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FABRICATION OF SWELLING RESISTANT
URANIUM METAL FUEL RODS
FOR THE CANADIAN
WHITESHELL REACTOR, WR-1

August 1969

AEC RESEARCH &
DEVELOPMENT REPORT

Seen for 60008 703 501 12 1969
W.C. Lauffen 52722 1764-D 11-13-69

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BNWL-1129

UC-25, Metals,
Ceramics, and Materials

FABRICATION OF SWELLING RESISTANT URANIUM
METAL FUEL RODS FOR THE
CANADIAN WHITESHELL REACTOR, WR-1

By

W. E. Gurwell, T. B. Correy, and J. O. Vining

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August 1969

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PACIFIC NORTHWEST LABORATORIES
RICHLAND, WASHINGTON 99352

Printed in the United States of America
Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U.S. Department of Commerce
Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.65

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ABSTRACT

Metallic uranium has properties that make it an attractive fuel material for organic cooled reactors, where the consequences of fuel rupture are not nearly so severe as in water cooled reactors. Uranium swelling can be accommodated by a properly designed internal void.

The purpose of this experiment is to develop an optimum fuel design that has center temperatures in the 500-700 °C range and average exposures of 7000 MWd/ton. One hundred thirty-four fuel rods with various combinations of void volume, geometry and cladding thickness were fabricated for the experiment. Half of the rods were pellet filled and one half were coextruded. A technique for coextruding fuel rods with small axial holes one-eighth inch in diameter was demonstrated to be economically feasible.

TABLE OF CONTENTS

LIST OF FIGURES	vii
LIST OF TABLES.	ix
INTRODUCTION	1
SUMMARY AND CONCLUSIONS.	3
FUEL DESIGN.	4
COEXTRUDED FUEL FABRICATION	12
Primary Extrusion of Uranium and Ozhennite	12
Coextrusion Billet Design and Assembly.	12
Coextrusion Details	17
Coextrusion Results	20
Beta Heat Treatment	24
Preparation of End Cap Recesses	24
End Cap Welding	25
Spacer Attachment and Machining	26
PELLET FUEL FABRICATION.	27
Primary Extrusion of Uranium and Ozhennite	27
Ozhennite Sheath Fabrication	27
Uranium Pellet Fabrication.	30
Pellet Fuel Assembly.	35
WELDING PROCESSES.	36
Coextrusion Billet Canning Welding	36
End Closure Welding	36
Spacer Tab Fabrication	42
Spacer Tab Welding Fixture.	44
Spacer Tab Welding	47
FINAL ASSEMBLY, AUTOCLAVING AND INSPECTION	59
ACKNOWLEDGEMENTS	61
APPENDIX I - DRAWINGS PREPARED BY CANADIAN WESTINGHOUSE CO. LTD. (ATOMIC FUEL DEPT.).	A.1
DRAWINGS PREPARED BY BATTELLE-NORTHWEST	A.1
APPENDIX II - ANALYSIS AND HISTORY OF 6 IN. DIAMETER URANIUM BILLETS.	A.2

APPENDIX III - COMPOSITION AND HISTORY OF THE 4 IN. DIAMETER OZHENNITE - 0.5 FORGING	A.3
APPENDIX IV - CLEANING AND ETCHING BATHS	A.4
APPENDIX V - FUEL ROD DATA	A.5
APPENDIX VI - SUPPLEMENTAL PELLET FUEL DATA	A.16
APPENDIX VII - GAMMA-RADIOGRAPHS OF FUEL ROD INTERIORS.	A.19

LIST OF FIGURES

1	Mock-Up of Experimental Metallic Fuel Bundle for the WR-1 Reactor	5
2	Fuel Rod Exterior	6
3	Fuel Rod Details	7
4	Completed Fuel Rods	8
5	Mock-Up of Pellet Fuel Showing Tube and End Cap Pellets	9
6	Coextruded Fuel Fabrication	13
7	Microstructures Primary Extrusions	14
8	Coextrusion Billet and Billet Components	15
9	Schematic of Small Hole Coextrusion Technique	18
10	Metallography of Coextrusions - Transverse Sections	21
11	Microstructure of "Dirty" Bond	22
12	Metallography of Coextrusions After Beta Heat Treatment	23
13	Unbonded Pellet Fuel Fabrication	28
14	Typical Flaws in Sheath Tubing	31
15	Photomicrographs of As-Extruded Pellet Rod	33
16	Electron Beam Welded Billet Joints	37
17	Electron Beam Welded Billet Joints	38
18	Representative Electron Beam Closure Welds	40
19	Representative Electron Beam End Closure Welds	41
20	Vent Hole Seal Weld for Loose Pellet Fuel	42
21	Spacer Tab Flanking Die	43
22	Spacer Tab Welding Fixture Set Up for Coextruded Fuel Rod	45
23	Spacer Tab Welding Fixture Set Up for Pellet Sheath	46
24	Spacer Tab Welding Electrode	48
25	Spacer Attachment Weld	50
26	Spacer Attachment Weld	51
27	Spacer Attachment Weld	53
28	Spacer Attachment Weld	53

29	Spacer Attachment Weld	54
30	Spacer Attachment Weld	54
31	Spacer Attachment Weld	55
32	Spacer Attachment Weld	56
33	Spacer Attachment Weld	57
34	Spacer Attachment Weld	57
35	Spacer Attachment Weld	58
36	Spacer Attachment Weld	58

LIST OF TABLES

1	Sixteen Uranium Alloy Fuel Permutations	10
2	Primary Extrusion Data	16
3	Billet and Mandrel Dimensions	17
4	Coextruded Fuel Rod Dimensions in Inches	20
5	Tube Blank Extrusion Data	29
6	Extrusion Data-Pellet Rod Stock	32
7	Pellet End Dishes-Tolerances Achieved	34
8	Spacer Tab Weld Tensile Shear Test	49

FABRICATION OF SWELLING RESISTANT URANIUM
METAL FUEL RODS FOR THE
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INTRODUCTION

This report describes the fabrication of metallic uranium fuel rods designed to eliminate fuel rod swelling by incorporation of a void in the fuel material.

Metallic uranium has properties that make it an attractive fuel material, especially in organic cooled reactors where the rupture of an unalloyed uranium fuel element is less serious than in a water cooled reactor. It offers many advantages over nonmetallic loadings such as high density, high thermal conductivity and low fabrication costs. One of its "traditional" disadvantages is lack of swelling resistance during irradiation. A means of accommodating uranium swelling and eliminating fuel rod dimensional increases has been found in the hollow rod concept.

Experiments were conducted by Battelle-Northwest under the Basic Swelling Program. Fuel rods were fabricated with central uncooled axial voids and were irradiated in the ETR at the low temperature and high pressure of PWR. They had excellent irradiation performance. These rods exceeded burnups of 15,000 MWd/ton with insignificant diameter changes, and with very small and usually slightly negative volume changes. Burnups of about 10,000 MWd/ton are usually considered to be economically optimum for a metal fuel cycle.

The fuel rods whose fabrication is described in this report will be irradiated in the WR-1 reactor at Whiteshell. The test will determine the effectiveness of various combinations of void volume, cladding thickness, and void geometry in reducing diametral growth of the fuel rods in the higher

temperature and lower pressure environment of an organic cooled reactor. The performance of bonded and unbonded clad fuels also will be compared. Irradiation conditions will be nominally 400 °C - 300 psi with fuel center temperatures into 500 to 700 °C range. The maximum required exposure is 12,000 MWd/ton.

A logical third experiment would be the application of the hollow rod concept to fast reactors. Recent unpublished data indicated considerable economic advantages for metallic fueled fast breeder reactors, if the swelling problem can be minimized. There is strong evidence that the hollow rod concept can be utilized in designing fast reactor fuels with adequate swelling resistance. Data generated in the Basic Swelling Program show that metallic uranium fuels can be operated at temperatures in and above the beta phase. Also, uranium corrosion in sodium or sodium-potassium is virtually nonexistent.

SUMMARY AND CONCLUSIONS

A total of 134 uranium metal fuel rods were fabricated, of which 19 were rejected for various reasons. A total of 16 different fuel rod permutations were made, all with identical exterior dimensions. The basic 12 permutations were generated by two Ozhennite-0.5 cladding thicknesses, 0.020 in. and 0.035 in., two fabrication methods, coextrusion and pellet canning, and three fuel void volumes, 0, 5, and 10%. An additional 4 permutations were generated by placing the void volume in the pellet fuel either as end dishes or as axial holes.

The following necessary developments were made in the course of the fabrication effort:

- 1) A technique for coextruding fuel rods with small axial holes was demonstrated to be economically feasible.
- 2) The proper techniques were developed for assembly of billets for small hole coextrusions. This encompassed billet welding, selection of the copper canning alloy, and machining of the small hole in the uranium billet.
- 3) High power density electron beam welding of the end caps was developed and qualified.
- 4) Tungsten inert gas spot welding was developed and qualified for final closure of the helium backfilled pellet fuels.
- 5) Spacer tab attachment to both sheath tubing and coextruded fuel rods was developed and qualified. Spike power resistance projection welding was used.

A reasonable level of quality assurance was attained through the use of extensive metallography, ultrasonic testing, X-radiography, helium leak checking, visual inspection, metrology, and finished fuel autoclaving.

FUEL DESIGN

The fuel rods will be assembled into bundles of 12, as shown in Figure 1, for irradiation in the WR-1. The bundles are designed so that the rods may be removed periodically during irradiation for inspection. The rods are held in one end by a ball and socket arrangement. The pin ends of the rods are held in place by a clamp. Six dummy elements occupy the center of the bundle and provide proper coolant flow balance compatible with the standard WR-1 oxide fuel bundle.

All fuel rods have the same exterior dimensions but they differ widely beneath the exterior. Figures 2 and 3 are sketches of the fuel rods. Figure 4 shows a group of completed fuel rods. Appendix I contains a list of drawings prepared for the fuel elements and assemblies. The various combinations of clad thickness, void volume, void shape and fabrication method listed in Table 1 make up a total of 16 fuel rod permutations.

All coextruded fuels are either solid or have axial holes and the pellets in some unbonded elements have identical axial holes. The remaining unbonded elements use pellets with conical end dishes as voids. Figure 5 shows the different void geometries in the pellets. The gamma-radiographs of the completed fuel rods in Appendix VII show graphically the variations in void shape and size for all fuel rods. Neutron radiographs taken at intervals during irradiation will show how the voids change with exposure to accommodate swelling.

