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MASTER

**POWER REACTOR
HIGH PERFORMANCE UO_2 PROGRAM
FABRICATION OF
CENTERMELT ASSEMBLIES**

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U.S. ATOMIC ENERGY COMMISSION
CONTRACT AT (04-3) - 189
PROJECT AGREEMENT 50

NUCLEAR FUELS DEPARTMENT
GENERAL ELECTRIC
SAN JOSE, CALIFORNIA

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POWER REACTOR HIGH PERFORMANCE UO_2 PROGRAM
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GENERAL ELECTRIC
SAN JOSE, CALIFORNIA

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TABLE OF CONTENTS

	<u>Page</u>
SECTION I INTRODUCTION	-1-
SECTION II FUEL ASSEMBLY DESIGN	-2-
2.1 Fuel Assembly Description	-2-
2.2 Fuel Rod Description	-6-
SECTION III MATERIALS	-10-
3.1 Uranium Dioxide	-10-
3.2 Zircaloy-2 Barstock and Tubing	-10-
3.3 Type-304 Stainless Steel	-10-
SECTION IV FABRICATION	-15-
4.1 Uranium Dioxide Pellets	-15-
4.2 Compactible Grade Uranium Dioxide	-15-
SECTION V FUEL ROD ASSEMBLY	-22-
SECTION VI FUEL BUNDLE ASSEMBLY	-24-
ACKNOWLEDGMENT	-33-
DISTRIBUTION	-34-

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LIST OF ILLUSTRATIONS

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
1	Drawing of 8 × 8 Fuel Lattice Centermelt Bundle	-3-
2	Drawing of 7 × 7 Fuel Lattice Centermelt Bundle	-4-
3	Distribution of Fuel Rods in Assembly According to Power Levels and UO ₂ Enrichments	-5-
4	Drawing of 0.570 o.d. Fuel Rod	-8-
5	Drawing of 0.700 o.d. Fuel Rod	-9-
6	Pellet Fabrication Flow Sheet	-18-
7	Preparation of Compactible Grade UO ₂ Powder	-19-
8	Microstructure of Sintered UO ₂ Pellet	-20-
9	Microstructure of Pellet and Powder	-21-
10	Bundle Design That Allows All Fuel Rods to be Removable	-25-
11	Fully Assembled 7 × 7 Bundle and Structural Details	-26-
12	Rod Loading Plan for Bundle No. D-50	-27-
13	Rod Loading Plan for Bundle D-51	-28-
14	Rod Loading Plan for Bundle D-52	-29-
15	Rod Loading Plan for Bundle D-53	-30-
16	Rod Loading Plan for Bundle D-54	-31-
17	Rod Loading Plan for Bundle D-55	-32-

FOREWORD

The United States and the European Atomic Energy Community (Euratom) on May 29 and June 18, 1958, signed an agreement which provides a basis for cooperation in programs for the advancement of the peaceful applications of atomic energy. This agreement, in part, provides for the establishment of a joint U.S. -Euratom research and development program which is aimed at reactors to be constructed in Europe under the Joint Program.

The work described in this report represents the Joint U.S. - Euratom effort which is in keeping with the spirit of cooperation in contributing to the common good by the sharing of scientific and technical information and minimizing the duplication of effort by the limited pool of technical talent available in Western Europe and the United States.

SECTION I

INTRODUCTION

In 1961, the U.S. Atomic Energy Commission and Euratom jointly undertook a research and development program with the Nuclear Energy Division of the General Electric Company to explore the problem of central melting in UO_2 fuel rods. It was subsequently shown in the program that the basic limitation to the attainment of fuel rod operation with central melting was the UO_2 phase change volume expansion on melting. When unaccommodated, this volume expansion led to gross cladding deformation and ultimately to cladding rupture. This problem was solved in these experiments by providing an adequate internal free volume, accessible to the molten UO_2 core, to accommodate the phase change volume increase. The free volume was provided by a central hole in sintered UO_2 pellets, and the inherent void volume between UO_2 particles in powder compacted fuel. Irradiations at high-performance conditions were concluded with burnups as high as 30,000 MWd/Te in the maximum power rod. The successful irradiation of the test rods in the High Performance UO_2 Program showed that there is no intrinsic life-limiting mechanism that will prevent the attainment of high burnup in fuel rods operating with central melting. However, the number of rods irradiated was relatively small and the operating conditions were not the same as might be experienced in a large power-producing water reactor.

The next logical step in exploring the operation of fuel with central melting of the UO_2 was performance demonstration of a significant number of rods in a commercial power-producing reactor. To this end, a research and development program was initiated on September 1, 1966, under Project Agreement 50 of Contract AT (04-3)-189, to irradiate a number of Zircaloy-2 clad UO_2 fuel rods to varying degrees of central melting in an operating power reactor. The joint AEC-Euratom program covers the detailed fuel design, including safeguards analysis and reactor license changes necessary to their irradiation, indirect fabrication supervision, irradiation following, and post-irradiation examination and reporting.

Six fuel assemblies were designed and fabricated for irradiation testing in the Consumers Big Rock Point reactor. Two of the assemblies were referred to as the intermediate performance fuel assemblies and were designed for incipient melting of the UO_2 at rated power conditions. There are 64 fuel rods arranged in an 8×8 array in each assembly. The fuel rods in one assembly contain UO_2 pellets, while the other assembly contains vibratory-compacted UO_2 . The remaining four assemblies were referred to as the advanced performance fuel assemblies. The fuel rods in these assemblies were designed for moderate melting of the UO_2 at rated power conditions. There are 49 rods in an assembly, arranged in a 7×7 array. The fuel rods in two assemblies contained sintered UO_2 pellets and those in the other two assemblies, contained vibratory-compacted powder.

The purpose of this report is to describe the fabrication used in the six assemblies.

