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This Document consists of

OFFSITE EXTRUSION PROGRAM
SUMMARY REPORT

By

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INTRODUCTION

The coextrusion process for fabricating zircaloy-2 clad metallic uranium fuel elements was developed by Nuclear Metals Incorporated, West Concord, Massachusetts. When the coextrusion process was selected for fabricating NPR fuel elements, it became necessary to acquire experience in this process. Since there were no extrusion facilities immediately available at HAPCO, it was necessary to initiate a development program using offsite extrusion facilities. Two basic objectives of this program were: (1) To acquire training in the art of coextrusion and, (2) to produce fuel material for the HAPCO process development program.

The extrusion work was performed at Nuclear Metals and at Bridgeport Brass Co., Adrain, Michigan.

At Nuclear Metals, a 1000 ton, direct drive, Watson-Stillman rod press was used.

At Bridgeport Brass, a 2200/200 ton, water accumulator, external manipulator, three column (Brooklyn Model) Loewy Hydropress was used.

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A total of 128 coextrusions were made. The date, location, description of material extruded and pertinent reports are summarized on Table I.

Detailed data, description and evaluation for each extrusion run is reported in Appendices I - IX inclusive. Significant observations and conclusions are summarized in each appendix.

SUMMARY & CONCLUSIONS

1. The offsite extrusion program provided an excellent opportunity to acquire extrusion technology. By working with knowledgeable personnel in their own extrusion plants, it was possible to acquire practical experience in minimum time.
2. The knowledge acquired from this program was successfully applied to the detail design of extrusion billets and press equipment now used in the 333 Pilot Plant.
3. The extruded material produced in this program was not of reactor quality.
4. Several extrusion variables were investigated and/or observed. Significant observations are as follows:

a. Reduction Ratio

A wide range of reduction ratios can be used to coextrude fuel elements. A lower limit of 15/1 reduction is recommended for any production operation. At low reductions extreme care is required to insure uniform bonding. For tubular extrusions the reduction should not exceed 35/1 to avoid unduly high extrusion stem stress.

Since reduction ratio variation will undoubtedly introduce texture variations in the extruded product the metallurgical properties are related to an undetermined extent to the reduction ratio. No particular attempt was made to evaluate this relationship since the extruded fuel is heat treated prior to irradiation. It is, however, probable that better understanding of the relationship could lead to improved fuel quality.

The data presented in Appendix II of this report should be interpreted to mean that from a study of the mechanical attributes of the extruded fuel the authors could not define a "preferred" reduction ratio for coextrusion. This should in no way de-emphasize the need for additional study of the metallurgical properties in relation to reduction ratio.

- b. The integral cone-die design works satisfactorily for included angles from 60° to 120°. Problems encountered in die breakage were caused by improper hardening; (acceptable range 46-54 Rockwell C scale) improper fit; or unsatisfactory materials (best steel tried is H-21).
- c. Extrusion yield can be optimized by using maximum billet length, minimum included cone angle and preshaped billet components

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- d. Four mandrel techniques were tried i.e. french, travelling, stationary, and free. Any one of these techniques can be used for coextrusion. Each system has some mechanical limitations but can be adapted to production. Final selection should be based on concentricity results and will require considerably more test data.
- e. Billet heating must be controlled carefully to prevent extrusion problems. Heating conditions resulting in temperature variations through the billet section can contribute to eccentricity. Copper oxide formation on the billet can cause lubrication problems. Insufficient preheating can cause zircaloy breakthrough and/or aggravate clad thickness variation.
5. Evaluation of the extruded product provided the following observations concerning the effects of process and component variables.
- a. Uranium core fabrication and extruded product quality are intimately related. The uranium metal used in this program was, in general, of poor quality. Two quality aspects must be considered. Metal purity i.e. freedom from impurities and casting defects is required to provide a fuel core free of defects and a core-clad interface which is clean enough to promote bonding during extrusion. Metal texture must be controlled by the fabrication process, such that the mechanical deformation of the core-clad during extrusion will result in a smooth interface.

Several core fabrication techniques were used in this program. They are as follows:

- (1) Cast to 4 inch diameter and beta heat treat.

The metal quality and texture of this metal were very poor. Some of the material was rejected due to porosity. Extruded material showed poor uranium quality and poor interface cleanliness. Clad thickness control was very poor on the inner clad of tube extrusions.

- (2) Cast to 7 inch diameter and beta heat treat.

The metal quality was improved over the 4 inch casting, but the billet texture was about the same as the 4 inch casting. Clad thickness control was poor.

- (3) Cast to 7 inch diameter, alpha extrude, beta heat treat.

The billet texture was improved by the introduction of alpha extrusion. Clad thickness control was improved, approaching satisfactory control on the outer clad, but still relatively poor for the inner clad of tube extrusions.

- (4) DIngot fabrication by combined gamma extrusion, alpha extrusion and heat treatment.

The billet textures were about equal to those obtained by (3) above. Metal quality was satisfactory.

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The core fabrication experiments confirmed the results of development work reported by N.M.I. Billet texture control is essential to coextrusion product quality. The preferred billet texture is obtained by primary alpha extrusion of the uranium ingot at reduction ratios up to 10/1. Beta heat treatment of the primary ingot will reduce the reduction ratio required in primary alpha extrusion. However, quantitative data on relationships of heat treat, primary reduction, and coextrusion quality, is not available.

- b. Bond quality and interface cleanliness are dependent upon the component cleaning and billet assembly techniques. Measurement techniques will differentiate between evacuated and non-evacuated billet assemblies.
- c. Dimensions can be closely controlled in the extrusion process. Wall thickness control will be the toughest problem. Close control will be achieved by proper billet heating and lubrication techniques and by precise tool adjustment. Estimated capability of the process is:

O.D. - nominal $\pm .008$ inch

I.D. - nominal $\pm .007$ inch

W.T. - nominal $\pm 2\frac{1}{2}\%$

TABLE I
SUMMARY OF OFFSITE EXTRUSION RUNS - 3-3-59 THROUGH 1-15-60

<u>Date</u>	<u>Location</u>	<u>Reference Reports</u>	<u>Extrusions</u>
3-3-59	Nuclear Metals Inc. West Concord, Mass.	1) HW-58545 Proposed Offsite Coextrusion Program 2) HW-59694 Trip Report-Coextrusion Run #1 3) HW-60146 Coextrusion Run #1 Product Eval.	12 ea. rods .648" O.D. 6 ea. rods .865" O.D. 4 ea. rods .853" O.D.
4-6-59	Nuclear Metals Inc. West Concord, Mass.	1) HW-58545 Proposed Offsite Coextrusion Program 2) HW-60105 Trip Report - Extrusion Run #2	3 tubes 1.240" O.D. x .694" I.D. 3 tubes 1.125" O.D. x .694" I.D. 3 tubes 1.050" O.D. x .694" I.D. 3 tubes .999" O.D. x .694" I.D. 3 tubes .963" O.D. x .694" I.D. 2 ea. rods .648" O.D.
6-17-59	Bridgeport Brass Co. Adrian, Michigan		7 tubes 2.460" O.D. x 1.850" I.D. 12 rods .830" O.D. 10 rods .615" O.D.
7-24-59	Bridgeport Brass Co. Adrian, Michigan	1) HW-62539 Evaluation of Tubes 16, 17, 18, 19	4 tubes 2.460" O.D. x 1.850" I.D. 3 rods .840" O.D. 7 rods .615" O.D.
8-28-59	Bridgeport Brass Co. Adrian, Michigan	1) HW-62102 Trip Report Coextrusion and Extrusion Tooling	9 tubes 2.460" O.D. x 1.850" I.D.
8-31-59	Nuclear Metals Inc. West Concord, Mass.	1) HW-62102 Trip Report Coextrusion and Extrusion Tooling	8 tubes 1.050" O.D. x .500" I.D.
11-20-59	Bridgeport Brass Co. Adrian, Michigan		5 tubes 1.820" O.D. x 1.450" I.D.
11-23-59	Nuclear Metals Inc. West Concord, Mass.		12 tubes 1.050" O.D. x .500" I.D.
1-15-60	Nuclear Metals Inc. West Concord, Mass.	1) HW-64197 Billet Length Tests	12 tubes 1.050" O.D. x .500" I.D.
Total Offsite Extrusions		31 rods KER size 25 rods NPR size 56 rods total	15 experimental tubes 20 NPR outer tubes 32 KER inner tubes 5 KER outer tubes 72 tubes total

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APPENDIX I

ROD EXTRUSIONS

NUCLEAR METALS INCORPORATED
WEST CONCORD, MASSACHUSETTS
MARCH 6, 1959

REF: HW-60146 - OFFSITE COEXTRUSION RUN #1 EXTRUSION PRODUCT EVALUATION

Clad Thickness & Interface Roughness

In addition to the data given in the referenced report, an analysis of interface roughness was completed. Statistical evaluation of the data was performed by J. L. Jaech, Operations Research and Synthetics, Hanford Laboratories Operation. Clad thickness and interface roughness measuring techniques are described in HW-62539.

The independent variables of interest in this analysis were:

1. Position along the rod (front, middle, rear).
2. Core material (dingot vs ingot uranium).
3. Reduction ratio (22/1 vs 39/1).

The dependent variables were:

1. Average clad thickness for each sample.
2. Range of clad thickness for each sample where range is (maximum reading - minimum reading) and is a measure of interface roughness confined to a small region.

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TABLE I

Rod #	D or I	22:1 or 39:1	Front		Middle		Rear	
			Ave.	Range	Ave	Range	Ave.	Range
3	D	22	25.7	5.3	23.3	5.0	18.8	5.3
4	D	22	24.8	7.0	23.0	5.7	20.8	5.3
5	I	22	25.6	7.0	23.4	3.6	20.8	5.5
6	I	22	24.8	6.5	23.4	5.6	21.5	5.7
7	I	22	24.9	3.5	23.4	5.0	18.5	4.0
8	I	22	25.2	4.0	23.5	5.7	19.8	4.5
9	I	22	24.2	4.1	23.4	4.4	22.1	5.7
10	I	22	25.2	5.5	22.7	6.0	20.0	5.0
12	I	39	25.9	3.8	24.1	3.5	23.4	3.5
13	I	39	25.6	4.6	23.8	3.2	19.8	3.7
14	I	39	23.4	4.9	23.3	5.3	23.5	5.5
15	I	39	26.1	6.3	23.8	5.3	18.8	3.9
16	I	39	27.8	7.0	24.8	5.0	21.2	5.5
17	I	39	24.9	4.5	23.7	5.1	23.5	4.8
18	I	39	26.4	2.8	24.7	4.2	20.7	5.1
19	I	39	26.2	3.8	24.3	3.4	21.0	5.4
20	I	39	24.2	3.4	24.0	4.3	21.8	4.8
21	D	39	26.6	4.2	24.0	4.9	21.8	8.5
22	D	39	26.9	8.1	24.4	5.9	18.6	4.7

An analysis of these data showed that:

1. There is a significant front to rear difference in the average clad thickness. The front pieces are estimated to be 2.1 mils thicker than the center which is, in turn, estimated to be 2.1 mils thicker than the rear.

See Figure I.

Figure 1 - Appendix 1
Rod #16 - Clad Thickness Variation

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2. There is no dingot vs ingot effect with respect to average clad thickness.
3. There is no front to rear or reduction ratio effect on interface roughness at a point as measured by the range.
4. The dingot pieces were significantly rougher than the ingots. The average range was 5.8 for dingots and 4.8 for ingots.

From the above data, it can be seen that closer clad thickness control will be required. The uranium cores were prepared as follows:

Ingot

Cast to 4 inch diameter, triple beta heat treated and machined to size.

Dingot

Gamma extruded to 4 inch diameter, triple beta heat treated and machined to size.

In addition, rods 1 and 2 were extruded with cores which had not been heat treated. On these two extrusions, the uranium core characteristics were so non-uniform that the clad was wrinkled.

From the work already done by N.M.I. on the inter-relation of core history and interface roughness, it was concluded that an improvement could be made by including an alpha work operation in the billet core fabrication.

Figure I shows the typical clad thickness variation as measured on this material. The general pattern confirms the conclusions reached as to the front to rear variation in thickness

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APPENDIX II

SMALL TUBE EXTRUSIONS

NUCLEAR METALS INCORPORATED
WEST CONCORD, MASSACHUSETTS

APRIL 6, 1959

SUMMARY & CONCLUSIONS

The small tube extrusion test was designed to evaluate the effects of reduction ratio between the practical limits of bonding (15/1) and tool stress (35/1).

Up to this time, tubing was usually coextruded at low (12/1 to 20/1) reductions to produce minimum length flowshapes for integral end seals

Due to material limitations, it was necessary to obtain reduction ratio changes by varying the extruded tube size rather than the billet size. All extrusions were satisfactory.

Several significant observations can be made concerning this test run.

1. There were no unusual problems encountered at the high reduction ratios. Lubrication techniques are adequate to withstand the increased pressure encountered. The apparent upper limit on reduction ratios will be stem stress.
2. All extrusions were close to calculated dimensions.
3. Extrusion yield does not change significantly with reduction ratio.
4. Clad thickness variation follows a fairly well defined pattern along the extrusion and is not significantly affected by reduction ratio.
5. Variation in O.D. and I.D. follows a well defined pattern along the length of the extrusion and is not significantly affected by reduction ratio.
6. Variation in wall thickness does not follow any particular pattern, but magnitude of variation is not particularly related to reduction ratio.

I. BILLET AND TOOL DESIGN Ref: HW-58545 Proposed Offsite Coextrusion Program

A. Billet Design

The designed sizes of billet components were as follows:

Outer copper clad	4 in. O.D. x .065 in. wall
Outer zircaloy clad	3.860 ± .003 in. O.D. x 3.590 ± .003 in. I.D.
Uranium core	3.585 ± .003 in. O.D. x 1.490 ± .003 in. I.D.
Inner zircaloy clad	1.485 ± .003 in. O.D. x .885 ± .003 in. I.D.
Inner copper clad	7/8 in. O.D. x .065 in. wall

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Uranium cores were 10 inches long and square on the ends (no preshape). The copper end plates were $\frac{1}{2}$ inch thick at the front (evacuation tube) and $\frac{1}{4}$ inch thick at the rear.

B. Tool Designs

The dies were the integral cone type (90° included angle) fabricated from H-21 tool steel hardened to Rockwell 48-52 C scale. Five separate dies were used. Sizes are given in Table I.

French mandrels (integral mandrel follower block) were used for all extrusions. The mandrels were .700 in. diameter and fabricated from high speed T-1 (18-4-1) tool steel hardened to Rockwell 44-48 C scale. They were 3 in. long with a nominal cold clearance of .015 in. between follower block and liner.

TABLE I

<u>Die Size</u> <u>(Inches)</u>	<u>Reduction</u> <u>Ratio</u>	<u>Calculated</u> <u>Tonnage CK=20</u>	<u>Calculated Extruded Dimensions</u>			
			<u>Copper Or</u>		<u>Clad Thickness</u>	
			<u>O.D.</u>	<u>I.D.</u>	<u>Outer</u>	<u>Inner</u>
1.250	14.84	670	1.239	.704	.029	.0335
1.135	19.93	750	1.125	.702	.0235	.025
1.060	25.11	800	1.050	.700	.020	.020
1.008	30.25	850	.999	.699	.0175	.017
.971	35.14	890	.963	.698	.0155	.0145

II. COMPONENT PREPARATION

A. Copper

The copper extrusion cans were fabricated from DLF copper tube and plate. The assemblies were outgassed. After outgassing they were stored in plastic bags to prevent contamination.

B. Zircaloy Clad

1. Outer Clad Sleeves

The outer sleeves were fabricated as follows:

- Ingot forged to 7 inch solid.
- Billet machined and then extruded to 4 inch O.D. x 3.485 inch I.D.
- Machined to final dimensions (IA).
- Cleaning:
 - Vapor degrease - trichlorethylene
 - Hand scrub in altrex

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- (3) Rinse - hot water
- (4) Rinse - cold water
- (5) Rinse - hot water
- (6) Hot air dry

2. Inner Clad Sleeves

- (a) Zircaloy ingot forged to 5 inch diameter
- (b) Billet machined and extruded to 1.6 inch O.D. x .75 inch I.D.
- (c) Machined to final dimensions (IA)
- (d) Cleaning - same as outer sleeves

C. Uranium

1. Fabrication

The billet cores were cast slightly oversize, triple beta heat treated and machined to size.

2. Cleaning

Billet cores were cleaned as follows:

- (a) Vapor degrease
- (b) Nitric acid pickle
- (c) Cold water rinse
- (d) Hot air dry

III. ASSEMBLY CONDITIONS

All billets were assembled and evacuated within two hours after billet core etch. All assemblies were checked for leaks and evacuated a minimum of two hours. Billets were packed carefully for shipment and no shipping damage was apparent.

IV. EXTRUSION CONDITIONS

A. Billet Preheat

Billets were heated in a muffle furnace. Four to five billets were heated in a furnace charge. To protect from direct radiation from the heating elements, the billets were enclosed in graphite cans.

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Heating time varied from two hours and 45 minutes to three hours and 50 minutes.

The billet temperature was measured by a thermocouple held in contact with the copper can.

B. Tool Preheat

Tools were preheated to 900° F in a muffle furnace. Immediately prior to extrusion, a die was removed from the furnace and inserted into the liner; a mandrel-follower block was removed, lubricated with oil dag, and placed on the loader. When the billet was placed on the loader, the mandrel was inserted through the billet and cutoff, and the assembly was loaded into the liner.

The container-liner was heated to 900° F. The heaters were turned off during extrusion. Indicated liner temperature remained fairly uniform during extrusion.

C. Extrusion Conditions

Extrusions were made in a 4.050 inch I.D. liner, at 13 inches per minute ram speed. The liner was lubricated with oil dag immediately prior to extrusion. Between extrusions, the liner was brushed with a rotating wire brush and blown out with compressed air.

Extrusion data is given in Table II. Extrusions are listed in the sequence of extrusion.

TABLE II

EXTRUSION DATA

<u>NMI Extrusion Number</u>	<u>Billet Number</u>	<u>Die Size</u>	<u>Mandrel Size</u>	<u>Reduction Ratio</u>	<u>Time</u>	<u>Tonnage</u>	
						<u>Max.</u>	<u>Min.</u>
20713	T-1	1.250	.700	14.84	15:45	700	600
20714	T-2	1.135	.700	19.93	15:53	760	690
20715	T-3	1.060	.700	25.11	16:00	780	720
20716	T-4	1.008	.700	30.25	16:08	800	790
20717	T-5	.971	.700	35.14	16:14	790	760
20718	T-6	1.250	.700	14.84	19:50	700	570
20719	T-7	1.135	.700	19.93	19:56	720	670
20720	T-8	1.060	.700	25.11	20:20	770	690
20721	*23			39.06	20:29	880	760
20722	T-9	1.250	.700	14.84	14:41	660	570
20723	T-10	1.008	.700	30.25	14:48	870	770
20724	T-11	.971	.700	35.14	15:47	890	780
20725	*24			39.06	15:53	880	770
20726	T-12	1.135	.700	19.93	19:20	730	660
20727	T-13	1.060	.700	25.11	19:25	740	700
20728	T-14	1.008	.700	30.25	19:40	820	760
20729	T-15	.971	.700	34.14	19:47	860	780

*Rod Extrusions

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Dies and mandrels were inspected and cleaned after each extrusion. Mandrels were inspected for straightness. No pickup was noticed. Tool dimensions did not change due to pressure, wear, or warp.

