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HANFORD ATOMIC PRODUCTS OPERATION - RICHLAND, WASHINGTON

PRELIMINARY REPORT ON CX-2 N-INNER FUEL
TUBE NUMBER 1055-8

L. E. Kuhlken and
R. G. Wheeler

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PRELIMINARY REPORT ON CX-2 N-INNER FUEL TUBE NUMBER 1055-8

L. E. Kuhlken and R. G. Wheeler

February 7, 1963

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PRELIMINARY REPORT ON CX-2 N-INNER FUEL TUBE NUMBER 1055-8

INTRODUCTION

The real cost of metallurgical examination of irradiated fuel elements is several times that of fuels before irradiation. Since post-irradiation study is necessary to determine the performance of prototype fuel designs in a reactor environment, complete physical characterization before irradiation provides an economical and efficient basis for comparing experimental data. Without such comparative study, unexpected damage to fuels in the reactor would be difficult, if not impossible, to interpret. This report presents such a characterization of one fuel element from a group of fuels prototypic of the initial charge in Hanford's N-Reactor.

This fuel element, 1055-8, is significant because it belongs to the Production Work Request CX-2 family of elements. The CX-2 charges were the first fuel elements fabricated in the 333 Building, N-Fuels Production Plant, and irradiated as tube-tube assemblies under conditions prototypic of the N-Reactor. The CX-2 charge started as sixteen inner and twenty-one outer fuel tube billets. These original billets represented a potential of 224 inner tube and 227 outer tube fuel elements. The actual yield of completed elements was low because the fuels plant was still in the shakedown phase of operation. Fuel element 1055-8 was singled out of the CX-2 batch of elements because it happened to receive all the special measurements that some of the other CX-2 fuels may have

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missed.

The two available KER loops recently converted to accept N-fuel assemblies will hold the equivalent of about one N-Reactor process tube charge. Statistically, however, the irradiation of N-fuel in these loops to goal exposure and beyond represents too small a fraction of the total N-Reactor load. Evans⁽¹⁾ has pointed out that an acceptable fuel rupture rate in the N-Reactor extrapolates to one rupture every 20 years in the loops.

Rather than wait for the first N-Reactor load of fuel to provide a statistically significant measure of the ability of the fuel elements to perform their function, another approach was taken. Every detail of the fabricated fuel and its production that conceivably could relate to service performance was measured or studied before irradiation. This preliminary report describes the pre-irradiation data taken and studies made on the CX-2 charge as exemplified by Element 1055-8. Upon completion of the KER Loops 3 and 4 irradiations, the test fuel elements will be examined in the KER Basin Facility⁽²⁾ and in the Radiometallurgy Laboratory. The pre- and post-irradiation examinations correlated with the reactor exposure parameters of the tests will provide the experimental check points deemed necessary to evaluate the existing N-fuel design. A report on the total program can then be written as a guide to future development of the fuel.

The N-fuel production process will inevitably change with time. An important purpose of this effort to carefully characterize a large sample of fuel is, therefore, to provide a reference from which the dimensional and metallurgical effects of process changes can be evaluated.

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FUEL MANUFACTURING PROCESS

The CX-2 charge was made from 0.94 wt. % U^{235} enriched uranium castings, 11 inches in diameter, which were reduced by extrusion to a nominal inner fuel tube billet size of 5.7 inches O.D. by 1.09 inches I.D. This primary extrusion is cut into three extrusion billets designated A, B, and C, respectively, as you progress from the head to the rear of the extrusion.

Presentation of Data

The manufacturing process flow sheet is illustrated in Figure 1. Data collected on the fuel and fuel components is organized to follow the flow of fuel and fuel components through the production plant.

One objective of the measurement program was to locate minor dimensional and metallurgical anomalies in the fuel or the components, and to assign to these anomalies a magnitude value. Cylindrical coordinates were used to describe the location. Front or high numbers represent the part of a billet that enters the extrusion die first or the part of a fuel element that comes out of the extrusion die first. The location angle is measured clockwise from some reference point as one faces the front of the billet or extrusion. The reference point (0° angle) on billet and components is the pump-out tube on the copper jacket and the reference point (0° angle) on the fuel is the up position as it comes out of the extrusion press. The two reference points are tied together by noting the position of the pump-out tube on the extrusion. For example, on Extrusion 1055, the pump-out tube was in the 310° position. Some of the special measurements made on the CX-2 fuels do not fit into the normal flow sheet. These data will be presented and discussed at the end of this section.