SECTION II

FUEL ASSEMBLY DESIGN

2.1 FUEL ASSEMBLY DESCRIPTION

The removable rod design used previously in the High Power Density Fuel Development Program was also utilized in both the advanced (7×7 bundle) and the intermediate (8×8 bundle) performance fuel assemblies. The advanced performance fuel rods are 0.700 inch in diameter and the intermediate performance fuel rods are 0.570 inch in diameter.

Key components of the support structure as shown in Figures 1 and 2 are:

- Handle: Completely removable to allow rod removal
- Pin: Fastens the handle to the support structure
- Spacer: Double-layer wire, constant pressure—spring type provides maximum protection against wear of the Zircaloy-2 cladding
- Angle: Acts as axial support member of bundle, provides a means to position spacers axially, and also minimizes the possibility of damage to rods and spacers during insertion and removal from the reactor core locations
- Base: A grid bar arrangement welded to the lower end of each corner angle; fuel rods rest on the grid

The support structure is fully capable of supporting the rods when the assembly is resting on the base or when hung from the handle.

The fuel bundles in the fully loaded condition will be of the following approximate weights (including weight of cage):

0.700-o.d. pellet UO_2 rods	385 lb	} 7x7 Advanced Performance Fuel Assemblies
0.700-o.d. powder UO_2 rods	358 lb	
0.570-o.d. pellet UO_2 rods	330 lb	} 8x8 Intermediate Performance Fuel Assemblies
0.570-o.d. powder UO_2 rods	309 lb	

The bundle designs include fuel rods with four different U-235 enrichments which would allow a significant number of them to operate at or very near $450,000 \text{ Btu/ft}^2\text{-h}$ without exceeding the Big Rock Point reactor thermal limits. The enrichments and placement of the rods were specified in order to provide the maximum number of fuel rod operating at or very close to the desired heat fluxes. The fuel rod arrangement for the intermediate and advanced performance fuel assemblies is shown in Figure 3.

FIGURE 1. DRAWING OF 8x8 FUEL LATTICE CENTERMELT BUNDLE

FIGURE 2. DRAWING OF 7x7 FUEL LATTICE CENTERMELT BUNDLE

D	A	B	B	B	B	A	D
0.13	1.65	1.75	1.73	1.73	1.74	1.63	0.13
A	A	D	D	D	D	A	A
1.65	1.53	0.10	0.10	0.10	0.10	1.49	1.63
B	D	D	C	D	C	D	B
1.75	0.10	0.10	1.79	0.10	1.81	0.10	1.74
B	D	C	D	C	D	D	B
1.73	0.10	1.79	0.09	1.72	0.10	0.10	1.73
B	D	D	C	D	C	D	B
1.73	0.10	0.10	1.72	0.09	1.79	0.10	1.73
B	D	C	D	C	D	D	B
1.74	0.10	1.81	0.10	1.79	0.10	0.10	1.75
A	A	D	D	D	D	A	A
1.63	1.49	0.10	0.10	0.10	0.10	1.53	1.65
D	A	B	B	B	B	A	D
0.13	1.63	1.74	1.73	1.73	1.75	1.65	0.13

a. RELATIVE POWERS OF FUEL RODS IN 8x8 ASSEMBLY AT BEGINNING OF LIFE

D	A	B	B	B	A	D
0.13	1.60	1.68	1.67	1.68	1.60	0.13
A	A	D	D	D	A	A
1.60	1.42	0.10	0.10	0.10	1.42	1.60
B	D	C	D	C	D	B
1.68	0.10	1.71	0.09	1.71	0.10	1.68
B	D	D	C	D	D	B
1.67	0.10	0.09	1.65	0.09	0.10	1.67
B	D	C	D	C	D	B
1.68	0.10	1.71	0.09	1.71	0.10	1.68
A	A	D	D	D	A	A
1.60	1.42	0.10	0.10	0.10	1.42	1.60
D	A	B	B	B	A	D
0.13	1.60	1.68	1.67	1.68	1.60	0.13

UO₂ ENRICHMENTS

A 4.3% U-235
 B 5.0% U-235
 C 5.6% U-235
 D 0.22% U-235

b. RELATIVE POWERS OF FUEL RODS IN 7x7 ASSEMBLY AT BEGINNING OF LIFE.

FIGURE 3. DISTRIBUTION OF FUEL RODS IN ASSEMBLY ACCORDING TO POWER LEVELS AND UO₂ ENRICHMENTS

2.2 FUEL ROD DESCRIPTION

2.2.1 Intermediate Performance Fuel

There were two intermediate performance fuel assemblies, each containing 64 rods in an 8×8 configuration. One assembly contained pellet-type fuel; the other contained powder-type fuel. Table 1 and Figure 4 describe the fuel rods in detail.

The rods in the assemblies were clad with 0.570 inch o.d. $\times$ 0.035 inch wall Zircaloy-2 tubing and contained a compression spring in the plenum region to minimize axial fuel movement during handling and shipping. A depleted UO_2 pellet was placed at each end of the active fuel column to minimize temperature effects at the lower end plug and the plenum spring. The UO_2 pellets were sintered to a nominal 94% of theoretical density. They were dished on one end to provide a void volume to accommodate the phase change volume expansion of the UO_2 during melting. The pellets were ground to provide a nominal diametral gap of 0.012 inch. The UO_2 powder was compacted to an apparent density of 85% of theoretical. The 15% distributed void volume was adequate to accommodate the volume expansion accompanying central melting in these rods.

2.2.2 Advanced Performance Fuel

There were four advanced performance fuel assemblies, each containing 49 rods in a 7×7 configuration. Two of the assemblies contained UO_2 in the form of sintered pellets, and the other two assemblies contained UO_2 in the form of vibratory-compacted powder. Further details are given in Table 1 and Figure 5.

All rods in the advanced performance fuel were clad with 0.700 inch o.d. $\times$ 0.040 inch wall Zircaloy-2 tubing, and contained a compression spring in the plenum region to minimize axial fuel movement during handling and shipping.