Calculated extrusions constant (TSI) is shown on Figure I. Comparison of extrusion temperature and K value shows a fair correlation for these extrusions.

V. EXTRUDED DIMENSIONS

The extruded dimensions given in the following tables are maximum and minimum readings recorded on samples taken from the acceptable fuel length of each tube. Table III shows the following data in order that the reader may better evaluate the significance of the data in Table IV through VI.

1. Overall length of the extruded tube, including the copper and defects.
2. Calculated maximum uranium core length i.e. the maximum length of acceptable core which would be yielded by extruding the core with no loss in end flowshapes.
3. Acceptable core length cut from the extrusion. Acceptable being defined as within reasonable limits as to O.D., I.D., and clad thickness variations.
4. Calculated yield of the extrusion

TABLE III

<u>Extrusion Number</u>	<u>Overall Length</u> <u>Inches</u>	<u>Calculated Core</u> <u>Length (Inches)</u>	<u>Acceptable Fuel</u> <u>Length (Inches)</u>	<u>Calculated</u> <u>Yield (%)</u>
1	154	143	110	78
2	206	192	146	76
3	259	241	176	73
4	314	292	228	78
5	365	339	258	76
6	151	143	110	78
7	206	192	148	77
8	259	241	185	77
9	153	143	110	78
10	314	292	228	78
11	365	339	258	77
12	205	192	150	78
13	260	241	185	77
14	311	292	228	78
15	354	330	254	77

The yield figures given above show that extrusion yield is essentially independent of reduction ratio.

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A. Dimensional Variations - General

As extruded dimensions are plotted on Figures II - VIII for typical tubes of each size. The entire clad length of each tube was recorded (including end flowshapes) to develop the patterns of dimensional variation through the complete length of each tube.

This data shows that:

1. The variation of clad thickness follows a well defined pattern regardless of reduction ratio or final clad thickness.

(a) Outer Clad

At the extreme front of the extrusion, the clad is quite thick for a distance of two-three inches. This resembles the characteristic shape of "dog-boning". For the extrusion designs used, it could probably be reduced by preshaping the front $1/8$ " or $1/4$ " of the clad. At the rear of the extrusion, the clad tapers down quite uniformly.

(b) Inner Clad

At the front, the clad generally starts thin and comes up to full thickness fairly uniformly. Some tubes show a slight tendency to "dog-bone", which will probably become more pronounced as the thickness of the inner clad sleeve is increased. At the rear, the clad thickens markedly. This is a result of the "piping" of the uranium core. This can probably be corrected by a slight preshape of the clad sleeve.

2. Variation in diameters follow a fairly well defined pattern regardless of reduction ratio.

(a) Outside Diameter

At the front, the O.D. is decreased because of increased copper thickness. This is probably caused by the shift in material balance resulting from forward displacement of the uranium core. At the rear, the O.D. increases due to decreased copper thickness and possibly due to a decrease in billet temperature and an increase in die temperature.

(b) Inside Diameter

Along the clad section, the I.D. variations are fairly small. Some increase in O.D. at the rear is caused by thickening of the copper due to "piping".

3. Wall thickness variation does not assume any reproduceable pattern. In general, thickness variation is related to "shift" location. Shift is caused by non-uniform material flow during extrusion.

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Shift can be caused by:

- (a) Non-uniform lubrication
- (b) Non-uniform temperature distribution around the billet
- (c) Variable metal stiffness (texture)
- (d) Tool misalignment

Although the dimensions of an extrusion may vary due to the inherent flowshape associated with extrusion and the inadvertant lack of uniformity of billet components, tools and lubricants, these tests have shown that the pattern of variation is uniform over a wide range of conditions. In the "steady state" portion of the extrusion, all variables seem to be in good control. Wall thickness is the least predictable and probably the hardest to control. The end flowshapes represent an inherent loss in yield. However, by preshaping the billet components (integral end closure techniques) this loss can be reduced.

B. Dimensional Variations in the Acceptable Fuel Length

In the following tables, the maximum and minimum values of each dimension measured are given. These measurements were taken on the tube sections after the end flowshapes were removed and the copper pickled off.

1. Diameter Measurements

Outside diameters were measured with a micrometer at three locations (0°, 120°, 240°) at each measuring point along the fuel length.

Inside diameters were measured with a micrometer and snap gage at three locations (0°, 120°, 240°) at each measuring point along the fuel length.

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TABLE IV

Extrusion Number	Reduction Ratio	Total Number of Readings	Outside Diameter			Inside Diameter		
			Max.	Min.		Max.	Min.	
T- 1	14.84	21	1.220	1.213	.007	.707	.705	.002
T- 2	19.93	21	1.107	1.105	.002	.702	.699	.003
T- 3	25.11	21	1.036	1.032	.004	.701	.699	.002
T- 4	30.25	21	.989	.985	.004	.704	.700	.004
T- 5	35.14	21	.954	.950	.004	.703	.701	.002
T- 6		24	1.217	1.211	.006	.708	.703	.005
T- 7		24	1.107	1.104	.003	.702	.701	.001
T- 8		30	1.038	1.033	.005	.704	.700	.004
T- 9		24	1.217	1.213	.004	.707	.704	.003
T-10		30	.990	.985	.005	.704	.701	.003
T-11		21	.955	.950	.005	.703	.700	.003
T-12		24	1.103	1.110	.007	.703	.700	.003
T-13		21	1.037	1.032	.005	.700	.699	.001
T-14		30	.992	.986	.006	.704	.702	.002
T-15		30	.955	.949	.006	.703	.696	.004

2. Wall Thickness Measurements

Wall thickness is measured with a micrometer at six locations (0°, 60°, 120°, 180°, 240°, 300°) at each measuring point along the fuel length.

TABLE V

Extrusion Number	Total Number of Readings	Wall Thickness			Variation in (±) % of Wall Thickness
		Max.	Min.		
T- 1	42	.263	.246	.017	3.3
T- 2	42	.207	.197	.010	2.5
T- 3	42	.173	.161	.012	3.6
T- 4	42	.147	.134	.013	4.6
T- 5	42	.129	.121	.008	3.2
T- 6	48	.259	.249	.010	2.0
T- 7	48	.204	.195	.009	2.2
T- 8	60	.173	.157	.016	4.8
T- 9	48	.258	.247	.011	2.2
T-10	60	.145	.137	.008	2.8
T-11	42	.130	.122	.008	3.2
T-12	48	.209	.194	.015	3.8
T-13	48	.174	.163	.011	3.3
T-14	60	.145	.136	.009	3.2
T-15	--	----	----	----	---

3. Clad Thickness Measurements

The fuel section was roughly polished and clad thickness measured with a calibrated travelling microscope (10 x magnification) at six locations (0°, 60°, 120°, 180°, 240°, 300°) at each measuring point along the fuel tube.

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TABLE VI

Extrusion Number	Total Number of Readings	Outer Clad			Inner Clad		
		Max.	Min.	---	Max.	Min.	---
T- 1	42	.033	.026	.007	.036	.025	.011
T- 2	42	.028	.022	.006	.029	.020	.009
T- 3	42	.022	.015	.007	.023	.013	.010
T- 4	42	.020	.015	.055	.018	.013	.005
T- 5	42	.018	.013	.005	.015	.011	.004
T- 6	48	.033	.026	.007	.037	.026	.011
T- 7	48	.029	.021	.008	.029	.019	.010
T- 8	60	.025	.017	.008	.023	.017	.006
T- 9	48	.033	.025	.008	.036	.028	.008
T-10	60	.021	.015	.006	.020	.014	.006
T-11	42	.019	.014	.005	.015	.010	.005
T-12	48	.027	.021	.006	.030	.021	.009
T-13	42	.022	.016	.006	.023	.015	.008
T-14	60	.021	.015	.006	.020	.013	.007
T-15	60	.017	.010	.007	.018	.010	.008

Rod Extrusions

Two rods (#23, 24) were extruded. Separate (mild steel) cones were used with a shear type die. On one extrusion, (#24) the cone was extruded into the die. From the as-extruded dimensions, it appeared that the cone failure started about midway through the extrusion. When the graphite cutoff hit the cone, it caused the cone to flow into the die until the press stalled.

Figure IX shows the diameter measurements of the two rod extrusions.

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Figure 1-Appendix -2

Billet Numbers, Reduction Ratios & Extrusion Sequence

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SCANNED
WITH JAGGED

**STANLEY
TANNER CLASS**

LOCATION - HIGHWAY 70, 1/2 MILE FROM FRONT OF BOTTLESHOP

11152 - GLEN MOUNTAIN

● 日本

③ THIN CLAD DUE TO ROUGH
DIE FACE

五山先生集

.030
 .026
 OUTER
 CLAD .022
 THICKNESS
 .018
 .014
 .010
 .006
 .002
 .000
 .002
 .006
 .010
 .014
 .018
 .022
 CLAD
 THICKNESS
 .016
 .014

INNER

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40 80 120 160 200 240 280 320

LOCATION - INCHES FROM FRONT

TUBE #A REDUCTION RATIO - 25.11/1

FIGURE VI

900
6-11-52

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TUBE #4 REDUCTION RATIO - 50.75/1

FIGURE VII

5-10-61

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Values Plotted Are Max. & Min.
of 3 Readings Spaced at 60°
Intervals

Reduction Ratio 39.06/1

Figure 9 - Appendix 2

Values Plotted Are Max. & Min. of 3 Readings
Placed at 60° Intervals

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APPENDIX III

NPR OUTER TUBES AND RODS EXTRUDED AT
BRIDGEPORT BRASS COMPANY, ADRAIN, MICHIGAN
JUNE 17, 1959

SUMMARY AND CONCLUSIONS

All tubes extruded exhibited some degree of clad failure due to tearing. Degree of failure varied from complete stripping of the outer clad, as shown in Figures I, to one or two slight circumferential tears along the length of the tube. The same type of circumferential tear failures were noted on the I.D. cladding. Cross sections of I.D. tears showed a fairly uniform necking typical of a failed tensile specimen.

The rod extrusions were satisfactory. Experiments with cone angle variation were completed and gave good results. Billet handling problems were encountered due to the necessity of using a short liner and stem extension. Maximum billet length is limited to 10 inches (core length) due to the sleeved liner design.

Several observations were made concerning this test run.

1. Although the billet and tool designs used for the tube extrusions were different than those generally used for tube coextrusions, the basic cause of the tube extrusion failures was insufficient billet preheat.
2. End flowshape length can be reduced by decreasing the included cone angle of the die.
3. Because of leaks on the preheat cans, several billets were coated with molten salt prior to extrusion. Although salts are sometimes used for extrusion lubricants, this particular salt (Houghtons 980) is not satisfactory as a co-extrusion lubricant. The salt caused pickup in both die and liner, resulting in scratching of the clad surface.

3A. NPR TUBE EXTRUSIONS

I. Billet & Tool Designs

A. Billet Design

The designed sizes of billet components were as follows:

Outer copper can	6 $\frac{1}{2}$ " O.D. x .065" wall
Outer zircaloy clad	6.357" O.D. x 6.115" I.D.
Uranium core	6.110" O.D. x 2.545" I.D.
Inner zircaloy clad	2.540" O.D. x 2.030" I.D.
Inner copper can	2.020" O.D. x .065" I.D.
Front end plate	$\frac{1}{2}$ " copper plate
Rear end plate	$\frac{1}{4}$ " copper plate

The uranium cores were 12" long. The billets were flat on the end with no preshape and no radii.

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B. Die Design

The dies were designed and fabricated by Bridgeport Brass Co. The dies were a combination of integral and separate cone i.e., a partial cone was built into the die but a separate half cone was used to avoid edge cracking of the die.

The cones were 120° included angle. The surface finish on both die and cone was about 32 micro inch. The land was polished to about a 16 micro inch.

C. Mandrel Design

The mandrels were designed and fabricated by Bridgeport Brass Co. The mandrels were ground with a taper of .010 over the working length. Surface finish was about 8 micro inch. Travelling mandrel technique was used on all extrusions.

II. Component Preparation

A. Copper

The extrusion cans were fabricated from DLP copper tube and plate. Can and cap components were outgassed before assembly.

B. Zircaloy Clad

The clad sleeves were fabricated as follows:

1. Outer Clad

- a. Ingot forged to $9\frac{1}{4}$ " O.D. x 5" I.D.
- b. Billets machined to 8.917" O.D. x 6.192" I.D.
- c. Extruded to $6\frac{1}{2}$ " O.D. x 6" I.D.
- d. Machined to final dimensions (IA)
- e. Cleaned for assembly by:
 - (1) Vapor degrease - trichlorethylene
 - (2) Hand scrub in altrex
 - (3) Triple rinsed in hot water and hot air dried

2. Inner Clad

- a. Ingot forged to $7\frac{1}{2}$ " O.D.
- b. Billets machined to $7\frac{1}{4}$ " O.D. x $2\frac{1}{16}$ " I.D.
- c. Extruded to 2.625" O.D. x 1.955" I.D.
- d. Cleaned for assembly as above

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C Uranium Cores

The uranium cores were fabricated by machining from 7" production ingots. The billets were rough machined, triple beta heat treated (salt bath heat and cold water quench) and finish machined.

Cores were cleaned for assembly by:

1. Vapor degrease in trichlorethylene
2. Etch in nitric acid
3. Double water rinse and hot air dry

Component identification by heat numbers is given in Table I.

TABLE I

<u>Billet Number</u>	<u>Outer Clad</u>	<u>Inner Clad</u>	<u>Uranium Core</u>
20	5663	5646	58995A
21	5663	5646	58986D
22	5667	5645	58798A
23	5667	5645	58986B
24	5663	5647	58986A
25	5665	5646	-----
26	5662	5645	58995B

The uranium designation is by ingot number plus location in the ingot. A is top and D bottom of the ingot.

III. Billet Assembly

The billets were evacuated for a minimum of two hours before seal off. Seal off pressure was about 5×10^{-5} mmhg.

IV. Extrusion Conditions

A. Billet Preheat

Billets were preheated in a salt bath furnace as described in HW-62539. Furnace temperature was 1170° F. Preheat time is given in Table II.

TABLE II

<u>Billet Number</u>	<u>Preheat Time Hours:Minutes</u>
20	1:58
21	2:00
22	2:14
23	1:58
24	3:40
25	3:14
26	4:29

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B. Tool Preheat

The tool temperature was difficult to measure and/or control with the equipment available.

The liner was preheated with gas burners around the O.D. of the container and the temperature remained fairly constant during extrusion. Liner temperature was 800° F.

Dies were preheated by closing the die head against the liner.

Mandrels were heated to 900° F in a muffle furnace and inserted into the mandrel holder immediately before extrusion.

C. Extrusion Conditions

The extrusions were made in a 6.625" liner. Reduction ratio was 14 2/1. Ram speed was about 15" per minute. The liner, die, and mandrel were lubricated with oil dag 170 for the first three composite extrusions and Fiskes 604 for the remainder.

Tool sizes were - die 2 495" I.D.
mandrel 1.850" O.D. with .010" taper

Extrusion data is given in Table III.

TABLE III

<u>Billet Number</u>	<u>Time</u>	<u>Tonnage *</u>		<u>K (tsi) *</u>	
		<u>Max.</u>	<u>Min.</u>	<u>Max.</u>	<u>Min.</u>
#1 Brass	09:17	1110	850	16	13
#2 Brass	09:23	1110	910	16	13.7
#3 Copper	09:30	730	500	11.6	8.8
T-20	09:38	1110	910	16	13.7
T-21	10:42	1175	1000	16.8	14.8
T-22	10:57	1230	970	17.5	14.4
T-23	11:09	1700	1550	23	21.2
#4 Copper	13:10	880	700	13.4	11.3
#5 Copper	13:16	840	760	14	11.9
T-24	13:31	1465	1175	17.3	13.8
T-25	14:00	1110	1000	16	14.0
T-26	15:37	1050	790	15.4	12.3

*The recorded pressures were apparently in error due to faulty pressure measurement equipment. No correction factor is available. Therefore, the data should be used for comparison purposes between individual extrusions in this extrusion run only.

V. Extrusion Results

The brass and copper extrusions were very good. The composite extrusions, however, showed severe breakthrough at the extreme front of each extrusion. The initial breakthrough resulted in zircaloy pickup on the die with severe

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Figure I-Appendix 3
Severe Clad Tearing: Extrusion #23

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scratching and aggravation of the breakthrough problem towards the back of the extrusion. Several clad tears were found along the I.D.

The degree of clad tearing varied from slight cracks in the clad to the complete failure as illustrated in Figure I.

During the extrusion run, several changes in lubrication techniques, lubricants, cone angle and cone finish were tried without success.

After evaluating the extrusions, consulting with Herb Sawyer of N.M.I., and measuring the preheating characteristics of the billets under conditions similar to those at Adrain, it was decided that the billets were not preheated to extrusion temperature. On a subsequent run, identical billet designs extruded properly when properly preheated.

3B. ROD EXTRUSIONS

I. Billet & Tool Designs

A. Billet Designs

1. KER Size (.635 inch rod)

Copper can	4" O.D. x .042" wall
Zircaloy clad	3.900" O.D. x 3.610" I.D.
Uranium core	3.600" O.D.

2. NPR Size (.840 inch rod)

Copper can	4" O.D. x .065" wall
Zircaloy clad	3.860" O.D. x 3.645" I.D.
Uranium core	3.640" O.D.

B. Die Designs

The dies were designed and fabricated by Bridgeport Brass Co. The conventional integral cone die design was used.

To test the affect of cone angle on surface condition and extrusion, three values of included cone angle (60°, 90°, and 120°) were used.

II. Component Preparation

A. Copper

The cans were fabricated from DLP copper tube and plate. Can and cap components were outgassed prior to assembly.