PROCESS FLOW SHEET - N FUEL ELEMENTS

III COPPER COMPONENTS

1. Receiving Inspection
2. Cleaning
3. Cleaning Inspection
4. Cap Assembly & Welding
5. Cap Assembly Test
6. Can Assembly & Welding
7. Can Assembly Test

I URANIUM BILLETS

1. Receiving Inspection
2. Billet Quality - N.D. Test
3. Billet Pickle
4. Billet Pickle Inspection

II ZIRCALOY-2 COMPONENTS

Billet Clads

1. Receiving Inspection
2. Clad Quality N.D. Tests
3. Cleaning
4. Cleaning Inspection

IV BILLET ASSEMBLY

1. Billet Component Assembly
2. Billet Welding
3. Evacuation & Leak Test
4. Evacuation Tube Cutoff

VII SUPPORTS - STEEL

1. Receiving Inspection
2. Cleaning
3. Cleaning Inspection

V. EXTRUSION

1. Billet Lubrication
2. Billet Preheat
3. Tool Preparation
4. Extrusion
5. Extruded Tube Handling

VI FUEL TUBE PREPARATION

1. Cut to Length & Identify
2. Destructive Test Evaluation
3. Copper Removal
4. Zircaloy Stripping
5. Surface, Dimension, N.D. Audit
6. End Closure Recessing
7. End Closure Brazing
8. Beta Heat Treat
9. Heat Treat Inspection
10. Straightening
11. Vapor Blast
12. End Closure Machining
13. End Closure Cleaning
14. End Closure Welding
15. Nondestructive Test
16. Degrease
17. Support Welding
18. Support Weld Inspection
19. Final Etch
20. Assembly & Autoclave
21. Disassembly & Autoclave Inspection
22. Outer Tube Steel Support Assembly
23. Final Assembly
24. Final Inspection & Storage

(II) END CAPS

5. Receiving Inspection
6. Integrity Testing
7. Cleaning
8. Cleaning Inspection

(II) BRAZE PIECES

9. Receiving Inspection
10. Cleaning
11. Cleaning Inspection

(II) SUPPORTS-ZIRCALOY

12. Receiving Inspection
13. Cleaning
14. Cleaning Inspection

Figure 1

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Uranium billet identification, dimensions and chemical analysis of the billet from which fuel 1055-8 was extruded are given in Tables 1 and 2. These data were obtained at a station in the flow process corresponding to Section I.1 of Figure 1.

One measure of the smoothness of the interface between the cladding and the uranium that a given billet will produce is obtained with an ultrasonic scan of the billet. Two scans are made simultaneously. One is focused through the billet wall radially to the core and the other scan measures the transmission of sonic energy near the outside surface of the billet across a cord of the cylinder.⁽³⁾ This test station corresponds with Section I.2 in the flow chart. Relative grain size data, Table 3, was taken from the recorded output of the radially directed ultrasonic scan because it was easier to assign position coordinates to this scan than it was to the scan across a cord of the billet. A circumferential and a longitudinal plot of the relative grain size in the billet from which Tube 1055 was extruded is given in Figures 2 and 3 respectively. Numbers assigned to grain size are not convertible to actual grain size because the ultrasound measures anisotropic texture effects as well as grain size.

Data collected on the Zircaloy-2 components at Section III.1 of the flow sheet are dimensions and chemical information given in Tables 4 and 5. Identification and dimensions of the copper components that go with this billet, Section III.1 of the flow sheet, are given in Table 6.

Relevant billet assembly and extrusion data (Sections IV and V of flow sheet, respectively) are given in Table 7.

Table 1

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BILLET IDENTIFICATION AND DIMENSIONS

Billet Number - 35188
 Billet Section - C
 Billet Heat Number - 75
 Billet U-235 Content - 0.946%
 Billet Cast Type - Hollow
 Billet Charge Makeup - 50% Derby, 35% Solid, 15% Briquette

	<u>Billet O.D.</u>				<u>Billet I.D.</u>	
	0°	120°	240°	0°	120°	240°
Front	5.362"	5.361"	5.363"	1.345"	1.344"	1.345"
Rear	5.361"	5.361"	5.361"	1.345"	1.344"	1.345"
Billet Length	- 19.013"					

