GEAP-4926
AEC RESEARCH AND
DEVELOPMENT REPORT
SEPTEMBER 1968

unclass
Kahn 9/29/69

**PERFORMANCE ANALYSIS OF
HIGH POWER DENSITY PROGRAM
FUEL RODS
IRRADIATED IN VBWR
TERMINAL EXAMINATION**

T.J. PASHOS
R.N. DUNCAN
W.H. ARLT
P.W. MATHAY

U.S. ATOMIC ENERGY COMMISSION
CONTRACT AT(04-3)-361

NUCLEAR FUELS DEPARTMENT
GENERAL ELECTRIC
SAN JOSE, CALIFORNIA

P2715

RESTRICTION OF THIS DOCUMENT IS UNCLASSIFIED

RECEIVED BY DTIC SEP 22 1969

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:
A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.
As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

GEAP-4926
AEC Research and
Development Report
September 1968

PERFORMANCE ANALYSIS OF HIGH POWER DENSITY PROGRAM FUEL RODS IRRADIATED IN VBWR—TERMINAL EXAMINATION

T. J. Pashos
R. N. Duncan
W. H. Arlt
P. W. Mathay

Approved:

C. M. Foster
Project Engineer

H. H. Klepfer, Manager
Fuel Development—Water Reactors

U. S. Atomic Energy Commission
Contract AT(04-3)361

*Printed in U.S.A. Available from the
Clearing House for Federal Scientific and Technical Information
National Bureau of Standards, U.S. Department of Commerce
Springfield, Virginia
Price: \$3.00 per copy*

5791-NFD-110
90 - AG - 9/69

ATOMIC POWER EQUIPMENT DEPARTMENT
GENERAL ELECTRIC
SAN JOSE, CALIFORNIA

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Key

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or*
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.*

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

TABLE OF CONTENTS

	<u>Page</u>
SECTION I SUMMARY	1
SECTION II OBSERVATIONS AND CONCLUSIONS	3
SECTION III DESIGN CRITERIA AND FABRICATION VARIABLES	5
3.1 Task IA Fuel	5
3.2 Task IB Fuel	6
SECTION IV FUEL PERFORMANCE EVALUATION	9
4.1 Fuel Operation in VBWR	9
4.2 Destructive Examinations of HPD Fuel in RML	9
SECTION V ILLUSTRATIONS	37
APPENDIX STATISTICAL EVALUATION OF HPD FUEL	117
REFERENCES	133
DISTRIBUTION	135

LIST OF ILLUSTRATIONS

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
1.	Typical High Power Density VBWR Fuel Assembly	39
2.	Swaged-over Pellet Process Schematic	40
3.	HPD-1A, Rod L, Failure	41
4.	HPD-2A Failure, Pellet UO_2	42
5.	HPD-2B Failure, Pellet UO_2	43
6.	HPD-3C Failure, Pellet UO_2	44
7.	HPD-1D Failure, Pellet UO_2	45
8.	HPD-2D Failure, Pellet UO_2	46
9.	HPD-3D Failure, Pellet UO_2	47
10.	HPD-1E Failure, Pellet UO_2	48
11.	HPD-2E Failure, Pellet UO_2	49
12.	HPD-3E Failure, Pellet UO_2	50
13.	HPD-4E Failure, Pellet UO_2	51
14.	HPD-6E Failure, Pellet UO_2	52
15.	HPD-1F, Rod Y, Failure, Pellet UO_2	53
16.	HPD-1G Failure, Pellet UO_2	54
17.	HPD-2G Failure, Pellet UO_2	55
18.	HPD-3G Failure, Pellet UO_2	56
19.	HPD-1SM-1 Vibratory Compacted Powder Failure	57
20.	HPD-2S Swaged Powder Failure	59
21.	HPD-2S, Rod A, Minor Failure in Swaged Powder	61
22.	HPD-3S Failure, Pellet UO_2	62
23.	HPD-3S Failure, Pellet UO_2	63
24.	HPD-3S Failure, Pellet UO_2	65
25.	HPD-3S Failure, Pellet UO_2	67
26.	HPD-6S Failure, Pellet UO_2	68
27.	HPD-6S Failure, Pellet UO_2	69
28.	HPD-12S, Rod A, Failure, Pellet UO_2	70
29.	Typical Gamma Scan and Cutting Diagram of Central Rod Fuel Follower	71
30.	Typical Gamma Scan and Cutting Diagram for Large Gas Plenum Rods	73
31.	Typical Gamma Scan and Cutting Diagram of Prototype Pellet UO_2 Rod	75

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
32.	Typical Gamma Scan and Cutting Diagram for Compacted Powder UO ₂ Fuel Rods	76
33.	Dimensional Profile Trace of Rod N of HPD-2B	77
34.	Dimensional Profile Trace of Rod M of HPD-2C	79
35.	Dimensional Profile Trace of Rod J of HPD-1C	79
36.	Dimensional Profile Trace of Rod H of HPD-1F	81
37.	Dimensional Profile Trace of Rod K of HPD-12S	81
38.	Dimensional Profile Trace of Rod V of HPD-1SM-1	83
39.	Dimensional Profile Trace of Rod O of HPD-6S	83
40.	Temperature-Dependent Pellet and Powder UO ₂ Fuel Fission Gas Release	85
41.	625°F (330°C) Yield Strength versus nvt >1 MeV for HPD Program Type-304 Stainless Steel	87
42.	Percent Total Elongation versus nvt >1 MeV for HPD Program Type-304 Stainless Steel	88
43.	HPD-1A, Rod C. Burst Test Specimen with Notch Causing Premature Release of Pressure	89
44.	HPD-1F, Rod A. Burst Test Specimen with Notch Causing Premature Burst of Specimen	89
45.	HPD-2B, Rod O. Burst Test Specimen	90
46.	Cladding Control Material Burst Specimen	90
47.	Comparison of Microhardness Changes Due to Irradiation in Annealed and Cold-worked Type 304 Stainless Steel used in HPD Program	91
48.	Typical Intergranular Attack on Type-304 Stainless Steel in HPD Program	92
49.	Intergranular Attack and Branching in Type-304 Stainless Steel	93
50.	Irradiated Sample of HPD-1A Clad Annealed Material	94
51.	Unirradiated Sample of HPD-1A Clad Annealed Material	94
52.	Unirradiated Sample of HPD-1F Clad Cold-Worked Material	95
53.	Irradiated Sample of HPD-1F Clad Cold-Worked Material	95
54.	HPD-1F, Rod Y, Major Crack Region Showing Structure at Inside Diameter Surface	96
55.	Inside Diameter Zone Etched with Glyceregia	97
56.	Inside Diameter Zone Etched with Alkaline-Ferrocyanide	97
57.	Glyceregia Etch on HPD-5S Cladding Revealing Grain Boundary Precipitation or Sensitization	98
58.	HPD-5S Cladding Etched with Picric-HCl	98
59.	HPD-5S Cladding Stained with Alkaline-Ferrocyanide	99

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
60.	UO ₂ Particle Penetration in Cladding Wall	100
61.	Unirradiated Sintered Pellet UO ₂ Microstructure	101
62.	Irradiated Sintered Pellet UO ₂ Microstructure, Etched	103
63.	Irradiated Sintered Pellet UO ₂ Microstructure, Polished	105
64.	Vibratory Compacted Powder UO ₂ Microstructure	107
65.	Vibratory Compacted Powder, UO ₂ Microstructure, Etched	109
66.	Tandem Rolled UO ₂ Powder, Micro-Etched	111
67.	Hot-Swaged UO ₂ Powder, Micro-Etched	113
68.	Cold-Swaged Powder UO ₂ Microstructure, Etched	115

LIST OF TABLES

<u>Table No.</u>	<u>Title</u>	<u>Page</u>
1	Task IA Fuel Design Variables	6
2	Task IB Fuel Design Variables	8
3	Tasks IA and IB Pellet UO_2 Fuel Operating Statistics	11
4	Task IB Powder UO_2 Fuel Operating Statistics	13
5	Tasks IA and IB Failure Description and Iodine Release	15
6	Summary of HPD Post-Irradiation—RML Examinations and Tests	17
7	Gross Dimensional Changes in Pellet and Powder Fuel Rods Irradiated in VBWR	19
8	Fission Gas Release from HPD Fuel Rods	23
9	HPD UO_2 Fuel Burnup Analysis Results	25
10	Elevated Temperature (625°F) Tensile Properties of Type 304 Stainless Steel Irradiated at Elevated Temperature ($>550^\circ\text{F}$)	27
11	Results of Burst Tests Performed on Irradiated and Unirradiated Type-304 Stainless Steel Clad Fuel Rods in HPD Program	29
12	Results of Microhardness Tests on Unirradiated and Irradiated Cladding Material Used in HPD Program	31

SECTION I

SUMMARY

This report documents final work performed on fuel rods irradiated in the Vallecitos Boiling Water Reactor (VBWR) under the High Power Density Development Project (HPD), AEC Contract AT(04-3)-361. These irradiations were intended to demonstrate high power density operation in a boiling water reactor (BWR) and to provide fabrication development and irradiation experience with fuel having low fabrication cost potential.

Following the termination of operation of the VBWR in December 1963, post-irradiation examinations were conducted on selected fuel rods that had been irradiated as part of the HPD Program.

The HPD program involved irradiation of approximately 800 UO_2 fuel rods clad with either cold-worked or annealed commercial grade Type-304 stainless steel. Some of the rods contained UO_2 pellets, the "standard" fabrication process. Others were fabricated by various powder compaction processes that showed potential for lower fabrication costs. Both freestanding and thin-wall clad designs were used.

The leading fuel rods had attained average and peak exposures of 9,910 and 16,850 MWd/T, respectively, at the termination of irradiations.

The most significant result of the irradiation program was the revelation of the unexpected susceptibility of unsensitized stainless steel cladding to intergranular cracking in a water-cooled reactor environment. Cladding cracking occurred at peak rod exposures ranging from 6,050 MWd/T for thin-wall, collapsed cladding to 16,850 MWd/T for freestanding cladding having an initial pellet-to-clad cold gap of up to 8 mils. There were 27 failed rods out of the 643 pellet rods irradiated, and 3 failed rods out of 154 compacted powder rods irradiated.

The post-irradiation examination of failed and nonfailed fuel rods included investigation of the cause and nature of the cladding failures, gamma scans, diameter profile and length measurements, fission gas release measurements, and measurement of changes in cladding mechanical properties during irradiation.

SECTION II

OBSERVATIONS AND CONCLUSIONS

- a. The partial core loading of HPD Program assemblies was compatible with the VBWR core physics, heat generation and removal capability and geometry, and with fuel assemblies from other programs in the VBWR.
- b. Fabrication processes were developed having potentially lower fabrication costs than the standard pellet fuel process. Unfortunately, the early failure of the stainless steel cladding prevented determining long-range performance differences between pellet fuel and fuel made by the various powder compaction processes.
- c. There appeared to be a relationship between cladding operating stress level and time to failure. Fuel rods with thin, collapsed cladding having essentially no initial pellet-to-cladding gap failed at lower exposure levels than thicker, freestanding cladding with initial gaps of up to 8 mils. Thus, cladding stresses resulting from fuel-cladding mechanical interactions appeared to have been a factor in causing the failures. A second indication of the influence of stress is the fact that the failures occurred in the highest heat flux (maximum stress) regions of the fuel rods.
- d. The fundamental mechanism for the failure of the Type-304 stainless steel cladding could not be determined. The failures were characterized as follows:
 1. The cladding failures were in the form of cracks varying in size from microscopic penetrations to large cracks in which the UO_2 was exposed to the reactor coolant.
 2. The cracks were predominantly intergranular in nature, starting at the cladding outer surface and progressing inward.
 3. No grain boundary precipitates or other evidence of sensitization were detected by either optical or electron microscopy.
 4. The orientation of the cracks differed, depending upon the initial condition of the cladding. The cracks in the cold-worked rods were predominantly longitudinal, whereas those in the annealed rods were predominantly circumferential and usually occurred at pellet interfaces. The circumferential cracks appeared to be related to the circumferential ridges in the cladding at the pellet interfaces.
 5. The fracture surfaces appeared to be corroded, and there was no detectable deformation of the metal at the crack tips.
 6. Statistical analyses indicated that there was no significant difference in susceptibility to cracking between the cold-worked and the annealed cladding (see Appendix).
- e. Compacted powder fuel rods failed at approximately the same exposure level as pellet rods having collapsed cladding, with no detectable loss of UO_2 from any of the three failed powder rods.
- f. The VBWR operated for sustained periods of time with a large number of failed fuel rods. However, after removal of the failed fuel segments, there was no evidence of appreciable residual fission product activity in the reactor coolant system.

At no time during the operation with failed fuel was enough UO_2 released to the VBWR system to compromise the safe operation of the plant. This is strong evidence that UO_2 in the form of pellets and powder is chemically and mechanically stable enough to resist the

effects of high-temperature water and steam long enough to permit operation for days, and possibly weeks. (Table 5, shown later in this report, lists the approximate hours operated with failures and references photographs showing the fuel rod condition after this period.)

g. Changes in cladding mechanical properties were as follows:

1. Tensile tests indicated a large increase in both the yield and ultimate strengths for the exposures attained in the program. In the case of annealed material, approximately 200% increase in yield strength and 100% increase in ultimate strength were observed at exposures approaching 2×10^{21} nvt (> 1 MeV). In the cold-worked cladding, approximately 100% increase in yield and 50% increase in ultimate strength were measured.
 2. Burst tests revealed a large degree of ductility still present in tubing that has been irradiated to 2×10^{21} (> 1 MeV).
- h. There was no difference in microstructure of the irradiated cladding as compared to the unirradiated condition.
- i. A very pronounced damage zone was noticed on the inside surface of both the annealed and cold-worked cladding. The zone is believed to be the layer penetrated by fission product fragments.
- j. The microstructure of the sintered pellet UO_2 was essentially unchanged from that of the unirradiated condition. No grain growth had occurred. The only change observed was in the character of the porosity visible in the central region of the pellet. The porosity of the central fuel regions tended to be in the grain boundaries, as opposed to being distributed throughout the grains in the unirradiated condition. The degree of open porosity was quite large in the central regions of the pellet fuel.
- k. The powder fuel microstructure indicated in-reactor sintering had occurred. Particles near the fuel surface apparently fused together, perhaps as a result of local temperature spikes as fissions occurred.
- l. Fission gas release from the compacted powder fuel was slightly higher than that from pellet fuel: 2 to 6% release from powder, compared with < 0.1 to 6% release from pellets at exposures of 4,000 to 10,000 MWd/TU.

SECTION III

DESIGN CRITERIA AND FABRICATION VARIABLES

The objective of the Task IA portion of the program was to evaluate the feasibility and study the performance of a partial reactor core operating in the VBWR at high power density conditions. Twenty-four assemblies utilizing pellet fuel fabrication processes made up the test group. The fuel was designed to operate at an average power density in excess of 90 kW/liter, 425,000 Btu/h-ft² peak surface heat flux, and 10,000 MWd/TU average burnup. ⁽¹⁾

The Task IB objective was to develop and test the feasibility of fabrication processes which offered potentially lower fabrication costs than the above-mentioned pellet fuel. Fuel was then fabricated by these processes for operational testing in VBWR at the same conditions as for Task IA fuel.

A secondary objective of both Tasks IA and IB was to test fuel with thin-wall stainless steel cladding as a means for improving the neutron economy and fuel cycle costs.

3.1 TASK IA FUEL

Twenty-four assemblies were fabricated in the IA group for irradiation in VBWR. Twenty of these were 25-rod assemblies in a 5 x 5 symmetrical array (Figure 1).^{*} The remaining four (1A, 2A, 1B, and 2B) assemblies comprised 16 rods in a 4 x 4 symmetrical array, and were designated control rod "fuel-followers." The followers occupied fixed positions in the core at the bottom of the "top-entry" control rods.

The following design and process variables were investigated as being applicable to the sintered pellet UO₂ fuel rod:

- a. Freestanding cladding versus non-freestanding cladding,
- b. Cold-worked versus annealed cladding,
- c. Large as-built diametral gap versus small as-built gap, and
- d. Ground pellets versus unground as-sintered pellets.

