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METALLURGY AND CERAMICS

THE FABRICATION OF CLAD MASSIVE UO_2 FUEL ELEMENTS BY COEXTRUSION

Second Quarterly Report

By
F. S. Gardner
J. G. Hunt

January 14, 1960

Nuclear Metals, Inc.
Concord, Massachusetts

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Nuclear Metals, Inc.
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Contract No. AT(30-1)-1565

A. R. Kaufmann
Technical Director

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I. INTRODUCTION

This is the second quarterly report, covering the months of August, September, and October 1959, on "The Fabrication of Clad Massive UO_2 Fuel Elements by Coextrusion". The first report is NMI-2502, issued September 15, 1959. This work is being carried out under Contract AT(30-1)-1565 as part of the AEC Fuel Cycle Development Program.

The purpose of the clad UO_2 program has been to develop a fabrication method that is less expensive than the present production method of pressing powders into pellets, sintering, grinding, and inserting these pellets into a stainless steel or Zircaloy tube, and completing the end closure.

Effort during the last period has emphasized trials of different fabrication techniques evaluated by direct visual examination of the coextrusions. In the next quarter, more of these trials will be made and a reference type adopted.

II. SUMMARY

Promising samples of two potential types of metal-clad UO_2 rods have been produced. The first contains a stainless clad over an oxide core with an intervening layer of graphite about 15 mils thick. The second has a refractory metal cladding instead of stainless steel and no interlayer; here the tantalum used is only indicative of what might be expected with the more desirable metals, columbium and molybdenum.

A third type, in which the graphite layer will be eliminated, is under investigation.

All of these have the approximate dimensions, oxide density, and oxygen to uranium ratio of the present design of fuel element for the Yankee Power Reactor.

Cold pressing and heating of commercial, fused UO_2 in graphite heating cans has yielded coextrusions of encouraging quality with respect to dimensions and apparent density.

Additional evidence for the hot densification and plastic deformation of UO_2 during the extrusion has been obtained. Since UO_2 flows so well, it is likely that other ceramics would also, for example, uranium carbide.

Graphite sleeve components in coextrusion billets undergo considerable gross deformation but the density and mechanical properties of the graphite have not been evaluated after extrusion.

III. EXPERIMENTAL

A. Hot-pressed Bodies

Hot-pressed bodies were developed for trials in some of the extrusions to be described, because the extrudability of ceramic UO_2 was considered somewhat better after hot pressing than after cold pressing and simple heating. Six graphitic die sets were made for production of bodies one inch in diameter by two inches in length. To conserve press time, each die set was located in the press and induction coil for about one-half hour for heating and pressing, but was loaded and unloaded elsewhere. Operating conditions included a top temperature of 3182°F (1750°C), a top pressure of 2-1/2 tsi, and cooling periods, obtained by immediate partial disassembly of the graphite units, as short as one hour. In general, uncracked solid UO_2 bodies of more than 95% theoretical density were obtained. Since their surfaces were not consistently dense, however, they were ground to 7/8-inch diameter to assure smooth, hard exteriors; the front end of the core component was also ground to a 120° cone. On occasion, the compacts fractured into two or more pieces, in which case the ends were finish-ground and a multipiece assembly, approximately two inches long, was made up. The use of Crystolon (bonded SiC) grinding wheels lubricated with soluble oil has been found satisfactory.

B. Starting Materials

During this period, only two types of commercial UO_2 have been employed, ceramic and fused (see Table I of NMI-2502).

C. Billet Design

Probably the most important single variable of this program has been the billet design adopted to achieve multitemperature rod coextrusion of a hot oxide core in a cold steel shell. Up to this time, six different designs have been evaluated. After Design I, described earlier, an attempt was made to heat bare, hot-pressed oxide bodies (Design II), but this could not even be extruded because of the poor thermal shock resistance of the oxide bodies which, on heating, consistently fractured and fell to the floor of the heating susceptor. Thereafter, placement of the UO_2 body in a 3/8-inch thick graphite heating can on an insulated handle was adopted to assure achievement of desired temperature of the core component, regardless of thermal-shock fracture (Design III, see Fig. 1). The next design was intended to avoid the graphite-UO_2 reaction, which sets in at about 3272°F (1800°C), according to Williams,[1] and leads to formation of uranium carbide. For this, a tantalum can on a tantalum handle was adopted for heating in a graphitic susceptor (Design IV, see Fig. 2). In Designs IV and V, a 1/4-inch thick stainless sleeve lined the inside of the shell, not to simulate a cladding in the final extrusion, but to test the possibility that a "stiffer" shell aided extrudability. Design V represented a modification of Design III (see Fig. 3), the wall thickness of the graphite heating can being reduced from 3/8 inch to 1/8 inch, and the difference given over to the stainless steel sleeve now residing in the cold-rolled steel shell. Finally, because this design gave favorable results, a billet was designed to duplicate as closely as possible a Yankee Reactor stainless steel clad fuel element.[2] Wherein the graphite can wall thickness ranged between 0.022 and 0.062 inch, and the stainless sleeve thickness was dropped to 0.063 inch (Design VI, see Fig. 4).