B. Zircaloy Clad

Clad sleeves were fabricated as follows:

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Billets #29 & 30

Centrifugally cast
Cold extruded at about 4/1 reduction
Machined to size

Billets #31, 32, & 33

Centrifugally cast
Cold extruded at about 4/1 reduction
Vacuum annealed (2 hours at 750° C)
Machined to size

Billets #35 through 51 inclusive

Forges to 6½ inch O.D.
Drilled and machined to billet size
Machined to size

Billets #52 through 59 inclusive

Forged to 8 inch O.D.
Upset in 8½" liner and pierced to 2.8" I.D.
Machined to 8.2" O.D. x 3.650" I.D.
Extruded to 4.0" O.D. x 3.49" I.D.
Reduction ratio about 17.1/1

C. Uranium Cores

1. Billets #30 through 37 inclusive
#44 through 46 inclusive

Dingot - Gamma extruded to 7" O.D.
Alpha extruded 39"
Triple beta heat treated
Machined

2. Billets #38 through 43 inclusive
#47 through 59 inclusive

Ingot - Cast production ingot
Alpha extruded to 3.9"
Triple beta heat treated
Machined

III. Billet Assembly

Same as for tubes 20 - 26

IV. Extrusion Conditions

A. Billet Preheat

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For details see Table IV

B. Tool Preheat

See 3A IV A

C. Extrusion Conditions

The extrusions were made in a 4.050" liner. Ram speed was about 15" per minute. Extrusion data is given on Table IV.

TABLE IV

Rod Number	Die Size	Cone Angle	Reduction Ratio	Time	Preheat Time Hours:Minutes	Tonnage		K (tsi)	
						Max.	Min.	Max.	Min.
30	.840	90°	22.75	13:55	2:56	530	410	13.4	10.2
35	.840	90°	22.75	14:10	3:13	556	468	14.1	11.9
36	.840	90°	22.75	14:25	3:24	530	410	13.4	10.2
53	.840	90°	22.75	14:31	3:31	556	438	14.1	11.1
54	.840	90°	22.75	15:10	4:08	530	410	13.4	10.2
29	.840	90°	22.75	15:23	4:29	530	410	13.4	10.2
56	.840	60°	22.75	17:14	2:37	530	410	13.4	10.2
57	.840	60°	22.75	17:23	2:45	556	410	14.1	10.2
58	.840	120°	22.75	17:39	2:59	556	410	14.1	10.2
59	.840	120°	22.75	17:47	3:07	585	438	14.8	11.1
31	.635	90°	40.86	17:58	2:26	705	585	14.7	12.3
32	.635	90°	40.86	18:05	2:28	644	585	13.4	12.3
33	.635	90°	40.86	18:35	1:15	790	585	16.4	12.3
37	.635	90°	40.86	14:41	1:15	760	585	15.8	12.3
38	.635	90°	40.86	18:51	1:08	880	645	18.3	13.4
39	.635	60°	40.86	19:02	1:12	1025	705	21.3	14.6
40	.635	60°	40.86	19:15	1:14	820	645	17.1	13.4
41	.635	60°	40.86	20:43	2:35	760	615	15.8	12.8
42	.635	60°	40.86	21:00	2:21	820	645	17.1	13.4
43	.635	60°	40.86	21:12	2:27	760	615	15.8	12.8
44	.840	120°	22.75	21:33	2:43	585	468	14.8	11.9
45	.840	120°	22.75	2:38	2:34	530	468	13.4	11.9

Several interesting observations were made during the extrusion run.

1. Due to stem stress limitations, the container was lined with a short sleeve and the stem was made up by using a 14" extension on an oversize base. A billet boat was used to load the billets. The design limits maximum billet core length to 10".
2. Some of the billet cans used to protect the billets in the salt bath leaked. The salt caused lubrication problems. The freezing point of the salt was above tool temperature and salt adhered to die and liner causing pickup on both.

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3. Due to problems with the handling system, two billets were dropped and damaged. These billets were decanned and found to be free from oxidization on the uranium:zircaloy interface.

One billet which came out of a leaky can was decanned. It had been a leaker or developed a leak during the preheat and salt had leaked into the assembly.

V. Evaluation

Before a complete evaluation of the product was made, the tube-tube design was selected for NPR. Evaluation effort was placed on tubular extrusions and the rod program was de-emphasized. However, the cone angle effect was evaluated and is summarized in Table V.

TABLE V

<u>Rod Size</u>	<u>Reduction Ratio</u>	<u>Cone Angle</u>	<u>Average Flowshape Length (Inches)</u>	<u>% Defect 90° = 100.0</u>
.840	22.75	120°	28	117.0
.840	22.75	90°	24	100.0
.840	22.75	60°	20	83.5
.635	40.86	90°	38	100.0
.635	40.86	60°	31	81.5

The end flowshape length is significantly reduced by decreasing the included cone angle. Actual flowshape length will vary between extrusions due to variations in shift. However, a definite improvement in average yield will result from decreasing the included angle.

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APPENDIX IV

NPR OUTER TUBES AND RODS EXTRUDED
BRIDGEPORT BRASS COMPANY, ADRAIN, MICHIGAN
JULY 24, 1959

SUMMARY & CONCLUSIONS

The results of these tube extrusions were reported in HW-62539, "Evaluation of Tubes 16, 17, 18, & 19". Also reported in this document were the evaluation methods and measuring techniques used.

The rod extrusions were satisfactory. However, it was decided to discontinue using the 4.050 inch liner at Adrain since the liner design restricted billet length to 10 inch cores.

ROD EXTRUSIONS

Ten rods were extruded on July 24, 1959. All extrusions were satisfactory. The billet and tool designs and the component material history for these billets are given in Appendix III, Section 3A.

Due to the decision to develop tubular geometrics for the NPR fuels, these rod extrusions were given only cursory evaluation.

The only significant data available is that pertaining to extrusion. This is given in Table I.

TABLE I
EXTRUSION DATA

Rod Number	Die Size	Cone Angle	Reduction Ratio	Time	Preheat Time Hours:Minutes	Tonnage		K (tsi)	
						Max.	Min.	Max.	Min.
55	.840	90°	22.75	14:21	3:09	935	585	22.2	13.9
60	.840	120°	22.75	15:02	3:51	527	410	12.5	9.8
61	.840	120°	22.75	15:25	4:05	527	410	12.5	9.8
47	.635	90°	40.86	15:55	4:35	760	585	18.1	13.9
48	.635	90°	40.86	16:05	4:45	820	645	19.5	15.4
49	.635	90°	40.86	17:35	3:03	850	700	20.2	16.7
50 ¹		120°	40.86	18:00	2:45	760	585	18.1	13.9
51 ¹		120°	40.86	18:15	2:37	730	585	17.4	13.9
52 ¹		120°	40.86	18:30	2:31	790	615	18.8	14.6
46 ²		120°	40.86	18:45	2:33	730	645	17.4	15.4

¹Extruded at 10" per minute ram speed

²Extruded at 30" per minute ram speed

Balance extruded at 15" per minute ram speed

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APPENDIX V

NPR OUTER TUBE EXTRUSION AT
BRIDGEPORT BRASS CO., ADRAIN, MICHIGAN
AUGUST 28, 1959

SUMMARY & CONCLUSIONS

Several significant observations can be made concerning this test run.

1. The billet texture provided by the cast plus beta heat treat billet fabrication technique is not satisfactory for coextrusion. Three separate heat treatments of the cast cores, (see Appendix V, paragraph II C), were used. With the least desirable i.e., heat treated solid and machined to size; the inner clad surface was extremely rough. At several locations along the inner clad, pinholes were observed, (see Figure I, Appendix V). Similar pinholes were found in the inner clad of extrusion 33.

From these observations, it can be concluded that extreme clad thinning (wanderlust) results from the use of cast plus beta heat treated cores. Further, clad penetrations can result if, a) heat treat efficiency is reduced or, b) a second variable such as improper billet heating is introduced.

2. H-21 is superior to H-26 and Vascaloy Supreme tool steel for extrusion dies. Although the basic problem with die performance on this test was improper press setup, the H-26 and Vascaloy Supreme dies proved to be more brittle and subject to cracking.
3. Bond strength is not considered satisfactory and a higher reduction ratio is recommended.
4. Clad surface condition is generally unsatisfactory. Both O.D. and I.D. surfaces were scratched and pitted from copper pickup on the tools.
5. Preheat time was confirmed as the significant variable in the failure of tubes 20-26 (Appendix 3). Tube #33 was given a minimum preheat time to duplicate the best temperature conditions attained in the previous run. The extrusion failed by clad tearing, confirming the failure mechanism as insufficient preheat.

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Mag ~ 2.3X

Figure 1 - Appendix 5

Defect in Inner Cladding - Tube No. 29

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I. BILLET AND TOOL DESIGNS

A. Billet Design

The designed sizes of billet components were as follows:

Outer copper can	6 $\frac{1}{2}$ " O.D. x .065" wall
Outer zircaloy clad	6.357" O.D. x 6.115" I.D.
Uranium core	6.110" O.D. x 2.545" I.D.
Inner zircaloy clad	2.540" O.D. x 2.030" I.D.
Inner copper can	2.020" O.D. x .065" wall
Front end plate	$\frac{1}{2}$ " copper plate
Rear end plate	$\frac{1}{4}$ " copper plate

The uranium cores were 12 inches in length.

B. Die Design

Dies were integral cone design with 2.495" I.D.; 90° included angle. Die materials were, H-21, H-26, and Vascloy Supreme hot work tool steels.

C. Mandrel Design

Mandrels were 1.850" O.D. Travelling mandrel techniques were used on all extrusions.

II. COMPONENT PREPARATION

A. Copper

The extrusion cans and caps were fabricated from DLP copper tube and plate. Both assemblies were outgassed prior to assembly.

B. Zircaloy Clad

The clad sleeves were fabricated as follows:

1. Outer Clad

- a. Ingot forged to 9 $\frac{1}{4}$ " O.D. x 5" I.D.
- b. Extrusion billets machined to 8.917" O.D. x 6.192" I.D.
- c. Extruded to 6.5" O.D. x 6.000" I.D.
- d. Machined to final dimensions
- e. Cleaned for assembly by (1) vapor degrease-trichlorethylene
(2) hand scrub in altrex
(3) triple rinsed in process water and hot air dried.

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2. Inner Clad

- a. Ingot forged to $7\frac{1}{2}$ " O.D.
- b. Extrusion billets machined to $7\frac{1}{4}$ " O.D. x $2\frac{1}{16}$ " I.D.
- c. Extruded to 2.625" O.D. x 1.955" I.D.
- d. Machined to final dimensions
- e. Cleaned for assembly as given above

C. Uranium Cores

The uranium cores were fabricated by machining from 7" production ingots.

These ingots were rough machined, triple beta heat treated, and finish machined. Two quench mediums were used; water and brine. One billet (#29) was heat treated as a solid round with no rough machining. Quenching was as follows:

Brine quench: 27; 32; 33; 35
Water quench: 28; 30; 31; 34
Heat treated solid: 29 (water)

Uranium cores were cleaned by (1) degrease-trichlorethylene
(2) nitric etch
(3) double water rinse and air dry

Heat numbers of billet components are given in Table I.

TABLE I

<u>Billet Number</u>	<u>Outer Clad</u>	<u>Inner Clad</u>	<u>Uranium Core</u>
27	5663	5645	B 68715
28	5662	5452	D 68715
29	5663	5452	C 68715
30	5662	5452	C 68709
31	5667	5452	B 68709
32	5667	5647	D 68709
33	5667	5452	B 68711
34	5667	5449	A 68711
35	5663	5449	C 68711

The uranium designation is by ingot number plus a designation of position in the ingot. A represents top and D bottom of the ingot.

III. BILLET ASSEMBLY

A. Assembly data is given in Table II.

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TABLE II

<u>Billet Number</u>	<u>Date Assembled</u>	<u>Evacuation Time Minutes</u>	<u>Seal-Off Pressure (mm.Hg)</u>
27	8-14-59	60	5×10^{-5}
28	8-14-59	80	5×10^{-5}
29	8-17-59	60	1×10^{-5}
30	8-17-59	70	5×10^{-5}
31	8-17-59	90	6×10^{-5}
32	8-17-59	65	5×10^{-5}
33	8-18-59	60	5×10^{-5}
34	8-18-59	Leaker	-----
35	8-19-59	55	1×10^{-5}

B. Assembly Notes

1. Billet 34 was a definite leaker at leak test. No repair was attempted.
2. Billet 35; copper outgassing equipment leaked. The copper components were brown in color showing a smooth oxide coat. No cleanup attempted.

IV. EXTRUSION CONDITIONS

A. Billet Preheat

Billets were preheated in the salt bath furnace as described in HW-62539. Furnace temperature was set at 1170°F. Preheat time is given in Table III.

TABLE III

<u>Billet Number</u>	<u>Preheat Time Hours:Minutes</u>
27	10:44
28	10:56
29	11:13
30	12:22
31	13:18
32	13:52
33	6:05*
34	8:46
35	7:42

*Failed - clad tearing

As discussed in HW-62539 and Appendix III, several extrusions had failed at Adrain in the first attempts to fabricate NPR outer tube. From the analysis of these failures and the succeeding successful extrusions, it was determined that the billets had not been preheated long enough. Based on thermocouple measurements, it was estimated that minimum preheat time would be six hours.

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To check this, billet 33 was extruded after 6 hours, 5 minutes preheat. The extrusion failed due to breakthrough. Using the same die, mandrel, billet design, etc., tube 34 and 35 were extruded successfully with longer preheat time. From this, it was concluded that insufficient billet preheat was definitely the cause of the failure of extrusions 20-26, inclusive.

For future extrusions of this billet design, using the heating equipment available, a minimum preheat time of 7 hours, 45 minutes will be used.

B. Tool Preheat

The tool temperature is difficult to measure and/or control with the extrusion methods used.

The liner is preheated with gas burners around the O.D. and is assumed to remain at essentially constant temperature during extrusion. Liner temperature was 800° F.

The dies are shrunk into a large die ring, and except for the initial push on a die, it is kept hot by closing it up against the liner. There are no temperature readings available.

The mandrels were preheated in a tool oven prior to each extrusion. However, by the time they were attached to the mandrel holder, they had cooled considerably. Contact pyrometer and templastik readings were taken for some of the extrusions and are recorded in Table IV along with the other extrusion data.

C. Extrusion Conditions

The extrusions were made in the 6.625" liner. Reduction ratio was 14.2:1. Ram speed was about 15" per minute. The liner was lubricated with oil dag 170 prior to each extrusion and blown clean with compressed air between extrusions. Dies and mandrels were lubricated by swabbing with dag 170 before extrusion.

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TABLE IV

Billet Number	Time	Mandrel Temp. °F		Tonnage		K (tsi)	
		Before	After	Max.	Min.	Max.	Min.
27	10:45 am	500°	700°	1640	1170	19.4	13.7
28	11:00 am	560°	730°	1230	880	14.5	10.4
29	11:19 am	520°	690°	1170	910	13.8	10.7
30	12:34 pm	600°	820°	1080	880	12.8	10.4
31	1:22 pm	520°	680°	1140	940	13.5	11.1
32	2:06 pm	---	---	1110	880	13.1	10.4
33	5:26 pm	---	---	1170	820	13.8	9.7
34	8:15 pm	600°	700°	1140	820	13.5	9.7
35	8:23 pm	---	---	1170	880	13.8	10.4

Several die and mandrel changes were required during extrusion. After extruding billet 28, the die showed a very slight crack on the edge of the cone. After the next extrusion (billet 29) the crack opened up considerably and the extrusion was slightly scored from pickup of copper in the crack.

A new die and mandrel were used for the extrusion of billet 30, but this die cracked severely and had to be replaced. Dies continued breaking on the next two extrusions, and one more die was broken on extrusions 31 and 32. Prior to extruding billet 33, the press was checked and the die head shims changed to better seat the die against the container. On extrusion 33, the mandrel adapter cracked. On the final extrusion, the mandrel adapter broke and released the mandrel. The extrusion was not affected, since the mandrel remained practically stationary (with respect to the billet) after breaking.

V. EXTRUSION EVALUATION

The extruded dimensions given in the following tables are maximum and minimum readings recorded on samples taken from the acceptable fuel length of each tube. Table V gives the acceptable fuel length cut from each tube. Tube 33 was not evaluated since it was "cobbled" during extrusion.

TABLE V

Extrusion Number	Overall Length (Inches)	Calculated Core Length (Inches)	Acceptable Fuel Length (Inches)	Calculated Yield (%)
27	178	162	131	80.9
28	178	162	136	84.0
29	179	162	135	83.3
30	177	162	131	80.9
31	176 1/2	162	129	79.6
32	176	162	133	82.1
34	177	162	129	79.6
35	177	162	131	80.9

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A. Outside Diameter

Table VI shows the maximum and minimum readings and total variation of outside diameter measured in the as-extruded condition (with copper on).

TABLE VI

OUTSIDE DIAMETER AS-EXTRUDED

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum (Inches)</u>	<u>Minimum (Inches)</u>	<u>O.D. (Inches)</u>
27	27	2.484	2.473	.011
28	24	2.480	2.473	.007
29	18	2.481	2.471	.010
30	24	2.482	2.474	.008
31	24	2.498	2.482	.016
32	21	2.493	2.484	.009
34	18	2.484	2.477	.007
35	18	2.485	2.480	.005
All Tubes	174	2.498	2.471	.027

Table VII shows the maximum and minimum readings and the total variation of outside diameter as measured after copper removal.

TABLE VII

OUTSIDE DIAMETER - COPPER OFF

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum (Inches)</u>	<u>Minimum (Inches)</u>	<u>O.D. (Inches)</u>
27	21	2.460	2.445	.015
28	6	2.455	2.451	.004
29	--	-----	-----	----
30	18	2.457	2.451	.006
31	18	2.469	2.458	.011
32	15	2.466	2.460	.006
34	12	2.457	2.447	.010
35	12	2.459	2.454	.005
All Tubes	102	2.469	2.445	.024

B. Inside Diameter

Table VIII shows the maximum and minimum readings, and the total variation of inside diameter in the as-extruded condition.

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TABLE VIII

INSIDE DIAMETER AS-EXTRUDED

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum (Inches)</u>	<u>Minimum (Inches)</u>	<u>Δ I.D. (Inches)</u>
27	27	1.850	1.832	.018
28	24	1.850	1.836	.014
29	18	1.846	1.835	.011
30	24	1.841	1.830	.011
31	24	1.851	1.832	.019
32	21	1.844	1.835	.009
34	18	1.841	1.833	.008
35	<u>18</u>	<u>1.842</u>	<u>1.831</u>	<u>.011</u>
All Tubes	174	1.851	1.930	.021

Table IX shows the maximum and minimum readings and the total variation of inside diameter as measured after copper removal.

TABLE IX

INSIDE DIAMETER - COPPER OFF

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum (Inches)</u>	<u>Minimum (Inches)</u>	<u>Δ I.D. (Inches)</u>
27	21	1.863	1.840	.023
28	6	1.854	1.845	.009
29	--	----	----	----
30	18	1.846	1.841	.005
31	13	1.858	1.848	.010
32	15	1.857	1.845	.012
34	12	1.851	1.842	.009
35	<u>12</u>	<u>1.853</u>	<u>1.844</u>	<u>.009</u>
All Tubes	102	1.863	1.840	.023

C. Wall Thickness

Table X shows the maximum and minimum readings, the total variation of readings, and the percentage variation of wall thickness as measured in the as-extruded condition.