All end caps are unbonded and welded to the cladding. The pellet fuels are backfilled with helium for heat transfer. There are five spacer tabs attached to each fuel rod. Four 0.025 in. thick tabs space the rods from one another. The single 0.042 in. thick tab separates the rod from the process tube.

Partially Disassembled

Assembled

Photos courtesy of the Atomic Energy Commission of Canada, Ltd.

FIGURE 1. *Mock-Up of Experimental Metallic Fuel Bundle for the
WR-1 Reactor*

Fuel Rod Exterior

FIGURE 2. Fuel Rod Exterior

Fuel Rod Details

FIGURE 3. Fuel Rod Details

FIGURE 4. Completed Fuel Rods

Neg 0683190-1

Neg 0683190-2

FIGURE 5. Mock-Up of Pellet Fuel Showing Tube and End Cap Pellets
(Both Axial Hole and Conical Dished Ends), and Finished
Autoclaved Element

TABLE 1. Sixteen Uranium Alloy Fuel Permutations

<u>Bonded - Coextruded</u>				
<u>Clad</u>	<u>Void Volume, %</u>	<u>Axial Hole Diameter, in.</u>		
0.020	0	None		
0.020	5	0.125		
0.020	10	0.177		
0.035	0	None		
0.035	5	0.119		
0.035	10	0.168		

<u>Unbonded - Pellet</u>				
<u>Clad</u>	<u>Void Volume, %</u>	<u>Conical End Dishes</u>		<u>Axial Hole Diameter, in.</u>
		<u>Diam, in.</u>	<u>Depth, in.</u>	
0.020	0	None	None	
0.020	5	0.451	0.091	0.125
0.020	10	0.451	0.182	0.177
0.035	0	None	None	
0.035	5	0.434	0.087	0.119
0.035	10	0.434	0.175	0.168

In order that all rods have the same central temperatures the fuel enrichment was required to be 2.1, 2.3, and 2.54% for void volumes of 0, 5, and 10%, respectively. The fuel alloy is adjusted uranium containing 600 ppm carbon, 350 ppm iron, 800 ppm aluminum, and 120 ppm silicon. This alloy has been shown to have good swelling resistance. The composition and enrichment of each of the three billets supplied by National Lead is listed in Appendix II.

The cladding alloy is Ozhennite-015, a zirconium base alloy containing 0.2% tin, 0.1% niobium, 0.1% nickel, 0.1% iron, and the balance zirconium. It has the lowest hydriding rate of the zirconium alloys studied to date and it also has superior corrosion resistance in the 400 to 500 °C range. The composition of the Ozhennite forging from which the cladding material was made is given in Appendix III.

COEXTRUDED FUEL FABRICATION

Figure 6 graphically illustrates the major steps required to fabricate the coextruded fuel beginning with a 4 in. diameter Ozhennite billet and a 6 in. diameter uranium billet.

PRIMARY EXTRUSION OF URANIUM AND OZHENNITE

Primary extrusion of the uranium improves the wall thickness uniformity of the coextruded clad by improving the uranium texture. Primary extrusion has a lesser, similar effect on the zirconium alloy cladding material. Table 2 gives the primary extrusion data. Figure 7 shows typical microstructures.

The uranium was also given a beta heat treatment before primary extrusion. Beta heat treatment breaks up the as-cast structure, and further improves the coextrusion characteristics.

COEXTRUSION BILLET DESIGN AND ASSEMBLY

A coextrusion billet is composed of a uranium cylinder with a surrounding Ozhennite sleeve. They are completely contained in a copper canning material. The copper aids lubrication of the billet during coextrusion and also provides the vacuum seal necessary to a good diffusion bond in the coextruded fuel. Figure 8 shows a typical billet and billet components.

Billet dimensions were calculated. The proper die size, 0.632 in. diameter, was selected by two trial coextrusions, since all coextrusions were to have the same outside diameter. Mandrel sizes were set by estimating thermal expansion of the mandrel and the uranium.

The basic building blocks of each billet were the 3.50 OD x 2.18 ID copper tube, 0.012 in. wall small diameter copper tubing, and 1/8 in. thick copper end caps. Assembly gaps of 0.010 in. on a diameter were used. A similar allowance was made between the mandrel and the inner diameter of the small copper tube. The only billet dimension to be calculated was

FIGURE 6. Coextruded Fuel Fabrication

Longitudinal

Transverse

Ozhennite - 500X

500X

250X

Uranium - Transverse

Bright Field

Polarized Light

FIGURE 7. *Microstructures Primary Extrusions*

Neg 0681515

FIGURE 8. Coextrusion Billet and Billet Components

TABLE 2. Primary Extrusion Data

	Uranium	Ozhennite
<u>Billet, in.</u>		
Outside Diameter	5.84	4.0
Inside Diameter	--	1.760
Length	15.0	7.625
<u>Extrusion, in.</u>		
Outside Diameter	2.32	2.25
Inside Diameter	--	1.75
Length	99	49
<u>Lubrication</u>		
Billet	Copper Can and "Aqua Dag"(a)	Cu Plate and "Aqua Dag"
Die	Oil Dag	"Fiske 604"(b) over "Electrofilm 1000"(c)
Mandrel	None	
<u>Extrusion Conditions</u>		
Temperature	620 °C	750 °C
Speed	15 in./min	30 in./min
Extrusion Ratio	6.4/1	6.7/1
Extrusion Constant	16.2 tons/in. ²	19.5 tons/in. ²

- a. Aqua Dag is a proprietary lubricant of the Acheson Colloids Co., Port Huron, Michigan.
- b. Fiske 604 is a proprietary hot die lubricant of Fiske Brothers Refining Co., Toledo, Ohio.
- c. Electrofilm 1000 is a proprietary lubricant of Electrofilm, Inc., North Hollywood, California.

the inner diameter of the Ozhennite sleeve. This dimension along with the mandrel diameter is given in Table 3 for each of the six coextruded fuel permutations.

The holes smaller than 0.188 in. in the uranium billets were extremely difficult to drill and were electrical discharge machined in some cases. The remainder were drilled oversize to 0.225 in. diameter. Either method yielded smooth, wrinkle free fuel rod voids.

TABLE 3. *Billet and Mandrel Dimensions*

<u>Cladding,</u> <u>in.</u>	<u>Void,</u> <u>%</u>	<u>Ozhennite ID,</u> <u>in.</u>	<u>Mandrel Diameter,</u> <u>in.</u>
0.020	0	2.014	None
0.020	5	2.007	0.123
0.020	10	2.000	0.175
0.035	0	1.906	None
0.035	5	1.897	0.117
0.035	10	1.887	0.166

The 0.012 in. wall copper tubing was difficult to weld to the 1/8 in. thick end caps even with a high power density electron beam. A change from DPH copper to a more weldable Cu-3% Si alloy solved the problem. Also, future billet designs should employ 0.035 in. wall in the small diameter tube. The thicker wall tube is much easier to obtain, can be welded at lower power density, and does not complicate removal of copper from the inside diameter of the coextrusion.

All billet components were cleaned and etched just prior to final closure by electron beam welding. The etching bath compositions are given in Appendix IV. The assembled billets were helium leak checked. They were preheated for coextrusion slowly in steel cans to prevent differential thermal expansion from tearing the copper welds apart.

COEXTRUSION DETAILS

A schematic of the small hole coextrusion technique is shown in Figure 9. The mandrel, the most critical piece of tooling, was T-1 tool steel hardened and tempered to Rc 59 to 62 or to a yield strength of 350,000 to 400,000 psi at room temperature. The calculated axial stress on a 1/8 in. diameter (5% void) mandrel approaches 100,000 psi during extrusion. The yield strength of the mandrel decreases to less than the applied stress at the coextrusion temperature of

FIGURE 9. Schematic of Small Hole Coextrusion Technique

625 °C. Hence, the mandrel must be kept as cool as possible for this technique to work. The mandrel must not be preheated, the mandrel must be inserted into the hot billet at the last possible moment, and the extrusion speed must be high. When these three conditions were met excellent coextrusions were made. The technique is less critical with 3/16 in. diameter mandrels which have twice the load bearing area. Mandrel friction was minimized by oxidizing the mandrel surface followed by coating with tungsten disulfide, and "Oil Dag." Mandrel friction was further reduced by tapering the mandrel diameter 0.006 to 0.010 in. along the mandrel length. The coextrusion experience imparts a brief, high temperature temper, under stress, to the tool steel. The hardness of all mandrels dropped during their first and subsequent use to Rc 55 to 58 or to a yield strength of 300,000 to 350,000 psi at room temperature. Several larger mandrels were used successfully for four coextrusions. Several small diameter mandrels were used for two coextrusions, but were reheat-treated between uses.

The following coextrusion conditions were used:

Billet Preheat - 625 °C, 2 1/2 hr
Container and Die - 500 °C
Billet Lubrication - "Aqua Dag"
Die Lubrication - "Necrolene"* and "Oil Dag"**
Container Lubrication - "Oil Dag"
Ram Speed - 58 in./min
Extrusion Ratio - 13 to 14/1
Extrusion Constant - 23 tons/in.²

-
- * *Necrolene is a petroleum lubricating grease manufactured by Crawford Emulsions, Pittsburgh, Pa.*
** *"Oil Dag" is a proprietary lubricant of the Acheson Colloids Co., Port Huron, Michigan.*

COEXTRUSION RESULTS

The resulting coextrusions had excellent clad uniformity and smooth axial holes. The dimensional data are listed in Table 4. Metallography of typical coextrusions is shown in Figure 10. With two exceptions, all coextrusions had clean diffusion bonds between the cladding and core. The two slightly "dirty" bonds probably resulted from the rupture of a copper weld during preheat or during upset of the billet in the extrusion container. The "dirty" bonds were sound and after beta heat treatment the bond was as well diffused as the clean bonds (Figures 11 and 12). The fuel rods made from the two coextrusions having slightly dirty bonds are numbered 62 through 65 and 111 through 115.

