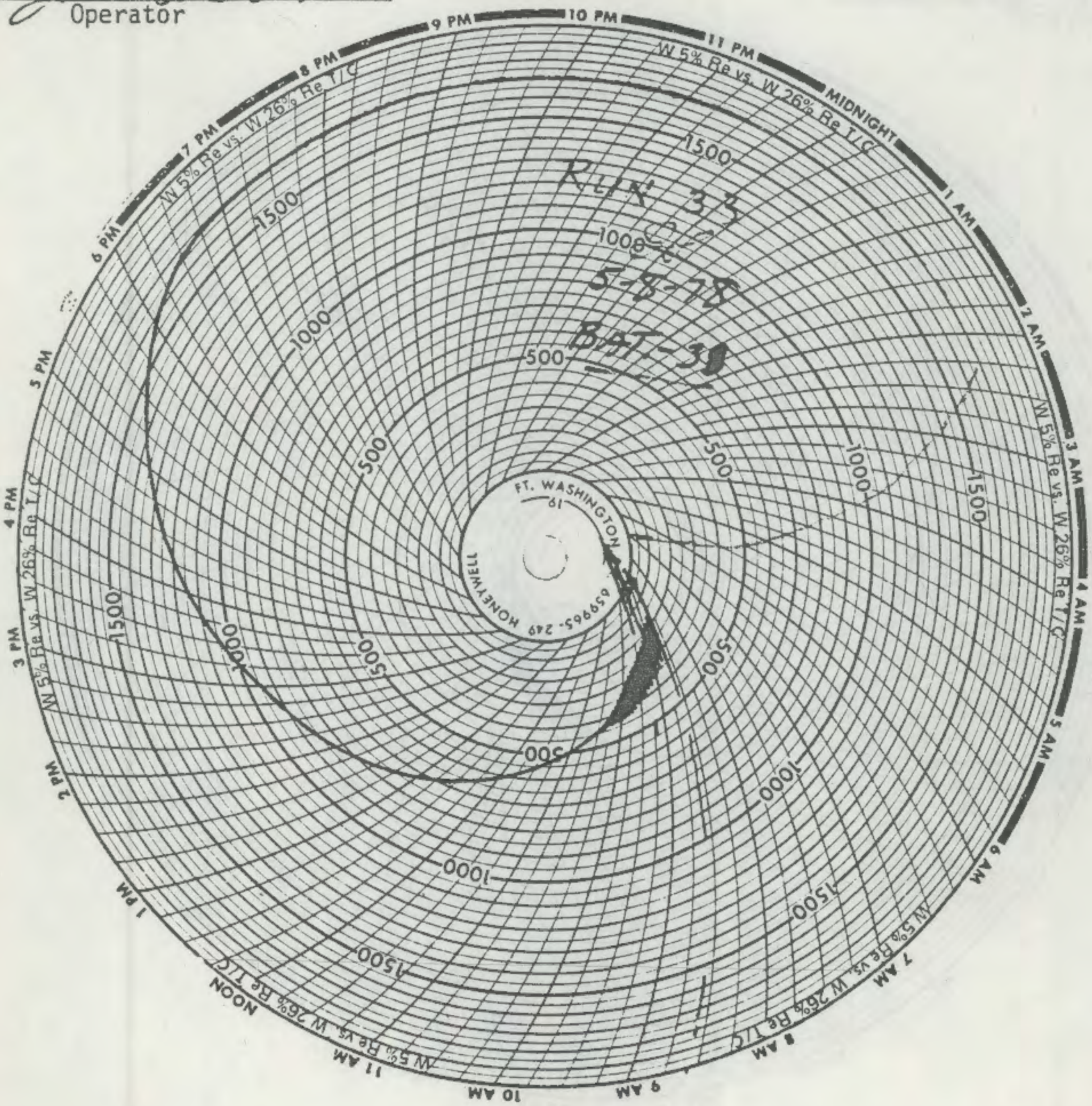
____

Operator

Run Number Brew #33

Furnace Content 3932 grams 9.9% UO_2 Pellets Batch #3