D. Equipment

The extrusion press was the same as described previously. However, the original induction furnace proved inadequate (Fig. 5), requiring a second induction furnace with a smaller susceptor to be built for heating of oxide cores to temperatures as high as 4532°F (2500°C) (Fig. 6). Both furnace designs have been energized with 3000 cycles ac at powers up to 60 kw.

E. Pre-extrusion Experimental Conditions

The various approaches to extrusion preparation conducted during this period are to be seen in Table I, in which the extrusions are listed in six horizontal groups, each representing an extrusion campaign of approximately a half day in duration.

F. Extrusion Pressures and Constants

One trend in the current period has been to drop the temperature of the extrusion billet shell, thereby increasing the extrusion force from 200/300 tons to 400/600 tons, and in turn increasing the extrusion pressures from 40/50 tsi to 75/85 tsi. There has been a corresponding change in the apparent extrusion constant from 20/25 tsi up to 30/35 tsi. Further increases of these forces and pressures, summarized in Table II, are not possible because the top ram pressure permitted with the containers and rams now available for this work is 100 tsi.

G. Evaluation Methods

It will be noted later that an improved method of sectioning samples has been employed to reveal results of the most recent Design VI extrusions. The use of Crystolon (SiC bonded) grinding wheels, cutting transversely, has been helpful in minimizing "pull-out" or accidental removal of solid UO_2 to create a void. Even with this improvement, however, it is still necessary when viewing such surfaces to make allowance for "pull-out". Density measurements on adjacent samples will be taken to establish the extent that these voids are indeed "pull-out" and not the result of extrusion.

IV. RESULTS

A. Importance of Billet Design and Oxide Temperature

One of the major process variables has turned out to be the design of the billet cross section, aside from considerations of end shape. Hereunder came the proper selection of composition and dimensions of the several sleeves making up the cross section. A second very important parameter has been the oxide temperature just prior to loading. In view of this, a summary table for the period to show all extrusions has been arranged by billet design and oxide heating temperature (Table III). This is not to say that other factors are not important, since one of the biggest improvements in extrusion quality has resulted from lowering the temperature of the outer steel shell.

B. Characterization

For exploratory evaluation, it is most helpful to compare the experimental extrusions with an imaginary length of ideal stainless-clad UO_2 fuel rod. From the start, this has been visualized as a smooth cylindrical oxide surface, free from edge cracks or axial taper, having a dense, crack-free bulk about 1/3-inch diameter, and a cladding smooth on both the inside and outside, with a uniform thickness of about 23 mils. No effort has been made to achieve integral end seals, since this is known to be relatively difficult; furthermore, the availability of welded end closures makes it unnecessary at this time.

The extent to which the experimental extrusions approached the ideal is given in Table IV, which employs the system of rating used previously. Of the ratings, the most important are now:

Oxide Diameter Rating - This measures all oxide surface defects, particularly shallow transverse cracks of significant width (edge checks), and total transverse cracks (wafering). For examples, see extrusions 21807 and 21930, respectively.

Oxide Soundness Rating - This reflects bulk defects of all kinds, but particularly internal cracks, transverse, longitudinal, or circumferential, as evidenced in extrusions 21923 through 21928.

Clad Thickness Rating - Here are included such undesired clad properties as a pebbly surface texture (orange-peeling), oxide penetration into the cladding, and variable thickness. Extrusions 21923 through 21928 provide illustrations of each.

Potential Rating - This is an over-all rating of the value of continuing to develop the subject type and kind of extrusion. The favorable listings for this screening were as follows:

Extrusion No.	Design No.	Oxide Temperature		Potential Rating
		(°F)	(°C)	
21476	III	3182	1750	Good
21806	V	3182	1750	Fair
21807	V	3676	2025	Fair
21861	IV	3632	2000	Good
21862	IV	4172	2300	Fair
21882	V	3182	1750	Fair
21923	VI	3182	1750	Good
21924	VI	3182	1750	Fair
21926	VI	2822	1550	Fair
21927	VI	2822	1550	Fair
21929	IV	3182	1750	Good

The general characteristics of Designs I, III, IV, V and VI are to be seen in macrophotographs of longitudinal sections, Figs. 7 to 11, respectively.

C. Demonstration of Technical Feasibility

In this exploratory group, the manner and quantity of the extrusions have been selected to provide qualitative information. This also leads, logically, to a presentation of results in terms of the major and minor process variables encountered, and one or two combinations which were evaluated as so favorable that their feasibility was demonstrated (see Table V).