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TABLE XWALL THICKNESS - AS-EXTRUDED

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum (Inches)</u>	<u>Minimum (Inches)</u>	<u>W.T. (Inches)</u>	<u>W.T. ± % of W.T.</u>
27	54	.348	.286	.062	10.3
28	48	.329	.305	.024	3.8
29	36	.326	.306	.020	3.2
30	48	.329	.311	.018	2.8
31	48	.331	.315	.016	2.5
32	42	.336	.310	.026	4.0
34	36	.329	.310	.019	3.0
35	<u>36</u>	<u>.330</u>	<u>.307</u>	<u>.023</u>	<u>3.6</u>
All Tubes	348	.348	.286	.062	10.3
Excluding Tube 27		.336	.305	.031	4.9

Table XI shows the maximum and minimum readings, the total variation of readings, and the percentage variation of wall thickness as measured after copper removal.

TABLE XIWALL THICKNESS - COPPER OFF

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum (Inches)</u>	<u>Minimum (Inches)</u>	<u>W.T. (Inches)</u>	<u>W.T. ± % of W.T.</u>
27	42	.326	.263	.063	10.7
28	12	.313	.291	.022	3.6
29	--	----	----	----	----
30	36	.314	.296	.018	2.9
31	36	.313	.300	.013	2.2
32	30	.315	.396	.019	2.8
34	24	.313	.292	.021	3.8
35	<u>24</u>	<u>.313</u>	<u>.288</u>	<u>.025</u>	<u>4.1</u>
All Tubes	204	.326	.263	.063	11.7
Excluding Tube 27		.315	.288	.027	4.5

D. Bonding

Table XII gives the bond ratings (peel test).

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TABLE XII

Tube No.	<u>O.D. BOND</u>					<u>I.D. BOND</u>				
	<u>Good</u>	<u>Quest.</u>	<u>Fair</u>	<u>Poor</u>	<u>Rating</u>	<u>Good</u>	<u>Quest.</u>	<u>Fair</u>	<u>Poor</u>	<u>Rating</u>
27	2	14	5	-	2.9	1	10	8	2	2.5
28	9	6	-	-	3.6	6	9	-	-	3.4
29	1	7	6	4	2.3	2	12	4	-	2.9
30	1	5	5	7	2.0	1	6	11	-	2.4
31	2	8	13	1	2.6	1	7	12	4	2.2
32	16	6	-	-	3.7	11	9	-	-	3.5
34	1	9	3	5	2.3	4	7	3	3	2.7
35	3	9	4	-	2.9	2	8	7	-	2.7

For all tubes - Average O.D. = 2.8
Average I.D. = 2.8
Tube Average = 2.8

E. Clad Thickness

The clad thickness was measured by projecting the clad image on to the view screen of a metallograph as described in HW-62539. Statistical evaluation of the data was performed by J. L. Jaech, Operation Research and Synthesis, Hanford Laboratories Operation.

In order to make a balanced analysis, the data used were selected from the entire set of data in such a way that four positions along the tube were common for all tubes. These were positions about 31, 40, 134, and 143 inches from the front.

In analyzing the resulting data, there were no significant differences due to positions along the tubes, or around the tubes circumferentially. This was true for the four measurements considered, viz. average and range for outer and inner clads. Likewise, there was no difference between the tubes except with respect to the roughness of the inner clad for tube 29 as measured by range. This tube was significantly rougher than the others. (II-c Billet 29 was heat treated as a solid ingot).

The data is summarized in Table XIII.

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TABLE XIII

CLAD THICKNESS

<u>Tube#</u>	<u>Ave-Outer</u>	<u>Ave-Inner</u>	<u>Range Outer</u>	<u>Range Inner</u>
27	22.1	22.3	2.3	2.0
28	22.0	21.1	1.9	2.0
29	22.8	21.4	2.4	3.5
30	22.8	22.8	2.2	2.1
31	23.1	21.8	2.2	1.9
32	23.0	22.0	2.7	2.0
34	22.7	21.5	2.5	1.8
35	<u>23.0</u>	<u>21.4</u>	<u>2.3</u>	<u>1.8</u>
Ave	22.7	21.8	2.3	1.9 (Excluding T-29)

"Tolerance statements" for these tubes are as follows:

Outer Clad - Average

The average thickness was 22.7 mils and we are 95% confident that 99% of these averages* lie between 19.1 and 26.3 mils.

Inner Clad - Average

The average thickness was 21.8 mils and we are 95% confident that 99% of the averages* lie between 13.5 and 30.1 mils.

Outer Clad - Range

The average range is 2.3 mils and we are 95% confident that 99% of the ranges are less than 4.7 mils.

Inner Clad - Range

Excluding tube 29, the average range is 1.9 mils and we are 95% confident that 99% of the ranges are less than 5.4 mils.

*This refers to average at point - not tube average. The average at a point is taken to be halfway between maximum and minimum measurements.

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APPENDIX VI

KER INNER TUBE EXTRUSIONS AT
NUCLEAR METALS INCORPORATED
AUGUST 31, 1959

SUMMARY & CONCLUSIONS

The billets used in this test were assembled using components originally intended for use in rod extrusions. Material fabrication techniques are not considered optimum.

All extrusions were satisfactory. No unusual problems in lubrication, tool failure or extrusion technique were encountered.

Several observations were made concerning this test run.

1. The free mandrel technique worked very well from a mechanical standpoint. Wall thickness variation was comparable to that obtained with the french mandrel technique.
2. Wall thickness variation was much greater than expected. Closer control of all possible contributing variables must be maintained to determine the extent of this problem.
3. Diameter variations were controlled very closely in this test. Apparently close control of tool temperatures will solve this problem.
4. Clad thickness variation is considerably greater than the ± 2 mil range desired. The variations do not appear to be related to any extrusion variable. The chief cause of variation is the roughness of the interface (i.e. wanderlust). This has been proven by NMI to be related to uranium core texture (fabrication history).

I. BILLET & TOOL DESIGNS

A. Billet Designs

The designed sizes of billet components were as follows:

Outer copper can	4" O.D. x .065" wall
Outer zircaloy clad	3.860" O.D. x 3.640" I.D.
Uranium core	3.630" O.D. x 1.110" I.D.
Inner zircaloy clad	1.100" O.D. x .635" I.D.
Inner copper can	.635" O.D. x .040" wall

Uranium core lengths were as follows:

<u>Billet Number</u>	<u>Core Length (Inches)</u>
36, 37	8
38, 39	10
40, 41	12
42, 43	14

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B. Mandrel Design

Two different mandrel systems were used:

1. The french mandrel design was used on seven extrusions. This is the standard technique for the NMI press because the press does not have a mandrel manipulator.
2. One billet was extruded using a free mandrel. The term "free mandrel" is used to describe this particular design since there is no means provided for aligning the mandrel with either the stem or container during extrusion. The mandrel is "free" to follow the billet during the complete extrusion cycle.

C. Die Design

The dies were the standard integral cone design. They were contained inside the liner during extrusion.

II. COMPONENT PREPARATION

A. Copper

The copper extrusion cans and caps were fabricated from DLP copper tube and plate. Both assemblies were outgassed prior to assembly.

B. Zircaloy Clad

1. The outer clad sleeves were fabricated as follows:
 - a. Ingot forged to 7" solid.
 - b. Billet machined and extruded to 4" O.D. x 3.485" I.D.
 - c. Machined to nominal dimensions of 3.900" O.D. x 3.700" I.D.
 - d. Cleaning - (1) vapor degrease - trichlorethylene
(2) hand scrub in altrex
(3) rinse - hot water
(4) rinse - cold water
(5) rinse - hot water
(6) hot air dry
2. The inner clad sleeves were fabricated as follows:
 - a. Zircaloy ingot forged to 5" diameter.
 - b. Billet machined and extruded to 1.6" O.D. x .75" I.D.
 - c. *Machined to 1.4" O.D. x .75" I.D.

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d. *Swaged to 1.2" O.D. x .55" I.D.

e. Machined to nominal dimensions of 1.110" O.D. x .635" I.D.

f. Cleaning - same as outer clad.

3. Identification

Identification of zircaloy clad components is as follows:

Outer clad heat number 87954

Inner clad heat number 8YM048A

C. Uranium

1. Fabrication

The uranium cores were fabricated from dingot and ingot stock available at HAPO. Fabrication history is as follows:

- a. Dingot -
 - (1) gamma extruded to 7" O.D.
 - (2) alpha extruded to 3.9" O.D.
 - (3) machined to 3.740" O.D. x 1.070" I.D.
 - (4) triple beta heat treated and water quenched
 - (5) machined to 3.690" O.D. x 1.120" I.D.
- b. Ingot -
 - (1) production ingot (7" diameter) alpha extruded to 3.9" O.D.
 - (2) machined to 3.740" O.D. x 1.070" I.D.
 - (3) triple beta heat treated and water quenched
 - (4) machined to 3.690" O.D. x 1.120" I.D.
- c. Identification - The uranium core identification is given in Table I. Dingot metal is designated by the letter D; ingot metal by the letter I. Several billets contained more than one piece of core metal. These composite cores were used to provide extrusion billets for this test using metal on hand. Use of composite cores is not recommended as a fuel fabrication technique.

In Table I, the pieces of core metal in the composite billets are listed showing the sequence of metal through the die, i.e., the first metal listed is at the front of the billet.

*Note: The machining and swaging operations were required to obtain stock for this size extrusion from material on hand from a previous extrusion experiment. This should not be considered as a recommended addition to the fabrication process.

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TABLE I

BILLET CORE MATERIAL IDENTIFICATION

<u>Billet Number</u>	<u>Core Identification</u>
36	D-5 and I-4-7
37	I-4-7, I-1-2, and I-1-11
38	I-4-7
39	I-6-7
40	I-1-12 and I-2-7
41	I-1-11 and I-1-2
42	D-5 (2 pieces)
43	D-5 (2 pieces)

III. BILLET ASSEMBLY

A. Assembly data are given in Table II.

TABLE II

BILLET ASSEMBLY DATA

<u>Billet Number</u>	<u>Date Assembled</u>	<u>Total Evacuation Time (Minutes)</u>	<u>Seal-off Pressure (mm-Hg)</u>
36	8-15-59	15	5×10^{-5}
37	8-15-59	30	5×10^{-5}
38	8-15-59	30	5×10^{-5}
39	8-15-59	30	5×10^{-5}
40	8-15-59	45	5×10^{-5}
41	8-15-59	30	5×10^{-5}
42	8-14-59	---	-----
43	8-14-59	60	5×10^{-5}

B. Assembly Notes

In the assembly of some billets, problems were encountered which could affect the quality of the extruded product. These problems are noted below:

1. Billet 36 - The uranium core did not clean up completely after heat treat about one inch from the rear over a 60° quadrant.
2. Billet 39 - Tool marks about 5 mils deep were found on the I.D. of the inner clad about $\frac{1}{2}$ " from the rear end and about 5 mils deep.
3. Billet 42 - The inner clad was about 20 mils undersize on the O.D. resulting in an increased clearance between core and inner clad.
4. Billet 43 - The billet core was undercut about 10 mils on the O.D. for a distance of $\frac{1}{4}$ " on the front end of the billet.

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IV. EXTRUSION CONDITIONSA. Billet Preheat

Billets were preheated in a muffle furnace. Four billets were heated in a furnace charge. To protect billets from direct radiation from heating elements, they were enclosed in graphite sleeves.

Billet temperature was monitored by inserting a thermocouple through a small hole in the graphite can. It was difficult to obtain uniform heating in a batch of billets since the billets tended to shield each other. In general, the two billets at the front of the furnace were cooler than the two in the rear.

Billet preheat data is given in Table III. The billet temperature given is the thermocouple reading immediately prior to extrusion.

TABLE IIIBILLET PREHEAT DATA

<u>Billet Number</u>	<u>Billet Temperature</u>	<u>Preheat Time</u>
36	1150°F	3 hours
37	1150°F	3 hours, 10 minutes
38	1160°F	3 hours, 30 minutes
39	1160°F	3 hours, 40 minutes
40	1145°F	3 hours
41	1150°F	3 hours, 15 minutes
42	1160°F	3 hours, 30 minutes
43	1160°F	3 hours, 45 minutes

B. Tool Preheat

All tools were preheated to 900°F in a muffle furnace. Immediately prior to extrusion, the die was removed and inserted into the liner; the mandrel was removed, lubricated with oil dag and placed on the loader. When the billet was placed on the loader, the mandrel was inserted through the billet and cutoff, and the entire assembly loaded into the liner.

The container-liner was heated electrically to 900°F. The heaters were turned off during extrusion. Indicated liner temperature was quite uniform during the series of extrusions.

C. Extrusion Conditions

The extrusions were made in the 4.050" liner at 13" per minute ram speed. Reduction ratio was 17.8. The liner was lubricated with oil dag immediately prior to each extrusion. Between extrusions, the liner was brushed with a rotating wire brush to remove all pickup. Loose material was blown out with compressed air.

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Extrusion data are given in Table IV. Extrusions are listed in sequence in which they were made.

TABLE IV

EXTRUSION DATA

NMI Extrusion Number	Billet Number	Die Number	Die I.D.	Mandrel O.D.	Tonnage		K (tsi)	
					Max.	Min.	Max.	Min.
21510	36	1	1.069	.497	740	610	20.2	16.8
21511	38	2	1.069	.497	730	570	19.9	15.6
21512	40	3	1.069	.497	730	570	19.9	15.6
21513	42	2	1.069	.497	760	570	20.8	15.6
21514	37	1	1.069	.497	730	600	19.9	16.4
21515	39	2	1.069	.497*	780	600	21.3	16.4
21516	41	3	1.069	.497	740	560	20.2	15.3
21517	43	1	1.069	.497	760	560	20.8	15.3

*Billet 39 was extruded using the "free" mandrel technique.

The dies and mandrels were inspected after each extrusion. Each die was cleaned and polished before re-use. Mandrels were cleaned and visually checked for straightness before re-use. No pickup was noticed. There were no tool failures.

The liner was visually checked after each extrusion. The bore remained smooth and shiny. Liner condition was excellent.

V. EXTRUDED DIMENSIONS

The extruded dimensions given in the following tables are maximum and minimum readings recorded on samples taken from the acceptable fuel length from each tube. Table V shoes data on acceptable fuel length, i.e. yield, in order that the reader may better evaluate the significance of the data in Table VI through XII. The data in Table V is defined by:

1. Overall length of the extrusion includes the copper and defects.
2. Calculated maximum core length is the maximum length of acceptable core which would be yielded by extruding the core with no loss to end defects.
3. Actual acceptable core length is that length that was cut from the extrusion for sampling and processing.
4. Calculated yield for the extrusion. The reader should note that this is not maximum yield. Extrusions are cut such at the end defect prction is entirely eliminated to insure uniform quality.

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TABLE V

<u>Extrusion Number</u>	<u>Overall Length (Inches)</u>	<u>Calculated Core Length (Inches)</u>	<u>Acceptable Fuel Length (Inches)</u>	<u>Calculated Yield (%)</u>
36	151	138	107	77.5
37	151	138	106	76.8
38	186	173	132	76.3
39	186	173	123	71.1
40	220	207	178	86.0
41	220	207	178	86.0
42	255	242	215	88.8
43	255	242	214	88.4

A. Outside Diameter

Table VI shows the maximum and minimum readings and total variation of outside diameter measured in the as-extruded condition (i.e. copper on).

TABLE VI

OUTSIDE DIAMETER AS-EXTRUDED

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum (Inches)</u>	<u>Minimum (Inches)</u>	<u>O.D. (Inches)</u>
36	18	1.062	1.062	.004
37	18	1.065	1.062	.003
38	21	1.066	1.062	.004
39	24	1.065	1.063	.002
40	27	1.065	1.062	.003
41	27	1.065	1.063	.002
42	30	1.064	1.061	.003
43	<u>33</u>	<u>1.064</u>	<u>1.061</u>	<u>.003</u>
All tubes	198	1.066	1.061	.005

Table VII shows the maximum and minimum readings and the total variation of readings of outside diameter as measured after copper removal.

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TABLE VII

OUTSIDE DIAMETER - COPPER OFF

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum (Inches)</u>	<u>Minimum (Inches)</u>	<u>O.D. (Inches)</u>
36	12	1.047	1.044	.003
37	12	1.046	1.044	.002
38	15	1.048	1.044	.004
39	18	1.047	1.044	.003
40	18	1.048	1.045	.003
41	21	1.048	1.045	.003
42	27	1.046	1.039	.007
43	24	1.046	1.043	.003
All Tubes	147	1.048	1.039	.009

The designed O.D. for this extrusion was 1.045 inches with the copper off. The O.D. control on this extrusion series is considered to be very good.

B. Inside Diameter

Table VIII shows the maximum and minimum readings and the total variation of readings of inside diameter as measured in the as-extruded condition.

TABLE VIII

INSIDE DIAMETER AS-EXTRUDED

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum (Inches)</u>	<u>Minimum (Inches)</u>	<u>I.D. (Inches)</u>
36	18	.495	.495	.002
37	18	.496	.495	.001
38	21	.493	.492	.001
39	24	.496	.495	.001
40	27	.496	.495	.001
41	27	.495	.494	.001
42	30	.496	.495	.001
43	33	.496	.495	.001
All Tubes	198	.496	.492	.004

Table IX shows the maximum and minimum readings and the total variation of readings of inside diameter as measured after copper was removed.

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TABLE IX

INSIDE DIAMETER - COPPER OFF

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum (Inches)</u>	<u>Minimum (Inches)</u>	<u>I.D. (Inches)</u>
36	12	.497	.497	----
37	12	.497	.497	----
38	15	.497	.496	.001
39	18	.499	.499	----
40	18	.500	.499	.001
41	21	.500	.498	.002
42	27	.500	.498	.002
43	24	.500	.498	.002
All Tubes	147	.500	.496	.004

The designed I.D. for this extrusion was .495 with the copper off. The I.D. control on this extrusion series is considered to be very good. This is attributed mainly to the close control of mandrel size and the care given to proper lubrication of the mandrel. The I.D. was uniform from front to rear.

C. Wall Thickness

Table X shows the maximum and minimum readings, the total variation of readings and the percentage variation in wall thickness as measured in the as-extruded condition.

TABLE X

WALL THICKNESS - AS-EXTRUDED

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum (Inches)</u>	<u>Minimum (Inches)</u>	<u>Δ W.T. (Inches)</u>	<u>W.T. ±% of W.T.</u>
36	36	.298	.298	.032	5.6
37	36	.301	.270	.031	5.4
38	42	.301	.268	.033	5.8
39	42	.292	.274	.018	3.2
40	54	.297	.266	.031	5.4
41	54	.299	.270	.029	5.1
42	60	.297	.270	.027	4.7
43	66	.306	.262	.044	7.7
All Tubes	390	.306	.262	.044	7.7

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Table XI shows the maximum and minimum readings, the total variation of readings and the percentage variation in wall thickness as measured after copper removal.