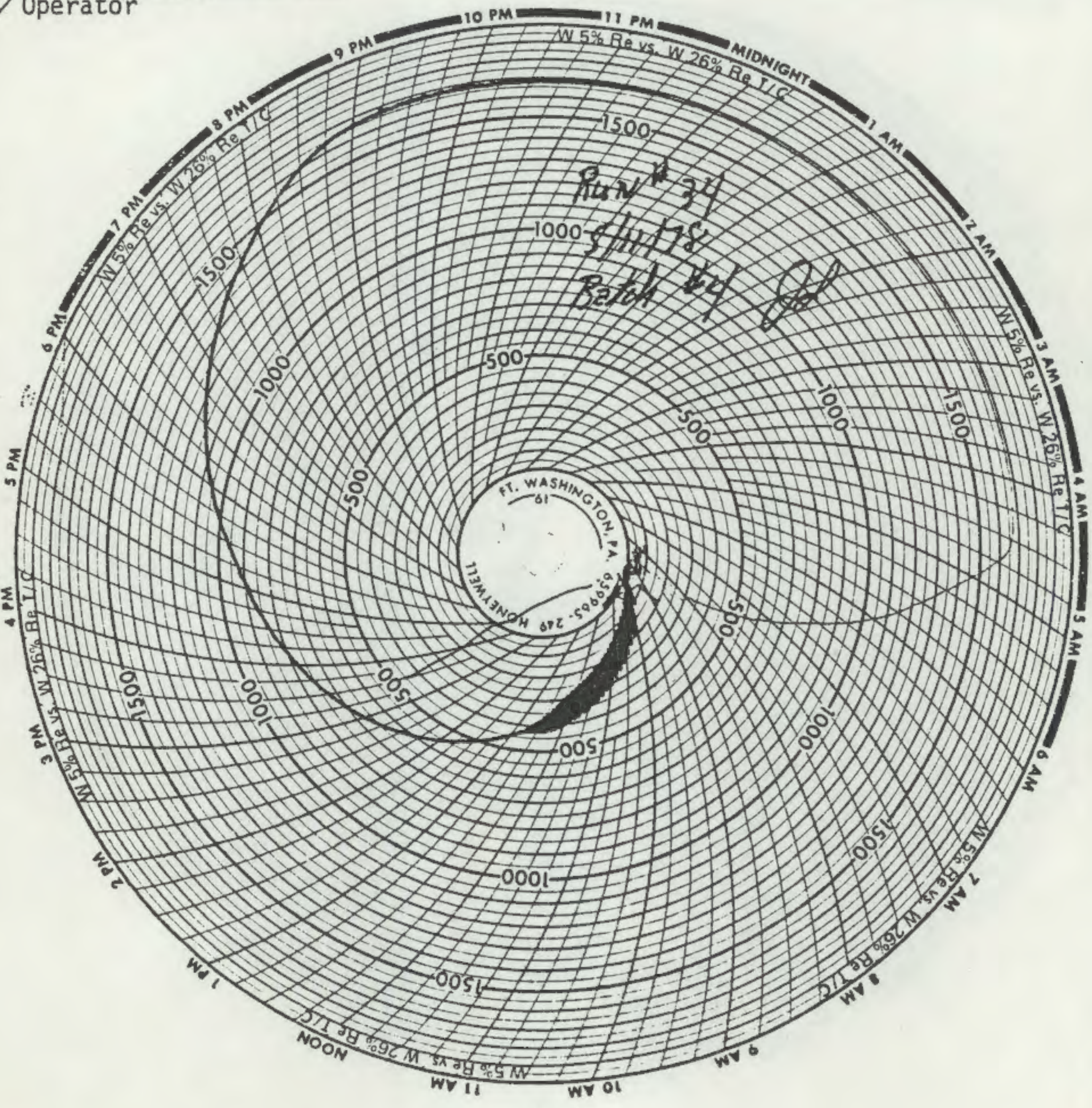
Remarks 100% H_2 to 900°C CONVERTED TO 50/50 H_2 + AR AT 900°C AT 2:40 PM — JL