<u>Billet Wall Thickness</u>						
	0°	60°	120°	180°	240°	300°
Front	2.011"	2.011"	2.009"	2.009"	2.008"	2.009"
Center	2.004"	2.001"	2.006"	2.011"	2.008"	2.003"
Rear	2.010"	2.008"	2.001"	2.008"	2.011"	2.012"

Table 2

CHEMICAL ANALYSIS OF URANIUM BILLET

Top Density (gm/cc)	<u>Chemical Analysis (PPM)</u>			<u>Spectrographic Analysis (PPM)</u>					
	H	C	N	B	Be	Cd	Cr	Cu	
18.95	0.7	432	24	70.2	71.0	70.2	75.0	18	
				Fe	Mg	Mn	Ni	Si	Zr
				182	74.0	11	56	133	17

Table 3

POSITION OF MAXIMUM AND MINIMUM GRAIN SIZE IN BILLET

<u>FINE GRAIN</u>			<u>COARSE GRAIN</u>	
	<u>Displ.</u>	<u>Angle</u>	<u>Displ.</u>	<u>Angle</u>
Front	15.1	240	9.5	160
Center	10.0	160	4.0	290
Rear	-0.4	--	-0.4	--

Circumferential Plot - See Fig. 1
 Longitudinal Plot - See Fig. 2

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FIGURE 2

Circumferential Variation of Grain Size of Billet 35188-C at Front, Center, Rear

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FIGURE 3

Longitudinal Variation of Grain Size Taken Spirally Along Billet 35188-C

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Table 4

ZIRCALOY-2 COMPONENTS IDENTIFICATION AND DIMENSIONS

Zircaloy Component Numbers

Outer Clad - 8YA-139-15

Inner Clad - 1340-5-7

Zircaloy Components Heat Numbers

Outer Clad - 66

Inner Clad - 12

Zircaloy Components Diameter

	<u>Outer I.D.</u>		<u>Inner O.D.</u>		
	<u>Max.</u>	<u>Min.</u>	0°	120°	240°
Front	5.389"	5.384"	1.318"	1.318"	1.318"
Rear	"	"	1.321"	1.321"	1.321"

Zircaloy Components Length

Outer - 19.011"

Inner - 18.994"

Zircaloy Components Warp

Outer - 0.002"

Inner - 0.001"

Zircaloy Components Wall Thickness

<u>Outer</u>	0°	60°	120°	180°	240°	300°
Front	0.230"	0.229"	0.230"	0.230"	0.229"	0.231"
Center	0.231"	0.231"	0.232"	0.231"	0.231"	0.231"
Rear	0.229"	0.228"	0.229"	0.230"	0.231"	0.229"
<u>Inner</u>						
Front	0.333"	0.333"	0.334"	0.335"	0.335"	0.334"
Rear	0.335"	0.335"	0.335"	0.336"	0.336"	0.336"

Table 5

CHEMICAL ANALYSIS OF ZIRCALOY-2 COMPONENTS

% Alloying Constituents

[illegible]

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Table 6

COPPER COMPONENTS IDENTIFICATION AND DIMENSIONS

Copper Components - DHP Copper

Copper Components Heat Numbers

Outer - 13

Inner - 9

Copper Components OD - Max. Min.

Outer - 6.024" 5.986

Inner - 0.625" 0.625"

Copper Components Length

Outer - 20.638"

Inner - 20.625"

Copper Components Wall Thickness

	0°	60°	120°	180°	240°	300°
Outer	0.068"	0.068"	0.068"	0.068"	0.068"	0.068"
Inner	0.065"	0.065"	0.066"	--	--	--

Table 7 -

BILLET PREPARATION AND EXTRUSION DATA

BILLET ASSEMBLY AND PREPARATION

Billet Evacuation Pressure - 1×10^{-4} mm Hg

Billet Evacuation Time - 3 min.

Billet Preheat Temperature - 1145 F (618 C)

Billet Preheat Time - 325 min (5.58 hrs)

Lubricant - Aqua Dag

EXTRUSION DATA

Extrusion Number - 1055

Date - November 3, 1961

Upset Force - 1360 tons

Ram Speed - 4 in/min.

Mandrel

Number - 8c

Type - Free Step

O.D. - 0.4239"

Temperature - Cold

Die

Number - 1A

I.D. - 1.2895"

Temperature - 735 F (391 C)

Liner Temperature - 800 F (427 C)

Billet Loader Delay - 36 sec out

- 10 sec in

Upset Delay - 64 sec.

Lubricant Delay - 51 sec.