TABLE XI

WALL THICKNESS - COPPER OFF

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum (Inches)</u>	<u>Minimum (Inches)</u>	<u>Δ W.T. (Inches)</u>	<u>W.T. +/- of W.T.</u>
36	24	.283	.264	.019	3.5
37	24	.284	.262	.022	4.1
38	30	.282	.259	.023	4.2
39	36	.282	.263	.019	3.5
40	36	.281	.265	.016	3.0
41	42	.280	.267	.013	2.4
42	54	.284	.285	.026	4.8
43	<u>48</u>	<u>.284</u>	<u>.285</u>	<u>.026</u>	<u>4.8</u>
All Tubes	294	.284	.258	.026	4.8

The wall thickness variation in Table XI is much greater than desired for a fuel element. Since wall thickness variation is difficult to correct in any tube and practically impossible to correct in a clad fuel element, control of this variable is of primary importance.

Comparing as-extruded to as-pickled wall thickness, some discrepancies became evident. On most tubes there is indicated a marked improvement in wall thickness variation in the as-pickled condition, but tube 19 shows no improvement. Since the measurements in the two conditions were not necessarily taken from the same samples, a difference such as this can occur. In future evaluation work, the two measurements are to be taken from the same samples at the same relative position and should reflect more closely the actual effect of copper on final dimensions. In some previous extrusion runs, this procedure was followed and the difference between the two conditions was not nearly as significant as is indicated by the results shown in this run.

1. Billet Fabrication Variables: Any eccentricity introduced into billet components during their manufacture is directly reflected in the extruded product.
2. Billet Preheat Variables: Although successful coextrusions have been made in a rather broad temperature range, temperature variation within a billet, i.e. variations across the billet section, can effect the concentricity of an extrusion. Since the plasticity (K value) of the materials is temperature dependent, a billet can exhibit variable stiffness if the temperature of the cross section is not uniform.

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3. Tool Conditions: Any tool condition which contributes to non-uniform friction forces around the billet or extrusion product can result in increased eccentricity. This would include (a) pickup during extrusion, (b) scores or rough surface condition due to prior damage or improper care and cleaning, and, (c) non-uniform lubrication. The primary factor in tool condition is probably lubrication. In a horizontal press, it is difficult to apply a wet lubricant uniformly on all surfaces.
4. Press Alignment: Although this effect should be negligible with the extrusion techniques used at NMI, it becomes a basic factor in normal tube extrusion techniques.

In the immediate future, the attempts to improve wall thickness variation will include close attention to improvement of the conditions listed above. Particular emphasis will be on improvement in billet temperature and lubrication informity.

For more complete consideration of this problem, it is necessary to study several factors which include:

- (1) Clearances between billet components
- (2) Clearance between billet and liner
- (3) Extrusion speed and reduction ratio effects
- (4) Mandrel techniques and design
- (5) Temperature relationships of billet, tools, cutoffs, etc.

Although some information will be obtained during planned extrusion work, the effects listed above can best be studied initially using small scale extrusion tests. Facilities for this type of testing are not presently available on-site.

D. Clad Thickness and Interface Roughness

Clad thickness was measured using the techniques described in HW-62539. For each sample measured, the maximum and minimum values were read at six points (60° intervals). In addition, each sample was inspected to locate any maximum or minimum value occurring between the intervals.

The measurement data were analyzed by J. L. Jaech, Operations Research and Synthesis, HLO. Results were reported as follows:

"Outer and inner clad thicknesses from 8 co-extruded tubes were measured with the maximum and minimum readings being recorded at several points along the tubes and at 6 degree positions around the tubes. Several independent variables were associated with these data as indicated below:

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<u>Variable</u>	<u>Tube Breakdowns</u>
(1) Core Length	T-36,37 : 8" T-38,39 : 10" T-40,41 : 12" T-42,43 : 14"
(2) Batch	T-36,38,40,42 : Batch 1 T-37,39,41,43 : Batch 2
(3) Die #	T-36,37,43 : Die #1 T-38,39,42 : Die #2 T-40,41 : Die #3
(4) Mandrel Type	T-39 had different type mandrel

GENERAL SUMMARY

The co-extrusion process gives about the same average clad thickness for outer and inner clads, but there is considerably more roughness associated with the inner clad, both at a point and between points within a tube. Tube 39, which was prepared with a different type mandrel, has significantly greater roughness associated with the inner clad than did the outer tubes. The effects of core length, batch, and die # were not significant, but it should be kept in mind that the sample size is not too large, making it extremely difficult to detect true differences unless the magnitude is appreciable.

DETAILED RESULTS

(1) Outer Clad Average thickness

There is no difference between the eight tubes with respect to average thickness. The over-all average is 21.8 mils, and we are 95% confident that 99% of the average thicknesses are between 18.9 and 24.7 mils.

(2) Inner Clad Average thickness

There is a significant difference between tubes, but this is not attributable to the identified variables (core length, batch, etc.). See the tube averages listed in the appendix. The over-all average is 21.8 mils (as was the outer clad average) and we are 95% confident that 99% of the averages are between 15.4 and 28.2 mils. This wider spread is due to more variation between degree positions, along the length of the tubes, and between tubes than observed for outer thicknesses.

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(3) Outer Clad Range between maximum and minimum

The range between maximum and minimum readings at a point is a measure of roughness of the clad at a given point. This was found to differ significantly from tube to tube, but the differences were not attributed to the identified variables. The average range was 2.6 mils, and we are 95% confident that 99% of the ranges are less than 4.5 mils.

(4) Inner Clad Range

One tube had significantly greater roughness than the others, viz., T-39 with an average range of 4.2 mils compared with 2.9 mils for the other 7 tubes. Note that tube T-39 was prepared using a different type mandrel. In general, even exclusive of tube 39, the inner clad thicknesses were significantly rougher than the outer clads. We are 95% confident that 99% of the ranges are less than 5.5 mils for inner clad."

E. Bonding

Table XII gives the as-extruded bond ratings as rated by the peel test.

TABLE XII

Tube No.	O.D. BOND					I.D. BOND				
	Good	Quest.	Fair	Poor	Rating	Good	Quest.	Fair	Poor	Rating
36	11	1	---	---	3.9	9	3	---	---	3.7
37	11	1	---	---	3.9	7	5	---	---	3.7
38	6	-	---	---	4.0	2	4	---	---	3.3
39	6	-	---	---	4.0	4	2	---	---	3.7
40	7	4	---	---	3.6	1	10	1	---	3.0
41	7	3	---	---	3.7	4	7	---	---	3.4
42	12	3	---	---	3.8	2	16	---	---	3.1
43	11	3	---	---	3.8	4	10	---	---	3.3

For all tubes - Average O.D. = 3.84
Average I.D. = 3.4
Tube Average = 3.61

F. Interface Cleanliness

Metallographic rating of the cleanliness of the uranium:zircaloy-2 interfaces was done at 500X against the standards shown in HW-63268¹. The results are shown in Table XIII below:

1. "Tentative Standards for Metallographic Rating of the Cleanliness of Interfaces of Uranium:Zircaloy-2 Sections", A. E. Guay, December 30, 1959.

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TABLE XIII

CLEANLINESS OF THE INTERFACES OF
KER-IT/TT NUMBER 36 THROUGH 43

<u>Sample Location and Position</u>	<u>Graded Cleanliness</u>		
	<u>O.D.</u>	<u>I.D.</u>	
T-36:21" :128"	16 <u>15</u> Average 15.5	18 <u>17</u> Average 17.5	Tube Average - 16.5
T-37:21" :127"	16 <u>15</u> Average 15.5	16 <u>16</u> Average 16	Tube Average - 15.8
T-38:31" :163"	15 <u>17</u> Average 16	17 <u>18</u> Average 17.5	Tube Average - 16.8
T-39:154"	15	15	
T-40:21" :199"	15 <u>15</u> Average 15	17 <u>17</u> Average 17	Tube Average - 16.0
T-41:21" :199"	15 <u>15</u> Average 15	17 <u>18</u> Average 17.5	Tube Average - 16.3
T-42:30" :236"	16 <u>14</u> Average 15	15 <u>16</u> Average 15.5	Tube Average - 15.3
T-43:21" :235"	15 <u>15</u> Average 15	15 <u>16</u> Average 15.5	Tube Average - 15.3

For All Tubes:

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G. Grain Size

As-coextruded grain size is given in Table XIV.

TABLE XIV

AS-COEXTRUDED URANIUM GRAIN SIZE

<u>Tube Number and Sample Location</u>	<u>Grain Size MM</u>	<u>Remarks</u>
T-36: 21 inch 128 inch	.045-.055 .035-.045	
T-37: 21 inch 127 inch	.045 .035	.005 for 2-4 grain band at I.D.
T-38: 31 inch 163 inch	.045 .035-.045	$\frac{1}{2}$ field .120 at I.D.
T-39: 64 inch 154 inch	.030-.035 .045	.055 for 2-3 grain band at I.D. .055 for 1-2 grain band at I.D.
T-40: 41 inch 199 inch	.030-.035 .030-.035	.065 for 3/4 field at I.D.
T-41: 21 inch 199 inch	.030-.035 .030-.035	.065 for $\frac{1}{2}$ field at I.D. .065 for 1/3 field at I.D.
T-42: 30 inch 236 inch	.045-.055 .045-.055	.150 for full field at I.D.
T-43: 21 inch 235 inch	.045-.055 .045-.055	.150 for full field at I.D.

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APPENDIX VII

KER OUTER TUBE EXTRUSIONS AT
BRIDGEPORT BRASS COMPANY, ADRAIN, MICHIGAN
NOVEMBER 20, 1959

SUMMARY & CONCLUSIONS

These were the first KER outer tubes extruded using HAPO billet designs. The extruded dimensions were within two to three mils of the nominal dimensions desired.

Significant observations are as follows:

1. Although the nominal dimensions correspond closely to calculated values, variation of O.D., I.D., and wall thickness was higher than expected. O.D., I.D. variation is probably due in part to improper tool heating techniques and facilities. Wall thickness variation will require further investigation.
2. Bond quality was poor. The increased reduction ratio (17.7/1 as compared to 13.5/1 for NPR outer tubes) did not yield the improvement expected.
3. A new defect, dimpling, was noted. This defect is apparently caused by excess lubricant on the mandrel.
4. Of the three mandrel techniques used (free, travelling, and stationary) the stationary technique produced the best concentricity. This observation is based on one extrusion. Further testing will be done.
5. The extrusion stem was bent during this test. No cause was determined. However, it was agreed that the design hardness will be increased on all stems to correspond to the maximum hardness range recommended by the manufacturer.

I. BILLET AND TOOL DESIGNS

A. Billet Designs

The designed sizes of billet components were as follows:

Outside copper can	5" O.D. x .065" wall
Outer zircaloy clad	4.860" O.D. x 4.560" I.D.
Uranium core	4.550" O.D. x 2.235" I.D.
Inner zircaloy clad	2.228" O.D. x 1.635" I.D.
Inner copper can	1.625" O.D. x .060" wall

The uranium cores were 12 inches long.

B. Mandrel Designs

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Two separate mandrel systems were used.

1. Travelling mandrel used with the mandrel manipulator (See HW-62539, Figure III).
2. Free mandrel used with solid follower block and shaped cutoff.

All mandrels were 1.450" O.D. ground straight (no taper) throughout the working length.

C. Die Design

The die design is similar to that shown in HW-62539, Figure II. Die I.D. was 1.850". Included cone angle 90°

II. COMPONENT PREPARATION

A. Copper

The copper extrusion cans were fabricated from DLP copper tube and plate. All components were outgassed prior to final assembly.

B. Zircaloy Clad

1. Outer Clad Sleeves

The outer clad sleeves were fabricated by forging, hot extrusion and machining. Primary extrusion reduction was about 7:1.

2. Inner Clad Sleeves

The inner clad sleeves were fabricated by forging, hot extrusion and machining. Primary extrusion reduction was about 14:1.

3. Cleaning

- a. Vapor degrease, trichlorethylene
- b. Hand scrub in altrex
- c. Rinse, hot water
- d. Rinse, cold water
- e. Rinse, hot water
- f. Hot air dry.

C. Uranium

The uranium billet cores were fabricated from standard production dingots as follows:

1. Dingot gamma pierced and extruded to 9" O.D. x 2 5/8" I.D.

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2. Machined to alpha extrusion billets.
3. Alpha extruded at about 4:1 reduction ratio.
4. Rough machined.
5. Triple beta quenched in water.
6. Finish machined to 4.550" O.D. x 2.235" I.D.

Identification - The identification of billet components by HAPO heat numbers is given in Table I.

TABLE I

BILLET COMPONENTS

<u>Billet Number</u>	<u>Outer Zircaloy Clad</u>	<u>Inner Zircaloy Clad</u>	<u>Uranium Core</u>
67	8YA055	5YH0184	8A
68	8YA655	5YH0185	8B
69	8YA055-2	5YH0187	9C
70	8YA055-2	5YH0188	11B
71	8YA055-5	5YH0181	8C

III. BILLET ASSEMBLY

A. Assembly data is given in Table II.

TABLE II

BILLET ASSEMBLY DATA

<u>Billet Number</u>	<u>Date Assembled</u>	<u>Evacuation Time Minutes</u>	<u>Seal-off Pressure In MM.Hg</u>
67	11-10-59	195	2×10^{-5}
68	11-10-59	240	2×10^{-5}
69	11-10-59	198	2×10^{-5}
70	11-10-59	70	1×10^{-5}
71	11-11-59	185	1×10^{-5}

B. Assembly Notes

In the assembly of these billets, the following conditions were noticed.

1. Billet 68 - Rough surface on the uranium I.D. after etch. Surface roughness visible on visual inspection. No measurements made.
2. Billet 69 - Same as 68.

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3. Billet 70 - Same as 68 on I.D. surface. Outside copper blistered on the I.D. about midway on the can.
4. Billet 71 - Same type of surface roughness but only at the rear of the billet.

IV. EXTRUSION

A. Billet Preheat

Billets are heated in the salt bath furnace as shown on Figure IV, HW-62539. Preheat data is given in Table III.

TABLE III
PREHEAT DATA

<u>Billet Number</u>	<u>Furnace Temp.</u>	<u>Billet Temp.</u>	<u>Preheat Time</u>
67	1175°	1175°	4 hours;55 min.
68	1175°	1175°	4 hours;48 min.
69	1175°	1175°	5 hours;15 min.
70	1175°	1175°	4 hours; 3 min.
71	1175°	1175°	4 hours;25 min.

B. Tool Preheat

1. Container-Liner - The liner was inserted into the hot container about three hours before the first extrusion. The first two extrusions were of copper dummies. Templstik measurements indicated a liner temperature of 600°F prior to the first dummy extrusion. After the two dummy extrusions were completed, the liner temperature was between 700 and 800°F. Estimated temperature for the composite extrusions was 750°F.
2. Dies - Dies were preheated in the tool furnace at 800°F prior to the initial extrusions. Between extrusions the die was kept hot by keeping the dieheat closed and heating the die from the container.

Billets 67 and 68 were extruded with the same die. This die cracked during extrusion of billet 68. A new die was used for billets 69, 70, and 71.

3. Mandrels - A free mandrel was used for billet 67. This mandrel was heated to 800°F in the tool oven and inserted directly into the billet.

On the balance of the extrusions a travelling mandrel was used.

For billet 68, the mandrel was inserted immediately prior to extrusion. The same mandrel was used for extrusion of billet 69. It was left in the press between extrusions. For billets 70 and 71 new mandrels were used.

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C. Extrusion Conditions

The new liner used in this extrusion run was "broken in" as follows:

The liner was coated uniformly with dag 154, mixed with 25% moly disulfide before preheating. The cold liner was inserted into the hot container for preheat. Immediately before extrusion, a light coating of dag 170 was applied. A 16" copper billet was extruded. After blowing out the loose scale the liner showed a fairly uniform coating with no rough spots. After the second dummy extrusion, the I.D. showed a uniform shiny surface along the front section.

Prior to each extrusion, dag 170 was swabbed into the liner. Subsequent inspections showed the liner surface to be very very smooth and shiny with no indication of buildup or scoring.

Since some defects had been found on the inner surface of the I.D. zircaloy clad, particular care was taken to observe the mandrel condition and lubrication techniques used. The mandrels were lubricated as follows:

Billet 67 - Mandrel was preheated to 200-300°F. A coat of dag 154 plus moly disulfide was applied and baked on during preheat to 800°F. Mandrel condition after extrusion could not be determined. (Free mandrel extrusion).

Billet 68 - Mandrel was lubed as for billet 67. In addition, dag 170 plus moly disulfide was swabbed on hot after the mandrel was in place.

After extrusion the mandrel showed some very hard flakes of graphite (?) adhering all along. Toward the rear the graphite cutoff had contributed to considerable buildup. Flakes chipped off the mandrel showed no trace of copper.

Billet 69 - Same as billet 68.

Billet 70 - Same as billet 67, no addition lube prior to extrusion.

After extrusion, the mandrel looked considerably better than for either billet 68 or 69. Still some slight pickup, but a substantial improvement over the use of wet lube prior to extrusion.

Billet 71 - Same as billet 70 except (1) the mandrel was sanded lightly to remove lumpy deposits; (2) the mandrel was held stationary during extrusion.

After extrusion there was heavy graphite pickup along the mandrel due to the graphite cutoff. In the land area the surface was smooth and shiny with no evidence of copper pickup, lube pickup, or breakdown of the lube film.

Table IV shows the extrusion conditions.

Reduction ratio for all extrusions is 17.7:1.

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TABLE IV

<u>Billet Number</u>	<u>Time</u>	<u>Ram Speed ipm(Ave.)</u>	<u>Tonnage</u>		<u>K(tsi)</u>	
			<u>Max.</u>	<u>Min.</u>	<u>Max.</u>	<u>Min.</u>
Copper Dummy	8:35 pm	34.4	1170	1000	22.0	18.7
Copper Dummy	8:50 pm	33.1	1170	1000	22.0	18.7
67	9:15 pm	38.2	1000	880	18.7	16.5
68	10:45 pm	30.9	760	690	14.3	12.9
69	11:07 pm	31.8	760	660	14.3	12.4
70	12:45 am	36.9	820	586	15.4	11.0
71	1:25 am	30.3	940	820	17.6	15.4

Die changes were made after the extrusion of the copper dummies and again after billet 68. In both cases, the dies cracked. Die material was Vascalloy Supreme steel. Since every V.S. die used to date has failed by cracking after one, two, or at the most three extrusions, the use of this steel will be discontinued. H-21 and H-26 steels perform better.

V. EXTRUDED DIMENSIONS

The extruded dimensions given in the following tables are maximum and minimum readings recorded on samples taken from the acceptable fuel length of each extrusion. Table V shows the following data in order that the reader may better evaluate the significance of the data given in subsequent tables.

A. Overall Length

Total length of the extrusion including copper end defects.

B. Calculated Maximum Core Length - i.e the maximum length of acceptable core which would be yielded by extruding the core with no loss in end defects.