BREW FURNACE NO. 3 SINTERING DATA

Date 5/11/78	Run Number Brew 434
Heating Rate 100° To 1000 - 200° To 1700°/hr.	Furnace Content 4369 grams 9.9%
Sintering Temperature 1700 °C	UO_2 Pellets Batch #4 contains 136
Sintering Time 8 hours	of High Pressure Pressed Pellets
Cooling Rate 400 °/hr	Remarks Run Aborted at
H_2 Humidifier ____ Dry Cylinder Gas	9^{30} AM 5-11-78 Temp Reached
H_2 passes ____ over X through water	200°c. JL
____ volts ____ K. amp at temp.	5pm - Temp 925°C
Gas Flow Atmosphere	Converted To 10/10 AR/H_2 NOT.
H_2 100 / 20 / 10 SCFH Argon 0 SCFH, 10 above 900°C	

J. E. Lester
Operator



LOG NO. 178

Hanford Engineering Development Laboratory

SPARK SOURCE MASS
SPECTROGRAPHIC ANALYSIS REPORT

MATERIAL: UO_2 99% ENRICHED

SUBMITTED BY: J LESTER | SUBMITTER'S NO.: DB 122 | ANALYZED BY: AH/RK | DATE REPORTED: 5/25/78

ELEMENT		ELEMENT		ELEMENT	
Li		Ga		Pm	
Be		Ge		Sm	<0.2
B	0.3	As		Eu	<0.2
F		Rb		Gd	<0.5
Na		Sr		Tb	
Mg		Y		Dy	<0.5
Al		Zr		Ho	
Si		Nb		Er	
P	10	Mo		Tm	
S		Ru		Yb	
Cl		Rh		Lu	
K		Pd		Hf	<0.3
Ca		Ag		Ta	<0.3
Sc		Cd		W	0.5
Ti		In		~~Re~~ Th	40
		Sn		Os	
Cr		Sb		Ir	
Mn		Cs	<0.1	Pt	
Fe		Ba	0.4	Au	
Co	0.2	La		Hg	
Ni		Ce		Tl	
Cu		Pr		Pb	
Zn		Nd		Bi	

TYPE OF ANALYSIS

☐ QUALITATIVE	☒ SEMIQUANTITATIVE	☐ QUANTITATIVE
☐ PARTS PER MILLION	☒ PARTS PER MILLION	☐ PARTS PER MILLION
☐ PERCENT	☐ PERCENT	☐ PERCENT
☐ ______	☐ ______	☐ ______
APPR'X PRECISION ± FACTOR ______	APPR'X PRECISION ± FACTOR 3	APPROX PRECISION ± FACTOR ______

REMARKS:

REPORT APPROVED: [signature]

BD-7340-021 (4-77)

FROM: Applied Chemistry and Analysis
DATE:
SUBJECT: ISOTOPIC ANALYSIS OF URANIUM

ANALYZED June 7, 1978

H[illegible]FORD ENGINEERING DEVELOPMENT LABORATORY

TO: J. LESTER

cc: File

M. S. #	Lab #	Customer I. D.	Wt. %
1178276	Q 0425	DB122	238 = 90.00 ± 0.05
			236 = 0.050 ± 0.002
			235 = 9.84 ± 0.05
			234 = 0.075 ± 0.002
			233 =
			238 =
			236 =
			235 =
			234 =
			233 =
			238 =
			236 =
			235 =
			234 =
			233 =
			238 =
			236 =
			235 =
			234 =
			233 =

APPROVED: ______________

CC: SPEC. LAB.

SC ______

SPECTROCHEMICAL ANALYSIS REPORT

MATERIAL: UO_2 ENRICHED 9.9%

SUBMITTED BY: LESTER

ANALYZED BY: AH/RK

DATE REPORTED: 6/28/75

SPEC. LAB. NO. SC	SUBMITTER'S NO.		Zn				REMARKS
191	DB-122		2				

TYPE OF ANALYSIS

☐ QUALITATIVE

SYMBOL	MEANING	APP'X CONC
SS	MAJOR DETECTABLE CONSTITUENT	
S	STRONG	GREATER THAN 1%
M	MODERATE	1% TO 0.01%
T	TRACE	LESS THAN 0.01%
—	NOT DETECTED	
•	INTERFERENCE	