Table 1 presents the design variables for comparison within the IA group. The process variables investigated and applied in the HPD program were:

a. Standard Pellet Process⁽¹⁾

This fabrication method served as the reference point for development of a modified process. Sintered and centerless ground UO₂ pellets were encased in Type-304 stainless steel cladding with welded end plugs. As-built gap was determined by the pellet size and inside diameter of the cladding.

b. Swaged Pellet Process (1, 2)

Two types of fuel rod were fabricated using rotary swaging techniques: (1) Centerless ground sintered UO₂ pellets were encased in stainless steel with welded collapsible end

^{*} See Section V for illustrations referenced in the body of this report.

plugs. The cladding was reduced in diameter using a rotary swaging machine with either steel dies or nylon dies; (2) Unground sintered UO_2 pellets were encased in stainless steel with welded collapsible end plugs. The cladding was then swaged, using nylon dies almost exclusively to prevent pellet breakage. Extensive use of this process was made in the Task IB fuel where non-freestanding cladding is used. The cladding in that case must depend upon the pellets to prevent collapse of the tube during operation at reactor pressures. Figure 2 is a schematic of the swaging processes used.

TABLE 1

TASK IA FUEL DESIGN VARIABLES

Fuel Group	Rods Per Fuel Assembly	Total Number Fuel Rods	Cladding OD (in.)	Cladding Thickness (in.)	Cladding Yield Strength (psi) ^(a)	Nominal UO_2 -Cladding Gap	Fabrication Process
A and B	16	64	0.420	0.020	38,000	0.005	Standard
1C	25	25	0.417	0.017	38,000	0.005	Standard
2C	25	25	0.417	0.017	95,000	0.005	Standard
3C, ^(b) 4C	25	50	0.410	0.017	95,000	0.003	Swaged
D	25	100	0.398	0.012	94,000	0.002	Swaged
E	25	29	0.363	0.014	44,000	0.005	Standard
		120	0.363	0.014	90,000	0.005	Standard
F	25	49	0.363	0.014	90,000	0.005	Standard
G	25	20	0.360	0.014	44,000	0.002	Swaged
		80	0.360	0.014	90,000	0.002	Swaged

(a) The as-received room temperature yield strength of the tubing in all cases. The swaging process, imposing a very light reduction, makes very small changes in mechanical properties. Yield strengths of 38,000 and 44,000 represent commercially annealed material. Cladding room temperature yield strengths of greater than the commercially annealed material are referred to as cold-worked material.

(b) Swaged-over unground pellets.

3.2 TASK IB FUEL

A total of 13 fuel assemblies made up the group irradiated in Task IB. Table 2 presents the various mechanical configurations and the fabrication processes developed and tested. Briefly, the objectives for testing were as follows:

- a. HPD-1S--originally fabricated to test various powder and pellet configurations with intentional defects. The main purpose was to determine the erosion stability of the UO_2 fuel under action of high-temperature water and steam.⁽³⁾

- b. HPD-2S, -5S, -7S, -8S, -9S, -10S -- to test the swaged powder process. Each group of rods incorporated variations in the process which may have affected the performance. These included differences in density, cladding wall thickness, rod diameter, powder particle sizes, three-pass cold-swage compaction, two-pass cold-swage compaction, hot swaging, etc. (2, 4)
- c. HPD-3S -- to irradiation test UO_2 powder compacted by tandem rolling. (5)
- d. HPD-4S -- to test the removable fuel rod assembly as a prototype for the Big Rock R & D fuel assemblies. (6) Rods were pellet UO_2 , similar to the 1G group in Task IA.
- e. HPD-6S -- to test thin-wall non-freestanding cladding swaged over unground pellets. This is the most undesirable pellet fuel configuration from the standpoint of stress and cyclic fatigue (discontinuities, local ovality), but one of the least expensive from the standpoint of fabrication and neutron economy.
- f. HPD-7S -- to test vibratory compacted powder fuel encased in non-freestanding cladding. The 85% of theoretical as-loaded density of the UO_2 was the lowest of any fuel type fabricated. (7)
- g. ISM-1 -- to continue irradiation of tandem rolled rods from assembly 3S and vibratory compacted rods from assembly 7S to higher exposure. The assembly 3S pellet corner rods failed, while no visual defects could be found in the tandem rolled rods. A 7S swaged powder rod was suspected of failure, while no defects could be found in the ViPak rods at the time of reconstitution.
- h. HPD-11S-1, -12S -- reconstituted from Task IA "E" series cold-worked pellet rods and annealed pellet rods, primarily to allow irradiation to continue on these rods.

TABLE 2

TASK IB FUEL DESIGN VARIABLES

<u>Fuel No.</u>	<u>No. Fuel Rods</u>	<u>Cladding OD (in.)</u>	<u>Cladding Thickness (in.)</u>	<u>Cladding Yield Strength (psi)(a)</u>	<u>Fuel Fabrication Process (b)</u>	<u>UO₂ %TD</u>
1S	23	0.400	0.012	94,000	Swaged Pellet ⁽¹⁾	95
	2	0.400	0.010	95,000	Vibratory Compacted Powder ⁽⁷⁾	83
1SM-1 ^(c)	17	0.400	0.012	95,000	Vibratory Compacted Powder ⁽⁷⁾	86-88
	8	0.400	0.016	90,000	Tandem Rolled Powder ⁽⁵⁾	88-89
2S	13	0.400	0.016	95,000	Cold-Swage Powder ^(2,4)	94
	12	0.400	0.010	95,000	Cold-Swage Powder ^(2,4)	93
3S	21	0.400	0.016	90,000	Tandem Rolled Powder ⁽⁵⁾	88-89
	4	0.400	0.012	90,000	Swaged Pellet (Corners) ⁽¹⁾	95
4S	16	0.360	0.014	40,000	Standard Pellet Fuel ⁽¹⁾	95
	9	0.360	0.014	90,000	Standard Pellet Fuel ⁽¹⁾	95
5S	10	0.400	0.008	95,000	Cold-Swage Powder ⁽²⁾	90-91
	5	0.400	0.010	95,000	Cold-Swage Powder ⁽²⁾	87-90
	10	0.400	0.016		Hot-Swage Powder ⁽²⁾	95
6S	12	0.400	0.010	45,000	Swaged-Over Unground Pellets ⁽¹⁾	95
	13	0.390	0.008	52,000	Swaged-Over Unground Pellets ⁽¹⁾	95
7S	12	0.400	0.012	80,000	Cold-Swage Powder ^(2,4)	90-91
	13	0.400	0.016	95,000	Vibratory Compacted Powder ⁽⁷⁾	86-88
8S	16	0.400	0.010	95,000	Cold-Swage Powder ^(2,4)	91-92
9S	16	0.400	0.010	95,000	Cold-Swage Powder ^(2,4)	91-92
10S	12	0.425	0.010	95,000	Cold-Swage Powder ^(2,4)	89-92
	4	0.425	0.010	40,000	Swaged Pellet (Corners) ⁽¹⁾	95
11S	4	0.425	0.010	40,000	Swaged Pellet (Corners) ⁽¹⁾	95
	12	0.425	0.010	95,000	Swaged Powder ^(2,4)	89-91
11S-1 ^(d)	16	0.363	0.014	90,000	Standard Pellet Fuel	95
12S ^(e)	25	0.363	0.014	40,000	Standard Pellet Fuel	95

(a) Cladding strength of three-pass cold swaged fuel is raised during processing from about 45,000 to about 95,000 psi. All swaged powder fuel rods started with commercially annealed tubing.

(b) Numbers indicate references describing fuel processes in detail.

(c) Assembly consisted of rods from assemblies 3S and 7S.

(d) Assembly consisted of cold-worked rods from assembly 1E in Task IA.

(e) Assembly consisted of annealed rods from "E" series assemblies in Task IA.

SECTION IV

FUEL PERFORMANCE EVALUATION

4.1 FUEL OPERATION IN VBWR

The Task IA fuel was loaded into the VBWR during September 1960. No appreciable irradiation exposure occurred until January 1961. The first Task IB fuel assemblies were loaded in April 1961, with subsequent assemblies inserted up to May 1962. The three reconstituted assemblies (ISM-1, 11S-1, and 12S) were loaded during the spring and summer of 1963.

4.1.1 Exposure and Power History

The early performance of all fuel rods in the program at high heat flux operation and high power density was quite satisfactory. The designs were adequate to meet the power requirements imposed by operation in the VBWR. The highest peak heat flux achieved by a pellet fuel assembly was 511,000 Btu/h-ft², with the powder fuel achieving an even higher level of 527,000 Btu/h-ft². Peak power density for pellets was 167.5 kW/liter. Powder fuel peak power density was 164 kW/liter. Tables 3 and 4 list the terminal operating statistics for all HPD fuel operated in the VBWR.

4.1.2 Failure History

Service failures occurred in eight Task IA type fuel rods during the months of April, July, August, and September, 1962. In September 1962, the VBWR was shut down for an extended period until January 1963. Subsequent to startup, failures continued to occur up until the time of VBWR deactivation in December 1963. Over 35 Type-304 stainless steel clad fuel rods were positively identified as failures out of approximately 800 rods total. Many other failures are probable, based upon results of activity sampling during operation or by sampling after shutdown in isolation cans. Table 5 and Figures 3 through 28 describe the failures.

4.2 DESTRUCTIVE EXAMINATIONS OF HPD FUEL IN RML

The following subsections present the data and correlations resulting from the HPD program analyses. Table 6 is a complete breakdown of examinations performed in the program.

4.2.1 Gamma Profile Scans

Figures 29 through 32 are typical gamma profile scans of rods examined in the program. These scans are used to locate the peak flux regions in the rod for various samples such as UO₂ burnup, metallography, cladding tensile tests, and cladding burst tests. Figure 29 is a profile of a fuel follower assembly. Up until the time of this gamma scan, the peak-to-average power ratio on the fuel follower assemblies had been assumed to be 1.5 for purposes of exposure and heat flux calculations. The reduction of the P/A ratio to ~1.3 for these assemblies reduced the calculated peak exposure on these rods by approximately 2000 MWd/T or by ~15%. In the case of the other fuel in the program, the P/A ratio was closer to 1.6 than the assumed 1.5 ratio (~1500 MWd/T peak increase).

4.2.2 Dimensional Changes in Fuel Rods

Near the end of the post-irradiation examination, a sensitive, profilometer-type measuring device became available. ⁽⁸⁾ Unfortunately, the usefulness of profilometry data depends heavily upon the availability of profilometer measurements taken on the tubing in the

unirradiated condition. The HPD pre-data on particular fuel rods were quite limited; therefore, there is no adequate basis for comparing absolute changes in dimensions. However, by qualitative comparison of different types of rods with each other, certain generalized conclusions are apparent. In addition, the profilometer measurements are quite valid for localized variations in rod dimensions along a specific rod. Table 7 presents the results of profilometer and dial gage dimensional measurements.

The range of dimensional variation is quite wide (± 0.002 in. on diameter and ± 0.0015 on ovality). A general trend is noticed when decreasing wall thickness and thickness to diameter ratios of the rods profiled are compared. Full-length profiles of the rods in order of decreasing wall thickness and thickness to diameter ratios are presented in Figures 33 through 39. Each scan includes three axial traces: (1) zero degree longitudinal, (2) longitudinal and rotational, and (3) 90 degree longitudinal. There are more local diameter variations present on the thin-wall rods than on heavier-wall rods. This is reasonable since one might expect a heavy-wall tube to be deformed less than a thin-wall tube by UO_2 mechanical interaction. The vibratory compacted powder rod (Figure 38) has a smooth pattern, with no evidence of localized cladding deformation, ovality, or change in diameter. This is compared with a swaged pellet rod (Figure 39).

This rod was fabricated by swaging-over unground pellets using nylon dies, resulting in a nonuniform diameter. No profiles were taken of the rod in the unirradiated condition, so it is difficult to determine whether any change in the average gross dimension has occurred. However, the shaded areas in Figure 39 are interpreted to be localized changes at pellet interfaces.

4.2.3 Fission Gas Release Rates

Approximately 15 fuel rods with different exposure and power history were punctured for collection of fission gas. Briefly, the procedure and equipment used to determine the amount of fission gas in a fuel rod involved:

- a. Placement of the fuel rod in a puncturing device,
- b. Sealing the fuel rod surface vacuum tight,
- c. Applying a vacuum of 10 microns or less, and
- d. Puncturing the rod with a hydraulically driven needle.

The free gases within the fuel rod then flow by pressure difference through the puncture head, a particulate filter, a cold iodine trap, and to a collection flask until the pressure is equalized. The volume of the entire collection system is known; therefore, the quantity of gas in the rod can be calculated. The internal free volume of the fuel rod is determined separately by allowing the rod to come to atmospheric pressure, and resealing it; then repeating the process of system evacuation followed by rod puncture and pressure measurement.

The gas released from the fuel rod is then analyzed, using gamma counting techniques and gas chromatography. In the first method, an aliquot of the collected gas is placed in the counting cell of a NaI crystal -- 256-channel gamma spectrometer. Counting is based on the 0.52 MeV gamma rays associated with Kr-85 decay. If the fraction of total fission gas in the aliquot, and the gas volume, are known, it is possible to calculate the number of Kr-85 atoms which had been released from the UO_2 .

In the second method, a sample of the gas mixture is admitted to an evacuated small glass container attached to the chromatograph. The sample is then carried by flowing helium from the

TABLE 3
TASKS IA AND IB PELLET UO₂ FUEL
OPERATING STATISTICS

Fuel No.	No. of Rods	Cumulative Average Heat Flux	Peak Heat Flux During Lifetime	Heat Flux in Last 500-1000 hours	Peak Power Density During Lifetime (kW/liter)	Power Cycles	Thermal Cycles	Hours Critical	Hours at Power	Average (MWd/TU)	Peak (MWd/TU)
1A	16	117,000	376,000	263,000	121.3	653	230	11,384	8,927	8,420	10,950
2A	16	118,000	372,000	261,000	119.6	653	230	11,384	8,927	8,300	10,890
1B	16	121,000	400,000	271,000	123.4	653	230	11,384	8,927	8,200	10,750
2B	16	123,000	417,000	203,000	129.0	653	230	11,384	8,927	8,500	11,400
1C	25	133,000	393,000	224,000	142.5	462	145	8,797	6,908	7,000	11,100
2C	25	130,000	409,000	386,000	152.9	467	153	7,635	5,827	5,900	10,000
3C	25	125,000	393,000	377,000	149.3	482	146	7,087	5,235	5,000	8,100
4C	25	117,000	393,000	330,000	136.2	562	195	8,416	6,256	5,620	9,100
1D	25	124,000	399,000	360,000	153.3	539	199	7,022	4,912	4,950	7,950
2D	25	122,000	399,000	399,000	152.0	439	180	5,844	3,932	4,030	6,050
3D	25	126,000	441,000	441,000	157.7	461	138	6,049	4,252	4,290	7,830
4D	25	110,000	360,000	268,000	133.7	190	80	2,840	1,641	1,770	2,840
1E ^{(a)(b)}	4	142,000	469,000	467,000	161.4	513	192	6,666	4,626	6,250	9,800
2E ^(a)	21	138,000	473,000	444,000	158.2	648	223	8,792	6,401	7,920	11,000
3E ^(a)	23	150,000	489,000	469,000	164.8	648	223	8,792	6,401	8,720	13,500
4E ^(a)	21	144,000	462,000	462,000	161.3	601	215	8,801	6,482	7,780	11,400
5E ^(a)	17	137,000	454,000	450,000	154.9	648	223	8,792	6,401	8,040	12,850
6E ^(a)	22	158,000	511,000	511,000	144.7	486	164	7,314	5,931	7,030	11,250
1F	25	153,000	480,000	231,000	159.4	501	180	9,367	7,281	10,000	13,600
2F	24	154,000	460,000	460,000	138.1	484	163	6,813	5,447	6,910	10,900
1G	25	133,000	480,000	443,000	165.0	523	196	6,803	4,716	5,990	9,000
2G	25	138,000	488,000	416,000	167.5	467	182	6,175	4,228	5,630	8,280
3G	25	140,000	500,000	457,000	167.2	618	211	7,863	5,573	7,250	10,900
4G	25	149,000	488,000	484,000	166.2	625	218	8,306	5,983	8,080	12,100
1S	23	115,000	377,000	191,000	137.5	236	101	2,794	1,958	1,740	2,700
3S	1	122,000	382,000	362,000	144.9	449	146	5,247	4,023	3,850	6,153
3S	3	122,000	382,000	336,000	144.9	486	156	6,039	4,691	4,490	6,300
4S	25	177,000	492,000	297,000	167.5	407	119	7,701	6,496	8,350	12,450
6S	25	135,000	408,000	384,000	151.0	504	168	6,917	5,469	5,500	9,150
10S	4	217,000	458,000	386,000	115.5	181	41	3,500	2,996	3,000	4,500
11S-1 ^(b)	16	146,000	469,000	222,000	161.4	513	192	8,193	6,059	6,529	10,600
1E-12S ^(a)	5	148,000	469,000	420,000	161.4	513	192	7,624	5,510	7,440	12,200
2E-12S ^(a)	4	144,000	473,000	420,000	158.2	648	223	9,750	7,285	9,120	15,700
3E-12S ^(a)	2	154,000	489,000	420,000	164.8	648	223	9,750	7,285	9,910	16,850
4E-12S ^(a)	4	149,000	462,000	420,000	161.3	601	215	9,759	7,366	9,621	15,800
5E-12S ^(a)	8	143,000	454,000	420,000	154.9	648	223	9,750	7,285	9,230	15,900
6E-12S ^(a)	2	162,000	511,000	420,000	144.9	486	164	8,272	6,815	8,850	15,300

Notes: (a) Annealed rods reconstituted in assembly 12S.
(b) Cold-worked rods reconstituted in assembly 11S.