C. Actual Core Length cut from the fuel for sampling and processing.

D. Calculated Yield For The Extrusion - The reader should note that this is not maximum yield. Extrusions are cut such that the end defect portion contains some good material to insure that only good quality material is released for subsequent use.

TABLE V

<u>Extrusion Number</u>	<u>Overall Length (Inches)</u>	<u>Calculated Core Length (Inches)</u>	<u>Acceptable Core Length (Inches)</u>	<u>Calculated Yield Per Cent</u>
67	224	205	156	76
68	219	205	156	76
69	219	205	156	76
70	218	205	160	78
71	224	196*	154	79

*Billet 71 was preshaped to reduce the end defect lengths.

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A. Outside Diameter

Table VI shows maximum and minimum readings and total variation of outside diameter measured in the as-extruded condition.

TABLE VI
O.D. AS-EXTRUDED

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum Inches</u>	<u>Minimum Inches</u>	<u>Δ O.D. Inches</u>
67	18	1.837	1.837	.005
68	18	1.840	1.833	.007
69	18	1.842	1.836	.006
70	18	1.839	1.832	.007
71	<u>18</u>	<u>1.841</u>	<u>1.834</u>	<u>.007</u>
All Tubes	90	1.842	1.832	.010

Table VII shows the maximum and minimum readings and the total variation of outside diameter as measured after copper removal.

TABLE VII
O.D. COPPER OFF

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum Inches</u>	<u>Minimum Inches</u>	<u>Δ O.D. Inches</u>
67	18	1.815	1.812	.003
68	18	1.819	1.813	.006
69	18	1.821	1.815	.006
70	18	1.818	1.811	.007
71	<u>18</u>	<u>1.820</u>	<u>1.813</u>	<u>.007</u>
All Tubes	90	1.821	1.811	.010

B. Inside Diameter

Table VIII shows the maximum and minimum readings and the total variation of inside diameter in the as-extruded condition.

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TABLE VIII
I.D. AS-EXTRUDED

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum Inches</u>	<u>Minimum Inches</u>	<u>Δ I.D. Inches</u>
67	18	1.443	1.438	.005
68	18	1.442	1.437	.005
69	18	1.445	1.440	.005
70	18	1.444	1.435	.009
71	<u>18</u>	<u>1.449</u>	<u>1.441</u>	<u>.008</u>
All Tubes		1.449	1.435	.014

Table IX shows the maximum and minimum readings and the total variation of inside diameter after copper removal.

TABLE IX
I.D. COPPER OFF

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum Inches</u>	<u>Minimum Inches</u>	<u>Δ I.D. Inches</u>
67	18	1.447	1.445	.002
68	18	1.450	1.442	.008
69	18	1.451	1.447	.004
70	18	1.451	1.441	.010
71	<u>18</u>	<u>1.454</u>	<u>1.448</u>	<u>.006</u>
All Tubes		1.454	1.441	.013

C. Wall Thickness

Table X shows the maximum and minimum readings, the total variation in inches and the percentage variation in wall thickness as measured in the as-extruded condition.

TABLE X
WALL THICKNESS - AS-EXTRUDED

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum Inches</u>	<u>Minimum Inches</u>	<u>Δ W.T. Inches</u>	<u>Δ W.T. ± % of W.T.</u>
67	36	.206	.192	.014	3.5%
68	36	.207	.192	.015	3.7%
69	36	.203	.192	.011	2.8%
70	36	.205	.192	.013	3.3%
71	<u>36</u>	<u>.200</u>	<u>.187</u>	<u>.013</u>	<u>3.3%</u>
All Tubes		.207	.187	.020	5.1%

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Table XI shows the maximum and minimum readings, the total variation in inches and the percentage variation of wall thickness after copper removal.

TABLE XI
WALL THICKNESS - COPPER OFF

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum Inches</u>	<u>Minimum Inches</u>	<u>Δ W.T. Inches</u>	<u>Δ W.T. ± % of W.T.</u>
67	36	.191	.176	.015	4.8%
68	36	.193	.176	.017	4.6%
69	36	.190	.180	.010	2.7%
70	36	.190	.178	.012	3.2%
71	36	<u>.185</u>	<u>.175</u>	<u>.010</u>	<u>2.8%</u>
All Tubes		.193	.175	.018	4.9%

D. Bonding

Table XII gives the bond rating (peel test) for tubes 67-71.

TABLE XII

<u>Tube No.</u>	<u>O.D. BOND</u>					<u>I.D. BOND</u>				
	<u>Good</u>	<u>Quest.</u>	<u>Fair</u>	<u>Poor</u>	<u>Rating</u>	<u>Good</u>	<u>Quest.</u>	<u>Fair</u>	<u>Poor</u>	<u>Rating</u>
67	3		6		2.7		6	3		2.7
68		3			3.0	3	3	3		3.0
69			6		2.0			6	3	1.7
70			3	6	1.3			3	6	1.3
71			3	3	1.5			6	3	1.7

For all tubes - Average O.D. = 2.1
Average I.D. = 2.1
Tube Average = 2.1

E. Clad Thickness

Two sets of clad thickness measurements were taken. The first as described in HW-62539. The second by etching out the uranium core material and measuring the clad directly with a point mike.

The data was analyzed by J. L. Jaech, Operation Research and Synthetics, HLO as follows:

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"Clad thickness data from tubes T-67 through T-71 were analyzed to:

(1) describe the roughness of the clad and (2) determine if similar results hold with the point mike measurements.

Considering first the metallograph measurements, we have the following results:

(1) Outer clad average:

There was no significant difference between tubes. The overall average was 22.5 mils. However, in tube 69, the difference between section averages (from front to rear) was significantly greater than for other tubes, indicating greater difficulty in achieving a uniform clad thickness throughout the length of the tube. The 30" section in this tube averaged 20.9 mils, while the two other sections averaged 23.2 mils. Thus, this front section was significantly low.

(2) Inner clad average:

No significant differences between tubes or sections were observed for the inner clad averages. The overall average was 22.3 mils, with the 95% - 99% tolerance statement giving values from 17.1 to 27.4 mils.

Discounting this section, we are 95% confident that 99% of the averages lie between 19.8 and 25.2 mils.

(3) Outer clad range:

No significant differences were observed. The average range was 20.5 mils, and we are 95% confident that 99% of the ranges are less than 4.0 mils.

(4) Inner clad range:

Again, no significant differences were observed. The average range was 1.77 mils, and the 95%-99% upper tolerance limit is 4.0 mils.

In comparing point mike values with the above, we find the results are comparable. For outer clad, the point mike values were biased significantly high by 0.4 mil, but this is of little practical consequence.

No such significant bias was observed for inner clad measurements.

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With respect to roughness, the results are again very comparable. We estimate the variance between outer averages to be 0.78 mils^2 from the metallograph data, and 0.95 mils^2 from the point mike data. These are clearly not different. For inner clad, these estimated variances are 2.87 mils^2 for Balphate, and 2.78 mils^2 for point mike. Thus, the same tolerance statements for average thicknesses would have resulted using point mike values.

Information about roughness at a point is, of course, not available from point mike data. However, this variation is minor, and any appreciable increase in this would be reflected by increased variation between averages."

As-coextruded grain size is given in Table XIII.

TABLE XIII
AS-COEXTRUDED URANIUM GRAIN SIZE

TUBE NUMBER AND SAMPLE LOCATION	GRAIN SIZE (mm)		
	O.D.	MID WALL	I.D.
T-67: 29"	.030-.045(3-5 mil of .055)	.030-.045	.130(20-25 mil)
: 94"	.030-.045(3-8 mil of .065-.110)	.030-.045	.130(10 mil)
: 187"	.035-.045(5-10 mil of .110-.150)	.035-.045	.065-.110(5-8 mil)
T-68: 30"	.075-.130(8-12 mil)	.030-.090	.110-.150(15-30 mil)
: 103"	.075-.090(4-8 mil)	.019-.026	.090-.110(8-12 mil)
: 161"	.075-.110(4 mil)	.019-.022	.090-.110(4-8 mil)
T-69: 30"	.130-.180(15-30 mil of .110-.130)	.130-.180	.180-.210(30 mil)
: 120"	.022-.150(10-30 mil of .130-.150)*	.022-.150*	.150-.180(15-30 mil)*
: 161"	.019(5-8 mil of .090-.110)	.019	.110-.130(5-10 mil)
T-70: 30"	.022-.150(2-30 mil of .090-.180)*	.022-.150*	.130-.180(20-30 mil)*
: 96"	.030-.110(5-30 mil of .110-.150)*	.030-.110*	.150(10-30 mil)
: 186"	.030-.035(2-6 mil of .110-.150)	.030-.035	.150-.180(8-15 mil)
T-71: 30"	.110-.210	.110-.180	.150-.210
: 140"	.130-.180	.110-.150	.210-.300
: 191"	.035-.180(5-30 mil of .045-.150)	.035-.180*	.150-.180(10-30 mil)

*These tubes show a pronounced duplexed structure at these locations.

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VI. INTERNAL CLAD DEFECTS

During extrusion a new type of clad defect was noted. The defect was called "dimpling". A "dimple" is a small depression in the inner clad surface, usually about 0.1 inch in diameter by 2 to 5 mils deep. The depressed area is smooth with no apparent breaks in the metal.

All dimples found were associated with similar defects in the copper clad. The depressed area in the copper clad was filled with a hard black deposite which appeared to be a dump of lubricant and/or copper oxide. Dimpling was least severe on extrusions where the mandrel was relatively free of heavy lubricant deposits. No dimples were found on the extrusion where the stationary mandrel technique (T-71) was used.

In the as-extruded condition, it was difficult to locate any defects due to the lubricant inclusions in the copper surface. However, by vapor blasting the copper surface the lubricant was removed without damage to the copper, and the dimples were easily located.

Examination and measurement showed that the clad was thinned from 1 to 4 mils at these defects.

VII. STEM FAILURE

After removing the extrusion stem, it was noted that the stem was bent. This condition was not noted prior to removal, so it is doubtful as to where the damage occurred.

The maximum stress placed on the stem during extrusion, as calculated from recorded pressure readings, was 150,900 psi. Stems of this design are usually considered safe for operating up to 180,000 psi.

Examination of the stem by Bridgeport Brass and Ajax Steel and Forge personnel revealed no particular reason for failure. However, the design hardness of the stem was 415-444 BHN. This slight variation in hardness should not cause failure, but it was decided that the hardness specifications should be increased for any future stem designs.

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APPENDIX VIII

KER INNER TUBE EXTRUSIONS AT
NUCLEAR METALS INCORPORATED
NOVEMBER 23, 1959

SUMMARY & CONCLUSIONS

Several significant observations can be made concerning this test run:

1. Although the average bond rating for all tubes was satisfactory, three tubes had inferior bonds. Of these three, two (#52, 54) were known to be leakers and one, (#51) was welded in the electron beam welder with no leak check on the assembly. In addition, two tubes had significantly lower interface cleanliness ratings (#51, 52).
2. Due to furnace size limitations, two billets (#54, 55) were preheated in a horizontal position. Both extrusions were extremely eccentric. Total wall thickness variation ranged up to $\pm 7\%$ in the worst locations along the tubes.
3. Three billets (#44, 45, 52) were heated in the furnace without any protective preheat can. All billets showed complete loss of lubricant and heavy copper oxide buildup after heating. Copper pickup on the die was severe. Galling of the extrusions were severe enough to damage the outer zircaloy clad. There was no pickup on the mandrel.
4. Significant differences in outer clad thickness variation were noted between dingot and ingot uranium.
5. NMI had recently installed a new pressure recorder which allowed closer analysis of pressure variations during extrusion. With this equipment it became obvious that the pressure rise toward the rear of an extrusion billet was fairly constant regardless of billet length. By heating the cutoff to 1100°F instead of 900°F it was possible to reduce this pressure rise considerably. It would be difficult to determine the difference in fuel quality (if any) caused by the cooling at the rear of the billet. However, it seems reasonable to assume that maintaining a more uniform billet temperature will provide better product uniformity.
6. This extrusion test completed the billet length tests which were designed to determine the effect of billet length to diameter limits. The results of this test are reported in detail in HW-64197.

I. BILLET AND TOOL DESIGNS

A. Billet Designs

The designed sizes of billet components were as follows:

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Outer copper can	4" O.D. x .065" wall
Outer zircaloy clad	3.860" O.D. x 3.640" I.D.
Uranium core	3.360" O.D. x 1.110" I.D.
Inner zircaloy clad	1.110" O.D. x .635" I.D.
Inner copper can	.625" O.D. x .040
Front end plate	$\frac{1}{2}$ " copper plate
Rear end plate	$\frac{1}{4}$ " copper plate

Uranium core lengths were as follows:

Billets 44-51 inclusive	10"
Billets 52-53	10" plus $\frac{1}{2}$ " preshape
Billet 54	16"
Billet 55	18"

B. Die Design

A 90° included angle integral cone-die design was used. Die I.D. - 1.080".

C. Mandrel Design

Both french and free mandrels were used. Mandrel O.D. - .495".
Free mandrel technique was used on billets 44, 54, and 55.

II. COMPONENT PREPARATION

A. Copper

The extrusion cans and caps were fabricated from DHP copper tube and plate.
Both assemblies were outgassed prior to assembly.

B. Zircaloy Clad

Zircaloy cladding was fabricated from primary ingots by forging, hot extrusion and machining. Primary extrusion reductions were as follows:

1. Outer Clad, about 10:1
2. Inner Clad, about 22:1

Zircaloy was cleaned as follows:

1. Vapor degrease - trichlorethylene
2. Hand scrub in Altrex
3. Rinse - hot water
4. Rinse - cold water
5. Rinse - hot water
6. Hot air dry

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C. Uranium

The billet cores were fabricated from dingot and ingot stock.

1. Dingot Fabrication (Billets 48-55)

- a. Gamma pierced and extruded from dingot to billet stock 9" O.D. x 2 5/8" I.D.
- b. Alpha extruded to 3.9" O.D. x .9" I.D.
- c. Triple beta quenched (water)
- d. Machined to size

2. Ingot Fabrication (Billets 44-47)

- a. Alpha extruded from 7" to 3.9" bar (3.2:1 reduction)
- b. Rough bored and machined
- c. Triple beta quenched, water
- d. Machined to size

Uranium cores are cleaned as follows: 1) Degrease - trichlorethylene
2) Nitric etch
3) Double water rinse and dry

D. Material Identification

Component material heat numbers for each extrusion billet are listed in Table I.

TABLE I

<u>Billet Number</u>	<u>Outer Clad</u>	<u>Inner Clad</u>	<u>Uranium Core</u>
44	87954	1C	5A-70570
45	87954	2A	5E-70570
46	87952	1C	2E-70570
47	87954	1E	5D-70570
48	60162	1F	2A
49	87954	1E	7A
50	87954	2A	7B
51	87954	1C	7C
52	87954	1E	6C
53	87954	1E	7D
54	87954	1F	6B
55	87954 (2 pcs)	2E	A-6

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III. BILLET ASSEMBLY

A. Assembly Data are given in Table II.

TABLE II

<u>Billet Number</u>	<u>Date Assembled</u>	<u>Total Evacuation Time (hrs:min)</u>	<u>Seal Off Pressure (mm-Hg)</u>
44	11-11-59	4:00	1×10^{-4}
45	11-11-59	3:35	1×10^{-4}
46	11-11-59	1:35	1×10^{-4}
47	11-11-59	1:20	1×10^{-4}
48	11-11-59	1:30	2×10^{-5}
49	11-11-59	1:25	2×10^{-5}
50	11-11-59	1:00	2×10^{-5}
51	11-12-59	----	Electron beam welded
52	11-11-59	Leaker	-----
53	11-11-59	0:45	1×10^{-5}
54	11-12-59	Leaker	-----
55	11-12-59	3:45	2×10^{-5}

B. Assembly Notes

In the assembly of some billets, problems were encountered which could effect the quality of the extrusion. These problems are noted below:

1. Billet 46 - Leak on the O.D.-cap end, rewelded with hand torch during evacuation.
2. Billet 47 - Leak on the I.D.-rear end, rewelded with hand torch during evacuation.
3. Billet 51 - Welded in electron beam welder.
4. Billet 52 - Billet assembled, unable to repair leaks on O.D. and I.D. at the front end. Extruded as a leaker.
5. Billet 54 - Billet leaked on front I.D.
6. Billet 55 - Leak on rear I.D., closed with hand torch during evacuation.

The copper components used for these billets were extremely difficult to weld. Several assemblies were re-canned and several required repair during leak testing. A leak check of the assembled can is now being made prior to final assembly to eliminate leaks around the rear end plate. The welding problems seem to be associated with the four-inch tubing used in this particular billet design (DHP copper). Tests with this material show porosity to varying degrees. Porosity increases with increased etch time.

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IV. EXTRUSION CONDITIONS

A. Billet Preheat

Billets were heated in a muffle furnace. With this furnace it is necessary to protect the billets from direct radiation from the elements and oxidation of the copper by inserting them in graphite or steel cans.

On this extrusion run, four billets were heated without canning to see the effects of open air heating. The billets were protected from direct radiation by inserting a steel liner in the furnace which covered the heating elements.

Due to the length of billets 54 and 55, it was necessary to heat them horizontally. All other billets were vertical during preheat.

Billet temperature was measured by contacting the billet surface with a thermocouple. It was difficult to obtain uniform billet temperature since the billets tend to shield each other. In general, the two billets at the front of the furnace were colder than the two in the rear.

Billet preheat data is given in Table III.

TABLE III

<u>Billet Number</u>	<u>Container</u>	<u>Temperature °F</u>	<u>Preheat Time hrs:min.</u>
44	Steel box	1170	3:30
45	Steel box	1170	3:00
46	Steel can	1160	3:30
47	Steel can	1170	3:30
48	Steel can	1180	3:45
49	Steel can	1175	3:45
50	Steel can	1150	2:45
51	Steel can	1160	2:45
52	Steel box	----	3:25
53	Steel can	1165	2:45
54	Steel can(in steel box)	----	----
55	Graphite can	1185	3:00

The three billets heated in the steel box without any protection showed a heavy oxide scale after preheat. The graphite coat was completely burned off. On extrusion, these billets gave very heavy pickup in the cone with heavy scratching on the copper surface.

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B. Tool Preheat

The dies and mandrels were preheated to 900°F. Immediately prior to extrusion, the diw was removed from the furnace and inserted into the liner. The mandrel was removed from the furnace, lubricated by hand and placed on the loader. When the billet was placed on the loader, the mandrel was inserted into the billet and cutoff(s) and the entire assembly loaded into the liner.

The container-liner was electrically heated to 900°F. Indicated liner temperature remained quite uniform during extrusion.

Two cutoff temperatures were used, 900°F and 1150°F. Cutoff temperature was varied to check out an interesting effect noted at the rear of the extrusion. On previous extrusions, an increase in extrusion pressure had been noted at the end of each billet. This has been thought to be due to cooling by the liner. However, with a new recorder recently installed by NMI, and the variable billet lengths used in this test, it was determined that this increase occurred over a fixed length at the back of the extrusion, regardless of billet length. Magnitude of the increase was about 30-40 tons.