☑ SEMIQUANTITATIVE

SYMBOL	MEANING
>	CONCENTRATION GREATER THAN
<	DETECTABLE CONCENTRATION LESS THAN
—	NOT DETECTED

NUMERICAL VALUES: ☑ PARTS PER MILLION ☐ PERCENT ☐

APPR'X-PRECISION ± FACTOR 3

☐ QUANTITATIVE

SYMBOL	MEANING
>	CONC. GREATER THAN CALIBRATED WORKING CURVE
<	CONC. LESS THAN CALIBRATED WORKING CURVE

NUMERICAL VALUES: ☐ PARTS PER MILLION ☐ PERCENT ☐

APPR'X. PRECISION ± ______

REMARKS: Analysis by Spark Source Mass Spectrography

REPORT APPROVED [signature]

BD-7340-020 (10-70) AEC-RL RICHLAND, WASH.

SC 195	Hanford Engineering Development Laboratory SPECTROCHEMICAL ANALYSIS REPORT	CC: SPEC. LAB.

MATERIAL: UO_2 2.9% ENRICHED

SUBMITTED BY	SUBMITTER'S NO.	ANALYZED BY	DATE REPORTED
J. KESTER	DB 127	RK	5/25/78

ELEMENT		ELEMENT		ELEMENT		ELEMENT	
Ag	<10	Hg		Re		Dy	
Al	<50	In		Rh		Er	
As		Ir		Ru		Eu	
Au		K	<20	Sb		Gd	
B	<2	La		Sc		Ho	
Ba		Li	<1	Si	<60	Lu	
Be	<2	Mg	<10	Sn	<10	Nd	
Bi		Mn	<10	Sr		Pr	
Ca	100	Mo	10	Ta		Sm	
Cd	<2	Na	<100	Th		Tb	
Ce		Nb		Ti	<20	Tm	
Co	2	Ni	50	Tl		Yb	
Cr	30	Os		U			
Cs		P		V	<50		
Cu	<20	Pb	<10	W			
Fe	100	Pd		Y			
Ga		Pt		Zn	40		
Ge		Pu		Zr			
Hf		Rb					

TYPE OF ANALYSIS

☐ QUALITATIVE

SYMBOL	MEANING	APP'X. CONC.
SS	MAJOR DETECTABLE CONSTITUENT	
S	STRONG	GREATER THAN 1 %
M	MODERATE	1 % TO 0.01 %
T	TRACE	LESS THAN 0.01 %
—	NOT DETECTED	
*	INTERFERENCE	
?	DETECTION UNCERTAIN. INTERFERENCE	

☒ SEMIQUANTITATIVE

SYMBOL	MEANING
G	CONCENTRATION GREATER THAN
L	DETECTABLE CONCENTRATION LESS THAN
—	NOT DETECTED

NUMERICAL VALUES: ☒ PARTS PER MILLION ☐ PERCENT ☐ ______

APPR'X. PRECISION ± FACTOR 2

☐ QUANTITATIVE

SYMBOL	MEANING
GX (LX)	CONC. GREATER THAN (LESS THAN) CALIBRATED WORKING CURVE

NUMERICAL VALUES: ☐ PARTS PER MILLION ☐ PERCENT ☐ ______

APPR'X. PRECISION ± ______

REMARKS:

REPORT APPROVED: RKO

LABORATORY INFORMATION

SPECTROGRAPH AND SOURCE	SIZE OF SAMPLE	METHOD OF ANALYSIS	PLATE NO.

BD-7340-021 (3-73)

SAMPLE IDENTIFICATION
BNW HALDEN BATCHES 1,2,3,4
SINT. PELLETS

DB-122

Hanford Engineering Development Laboratory

FUELS AND CONTROL SAMPLE ANALYSIS

LAB. SERIAL NO. Q0425

DATE REC. 5-18-78

SAMPLE SUBMITTER	ADDRESS	PHONE	WORK ORDER NO.
Lester	306 W. Rich	3184	C-98073

TYPE OF MATERIAL:

- [ ] PuO_2
- [x] UO_2
- [ ] MIXED OXIDE: ______ % PuO_2
- [ ] B_4C
- [ ] OTHERS ______

SPECIAL INSTRUCTIONS
* S.S. – Dy, Eu, Gd, Hf, Sm, Ba, Cd, W, P, B, Th, Ta, Cs
<0.5 PPM