Shift - 1.5" @ 270°

Angle of Components Reference From

12⁰⁰ Die Position - 310°

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After extrusion (Section VI in the flow sheet) about 4 feet is cut from each end of the tube to remove the end defect. Normally three destructive test samples are cut from each end to evaluate cladding to core bond, interface cleanliness, and wall thickness of components. With the CX-2 charge, 4-inch long samples were taken between each of the inner tube elements. The cutting log for Tube 1055 is illustrated in Figure 4. Dimensions of fuel 1055-8 before copper removal are given in Table 8.

One of the big problems with the inner fuel tube is control of warp during fuel production and prediction of warp behavior in-reactor. This is one reason so much emphasis is placed on warp measurement and on determining the angular position of dimensional and metallurgical anomalies in the core and components. The warp data before and after heat treatment is grouped into Table 9. Some of these data were taken in other steps in the flow sheet than VI 8, 9, and 10; but, since it is all related, one table gives a better picture of the change in warp during the fabrication process. The warp reported is obtained by placing the fuel on two sets of rollers 22 inches apart. As the fuel is rotated, the amount of warp is obtained by noticing the maximum change in the reading of a dial gage resting at the mid-length of the element. Direction of warp is determined by the position of the fuel when the dial gage hits a maximum plus value. Warp data in Table 9 are explained in the Appendix.

Fuel elements 12 and 13 of Tube 1055 were rejected for warp exceeding 0.075 inch. Element Number 1055-9 could be straightened because its warp fell between 0.030 inch and 0.075 inch. On reheat

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FIGURE 4

Cutting Log for NPR Inner Fuel Tube Extrusion No.1055

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Table 8

WALL THICKNESS - COPPER ON

<u>0°</u>	<u>60°</u>	<u>120°</u>	<u>180°</u>	<u>240°</u>	<u>300°</u>
0.431"	0.428"	0.425"	0.426"	0.431"	0.433"

Table 9

WARP TAKEN AT DIFFERENT STAGES OF PROCESS

Length Before and After Heat Treatment:		Before - 23.238"
		After - 23.286"
With Copper On	- 0.011" @300°	
With Copper Off	- 0.005" @40°	
Hot Alpha Annealed	- 0.005" @80°	
Cold Alpha Annealed	- 0.006" @80°	
Hot Beta Heat Treated	- 0.027" @100°	
Cold Beta Heat Treated	- 0.026" @100°	
Vector Alpha Heating	- 0.0034" @150°	
Vector Alpha Cooling	- 0.001" @150°	
Vector 1	- 0.0205" @106°	
Vector 1 Cooling	- 0.001" @280°	
Vector Preferred Orientation	- 0.0029" @166°	
Before Autoclave	- 0.025" @90°	
After Autoclave	- 0.028" @100°	
At Final Inspection	- 0.027" @105°	

Table 10

CLAD THICKNESS AS DETERMINED BY EDDY CURRENT

	<u>0°</u>	<u>300°</u>	<u>240°</u>	<u>180°</u>	<u>120°</u>	<u>60°</u>
Outer -						
Front	0.0393"	0.0400"	0.0393"	0.0390"	0.0387"	0.0390"
Center	0.0391"	0.0382"	0.0391"	0.0379"	0.0389"	0.0380"
Rear	0.0370"	0.0400"	0.0397"	0.0379"	0.0370"	0.0367"
Inner -						
Front	0.0270"	0.0272"	0.0260"	0.0269"	0.0270"	0.0270"
Center	0.0270"	0.0290"	0.0263"	0.0271"	0.0272"	0.0265"
Rear	0.0282"	0.0281"	0.0263"	0.0270"	0.0280"	0.0269"

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treatment into the beta phase it again has more than 0.030 inch warp; therefore, it was rejected.

In Section VI.15 of the flow sheet, the fuel elements are non-destructively tested ultrasonically for cap-to-core bond quality and cap-to-cladding bond quality. Here also, they are tested ultrasonically for voids, inclusions or cracks in the uranium. An overlapping scan of the entire cladding surface is made by eddy current technique to determine cladding thickness. Element 1055-3 was rejected at this station for pin holes in the Zr-5 wt.% Be braze alloy between the end cap and the core. Element 1055-11 was rejected for lack of bond between the end cap and the cladding. Cladding thickness data was extracted from the eddy current scan charts of all CX-2 elements for correlation purposes. This data for 1055-8 is given in Table 10.