TABLE 4
TASK 1B POWDER UO₂ FUEL
OPERATING STATISTICS

Assembly No.	No. of Rods	Cumulative Ave. Heat Flux (Btu/h ft ²)	Lifetime Peak Heat Flux (Btu/h ft ²)	Heat Flux in Last 500 - 1000 Hours (Btu/h ft ²)	Lifetime Peak Power Density (kW/liter)	Power Cycles	Thermal Cycles	Hours Critical	Hours at Power	Ave. Bundle Exposure (MWd/TU)	Peak Bundle Exposure (MWd/TU)
2S	25	114,000	379,000	368,000	141.9	530	173	6806	5271	4500	7500
3S	13	122,000	380,000	362,000	145.2	486	156	6039	4691	4500	6300
5S	25	217,000	471,000	344,000	164.0	421	109	6126	5024	4600	7350
7S	12	106,000	381,000	261,000	140.7	456	135	5604	4408	3800	6100
8S	16	167,000	527,000	441,000	132.1	265	50	3363	2741	3750	5550
9S	16	157,000	499,000	321,000	157.6	270	57	6054	5267	6200	9100
10S	12	217,000	458,000	386,000	114.7	181	41	3500	2996	3000	4500
(1S) 1SM-1	2	133,000	424,000	424,000	137.5	236	101	3910	2967	2820	4950
(3S) 1SM-1	8	132,000	424,000	424,000	145.2	488	158	6997	5575	5580	9500
(7S) 1SM-1	13	105,000	424,000	424,000	140.7	458	137	6562	5292	4880	8000
(New) 1SM-1	2	196,000	424,000	424,000	137.1	2	2	958	884	1080	1675

TABLE 5

TASKS 1A AND 1B FAILURE DESCRIPTION AND IODINE RELEASE

<u>Assembly No.</u>	<u>Date of Irradiation Termination</u>	<u>Hours Operated W/Failure</u>	<u>Description of Failure</u>	<u>Illustration (Figure No.)</u>	<u>Sample-to-Background Ratio, I-131</u>	<u>Sample-to-Background Ratio, I-132</u>
1A	12/9/63	600	Severe circumferential cracking, sections of rod broken out and missing. One rod failed.	Figure 3	1.22	2.99
2A	12/9/63	300	Severe circumferential cracking, no segments of rod broken out. Two rods failed.	Figure 4	3.8	1.2
1B	12/9/63	-	No visible failures.	-	<1	1.15
2B	12/9/63	150	Circumferential cracks visible. No broken segments; two rods failed.	Figure 5	<1	1.25
1C	12/9/63	-	No visible failures.	-	<1	<1
2C	6/23/63	<100	No visible failures.	-	3.24	2.48
3C	6/23/63	200	Very minute longitudinal cracking visible; some areas of possible UO ₂ leaching through defects. Four rods failed.	Figure 6	2.1	1.81
4C	6/23/63	<100	No cracks visible.	-	2.62	1.96
1D	8/5/62	300	Longitudinal cracking around circumference 9-12 in. from bottom of rod, swelling apparent. One rod failed.	Figure 7	<1	5.2
2D	4/29/62	300	Many apparently disconnected fine longitudinal hairline cracks; one rod failed.	Figure 8	No data	No data
3D	3/5/63	400	Fine longitudinal hairline cracks. In-core sample indicated failure. One rod failed.	Figure 9	2.39	1.84
4D	4/20/62	-	No visible defects.	-	No data	No data
1E	7/8/62	~500	Hairline cracks ~1-1/2 in. long. Little incidence of corrosion product in cracking. One rod failed.	Figure 10	~110	~100
2E	4/25/63	<300	Very fine longitudinal crack. One rod failed.	Figure 11	587	35
3E	4/25/63	<1500	Gross cracking, UO ₂ completely exposed to coolant. One rod failed.	Figure 12	<1	4000
4E	5/12/63	<500	Circumferential cracks at pellet interfaces. One rod failed.	Figure 13	2.67	3.42
5E	4/25/63	<100	No visible failures on any rods.	-	4.4	88.2
6E	6/2/63	<500	Longitudinal cracking. One rod failed. In-core sample indicated failure.	Figure 14	172	156

TABLE 5 (Continued)

Assembly No.	Date of Irradiation Termination	Hours Operated W/Failure	Description of Failure	Illustration (Figure No.)	Sample-to-Background Ratio, I-131	Sample-to-Background Ratio, I-132
1F	12/9/63	500	Longitudinal cracking. One rod failed.	Figure 15	1.61	1.85
2F	4/25/63	<100	No failures observed on peripheral rods.	-	8.83	18.6
1G	7/24/62	300	Circumferential and longitudinal cracks on interior rod. One rod failed, in-core sample indicated failure.	Figure 16	3.38	338
2G	6/12/62	200	Longitudinal cracking. One rod failed.	Figure 17	7.95	168
3G	3/5/63	250	Severe longitudinal cracking. Three rods failed. Complete exposure of UO ₂ to coolant.	Figure 18	3.44	2.94
4G	3/23/63	<100	No observed failures. In-core samples indicated probable failure.	-	1.24	1.5
ISM-1	9/28/63	100	Fine longitudinal cracks. In-core sample indicated failure. One vibratory compacted powder rod failed.	Figure 19	No data	No data
2S	3/5/63	<350	Very severe longitudinal crack in one 10-mil wall swaged powder rod. Minute crack in 16-mil wall swaged powder rod.	Figure 20 Figure 21	34.2	32.8
3S	9/13/62	<500	Severe longitudinal cracking in localized region in corner rod. Rod removed and replaced by dummy.	Figure 22	No data	No data
	3/23/63	700	Very severe cracking in three other corner rods. One rod in particular had pieces of cladding missing. In-core sample indicated failure.	Figure 23 Figure 24 Figure 25	No data	No data
4S	12/9/63	<100	No failures visible on peripheral rods.	-	10.5	3.72
5S	12/9/63	<100	No failures observed in any rods.	-	No data	No data
6S	4/4/63	400	Severe cracking on two peripheral rods. UO ₂ completely exposed to coolant.	Figure 26 Figure 27	7.8	43.2
7S	4/25/63	100	Minute failure observed on one 16-mil wall swaged powder rod.	-	1.1	1.1
8S	4/25/63	<100	No failures observed.	-	5.4	179
9S	12/9/63	-	No failures observed	-	No data	No data
10S	12/9/63	-	No failures observed	-	<1	<1
11S-1	12/9/63	-	No failures observed	-	No data	No data
12S	9/7/63	500	Circumferential cracking in one rod. In-core sample indicated failure.	Figure 28	No data	No data

TABLE 6

SUMMARY OF HPD POST-IRRADIATION — RML EXAMINATIONS AND TESTS

Assembly Number	Fuel Type	Cladding Condition	Cladding Thickness (in.)	Ultrasonic Tests	Gamma Scan	Gross Dimensions (Table 7)	Profilometer Tests (Table 7)	Fission Gas Puncture (Table 8)	Burnup Analysis (Table 9)	Hot Tensile Tests (Table 10)	Burst Tests (Table 11)	Metal- lography	Micro- Hardness (Table 12)	X-Ray Diffraction	Electron Microscopy	Electron Microprobe
1A	Ground Pellet UO ₂	Annealed	0.020	X	X	X		X	X	X	X	X	X	X	X	
2B	Ground Pellet UO ₂	Annealed	0.020	X	X	X	X			X	X					
1C	Ground Pellet UO ₂	Annealed	0.017	X	X	X	X	X	X							
2C	Ground Pellet UO ₂	Cold-worked	0.017				X		X	X		X				
2D	Ground Pellet UO ₂	Cold-worked	0.012	X	X	X		X	X			X	X			
1E	Ground Pellet UO ₂	Cold-worked	0.014	X	X				X			X	X			
2E	Ground Pellet UO ₂	Annealed	0.014	X	X							X	X			
4E	Ground Pellet UO ₂	Cold-worked	0.014									X	X			
	Ground Pellet UO ₂	Annealed	0.014									X	X			
1F	Ground Pellet UO ₂	Cold-worked	0.014	X	X	X	X	X	X	X	X	X	X			
1G	Ground Pellet UO ₂	Annealed	0.014	X	X	X			X	X	X	X	X	X	X	
	Ground Pellet UO ₂	Cold-worked	0.014	X	X	X			X	X	X	X	X			
2G	Ground Pellet UO ₂	Cold-worked	0.014		X	X		X	X			X	X			
1SM-1	Vibpak Powder	Cold-worked	0.012	X	X	X	X	X	X			X	X	X	X	X
	Tandem Rolled Powder	Cold-worked	0.016	X	X	X		X	X			X	X			
2S	Swaged Powder	Cold-worked	0.016	X	X	X		X	X			X	X			
3S	Ground Pellet UO ₂	Cold-worked	0.012		X	X			X			X	X			
5S	Hot Swaged Powder	Annealed	0.016		X	X		X	X			X	X			
6S	Swaged Over Unground Pellets	Annealed	0.010	X	X	X	X									
			0.008	X	X	X	X									
8S	Swaged Powder	Cold-worked	0.010	X	X	X			X			X				
9S	Swaged Powder	Cold-worked	0.010	X	X	X		X	X			X	X			
12S	Ground Pellet UO ₂	Annealed	0.014	X	X	X	X	X	X	X	X	X	X			

TABLE 7
GROSS DIMENSIONAL CHANGES IN PELLETT AND POWDER FUEL RODS IRRADIATED IN VBWR

Fuel Type	Measurements Made Using Dial Gage Techniques							Measurements Made Using Profilometer Techniques					Average Terminal Rod Exposure
	Assembly Number	Rod Measured	Average Unirradiated Outside Diameter	Average Irradiated Outside Diameter	Average Δ D	Maximum Ovality	Maximum Δ D (2)	Assembly Number	Rod Measured	Average Irradiated Outside Diameter	Maximum Ovality	Maximum Δ D (2)	
Pellet UO ₂ - 0.020 Wall	1A	C	0.420	0.420	0	0.001	+0.001	2B	N	0.420	0.0015	+0.001	8,420
Annealed Type 304 SS	1A	M	0.420	0.421	+0.001	0.001	+0.001						
Pellet UO ₂ - 0.017 Wall	1C	C	0.413	0.413	0	0.001	+0.002	1C	J	0.4135	0.006	+0.0065	7,000
Annealed Type 304 SS													
Pellet UO ₂ - 0.017 Wall	-	-	0.413	-	-	-	-	2C	M	0.4138	0.0015	+0.0023	5,900
Cold-Worked Type 304 SS													
Pellet UO ₂ - 0.014 Wall	1G	* W	0.359	0.360	+0.001	0.001	+0.003						5,990
Annealed Type 304 SS													
Pellet UO ₂ - 0.014 Wall	1G	* Q	0.359	0.360	+0.001	0.001	+0.002						5,990
Cold-Worked Type 304 SS	2G	* B	0.359	0.357	-0.002	0.004	-0.002						8,280
Pellet UO ₂ - 0.014 Wall	12S	B	0.362	0.363	+0.001	0.001	+0.0026						8,850
Annealed Type 304 SS	12S	K	0.364	0.364	0	0.001	+0.002	12S	K	0.363	0.005	+0.0035	9,910
Pellet UO ₂ - 0.014 Wall	1F	Y	0.361	0.361	0	0.004	+0.005	1F	H	0.362	0.0013	+0.0025	10,000
Cold-Worked Type 304 SS													
Pellet UO ₂ - 0.012 Wall	2D	* A	0.398	0.399	+0.001	0.004	+0.004						4,030
Cold-Worked Type 304 SS	2D	* F	0.398	0.399	+0.001	0.002	+0.002						4,030
Pellet UO ₂ - 0.010 Wall													
Annealed Type 304 SS	6S	O	0.3928					6S	O	0.3947	0.003	+0.0052	5,550
Powder UO ₂ - Tandem Rolled													
0.016 Wall Cold-Worked Type 304 SS	1SM-1	I	0.4015	0.4015	0	0.002	-0.002						5,580
Powder UO ₂ - Vibratory Compacted													
0.012 Wall Cold-Worked Type 304 SS	1SM-1	V	0.403	0.4035	+0.0005	0.002	+0.002	1SM-1	E	0.4025	0.0015	+0.0002	4,880
Powder UO ₂ - Hot Swaged													
0.016 Wall Annealed Type 304 SS	5S	Q	0.398	0.3983	+0.0003	0.001	0.001						4,600
Powder UO ₂ - Cold Swaged													
0.010 Wall Cold-Worked Type 304 SS	5S	S	-	0.397	-0.002	0.001	-0.003						4,600
Powder UO ₂ - Cold Swaged													
0.010 Wall Cold-Worked Type 304 SS	8S	B	0.406	0.4048	-0.0012	0.001	-0.001						3,750
Powder UO ₂ - Cold Swaged													
0.010 Wall Cold-Worked Type 304 SS	9S	J	0.406	0.4059	-0.0001	0.001	-0.001						6,200

(1) Based on statistical sampling of rods prior to irradiation - Actual range of outside dimensions varies + or - 0.002 inches.
(2) Difference between statistical O. D. and maximum O. D. observed on profile traces.

* Reported in GEAP 4360

container into the chromatograph, which employs columns of either molecular sieves or silica gel. Determination of total Kr and total Xe is performed, using calibration curves, and employing either peak heat or peak area correlation. Stable Kr and Xe are used for calibration.

Table 8 presents the various parameters used in making a correlation of percent fission gas released versus volumetric average fuel temperature as shown in Figure 45. The heavy line is reproduced from Reference 9, with the HPD data points superimposed as indicated. Significant is the fact that the powder UO_2 tends to have a higher release rate than the pellet UO_2 , at least in the range of exposures and power attained. Part of the reason for the higher fission gas release rates in the powder fuels undoubtedly lies in the fact that early in life, the thermal conductivity of the powder UO_2 is somewhat lower than pellet UO_2 . This difference raises the bulk volumetric average temperature of the powder to a level substantially higher than that occurring in pellet UO_2 when both are operated at similar power levels. Also, powder has more free surface and shorter diffusion paths than pellets, permitting easier escape of gases. At higher exposures and temperatures, it is not unreasonable to expect that powder and pellet gas release rates will approach each other; i. e., as powder is operated at high temperatures for long periods, it sinters together and begins to act more and more like sintered pellet UO_2 . The metallography of the powder fuel substantiates this sintering hypothesis.