TABLE 4. *Coextruded Fuel Rod Dimensions in Inches*

Average Copper OD	0.626 ± 0.002	
Average Ozhennite OD	0.605 ± 0.002	
Cladding Thickness*	0.022 ± 0.002 and 0.037 ± 0.002	
Average Cladding Thickness at a Transverse Section	0.022 and 0.037	
Axial Hole Diameter, Copper Removed		
0.020 Cladding - 5% Void	0.126 ± 0.003	
0.020 Cladding - 10% Void	0.176 ± 0.003	
0.035 Cladding - 5% Void	0.120 ± 0.002	
0.035 Cladding - 10% Void	0.169 ± 0.002	
Usable Fuel Rod Length		
	<u>Total Extrusion</u>	<u>Usable Rod Length</u>
Solid	55	37
5% Void	56	38
10% Void	58	40
Billet Length, 4.25 in. (includes 0.25 in. of copper end caps)		

* Cladding thickness was increased 0.002 in. to compensate for later chemical etching.

500X
Uranium and Cladding to
Core Diffusion Bond

500X
Ozhennite Cladding

0.020 in.
Cladding

0.035 in.
Cladding

Front
Extrusion
Defect

Middle
Sections

1.5X
Rear
Extrusion
Defect

Sections of two coextrusions showing cladding uniformity, uranium grain structure, and extrusion defects. Apparent cracks in bond are actually steps created by uranium etch.

FIGURE 10. Metallography of Coextrusions - Transverse Sections

500X

As-Extruded

500X

*After beta heat treatment.
The bond is well diffused which
indicates little degradation of
bond strength.*

 Zr Zr_2U U

FIGURE 11. Microstructure of "Dirty" Bond

100X
Uranium Grains
As-Polished

100X
Uranium Grains
Electrolytic Etch

500X
Cladding to Core Diffusion
Bond

500X
Ozhennite Cladding

FIGURE 12. Metallography of Coextrusions After Beta Heat Treatment
(Transverse Sections)

BETA HEAT TREATMENT

Beta heat treatment is used to optimize the swelling resistance of uranium fuels. After the extent of front end extrusion defect was determined metallographically, the coextrusion was cut into fuel rod lengths to facilitate handling during heat treatment. This defect varied slightly with the void volume and was approximately 10, 9, and 8 in. for 0, 5, and 10% voids, respectively.

The following beta heat treat cycle was used:

- 1) NaCl-KCl Salt Bath - 10 min at 735 °C
- 2) 10 to 20 sec transfer to nitrate salt at 300 °C
- 3) Isothermal quench in nitrate salt bath
(Draw Temp 275*) - 5 min at 300 °C
- 4) Air cool to room temperature.

Although beta heat treatment warped some rods as much as 0.075 to 0.100 in. in 7 1/2 in. of length, straightening was easily accomplished by a three point loading using lead cushioned end supports and a rubber mallet judiciously placed at the center of the fuel. This method works very well while introducing a minimum amount of cold work to the fuel material.

PREPARATION OF END CAP RECESSES

A conservative, three step approach was used which minimized the hazards of poor machining tolerances and cladding damage. Close tolerances were required in order to produce the good fit-up with the end cap which is necessary for quality electron beam welds.

- 1) Rough machine end cap recesses to a depth of 0.430 in.
leaving 10 to 20 mils of uranium on the clad ID.

* Draw Temp 275 is a product of E. F. Houghton and Co.,
Philadelphia, Pa.

- 2) Chemically mill the end cap recesses. First the copper is stripped from the coextruded pieces. Up to now the copper has served to protect the pieces from mechanical damage and molten salt attack. Its presence upsets the composition of the chemical milling solution. The composition of the copper strip bath and the chemical milling bath are given in the Appendix III.

In this step all the remaining uranium is removed from the clad inside diameter and the hole is milled to a depth of 0.464 ± 0.003 in. This allows a 20 to 30 mil gap between the uranium and the end cap. The gap accomodates differential thermal expansion between the hot fuel center and the relatively cold fuel exterior. Plastic plugs made from polyvinyl chloride rod kept the chemical milling solution from reaching the axial void holes.

- 3) Using a self-centering boring tool, bore out the end cap recesses to a diameter 2 to 3 mils smaller than the mating end cap diameter. This removes minor variations in cladding thickness and small irregularities on the clad inside diameter. When the end caps and uranium rod were etched for welding an optimum fit-up resulted. The first fuel rods made (fuel rod 1 through 96) did not have the benefit of this third step and slightly poorer welds resulted.

END CAP WELDING

Proper etching of the end cap and cladding before welding is important. The etch must be sufficient to remove the oxide layer, absorbed gases, and ground-in dirt. The etch cannot be too extensive or mechanically poor welds result from bad fit-up. Because the zirconium etch produces a film on the uranium, it must be followed by a dip in cold dilute nitric acid to remove the film. Both components should be thoroughly rinsed in

water and alcohol or acetone and dried before welding. Details of end cap weld are given in the WELDING Section.

SPACER ATTACHMENT AND MACHINING

Proper etching of the spacer tabs and cladding before welding is also important if a mechanically strong weld is to result. Details of spacer attachment are explained in the WELDING Section.

After welding, four of the five tabs were machined to the proper thickness of 0.025 in. by grinding.

PELLET FUEL FABRICATION

Figure 13 graphically illustrates the steps required to fabricate the unbonded pellet fuels. Essentially three steps were required: sheath fabrication, pellet fabrication, and fuel rod assembly. All pellet filled rods were backfilled with helium (for good heat transfer) through a hole in the pin type end cap. This hole was sealed with a T.I.G. closure. The end cap welds were electron beam welded in exactly the same fashion as the coextruded fuels were.

PRIMARY EXTRUSION OF URANIUM AND OZHENNITE

Primary extrusion of the uranium was described in detail previously under COEXTRUDED FUEL FABRICATION. Primary extrusion of the Ozhennite was also similar to that described before. The difference was the material was extruded into a 2.25 in. diameter solid rather than a 2.25 in. OD by 1.75 in. ID tube and the extrusion ratio was lowered to 3.24.

OZHENNITE SHEATH FABRICATION

Tube blanks were extruded at the highest extrusion ratio (thinnest wall) consistent with the allowable stress on the extrusion container. Further reduction of the blanks to tubing was done by combined swaging and drawing over mandrels of progressively smaller size until the required sheath diameter and wall thickness were obtained.

Tube blank extrusion data are presented in Table 5. The outside and inside diameter of the billet were clad with 0.035 in. wall copper tubing for lubrication to lower the extrusion force, eliminate die galling, and protect the Ozhennite from contamination. Ends of the billet were protected by 0.125 in. thick copper end caps welded to the copper tubing.

SHEATH FABRICATION

PELLET FABRICATION

FIGURE 13. Unbonded Pellet Fuel Fabrication

TABLE 5. *Tube Blank Extrusion Data*Billet, in.

Outside Diameter	2.17
Inside Diameter	0.75
Length	4.5

Extrusion

Outside Diameter	0.773
Inside Diameter	0.656
Length	9 ft

Lubrication

Billet	Copper Clad and "Aqua Dag"
Die	"Necrolene" and "Oil Dag"
Mandrel	"Oil Dag"

Extrusion Conditions

Temperature	710 °C
Preheat Time	2 1/2 hr
Speed	60 in./min
Extrusion Ratio	25.7/1
Extrusion Constant	21 tons/in. ²

There was some unexpected reaction between the Ozhennite and the copper which resulted in scattered islands of thin Cu-Zr intermetallic. The intermetallic could not be removed in the copper strip bath or zirconium bright etch but had to be removed mechanically by honing. The Zr-Cu reaction can be avoided by slightly lower extrusion temperatures, or smearing graphite or "Aqua Dag" on the Zr-Cu interface.

The blanks were reduced to 0.603 OD and 0.022 or 0.037 wall by combined swaging and drawing over mandrels. A free sink of a few mils was used as a final sizing pass, after the wall thickness had been set. An intermediate recrystallization anneal was required in producing the 0.022 wall tubing. None was needed for the 0.037 wall tubing. Both sizes of tubing were drawn to final size with a total of 45 to 50% cold work. The material exhibited very good ductility. A sample of sheet material was rolled to 75% reduction in thickness without cracking.

All tubing was given a final recrystallization anneal over stainless steel mandrels at 600 °C for 1 hr to straighten the tubing and to stabilize the metallurgical structure of the Ozhennite.

Ultrasonic testing of the tubing uncovered some minor flaws but none that were greater than 10% of wall thickness. Extensive metallography was performed on a series of indicated flaws. Only minor flaws were found as illustrated in Figure 14.

URANIUM PELLET FABRICATION

Uranium pellets were machined from extruded and beta heat treated rod. The conical voids were machined into the pellets. The axial voids were fabricated in situ in the rod stock in a fashion similar to the coextruded fuel, the only difference being the absence of the Ozhennite component in the billet. Extrusion data are presented in Table 6. An interesting thermal effect was observed in the solid pellet rod extrusions. Figure 15 shows the difference in as-extruded grain size with small variation in temperature. The finer grain structures resulted from a 20 to 30 °C lower preheat temperature which was due to the preheat furnace controlling improperly. Subsequent beta heat treatment eliminates this effect completely. Grain structure and inclusion distribution after beta heat treatment were the same as the coextruded fuels (Figure 12).

All pellet rod stock was beta heat treated the same as the coextruded fuels were, before the copper "cladding" was removed chemically. The rod was centerless ground to diameter and cut into pellet lengths. The axial hole rod was ground in 7 in. lengths. Because the rod was not perfectly straight, some non-concentricity was introduced into the axial hole pellets. Concentricities of the pellets are noted in the fuel rod data in the Appendix VI. Conical voids were machined in the ends of the pellets using a machine tool set on a compound feed. The angle

*ID Crack,
1.2 mils deep*

250X

*Surface Roughness,
0.8 mil deep*

250X

*ID Lap,
0.4 mil thick*

250X

FIGURE 14. *Typical Flaws in Sheath Tubing*

TABLE 6. *Extrusion Data-Pellet Rod Stock*

		<u>Solid Rod (Conical Voids)</u>	<u>Rod with Axial Hole Void</u>
<u>Billet</u>			
Outside Diameter, in.		2.17	2.17
Inside Diameter, in.		--	0.225
<u>Extrusion</u>			
Outside Diameter, in.		0.598	0.600
Inside Diameter (Axial Hole Void Only)			
<u>Cladding, in.</u>	<u>Void, %</u>	<u>Mandrel Diameter, in.</u>	<u>Inside Diameter, in.</u>
0.020	5	0.123	0.125 ± 0.002
0.020	10	0.175	0.180 ± 0.001
0.035	5	0.117	0.123 ± 0.002
0.035	10	0.166	0.171 ± 0.001
<u>Lubrication</u>			
Billet	Copper Can and "Aqua Dag"		
Die	"Necrolene" and "Oil Dag"		
Mandrel	"Oil Dag" over air oxide film and WS ₂		
<u>Extrusion Conditions</u>			
Temperature	625 °C		625 °C
Speed	35 in./min		60 in./min
Extrusion Ratio	13.3/1		13.7/1
Extrusion Constant	22 ton/in. ²		23 tons/in. ²

1.5X

Variation of Grain Size in Uranium Pellet Rod Extrusions. Fine Grained Extrusions Had 20 to 30 °C Colder Preheat Temperature.