Autoclave data for fuel Element 1055-8 corresponding to Section VI.20 in the flow chart, is given in Table 11. Elements 1055-4 and 11 were rejected at step VI.21 in the flow sheet because the autoclave cycle produced white oxide on the end closure welds. These two elements were not autoclaved during the same cycle as shown in Table 11.

After undergoing special measurements discussed in the next section, Element 1055-8 was assembled into outer fuel tube 2087-7 with the zero degree reference mark on each tube aligned radially.

FUEL DATA NOT SPECIFICALLY RELATED TO FLOW SHEET

In addition to the final dimensions listed in Table 12, the fuel elements are measured on semiautomatic air gaging equipment. The inside and outside circumference of the fuel elements are scanned with the air gages at 10 stations down the length of the fuel. The output from the

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Table 11

AUTOCLAVE DATA

Vessel Number - 3
 Time Into Autoclave - 12:45 p.m. (3/8/62)
 Time Out of Process - 8:00 p.m. (3/8/62)
 Time Out of Process - 6:45 a.m. (3/11/62)
 Time at Process Conditions - 69 hr., 25 min.
 Temperature - 750 F (399 C)
 Time to Reach Temperature - 6:10 p.m. (3/8/62)
 Pressure - 1,500 psi
 Time to Reach Temperature - 6:10 p.m. (3/8/62)

Table 12

DIMENSIONS AT FINAL INSPECTION

	<u>0°</u>	<u>90°</u>
O.D. F	1.248"	1.249"
R	1.248"	1.249"
I.D. F	0.437"	0.437"
R	0.437"	0.437"

Length - 23.148"

Weight - 14.80 lb.

Support Height

	<u>0°</u>	<u>120°</u>	<u>240°</u>
Front	0.281"	0.279"	0.280"
Center	0.243"	0.245"	0.245"
Rear	0.280"	0.280"	0.280"

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four air gages at ten stations down the length of the fuel. The output from the four air gages is recorded on strip charts. Distance of the outside surface of the fuel from the axis about which it is rotated is recorded; tube wall thickness is recorded; also inside and outside diameters are recorded. The latter two measurements are redundant, but they are convenient to interpret and they serve to check the first two. The distance from center of rotation and wall thickness is recorded on punched tape and analyzed using an electronic data processing program code named TUM-101. The output from this program is illustrated for fuel Element 1055-8 in Table 13. HW-71521-Rev. describes the TUM program in detail. Dimensions readily obtainable from the information listed in Table 13 is as follows:

Column Heading

- Ao - Diameters at Station 1 through 10 (least mean square fit.)
- Al - Distance of mid diameters above of Station 2 through 9 from a centerline connecting the mid-diameters of Stations 1 and 10.
- PH₁ - Angle of above displacements from zero reference position (angle of warp).
- A₂ - Amount of ellipticity.
- PH₁ - Angle of major axis of ellipticity.

Figure 5 shows a polar representation of the warp as obtained by plotting the vectors represented by columns Al, and Ph₁ of Table 13.

The length of each fuel element was measured on a gage that is not affected by warp of the fuel or non-parallism of the face of the end caps. The anvils of this gage are tripods that automatically average the length. After irradiation, when non parallism of ends may be more severe, the same type of length gage will be used. Length obtained on 1055-8 with the

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Table 13COMPUTER ANALYSIS OF FUEL ELEMENTSFUEL ELEMENT NO. 1055

8-After Autoclave

OD# 1.250

ID#0.440

INITIAL AXIAL LOCATION# 1.750

AXIAL INCREMENT# 2.166

Outside

<u>No.</u>	<u>A0</u>	<u>A1</u>	<u>PH1</u>	<u>A2</u>	<u>PH2</u>
1	0.335	0.	0.	0.411	-78.560
2	0.640	3.595	102.840	0.321	89.361
3	0.578	6.359	104.905	0.318	84.499
4	0.477	8.381	104.565	0.377	82.392
5	0.252	9.660	99.670	0.301	79.980
6	0.163	10.318	95.148	0.298	87.863
7	-0.000	9.536	93.585	0.311	82.566
8	0.024	7.632	95.680	0.306	74.364
9	-0.022	4.559	97.029	0.320	73.475
10	-0.296	0.	0.	0.245	79.433

Initial PH1# 105.843

Delta PH1 per inch -0.682

Axial Four Coef - 10.43845 -0.68874 0.41728 0.00854 0.12657
-0.06740 0.03268 0.03012