The pellet fuel was fabricated with a 0.100-inch-diameter central hole to accommodate the phase change volume expansion of the UO_2 on melting. The pellets were ground to give a nominal diametral pellet-to-cladding gap of 0.013 inch. The 15% distributed void space was considered sufficient to accommodate the volume expansion on melting in the powder fuel.

TABLE 1. Centermelt Fuel Design Details and Operating Conditions

Fuel Assembly	UO ₂ Fuel			Number of Rods	Cladding (Zircaloy-2, Tube Reduction Process)		Condition
	Type	TD	U-235		Outside Diameter (inches)	Wall Thickness (inches)	
<u>Group A</u>							
D-50 (8 x 8 Lattice)	Pellet	95	4.3	12	0.570	0.035	Cold Worked and Stress Relieved
	Pellet	95	5.0	16			
	Pellet	95	5.6	8			
	Powder	85	0.22	28			
D-51 (8 x 8 Lattice)	Powder	85	4.3	12	0.570	0.035	Cold Worked and Stress Relieved
	Powder	85	5.0	16			
	Powder	85	5.6	8			
	Powder	85	0.22	28			
<u>Group B</u>							
D-52 and	Pellet	95	4.3	12	0.700	0.040	Cold Worked and Stress Relieved
	Pellet	95	5.0	12			
D-53 (7 x 7 Lattice)	Pellet	95	5.6	5	0.700	0.040	Cold Worked and Stress Relieved
	Powder	85	0.22	20			
D-54 and	Powder	85	4.3	12	0.700	0.040	Cold Worked and Stress Relieved
	Powder	85	5.0	12			
D-55 (7 x 7 Lattice)	Powder	85	5.6	5	0.700	0.040	Cold Worked and Stress Relieved
	Powder	85	0.22	20			

<u>UO₂ Fuel</u>	<u>Fuel Rod</u>	<u>Design Burnup (MWd/TU)</u>	<u>Design Heat₂ Flux (Btu/hr-ft²)</u>		<u>Fuel Rod Power (kW/ft)</u>	
			<u>Normal</u>	<u>Overpower</u>	<u>Normal</u>	<u>Overpower</u>
<u>Group A 8 x 8</u>						
Cold Press and Sinter	Standard	20,000	450,000	550,000	19.65	24.0
	Dished		±50,000		±2.18	
Dynapak	Vibratory	20,000	450,000	550,000	19.65	24.0
	Compaction		±50,000		±2.18	
<u>Group B 7 x 7</u>						
Cold Press and Sinter	Standard	20,000	450,000	550,000	24.15	29.6
	0.100-inch Central Hole		±50,000		±2.68	
Dynapak	Vibratory	20,000	450,000	550,000	24.15	29.6
	Compaction		±50,000		±2.68

FIGURE 4. DRAWING OF 0.570 o.d. FUEL ROD

FIGURE 5. DRAWING OF 0.700 o.d. FUEL ROD

SECTION III

MATERIALS

3.1 URANIUM DIOXIDE

The enriched uranium dioxide was procured from a commercial fuel vendor. All material was sintered to within the 94 to 97% theoretical density range. The chemical analysis and impurity contents of the powder as determined by the vendor and GE are shown in Table 2.

3.2 ZIRCALOY-2 BARSTOCK AND TUBING

The Zircaloy-2 barstock required for the end plugs and the Zircaloy-2 tubing were procured from commercial vendors. The ingot analysis and product properties as reported by the vendor are shown in Table 3. The composition and impurity content of the billets are shown in Table 4. The tubing properties reported by the vendor are shown in Table 5.

3.3 TYPE-304 STAINLESS STEEL

The assembly support structures were fabricated using commercial nuclear grade Type-304 stainless steel.

T A B L E 2

UO₂ POWDER CHEMICAL AND IMPURITY ANALYSIS

	<u>Vendor</u>	<u>APED</u>	<u>Vendor</u>	<u>APED</u>	<u>Vendor</u>	<u>APED</u>
Vendor Lot No.	4188-XD-1	4188-XD-1	4188-FE-1	4188-FE-1	4188-EE-1	4188-FE-1
Enrichment	4.281	4.258	4.981	5.06	5.615	5.60
NTR Analysis	-	4.295	-	5.00	-	5.62
O/U Ratio	2.09	2.061	2.06	2.02	2.07	2.02
Bulk Density g/cc	1.23	1.62	0.86	1.68	0.98	1.42
Particle Size, μ	1.35	1.02	0.89	0.70	0.93	0.68
Agglomerate Size	100%-10 mesh	-	100%-10 mesh	-	100%-10 mesh	-
Moisture	<5000 ppm	660 ppm	<5000 ppm	680 ppm	<5000 ppm	770 ppm
N	225 ppm	< 5 ppm	25 ppm	72 ppm	35 ppm	< 5 ppm
C	106 ppm	69 ppm	54 ppm	27 ppm	27 ppm	64 ppm
F	< 10 ppm	12 ppm	20 ppm	22 ppm	35 ppm	7 ppm
Mg	5	4	5	4	< 4	4
Si	40	6	15	16	20	6
Ca	< 10	200	< 10	5	< 10	25
Cl	< 5	< 3	< 10	< 3	< 5	< 3
Cd	0.4	<0.5	<0.3	<0.5	<0.3	<0.5
B	0.5	0.6	<0.3	0.2	0.8	0.6
Al	< 24	10	< 24	8	< 24	10
Cr	150	34	< 24	40	15	34
Co	< 5	< 2	< 10	< 2	< 5	< 2
Cu	4	2	5	1	2	< 1
Fe	170	18	< 36	14	< 36	10
Pb	4	8	< 2	< 1	< 2	5
Mn	< 4	2	< 4	1	< 4	< 1
Mo	< 3	< 3	< 3	< 3	3	< 3
Ni	220	500	30	< 2	35	10
Na	< 10	< 15	< 10	< 15	< 10	< 15
Ag	<0.2	<0.1	0.3	<0.1	<0.2	0.5
Sn	< 2	< 1	< 2	1	< 2	< 1
W	< 10	-	< 20	-	< 10	-
U	< 5	< 11	< 5	< 11	< 5	< 11
Zn	< 20	< 10	< 20	10	< 20	< 10
Sb	-	< 2	-	< 2	-	< 2
Bi	-	< 1	-	< 1	-	< 1