4.2.4 Burnup Analysis and Results

Twelve individual samples were taken for burnup analysis in the terminal examinations. These were in addition to the eight samples reported previously in the interim examination report. ⁽¹⁰⁾ Sections of cladding and fuel were cut from selected areas of the fuel rods subsequent to the gamma scan. Figures 29 to 32 show typical areas sectioned. In most cases, the burnup sample was taken from the peak flux region on the rod. The UO_2 fuel was then separated from the cladding by dissolution in 50% HNO_3 solution containing cesium carrier. Duplicate aliquots of each sample were taken as backup in case of analysis difficulties.

The burnup was determined by radiochemical techniques and by mass spectrometer analysis. Radiochemical burnup analysis involves the measurement of a fission product to uranium ratio in the irradiated fuel ⁽¹¹⁾ -- in this case, cerium-144/uranium. Mass spectrometer analysis relates burnup to the disappearance of the fissionable U-235 isotope. Physics burnup predictions are generally slightly higher than the experimental values. Table 9 presents the burnup results.

4.2.5 Mechanical Property Changes of Cladding

Tests were performed on the Type-304 stainless clad material to assess the changes induced by neutron exposure. These tests were: hot tensile tests, room-temperature burst tests, hot burst tests, and microhardness tests.

4.2.5.1 Hot Tensile Tests

The tensile tests were run at 625°F to duplicate the temperature at which the cladding operates in the reactor. Unirradiated samples of the same materials were tested for comparison.

The tests indicated a large increase in both the yield and ultimate strengths for the exposures attained. A marked decrease in the total elongation accompanied the strength increases. The results, summarized in Table 10, indicate that for exposures up to 2×10^{21} nvt

1 MeV on annealed (26,000 to 30,000 psi at 625°F) material (1) yield strength increased 200 to

300%, (2) ultimate strength increased 40 to 80%, and (3) elongation decreased to below 4%. The corresponding exposure in cold-worked material (69,000 to 73,000 psi at 625°F) resulted in almost a 100% increase in yield strength, a 50% increase in ultimate strength, and a reduction in total elongation to as low as 2%.

In the range of exposures experienced in the HPD program, the higher rate of strength increase that occurs in the annealed material as compared to the cold worked material indicates that at some point in time both materials will eventually reach the same strength level. Figures 41 and 42 depict this trend.

4.2.5.2 Burst Tests

The series of burst tests performed in the terminal examinations included both annealed Type-304 stainless steel and cold-worked Type-304 to exposures approaching 2.0×10^{21} nvt > 1 MeV. Table 11 summarizes the results of these tests. Included are the results of previous tests reported earlier in the program. (10)

Two of the tests, 1A Rod C and 1F Rod A, were apparently invalid because of incipient cracks in the cladding (see Figures 43 and 44, respectively). The amount of ductility present in those irradiated samples bursting in a normal manner is characterized by Figure 45. Note that the expansion of the irradiated tube is quite localized. Figure 46 shows the manner of burst in similar material in the unirradiated condition. The degree of ductility present in stainless steel tubing irradiated to 2.0×10^{21} nvt > 1 MeV would seem to indicate that the tubing is still capable of deforming locally without failure.

4.2.5.3 Microhardness Tests

Microhardness tests were performed on metallographic samples of cladding from some 30 fuel rods. Both annealed and cold-worked cladding were examined, with exposures ranging from 0 nvt > 1 MeV to approximately 2×10^{21} nvt > 1 MeV. The data are summarized in Table 12.

The data again point out the different rate of hardness increase (or damage) in the two types of cladding, as was noted in the tensile tests. Significantly, in the microhardness data, the difference appears to be present only early in life, as indicated in Figure 47. Later in life, the rate of hardness increase appears to stabilize at the same value for both annealed and cold-worked.

4.2.6 Metallography of Cladding

The failures that have occurred in the HPD program have all been intergranular, regardless of fuel type, rod diameter, or wall thickness, as shown in Figures 48 and 49. No evidence of deformation at crack roots has been observed, although residual plastic deformation has been observed on a macroscopic scale (profile measurements). Those rods examined metallographically have been listed in Table 6. Unirradiated samples of some of the rods were available, so direct metallographic comparison was possible.

4.2.6.1 Metallographic Observations of Cladding

a. HPD-1A - Rod C (Annealed Cladding)

This rod was not failed. Figure 50 shows the material irradiated to approximately 1.8×10^{21} nvt > 1 MeV. Figure 51 shows the unirradiated control sample. A close look at Figure 50 in the inside diameter region of the cladding reveals the "damage zone". This zone is believed to be a result of neutron bombardment with a resulting precipitate or line of deposited fission fragments.

TABLE 8

FISSION GAS RELEASE FROM HPD FUEL RODS

Assembly No.	Rod	Fuel Type	Average Rod Exposure		Lifetime Peak Heat Flux		Temperature Fuel Surface (° F)	Peak Volumetric * Average Temperature		KRYPTON-85		
			MWd/TU	(Fissions/cc)	Btu/h ft ²	(W/cm ²)		(° F)	(° C)	Mass Spectography (No. Atoms)	Gamma Count (No. Atoms)	Percent Fission Gas Released
1A	C	Pellet	8,420	2.3 x 10 ²⁰	376,000	119	1060	1709	932	-	1.88 x 10 ¹³	0.0000521
1A	M	Pellet	8,420	2.3 x 10 ²⁰	376,000	119	1060	1720	938	-	1.99 x 10 ¹⁵	0.00554
1C	C	Pellet	7,000	1.91 x 10 ²⁰	393,000	124	1071	1409	765	6.17 x 10 ¹⁶	7.0 x 10 ¹⁶	0.184
2D	F	Pellet	4,030	1.1 x 10 ²⁰	399,000	126	1051	1490	810	-	3.29 x 10 ¹⁶	0.155
1F	A	Pellet	10,000	2.73 x 10 ²⁰	480,000	152	1171	1589	865	5.62 x 10 ¹⁷	5.05 x 10 ¹⁷	1.23
1F	F	Pellet	10,000	2.73 x 10 ²⁰	480,000	152	1171	1549	843	3.74 x 10 ¹⁷	3.4 x 10 ¹⁷	0.83
1F	M	Pellet	10,000	2.73 x 10 ²⁰	480,000	152	1171	1640	893	1.46 x 10 ¹⁷	1.34 x 10 ¹⁷	0.324
2G	B	Pellet	5,630	1.54 x 10 ²⁰	488,000	156	1182	1648	898	-	3.71 x 10 ¹⁶	0.162
12S	M	Pellet	9,230	2.52 x 10 ²⁰	454,000	143	1137	1560	849	1.06 x 10 ¹⁸	1.65 x 10 ¹⁸	4.39
12S	B	Pellet	8,850	2.42 x 10 ²⁰	511,000	161	1211	1788	976	2.17 x 10 ¹⁸	2.17 x 10 ¹⁸	6.02
1SM-1	E	Tandem Roll Powder	5,580	1.46 x 10 ²⁰	424,000	134	875	1328	720	4.34 x 10 ¹⁷	4.45 x 10 ¹⁷	1.89
1SM-1	I	Vibratory Compacted Powder	4,880	1.21 x 10 ²⁰	424,000	134	848	1427	775	5.97 x 10 ¹⁷	1.88 x 10 ¹⁸	6.35
5S	Q	Hot-Swaged Powder	4,600	1.26 x 10 ²⁰	471,000	149	913	1544	845	7.57 x 10 ¹⁷	7.75 x 10 ¹⁷	3.22
5S	S	Cold-Swaged and Annealed Powder	4,600	1.26 x 10 ²⁰	471,000	149	887	1477	803	7.47 x 10 ¹⁷	8.6 x 10 ¹⁷	3.63
9S	J	Cold-Swaged Powder	6,200	1.62 x 10 ²⁰	499,000	158	908	1765	963	7.28 x 10 ¹⁷	1.1 x 10 ¹⁸	3.14

* Peak Volumetric Average Temperature = $\left(\frac{T_{CL} + T_s}{2} \right)_{\text{peak}} \left(\frac{1}{P/A} \right)$
where: T_{CL} = Centerline temperature of UO₂ Pellet or UO₂ Powder Compact
 T_s = Surface temperature of UO₂ Pellet or UO₂ Powder Compact
P/A = Peak-to-Average power ratio

TABLE 9

HPD UO₂ FUEL BURNUP ANALYSISRESULTS

<u>Assembly/Rod</u>	<u>Ce-144/U</u>		<u>Mass Spectrometry</u>		<u>Physics Calculation</u>
	<u>%BU</u>	<u>MWd/t</u>	<u>%BU</u>	<u>MWd/t</u>	<u>MWd/t</u>
1A/C	1.06	9200	1.13	9800	10,950
1C/C	1.00	8700	1.20	10,400	11,100
2C/C	1.08	9400	1.13	9800	10,000
2D/A	0.35	3100	-	-	4,000
2D/E	0.90	7800	-	-	6,400
1E/E	-	-	1.13	9800	10,000
1F/A	1.49	13,000	1.75	15,200	15,700
1F/Y	1.56	13,600	1.78	15,500	15,700
1G/Q	0.85	7400	1.00	8,700	9,600
1G/R	0.95	7800	0.74	6,400	6,000
2G/B	0.49	4300	-	-	5,600
2G/B	1.30	11,330	-	-	9,000
1SM-1/I	0.90	7,800	0.89	7800	9,500
1SM/V	0.81	7,000	0.90	7800	8,000
3S/E	0.85	7400	-	-	7,200
12S/B	1.53	13,300	1.55	13,500	15,300
5S/Q	0.78	6800	0.78	6800	7350
5S/S	0.80	7000	0.78	6800	7350
8S/B	0.56	4900	0.67	5800	5550
9S/J	0.83	7200	0.91	7900	9100

Percent error:

Ce-144/U = $\pm 10\%$ Mass Spectrometry = $\pm 15\%$

TABLE 10

ELEVATED TEMPERATURE (625° F) TENSILE PROPERTIES OF
TYPE-304 STAINLESS STEEL IRRADIATED AT ELEVATED TEMPERATURE (> 550° F)

Sample	nvt > 1/MeV	Yield Strength			Tensile Strength			Percent Elongation			Remarks
		Unirradiated (at 625° F)	Irradiated (at 625° F)	Δ	Unirradiated (at 625° F)	Irradiated (at 625° F)	Δ	Unirradiated (at 625° F)	Irradiated (at 625° F)	Δ	
1A-C	1.82 x 10 ²¹	31,100	69,700	38,600	75,900	114,700	38,800	33.2	6.5	-26.7	Sample from peak flux region
2B-0	1.53 x 10 ²¹	31,100	104,000	72,900	75,900	114,800	38,900	33.2	4.05	-27.15	Sample from peak flux region
1C-C	1.72 x 10 ²¹	32,400	104,000	71,600	65,300	117,700	52,400	20.1	5.3	-14.8	Sample from peak flux region
12S-B	1.82 x 10 ²¹	27,500	91,600	63,100	64,000	92,600	28,600	25	4.0	-21.0	Sample from peak flux region
1G-B*	1.0 x 10 ²¹	26,500	97,500	71,000	63,500	100,700	37,200	25	7.1	-17.9	Sample from peak flux region
1G-B*	6.0 x 10 ²⁰	26,500	73,100	46,600	63,500	84,900	21,400	25	6.7	-18.3	Sample from average flux region
1G-W*	1.0 x 10 ²¹	26,500	103,100	76,600	63,500	103,700	40,200	25	3.6	-21.4	Sample from peak flux region
1G-W*	6.0 x 10 ²⁰	26,500	76,300	49,800	63,500	84,600	21,100	25	6.7	-18.3	Sample from average flux region
5S-S	1.02 x 10 ²¹		83,900			88,200			1.7		Cold-swaged powder -- cladding annealed after swage
5S-Q	1.02 x 10 ²¹		99,700			100,600			1.3		Hot-swaged powder -- annealed cladding results
1F-A	1.77 x 10 ²¹	73,300	107,000	33,700	89,500	126,300	36,800	7.5	2.6	-4.9	Sample from peak flux region
1F-A	?	73,300	76,500	3,200	89,500	89,600	100	7.5	6.9	-0.6	Sample from plenum zone-very little nvt > 1 MeV exposure
2C-C	1.54 x 10 ²¹	70,100	111,800	41,700	88,100	117,400	29,300	14.1	2.1	-12.0	Sample from peak flux region
1G-Q*	1.0 x 10 ²¹	69,000	118,500	49,500	80,000	119,500	39,500	15	1.4	-13.6	Sample from peak flux region
1G-Q*	6.0 x 10 ²⁰	69,000	101,500	32,500	80,000	108,700	28,700	15	4.0	-11.0	Sample from average flux region
1G-R*	6.0 x 10 ²⁰	69,000	108,400	39,400	80,000	111,500	31,500	15	3.9	-11.1	Sample from average flux region

* Data previously reported in GEAP-4360⁽¹⁰⁾

TABLE 11
RESULTS OF BURST TESTS PERFORMED ON IRRADIATED AND
UNIRRADIATED TYPE-304 STAINLESS STEEL CLAD FUEL RODS
IN HPD PROGRAM

Sample	Exposure (nvt > 1 MeV)	Test Temperature	Maximum Pressure		Hoop Stress		% Δ D	
			Unirradiated (psi)	Irradiated (psi)	Unirradiated (psi)	Irradiated (psi)	Unirradiated	Irradiated
1A Rod C	1.82 x 10 ²¹	RT	8,000	13,350	84,000	140,300	37.6	2.14
2B Rod O	1.53 x 10 ²¹	RT	8,000	14,600	84,000	153,300	37.6	34.3
1F Rod A	1.77 x 10 ²¹	RT	7,910	12,860	102,900	166,700	36.8	1.10
12S Rod B	1.82 x 10 ²¹	RT	—	11,400	85,000	147,800	—	35.6
1G Rod B	6.2 x 10 ²⁰	600° F		7,500		95,700		15.6
1G Rod B	9.4 x 10 ²⁰	550° F		8,700		111,200		15.0
1G Rod W	9.4 x 10 ²⁰	500° F		8,400		107,500		14.8
1G Rod W	6.2 x 10 ²⁰	600° F		7,100		91,000		20.9
1G Rod R	6.2 x 10 ²⁰	600° F		8,400		107,500		21.6

TABLE 12

RESULTS OF MICROHARDNESS TESTS ON UNIRRADIATED AND
IRRADIATED CLADDING MATERIAL USED IN HPD PROGRAM

<u>Assembly and Rod</u>	<u>Cladding Condition</u>	<u>Axial Position of Indentations</u>	<u>Fluence nvt > 1 MeV</u>	<u>Diamond Pyramid Hardness</u>	<u>ΔDPH^(a)</u>
<u>Unirradiated Control Samples</u>					
1A	Annealed		0	139	0 Transverse specimen
1A	Annealed		0	135	0 Longitudinal specimen
1F	Cold-worked		0	218	0 Transverse specimen
1F	Cold-worked		0	219	0 Longitudinal specimen
<u>Irradiated Samples</u>					
1A Rod C	Annealed	Peak flux	1.82×10^{21}	293	+154
1A Rod L	Annealed	Peak flux	1.82×10^{21}	287	+148
1C Rod C	Annealed	Peak flux	1.59×10^{21}	289	+148
2E Rod E	Annealed	Peak flux	1.31×10^{21}	298	+159
2E Rod E	Annealed	5% of peak	6.5×10^{19}	203	+ 64
2E Rod E	Annealed	50% of peak	6.5×10^{20}	217	+ 78
2E Rod E	Annealed	63% of peak	8.2×10^{20}	238	+ 99
2E Rod E	Annealed	84% of peak	1.1×10^{21}	264	+125
4E Rod C	Annealed	Peak flux	1.55×10^{21}	316	+177
4E Rod C	Annealed	19% of peak	2.8×10^{20}	204	+ 65
4E Rod C	Annealed	54% of peak	8.3×10^{20}	263	+124
4E Rod C	Annealed	70% of peak	1.08×10^{21}	240	+101
4E Rod C	Annealed	93% of peak	1.44×10^{21}	323	+184
1G Rod B	Annealed	Peak flux	9.48×10^{20}	293	+154
1G Rod W	Annealed	Peak flux	9.6×10^{20}	284	+145
12S Rod B	Annealed	Peak flux	1.82×10^{21}	288	+149
2D Rod A	Cold-worked	Average flux	8.7×10^{20}	284	+ 66
2D Rod A	Cold-worked	Peak flux	1.40×10^{21}	308	+ 90
2D Rod E	Cold-worked	Peak flux	1.34×10^{21}	342	+124
1E Rod E	Cold-worked	Peak flux	1.15×10^{21}	294	+ 76