Inside

<u>No.</u>	<u>H0</u>	<u>H1</u>	<u>HPH1</u>	<u>H2</u>	<u>HPH2</u>
1	-0.682	0.	0.	0.173	28.148
2	-0.446	3.288	105.138	0.192	31.166
3	-0.455	5.904	107.082	0.173	27.813
4	-0.457	7.627	105.873	0.193	31.116
5	-0.616	8.425	99.391	0.168	28.079
6	-0.861	8.795	93.880	0.147	34.808
7	-1.000	7.817	91.845	0.094	37.104
8	-1.044	5.758	94.363	0.124	34.845
9	-0.687	2.749	97.258	0.187	37.061
10	-1.728	0.	0.	0.207	57.094

Initial PH1# 108.273

Delta PH1 per inch -0.914

Axial Four Coef - 8.86553 0.04385 0.09241 0.21857 -0.07741
0.00436 -0.02641 0.06445

Thickness

<u>No.</u>	<u>T0</u>	<u>T1</u>	<u>TPH1</u>
1	1.017	2.300	-23.641
2	1.086	2.314	-13.228
3	1.033	2.417	-10.490
4	0.934	2.355	-6.037
5	0.868	2.204	2.733
6	1.024	2.227	8.109
7	1.000	2.318	10.835
8	1.068	2.442	11.876
9	0.664	2.608	8.055
10	1.432	2.884	3.709

A0, H0 & T0 are mean departures from radii or wall thickness.

A1, PH1, H1, HPH1 & T1, TPH1 are measures of the amplitude and phase angle of eccentricity.

A2, PH2 & H2, HPH2 are half the ovality and the phase angle of the major axis.

Axial Fourier Coefficient - the first coefficient is a measure of the single throw warp.

Length: 23.149"

NOTE All amplitudes are in mils and angles are in degrees.

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averaging gage was 0.001 inch greater than 23.148 inch obtained (Table 12) with a standard gage.

The thermal expansion coefficient of Zircaloy-2 is 6.5×10^{-6} per deg. C and that of beta heat-treated uranium has been reported variously to 15×10^{-6} to 20×10^{-6} per deg. C. Obviously, the thermal coefficient of expansion of a completed fuel tube will be somewhere between the value for Zircaloy-2 and uranium. Theoretical and experimental fuel element thermal coefficients of expansion as obtained from CX-2 elements are reported in HW-76498. The value obtained for 1055-8 was 12.87×10^{-6} in/in/°C.

It has been shown that the residual stress in the cladding of N-reactor fuels affects their warp behavior.^(4,5) Residual stress in the cladding of a fuel element from tube 1055 (1055-3) was determined by measuring the change in cladding dimensions that occurred when the uranium core was dissolved away with acid. These residual stresses were 57,995 psi for the inner cladding and 54,174 psi for the outer cladding.

Immediately before the fuel elements are autoclaved they are given a final etch. Grain structure of the cladding revealed by this etch is retained in the surface of the ZrO_2 film produced on the surface of the fuel by the autoclave cycle. Figure 6 is a photomicrograph of a Fax-film replica of the outside cladding taken over the transition zone between the portion of the cladding heated into the Zircaloy-2 beta phase and that portion not heated to that temperature.

Distortion of the ends of the fuel elements occurs during the brazing operation. This is referred to as the dog-bone effect. The shape of the outer surface dog-bone, a profile of the weld bead, and a profile of one of the supports was obtained by making X-ray silhouettes of all the CX-2

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4.

Alpha Zircaloy-2 Untransformed

Transition Between Beta-
Transformed Zircaloy-2 and Alpha
Zircaloy-2

Beta Transformed Zircaloy-2

FIGURE 6

Grain Structure of Zircaloy-2 Cladding After Autoclave at Three Points
Across the Braze Zone, 100X

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fuels. Figure 7a is a copy of the silhouette of 1055-8. Figure 7b is a 10X magnification of the head end with the right and left silhouettes laid side by side. The silhouettes are calibrated against a standard cylinder so that dimensions can be read from the negative to the nearest 0.001 inch.

One of the most important types of measurements on the fuel are those which permit evaluation of the volume change in the uranium resulting from swelling during irradiation. Weighing the fuel in and out of water before irradiation and in water after irradiation has proved to be a convenient and accurate way to determine the gross change in uranium volume. The weight of fuel 1055-8 out of water was 14.8016 lb. (as shown in Figure 12) and the weight in room temperature water was 6324.90 gm.