500X

Cu-U Diffusion-Layer Which is Removed by the Copper Stripping Solution.

FIGURE 15. *Photomicrographs of As-Extruded Pellet Rod*

of the conical void was verified by measuring the included angle of an inverted cone machined with the same tool setup. The angle was later rechecked on "type metal" replicas of the conical voids. The depth of the conical void could then be inspected by measuring the position of a spherical steel ball placed in the cone. The dimensions of the conical end dishes are listed in Table 7.

*TABLE 7. Pellet End Dishes-Tolerances Achieved**

Cladding, in.	Void, %	"B" Diam, in.	"A" Diam, in.	"H"	α (Ref)
0.020	5	$\frac{0.558}{0.559}$	0.451	0.091 ± 0.002	$21^\circ 55'$
0.020	10	$\frac{0.558}{0.559}$	0.451	0.182 ± 0.002	$38^\circ 54'$
0.035	5	$\frac{0.528}{0.529}$	0.434	0.087 ± 0.003	$21^\circ 55'$
0.035	10	$\frac{0.528}{0.529}$	0.434	0.175 ± 0.002	$38^\circ 54'$

* All tolerances ± 0.005 unless otherwise noted.

PELLET FUEL ASSEMBLY

First the ball end cap was electron beam welded to the sheath tube. Then spacer tabs were oriented with respect to the square shank on the end cap and attached to the sheath by resistance welding. The function of the tabs is to separate the elements from one another in the fuel assembly and to separate each element from the process tube.

The inside diameter of each tube was carefully measured. Pellets were etched 0 to 2 mils to a diameter that yielded a nominal 3 mil diametral assembly gap. Etch baths and procedures are listed in Appendix IV.

The pellet stack for each tube was a nominal 6.320 in. long, which required 8 dished end pellets or three axial hole pellets. The length between end caps in the finished fuel rod is 7.490 in., which allows a generous 0.170 in. for differential thermal expansion between the pellets and the fuel.

When the pellets were loaded into the tubes the pin end cap was electron beam welded, and the fuel rod was backfilled with helium through a hole in the pin end cap. The hole was then sealed with a TIG process described in the welding Processes Section of this report.

WELDING PROCESSES

COEXTRUSION BILLET CANNING WELDING

The coextrusion billets were assembled in an outer copper tube, an Ozhennite sleeve, a uranium billet and an inner copper tube. The outer tube was 1/16 in. thick and the inner tube was 0.010 in. thick. The outer tube was purchased as double phosphorous deoxidized copper and the inner tube was reduced from new refrigeration copper tubing. The end plates were made of 1/8 in. thick commercially pure copper plate with a counter-bored joint for heat balance.

To produce a high quality bond between the Ozhennite and uranium it is necessary to maintain a vacuum of at least 5×10^{-4} torr in the billet assembly until it is upset in the extrusion press. To obtain the required vacuum in the billet assembly high power density electron beam welding was used for the closure welds.

During welding there was severe outgassing and expulsion of particles from the fusion zone producing voids in the outer welds and undercutting and holes through the inner welds, Figure 16. In an attempt to overcome this problem the end plates were changed to 3% silicon copper with counterboring for only the inner weld. This corrected the problem with the outer tubes but did not eliminate it with the inner tubes. By making the inner tubes of 3% silicon copper the problem was eliminated (Figure 17).

END CLOSURE WELDING

Considerable effort was made to develop the gas tungsten arc welded closure for the pellet fuel using the joint design supplied. The effort expended was unable to provide reproducible weld quality. Part of the problem was caused by heat unbalance of the joint design (thin edge tube to a grooved thick cap) and

Neg 468-5885

25X

Neg 468-5882

25X

0.010 in. Copper Tubes to Copper Plates

Neg 468-5884

25X

1/16 in. Copper Tube to Copper Plate

FIGURE 16. *Electron Beam Welded Billet Joints*

Neg 468-5886

25X

Bright Field

Neg 468-5886

25X

Polarized Light

*1/16 in. Thick Copper Tube to 1/8 in. Thick 3% Silicon
Copper Plate*

Neg 468-5883

20X

Composite

0.010 in. 3% Silicon Copper Tube to 3% Silicon Copper Plate

FIGURE 17. *Electron Beam Welded Billet Joints*

part by lack of precision in the welding equipment. Several modifications of the joint (including the use of copper chill and design alterations) were made by eliminating the melt-down shoulder and then the groove in the cap. This produced a good weld but reproducibility could not be maintained due to equipment limitation.

Since high power density electron beam welding was to be used to make the end closures for the coextruded fuel and since the cladding was virtually the same thickness the decision was made to electron beam weld the end caps for the pelletized fuel. The same welding parameters were used for both coextruded and pellet fuels. Photomicrographs of representative weld variation for the 0.020 and 0.035 in. thick cladding are shown in Figures 18 and 19.

The machine and settings for the high power density electron beam welding were:

HAMILTON-STANDARD 6 kW

<u>Machine Settings</u>	<u>Wall Thickness</u>	
	<u>0.020 in.</u>	<u>0.035 in.</u>
Kilovolts	97	120
Milliamperes	3	3
Welding Speed	25.2/in./min	25.2/in./min
Focal Point	At surface	At surface
Spot Size	Minimum	Minimum

The requirement for backfilling the pellet fuels with 1 atmosphere of helium was accomplished by providing a 0.030 in. diameter vent hole in the end cap with the straight pin end. After end cap welding, the fuels were placed in a chamber and evacuated to at least 1×10^{-4} torr and the chamber was back-filled with welding grade helium. The vent holes were

Neg 568-989

10X

Neg 568-992

10X

0.020 in. Cladding

FIGURE 18. *Representative Electron Beam Closure Welds*

Neg 568-986

10X

Neg 568-987

10X

0.035 in. Cladding

FIGURE 19. *Representative Electron Beam End Closure Welds*

autogenously fused shut using a gas tungsten arc counting tube controlled spot welder. Figure 20 shows a representative vent hole seal weld.

Neg 0683459

10X

*Bright Field
Composite*

0.020 in. Fuel Cladding

FIGURE 20. *Vent Hole Seal Weld for Loose Pellet Fuel*

SPACER TAB FABRICATION

The blanking die for the fuel rod spacer as shown in Figure 21, produces the spacer having the correct contour in one stroke.

Material 0.042 to 0.045 in. thick x 0.313 in. wide is used in the die. On the first stroke the material is fed into the die only as far as the second side spring plunger, using this spring plunger as a stop, this distance is approximately 5/8 in. from the front. Tripping the press pierces a pilot hole

FIGURE 21. Spacer Tab Blanking Die

Neg 0684311-2

in the stock. After piercing, the stock is then advanced and the pilot hole is picked up by the manually operated spring loaded index pin. The second stroke of the press pierces another locating hole and coins the two welding projections. Again the part is manually indexed and on the third stroke and each succeeding stroke a new locating hole, the welding projections, and a blanked finished piece are produced. After the strip has been fed through the die the first time the end of the strip can be cut midway of the length of the first blanked spacer hole and rerun through the die using the same procedure as previously stated.

Care should be taken at the end of the strip when running so that the locating hole punch does not pierce only part of a hole in the material. This locating hole punch is small and any unbalanced piercing has a tendency to bend or break it.

The contour of the spacer tab is obtained by relief grinding the face of the blanking punch to the desired radius, which allows shearing of opposite corners of the tab first during blanking.

The projection welding dimples are very critical as to height and finish, and must be free of cracking and orange peel effect. The die as presently used produces acceptable parts.

SPACER TAB WELDING FIXTURE

The welding fixture for attaching the spacer tabs to the Canadian fuel rods is shown in Figures 22 and 23.

The part is clamped on the ball end cap that has the four flats and all spacer tabs are oriented to one of the flats. The thicker spacer (0.045 in.) is assembled first and is located relative to the end by locating the clamp head, that has a special slot, with a pin. After assembling this tab the pin is removed and the spring loaded clamp head can slide

Neg 0684311-1

FIGURE 22. Spacer Tab Welding Fixture Set Up for Coextruded Fuel Rod

Neg 0684611-2

FIGURE 23. *Spacer Tab Welding Fixture Set Up for Pellet Sheath*

forward sufficiently to locate the remaining four tabs centrally to the ends of the fuel rod. These four tabs are located radially on the fuel rod by an index pin that will engage in the clamp head.

The welding electrode (Figure 24) is a three piece design brazed together to ease rework and/or replacement. The main body is made of commercial copper and the two piece welding tip is made of Grade 10 welding copper. The tab is retained on the welding tip during welding by a vacuum line. The tab recess in the welding tip is positioned 15° off center to the locating key slot in the copper holder to assure positioning on the fuel rod. A relief is provided on one side of the electrode parallel to the long axis of the spacer to provide clearance for the adjacent spacer tab.

SPACER TAB WELDING

Considering the dimensions of the spacer tabs, the precision of location required, and that there were both loose pellet and coextruded fuels, the decision was made to attach the spacers by resistance welding. Also since PNL has had extensive experience attaching similar but larger items to fuel tubes using spike power resistance projection welding. The decision was made to use these techniques as they appeared to have the greatest chance of success.

The attaching of the fuel spacing tabs posed five problems:

1. Physical dimensions of tabs
2. Two thicknesses of tabs
3. Loose pellet fuel
4. Coextruded fuel
5. Compound curvature of tabs.

The physical dimensions of the tabs posed what appeared to be a serious holding problem during welding. Because of the small dimensions of the tabs the welding current might go in through

Neg 0684311-4

FIGURE 24. *Spacer Tab Welding Electrode*

the edge of the tab, burning it and the electrode, instead of going straight through the tab. This posed no serious problem.