T A B L E 3

ZIRCALOY-2 BARSTOCK - INGOT AND PRODUCT PROPERTIESINGOT PROPERTIESINGOT ANALYSIS
COMPOSITION IN PERCENT

	<u>TOP</u>	<u>BOTTOM</u>
Sn	1.54	1.34
Fe	0.15	0.15
Cr	0.09	0.09
Ni	0.06	0.06

INGOT HARDNESS IN BHN

Average	172.0
Range	167-179

INGOT IMPURITIES IN PPM

	<u>TOP</u>	<u>BOTTOM</u>
Al	<25	<25
B	0.2	0.2
C	80	100
Ca	<10	<10
Cb	<100	<100
Cd	< 0.2	< 0.2
Ce	< 5	< 5
Cu	15	14
H	3.3	3.5
Hf	88	98
Mg	< 5	< 5
Mn	<10	<10
Mo	<10	<10
N	21	24
O	1040	1250
Pb	<20	<20
Si	55	48
Ta	<200	<200
Ti	<15	<17
U	< 0.5	< 0.5
V	< 5	< 5
W	<25	<25
U	<20	<20
Na	<10	<10

BARSTOCK PROPERTIESBARSTOCK IMPURITIES IN PPM

	<u>0.580" Dia.</u>	<u>0.710" Dia.</u>
H		
H	9	4
N	21	27

BARSTOCK TENSILE PROPERTIES

	<u>U.T.S.</u>	<u>Yield Strength</u> <u>(0.2% Offset)</u>	<u>Elongation</u> <u>(%)</u>
0.580" Dia.	76,400	50,000	27
0.710" Dia.	78,000	54,000	25

BARSTOCK HARDNESS R_b

0.580" Dia.	88 - 89
0.710" Dia.	87 - 88

BARSTOCK ASTM GRAIN SIZE

0.580" Dia.	9 - 9.5
0.710" Dia.	9.5 - 10

BARSTOCK CORROSION TEST
(3 days @ 750°F and 1500 psi)

0.580" Dia.	14 Mg/dm ² gain
0.710" Dia.	14 Mg/dm ² gain

GEAP-10032

T A B L E 4

ZIRCALOY-2 BILLET CHEMISTRY

	<u>Heat No. K-1013</u>					<u>Heat No. 39436</u>					<u>Heat No. 370115</u>				
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
	Chemical Composition (%)														
Sn	1.51	1.55	1.51	1.43	1.38	1.53	1.41	1.57	1.40	1.39	1.52	1.44	1.46	1.46	1.40
Fe	0.14	0.13	0.13	0.13	0.13	0.14	0.16	0.13	0.12	0.13	0.14	0.14	0.15	0.14	0.14
Cr	0.06	0.08	0.08	0.06	0.07	0.09	0.09	0.09	0.09	0.09	0.08	0.09	0.10	0.10	0.10
Ni	0.05	0.05	0.05	0.05	0.04	0.06	0.06	0.06	0.05	0.05	0.06	0.06	0.06	0.06	0.06
	Impurities Analysis (PPM)														
Al	<20		<20		<20	<25		30		27	37		39		34
B	<0.2		<0.2		<0.2	0.2		0.2		0.2	0.2		0.2		0.2
C	129		103		115	180		130		160	100		100		110
Ca	<20		<20		<20	<10		<10		<10	<10		<10		<10
Cb						<100		<100		<100	<100		<100		<100
Cd	<0.2		<0.2		<0.2	<0.2		<0.2		<0.2	<0.2		<0.2		<0.2
Cl	<15		<15		<15	<15		<15		<15	<15		<15		<15
Co	<10		<10		<10	< 5		< 5		< 5	< 5		< 5		< 5
Cu	<20		<20		<20	<10		<10		<10	<10		<10		<10
H	5				8	4.7				8	8				4.3
Hf	69	75	53	67	82	71		88		82	70		62		72
Mg	<10		<10		<10	<10		<10		<10	< 5		< 5		< 5
Mn	<20		<20		<20	<10		<10		<10	<10		<10		10
Mo	<20		<20		<20	<10		<10		<10	<10		<10		<10
N	42		37		40	18	31	33	30	14	38		43		49
O	1210	1400	1220	1390	1320	1110				1310	1070				1260
Pb	<20		<20		<20	<20		<20		<20	<20		<20		<20
Si	<30		<30		<30	<40		40		<40	80		70		60
Ta						<200		<200		<200	<200		<200		<200
Ti	<20		<20		<20	<15		<15		16	15		17		15
U	< 1				< 1	0.6		<0.5		<0.5	<0.5		<0.5		<0.5
V	<20		<20		<20	< 5		< 5		< 5	< 5		< 5		< 5
W	<50		<50		<50	<25		<25		<25	<25		<25		<25