A transverse plane section through a billet does not remain a flat plane during extrusion. Also the lathe-turning tool marks on the cladding are grossly distorted by the extrusions process. Considering a single circumferential lathe tool mark, the maximum distance of this mark from the end of the extrusion minus the minimum distance of the mark from the end of the extrusion is related to a shift. (The amount of shift in the outer cladding of 1055-8 was 1.5 inches.

A summary of the special measurements, other than the dimensions measured on the air gaging equipment, are given in Table 14. The metallography study was designed to pictorially characterize the bond and grain structure of the CX-2 element as a function of extrusion texture, beta heat treatment, position in tube, brazeability, and weldability. The pictures represent two non-heat-treated 4-inch samples in Figures 8 and 9, and two heat-treated reject elements in Figures 10, 11, 12, and 13.

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Table 14

SPECIALIZED MEASUREMENTS AND STUDIES

THERMAL EXPANSION - 12.871×10^{-6} in/in/°C

RESIDUAL STRESS

Outer Clad

% Change in length = 0.2554%
% Change in diameter = 0.3445%
Residual Stress = 57,174 psi

Inner Clad

% Change in length = 0.3064%
% Change in diameter = 0.2061%
Residual Stress = 57,995 psi

STRUCTURE AT THE BRAZE ZONE

(See Figure 6)

DOG BONE PROFILE

(See Figure 7)

Orientation of 0° Support -8°

WEIGHT IN WATER - 6324.90 gm

METALLOGRAPHY SAMPLES

4" Samples

1055-4-8 wafer - See Figure 8.

1055-5-9 wafer - See Figure 9.

Reject Elements

1055-3

Wafer from center - See Figure 10.

End cap profile - See Figure 11.

1055-11

Wafer from center - See Figure 12.

End cap profile - See Figure 13.

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Fuel Tube 1055-8 was charged into KER Loop 4 on April 27, 1962 and is expected to receive 2000 MWD/T exposure. It was assembled with outer Tube 2087-7 with no locking clip on the outer tube. The zero orientation of both the inner tube and the outer tube was in the down position at charging. The assembly was the seventh element from downstream of a 14-assembly charge.

LEK:RGW:LH

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3. Waldkoetter, G. L., Ultrasonic Inspection of Uranium Billets to Predict Coextrusion Performance, HW-70821, August 22, 1961, Unclassified.
4. Wheeler, R. G., Analysis of Diameters and Warp of NPR Inner Fuel Elements, HW-68372, February 2, 1961.
5. Wheeler, R. G., Eccentricity of Clad and Core as a Cause of Fuel Element Warp, HW-69948, June 14, 1961.
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FIGURE 7

Outer Surface of the Fuel Element Showing Dog Bone Caused by End Cap

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FIGURE 8

Metallography Sample 1055-8 Before Heat Treatment. Transverse Sections

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Uranium-Zircaloy-2 Interface
Outside Cladding 250-X
Bright Field

Uranium-Zircaloy-2 Interface
Outside Cladding 50-X
Polarized Light

Section Through Fuel Tube
1.5X

Fine Grained Uranium At
Midwall of Tube 50-X
Polarized Light

Uranium-Zircaloy-2 Interface
Inside Cladding 250-X
Bright Field

Uranium-Zircaloy-2 Interface
Inside Cladding 50-X
Polarized Light

FIGURE 9

Metallography Sample 1055-9 Before Heat Treatment. Transverse Sections

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FIGURE 10

Fuel Element 1055-3 After Heat Treatment. Transverse Section At
Midlength of Fuel Element

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FIGURE 11

Fuel Element 1055-3 After Heat Treatment. Longitudinal Section Through End Cap

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FIGURE 12

Fuel Element 1055-11 After Heat Treatment. Transverse Section At
Midlength of Fuel Element

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FIGURE 13

Fuel Element 1055-11 After Heat Treatment. Longitudinal Section Through End Cap

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APPENDIX IDEFINITION AND DESCRIPTION OF WARP
MEASUREMENTS(6)DEFINITION OF VECTOR QUANTITIES