The two tab thicknesses, 0.025 and 0.042 in., posed both handling and welding problems. A welding machine setting and electrode would be required for each thickness. This was overcome by making all tabs 0.042 in. thick, offsetting the thick tab one-half inch along the centerline of the fuel towards the pin end and grinding the remaining four spacers down to 0.025 in.

The wall thicknesses of the tubing for the loose pellet fuel were not sufficient to support the electrode force required or absorb the thermal pulse without burning a hole through the wall. To overcome this problem a copper mandrel was used whose slots were positioned as far as possible from tab welds.

The coextruded fuel posed no problems as they were radially self-supporting and the use of two projections on the tabs overcame the problem of variable cladding surface roughness.

Compound curving of the spacer tab was assured by the design of the welding electrode. The curve of the contact surface of the electrode was the same as the tab. Tensile shear strength reproducibility of the spacer tab welds was found to be very good as shown in Table 8.

TABLE 8. *Spacer Tab Weld Tensile Shear Test*

(Crosshead Travel Rate, 0.050 in./min)

<u>Fuel Type</u>	<u>Cladding Thickness, in.</u>	<u>Number of Spacers Tested</u>	<u>Force to Fracture Double Welds, lb</u>		
			<u>Maximum</u>	<u>Minimum</u>	<u>Average</u>
Pellet	0.020	23	660	445	568
Pellet	0.035	24	735	570	670
Coextruded	0.020	24	860	715	792
Coextruded	0.035	32	1110	800	970

The criteria that was used for all of the spacer tab welding techniques was the same as used at PNL. The heat affected zone in the cladding should not penetrate more than two-thirds of the way through the cladding. On the loose pellet fuel this was a general guide as it was not practical to obtain uniform contact between the copper mandrel and the inner tube wall. The effects of this variable contact are shown in Figures 25, 26, 28 and 30. Only one case of burning inside the tube was found (Fuel Rod 88 with 0.035 in. tube wall) and was not considered serious. The variation in attachment weld pattern for

Neg 568-6057B

50X

Bright Field
0.020 in. Cladding Loose Pellet Fuel

Neg 568-6057B

50X

Polarized Light

FIGURE 25. *Spacer Attachment Weld*

Neg 568-5943A

Bright Field

50X

0.020 in. Cladding Loose Pellet Fuel

Neg 568-5943B

Polarized Light

50X

FIGURE 26. Spacer Attachment Weld

loose pellet tubes having 0.020 in. wall are shown in Figures 25 and 26 while those for 0.035 in. wall are shown in Figures 27, 28, 29, and 30. The pits shown in the inner surface of the cladding in Figures 27 and 28 were produced by the polishing operation penetrating through the specimen. All specimens were polished to the centerline of the projection. Spacer tab welding to coextruded material was considerably simpler. Typical spacer welds are shown in Figures 31 to 36.

Twenty test welds of each type were sectioned, polished, and examined microscopically to determine the reproducibility of the technique. Following is the description of the spike power welder and the machine settings:

Weldex

Detroit, Michigan

Model 10HF2

Serial Number 63-586-2

Capacitor Switch 2

Weld Cycles 1

Transformer Switch 4

Squeeze 110

Air 40 psi

Hold 60

Electrode Force 250 pounds

Electrode Spring Length:

Up 3 11/32 in.

Down 3 7/32 in.

No charge on capacitor at start of weld.

<u>Fuel Type</u>	<u>Wall Thickness, in.</u>	<u>Peak Current</u>	
		<u>Maximum</u>	<u>Minimum</u>
Pellet	0.020	12,000	---
	0.035	15,000	14,000
Coextruded	0.020	12,000	10,000
	0.035	14,500	12,500

Neg 568-5941A *Bright Field* 38X
 NOTE: Defects in Tube Inside Diameter Caused By Polishing
 Through Specimen.
 0.035 in. Cladding Loose Pellet Fuel
FIGURE 27. *Spacer Attachment Weld*

Neg 568-5941B *Polarized Light* 38X
 0.035 in. Cladding Loose Pellet Fuel
FIGURE 28. *Spacer Attachment Weld*

Neg 568-5942A

38X

Bright Field
0.035 in. Cladding Loose Pellet Fuel
FIGURE 29. *Spacer Attachment Weld*

Neg 568-5942B

39X

Polarized Light
0.035 in. Cladding Loose Pellet Fuel
FIGURE 30. *Spacer Attachment Weld*

Neg 586-6000A

Bright Field
0.020 in. Cladding Coextruded Fuel

50X

Neg 586-6000B

Polarized Light

50X

FIGURE 31. Spacer Attachment Weld

Neg 586-6001A

Bright Field
0.020 in. Cladding Coextruded Fuel

50X

Neg 586-6001B

Polarized Light
FIGURE 32. Spacer Attachment Weld

50X

Neg 568-5996A *Bright Field*
0.035 in. Cladding Coextruded Fuel
FIGURE 33. *Spacer Attachment Weld*

40X

Neg 568-5996B *Polarized Light*
0.035 in. Cladding Coextruded Fuel
FIGURE 34. *Spacer Attachment Weld*

38X

Neg 586-5999A

Bright Field

40X

0.035 in. Cladding Coextruded Fuel

FIGURE 35. Spacer Attachment Weld

Neg 568-5999B

Polarized Light

38X

0.035 in. Cladding Coextruded Fuel

FIGURE 36. Spacer Attachment Weld

FINAL ASSEMBLY, AUTOCLAVING AND INSPECTION

At this point each element was helium leak checked and the welds were radiographed. Full length γ -radiographs of the fuel rod interiors were made. These will be compared with γ -radiographs from time to time during irradiation. The final assembly step was grinding of four of the spacer tabs to 0.025 in. thickness. These four separate the individual elements in the fuel bundle. The other 0.042 in. thick spacer separates the element from the process tube.

The elements were prepared for autoclaving by etching and thorough rinsing. Autoclaving conditions were 400 °C steam at 300 psi for 72 hr using deionized feed water with initial resistivity of 10^6 ohms or better. After final autoclaving each element was inspected, measured (see Appendix V), weighed in air, and weighed in liquid (FC-75 density fluid, du Pont).

Some of the elements had gray oxide films after autoclaving. They were recovered by dry blasting the surfaces with glass beads, re-etching and reautoclaving. The procedure considerably improved most rods. The cause of the white oxide was associated with either the etching procedures, that is, amount of surface removed or possibly inadequate rinsing or a particular autoclave.

A rupture was experienced during autoclaving of one batch of fuel rods. A defect in an end cap weld was responsible. The remaining 24 fuel rods in the autoclave had a short-time (1-1/2 hr) exposure to the UO_2 contaminated water. They were salvaged by blasting the surfaces with glass beads, and etching to remove uranium contamination from the surfaces of the rods. Then they were autoclaved. Two fuel rods adjacent to the ruptured rod were tested destructively for hydriding of the zirconium cladding, spacer tabs, and end caps. Both metallography and quantitative hydrogen analyses showed between

14 and 31 ppm hydrogen for both these samples and routinely autoclaved fuel rods. The rods in this group are all numbered 100 and greater and are noted as being "reautoclaved" in Appendix V.

The areas of the edge of the spacer tabs had some white oxide present after reautoclaving. The white oxide results from the original oxide under the tab that was not blasted away. The interface between the blasted metal and unblasted oxide contains oxide particles disturbed but not removed. When the fuel piece is reautoclaved this loose oxide initially prevents formation of a dense black oxide. It has no effect on long term corrosion resistance.

Since the areas underneath the spacer tabs were not blasted there is some possibility that uranium contamination exists there. The areas are small (0.01 in.^2 for each of the five tabs on an element). Access of the uranium contaminated autoclave water to the areas is limited because the tabs are welded flush to the fuel rod cladding. Selected tabs were taken from these fuel rods and submitted to spark source mass spectroscopy. Readings on these samples and normally autoclaved samples were the same. The limit of detection of the technique was estimated at 0.2 nanogram of uranium when 1 microgram of surface material is consumed by the spark.

ACKNOWLEDGEMENTS

The following people made essential contributions to this work:

G. S. Allison - Demonstrated small hole coextrusion technique and supervised coextrusion for this project.

F. B. Quinlan, - Swaged and drew tube blanks into
D. M. Reynolds tubing.

Nondestructive Testing

Department, Customer

Application Section: - Provided X-radiography and ultrasonic testing services.

APPENDICES

APPENDIX I

DRAWINGS PREPARED BY CANADIAN WESTINGHOUSE CO. LTD.
(ATOMIC FUEL DEPT.)

<u>Title</u>	<u>Drawing Number</u>
Parts list	LP 3001
Uranium metal bundle	DS 3000
Element assembly	C 3002
Element assembly	C 3003
Element assembly	C 3004
Element assembly	C 3005
Coextruded fuel and sheath	B 3006
Sheath	B 3007
Sheath assembly	C 3008
End cap	B 3009
End cap	B 3010
End cap	B 3011
End cap	B 3013
End cap	B 3014
End cap	B 3015
Skewed spacer	C 3016
Sheath assembly	C 3018
Inner element assembly	C 3019
Sheath assembly	C 3020
Sheath	B 3021
End cap	C 3022
Spacer	C 3023
End bearing plate	B 3024
Support pin	A 3025
Support pin	A 3026
End plate	C 3027
End plate	C 3028
Retaining Ring	C 3029
Subassembly of inner elements	D 3030

DRAWINGS PREPARED BY BATTELLE-NORTHWEST

<u>Title</u>	<u>Drawing Number</u>
Uranium pellets, solid, dished void	H-3-28982
End cap, EB weld	H-3-28052
End cap, EB weld	H-3-28051
End cap, TIG closure EB weld	H-3-29199
Uranium pellets, axial hole void	H-3-26979

APPENDIX II
ANALYSIS AND HISTORY OF 6 IN. DIAMETER URANIUM BILLETS

Ingot Number	Isotopic	Chemical Analysis		Spectrochemical Analysis											
		Comp. C	N ₂	T.D. H ₂	Al	B	Be	Cd	Cr	Cu	Fe	Mg	Mn	Ni	Zr
21161															
Top	2.096	576	18	18.79	0.6	842	0.14	1	0.19	12	16	366	3	7	45 122 19
Bottom	2.098	664	25	18.80	0.8	810	0.14	1	0.19	10	14	366	3	6	45 138 19
21163															
Top	2.301	679	17	18.81	0.6	815	0.14	1	0.19	4	12	364	3	5	35 142 19
Bottom	2.299	572	18	18.81	0.5	821	0.14	1	0.19	14	13	355	3	6	38 133 19
21134															
Top	2.545	630	15	18.83	0.8	672	0.14	1	0.19	8	15	338	3	6	44 135 19
Bottom	2.542	639	13	18.81	0.8	656	0.14	1	0.19	8	15	347	3	6	42 135 19

Isotopic - %U-235 by weight.