T A B L E 5

TUBING PROPERTIES - VENDOR CERTIFICATION

	0.570" Diameter x 0.035" Wall Tubing			0.700" Dia. x .035" Wall Tubing
ALLOY	ZIRCALOY 2			
SAMPLE INTERVAL				
LOT NO./PIECES	10FF13/5	12A8/24	10FF13/73	2GB4093
INGOT & ANNEAL CHARGE	2FD-4009	2CX-4047	2FD-4009	2GB4095
INVOICE NUMBER	DH 93981	DH 93981	DH 93981-1	DH 939802
CHEMICAL ANALYSIS				
HYDROGEN	4/8	8/10	4/8	4/7
NITROGEN	44/45	48/40	37/45	22/45
OXYGEN				
MECHANICAL PROPERTIES & TESTS				
ULTRASONIC TEST	PASSED	PASSED	PASSED	PASSED
FLARE TEST TO 15 % of O.D.	PASSED	PASSED	PASSED	PASSED
FLATTENING TEST TO % of O.D.				
GRAIN SIZE-ASTM NO. TRANS./LONG.	11.0/11.0	11.5/11.5	11.0/11.0	11.0/11.0
ROCKWELL B SCALE	94/95	94/95	94/95	93/94
CORROSION TEST	MG/DM ²	MG/DM ²	MG/DM ²	MG/DM ²
3 DAY STEAM 1500 PSI 750°F	17.5/170	16.8/17.0	16.5/17.5	17.0/17.8
BURST PRESSURE x 10 ³ PSI	12.0	14.3	14.4	12.5
BURST YIELD x 10 ³ PSI				
CIRCUMFERENTIAL ELONGATION	23.0	22.2	22.2	25.0
ROOM TEMPERATURE				
ELONGATION % in 2"	29.0/27.0	23.5/23.0	23.5/23.0	25.5/25.5
TENSILE STRENGTH x 10 ³ PSI	87.4/92.3	92.4/92.4	92.4/92.4	90.6/91.6
YIELD STRENGTH x 10 ³ PSI	67.5/74.4	70.4/70.4	70.4/70.4	72.3/71.9
HOT TENSILE - TEMPERATURE 650°F				
ELONGATION % in 2"	18.0/20.5	27.0/23.5	22.5/24.5	22.5/21.5
TENSILE STRENGTH x 10 ³ PSI	57.9/54.8	55.2/58.4	57.6/55.7	56.8/56.8
YIELD STRENGTH x 10 ³ PSI	44.0/45.4	41.0/45.2	41.5/39.5	41.8/42.7
HYDRIDE ORIENTATION Fn. NO.	.200	.190	.146	.150
SURFACE OD/ID RMS	10-15/20-25	15-20/20-30	10-15/20-25	10-15/20-25
REMARKS ULTRASONIC STANDARD USED - SEE STANDARD FOR P.O. 86031. CORROSION SAMPLES				
PROHIBITED A BLACK LUSTROUS SURFACE OD & ID. LOTS ANNEALED 8 HRS AT 950°F. INGOTS 2FD &				
X REFER TO WAH CHANG HEAT NO. 39436 & CARBORUNDUM HEAT NO. K-1013. INGOT 2GB REFERS TO				
WAH CHANG HEAT NO. 370115.				

SECTION IV

FABRICATION

The fuel rod hardware, which included end plugs, plenum springs, and stainless steel wafers, was fabricated by outside vendors. The UO_2 fuel pellets and compactible grade powder were fabricated in the Fuel Development Laboratory.

4.1 URANIUM DIOXIDE PELLETS

The UO_2 pellets were fabricated according to the process diagrammed in Figure 6. The press-with-binder process was used in all cases.

The pellets for the intermediate performance fuel rods were fabricated with a dish shaped like a truncated cone in one end. The amount of dishing corresponds to 5% of the pellet volume. The enrichment symbol was placed on the face of the lower punch.

The following were the enrichment symbols embossed in the ends of each pellet. Strict controls were followed to prevent any mixing of the fuel enrichments.

5.6% U-235
5.0% U-235
4.3% U-235
0.22% U-235 (depleted)

The pellets for the advanced performance fuel rods were made with a 0.100-inch central hole. Dies equipped with a central core rod of 0.072-inch diameter were used. The central hole during sintering increased in diameter to approximately 0.095 inch. The central hole was then opened to 0.100 inch by drilling with a 0.100-inch diamond burr. Pellets were randomly selected for density determinations and for chemical analysis. Typical analysis of each enrichment is shown in Table 6, and typical microstructures are shown in Figures 8 and 9.

Following sintering, all pellets were ground to the required diameter and furnace dried.

4.2 COMPACTIBLE GRADE URANIUM DIOXIDE

The compactible grade uranium dioxide required was prepared by the "Dynapak Process." The feed UO_2 powder is compacted into a solid, essentially 100% dense, UO_2 tablet which is subsequently crushed and screened to give a desired particle size distribution suitable for vibratory compaction. The UO_2 feed material was a combination of ceramic grade UO_2 and hard scrap from the pelletizing process.

The flow diagram for preparing the compactible grade UO_2 is shown in Figure 7. A chemical and spectrographic analysis of the product for each enrichment is shown in Table 7. The microstructure of the compactible grade UO_2 is shown in Figure 8.

TABLE 6

CHEMICAL AND SPECTROGRAPHIC ANALYSISSINTERED UO₂ PELLETS

Element	Nominal Enrichment		
	5.6% U-235	5.0% U-235	4.3% U-235
U-235	5.63 $\pm$.03%	5.05 $\pm$.04%	4.32 $\pm$.04%
O/U Ratio	2.016	2.016	2.008
Moisture	63 ppm	61 ppm	12 ppm
C	4	4	7
Cl	< 3	< 3	< 3
F	3	4	1
N	25	< 5	6
Al	24	54	60
Sb	< 2	< 2	< 2
B	0.3	0.3	< 0.2
Bi	< 1	< 1	< 1
Cd	< 0.5	< 0.5	< 0.5
Ca	< 2	< 2	5
Cr	8	24	8
Co	< 2	< 2	< 2
Cu	1	< 1	1
Fe	16	30	22
Pb	< 1	< 1	< 1
Mg	2	2	1
Mn	1	< 1	1
Mo	3	< 3	< 3
Ni	6	6	110
Si	50	16	50
Ag	< 0.1	< 0.1	< 0.1
Na	<15	<15	<15
Sn	1	< 1	< 1
V	<11	<11	<11
Zn	<10	<10	<10
Gas Evolution @ 1700°C for 1/2 hour	15.2 μ liters/gm	8.0 μ liters/gm	5.0 μ liters/gm