By heating the cutoff to billet temperature, it was possible to reduce this effect. The same pattern of pressure change was seen but the magnitude of increase was reduced substantially, i.e. to 5-10 tons.

C. Extrusion Conditions

The extrusions were made in the 4.050" liner at 13 rpm ram speed. The reduction ratio was 17.8:1.

The liner was lubricated with oil dag prior to each extrusion. Between extrusions the liner bore was cleaned with a rotating wire brush. Loose material was blown out with compressed air. Liner condition was excellent. The entire bore was bright and shiny with no pickup or score marks.

Extrusion data is given in Table IV.

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TABLE IV

NMI Extrusion Number*	Billet Number	Time	Tonnage		K(tsi)	
			Max.	Min.	Max.	Min.
22964	44	1:30 pm	690	600	18.9	16.4
22965	45	1:55 pm	680	570	18.6	15.6
22967	46	6:25 pm	700	590	19.2	16.1
22968	47	6:38 pm	710	580	19.4	15.9
22969	48	6:45 pm	660	590	18.1	16.1
22970	49	6:55 pm	670	595	18.3	16.3
22971	50	9:45 pm	750	600	20.5	16.4
22972	51	9:52 pm	720	570	19.7	15.6
22963	52	2:00 pm	630	590	17.2	16.1
22973	53	10:00 pm	720	630	19.7	17.2
22966	54	2:53 pm	700	595	19.2	16.3
22974	55	10:18 pm	730	600	20.0	16.4

*The NMI extrusion number usually shows the actual extrusion sequence. However, it was necessary to break this sequence on the first four extrusions. The actual sequence (as shown by the extrusion time) was:

1st - 22964 Billet 44
2nd - 22965 Billet 45
3rd - 22963 Billet 52
4th - 22966 Billet 54

All other extrusions are in sequence.

There were no tool failures during extrusion. As previously noted, there was some pickup on the extrusions heated without preheat cans.

V. EXTRUDED DIMENSIONS

The extruded dimensions given in the following tables are maximum and minimum readings recorded on samples taken at the front, middle and rear of the acceptable fuel length of each tube. Table V shows the overall extrusion length, including copper and end defects; the calculated core length, assuming no loss due to end defects; the acceptable length actually used from each extrusion; and the yield (calculated vs acceptable) for each extrusion.

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TABLE V

<u>Extrusion Number</u>	<u>Overall Length Inches</u>	<u>Calculated Core Length Inches</u>	<u>Acceptable Fuel Length Inches</u>	<u>Yield %</u>
44	186	173	128	74
45	186	173	128	74
46	186	173	128	74
47	186	172	129	74.5
48	186	173	129	74.5
49	183	173	127	73.5
50	186	173	127	73.5
51	186	173	126	73.0
52	195	173	136	78.5
53	195	173	136	78.5
54	290	277	230	83
55	324	312	262	84

A. Outside Diameter

Table VI shows the maximum and minimum readings and total variation of outside diameter measured in the as-extruded condition (copper on).

TABLE VI
OUTSIDE DIAMETER AS-EXTRUDED

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum (Inches)</u>	<u>Minimum (Inches)</u>	<u>O.D. (Inches)</u>
44	9	1.075	1.073	.002
45	9	1.075	1.073	.002
46	9	1.077	1.074	.003
47	9	1.074	1.072	.002
48	9	1.075	1.073	.002
49	9	1.076	1.072	.004
50	9	1.076	1.073	.003
51	9	1.076	1.073	.003
52	9	1.076	1.073	.003
53	9	1.076	1.074	.002
54	9	1.076	1.072	.004
55	9	1.074	1.071	.003
All Tubes	108	1.077	1.071	.006

Table VII shows the maximum and minimum readings and total variation of outside diameter measured after copper removal.

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TABLE VII
OUTSIDE DIAMETER - COPPER OFF

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum (Inches)</u>	<u>Minimum (Inches)</u>	<u>O.D. (Inches)</u>
44	9	1.047	1.044	.003
45	9	1.049	1.046	.003
46	9	1.049	1.046	.003
47	9	1.049	1.045	.004
48	9	1.047	1.042	.005
49	9	1.047	1.045	.002
50	9	1.050	1.046	.004
51	9	1.047	1.038	.009
52	9	1.047	1.044	.003
53	9	1.051	1.046	.005
54	9	1.048	1.045	.003
55	<u>9</u>	<u>1.047</u>	<u>1.042</u>	<u>.005</u>
All Tubes	108	1.051	1.038	.013

B. Inside Diameter

Table VIII shows the maximum and minimum readings and the total variation of inside diameter in the as-extruded condition.

TABLE VIII
INSIDE DIAMETER AS-EXTRUDED

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum (Inches)</u>	<u>Minimum (Inches)</u>	<u>I.D. (Inches)</u>
44	9	.495	.494	.001
45	9	.495	.494	.001
46	9	.495	.494	.001
47	9	.493	.492	.001
48	9	.495	.494	.001
49	9	.495	.494	.001
50	9	.495	.494	.001
51	9	.492	.491	.001
52	9	.492	.491	.001
53	9	.495	.494	.001
54	9	.493	.491	.002
55	<u>9</u>	<u>.493</u>	<u>.492</u>	<u>.001</u>
All Tubes	108	.495	.491	.004

Table IX shows the maximum and minimum readings and the total variation of inside diameter after copper removal.

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TABLE IX
INSIDE DIAMETER - COPPER OFF

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum (Inches)</u>	<u>Minimum (Inches)</u>	<u>I.D. (Inches)</u>
44	9	.498	.497	.001
45	9	.498	.497	.001
46	9	.499	.498	.001
47	9	.497	.496	.001
48	9	.498	.497	.001
49	9	.498	.497	.001
50	9	.500	.498	.002
51	9	.395	.494	.001
52	9	.497	.496	.001
53	9	.500	.490	.001
54	9	.498	.497	.001
55	9	.498	.497	.001
All Tubes	108	.500	.494	.006

Measurements in the as-extruded condition are used to check the tool performance. The copper surfaces are formed by the tools and should reflect changes in tool dimensions and surface condition. Billet temperature variation is also reflected in the measurement. However, as shown in Table VI and VIII, these variables were under good control in this test. The total O.D. variation of 6 mils is considered very close control in a coextrusion run.

Measurements in the as-pickled condition more directly reflect the quality of the extruded product. In general, the variation in this condition is greater. The extruded copper clad acts as a buffer between the tools and the zircaloy clad. Therefore, the zircaloy clad dimensions are directly influenced by the additional variable of copper thickness variation. In addition, the copper layer can be deformed by the zircaloy if the zircaloy is influenced by "memory" within its own structure; ingotism within the uranium core, or localized variation in billet temperature uniformity.

The actual effect of the copper varies between O.D. and I.D. since the residual copper thickness is different. The as-extruded O.D. copper is 8 to 12 mils thick and the I.D. copper 1 to 3 mils thick.

The total variation in O.D., as shown in Table VII, was 13 mils. This is not considered good control. The I.D. variation, shown in Table IX, of 6 mils is considered good control.

There is no real limit set as to the dimensional variations allowable in the extrusion process. In the process specifications for SRL power tubes, the O.D. and I.D. variations are set at 20 mils total. However, this process uses the integral end seal technique and finishing operations after extrusion

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are strictly minimum. In the HAPO process, end closures must be made on each short length fuel element cut from the full length extrusion. Several end closure processes are being considered. In all these processes, variation in as-extruded dimensions introduce complications in the closure process.

With the limited experience available, it is difficult to estimate the control limits which can be achieved under closely controlled production conditions. There is no comparable commercial extrusion process which can be used as a basis for direct comparison.

Based on the tolerance ranges which may be required in the closure process, the requirements on as-extruded dimensions will probably closely resemble the requirements for commercial fabrication of drawn copper tubing. If these are used as a goal for coextrusion, the ranges would be ⁽¹⁾.

	<u>KERIT</u>	<u>NPRIT</u>	<u>KEROT</u>	<u>NPROT</u>
O.D. Tolerance	+ 3 mils	+ 3 mils	+ 3 mils	+ 4 mils
I.D. Tolerance	+ 2 mils	+ 2 mils	+ 3 mils	+ 3 mils

Matching draw-bench tolerances with a hot extrusion operation is a difficult goal. From existing data it can be concluded that this can be done on a single tube basis, but the variation between extrusions is too great to maintain this control on a large group of tubes.

If the tolerance ranges shown above are necessary, they can be attained only by selective grouping techniques, i.e. grouping similar tubes into size ranges to minimize tolerance ranges within each group. This technique can minimize tolerance ranges, but will require processing of several, probably two or three, size classifications for each of the two tube geometrics.

C. Wall Thickness

Table X shows the maximum and minimum readings, the total variation of readings and the per cent variation in wall thickness as measured in the as-extruded condition. In summarizing wall thickness data, tubes 54 and 55 have been excluded. These billets, because of their length, were heated horizontally and showed abnormally high wall thickness variation due to non-uniform heating.

(1) ASTM-B251-55T - Average diameter tolerances for copper and copper alloy tube.

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TABLE X
WALL THICKNESS AS-EXTRUDED

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum (Inches)</u>	<u>Minimum (Inches)</u>	<u>Δ W.T. (Inches)</u>	<u>Δ W.T. ± % of W.T.</u>
44	18	.295	.284	.011	1.9
45	18	.298	.283	.015	2.6
46	18	.295	.285	.010	1.7
47	18	.295	.286	.009	1.6
48	18	.297	.282	.015	2.6
49	18	.299	.281	.018	3.1
50	18	.296	.283	.013	2.2
51	18	.302	.279	.023	4.0
52	18	.295	.284	.011	1.9
53	18	.313	.274	.039	6.7
All Tubes	180	.313	.274	.039	6.7

Table XI shows the maximum and minimum readings, the total variation in reading, and the percentage variation in wall thickness as measured after copper removal.

TABLE XI
WALL THICKNESS - COPPER OFF

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Maximum (Inches)</u>	<u>Minimum (Inches)</u>	<u>Δ W.T. (Inches)</u>	<u>Δ W.T. ± % of W.T.</u>
44	18	.278	.268	.010	1.8
45	18	.278	.269	.009	1.65
46	18	.279	.270	.009	1.65
47	18	.279	.270	.009	1.65
48	18	.282	.267	.015	2.7
49	18	.283	.265	.018	3.3
50	18	.281	.269	.012	2.2
51	18	.285	.265	.020	3.7
52	18	.280	.267	.013	2.4
53	18	.291	.250	.041	7.5
All Tubes	180	.291	.250	.041	7.5

Wall thickness control is affected by the following variables:

1. Billet Design and Fabrication

Any eccentricity introduced into billet components during their manufacture is directly reflected in the extruded product.

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The relative fit between the billet and the liner and tools is of primary importance. In general, the most ideal condition for producing concentric tubing would be that of a press fit between liner mandrel and billet and between components within the billet. With this condition, the "upset" of the billet into the liner would be negligible and any tendency for displacement of the mandrel from the true centerline of the extrusion would be minimized.

Since clearances are required to assemble the billet and to insert it into the liner, this condition must be classed as ideal.

Billet designs are used which permit assembly with minimum clearances. Component tolerances are set to require careful machining.

2. Billet Temperature

Although successful coextrusions have been made in a rather broad temperature range (1100-1200°F), temperature variations within a billet can effect concentricity. The plasticity (K value) of the materials is temperature dependent. A billet can exhibit variable stiffness through any cross-section if temperature gradients exist in that cross-section.

3. Tool Condition and Lubrication

Any tool condition which results in non-uniform friction forces around the billet can result in increased eccentricity. Pickup on the die cone or land; scarred or poorly finished tool surfaces, non-uniform lubrication all contribute toward non-uniform friction forces.

Lubrication is the most difficult variable to control. In a horizontal press, it is difficult to apply a uniform lubricant coat to the hot liner. Application technique, as well as lubricant composition, require close study.

From the above it can be seen that wall thickness variation is affected by more variables than either the I.D. or O.D. In addition, the wall thickness variation cannot be corrected in subsequent sizing operations.

For comparison basis, the standard tolerances for wall thickness variation in commercially drawn copper tubing of comparable sizes is given below:

	<u>KERIT</u>	<u>NPRIT</u>	<u>KEROT</u>	<u>NPROT</u>
Wall Thickness Variation	+ 10 mils (+ 3.6%)	+ 5 mils (+ 22 mils)	+ 8 mils (+ 4.3%)	+ 14 mils (+ 4.6%)

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With coextrusion techniques, these tolerance ranges can be met. With selective grouping of extrusions these ranges can be reduced substantially. It will be possible to select a significant percentage of the total production with wall thickness variation within a range of $\pm 2.5\%$. This would represent an additional product split with the ensuing complications.

D. Clad Thickness

Two clad thickness measurement systems were used in evaluating these tubes. The system described in HW-62539 was supplemented by etching the uranium out of tube sections and measuring clad thickness directly with a micrometer. The results of both measurement systems is reported.

The data was analyzed by J. L. Jaech, Operations Research and Synthetics, HLO. The results of his analysis are given below:

"The conclusions given below pertain to Metallograph measurements.

(1) Average ... Outer Clad:

Tubes prepared from ingot stock differed significantly from those prepared from dingot stock in 2 respects:

- (a) a slightly higher average (24.1 vs 23.6 mils)
- (b) considerably less variation between averages.

There were no significant differences due to mandrel types or core length. The 95%-99% tolerance statements are 21.6 to 26.6 mils for the ingots, and 18.4 to 28.8 mils for dingots.

(2) Range ... Outer Clad:

The smaller variation between averages observed for ingots was also reflected in a significantly smaller range. The average ranges were 2.2 and 2.7 mils for ingot and dingot respectively. The corresponding 95%-99% upper tolerance limits are 3.8 and 6.1 respectively.

There were no differences between mandrel types or core lengths.

(3) Average ... Inner Clad:

Due to the missing data, it was not possible to test for differences between core material, mandrel type, or core length. The overall average for the 7 tubes listed in the appendix for which data were available was 23.2 mils. The 95%-99% tolerance limits are rather spread out because of the large variation observed on these averages, and are 16.3 to 30.1 mils.

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(4) Range ... Inner Clad:

The overall average range was 1.7 mils, with the 95%-99% upper tolerance limit being 3.7 mils.

Point mike measurements were also taken. In comparing with metallograph measurements, we find general agreement, with one interesting exception. In tubes 67-71, we had noted that the point mike outer clad measurements were biased high by about 0.4 mil. This same type of bias was noted for the dingot stock here, being estimated at .6 mil. However, for the ingot stock, the measurements were biased about .2 mil low. The net result is that, while for Metallograph measurements, the ingots had significantly higher averages than the dingots, if we regard point-mike measurements, the situation is reversed. In this case the averages are 23.9 and 24.2 mils for the ingots and dingots respectively. As before, there are no differences between mandrel types and core lengths. The point mike measurements failed to detect the greater roughness existing in dingot stock.

For inner clad, the point mike measurements are complete, which was not the case for the Metallograph measurements. Taken overall, there is a significant difference between tube average thicknesses. However, these are not attributable to differences in core material, mandrel type, or core length. For the seven tubes having both type measurements, the point mike measurements are biased high by 0.5 mil. It is difficult to say whether this is true for ingot material too, since there was only one ingot tube (T-47) having both type measurements. This showed an estimated bias of only 0.1 mil.

To summarize, the major point appears to be the difference in outer clad characteristics between ingots and dingots, where the ingots are smoother as reflected in the smaller ranges and also the smaller variation between averages. This is consistent with results detected earlier."

E. Bonding

Table XII gives the bond ratings for Tubes 44-55 (peel test).

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TABLE XII

Tube No.	<u>O.D. Bond</u>				<u>I.D. Bond</u>			
	Good	Quest.	Fair	Poor	Good	Quest.	Fair	Poor
44	9				6	3		
45	6	3			6	3		
46	9				9			
47	4	5			3	6		
48	9					9		
49	8	1				9		
50	9				3	5	1	
51	3	3		3		6	3	
52	3	3		3		9		
53	9				5			4
54	3	3		3	1	7		
55	1	5	3			6		3

For All Tubes - Average O.D. = 3.5
 Average I.D. = 3.1
 Tube Average = 3.3

F. Interface Cleanliness

Interface cleanliness ratings are given in Table XIII.

TABLE XIII
CLEANLINESS RATING OF INTERFACES

<u>Sample Location and Position</u>	<u>Graded Cleanliness</u>		
	<u>O.D.</u>	<u>I.D.</u>	
T-44: 25"	16	18	Average
: 99"	16	16	
:155"	18	18	
	16.7	17.3	
			Tube Average - 17.0
T-45: 25"	13	13	Average
: 99"	15	13	
:155"	15	14	
	14.3	13.3	
			Tube Average - 13.8
T-46: 25"	16	16	Average
: 90"	14	14	
:155"	16	18	
	15.3	16.0	
			Tube Average - 15.7

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Sample Location
and Position

Graded Cleanliness

O.D.

I.D.

T-47: 25"	11	14	
: 90"	16	14	
:156"	17	14	
Average	<u>14.7</u>	Average	<u>14</u> Tube Average 14.4
T-48: No data are available.			
T-49: 25"	21	21	
: 92"	21	21	
:154"	20	21	
Average	<u>20.7</u>	Average	<u>21</u> Tube Average - 20.9
T-50: 25"	13	15	
: 92"	15	17	
:154"	14	15	
Average	<u>14</u>	Average	<u>15.7</u> Tube Average - 14.9
T-51: 25"	3	3	
: 92"	18	13	
:153"	9	10	
Average	<u>10</u>	Average	<u>8.7</u> Tube Average - 9.4
T-52: 25"	3	3	
: 92"	15	3	
:163"	6	3	
Average	<u>8</u>	Average	<u>3</u> Tube Average - 5.5
T-53: 25"	18	15	
: 79"	18	17	
:163"	18	19	
Average	<u>18</u>	Average	<u>17</u> Tube Average - 17.5
T-54: 25"	13	14	
:140"	18	18	
:257"	18	17	
Average	<u>16.3</u>	Average	<u>16.3</u> Tube Average - 16.3
T-55: 25"	15	10	
:156"	18	15	
:285"	18	17	
Average	<u>17</u>	Average	<u>14</u> Tube Average - 15.5

For All Tubes: O.D. Average - 15.0; I.D. Average - 14.2; Per Tube Average - 14.6

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G. Uranium Grain Size

Uranium grain size measurements are given in Table XIV.