T.D. - Uranium metal density in g/cm³

All others - ppm

Each of the ingots was single beta heat treated and water quenched prior to final machining. The heat treat cycle was as follows:

60 min in 1350 °F salt bath.

19 sec transfer time.

5 min in 65-100 °F water quench.

APPENDIX III
COMPOSITION AND HISTORY OF THE 4 IN. DIAMETER
OZHENNITE - 0.5 FORGING

Ingot Analysis, %		Impurities, ppm			
Sn	0.21	Al	64	Mo	<10
		B	<0.02	N	55
Fe	0.10	C	95	Na	<10
		Cd	<0.3	O	935
Nb	0.09	Co	<5	Pb	<5
		Cr	60	Si	53
Ni	0.10	Cu	<10	Ta	<200
		H	6	Ti	19
		Hf	57	U	<0.5
		Mg	<10	V	<5
		Mn	<10	W	<25
				Zn	<50

FABRICATION HISTORY

1. Forge at 1860 °F to 6 1/2 in. from 17 in. diameter ingot.
2. Reheat to 1900 °F for 25 min at temperature; water quench.
3. Condition.
4. Forge at 1450 °F to 4 1/4 in. diameter.
5. Air anneal at 1450 °F for 30 min at temperature.
6. Sand blast and pickle.
7. Condition, inspect, and ship material.

APPENDIX IV

CLEANING AND ETCHING BATHS

<u>Use</u>	<u>Composition*</u>	<u>Temp</u>	<u>Time</u>
Copper Clean- ing	"Zinctone," Turco Products, Inc., used with adequate rinse	Room	1 to 3 min
Zirconium Etch	50% by volume HNO_3 (70%) 50% by volume Deionized H_2O plus 1/4 lb/gal NH_4HF_2	Room	1 to 2 min
Zirconium Stop Bath	252 mliters HNO_3 (70%) 1.6 lb $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ plus deionized H_2O to make 4 liters.	Room	5 to 10 min
Uranium Etch Coextrusion Billets	10% by volume HNO_3 (70%) 90% by volume deionized H_2O followed by: 10% by volume HNO_3 (70%) 90% by volume deionized H_2O	70 °C Room	1 to 2 min 1 to 5 min
Uranium Pellet Etch	30% by volume HNO_3 (70%) 70% by volume deionized H_2O followed by: 10% by volume HNO_3 (70%) 90% by volume deionized H_2O	40 °C Room	Minimum of 1 min more to reduce diameter 1 min
Chemical Mill- ing of Uranium for End Cap Recesses	Cu 0.175 lb/gal NO_3^- 1.30 lb/gal $\text{SO}_4^{=}$ 4.50 lb/gal U 0.3 to 0.5 lb/gal	75 °C	Removes Uranium at about 0.002 in./min
Stripping Copper from Extrusions	Bulk nitric acid 57 wt% HNO_3 43 wt% H_2O	Room	5 to 15 min

* All etches were preceded by degreasing steps and followed by deionized water rinses and V alcohol or acetone rinses where advantageous. All Nitric Acid used was reagent grade, 70% by weight HNO_3 .

APPENDIX V

FUEL ROD DATA

FUEL ROD DATA - TABLE 1

Ledger: Fuel Type - Ex: Coextruded, P: Pellet
Void - DE: Dished Ends

S.C.: Shipping Container - PNL 1 through 4, N.S.: Not shipped
* In autoclave when Rod No. 138 failed, rod reclaimed and reautoclaved

Rod No.	Fuel Type	Enrich.	Void %	Nominal Clad	Weight Data		Gross Volume cm ³	S.C. PNL	Remarks
		% U ²³⁵		mils	Uranium gms	Gross gms			
1	Ex	2.1	0	20	483	549.75	36.30	N.S.	REJECT - Contaminated weld, Archive
2					486	553.41	36.51	1	
3					486	552.25	36.40	1	
4					485	551.70	36.33	1	
5					485	551.41	36.42	2	
6					483	550.10	36.35	2	
7					483	549.56	36.26	3	
8					484	552.04	36.50	3	
9		2.3	5		458	523.73	36.20	1	Rewelded
10					460	526.10	36.01	1	REJECT - Less than 80% weld closure leak path after
11					464.5	531.32	36.50	1	rewelding
12					461.5	527.80	36.42	2	Rewelded
13					460.5	526.53	36.06	N.S.	REJECT - Less than 80% weld closure leak path, Archive
14*					462	527.41	36.22	2	Rewelded, spacer rewelded also
15					460	526.61	36.08	3	REJECT - Less than 80% weld closure leak path
16					460	528.00	36.27	3	REJECT - Less than 80% weld closure leak path
17		2.54	10		442	507.43	36.50	1	
18					442	506.21	36.32	1	Reautoclaved, intial film grey and mottled
19					442	509.86	36.87	1	
20					438	504.10	36.61	2	
21					442	506.07	36.24	N.S.	REJECT - White oxide in autoclave film after reautoclaving,
22					443	510.55	36.79	2	Archive
23					443	510.15	36.68	3	
24					443	510.76	36.82	3	

A.5

BNWL-1129

FUEL ROD DATA - TABLE 1 (contd)

Rod No.	Fuel Type	Enrich. % U ²³⁵	Void %	Nominal Clad mils	Weight Uranium gms	Data Gross gms	Gross Volume cm ³	S.C. PNL	Remarks
25	P	2.54	10 DE	20	414.5	481.84	36.62	1	
26					413.5	477.50	36.29	1	Reautoclaved, initial film grey and mottled
27					417.5	485.60	36.75	1	
28					417.5	485.04	36.57	2	
29					416.5	480.31	36.12	2	Reautoclaved, initial film grey and mottled
30					418	486.30	36.67	3	
31					415	481.82	36.54	3	
32					413.5	479.89	36.55	3	
33		2.1	0		470.5	538.57	36.58	1	
34					468.5	536.71	36.67	1	
35					466	534.40	36.74	1	
36					468	535.54	36.59	2	
37					464	527.74	36.24	2	Reautoclaved, initial film grey and mottled
38					466	530.78	36.18	3	Reautoclaved, initial film grey and mottled
39					464	529.84	36.38	3	
40					461	527.86	36.56	3	7 pellets out of round, end of spacer squashed during welding
41		2.3	5 DE		441	508.89	36.62	1	
42					441	508.84	36.69	1	
43					441	508.81	36.73	1	
44					441.5	508.85	36.59	2	
45					442	506.31	36.19	2	Reautoclaved, initial film grey and mottled
46					440.5	506.80	36.68	3	
47					441	507.76	36.53	3	
50	Ex	2.1	0	35	436	518.91	36.40	1	Rewelded
51					437	521.25	36.54	1	
52					437	519.78	36.36	2	
53					436	519.96	36.50	2	
54					434	517.97	36.41	2	
55					434	516.70	36.22	N.S.	REJECT - White oxide in autoclave film in closure area,
56					434	517.72	36.38	3	Archive
57					434	516.95	36.31	3	

A.6

BNWL-1129

FUEL ROD DATA - TABLE 1 (contd)

Rod No.	Fuel Type	Enrich. % U ²³⁵	Void %	Nominal Clad mils	Weight Data		Gross Volume cm ³	S.C. PNL	Remarks
					Uranium gms	Gross gms			
58		2.3	5		411	495.25	36.39	1	
59					414	499.00	36.66	1	
60					414.5	499.89	36.68	2	REJECT - Less than 80% weld closure leak path
61					415	498.74	36.49	2	
62					416	499.85	36.71	N.S.	REJECT - White oxide in autoclave film in closure area
63					417	501.58	36.83	2	Archive
64					416	499.16	36.64	3	
65					416	499.25	36.64	3	
66		2.54	10		395	479.95	36.86	1	
67					397	482.33	36.93	1	
68					399	482.72	36.06	2	
69					397	483.54	36.93	2	
70					392	476.29	36.54	2	
71					393	477.41	36.59	3	
72					394.5	478.38	36.55	3	
73					394	478.05	36.58	N.S.	REJECT - in assembly, Archive
74	P	2.1	0	35	424	506.97	36.49	1	
75	P				424.5	509.11	36.54	1	
76					424.5	505.61	36.12	4	
77					425	507.53	36.41	2	
78					426	505.15	36.01	2	Reautoclaved, initial film grey and mottled
79					425	507.74	36.42	2	Numbered 7σ
80					426	508.45	36.56	3	
81					416.5	500.33	36.77	3	REJECT - Fuel-to-clad gap 0.006 in. (0.003 in. criteria)
82		2.3	5 DE		404.5	487.55	36.54	1	
83					403.5	488.51	36.85	1	
84					403.5	487.82	36.73	2	
85					404	486.86	36.62	2	
86					403.5	483.38	36.07	2	Numbered 868; reautoclaved, initial film grey and mottled
87					404	488.37	36.81	3	
88					404	485.77	36.45	3	REJECT - Excessive weld splatter at one spacer tab

A.7

BNWL-1129

FUEL ROD DATA - TABLE 1 (contd)

Rod No.	Fuel Type	Enrich. % U-235	Void %	Nominal Clad mils	Weight Data Uranium gms	Gross gms	Gross Volume cm ³	S.C. PNL
89		2.54	10 DE		384.5	468.17	36.62	1
90					385	468.90	36.71	1
91					384.5	465.66	36.26	2
92					384	466.96	36.55	2
93					384	464.21	36.12	2
94					384.5	464.41	36.66	3
95					385	467.66	36.54	3
96					385	467.83	36.60	4
100*	P	2.3	5	35	406	488.01	36.52	4
101					406	489.39	36.77	1
103*		2.54	10		376	458.64	36.34	
104*					378	460.09	36.25	
105					376	460.32	36.66	
106*		2.3	5		398	481.31	36.40	
107		2.54	10		375	459.45	36.67	
108*		2.3	5		398	479.53	36.28	
109		2.54	10		372.5	456.86	36.69	
110*					374	455.99	36.31	
111*	Ex	2.3	5		414	497.41	36.67	
112*					417	501.23	36.76	
113					417	502.30	36.92	
114*					414.5	497.06	36.41	
115					411	496.96	36.92	
116*		2.54	10		398	481.16	36.80	
117*					398	482.43	36.94	
118*					399			N.S.
119					398	483.60	37.19	4
120*					390.5	474.52	36.85	4