(a) Same cladding as in 1G and 2G

(b) Same cladding as in 2D

TABLE 12 (Continued)

<u>Assembly and Rod</u>	<u>Cladding Condition</u>	<u>Axial Position of Indentations</u>	<u>Fluence nvt > 1 MeV</u>	<u>Diamond Pyramid Hardness</u>	<u>Δ DPH^(a)</u>
4E Rod B	Cold-worked	Peak flux	1.55×10^{21}	300	+ 82
4E Rod B	Cold-worked	19% of peak	2.88×10^{20}	250	+ 32
4E Rod B	Cold-worked	54% of peak	8.3×10^{20}	282	+ 64
4E Rod B	Cold-worked	70% of peak	1.08×10^{21}	282	+ 64
4E Rod B	Cold-worked	93% of peak	1.44×10^{21}	306	+ 88
1F Rod Y	Cold-worked	Peak flux	1.77×10^{21}	309	+ 91
1F Rod A	Cold-worked	Peak flux	1.52×10^{21}	339	+121
1G Rod Q	Cold-worked	Peak flux	9.35×10^{20}	305	+ 87
1G Rod R	Cold-worked	Peak flux	9.24×10^{20}	306	+ 88
2G Rod G	Cold-worked	Peak flux	8.5×10^{20}	328	+110
2G Rod G	Cold-worked	Average flux	5.8×10^{20}	271	+ 53
2G Rod B	Cold-worked	Average flux	5.8×10^{20}	264	+ 46
3S Rod E ^(a)	Cold-worked	Peak flux	1.05×10^{21}	328	+110
1SM-1 Rod V ^(b)	Cold-worked	Peak flux	1.12×10^{21}	310	+ 92
1SM-1 Rod I	Cold-worked	Peak flux	1.48×10^{21}	361	+143
2S Rod I	Cold-worked	Peak flux	1.24×10^{21}	356	No pre-data available
5S Rod Q	Cold-worked	Peak flux	1.02×10^{21}	319	No pre-data available
5S Rod S	Annealed	Peak flux	1.02×10^{21}	272	No pre-data available
9S Rod T	Cold-worked	Peak flux	6.9×10^{21}	310	No pre-data available

(a) Same cladding as in 1G and 2G

(b) Same cladding as in 2D

b. HPD Assembly 1F (Cold-Worked Material)

The unirradiated control is shown in Figure 52. The inside diameter band is barely discernible in the Assembly 1F, Rod A sample (Figure 53), but is present in other samples of cladding of the same type irradiated to the same exposures. HPD 1F, Rod Y cladding is shown in Figure 54. The major crack in the cladding is also shown.

In most cases, the metallographic samples can be prepared to bring out additional features of the "damage zone." Figure 55 shows the zone in cold-worked cladding when etched lightly with glyceresia. Figure 56 shows the zone when etched with alkaline-ferrocyanide. A study of the damage zone was conducted, using electron microscope, x-ray diffraction, and electron beam microprobe techniques, and is reported in Reference 12.

c. HPD-5S - Rod S (Annealed Cladding)

Rod S from Assembly 5S in the Task 1B cold-swaged powder group was annealed and sensitized after the final swage pass. Examination of this rod provided an opportunity to study austenitic stainless steel material in the classical condition most susceptible to intergranular corrosion attack. Post-irradiation visual observations of the rod revealed no cladding penetrations. This was confirmed by the apparent validity of the fission gas measurements (Table 8).

Metallographic examination confirmed that the cladding was sensitized. Figure 57 was the first etch in the examination; it revealed a large degree of precipitation in the grain boundaries. The reagent used was glyceresia. The second polish and etch used was picric-HCl; again, general precipitation in the grain boundaries was in evidence, as shown in Figure 58. The third polish and etch used the staining etch, alkaline-ferrocyanide, to reveal the inside diameter structure. Figure 59 shows this zone. The alkaline-ferrocyanide also appears to attack or stain the outside diameter grain boundaries as well. The level of exposure attained by this material was at least as high as that attained by the early failures experienced in the program (failed assembly 2D achieved 6080 MWd/t peak exposure, while 5S attained 7380 MWd/t peak).

4.2.6.2 General Metallographic Observations of Cladding from Powder Fuel Rods

Observations of the cladding microstructure of various powder fuel types (tandem-rolled, vibratory-compacted powder, cold-swaged and hot-swaged) were similar to the observations made on pellet fuel. The only additional powder failure, other than the two previously failed rods in HPD 2S, ⁽¹³⁾ occurred in a vibratory-compacted powder rod. The cracks observed were confirmed as being intergranular. None of the other powder rods had failed up to the time of VBWR deactivation. Metallographic observation on the cladding microstructure has revealed essentially no changes from the pre-irradiation condition except as previously mentioned -- the formation of the inside diameter "damage zone."

Large fuel particles in close contact with the cladding may be embedded in the inside diameter surface during swaging, with a resulting localized decrease in the wall at that point. Several of these areas were observed in the metallographic specimens of the various powder rods examined. Theoretically, these areas should be under higher local stress (or strain) during operation and conceivably could be the areas most likely to incubate a failure. Figure 60 is one

such typical area. The examination of many such areas leads to the conclusion that localized particle penetration due to swaging is apparently not a limiting factor in the operation of compacted powder fuel.

4.2.7 Metallography of UO_2 Pellet and Powder Fuel Rods

The metallographic specimens selected for observation in the terminal examinations were primarily from those rods which either had high exposure or had been subjected to high heat flux conditions during their lifetime. Pellet rods examined included UO_2 with exposures exceeding 15,000 MWd/TU in the areas examined metallographically. Powder rods had exposures approaching 10,000 MWd/TU locally, and in most cases during operation had surface heat fluxes exceeding 500,000 Btu/h-ft².

4.2.7.1 Sintered Pellet UO_2

The microstructure of pellet UO_2 in the unirradiated condition is shown in Figure 61. Figure 62 is a typical cross section of fuel irradiated to exposures approaching 15,000 MWd/t. The peak heat flux operated at during the lifetime of the fuel was 511,000 Btu/h-ft². This corresponds to a centerline temperature of about 4000°F.

The structure of the UO_2 at the outside diameter of the pellet looks similar to the unirradiated fuel (Figure 61). The grain size is essentially the same, and the porosity is distributed through the grains. Toward the center of the pellet, the similarity decreases. A porosity transition zone (Figure 62b) is noticeable in that the grain boundaries begin to show more and more porosity until finally, in the center of the pellet (Figure 62b), the grains are almost completely surrounded by porosity in the boundaries. Very little grain growth is visible at the center. Apparently, the short times at the peak conditions of operation do not allow significant grain growth to occur; rather, the sintered compact tends to become more and more porous as the entrapped residual gases and fission product gases reorientate in the hot portions of the fuel.

The degree of open porosity is perhaps illustrated better by a polished section of the UO_2 . Figure 63 is the central region, as shown in Figure 62c, but without the etched surface. Note how completely the grain boundaries are outlined in some cases.

4.2.7.2 Powder UO_2 Fuel

The vibratory-compacted powder fuel rod, HPD-1SM-1, Rod V No. 273, was examined metallographically (a) to determine the degree of fuel lost, if any, through the clad failure; (b) to assess the changes that may have occurred due to in-reactor operation; and (c) to enable a comparison to be made between pellets and vibratory-compacted powder.

Figure 64a is a cross section of the fuel rod taken at the peak flux region and failure zone. The first significant observation made was that the compact appeared very stable mechanically; that is, very little powder, if any, was lost during the cutting, grinding and polishing operation performed. The central core of the fuel has sintered extensively (Figure 64 and 65). Groups of particles appear to have fused together even near the outer radius of the fuel compact. Calculations show that the central temperature of the rod never exceeded 3500°F, based upon

thermal conductivity given by Coplin and Lyons⁽¹⁴⁾ at the peak power condition (425,000 Btu/h-ft²). The zone of porosity shown in Figure 64b is a temperature effect. The porosity transition zone observed at about the mid-radius corresponds to that observed in pellet UO₂ (Figure 62b), although the character of the porosity differs in that no individual grains are present.

The tandem-rolled powder fuel is shown in Figures 66a, 66b, and 66c, which are taken at the outside diameter mid-radius and center, respectively. The degree of sintering that has occurred is difficult to determine visually. The fact that some has occurred is evidenced by the cracks in the compact which run through large and small particles without separation at particle interfaces. This is particularly noticeable in Figure 66b on the right side of the photo.

Hot-swaged powder fuel is shown in Figures 67a, 67b, and 67c, taken at the fuel-cladding interface, mid-radius, and center, respectively. Sintering and grain growth are not clearly defined, but as previously noted, the character of the thermal cracks through the compact indicates good particle bonding.

Cold-swaged powder fuel is shown in Figures 68a, 68b, and 68c at the fuel cladding interface, mid-radius, and center, respectively. Sintering and grain growth in the central region of the compact is well defined.

In general, the observations made on the powder fuel in the metallographic examinations do not reveal any potential limitation, either on lifetime or for power levels experienced in the HPD test program.

The fuel appears completely compatible with the stainless cladding, even in the cases where particle penetration has occurred on inside diameter surfaces. There is very strong evidence that as time in reactor at high power conditions increases, the powder tends to assume the characteristics of pellet fuel; i. e., sintering takes place and void or porosity formations occur similar to those in pellets.

SECTION V

ILLUSTRATIONS

The following illustrations are contained in this section:

<u>Figure No.</u>	<u>Title</u>
1.	Typical High Power Density VBWR Fuel Assembly
2.	Swaged-over-Pellet Process Schematic
3.	HPD-1A, Rod L, Failure
4.	HPD-2A Failure, Pellet UO_2
5.	HPD-2B Failure, Pellet UO_2
6.	HPD-3C Failure, Pellet UO_2
7.	HPD-1D Failure, Pellet UO_2
8.	HPD-2D Failure, Pellet UO_2
9.	HPD-3D Failure, Pellet UO_2
10.	HPD-1E Failure, Pellet UO_2
11.	HPD-2E Failure, Pellet UO_2
12.	HPD-3E Failure, Pellet UO_2
13.	HPD-4E Failure, Pellet UO_2
14.	HPD-6E Failure, Pellet UO_2
15.	HPD-1F, Rod Y, Failure, Pellet UO_2
16.	HPD-1G Failure, Pellet UO_2
17.	HPD-2G Failure, Pellet UO_2
18.	HPD-3G Failure, Pellet UO_2
19.	HPD-1SM-1 Vibratory Compacted Powder Failure
20.	HPD-2S Swaged Powder Failure
21.	HPD-2S, Rod A, Minor Failure in Swaged Powder
22.	HPD-3S Failure, Pellet UO_2
23.	HPD-3S Failure, Pellet UO_2
24.	HPD-3S Failure, Pellet UO_2
25.	HPD-3S Failure, Pellet UO_2
26.	HPD-6S Failure, Pellet UO_2
27.	HPD-6S Failure, Pellet UO_2
28.	HPD-12S, Rod A, Failure, Pellet UO_2
29.	Typical Gamma Scan and Cutting Diagram of Central Rod Fuel Follower
30.	Typical Gamma Scan and Cutting Diagram for Large Gas Plenum Rods
31.	Typical Gamma Scan and Cutting Diagram of Prototype Pellet UO_2 Rod
32.	Typical Gamma Scan and Cutting Diagram for Compacted Powder UO_2 Fuel Rods
33.	Dimensional Profile Trace of Rod N of HPD-2B
34.	Dimensional Profile Trace of Rod M of HPD-2C
35.	Dimensional Profile Trace of Rod J of HPD-1C
36.	Dimensional Profile Trace of Rod H of HPD-1F
37.	Dimensional Profile Trace of Rod K of HPD-12S
38.	Dimensional Profile Trace of Rod V of HPD-1SM-1
39.	Dimensional Profile Trace of Rod O of HPD-6S

<u>Figure No.</u>	<u>Title</u>
40.	Temperature-Dependent Pellet and Powder UO_2 Fuel Fission Gas Release
41.	625°F (330°C) Yield Strength versus nvt >1 MeV for HPD Program Type-304 Stainless Steel
42.	Percent Total Elongation versus nvt >1 MeV for HPD Program Type-304 Stainless Steel
43.	HPD-1A, Rod C. Burst Test Specimen with Notch Causing Premature Release of Pressure
44.	HPD-1F, Rod A. Burst Test Specimen with Notch Causing Premature Burst of Specimen
45.	HPD-2B, Rod O. Burst Test Specimen
46.	Cladding Control Material Burst Specimen
47.	Comparison of Microhardness Changes Due to Irradiation in Annealed and Cold- worked Type 304 Stainless Steel used in HPD Program
48.	Typical Intergranular Attack on Type-304 Stainless Steel in HPD Program
49.	Intergranular Attack and Branching in Type-304 Stainless Steel
50.	Irradiated Sample of HPD-1A Clad Annealed Material
51.	Unirradiated Sample of HPD-1A Clad Annealed Material
52.	Unirradiated Sample of HPD-1F Clad Cold-Worked Material
53.	Irradiated Sample of HPD-1F Clad Cold-Worked Material
54.	HPD-1F Rod Y, Major Crack Region Showing Structure at Inside Diameter Surface
55.	Inside Diameter Zone Etched with Glyceregia
56.	Inside Diameter Zone Etched with Alkaline-Ferracyanide
57.	Glyceregia Etch on HPD-5S Cladding Revealing Grain Boundary Precipitation or Sensitization
58.	HPD-5S Cladding Etched with Picric-HCl
59.	HPD-5S Cladding Stained with Alkaline-Ferrocyanide
60.	UO_2 Particle Penetration in Cladding Wall
61.	Unirradiated Sintered Pellet UO_2 Microstructure
62.	Irradiated Sintered Pellet UO_2 Microstructure, Etched
63.	Irradiated Sintered Pellet UO_2 Microstructure Polished
64.	Vibratory Compacted Powder UO_2 Microstructure
65.	Vibratory Compacted Powder UO_2 Microstructure, Etched
66.	Tandem Rolled Powder UO_2 , Micro-Etched
67.	Hot-Swaged Powder UO_2 , Micro-Etched
68.	Cold-Swaged Powder UO_2 Microstructure, Etched

FIGURE 1. TYPICAL HIGH POWER DENSITY VBWR FUEL ASSEMBLY

(a) CONVENTIONAL SWAGING OF SORTED OR CENTERLESS-GROUND PELLETS.

(b) CONVENTIONAL SWAGING OF AS-SINTERED PELLETS.

(c) NYLON DIE SWAGING OF AS-SINTERED PELLETS.