T A B L E 7

CHEMICAL AND SPECTROGRAPHIC ANALYSIS - COMPOSITE BLENDSDYNAPAKED URANIUM DIOXIDE

	5.6% U-235	5.0% U-235	4.3% U-235
U-235 Content	5.600 %	4.954 %	4.25 %
O/U Ratio	2.013	2.011	2.014
C	4 ppm	13 ppm	9 ppm
Cl	< 3	< 3	< 3
F	5	1	4
Al	24	40	50
Sb	< 1	< 2	< 2
Bi	< 1	< 1	< 1
B	0.3	0.2	0.3
Ca	2	2	10
Cd	< 0.5	< 0.5	< 0.5
Cr	10	14	48
Co	< 2	< 2	< 2
Cu	1.0	2	3
Fe	14	22	30
Pb	1	1	5
Mg	2	2	2
Mn	1	2	1
Mo	100	3	6
Ni	6	10	150
Si	16	16	50
Ag	< 0.1	< 0.1	< 0.1
Na	< 15	< 15	< 15
Sn	< 1	2	2
V	< 11	< 11	< 11
Zn	< 10	< 10	20
N	13	< 5	< 5
Moisture	12	15	63

FIGURE 6. PELLET FABRICATION FLOW SHEET

FIGURE 7. PREPARATION OF COMPACTIBLE GRADE UO_2 POWDER

ASTM GRAIN SIZE 9-10

5.6% ENRICHED UO₂ PELLET

100X

ASTM GRAIN SIZE 9

4.3% ENRICHED UO₂ PELLET

100X

FIGURE 8. MICROSTRUCTURE OF SINTERED UO₂ PELLET

ASTM GRAIN SIZE 8-9

5% ENRICHED UO₂ PELLET

100X

ASTM GRAIN SIZE 8-9

5% ENRICHED UO₂
COMPACTIBLE GRADE (DYNAPAKED) PARTICLE

100X

FIGURE 9. MICROSTRUCTURE OF PELLET AND POWDER

SECTION V

FUEL ROD ASSEMBLY

The fuel rods were fabricated using conventional fuel loading procedures. The tubing was prepared, with some autoclaved on the outside surface only and some autoclaved on both inside and outside surfaces. The purpose for having these two surface conditions was to investigate the relative protective nature of the autoclave oxide film among the 188 power-producing rods in the six assemblies; 76 rods have tubing without the internal autoclaved surface. The tube conditions of the specific rods are indicated in Figures 12 through 17.

In the assembly procedure for the pellet rods, the fuel column was mocked-up with the proper length of pellets in a V-trough, weighed, and loaded into the tubes. The actual fuel weights and lengths were recorded for each rod. In the loading of the powder rods, a UO_2 powder charge consisting of the following blend was used:

65 wt %	6/24 mesh Tyler Screen Scale
35 wt %	-24 mesh Tyler Screen Scale

A pre-weighed powder charge was vibratory compacted with a pneumatic vibrator to a specified fuel column height which would result in a final density of 85% of theoretical density. All power-producing compacted powder fuel rods were given an outgassing treatment at 850°F for 4 hours in high vacuum. This procedure was similar to that applied on compacted powder fuel in the High Performance UO_2 Program [P.A. 17, Contract AT(04-3)-189].

Since the fuel column of these centermelt rods were shorter than the standard BRP fuel rods due to the longer plenum necessitated by expected higher gas release, tantalum strips were placed in the plenum to act as neutron absorbers to prevent flux peaking in the upper end of the adjacent standard fuel assemblies. The length of these strips was made to compensate for the difference in the fuel column lengths.

The fuel rods were evacuated and backfilled with reactor-grade helium at ambient pressure prior to welding the upper end plug. The weld bead at the joint between the lower end plug and the tubing was swaged down to the same diameter as the tube to facilitate the insertion and removal of the fuel rods from the assembly.

Individual fuel rods were identified by a serial number metal-stamped on the bottom end plugs. The rods were further identified with an enrichment code metal-stamped onto the end of each top end plug, as illustrated on the following page.

67-01375

TOP END PLUG IDENTIFICATION
FOR FUEL ENRICHMENT

Each fuel rod was measured for overall length and diameter (0- and 90-degree orientation) at 12-inch intervals. Outside diameter profiles were also taken on 72 power-producing rods. Profilometer measurements of the rotational type and of the nonrotational type at 0- and 90-degree orientations were taken. The specific rods that were profiled are shown in Figures 12 through 17.

Each rod was helium leak-checked, and radiographs were taken of the bottom end and upper plenum regions to verify that the internal parts were correctly assembled.

SECTION VI

FUEL BUNDLE ASSEMBLY

The bundle cages for the centermelt fuel were fabricated in the Development Shop. The bundle design and structural features are illustrated in Figures 10 and 11. Each bundle is identified by a system of binary code notches machined in the handles. The assemblies were numbered D-50 through D-55.

The fuel rods and cages were shipped separately and assembled at Consumers Big Rock Point (BRP) reactor site just prior to insertion into the reactor core. Additional dimples were put into the corner angles of the cages at the BRP site to ensure minimum clearance of 80 mils (dimple height) between rods and corner angles, in the event that the rods bowed or corner angles were distorted. In the cold condition, there was a clearance of 10 to 15 mils between the fuel rod and the apex of the dimples, resulting in a total clearance of 90 to 95 mils to the corner angles.

The fuel rods were assembled into the bundles according to the positions shown in Figures 12 through 17. Special precautions were taken to ensure that the fuel rods were placed in their correct positions. After the bundle was fully loaded, the entire loading pattern was cross-checked against the master charts and photographed.

Each completed fuel assembly was given a routine but thorough final inspection by NED Fuel Manufacturing Q.C. personnel and verified to meet specifications before being released for core loading.