Reautoclaved, initial film grey and mottled
Weld metal blew out from under one tab
Reautoclaved, initial film grey and mottled

Spacer tabs misaligned 15° from square shank reference

REJECT - Pitted clad surface from spacer tab welding

REJECT - External defect near end closure weld

Adjacent to #138 in autoclave, not reautoclaved, sectioned for metallographic examination

FUEL ROD DATA - TABLE 1 (contd)

Rod No.	Fuel Type	Enrich.	Void	Nominal	Weight Data		Gross Volume cm ³	S.C. PNL	Remarks
		% U ²³⁵	%	Clad mils	Uranium gms	Gross gms			
126*	P	2.3	5	20	439	510.47	36.48	4	Adjacent to #138 in autoclave, not reautoclaved, sectioned for metallographic examination
127*					443	509.49	36.54		
128*					440			N.S.	
129					444	513.57	36.76	4	
130*					440	510.20	36.46		
131		2.54	10		418	486.67	36.71		REJECT - slight copper contamination of clad surface
132*					418	484.68	36.51		
133					418	485.11	36.75		
134*					414	480.54	36.53		
135					414	481.35	36.80		
137	Ex	2.3	5		465	532.95	36.84		Failed in autoclave, defective end closure weld
138*					465			N.S.	
139					447	514.91	36.87	4	
140*					451.5	518.05	36.46		
141					454.5	522.84	36.31		
142*		2.54	10		431	497.24	36.22		REJECT - Less than 80% weld closure leak path
143					434	500.09	36.63		
144*					438	500.55	36.25		
145					438	505.92	36.70		
146*					432	504.30	36.41		

FUEL ROD DATA - TABLE 2 (All Dimensions in Inches)

Rod No.	Length	Outside Diameter		Warp	Ball Dia.	Square Shank	Pin Dia.	Spacer Diameter	
		Ball End	Pin End					Thin	Thick
1	9.184	0.600	0.599	0.006	0.345	0.175	0.196	0.629	0.647
2	9.191	.601	.600	.008	.344	.173	.197	.628	.643
3	9.192	.600	.599	.002	.342	.170	.199	.629	.642
4	9.192	.598	.599	.008	.345	.169	.195	.631	.641
5	9.198	.599	.599	.005	.340	.168	.194	.633	.644
6	9.189	.599	.598	.012	.344	.170	.194	.630	.643
7	9.192	.598	.597	.005	.342	.171	.199	.631	.642
8	9.206	.600	.600	.003	.344	.176	.196	.627	.641
9	9.197	.598	.599	.010	.345	.178	.197	.627	.637
10	9.197	.595	.596	.014	.346	.178	.193	.626	.643
11	9.183	.601	.601	.008	.345	.174	.194	.628	.644
12	9.185	.603	.601	.010	.342	.179	.197	.627	.642
13	9.178	.597	.597	.006	.342	.177	.199	.625	.641
14	9.192	.599	.599	.010	.343	.178	.197	.625	.637
15	9.183	.596	.595	.007	.342	.172	.194	.630	.638
16	9.186	.598	.601	.007	.344	.175	.194	.628	.642
17	9.184	.600	.601	.010	.341	.173	.188	.628	.644
18	9.181	.602	.602	.010	.337	.164	.188	.626	.645
19	9.192	.602	.602	.006	.343	.176	.197	.629	.643
20	9.185	.602	.601	.005	.343	.173	.190	.628	.641
21	9.177	.599	.599	.009	.347	.167	.192	.626	.640
22	9.189	.603	.602	.007	.345	.171	.196	.632	.647
23	9.191	.602	.602	.007	.344	.172	.196	.632	.646
24	9.192	.603	.604	.012	.344	.175	.196	.628	.645
25	9.190	.600	.600	.010	.345	.174	.196	.627	.641
26	9.186	.601	.599	.004	.341	.167	.195	.623	.637
27	9.193	.600	.600	.004	.345	.176	.199	.629	.644
28	9.192	.599	.599	.008	.345	.173	.196	.629	.639
29	9.186	.596	.596	.002	.336	.168	.193	.623	.637
30	9.187	.600	.600	.012	.345	.173	.198	.633	.644
31	9.193	.598	.599	.005	.344	.176	.198	.631	.640
32	9.191	.600	.599	.005	.345	.174	.197	.631	.640
33	9.187	.599	.599	.012	.346	.175	.199	.629	.641
34	9.190	.600	.600	.009	.345	.174	.197	.630	.644
35	9.194	.602	.601	.004	.347	.176	.196	.629	.644
36	9.189	.600	.600	.006	.341	.173	.193	.632	.641
37	9.190	.598	.599	.006	.340	.169	.194	.623	.637
38	9.190	.597	.597	.005	.339	.170	.194	.625	.638
39	9.189	.598	.598	.006	.348	.171	.192	.625	.637
40	9.192	.599	.599	.006	.346	.175	.198	.631	.641
41	9.189	.599	.599	.010	.346	.173	.198	.629	.642
42	9.199	.600	.600	.008	.346	.175	.197	.627	.641
43	9.195	.601	.601	.010	.347	.176	.199	.629	.642
44	9.191	.594	.599	.014	.345	.175	.196	.631	.637
45	9.191	.596	.596	.004	.341	.173	.194	.623	.638
46	9.184	.600	.601	.004	.345	.174	.198	.629	.640
47	9.190	.600	.599	.005	.345	.175	.197	.630	.639

FUEL ROD DATA - TABLE 2 (contd)

Rod No.	Length	Outside Diameter		Warp	Ball Dia.	Square Shank	Pin Dia.	Spacer Diameter	
		Ball End	Pin End					Thin	Thick
50	9.154	0.600	0.600	0.013	0.341	0.175	0.198	0.626	0.641
51	9.184	.601	.601	.009	.341	.173	.192	.627	.645
52	9.184	.600	.599	.005	.340	.168	.188	.631	.640
53	9.179	.600	.602	.008	.341	.170	.194	.628	.646
54	9.187	.601	.601	.010	.337	.165	.198	.630	.645
55	9.194	.601	.598	.009	.345	.173	.198		
56	9.179	.600	.599	.011	.341	.169	.198	.627	.644
57	9.181	.600	.600	.003	.344	.168	.197	.631	.644
58	9.179	.601	.601	.007	.341	.170	.190	.628	.643
59	9.191	.599	.602	.009	.344	.173	.195	.628	.645
60	9.189	.603	.601	.009	.344	.171	.195	.630	.647
61	9.182	.601	.602	.006	.342	.172	.194	.629	.645
62	9.184	.603	.603	.007	.343	.170	.196	.633	.644
63	9.190	.604	.603	.012	.342	.173	.194	.630	.646
64	9.185	.601	.601	.010	.346	.170	.198	.629	.646
65	9.189	.601	.603	.014	.341	.173	.193	.625	.649
66	9.194	.603	.603	.008	.345	.174	.196	.627	.646
67	9.188	.606	.605	.012	.339	.169	.196	.629	.647
68	9.198	.604	.604	.010	.346	.176	.197	.630	.647
69	9.195	.604	.604	.006	.345	.175	.196	.629	.647
70	9.186	.601	.601	.010	.345	.175	.199	.631	.642
71	9.186	.602	.601	.009	.340	.173	.199	.629	.648
72	9.193	.599	.600	.008	.345	.175	.199	.630	.644
73	9.181	.602	.603	.011	.341	.172	.194	.627	.639
74	9.194	.600	.600	.013	.346	.179	.196	.627	.642
75	9.188	.600	.600	.005	.346	.175	.197	.627	.643
76	9.195	.596	.596	.010	.343	.173	.195	.625	.638
77	9.188	.589	.599	.020	.345	.175	.198	.628	.640
78	9.181	.597	.597	.009	.341	.168	.194	.625	.637
79	9.186	.599	.598	.010	.345	.175	.198	.630	.639
80	9.187	.601	.600	.003	.345	.175	.198	.629	.642
81	9.189	.602	.602	.012	.346	.178	.199	.630	.641
82	9.188	.600	.600	.008	.346	.178	.198	.629	.646
83	9.196	.602	.602	.010	.347	.176	.197	.629	.643
84	9.191	.601	.601	.008	.346	.175	.197	.629	.643
85	9.186	.601	.601	.008	.345	.173	.196	.631	.641
86	9.187	.598	.599	.012	.339	.165	.193	.623	.637
87	9.190	.601	.602	.010	.347	.177	.198	.630	.643
88	9.191	.600	.600	.009	.344	.175	.196	.631	.641
89	9.186	.601	.601	.003	.346	.175	.198	.628	.644
90	9.195	.601	.601	.004	.345	.176	.198	.629	.642
91	9.181	.598	.598	.005	.341	.174	.194	.626	.639
92	9.187	.600	.600	.005	.345	.173	.196	.631	.646
93	9.179	.598	.598	.010	.339	.165	.192	.625	.638
94	9.186	.601	.601	.007	.345	.176	.191	.629	.642
95	9.187	.600	.600	.010	.345	.172	.198	.629	.642
96	9.186	.600	.601	.008	.345	.174	.198	.628	.641

FUEL ROD DATA - TABLE 2 (contd)