FIGURE 2. SWAGED-OVER PELLET PROCESS SCHEMATIC

(a)
SEGMENT OF ROD MISSING

(b)
TYPICAL CIRCUMFERENTIAL
CRACKING IN ANNEALED TYPE 304

0.420 x 0.020 in. 304 SS CLAD UO_2 GROUND PELLETS

0.005 in. NOMINAL GAP

INITIAL CLADDING CONDITION: ANNEALED, 38,000 psi Y.S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

HEAT FLUX IN FAILURE LOCATION: 376,000 Btu/h-ft²

(c)
SEGMENT OF ROD MISSING IN (a) ABOVE, FOUND LODGED IN LOWER TIE PLATE OF ASSEMBLY

FIGURE 3. HPD-1A, ROD L, FAILURE

(a)
CORROSION PRODUCT FORMED OVER
CIRCUMFERENTIAL CRACKS

(b)
COMPLETE CIRCUMFERENTIAL
SEPARATION

0.420 x 0.020 in., 304 SS CLAD UO_2 GROUND PELLETS

0.005 in. NOMINAL GAP

INITIAL CLADDING CONDITION: ANNEALED, 38,000 psi Y. S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

HEAT FLUX IN FAILURE LOCATION: 372,000 Btu/h-ft²

FIGURE 4. HPD-2A FAILURE, PELLET UO_2

(a) (b)
CIRCUMFERENTIAL CRACKING AT PELLET INTERFACE LENGTHS

0.420 x 0.020 in. 304 SS CLAD UO_2 GROUND PELLETS

0.005 in. NOMINAL GAP

INITIAL CLADDING CONDITION: ANNEALED, 38,000 psi Y.S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

HEAT FLUX IN FAILURE LOCATION: 417,000 Btu/h-ft²

PELLET $L/D = \sim 1.4$

$D = 0.375$

$L = 0.525$

FIGURE 5. HPD-2B FAILURE, PELLET UO_2

(a)
VISIBLE MICROCRACKS OUTLINED BY
CORROSION PRODUCT

(b)
SAME AS (a) AFTER ACETONE WIPE

0.412 x 0.017 in. 304 SS GROUND UO_2 PELLETS
0.003 in. NOMINAL GAP
INITIAL CLADDING CONDITION: COLD WORKED, 95,000 psi Y.S.
FAILURE LOCATION: PEAK HEAT FLUX REGION
HEAT FLUX: 393,000 Btu/h-ft²

STREAMING OF CORROSION PRODUCT.
BLISTERS IDENTIFIED AS FISSION
PRODUCT OXIDES. →

↑
DIRECTION OF
FLOW

FIGURE 6. HPD-3C FAILURE, PELLET UO_2

LONGITUDINAL CRACKING OBSERVED IN FAILED ROD

0.398 x 0.012 in., 304 SS CLAD UO_2

0.002 in. NOMINAL GAP

INITIAL CLAD CONDITION: COLD WORKED 94,000 psi Y.S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

EXPOSURE AT FAILURE LOCATION: 7900 MWd/t

HEAT FLUX AT FAILURE LOCATION: 400,000 Btu/h-ft²

FIGURE 7. HPD-1D FAILURE, PELLET UO_2

SHORT LONGITUDINAL CRACKS IN FUEL CLADDING

0.398 x 0.012 in., 304 SS CLAD UO_2

0.002 in. NOMINAL GAP

INITIAL CLADDING CONDITION: COLD WORKED, 94,000 psi Y.S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

EXPOSURE AT FAILURE LOCATION: 6400 MWd/t

HEAT FLUX AT FAILURE LOCATION: 399,000 Bt/h-ft²

FIGURE 8. HPD-2D FAILURE, PELLET UO_2

1.20X

FAILURE OCCURRED 8-1/2 TO 9-1/2 in. FROM BOTTOM END

0.398 x 0.012 in., 304 SS CLAD UO_2

0.002 in. NOMINAL GAP

INITIAL CLADDING CONDITION: COLD WORKED, 94,000 psi Y.S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

EXPOSURE AT FAILURE LOCATION: 6900 MWd/t

HEAT FLUX AT FAILURE LOCATION: 440,000 Btu/h-ft²

FIGURE 9. HPD-3D FAILURE, PELLETT UO_2

FAILURE OCCURED 9-1/2 TO 10 1/2 in. FROM BOTTOM

0.363 x 0.014 in., 304 SS CLAD UO_2

0.005 in. NOMINAL GAP

INITIAL CLADDING CONDITION: COLD WORKED,
90,000 psi Y.S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

EXPOSURE AT FAILURE LOCATION: 10,000 MWd/t

HEAT FLUX AT FAILURE LOCATION: 470,000 Btu/h-ft²

FIGURE 10. HPD-1E FAILURE, PELLET UO_2

(a)
CRACK BEFORE CLEANING

(b)
PHOTO (a) AFTER ACETONE WIPE

LONGITUDINAL CRACK 11 in. FROM BOTTOM

0.363 x 0.014 in., 304 SS CLAD UO_2

0.005 in. NOMINAL GAP

INITIAL CLADDING CONDITION: COLD-WORKED, 90,000 psi Y.S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

EXPOSURE AT FAILURE LOCATION: 12,700 MWd/t

HEAT FLUX AT FAILURE LOCATION: 470,000 Btu/h-ft²

FIGURE 11. HPD-2E FAILURE, PELLET UO_2

GROSS FAILURE 10-1/2 TO 16 in. FROM BOTTOM

0.363 x 0.014 in., 304 SS CLAD UO_2

0.005 in. NOMINAL GAP

INITIAL CLADDING CONDITION: COLD WORKED 90,000 psi Y.S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

EXPOSURE AT FAILURE LOCATION: 13,900 MWd/t

HEAT FLUX AT FAILURE LOCATION: 490,000 Btu/h-ft²

FIGURE 12. HPD-3E FAILURE, PELLET UO_2

(a)

0 DEGREES

(b)

90 DEGREES

CIRCUMFERENTIAL CRACKING

0.363 x 0.014 in. 304 SS CLAD UO_2

0.005 in. NOMINAL GAP

INITIAL CLADDING CONDITION: ANNEALED 44,000 psi Y.S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

EXPOSURE AT FAILURE LOCATION: 13,500 MWd/t

HEAT FLUX AT FAILURE LOCATION: 460,000 Btu/h-ft²

FIGURE 13. HPD-4E FAILURE, PELLET UO_2

0.363 x 0.014 in., 304 SS CLAD UO_2

0.005 in. NOMINAL GAP

INITIAL CLADDING CONDITION: COLD-WORKED 90,000 psi Y.S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

EXPOSURE AT FAILURE LOCATION: 12,200 MWd/t

HEAT FLUX AT FAILURE LOCATION: 470,000 Btu/h-ft²

FIGURE 14. HPD-6E FAILURE, PELLET UO_2

(a)
CORROSION PRODUCT IN CRACK

(b)
PHOTO (a) AFTER ACETONE WIPE

0.360 x 0.014 in. 304 SS CLAD UO_2 GROUND PELLETS

0.005 in. NOMINAL GAP

INITIAL CLADDING CONDITION: COLD WORKED, 90,000 psi Y.S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

HEAT FLUX: 480,000 Btu/h-ft²

FIGURE 15. HPD-1F, ROD Y FAILURE, PELLETT UO_2

LONGITUDINAL CRACKING

0.360 x 0.014 in., 304 SS CLAD UO_2
0.002 in. NOMINAL GAP
INITIAL CLADDING CONDITION: COLD WORKED 90,000 psi Y.S.
FAILURE LOCATION: PEAK HEAT FLUX REGION
EXPOSURE AT FAILURE LOCATION: 9600 MWd/t
HEAT FLUX AT FAILURE LOCATION: 480,000 Btu/h-ft²

FIGURE 16. HPD-1G FAILURE—PELLET UO_2

2.0X

18300

IRREGULAR LONGITUDINAL CRACK IN PEAK FLUX REGION

0.360 x 0.014 in., 304 SS CLAD UO_2

0.002 in. NOMINAL GAP

INITIAL CLADDING CONDITION: COLD WORKED, 90,000 psi Y.S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

EXPOSURE AT FAILURE LOCATION: 9000 MWd/t

HEAT FLUX AT FAILURE LOCATION: 480,000 Btu/h-ft²

FIGURE 17. HPD-2G FAILURE, PELLET UO_2

a. HPD-3G — ROD B SERVICE FAILURE

b. HPD-3G — ROD C SERVICE FAILURE

c. HPD-3G — ROD E SERVICE FAILURE

0.360 x 0.014 in., 304 SS CLADDING
 0.002 in. NOMINAL GAP
 INITIAL CLADDING CONDITION: COLD WORKED, 90,000 psi Y.S.
 FAILURE LOCATION: PEAK FLUX REGION
 EXPOSURE AT FAILURE LOCATION: 11,600 MWd/t
 HEAT FLUX AT FAILURE LOCATIONS: 500,000 Btu/h-ft²

FIGURE 18. HPD-3G FAILURE, PELLET UO₂

(a)

CORROSION PRODUCT IN CRACKS

(b)

PHOTO (a) AFTER ACETONE WIPE

0.400 x 0.012 in., 304 SS CLAD COMPACTED POWDER
INITIAL CLADDING CONDITION: COLD WORKED, 95,000 psi Y.S.
FAILURE LOCATION: PEAK FLUX REGION
HEAT FLUX IN FAILURE LOCATION: 424,000 Btu/h-ft²

FIGURE 19. HPD-1SM-1 VIBRATORY COMPACTED POWDER FAILURE

LONGITUDINAL SPLIT IN ROD No. 437, ROD I, ASSEMBLY HPD-2S
THE CLADDING IS TYPE-304 STAINLESS STEEL, 0.011 in. THICK.
THE FUEL IS FUSED URANIUM DIOXIDE SWAGED TO A DENSITY OF
 $93 \pm 1\%$ OF THEORETICAL. ONLY A SMALL AMOUNT OF FUEL WAS
LOST TO THE REACTOR COOLANT

FIGURE 20. HPD-2S SWAGED POWDER FAILURE

MINOR CRACK IN 16-mil WALL SWAGED POWDER ROD

FIGURE 21. HPD-2S, ROD A, MINOR FAILURE IN SWAGED POWDER

(a) 0 DEGREE

(b) 90 DEGREES

LONGITUDINAL CRACKING — NOTE DEGREE OF PELLET BREAKAGE

0.400 x 0.012 in., 304 SS CLAD UO_2

0.002 in. NOMINAL GAP

INITIAL CLADDING CONDITION: COLD WORKED, 80,000 psi Y.S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

EXPOSURE AT FAILURE LOCATION: 6200 MWd/t

HEAT FLUX AT FAILURE LOCATION: 380,000 Btu/h-ft²

FIGURE 22. HPD-3S FAILURE, PELLET UO_2

LONGITUDINAL CRACKING

0.400 x 0.012 in., 304 SS CLAD UO_2

0.002 in. NOMINAL GAP

INITIAL CLADDING CONDITION: COLD WORKED, 80,000 psi Y.S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

EXPOSURE AT FAILURE LOCATION: 7200 MWd/t

HEAT FLUX AT FAILURE LOCATION: 380,000 Btu/h-ft²

FIGURE 23. HPD-3S FAILURE, PELLET UO_2

LONGITUDINAL CRACKING — PELLET UO_2 COMPLETELY EXPOSED TO COOLANT
 0.400 x 0.012 in., 304 SS CLAD UO_2
 0.002 in. NOMINAL GAP
 INITIAL CLADDING CONDITION: COLD WORKED, 80,000 psi Y. S.
 FAILURE LOCATION: PEAK HEAT FLUX REGION
 EXPOSURE AT FAILURE LOCATION: 7200 MWd/t
 HEAT FLUX AT FAILURE LOCATION: 380,000 Btu/h-ft²

FIGURE 24. HPD-3S FAILURE, PELLET UO_2

LONGITUDINAL CRACKING

0.400 x 0.012 in., 304 SS CLAD UO_2

0.002 in. NOMINAL GAP

INITIAL CLADDING CONDITION: COLD WORKED, 80,000 psi Y.S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

EXPOSURE AT FAILURE LOCATION: 7200 MWd/t

HEAT FLUX AT FAILURE LOCATION: 380,000 Btu/h-ft²

FIGURE 25. HPD-3S FAILURE, PELLET UO_2

COMBINED LONGITUDINAL AND CIRCUMFERENTIAL CRACKING

0.390 x 0.008 in., 304 SS CLAD UO_2 UNGROUND PELLETS

0 TO 0.002 in. NOMINAL GAP

INITIAL CLADDING CONDITION: COLD WORKED, 52,000 psi Y.S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

EXPOSURES IN FAILURE LOCATION: 8450 MWd/t

HEAT FLUX IN FAILURE LOCATION: 410,000 Btu/h-ft²

FIGURE 26. HPD-6S FAILURE, PELLET UO_2

0.390 x 0.008 in., 304 SS CLAD SWAGED-OVER UO_2 UNGROUND PELLETS

0 TO 0.002 in. NOMINAL GAP

INITIAL CLADDING CONDITION: COLD-WORKED, 52,000 psi Y.S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

EXPOSURES IN FAILURE LOCATION: 8450 MWd/t

HEAT FLUX IN FAILURE LOCATION: 410,000 Btu/h-ft²

FIGURE 27. HPD-6S FAILURE, PELLET UO_2

CIRCUMFERENTIAL CRACK, SAME TYPE ROD AS SHOWN IN FIGURE 13.

0.360 x 0.014 in., 304 SS CLAD UO_2 GROUND PELLETS

0.005 in. NOMINAL GAP

INITIAL CLADDING CONDITION: ANNEALED 44,000 psi Y.S.

FAILURE LOCATION: PEAK HEAT FLUX REGION

HEAT FLUX FAILURE LOCATION: 500,000 Btu/h-ft²

FIGURE 28. HPD-12S, ROD A, FAILURE, PELLET UO_2

FIGURE 29. TYPICAL GAMMA SCAN AND CUTTING DIAGRAM OF CENTRAL ROD FUEL FOLLOWER

FIGURE 30. TYPICAL GAMMA SCAN AND CUTTING DIAGRAM FOR LARGE GAS PLENUM RODS

FIGURE 31. TYPICAL GAMMA SCAN AND CUTTING DIAGRAM OF PROTOTYPE PELLETT UO_2 ROD

3.5% ENRICHED VIBRATORY COMPACTED
POWDER AT 85% TD

CLADDING TYPE: 0.400 DIAMETER x 0.012 WALL,
304 SS COLD WORKED

PEAK-TO-AVERAGE POWER RATIO = 1.64

FIGURE 32. TYPICAL GAMMA SCAN AND CUTTING DIAGRAM FOR COMPACTED POWDER UO_2 FUEL RODS

FIGURE 33. DIMENSIONAL PROFILE TRACE
 OF ROD N OF HPD-28

FIGURE 34. DIMENSIONAL PROFILE TRACE
OF ROD M OF HPD-2C

FIGURE 35. DIMENSIONAL PROFILE TRACE
OF ROD J OF HPD-1C

FIGURE 36. DIMENSIONAL PROFILE TRACE OF ROD H OF HPD-1F

FIGURE 37. DIMENSIONAL PROFILE TRACE OF ROD K OF HPD-125

FIGURE 38. DIMENSIONAL PROFILE TRACE OF ROD V OF HPD-1 SM-1

FIGURE 39. DIMENSIONAL PROFILE TRACE OF ROD O OF HPD-65

FIGURE 40. TEMPERATURE-DEPENDENT PELLET AND POWDER UO_2 FUEL FISSION GAS RELEASE

FIGURE 41. 625°F (330°C) YIELD STRENGTH VERSUS $nvt > 1 \text{ MeV}$ FOR HPD PROGRAM TYPE-304 STAINLESS STEEL

FIGURE 42. PERCENT TOTAL ELONGATION VERSUS $nvt > 1 \text{ MeV}$ FOR HPD PROGRAM TYPE -304 STAINLESS STEEL

FIGURE 43. HPD-1A, ROD C. BURST TEST SPECIMEN WITH NOTCH CAUSING PREMATURE RELEASE OF PRESSURE

FIGURE 44. HPD-1F, ROD A. BURST TEST SPECIMEN WITH NOTCH CAUSING PREMATURE BURST OF SPECIMEN

FIGURE 45. HPD-2B, ROD O. BURST TEST SPECIMEN. DUCTILITY PRESENT IN SAMPLE IRRADIATED TO 1.5×10^{21} nvt > 1 MeV

FIGURE 46. CLADDING CONTROL MATERIAL BURST SPECIMEN. UNIRRADIATED CONTROL SAMPLE OF MATERIAL SHOWN IN FIGURE 45.