HANDLE AND LOCKING PINS

7x7, PARTIALLY LOADED

8x8, PARTIALLY LOADED

FIGURE 10. BUNDLE DESIGN THAT ALLOWS ALL FUEL RODS TO BE REMOVABLE

FIGURE 11. FULLY ASSEMBLED 7x7 BUNDLE AND STRUCTURAL DETAILS

D CP-759 AI	A CP-106 AI	B CP-212 AO P	B CP-210 AO	B CP-213 AO	B CP-214 AO P	A CP-105 AI	D CP-753 AI	H
A CP-110 AO	A CP-100 AI	D CP-705 AI	D CP-702 AI	D CP-706 AI	D CP-701 AI	A CP-103 AI	A CP-112 AO	G
B CP-201 AI P	D CP-700 AI	D CP-703 AI	C CP-302 AI	D CP-704 AI	C CP-300 AI	D CP-755 AI	B CP-204 AI P	F
B CP-215 AO	D CP-756 AI	C CP-305 AO P	D CP-747 AI	C CP-303 AI P	D CP-746 AI	D CP-750 AI	B CP-216 AO	E
B CP-202 AI	D CP-749 AI	D CP-751 AI	C CP-308 AO	D CP-745 AI	C CP-306 AO	D CP-748 AI	B CP-205 AI	D
B CP-203 AI P	D CP-711 AI	C CP-307 AO P	D CP-758 AI	C CP-304 AI P	D CP-707 AI	D CP-710 AI	B CP-200 AI P	C
A CP-108 AO	A CP-104 AI	D CP-708 AI	D CP-709 AI	D CP-712 AI	D CP-713 AI	A CP-107 AI	A CP-111 AO	B
D CP-754 AI	A CP-113 AO	B CP-207 AI P	B CP-209 AO	B CP-211 AO	B CP-206 AI P	A CP-109 AO	D CP-752 AI	A
1	2	3	4	5	6	7	8	

8 x 8 INTERMEDIATE PERFORMANCE FUEL
BUNDLE NO. D-50

ENRICHMENT

A = 4.3%

B = 5.0%

C = 5.6%

D = Depleted (0.22%)

P = Profilometer measurement

AI = Autoclaved inside & outside

AO = Autoclaved outside only

NOTCHES IN UPRIGHTS
LOWER RIGHT HAND CORNER
FOR BUNDLE ORIENTATION

FIGURE 12: ROD LOADING PLAN FOR BUNDLE NO. D-50

D CP-733 AI	A CP-406 AI	B CP-507 AI P	B CP-516 AO	B CP-517 AO	B CP-511 AO P	A CP-404 AI	D CP-728 AI	H
A CP-410 AO	A CP-403 AI	D CP-735 AI	D CP-725 AI	D CP-722 AI	D CP-719 AI	A CP-400 AI	A CP-412 AO	G
B CP-505 AI P	D CP-729 AI	D CP-734 AI	C CP-606 AO	D CP-726 AI	C CP-608 AO	D CP-715 AI	B CP-504 AI P	F
B CP-514 AO	D CP-721 AI	C CP-609 AO P	D CP-724 AI	C CP-603 AI P	D CP-723 AI	D CP-744 AI	B CP-508 AI	E
B CP-500 AI	D CP-741 AI	D CP-738 AI	C CP-604 AI	D CP-739 AI	C CP-607 AO	D CP-737 AI	B CP-509 AO	D
B CP-512 AO P	D CP-717 AI	C CP-602 AI P	D CP-736 AI	C CP-605 AO P	D CP-718 AI	D CP-716 AI	B CP-503 AI	C
A CP-402 AI	A CP-405 AI	D CP-714 AI	D CP-743 AI	D CP-727 AI	D CP-720 AI	A CP-411 AO	A CP-409 AO	B
D CP-731 AI	A CP-407 AI	B CP-502 AI P	B CP-513 AO	B CP-501 AI	B CP-506 AI P	A CP-413 AO	D CP-732 AI	A
1	2	3	4	5	6	7	8	

8 X 8 INTERMEDIATE PERFORMANCE FUEL
BUNDLE NO. D-51

ENRICHMENT

A = 4.3%
B = 5.0%
C = 5.6%
D = Depleted (0.22%)

P = Profilometer measurement
AI = Autoclave inside & outside
AO = Autoclaved outside only

NOTCHES IN UPRIGHTS
LOWER RIGHT HAND CORNER
FOR BUNDLE ORIENTATION

FIGURE 13: ROD LOADING PLAN FOR BUNDLE D-51

D CM-728 AI	A CM-106 AI	B CM-216 AI P	B CM-213 AI	B CM-211 AI P	A CM-110 AI	D CM-753 AI	G
A CM-108 AI	A CM-104 AI	D CM-739 AI	D CM-755 AI	D CM-777 AI	A CM-105 AI	A CM-112 AI	F
B CM-217 AO P	D CM-746 AI	C CM-306 AO P	D CM-745 AI	C CM-305 AI P	D CM-715 AI	B CM-205 AI P	E
B CM-206 AI	D CM-743 AI	D CM-744 AI	C CM-303 AI	D CM-751 AI	D CM-740 AI	B CM-208 AI	D
B CM-204 AI P	D CM-742 AI	C CM-308 AO P	D CM-741 AI	C CM-300 AI P	D CM-750 AI	B CM-224 AO P	C
A CM-107 AI	A CM-116 AO	D CM-734 AI	D CM-748 AI	D CM-717 AI	A CM-111 AI	A CM-102 AI	B
D CM-757 AI	A CM-119 AO	B CM-221 AO P	B CM-220 AO	B CM-223 AO P	A CM-103 AI	D CM-754 AI	A
1	2	3	4	5	6	7	