Rod No.	Length	Outside Diameter		Warp	Ball Dia.	Square Shank	Pin Dia.	Spacer Diameter	
		Ball End	Pin End					Thin	Thick
100	9.190	0.599	0.599	0.002	0.343	0.168	0.194	0.625	0.642
101	9.192	.602	.602	.009	.346	.173	.198	.628	.645
103	9.187	.598	.598	.009	.343	.173	.195	.624	.642
104	9.190	.600	.599	.005	.343	.168	.194	.624	.640
105	9.194	.601	.601	.008	.346	.175	.197	.628	.643
106	9.189	.598	.599	.005	.343	.170	.196	.625	.642
107	9.195	.601	.601	.015	.346	.173	.198	.627	.644
108	9.187	.599	.598	.002	.343	.168	.193	.624	.641
109	9.190	.601	.602	.011	.346	.171	.198	.627	.645
110	9.190	.599	.599	.008	.344	.168	.194	.624	.640
111	9.191	.601	.602	.009	.344	.169	.195	.624	.647
112	9.194	.603	.602	.014	.344	.168	.194	.624	.648
113	9.197	.603	.604	.005	.347	.174	.198	.626	.646
114	9.192	.598	.599	.010	.343	.168	.193	.623	.646
115	9.199	.604	.604	.009	.347	.173	.199	.626	.649
116	9.191	.601	.605	.007	.344	.168	.192	.626	.651
117	9.194	.603	.604	.012	.344	.170	.195	.622	.649
118	Sectioned for Metallographic Examination								
119	9.198	.607	.606	.007	.348	.170	.198	.628	.651
120	9.198	.603	.602	.005	.345	.169	.195	.626	.649
126	9.196	.599	.600	.012	.343	.170	.196	.625	.644
127	9.200	.600	.600	.008	.343	.171	.196	.625	.643
128	Sectioned for Metallographic Examination								
129	9.204	.601	.601	.006	.346	.173	.198	.626	.644
130	9.199	.599	.600	.009	.343	.171	.196	.625	.643
131	9.195	.601	.601	.005	.347	.175	.198	.627	.645
132	9.198	.599	.601	.009	.344	.170	.196	.625	.641
133	9.202	.601	.601	.010	.347	.173	.197	.626	.643
134	9.196	.601	.600	.005	.343	.170	.195	.624	.641
135	9.203	.602	.601	.005	.346	.174	.198	.626	.645
137	9.204	.602	.602	.010	.347	.174	.199	.625	.647
138	Failed During Autoclaving								
139	9.201	.604	.603	.007	.347	.175	.198	.626	.626
140	9.207	.600	.598	.006	.343	.170	.195	.626	.644
141	9.202	.596	.602	.007	.347	.176	.196	.627	.640
142	9.216	.594	.599	.013	.345	.171	.194	.623	.640
143	9.208	.581	.600	.008	.347	.176	.198	.628	.644
144	9.198	.597	.597	.010	.343	.170	.195	.623	.643
145	9.204	.597	.598	.008	.347	.175	.198	.625	.649
146	9.202	.600	.598	.012	.343	.168	.195	.624	.640

EXPLANATION OF DATA (Tables 1 and 2)Uranium Weight

Direct measurement for pellet fuels. Difference in grams in the coextruded fuels by subtracting calculated clad weight from the rod section weight.

Total Weight

Weight in grams of finished, autoclaved fuel.

Volume

Volume in cm^3 of finished, autoclaved fuel rod. Measured by weighing element in fluid, FC-75, du Pont Chemical Co.

Outside Diameter

Average in inches of three measurements at 2 1/2 in. from the end cap.

Length

Overall length in inches of fuel rod including end caps.

Warp

Double throw warp in inches measured at center of fuel rod when rotated about the ends of the clad fuel section.

Ball Diameter

Diameter in inches of ball-on-ball end cap.

Square Shank

Thickness in inches of shank on ball end cap. Fuel rod number located here.

Pin Diameter

Diameter in inches of pin-on-pin end cap.

Spacer Diameter

Measurement of fuel rod diameter plus one spacer tab thickness. Measurements in inches on thin (0.025) and thick (0.042) tabs.

FUEL ROD SHIPPING DATA - TABLE 3

<u>Material Shipped</u>	<u>Description</u>			
Four DOT-6L Containers (No. PNL-1, 2, 3 and 4)	Containing Fuel Rods with Enriched Uranium			
	<u>Rod Weight,</u> <u>g</u>	<u>Uranium,</u> <u>g</u>	<u>²³⁵U,</u> <u>%</u>	<u>²³⁵U,</u> <u>g</u>
30 only Fuel Rods	15,807	13,559	2.1	284.7
45 only Fuel Rods	22,716	19,310	2.3	444.1
<u>50</u> only Fuel Rods	<u>24,112</u>	<u>20,354</u>	2.54	<u>517.0</u>
125	62,635	53,223		1245.8

FUEL ROD SHIPPING DATA DETAILS - TABLE 4

<u>Material Shipped</u>	<u>Description</u>			
	<u>Rod Weight,</u> <u>g</u>	<u>Uranium,</u> <u>g</u>	<u>²³⁵U,</u> <u>%</u>	<u>²³⁵U,</u> <u>g</u>
<u>Contents of Container No. PNL-1</u>				
10 only Fuel Rods	5323	4583.5	2.1	96.25
10 only Fuel Rods	5079	4338.5	2.3	99.79
<u>10</u> only Fuel Rods	<u>4868</u>	<u>4133</u>	2.54	<u>104.98</u>
30	15,270	13,055		301.02
<u>Contents of Container No. PNL-2</u>				
10 only Fuel Rods	5244	4483	2.1	94.14
10 only Fuel Rods	5029	4264.5	2.3	98.08
<u>10</u> only Fuel Rods	<u>4820</u>	<u>4055.5</u>	2.54	<u>103.01</u>
30	15,093	12,803		295.23
<u>Contents of Container No. PNL-3</u>				
9 only Fuel Rods	4734	4068	2.1	85.43
8 only Fuel Rods	4042	3441.5	2.3	79.15
<u>9</u> only Fuel Rods	<u>4356</u>	<u>3689.5</u>	2.54	<u>93.71</u>
26	13,132	11,199		258.29
<u>Contents of Container No. PNL-4</u>				
1 only Fuel Rod	506	424.5	2.1	8.9
17 only Fuel Rods	8566	7265.5	2.3	167.1
<u>21</u> only Fuel Rods	<u>10,068</u>	<u>8476</u>	2.54	<u>215.3</u>
39	19,140	16,166.0		391.3

LISTING OF FUEL ROD NUMBERS SHIPPED IN CONTAINERS
NO. PNL-1 THROUGH 4 - TABLE 5

<u>PNL-1</u>	<u>PNL-2</u>	<u>PNL-3</u>	<u>PNL-4</u>
2	5	7	76
3	6	8	96
4	12	15*	100
9	14	16*	101
10*	20	23	103
11	22	24	104
17	28	30	105
18	29	31	106
19	36	32	107*
25	37	38	108
26	44	39	109*
27	45	40	110
33	52	46	111
34	53	47	112
35	54	56	113
41	60*	57	114
42	61	64	115
43	63	65	116
50	68	71	117
51	69	72	119
58	70	80	120
59	77	81*	126
66	78	87	127
67	79	88*	129
74	84	94	130
75	85	95	131*
82	86		132
83	91		133
89	92		134
90	93		135
			137
			139
			140
			141
			142
			143
			144*
			145
			146

* *REJECT* flagged with a Zr-2 wire wrapped around square shank, ball end. See Fuel Rod Data - Table 1 for details.

APPENDIX VI

SUPPLEMENTAL PELLETT FUEL DATA

<u>Fuel Rod No.</u>	<u>Tube ID, in.</u>	<u>Diametral Gap, in.</u>
25	0.5598	3.0
26	0.5600	3.2
27	0.5597	2.9
28	0.5596	2.8
29	0.5599	3.1
30	0.5599	3.1
31	0.5602	3.4
32	0.5600	3.2
33	0.5602	3.2
34	0.5592	2.2
35	0.5598	2.8
36	0.5598	2.8
37	0.5603	3.3
38	0.5601	3.1
39	0.5601	3.1
40	0.5595	2.5
41	0.5599	3.1
42	0.5598	3.0
43	0.5602	3.4
44	0.5598	3.0
45	0.5603	3.5
46	0.5597	2.9
47	0.5601	3.3
74	0.5313	3.2
75	0.5309	2.8
76	0.5307	2.6
77	0.5312	3.1
78	0.5315	3.4
79	0.5313	3.2
80	0.5325	4.4
81	0.5313	6.3

<u>Fuel Rod No.</u>	<u>Tube ID, in.</u>	<u>Diametral Gap, in.</u>
82	0.5312	2.1
83	0.5318	2.7
84	0.5322	3.1
85	0.5320	2.9
86	0.5322	3.1
87	0.5321	3.0
88	0.5323	3.2
89	0.5324	3.0
90	0.5328	3.4
91	0.5316	2.2
92	0.5324	3.0
93	0.5323	2.9
94	0.5322	2.8
95	0.5323	2.9
96	0.5326	3.2

<u>Fuel Rod No.</u>	<u>Tube ID, in.</u>	<u>Diametral Gap, in.</u>	<u>Hole Size, in.</u>	<u>Concentricity</u>
100	0.5330	3.2	0.121,1,5	7,17,8
101	0.5334	3.6	0.122,3,3	6,16,12
103	0.5307	3.2	0.172	6,9,22
104	0.5307	3.2	0.172	7,10,32
105	0.5309	3.6	0.171,1,2	12,27,13
106	0.5315	3.4	0.122	5,13,15
107	0.5309	3.2	0.171	15,20,27
108	0.5313	3.3	0.122	8,16,17
109	0.5311	3.5	0.171	8,9,18
110	0.5309	3.2	0.171	22,25,26
126	0.5605	4.5	0.125	5,9,10
127	0.5604	3.9	0.124,7,7	7,6,7
128	0.5607	3.2	0.125	2,5,6
129	0.5596	3.1	0.126	3,5,6
130	0.5597	4.7	0.124,6,7	10,10,10

<u>Fuel Rod No.</u>	<u>Tube ID, in.</u>	<u>Diametral Gap, in.</u>	<u>Hole Size, in.</u>	<u>Concentricity</u>
131	0.5604	3.9	0.179	3,8,12
132	0.5601	4.1	0.175,9,9	5,4,7
133	0.5604	4.4	0.179	4,5,11
134	0.5607	4.7	0.175,9,9	12,4,7
135	0.5604	5.4	0.179,181,1	22,16,3

EXPLANATION OF DATA

Tube ID

Inside diameter of tube in inches averaged from at least three measurements.

Diametral Gap

Difference in mils between average tube ID and pellet OD.

Hole Size

Measured diameter in inches of axial hole of each pellet.

Concentricity

Concentricity of axial hole with pellet OD determined by rotating pellet about hole center line and by measuring double throw movement of pellet OD at this pellet middle.

The nonconcentricity was introduced during grinding of the extruded rod and could be avoided by centerless grinding in one pellet lengths.

APPENDIX VII

γ -RADIOGRAPHS OF FUEL ROD INTERIORS

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