FIGURE 47. COMPARISON OF MICROHARDNESS CHANGES DUE TO IRRADIATION IN ANNEALED AND COLD-WORKED TYPE-304 STAINLESS STEEL USED IN HPD PROGRAM

FIGURE 48. TYPICAL INTERGRANULAR ATTACK ON TYPE-304 STAINLESS STEEL IN HPD PROGRAM

250X

FIGURE 49. INTERGRANULAR ATTACK AND BRANCHING IN TYPE-304 STAINLESS STEEL

FIGURE 50. IRRADIATED SAMPLE OF HPD-1A CLAD ANNEALED MATERIAL

FIGURE 51. UNIRRADIATED SAMPLE OF HPD-1A CLAD ANNEALED MATERIAL

FIGURE 52. UNIRRADIATED SAMPLE OF HPD-1F CLAD COLD-WORKED MATERIAL

FIGURE 53. IRRADIATED SAMPLE OF HPD-1F CLAD COLD-WORKED MATERIAL

UO₂

i. d.

FIGURE 54. HPD-1F, ROD Y, MAJOR CRACK REGION SHOWING
STRUCTURE AT INSIDE DIAMETER SURFACE

FIGURE 55. INSIDE DIAMETER ZONE ETCHED WITH GLYCEREGIA

FIGURE 56. INSIDE DIAMETER ZONE ETCHED WITH ALKALINE-FERROCYANIDE

FIGURE 57. GLYCERIC ACID ETCH ON HPD-5S CLADDING REVEALING GRAIN BOUNDARY PRECIPITATION OR SENSITIZATION

FIGURE 58. HPD-5S CLADDING ETCHED WITH PICRIC-HCl

FIGURE 59. HPD-5S CLADDING STAINED WITH ALKALINE-FERROCYANIDE. NOTE DEGREE OF GRAIN-BOUNDARY STAINING AT OUTSIDE DIAMETER OF CLAD SECTION.

FIGURE 60. UO_2 PARTICLE PENETRATION IN CLADDING WALL ($\bar{r} = 0.010$ in.).
THE INITIAL SWAGING OF THE ROD IS THE CAUSE OF THIS, RATHER
THAN UO_2 - CLAD INTERACTION DURING OPERATION.

(a)

100X

SINTERED UO_2 ($\sim 95\%$ TD) EQUIAXED GRAIN STRUCTURE WITH UNIFORM POROSITY
IN UNIRRADIATED CONDITION

(b)

500X

FIGURE 61. UNIRRADIATED SINTERED PELLET UO_2 MICROSTRUCTURE

HPD-12S ROD B

EXPOSURE: $\sim 15,000$ MWd/t
PEAK HEAT FLUX: $511,000$ Btu/h-ft²
PEAK CENTERLINE TEMPERATURE: $\sim 4000^{\circ}\text{F}$
ROD DIAMETER: 0.363 inch
WALL THICKNESS: 0.014 inch

FUEL CLADDING SPECIMEN

└─┬─> POROSITY TRANSITION ZONE

ETCHED

100X

(a) CLADDING — FUEL INTERFACE

ETCHED

100X

(b) MID-RADIUS FUEL

ETCHED

100X

(c) CENTRAL REGION OF FUEL

FIGURE 62. IRRADIATED SINTERED PELLETS UO_2 MICROSTRUCTURE, ETCHED

100X

POLISHED SECTION OF UO_2 PELLET CENTRAL REGION
IRRADIATED TO $\sim 15,000$ MWd/t
PEAK TEMPERATURE REACHED AT THIS POINT DURING LIFETIME
WAS $\sim 4000^\circ\text{F}$.

FIGURE 63. IRRADIATED SINTERED PELLET UO_2 MICROSTRUCTURE, POLISHED

HPD — ISM-1, ROD V

~ 85% TD
8,000 MWd/t
425,000 Btu/h-ft²

(a) FUEL CLADDING CROSS SECTION

~ 6X

(b) RADIAL COMPOSITE OF POWDER COMPACT IN POLISHED CONDITION

~ 50X

FIGURE 64. VIBRATORY COMPACTED POWDER UO_2 MICROSTRUCTURE

REDUCED TO 65% FOR REPRODUCTION PURPOSES

100X

(a) FUEL CLADDING INTERFACE

100X

(b) UO_2 MID-RADIUS

100X

(c) UO_2 CENTER

FIGURE 65. VIBRATORY-COMPACTED POWDER, UO_2 MICROSTRUCTURE, ETCHED

(a) FUEL CLADDING INTERFACE

(b) MID-RADIUS

(c) CENTER OF FUEL

FIGURE 66 TANDEM-ROLLED UO_2 POWDER,
MICRO-ETCHED

(a) FUEL CLADDING INTERFACE

(b) MID-RADIUS UO_2

(c) CENTER OF UO_2

FIGURE 67. HOT-SWAGED UO_2 POWDER, MICRO-ETCHED

(a) FUEL CLADDING INTERFACE

(b) MID-RADIUS UO_2

(c) CENTER OF UO_2

FIGURE 68. COLD-SWAGED POWDER UO_2
MICROSTRUCTURE, ETCHED

APPENDIX

STATISTICAL EVALUATION OF HPD FUEL

by J. L. Jaech

The HPD-VBWR fuel failures and ultrasonic examination results were evaluated statistically.

A.1 STATISTICAL ANALYSIS OF HPD FUEL FAILURES

The number of failures experienced in reactor service in Type-304 stainless steel clad material, and the nature of the failures, prompted a study from purely a statistical viewpoint. These analyses were directed at obtaining a failure rate comparison of: (a) freestanding and collapsed cladding, (b) annealed and cold-worked, (c) collapsed cladding UO_2 powder fuel, (d) effect of UO_2 pellet-to-cladding gap, and (e) effect of fuel rod surface heat flux.

The results of these analyses indicate the following:

- a. The burnup achieved by Type-304 stainless steel fuel rods prior to cladding rupture in the HPD Program was a function of (1) freestanding or collapsed cladding, (2) the gap between UO_2 pellets and cladding, and (3) the surface heat flux the fuel rods experienced during the last 500 to 1000 hours prior to failure.
- b. Cold-worked and annealed Type-304 stainless steel cladding failed at approximately the same fuel burnups.
- c. UO_2 powder-filled fuel rods failed after achieving approximately the same burnups as the collapsed cladding fuel rods containing UO_2 pellets.
- d. Weibull function failure curves with confidence intervals can be established for the various types of Type-304 stainless steel clad fuel rods irradiated under the HPD Program in the VBWR.
- e. The Weibull function parameters established the curve of percentage failure versus burnup to be very steep for Type-304 stainless steel fuel rods irradiated in the VBWR; that is, after a few failures were encountered, many more occurred in a short period of time.
- f. The Weibull function has a parameter (ν) which takes into account a period of burnup before any failures could occur. Estimates of this parameter could not be made because of the limited spread of failure points encountered in the VBWR. Extrapolation to very low failure rates is not greatly affected since no fewer than one fuel rod failure is detectable.

The fuel rod failure data are summarized in Tables A-1 and A-2 for all types of HPD fuel rods. The letter type designations define the groupings used in the statistical analysis. The exposures are peak fuel rod exposures, and are applicable since all fuel rod failures have occurred at regions corresponding to the maximum fuel burnup position along the length of the fuel rods. Fuel burnup units are expressed as megawatt days per 2000 pounds of contained uranium.

The combined data in Table A-3 for Types A, C, and D versus E, G, and H give the most information on the failure rate and exposure for comparison of annealed and cold-worked Type-304 stainless steel cladding, without separating effects of freestanding and collapsed cladding or the effect of pellet-to-cladding gap.

TABLE A-1

HPD FUEL ROD FAILURE DATA FOR UO₂ PELLET FUEL RODS

Type	HPD Assemblies	Description	Exposures at Discharge (MWd/TU, Axial Peak)	Number of Rods	Number of Rods Failed
A	1E, 2E, 3E	Freestanding	15,857	2	0
	4E, 5E, 6E	Annealed cladding	15,393	4	0
		0.005 nominal gap	14,585	4	0
		>300,000 Btu/h-ft ²	14,474	8	1
			14,166	2	0
			12,672	1	0
			12,451	2	2
			11,905	5	0
			9,995	1	0
				29 Total	
B	1A, 2A	Freestanding	13,144	16	0
	1B, 2B	Annealed cladding	12,750	16	0
	1C, 4S	0.005 nominal gap	12,450	32	2
		<300,000 Btu/h-ft ²	12,300	16	0
			10,500	25	0
				105 Total	
C	1G, 2G	Freestanding	12,934	2	0
	3G, 4G	Annealed	11,603	6	0
		<0.005 gap	9,576	4	0
		>300,000 Btu/h-ft ²	9,000	8	0
				20 Total	
D	6S, 10S	Nonfreestanding	8,441	25	2
		Annealed	4,500	4	0
		<0.005 gap		29 Total	
		>300,000 Btu/h-ft ²			

(Continued next page)

TABLE A-1 (Cont'd.)

HPD FUEL ROD FAILURE DATA FOR UO_2 PELLET FUEL RODS

Type	HPD Assemblies	Description	Exposures at Discharge (MWd/TU, Axial Peak)	Number of Rods	Number of Rods Failed
E	1E, 2E, 3E	Freestanding	13,944	23	1
	4E, 5E, 6E	Cold-worked	12,862	17	0
	2F	0.005 gap	12,672	20	1
		>300,000 Btu/h-ft ²	12,451	19	0
			11,249	22	1
			11,057	25	0
			9,995	3	1
			129 Total		
F	1F, 11S-1	Freestanding	15,000	25	1
		Cold-worked	10,500	16	0
		0.005 gap		41 Total	
		<300,000 Btu/h-ft ²			
G	1G, 2G, 3G	Freestanding	12,934	23	1
	4G, 3C, 4C	Cold-worked	11,603	19	3
		0.005 gap	9,576	21	1
		>300,000 Btu/h-ft ²	9,400	25	0
			9,000	42	2
			8,000	25	1
			155 Total		
H	1D, 2D	Nonfreestanding	7,900	25	1
	3D, 3S	Cold-worked	7,183	3	3
		0.005 gap	6,900	25	1
		>300,000 Btu/h-ft ²	6,400	25	1
			6,153	1	1
			79 Total		
I	1S, 4S, 4D	Nonfreestanding	13,144	9	0
		Cold-worked	2,830	25	0
		0.005 gap	2,700	25	0
		<300,000 Btu/h-ft ²		59 Total	

TABLE A-2

HPD FUEL ROD FAILURE DATA FOR UO₂ POWDER FUEL RODS

Type	HPD Assemblies	Description	Exposure at Discharge MWd/TU Peak	Number of Rods	Number of Rods Failed
P	1SM, 2S, 5S	UO ₂ Powder Fuel	9100	16	0
		> 300,000 Btu/h-ft ²	7900	21	0
			7500	25	2
			8000	13	1
			6900	25	0
			6098	12	0
			5637	16	0
			4500	12	0
			2700	2	0

By using a nonparametric approach, exposure intervals may be set up to cover the range of the data. Within each interval, the pertinent data are the number of rods present at the beginning of the interval, the number of failures occurring in the interval, and the number of rods discharged in the interval without failing. These data are used to estimate the instantaneous failure rate at a given exposure, which data, in turn, are appropriately combined to give a cumulative failure rate curve.

The estimating procedure for Types A, C, and D, as well as Types E, G, and H, is shown in Table A-3. The column headings used in the table are defined below the table.

Different groups of fuel elements can be compared with respect to failure rates on a completely nonparametric basis by comparing the $F(x)$ values at given values of the exposure "x". It is evident from Table A-3 that the failure rate experience for these two groups is comparable.

A model of wide applicability in failure rate studies is the Weibull model, whose cumulative failure distribution is written:

$$F(x) = 1 - e^{-\frac{(x-\mu)^a}{b}}$$

The three parameters of the model (μ , a , and b) are called location, shape, and scale parameters, respectively.

Table A-3(a)

FAILURE RATE FOR DATA OF TYPES A, C, AND D FROM TABLE A-1

Exposure Interval (hours)	Ni	Li	ri	mi	Pi	$\pi (1-Pi)$	F(x)
6,000 to 7,000	74	0	0	74	0	1	0
7,000 to 8,000	74	0	0	74	0	1	0
8,000 to 9,000	74	23	2	62.5	0.0320	0.9680	0.0320
9,000 to 10,000	49	13	0	42.5	0	0.9680	0.0320
10,000 to 11,000	36	0	0	36	0	0.9680	0.0320
11,000 to 12,000	36	11	0	30.5	0	0.9680	0.0320
12,000 to 13,000	25	3	2	23.5	0.0851	0.8856	0.1144
13,000 to 14,000	20	0	0	20	0	0.8856	0.1144
14,000 to 15,000	20	13	1	13.5	0.0741	0.8200	0.1800
15,000 to 16,000	6	6	0	3	0	0.8200	0.1800

Table A-3(b)

FAILURE RATE FOR DATA OF TYPES E, G, AND H FROM TABLE A-1

Exposure Interval (hours)	Ni	Li	ri	mi	Pi	$\pi (1-Pi)$	F(x)
6,000 to 7,000	338	48	3	314	0.0096	0.9904	0.0096
7,000 to 8,000	287	0	3	287	0.0105	0.9800	0.0200
8,000 to 9,000	284	24	1	272	0.0037	0.9764	0.0236
9,000 to 10,000	259	87	4	216.5	0.0185	0.9583	0.0417
10,000 to 11,000	168	0	0	168	0	0.9583	0.0417
11,000 to 12,000	168	62	4	137	0.0292	0.9303	0.0697
12,000 to 13,000	102	77	2	64.5	0.0310	0.9015	0.0985
13,000 to 14,000	23	22	1	12	0.0833	0.8264	0.1736

(Continued next page)

N_i = Number of rods present at beginning of interval
 L_i = Number of rods discharged without failure in interval
 r_i = Number of failures in interval
 m_i = $N_i - L_i/2$
 P_i = Instantaneous failure rate = r_i/m_i
 $F(x)$ = Cumulative failure rate = $1 - \pi(1 - P_i)$
 π = $1 - F(x)_{i-1}$

If the model is rewritten:

$$\ln \{ - \ln [1 - F(x)] \} = a \ln (x - \mu) - \ln b,$$

a plot of this particular function of $F(x)$ against the logarithm of $(x - \mu)$ will result in a straight line. When the data are plotted in this fashion, it is observed that linearity of the points is obtained when $\mu = 0$, whereas for other positive values of μ , deviations from linearity occur. This suggests that the location parameter μ may be set equal to zero, and the model rewritten:

$$y = \ln \{ - \ln [1 - F(x)] \} = a \ln x - \ln b.$$

Joint estimates of the parameters a and b may be found by regressing y on $\ln x$. Ordinary regression techniques should not be used in view of the heterogeneity in variance for the various points and the lack of independence between them. Aitken's method⁽¹⁵⁾, however, may be used to obtain the parameter estimates.

Estimates of the a parameter were made for two fuel groups and were found to be:

Type	a
A, C, D (pellet, annealed, high flux)	3.53 ± 1.55
E, G, H (pellet, cold-worked, high flux)	3.25 ± 0.79

where the $\pm$ limits on a correspond to one standard deviation uncertainty. Experience has shown that when groups of fuels exhibit different failure rate experience, this is reflected in different values for the scale parameter (b) with the shape parameter (a) being the same. This is equivalent to stating that the different cumulative failure rate curves are parallel but possibly have different intercepts.

The comparison of the a parameter estimate for the two groups of fuel is clearly in agreement with this experience.

Since, however, combining failure data from dissimilar groups of fuel can lead to a biased estimate of a , it was re-estimated from differently grouped data using the same techniques. Groups E, G, and H are the only individual groups that permit estimation of this shape parameter. The estimates, with one standard deviation uncertainty, are:

Type	a
E	6.81 ± 3.18
G	5.14 ± 1.55
H	4.54 ± 2.11

These, again are not clearly different. Although the combined estimate of $a = 5.18 \pm 1.16$ is higher than the 3.3 for the combined groupings, the difference is not statistically significant.

For purpose of comparing the failure rates of the individual groups of fuels, a was treated as a constant and assumed to equal 5. Comparisons of groups of fuels with similar irradiation history are not greatly affected by the use of a slightly incorrect value for a , although extrapolations to different exposure levels would be.