7 X 7 ADVANCED PERFORMANCE FUEL
BUNDLE NO. D-52

ENRICHMENT

A = 4.3%

B = 5.0%

C = 5.6%

D = Depleted (0.22%)

P = Profilometer measurement

AI = Autoclave inside & outside

AO = Autoclaved outside only

NOTCHES IN UPRIGHTS
LOWER RIGHT HAND CORNER
FOR BUNDLE ORIENTATION

FIGURE 14: ROD LOADING PLAN FOR BUNDLE D-52

D CM-760 AI	A CM-113 AI	B CM-212 AI P	B CM-207 AI	B CM-215 AI P	A CM-115 AI	D CM-761 AI	G
A CM-118 AO	A CM-114 AI	D CM-764 AI	D CM-704 AI	D CM-765 AI	A CM-117 AO	A CM-121 AO	F
B CM-200 AI	D CM-762 AI	C CM-304 AI P	D CM-703 AI	C CM-309 AO P	D CM-767 AI	B CM-219 AO P	E
B CM-202 AI	D CM-705 AI	D CM-774 AI	C CM-310 AO	D CM-769 AI	D CM-773 AI	B CM-209 AI	D
B CM-218 AI P	D CM-701 AI	C CM-302 AI P	D CM-770 AI	C CM-301 AI P	D CM-766 AI	B CM-214 AI P	C
A CM-122 AO	A CM-123 AO	D CM-702 AI	D CM-771 AI	D CM-768 AI	A CM-109 AI	A CM-101 AI	B
D CM-759 AI	A CM-120 AO	B CM-203 AI P	B CM-210 AI	B CM-222 AO P	A CM-124 AO	D CM-763 AI	A
1	2	3	4	5	6	7	

7 X 7 ADVANCED PERFORMANCE FUEL
BUNDLE NO. D-53

ENRICHMENT

A = 4.3%

B = 5.0%

C = 5.6%

D = Depleted (0.22%)

P = Profilometer measurement

AI = Autoclave inside & outside

AO = Autoclaved outside only

NOTCHES IN UPRIGHTS

LOWER RIGHT HAND CORNER

FOR BUNDLE ORIENTATION

FIGURE 15: ROD LOADING PLAN FOR BUNDLE D-53

D CM-710 AI	A CM-422 AI	B CM-503 AI P	B CM-510 AI	B CM-507 AI P	A CM-421 AI	D CM-706 AI	G
A CM-413 AO	A CM-418 AI	D CM-713 AI	D CM-723 AI	D CM-714 AI	A CM-416 AO	A CM-411 AO	F
B CM-500 AI P	D CM-731 AI	C CM-606 AI P	D CM-719 AI	C CM-610 AI P	D CM-721 AI	B CM-512 AO P	E
B CM-508 AI	D CM-732 AI	D CM-729 AI	C CM-603 AO	D CM-726 AI	D CM-727 AI	B CM-501 AI	D
B CM-511 AO P	D CM-725 AI	C CM-608 AI P	D CM-749 AI	C CM-604 AO P	D CM-711 AI	B CM-502 AI P	C
A CM-412 AI	A CM-404 AI	D CM-724 AI	D CM-737 AI	D CM-708 AI	A CM-415 AI	A CM-414 AI	B
D CM-709 AI	A CM-409 AO	B CM-504 AI P	B CM-509 AI	B CM-515 AO P	A CM-405 AO	D CM-707 AI	A
1	2	3	4	5	6	7	

7 X 7 ADVANCED PERFORMANCE FUEL
BUNDLE NO. D-54

ENRICHMENT

A = 4.3%

B = 5.0%

C = 5.6%

D = Depleted (0.22%)

P = Profilometer measurement

AI = Autoclave inside & outside

AO = Autoclaved outside only

NOTCHES IN UPRIGHTS
LOWER RIGHT HAND CORNER
FOR BUNDLE ORIENTATION

FIGURE 16: ROD LOADING PLAN FOR BUNDLE D-54

D CM-758 AI	A CM-423 AI	B CM-513 AO P	B CM-514 AI	B CM-521 AI P	A CM-424 AI	D CM-785 AI	G
A CM-420 AI	A CM-417 AI	D CM-788 AI	D CM-775 AI	D CM-779 AI	A CM-402 AO	A CM-401 AI	F
B CM-524 AI P	D CM-776 AI	C CM-602 AO P	D CM-722 AI	C CM-601 AO P	D CM-787 AI	B CM-505 AI	E
B CM-517 AO	D CM-716 AI	D CM-712 AI	C CM-600 AO	D CM-730 AI	D CM-747 AI	B CM-523 AO	D
B CM-520 AI P	D CM-756 AI	C CM-605 AI P	D CM-752 AI	C CM-609 AI P	D CM-782 AI	B CM-518 AI P	C
A CM-406 AO	A CM-400 AI	D CM-736 AI	D CM-733 AI	D CM-783 AI	A CM-407 AO	A CM-419 AI	B
D CM-780 AI	A CM-403 AI	B CM-519 AO P	B CM-516 AO	B CM-522 AI P	A CM-408 AI	D CM-778 AI	A
1	2	3	4	5	6	7	

7 X 7 ADVANCED PERFORMANCE FUEL
BUNDLE NO. D-55

ENRICHMENT

A = 4.3%

B = 5.0%

C = 5.6%

D = Depleted (0.22%)

P = Profilometer measurement

AI = Autoclave inside & outside

AO = Autoclaved outside only

NOTCHES IN UPRIGHTS
LOWER RIGHT HAND CORNER
FOR BUNDLE ORIENTATION

FIGURE 17: ROD LOADING PLAN FOR BUNDLE D-55

ACKNOWLEDGMENT

The fabrication of these centermelt assemblies involved numerous individuals from various groups within the Division. Their contributions to this program are acknowledged. We are especially grateful to the members of the Manufacturing Development Shop and the Fuels Laboratory for their extra effort made toward completing the assemblies within a very limited time schedule.

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