TABLE XIV
AS-COEXTRUDED URANIUM GRAIN SIZE

Tube Number and Sample Location	O.D.	Grain Size (MM)	
		Mid Wall	I.D.
T-44: 25"	.019-.022	.022-.026	.055-.065(5-8 mil)
: 99"	.022-.035	.030-.035	.045-.055(5-30 mil)
:155"	.030-.045	.035	.045
T-45: 25"	.030-.035	.030-.035	.055(15 mil)
: 99"	.030-.035	.030-.035	.055(10 mil)
:155"	.030-.035(0-2 mil of .045)	.030-.035	.045-.055(5 mil)
T-46: 25"	.030-.035	.026-.035	.055(10 mil)
: 90"	.030-.035	.030-.035	.055(10 mil)
:155"	.035-.045	.035-.045	.045-.055(10 mil)
T-47: 25"	.035-.045	.035-.045	.055(20-25 mil)
: 90"	.035-.045	.035-.045	.065(20-25 mil)
:156"	.030-.035(5 mil of .045)	.030-.035	.055(10 mil)
T-48: 25"	.016-.030	.016-.030	.130-.150(20-25 mil)
: 78"	.019-.026	.022-.030	.130(15 mil)
:156"	.019-.022	.022-.030	.110-.130(4-8 mil)
T-49: 25"	.035(0-8 mil of .090)	.035	.110-.130(20-30 mil)
: 92"	.035(0-8 mil of .090)	.035	.130(15 mil)
:154"	.035-.045(0-8 mil of .090)	.035	.130(10 mil)
T-50: 25"	.020	.026	.130(15 mil)
: 92"	.022(0-8 mil of .035-.045)	.022	.130-.150(15 mil)
:154"	.022(10 mil of .045-.090)	.022	.110-.150(10 mil)
T-51: 25"	.026(0-8 mil of .035-.045)	.026	.150(20-30 mil)
: 92"	.026(10 mil of .030-.090)	.026	.150(15-25 mil)
:153"	.026(10-15 mil of .030-.055)	.026	.150-.180(15 mil)
T-52: 25"	.035-.045	.035-.045	.150(20-30 mil)
: 92"	.035-.045(0-8 mil of .090)	.035-.045	.150(5-15 mil)
:163"	.045	.035-.045	.090(5 mil)
T-53: 25"	.022-.026	.026-.030	.090(8 mil)
: 79"	.026	.030-.035	.075-.110(4-8 mil)
:163"	.026-.030	.030-.035	.056-.075(4-8 mil)

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T-54: 25"	.026-.030	.026-.030	,150(15 mil)
:154"	.035-.045	.035-.045	.110(10 mil)
:275"	.022-.030	.022-.030	.022-.030
T-55: 25"	.035-.045*	.035-.180*	.110-.180(45-60 mil)*
:156"	.035-.045(0-6 mil of .055)	.035-.045	.180(20-25 mil)
:285"	.035-.045(0-30 mil of .075)	.045	.065(2-6 mil)

*Billet exhibits an extreme duplex grain structure at this location.

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APPENDIX IX

KER INNER TUBE EXTRUSIONS AT
NUCLEAR METALS INCORPORATED
JANUARY 15, 1960

SUMMARY & CONCLUSIONS

Dimensions were controlled better on this test than any other to date. The tolerances obtained should be satisfactory for fuel element productions.

The billets were preheated without protective graphite cans. Pickup was avoided by lubricating the liner twice before each extrusion, the second time immediately prior to extrusion as that the liner was still "wet" when the billet was loaded.

Bonding was satisfactory except for the "leaker" which were extruded. Although some billets of questionable integrity have bonded satisfactorily, it is evident that any loss of billet evacuation will appreciably affect bond characteristics. It is doubtful that the peel test is a satisfactory means of measuring relative bond quality. However, it will detect gross unbonding, and it appears that the interface cleanliness rating system will provide a fairly good measurement of overall billet integrity and cleanliness.

I. BILLET AND TOOL DESIGNS

A. Billet Designs

The designed sizes of billet components were as follows:

Outer copper can	4" O.D. x .065" wall
Outer zircaloy clad	3.860" O.D. x 3.650" I.D.
Uranium core	3.640" O.D. x 1.120" I.D.
Inner zircaloy clad	1.110" O.D. x .635" I.D.
Inner copper can	.625" O.D. x .545" I.D.
Front end plate	1/2"
Rear end plate	1/4"

Nominal uranium length was 12". However, billets 82 and 83 had short cores. Billet 82 was assembled with a 1/4" copper spacer. Billet 83 was assembled with a 1/2" copper spacer.

B. Die Designs

Dies were integral cone design - 1.082" I.D.; 90° included angle.

C. Mandrel Designs

French mandrels were used on all extrusions. Mandrel O.D. was .495".

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II. COMPONENT PREPARATION

A. Copper

The extrusion caps and cans were fabricated from DLP copper tube and plate. Both assemblies were outgassed for ten of the billets. Billets #81 and 83 were assembled without outgassing.

B. Zircaloy Clad

The uranium cores were fabricated from production dingot stock as follows:

1. Gamma pierced and extruded to 9" O.D. x 1 1/6" I.D.
2. Alpha extruded to 3.9" O.D. x 0.9" I.D.
3. Rough machined to 3.700" O.D. x 1.050" I.D.
4. Triple beta heat treated and quenched in water.
5. Finish machined to final dimensions.

III. BILLET ASSEMBLY

Assembly data is given in Table I.

TABLE I

<u>Billet Number</u>	<u>Date Assembled</u>	<u>Evacuation Time Hours:Minutes</u>	<u>Seal Off Pressure MM:HG</u>
72	12-9-59	1:10	9×10^{-5}
73	12-9-59	Leaker	Leaker
74	12-10-59	3:50	1×10^{-5}
75	12-10-59	1:30	-----
76	12-11-59	2:20	3×10^{-5}
77	12-11-59	1:30	3×10^{-5}
78	12-11-59	1:35	1×10^{-5}
79	12-11-59	1:05	2×10^{-5}
80	12-11-59	Leaker	Leaker
81	12-15-59	4:20	5×10^{-5}
82	12-15-59	1:20	5×10^{-5}
83	12-15-59	:30	2×10^{-5}

IV. EXTRUSION CONDITIONS

A. Billet Preheat

The billets were preheated in a muffle furnace. They were protected from direct radiation by a steel liner used to cover the elements. No additional protection was provided to prevent oxidization. (Closed steel or graphite can were not used).

Preheat conditions are given in Table II.

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TABLE II

<u>Billet Number</u>	<u>Temperature °F</u>	<u>Preheat Time Hours:Minutes</u>
72	1150	3:45
73	1160	3:54
74	1170	4:05
75	1170	4:20
76	1160	3:00
77	1155	3:09
78	1170	3:20
79	1170	3:30
80	1160	3:10
81	1160	3:20
82	1165	3:27
83	1175	3:35

B. Tool Preheat

Same as KER inner tubes, Appendix VIII.

C. Extrusion Conditions

Extrusions were made in a 4.050" liner. Ram speed was 13" per minute. Reduction ratio was 17.3/1. The liner was lubricated with oil dag 170 about two minutes before extrusion, wiped down to remove excess lubricant and relubricated immediately before the billet was loaded.

TABLE III
EXTRUSION DATA

<u>Billet Number</u>	<u>Time</u>	<u>Tonnage</u>		<u>K(tsi)</u>	
		<u>Max.</u>	<u>Min.</u>	<u>Max.</u>	<u>Min.</u>
72	13:48	678	620	18.8	17.2
73	14:02	632	568	17.6	15.8
74	14:13	632	568	17.6	15.3
75	14:26	642	560	17.8	15.6
76	17:33	632	575	17.6	16.0
77	17:42	625	575	17.4	16.0
78	17:51	632	583	17.6	16.2
79	17:59	625	575	17.3	16.0
80	21:15	632	600	17.6	16.2
81	21:24	625	600	17.4	16.7
82	21:36	625	550	17.4	15.3
83	21:45	620	510	17.2	14.2

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V. EXTRUSION EVALUATION

A. Outside Diameter

Table IV shows the maximum and minimum readings and total variation of readings, both as-extruded and after copper removal.

TABLE IV
OUTSIDE DIAMETER

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>As-Extruded</u>			<u>Copper off (Inches)</u>		
		<u>Max. Inches</u>	<u>Min. Inches</u>	<u>△ Inches</u>	<u>Max. Inches</u>	<u>Min. Inches</u>	<u>△ Inches</u>
72	9	1.079	1.075	.004	1.050	1.043	.007
73	9	1.078	1.075	.003	1.050	1.047	.003
74	9	1.080	1.076	.004	1.051	1.048	.003
75	9	1.077	1.074	.003	1.047	1.044	.003
76	9	1.081	1.075	.006	1.055	1.050	.005
77	9	1.078	1.075	.003	1.053	1.049	.004
78	9	1.078	1.075	.003	1.051	1.049	.002
79	9	1.078	1.074	.004	1.050	1.046	.004
80	9	1.078	1.076	.002	1.054	1.046	.008
81	9	1.078	1.076	.002	1.050	1.045	.005
82	9	1.078	1.075	.003	1.051	1.044	.007
83	9	1.076	1.074	.002	1.052	1.049	.003
Total - All Tubes		1.081	1.074	.007	1.055	1.043	.012

Inside Diameter

Table V shows the maximum and minimum readings and variation of inside diameter, both as-extruded and after copper removal.

TABLE V
INSIDE DIAMETER

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>As-Extruded</u>			<u>Copper off (Inches)</u>		
		<u>Max. Inches</u>	<u>Min. Inches</u>	<u>△ Inches</u>	<u>Max. Inches</u>	<u>Min. Inches</u>	<u>△ Inches</u>
72	9	.492	.492	-----	.498	.497	.001
73	9	.492	.491	.001	.497	.496	.001
74	9	.493	.492	.001	.498	.497	.001
75	9	.494	.494	-----	.500	.499	.001
76	9	.493	.492	.001	.497	.496	.001
77	9	.492	.491	.001	.496	.496	-----
78	9	.492	.492	-----	.498	.497	.001
79	9	.495	.494	.001	.500	.499	.001
80	9	.494	.492	.002	.498	.497	.001
81	9	.493	.492	.001	.497	.496	.001
82	9	.493	.492	.001	.497	.496	.001
83	9	.494	.494	-----	.499	.498	.001
Total - All Tubes		.495	.491	.004	.500	.496	.004

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B. Wall Thickness

Table VI shows the maximum and minimum readings and variation of wall thickness, both as-extruded and after copper removal.

TABLE VI
WALL THICKNESS

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>As-Extruded</u>				<u>Copper Off</u>			
		<u>Max. Inches</u>	<u>Min. Inches</u>	<u>WT Inches</u>	<u>WT + % WT</u>	<u>Max. Inches</u>	<u>Min. Inches</u>	<u>WT Inches</u>	<u>WT + % WT</u>
72	18	.300	.286	.014	2.4	.283	.267	.016	2.9
73	18	.305	.279	.026	4.5	.288	.262	.016	2.9
74	18	.298	.288	.010	1.7	.281	.271	.010	1.8
75	18	.298	.281	.017	2.9	.287	.265	.013	2.4
76	18	.301	.286	.015	2.5	.282	.272	.010	1.8
77	18	.300	.284	.016	2.8	.284	.271	.013	2.4
78	18	.299	.286	.013	2.2	.282	.271	.011	2.0
79	18	.301	.278	.023	4.0	2.85	.264	.021	4.2
80	18	.296	.288	.008	1.4	.280	.272	.008	1.4
81	18	.299	.287	.012	2.1	.282	.270	.008	1.4
82	18	.297	.286	.011	1.9	.281	.271	.010	1.8
83	18	.295	.284	.011	1.9	.282	.270	.012	2.2

C. Clad Thickness

Table VII shows the maximum and minimum readings and total variation of outer clad thickness as measured by both the metallograph and point micrometer techniques.

TABLE VII
OUTER CLAD THICKNESS

<u>Extrusion Number</u>	<u>Total Number of Readings</u>	<u>Metallograph</u>			<u>Point Micrometer</u>		
		<u>Max. Mils</u>	<u>Min. Mils</u>	<u>△ Mils</u>	<u>Max. Mils</u>	<u>Min. Mils</u>	<u>△ Mils</u>
72	36	26.0	20.0	6.0	27	22	5
73	36	26.1	20.0	6.0	25	22	3
74	36	26.0	20.0	6.0	26	22	4
75	36	25.9	20.0	5.9	25	22	3
76	36	25.8	20.0	5.8	26	22	4
77	36	25.8	21.0	4.8	26	22	4
78	36	27.7	21.2	6.5	25	23	2
79	36	27.7	20.4	7.3	26	22	4
80	36	26.2	21.0	5.2	26	23	3
81	36	26.9	20.8	6.1	27	22	5
82	36	28.5	20.0	8.5	27	22	5
83	36	27.0	20.6	6.4	26	21	5

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Table VIII shows the maximum and minimum readings and total variation of inner clad thickness as measured by both the metallograph and point micrometer techniques.

TABLE VIII
INNER CLAD THICKNESS

Extrusion Number	Total Number of Readings	Metallograph			Point Micrometer		
		Max. Mils	Min. Mils	△ Mils	Max. Mils	Min. Mils	△ Mils
72	36	28.0	20.5	7.5	29	22	7
73	36	26.0	20.0	6.0	27	20	7
74	36	27.0	19.6	7.4	27	22	5
75	36	24.8	19.2	5.6	26	21	5
76	36	26.9	20.5	6.4	27	21	6
77	36	26.8	19.6	7.2	26	21	5
78	36	25.9	19.7	6.2	26	21	5
79	36	27.1	19.6	7.5	27	20	7
80	36	27.0	20.7	6.3	27	22	5
81	36	28.5	19.2	9.3	27	21	6
82	36	25.3	20.0	5.3	27	22	5
83	36	25.8	20.0	5.8	26	22	4

D. Bonding

Table IX gives the bond ratings (peel test).

TABLE IX
BOND TESTS

Tube No.	O.D. Bond				Rating	I.D. Bond				Rating
	Good	Quest.	Fair	Poor		Good	Quest.	Fair	Poor	
72	6	2			3.75		7	1		2.88
73*	7	2			3.78	1	9			3.1
74	5	3			3.63		7	1		2.88
75	6	2			3.75	1	8			3.12
76	5	4			3.56	1	8			3.12
77	3	6			3.33	3	6			3.33
78	6	3			3.67		9			3.0
79	5	4			3.56	1	8			3.12
80*	2	3	2	2	2.56	1	8			3.12
81	3	5	1		3.23	1	9			3.1
82	4	5			3.45	2	7			3.23
83	3	3			3.50	1	7			3.13

Average O.D. = 3.47

Average I.D. = 3.09

*Leakers

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E. Interface Cleanliness Rating

The interface cleanliness ratings are given in Table X. The rating system is based on a numerical scale of 1 through 8 where 8 represents a metallurgically clean bond zone free from inclusions of any type.

TABLE X

Tube Number	Position Inches	O.D.			I.D.			Position Rating	Tube Rating
		0°	120°	240°	0°	120°	240°		
72	20	6	6	6	6	6	6	6.0	5.8
	91	6	7	6	6	7	7	6.5	
	193	5	4	5	5	6	4	5.8	
73	20	2	3	3	3	4	4	3.2	4.4*
	91	4	6	6	5	7	6	5.7	
	192	3	5	5	3	5	5	4.3	
74	20	1	1	1	1	1	1	1	2.2
	92	5	6	4	2	1	1	3.1	
	192	3	3	5	1	1	1	2.3	
75	20	5	5	5	1	1	2	3.1	4.7
	93	7	7	7	6	5	5	6.1	
	192	7	6	5	6	6	2	4.3	
76	20	5	5	5	6	5	6	5.3	5.5
	91	7	7	7	7	7	7	7	
	191	1	1	6	1	6	5	3.3	
77	20	5	4	6	5	6	6	5.3	5.8
	91	6	5	6	7	6	5	5.8	
	192	7	6	6	6	6	7	5.3	
78	20	7	7	5	6	6	6	6.1	5.8
	91	5	5	6	5	7	7	6.5	
	190	5	5	6	6	6	5	5.5	
79	20	6	5	6	6	6	7	6.0	5.7
	91	6	6	5	6	6	5	5.6	
	192	5	5	6	5	6	6	5.5	
80	21	1	1	1	2	1	1	1.1	2.2*
	92	5	5	6	2	1	1	3.3	
	191	5	1	1	2	2	2	2.1	
81	20	3	3	3	6	5	5	4.2	5.1
	91	5	5	6	7	7	7	6.2	
	192	5	4	4	5	5	6	4.8	

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<u>Tube Number</u>	<u>Position Inches</u>	<u>0°</u>	<u>120°</u>	<u>240°</u>	<u>0°</u>	<u>120°</u>	<u>240°</u>	<u>Position Rating</u>	<u>Tube Rating</u>
82	20	5	7	5	6	6	6	5.8	5.6
	91	6	6	5	5	6	6	5.6	
	192	6	6	5	5	6	6	5.6	
83	23	1	1	1	2	2	2	1.5	3.4
	91	5	6	6	6	5	7	5.8	
	191	4	4	5	1	2	2	3.0	

F. Uranium Grain Size

Table XI gives the uranium grain size measurements for these tubes.

TABLE XI
URANIUM GRAIN SIZE (MM)

<u>Tube Number</u>	<u>Location Inches</u>	<u>O.D.</u>	<u>Midwall</u>	<u>I.D.</u>
72	20	.035-.030	.035	.180
	91	.065-.030	.035	.150-.045
	193	.055-.030	.030	.045-.035
73	20	.035-.030	.035	.150-.130
	91	.035-.030	.045-.035	.110
	192	.035-.030	.035	.045
74	21	.030	.035-.030	.130-.110
	92	.030	.035	.130-.110
	192	.030	.035	.045
75	20	.030	.035	.150
	93	.030-.025	.035	.130
	197	.035-.030	.035	.045
76	20	.030	.030	.130
	91	.030	.035-.030	.130
	196	.030	.035-.030	.065-.060
77	20	.030-.025	.035-.025	.180-.130
	91	.035-.030	.035	.210-.150
	192	.030	.035	.065
78	20	.030	.035	.150-.110
	91	.035-.030	.035	.130
	190	.303	.035	.075
79	20	.035	.045	.150
	91	.035-.030	.045-.035	.110
	192	.030	.035	.065

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<u>Tube Number</u>	<u>Location Inches</u>	<u>O.D.</u>	<u>Midwall</u>	<u>I.D.</u>
80	21	.035-.030	.045-.035	.180-.150
	92	.030	.035	.150
	191	.035	.035	.065-.045
81	20	.055-.030	.045-.035	.150
	91	.045-.030	.045-.035	.130
	192	.035	.035	.065
82	20	.035-.030	.035	.150
	91	.035-.030	.035	.180-.150
	192	.030	.035	.075-.065
83	22	.035	.035	.180-.150
	91	.035-.030	.035	.150
	191	.030	.035-.030	.130-.110

J. W. Nickolaus, Manager
Coextrusion Shop

A. E. Guay, Engineer
Coextruded Product Engineering

JWN:AEG:ssst

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8/16/94

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