The "scale" parameter, b , was then estimated for each group of fuel, using the estimating procedure:

$$b = \frac{\sum_i x_i^a}{k}$$

where x_i is the exposure at discharge or failure for the i^{th} rod, and k is the number of failures in the group. Estimates are given as follows:

Group	b	Number of Failures
A	5.47×10^{21}	3
B	1.46×10^{22}	2
C	$>2.78 \times 10^{21}$	0
D	5.41×10^{20}	2
E	9.78×10^{21}	4
F	2.08×10^{22}	1
G	2.39×10^{21}	8
H	2.13×10^{20}	7
I	$>3.60 \times 10^{21}$	0

The estimates for groups C and I are lower bounds in the sense that no failures occurred in either group; the values given are what would have been obtained had one failure occurred in each group.

In evaluating the various effects, use is made of the fact that the natural logarithm of b has an approximate variance of $1/k$. Therefore, a weighted multiple regression analysis may be performed on the transformed data. The independent variables are defined:

Let $x_1 = -1$ if freestanding,
 $= +1$ if collapsed;

Let $x_2 = -1$ if annealed,
 $= +1$ if cold worked;

Let $x_3 = -1$ if gap > 0.005 mil,
 $= +1$ if gap < 0.005 mil; and

Let $x_4 = -1$ if flux $< 300,000$ Btu/h-ft²,
 $= +1$ if flux $> 300,000$ Btu/h-ft².

With these definitions, the input data for the multiple regression analysis are listed. Data from groups C and I are not included.

Group	x_1	x_2	x_3	x_4	$\ln b \times 10^{-20}$	weight k
B	-1	-1	+1	-1	4.98	2
A	-1	-1	+1	+1	4.00	3
G	-1	+1	+1	+1	3.17	8
F	-1	+1	+1	-1	5.34	1
E	-1	+1	-1	+1	4.58	4
D	+1	-1	-1	+1	1.39	2
H	+1	+1	-1	+1	0.76	7

The regression model is written:

$$\text{Avg}(\ln b) = A_0 + A_1 x_1 + A_2 x_2 + A_3 x_3 + A_4 x_4.$$

The following table shows how the coefficients are estimated as linear functions of the $\ln b$'s as a result of the regression analysis.

Group	$\ln b$	Freestanding versus Collapsed A_1	Annealed versus Cold Worked A_2	Gap A_3	Heat Flux A_4
B	4.98	-0.019	-0.085	-0.036	-0.313
A	4.00	-0.048	-0.218	0.121	0.266
G	3.17	-0.500	0.000	-0.500	0.000
F	5.34	0.019	0.085	0.036	-0.187
E	4.58	0.048	0.218	0.379	0.234
D	1.69	0.067	-0.198	-0.085	0.047
H	0.76	0.433	0.198	0.085	-0.047

For example, A_1 (the freestanding effect) is estimated as $(-0.019)(4.98) - (0.048)(4.00) + \dots$. These coefficients are instructive in pointing out how the multiple regression approach compares with the "direct comparison" approach. For example, for A_1 , the effect is estimated primarily from groups G and H. These would be the only groups involved in a "direct comparison" approach. Also, note that the annealed cold-worked effect is based on the weighted average of three "direct comparisons," B versus F, A versus g, and D versus H, the weighting depending on the numbers of failures involved.

Estimates of the coefficients, together with the one standard deviation limit, are given as follows:

Freestanding versus collapsed cladding	$A_1 = -1.108 \pm 0.249$
Annealed versus cold-worked	$A_2 = -0.027 \pm 0.252$
Gap	$A_3 = +0.569 \pm 0.280$
Heat flux	$A_4 = -0.378 \pm 0.350$

Clearly, the difference between annealed and cold worked cladding is negligible, but the other effects are real. The heat flux effect does not show up strongly, although the estimate does indicate that fuel rods operating at higher surface heat fluxes have higher failure rates.

The annealed and cold-worked groups were combined and the effects were re-estimated with very little change appearing in the coefficients:

Freestanding versus collapsed	$A_1 = -1.130 \pm 0.243$
Gap	$A_3 = +0.530 \pm 0.259$
Heat flux	$A_4 = -0.375 \pm 0.345$

The ratio of expected failures at a given fuel rod exposure is defined as the factor of difference and is a measure of the magnitude of the various effects. The factor of difference is shown for each significant effect as follows:

- Freestanding better by factor of 9.6 over collapsed cladding,
- 0.005 gap better by factor of 2.9 over 0 gap, and
- Low heat flux better by factor of 2.1 over heat fluxes $> 300,000 \text{ Btu/h-ft}^2$.

A.2 STATISTICAL EVALUATION OF ULTRASONIC TESTING

The search for failures in HPD cladding used ultrasonic techniques. The ultrasonic tests should indicate the presence of incipient failures, and therefore statistical analysis should produce failure rate curves comparable with those for visible failures.

The data have been analyzed in a manner similar to the failure data to see if ultrasonic data correlate with in-reactor performance. The fuel types examined were the same as for the failure analysis (Table A-1); namely:

Fuel Type	A	B	C	E	F	G	H
Freestanding	x	x	x	x	x	x	
Non-Freestanding							x
Annealed Cladding	x	x	x				
Cold-Worked				x	x	x	x
> 0.005 gap	x	x		x	x		
< 0.005 gap			x			x	x
> 300,000 Btu/h-ft ²	x		x	x		x	x
< 300,000 Btu/h-ft ²		x			x		

The numbers and types of rods ultrasonically examined included the following:

<u>Fuel Type</u>	<u>Bundle</u>	<u>No. of Rods</u>	<u>Longitudinal Signal</u>	<u>Circum- ferential</u>	<u>Date Measured</u>
A	1E	6	X	X	6/63
	2E	5	X	X	6/63
	3E	2	X	X	6/63
	4E	5	X	X	6/63
	5E	8	X	X	6/63
	6E	2	X	X	6/63
	12S (reconstituted)	10	X	X	7/64 (Different Operator)
B	1A	10	X	X	7/64 (Different Operator)
	2B	10		X	7/64 (Different Operator)
	1C	10		X	7/64 (Different Operator)
C	1G	4	X		8/62
	2G	7	X		9/62
E	1E	18	X	X	8/63
	2E	4	X	X	6/63
	3E	4	X	X	6/63
	4E	3	X	X	6/63

<u>Fuel Type</u>	<u>Bundle</u>	<u>No. of Rods</u>	<u>Longitudinal Signal</u>	<u>Circum- ferential</u>	<u>Date Measured</u>
	5E	1	X	X	6/63
	6E	20	X	X	7/63
F	1F	10	X	X	7/64 (Different Operator)
G	1G	20	X		8/62
	2G	17	X		9/62
	3C	16	X		10/63
	4C	16	X	X	8/63
H	1D	20	X		9/62

A. 3. DATA CHARACTERIZATION

For longitudinal cracks, the ultrasonic signals were interpreted to give indications of crack depth and crack length. Each signal, or series of closely-spaced signals, was used to record an observation in one of the following cells:

		<u>Crack Length (inches)</u>							
		0.5	0.5-1	1-2	2-3	3-4	4-5	5-6	6
Crack	1.75-3 (S)	3	1	1					
Depth	3-5 (M)	4	2		1		1		
(mils)	5 (L)		1						

Entries in the table give the data for a typical rod.

Various "statistics" were investigated to see which one might best correlate with in-reactor performance. There was little to choose from among the many selected. The one eventually chosen is defined:

$$X = (1) (S) + (2) (M) + (3) (L),$$

where

S = number of small (shallow) cracks,

M = number of medium cracks, and

L = number of large (deep) cracks.

This statistic is independent of crack length.

For the data tabulated in the example, we would have

$$X = (1)(4) + (2)(8) + (3)(1) = 23.$$

The same statistic was used to describe the extent of indicated circumferential cracking.

A.4 ANALYSIS

First, data for the rods from the reconstituted bundle 12S were analyzed. These rods were originally irradiated, measured, then irradiated for an additional period, and re-measured. The pertinent data are presented as follows, where the tabular entries are values for the X statistic defined previously.

Rod (Original Designation)	Longitudinal		Circumferential	
	Original	Remeasured	Original	Remeasured
1E-P	17	0	6	5
1E-S	7	0	-	-
1E-Q	13	1	-	-
2E-D	4	1	0	2
3E-K	-	0	4	7
4E-T	5	11	-	-
5E-Q	13	4	11	0
5E-O	14	5	10	14
5E-W	9	0	12	4
6E-B	3	6	-	-

The much lower values after re-measurement, generally speaking, cast doubt on the validity of the comparison. Because of the increased irradiation, more signals would be expected, rather than less. The re-measurements were, of course, taken 1 year later, and by a different operator. With a measuring instrument such as an ultrasonic tester, a certain amount of variation with time - and between testers - is to be expected. The net effect is that while comparisons of rods on a relative basis can be meaningful when taken under the same conditions, it is difficult to interpret a signal in an absolute fashion because of apparent gross measurement difficulties over time and between operators. By restricting attention to

measurements recorded under the same set of conditions, it is found that the following comparisons can be made:

A versus E for 6/63 data

B versus F for 7/64 data

C versus G versus H for 8, 9/62 data

It did not appear meaningful to make comparisons other than these.

A. 4.1 A Versus E

Peak rod exposures were computed for each rod. Values of the X statistic were then plotted against rod exposure for the Type A and Type E rods. The results are shown in Figures A-1 and A-2 for the longitudinal and circumferential cracks, respectively. The lines shown are the 'best fit' least-squares lines for the X ratings as functions of exposure. It is interesting to note that in no case was the slope significantly different from zero; that is, no exposure effect is detectable even though there is a wide range of rod exposures involved. This is far different from the failure situation where the exposure effect is very evident.

Neglecting exposure, average ratings for Types A and E are as follows:

Longitudinal: Type A $\bar{X}_A = 9.6$
 Type E $\bar{X}_E = 14.3$

Circumferential: Type A $\bar{X}_A = 8.5$
 Type E $\bar{X}_E = 9.7$

The difference between types is significant for longitudinal cracking, but not for circumferential. Types A and E are identical except that Type A has annealed cladding and Type E cold-worked.

It should be recalled from the failure analyses that no difference between Types A and E was found.

A. 4.2 B Versus F

Pertinent averages are as follows:

Longitudinal: Type B (Eight 0's, and two 1's)
 Type F (Six 0's, a 1, a 5, an 8, and a 16)

FIGURE A-1. ROD EXPOSURE VERSUS "X" RATING FOR STATISTICS OF ULTRASONIC DATA ON LONGITUDINAL CRACKING

GEAP-4926

FIGURE A-2. ROD EXPOSURE VERSUS "X" RATING FOR STATISTICS OF ULTRASONIC DATA ON CIRCUMFERENTIAL CRACKING

Circumferential: Type B $\bar{X}_B = 5.6$

Type F $\bar{X}_F = 5.7$

Types B and F correspond to Types A and E, respectively. except they are at lower power. Again, with the circumferential cracking, they do not differ. The longitudinal data are sketchy, but the tendency is for the Type F to have more cracks than the Type B, which is the same result as found at high power.

A. 4.3 C Versus G Versus H

For these types, only the longitudinal measurements were taken, with the following average values:

Type C $\bar{X}_C = 4.1$

Type G $\bar{X}_G = 2.3$

Type H $\bar{X}_H = 1.3$

None of these differences are significantly different from one another.

REFERENCES

1. Fowler, W. D. and Lingafelter, J. W., "Design and Fabrication of High Power Density Fuel Assemblies for VBWR Irradiation Testing," GEAP-3609, November 1960.
2. Lees, E. A., "Fuel Element Fabrication by Swaging," GEAP-3819, May 1962.
3. Lingafelter, J. W., et al., "Erosion Flow Testing of Purposely Defected Stainless Steel Clad Compacted UO_2 Powder Fuel," GEAP-4020, February 1962.
4. Ryer, C. M., "Powder Fuel Processing by Two-Pass Swaging," GEAP-3891, April 1962.
5. Lingafelter, J. W., "Fabrication of Fuel Rods by Tandem Rolling," GEAP-3775, July 1961.
6. Fowler, W. D., "Mechanical Design and Testing of Development Fuel for Consumers Power Big Rock Point Reactor," GEAP-3851, April 1962.
7. DeHollander, W. R., "Vibrational Compaction of Uranium Dioxide," GEAP-4032, March 1962.
8. Holladay, R. L., "High Power Density Development Project, Fifteenth Quarterly Progress Report, October-December, 1963," GEAP-4488, January 1964.
9. Hoffmann, J. P., and Coplin, D. H., "The Release of Fission Gases from Uranium Dioxide Fuel Operated at High Temperatures," GEAP-4596, September 1964.
10. Arlt, W. H., and Vandenberg, S. R., "Fuel Failure Examinations and Analyses in the High Power Density Development Program," GEAP-4360, September 1963.
11. Rider, B. F., et al., "The Determination of Uranium Burnup in MWd/T," GEAP-3373, March 1960.
12. Rosenbaum, H. S., et al., "Fission Fragment Damage to Type-304 Stainless Steel Fuel Cladding," GEAP-5002, January 1966.
13. Lees, E. A., "Analysis of Failure of Type-304 Stainless Steel Clad Swaged Powder Fuel Assembly," GEAP-4400, October 1963.
14. Lyons, M. F., et al., " UO_2 Thermal Conductivity from Irradiations with Central Melting," GEAP-4624, July 1964.
15. Aitkin, A. C., "On Least Squares and Linear Combinations of Observations," Proceedings Royal Society of Edinburgh, Vol. 55 (1935), pp 42-48.

DISTRIBUTION

	<u>Copies</u>		<u>Copies</u>
U. S. Atomic Energy Commission Division of Reactor Development Washington 25, D. C. Attn: Chief, Water Reactors Branch Civilian Power	3	Combustion Engineering, Inc. Nuclear Division 1000 Prospect Hill Road Windsor, Connecticut Attn: Mr. J. M. West	1
U. S. Atomic Energy Commission Division of Reactor Development Washington 25, D. C. Attn: Chief, Water Systems Branch Army Reactors	1	Westinghouse Electric Corporation Bettis Atomic Power Laboratory P. O. Box 79 West Mifflin, Pennsylvania Attn: W. E. Johnson	1
U. S. Atomic Energy Commission Division of Reactor Development Washington 25, D. C. Attn: Chief, Reactor Engineering Branch Naval Reactors	1	Consumers Power Company 212 W. Michigan Avenue Jackson, Michigan Attn: R. L. Haueter	5
U. S. Atomic Energy Commission Division of Reactor Development Washington 25, D. C. Attn: Chief, Research and Develop- ment Branch, Nuclear Safety	1	Northern States Power Company 414 Nicollet Avenue Minneapolis, Minnesota 55401 Attn: Mr. E. C. Ward	1
U. S. Atomic Energy Commission Division of Reactor Development Washington 25, D. C. Attn: Chief, Fuels and Materials Development Branch	1	Argonne National Laboratory P.O. Box 258 Idaho Falls, Idaho Attn: Meyer Novick	1
U. S. Atomic Energy Commission Chicago Operations Office 9800 South Cass Avenue Argonne, Illinois Attn: Director, Reactor Engineering Div.	2	Argonne National Laboratory Library Services Department Report Section Building 203-Rm-Ce-125 9700 South Cass Avenue Argonne, Illinois	1
U. S. Atomic Energy Commission San Francisco Operations Office 2111 Bancroft Way Berkeley, California Attn: Director, Contracts Division	2	U. S. Atomic Energy Commission Technical Information Extension P.O. Box 62 Oak Ridge, Tennessee Attn: R. L. Metter	3
U. S. Atomic Energy Commission San Francisco Operations Office 2111 Bancroft Way Berkeley, California Attn: Director, Reactor Division	1	Senior AEC Representative USAEC APO New York 09667	1
Mr. Harold C. Tellock Manager of Administration Allis-Chalmers 5401 Westbard Avenue Bethesda, Maryland 20016	1	Nuclear Utilities Services, Inc. 1730 M Street NW Washington, D. C. Attn: J. C. Scarborough	1
Babcock & Wilcox Company Atomic Energy Division Lynchburg, Virginia Attn: J. F. Mumm	1	R. E. Shimshak Dairyland Power Cooperative La Crosse Boiling Water Reactor P.O. Box 135 Genoa, Wisconsin	1