Pu ISOTOPIC: ______ % 240

U ISOTOPIC:
- [ ] NORMAL
- [x] 9.91 % ENRICHED

B ISOTOPIC:
- [ ] NATURAL
- [ ] ______ % ENRICHED

NO. OF ANALYSIS		RESULTS
	Pu WT. %	
1	U WT. %	88.08
	^{241}Am ppm	
1	O/M	2.004
1	C ppm	33
	S ppm	
1	OFF-GAS cc/g @ STP	.007
1	Cl ppm	<10
1	F ppm	<5
1	@ 400°C H_2O ppm	<5
1	N ppm	<10
	O ppm	
	SOLUBLE C WT %	
	SOLUBLE B WT % [ ] HNO_3 [ ] HCl	
	TOTAL C WT %	
	TOTAL B WT %	

NO. OF ANALYSIS		RESULTS
	LOSS ON IGNITION WT %	
	DENSITY g/cc	
	POROSITY	SEE SPECIAL REPORT
	SURFACE AREA M^2/g	
	PARTICLE SIZE	SEE SPECIAL REPORT
	PARTICLE SIZE, FISHER SUBSIEVE	
	OTHERS	
	OTHERS	
	SPECTROCHEMICAL ANALYSES	
* 1	SPARK SOURCE GENERAL	SEE SPECIAL REPORT
	SPARK SOURCE R.E. + Ta + W	SEE SPECIAL REPORT
1	EMISSION SPEC. GENERAL	SEE SPECIAL REPORT
	ISOTOPIC ANALYSES	
	Pu ISOTOPIC	SEE SPECIAL REPORT
1	U ISOTOPIC	SEE SPECIAL REPORT
	B ISOTOPIC	SEE SPECIAL REPORT

SPECIAL OBSERVATIONS – REMARKS

COMPOSITE SAMPLE, CRUSH PELLETS AND MIX THROUGHLY.

REPORT APPROVED BY	DATE COMPLETED
CA Sprain	6/9/78

BD-7340-022 (9-76)

DISTRIBUTION: WHITE-Sample Submitter; YELLOW-Laboratory Record; PINK-Fuels QA; GOLDENROD-Originator

APPENDIX D

FUEL THERMAL CONDUCTIVITY DATA

TABLE D.1. Instrumented Fuel Assembly (IFA)-527 (Pellet 822) Measured Diffusivity and Calculated Thermal Conductivity

Specimen 1			Specimen 2		
T, °C	α, m^2/s	λ, W/m-K	T, °C	α, m^2/s	λ, W/m-K
179	2.242-6	6.425	186	2.121-6	6.102
398	1.546-6	4.855	284	1.779-6	5.355
494	1.400-6	4.416	397	1.529-6	4.745
581	1.266-6	4.037	491	1.345-6	4.243
698	1.158-6	3.732	601	1.217-6	3.886
800	1.043-6	3.383	719	1.143-6	3.688
900	9.440-7	3.076	826	1.063-6	3.452
1007	8.839-7	2.893	908	9.539-7	3.109
1099	8.437-7	2.769	1005	8.915-7	2.917
1301	7.021-7	2.324	1098	8.679-7	2.848
1379	6.821-7	2.269	1198	7.550-7	2.486
1379	6.979-7	2.325	1283	7.207-7	2.383
1294	7.309-7	2.418	1391	6.712-7	2.238
1202	7.623-7	2.511	1390	6.579-7	2.193
1098	8.242-7	2.705	1281	7.182-7	2.374
1010	8.743-7	2.861	1198	7.661-7	2.523
891	9.596-7	3.128	1104	8.269-7	2.714
795	1.043-6	3.382	1007	9.044-7	2.959
679	1.177-6	3.787	909	9.836-7	3.206
542	1.361-6	4.322	814	1.056-6	3.425
434	1.518-6	4.745	490	1.378-6	4.344
266	1.923-6	5.747	403	1.520-6	4.723
358	1.647-6	5.065	211	2.022-6	5.899
483	1.429-6	4.499	765	1.053-6	3.407
598	1.252-6	3.997	665	1.199-6	3.853
698	1.130-6	3.639	522	1.320-6	4.181
817	1.009-6	3.274	436	1.454-6	4.545
910	9.427-7	3.074	312	1.736-6	5.273
1001	8.737-7	2.859	422	1.471-6	4.585
1102	8.267-7	2.714	468	1.377-6	4.325
1190	7.552-7	2.487	531	1.338-6	4.240
1301	7.261-7	2.404	594	1.267-6	4.041
1384	6.964-7	2.321	641	1.197-6	3.835
1382	6.614-7	2.203	708	1.115-6	3.593
1306	6.944-7	2.294	852	1.017-6	3.304
1190	7.565-7	2.491	861	1.009-6	3.280
1092	8.268-7	2.713	813	9.967-7	3.231
968	8.960-7	2.928	756	1.064-6	5.438
873	9.648-7	3.140	698	1.120-6	3.607
770	1.064-6	3.443	643	1.169-6	3.750
674	1.147-6	3.690	582	1.258-6	4.009
540	1.370-6	4.348	534	1.327-6	4.206
441	1.504-6	4.706	472	1.385-6	4.335
354	1.674-6	5.146	390	1.571-6	4.867
211	1.940-6	5.660	264	1.825-6	5.452
			277	1.810-6	5.434
			377	1.569-6	4.848
			479	1.584-6	4.356
			880	9.814-7	3.195
			964	9.245-7	3.021
			1061	8.539-7	2.799
			1161	7.819-7	2.572
			1253	7.304-7	2.411
			1355	6.927-7	2.302
			1355	7.061-7	2.347
			1258	7.335-7	2.422
			1169	7.821-7	2.573
			1074	8.461-7	2.775
			981	9.043-7	2.959