<u>Quantity</u>	<u>Measured From</u>	<u>Definition</u>
1. $V_{\alpha H}$	$(\alpha H) - (R)$	The thermal instability of a piece prior to beta heat treating.
2. $V_{\alpha C}$	$(\alpha C) - (\alpha H)$	As in $V_{\alpha H}$
3. $V_{\alpha A}$	$(\alpha C) - (R)$	A measure of asymmetrical residual stresses in excess of the yield strength at 300 C.
4. V_1	$\{\beta_1\} - (R)$ or $\{\beta_1\} - (\alpha C)$	The change in warp as a result of beta heat treating.
5. $V_1 C$	$(\beta_1 H) - (\beta_1)$	The thermal instability of a beta heat treated piece.
6. VPO	$(V_{\alpha H}) + (V_1 C)$	A measure of non-uniform preferred orientation in the uranium and the <u>MAJOR DRIVING FORCE FOR WARP.</u>
7. Z	$2.3/VPO/ - /V_1/$	A check on the measurements of 1, 2, 3, 4 and the calculation of 6.
8. VA	$(AA) - (BA)$	A measure of asymmetrical residual stress relaxation during autoclaving.

DESCRIPTION AND APPLICATION OF MEASUREMENTS(A) R - Received Warp

These data will serve two purposes:

1. Control of the Coextrusion Process

If clad thickness and wall thickness are within general specifications, R will be small. R will be large if -

- a) clad thickness eccentricity is large

- (b) the uranium core eccentricity is gross
- (c) abnormal temperatures and/or temperature gradients existed during coextrusion.

There is a choice of when this measurement can be made:

- (a) immediately prior to beta heat treating - serves the best interest of both the coextrusion and the heat treating processes
- (b) just after coextrusion with the copper still on - serves the best interest of the coextrusion process but not the beta heat treating process.

2. Control of the Beta Heat Treating Process

Using received warp as a starting point and then measuring β_1 , the beta heat treated warp, allows the calculation of V_1 . V_1 is defined as the change in warp as a result of beta heat treating.

(B) αH - Warp at 300 C

This measurement is mainly of theoretical interest. The warp change, $V_{\alpha H}$, shows the combined effect of

- 1) bimetallic bending, i.e. the bimetallic strain that is similar to the distortion of a bimetallic switch as temperature is changed.
- 2) unimetallic bending of primarily the uranium and to a lesser extent the zircaloy, i.e. variation in longitudinal fiber texture of the uranium and the zircaloy
- 3) asymmetrical residual stress relaxation.

(C) αC - Warp at 300 C

The parameter obtained here is $V_{\alpha C}$. It is analogous to $V_{\alpha H}$.

The most important practical measure that can be made from the alpha annealing step is:

- 1) asymmetrical residual stresses due to handling and/or cooling on the runout table.

Of greatest theoretical importance is the measure of combined bending moments (bimetallic and unimetallic).

(D) $\beta_1 H$ - Warp at 300 C in the Beta Heat Treated Condition

This measurement should give a value equivalent to the warp of a fuel

element in reactor at 300 C. This measurement is the most important measurement to relate pre- and post-irradiation data.

(E) β_1 Warp After Beta Heat Treating

This measurement determines whether the piece is:

- a) acceptable (> 25 mils for inners and > 30 mils for outers)
- b) recoverable (25 to > 75 mils for inners and 31 to > 75 mils for outers)
- c) reject (> 75 mils for inners and outers)

(F) RB - Warp After Double Reverse Bending

Recoverable fuel elements having + X mils single throw warp are double reverse bent to -2X mils single throw. After reverse bending and re-beta heat treating, they should be straight, i.e. have zero warp.

This measurement serves as a check of the reverse bending operation.

(G) β_2 - Warp After Re-Beta Heat Treating of Reverse Bent Pieces

This measurement determines if the recovered pieces are acceptable or rejectable.

(H) BA - Warp Before Autoclaving

This measurement is a duplicate of either (E) β_1 or (G) β_2 , and serves only to record an off-mid-length measure of warp before autoclaving.

(I) AA - Warp After Autoclaving

This measurement is the final warp inspection of the piece.

SUMMARY:

The most important measurements for process control are:

R - Received Warp - as a control of the coextrusion process and a prediction of quality after heat treating.

β_1 - Heat Treated Warp - criteria of quality after heat treating and determination of the need for straightening.

AA - Warp After Autoclaving - the final inspection for warp.

The most important measurements for correlation of pre- and post-irradiation are:

$\beta_1 H$ - The warp of a finished fuel element operating at 300 C.

VA - The measure of warp change from a single thermal cycle (analogous to a slow startup and a slow shutdown).

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6/16/94

END