TABLE D.2. Instrumented Fuel Assembly (IFA)-513 (Pellet 324) Measured Diffusivity and Calculated Thermal Conductivity

Specimen 1			Specimen 2		
T, °C	α, m^2/s	λ, W/m-K	T, °C	α, m^2/s	λ, W/m-K
179	2.062-6	5.907	187	2.057-6	5.920
281	1.752-6	5.265	188	2.094-6	6.029
384	1.560-6	4.825	279	1.766-6	5.305
466	1.378-6	4.328	356	1.574-6	4.839
659	1.161-6	3.727	611	1.234-6	3.945
750	1.070-6	3.458	680	1.118-6	3.593
840	9.848-7	3.200	914	9.313-7	3.036
927	9.244-7	3.016	990	8.940-7	2.923
1027	8.860-7	2.901	1067	8.583-7	2.814
1124	8.046-7	2.642	1140	8.053-7	2.646
1217	7.682-7	2.531	1228	7.483-7	2.467
1305	7.186-7	2.379	1310	7.177-7	2.376
1415	6.614-7	2.211	1384	8.763-7	2.253
1413	6.689-7	2.235	1284	6.783-7	2.260
1344	6.954-7	2.309	1335	6.975-7	2.314
1268	7.347-7	2.427	1266	7.373-7	2.435
1169	7.694-7	2.531	1193	7.730-7	2.545
1071	8.416-7	2.759	1117	8.160-7	2.679
970	9.007-7	2.943	1043	8.655-7	2.835
884	9.530-7	3.103	960	9.096-7	2.971
798	1.041-6	3.373	878	9.638-7	3.137
700	1.091-6	3.513	790	1.023-6	3.315
595	1.225-6	3.909	714	1.117-6	3.602
508	1.315-6	4.186	648	1.151-6	3.692
430	1.451-6	4.555	576	1.243-6	3.958
334	1.646-6	5.049	504	1.325-6	4.184
230	1.936-6	5.709	391	1.509-6	4.675
188	2.101-6	6.052	308	1.685-6	5.110
182	2.044-6	5.867	218	1.972-6	5.772
			218	1.972-6	5.770

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This report is a resource document covering the rationale, design, fabrication, and preirradiation characterization of instrumented fuel assembly (IFA)-527. This assembly is being irradiated in the Halden Boiling Water Reactor (HBWR) in Norway as part of the Experimental Support and Development of Single-Rod Fuel Codes Program conducted by Pacific Northwest Laboratory (PNL) and sponsored by the Fuel Behavior Research Branch of the U.S. Nuclear Regulatory Commission (NRC). Data from this assembly will be used to better understand light water reactor (LWR) fuel behavior under normal operating conditions.

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