Note that combination No. 1 is based on results from extrusion No. 21923, described earlier as having a potential rating of "good". This is the best example from those extrusions in which a graphite heating can was employed. Similarly, combination No. 2 is based on results from extrusion No. 21861, also having a potential rating of "good", and being the best sample so far from those in which a tantalum heating can was used.

While the two combinations cited are those for two particular extrusions, their validity is also supported by the results from all the other extrusions so far made.

D. Density and O/U Ratio of Selected Samples

A few density measurements of the hot-pressed oxide bodies indicate that this property is somewhat variable, running between 9.5 and 10.5 g/cc (see Table VI). Spot checks of the O/U ratio of the extruded oxide show that it lies between 2.00 and 2.10. For example, note that this property for "good" extrusion No. 21476 is 2.04. Also, selected measurements of the density of extruded oxide show that it is probably greater than 10.39 g/cc. According to Gronvold,[3] the calculated x-ray density (theoretical density) of $UO_{2.00}$ is 10.95; increasing for $UO_{2.25}$ to 11.30, and decreasing thereafter for $UO_{2.66}$ to 8.4.

E. Discussion of Results

1. Approximately 28 coextrusions have been made in the last three-month period, affording an evaluation of five different billet designs. In these, the oxide core has always been heated in a can which became part, or all, of the cladding. Another billet design is needed offering greater flexibility in the choice of cladding, or even the elimination of it.

2. Billet designs incorporating a graphite heating can yield coextrusions having a potential rating of "good" (Designs III, V, and VI). Extrusions from Designs V and VI represent possible fuel element prototypes, since they have only a thin layer of graphite inside stainless steel cladding of usual thickness. Attainment of specific thicknesses are tentatively indicated simply by proper design of the wall thickness in the billet component and proper choice of extrusion reduction.

3. A billet design (Design IV) for which the heating can is of tantalum also produces coextrusions with a potential rating of "good", assuming, of course, that simple replacement of the tantalum component by columbium or molybdenum is now feasible.

4. The original billet design (Design I) employing a heating can of stainless steel is unsatisfactory because its melting range limits the maximum oxide temperature to about 2450°F (1343°C).

5. The billet concept (Design II), wherein preformed and bare UO_2 bodies are supported and heated to extrusion temperature in an inert gas protected chamber, is experimentally difficult and so far impractical because of the poor thermal shock properties of the oxide.

6. Cold-pressed ceramic powder, hot-pressed ceramic bodies, and cold-pressed, fused aggregates have been tried as UO_2 loadings in graphite or tantalum heating cans. Under the conditions employed, the quality of the extruded core is best in the hot-pressed bodies and worst in the cold-pressed, with the fused aggregate in an encouraging intermediate position. Application of these findings to other ceramic materials is suggested for future work.

7. Preformed UO_2 bodies, 7/8-inch diameter by 2 inches long, may be hot pressed from the ceramic powder to densities of at least 10.54 g/cc.

8. Hot-pressed and coextruded UO_2 has been reduced up to 12.3X yielding oxide fragments with densities of 10.44 and 10.39 g/cc in two separate coextrusions (Design III).

9. Intermediate core heating temperatures between 1750 and 2000°C yield the best appearing oxide and cladding-oxide interface. Temperatures between 1450°F (788°C) and 4532°F (2500°C) have been tried. The lower temperatures are associated with inadequate plastic flow, while the higher yield excessive cracking and void formation in the UO_2.

10. By decreasing the temperature of the cold-rolled steel shell from 1750°F (954°C) to 1200°F (649°C), the extrusion pressure may be maintained between 75 and 85 tsi, thereby achieving oxide of high fragment density and superior soundness. Such high hydrostatic pressure is also associated with a relatively uniform oxide diameter and a smooth interface. Further reductions of shell temperature deserve attention.

11. The O/U ratio of starting materials with satisfactory extrudability lies between 2.00 and 2.10. Addition of oxygen during preparation for extrusion has not been a necessary step, either for the ceramic or fused grades of UO_2 employed in this work.

12. Coextrusions have been made with cross sections approximating that of a Yankee Reactor fuel element [stainless-clad (21-mil wall) UO_2 pellet element of 294 mils diameter].

13. In coextrusion billets, graphite sleeves with wall thicknesses varying between 0.062 and 0.250 inch may be extruded with reductions of about 10X (Designs III and VI).

V. CONCLUSIONS

1. Two different types of clad UO_2 rod extrusions have been made in sufficient numbers and of such quality that they demonstrate technical feasibility.

2. Because the stainless-clad UO_2 fuel element planned for the Yankee Reactor has been selected for comparative testing of the subject method, it will be necessary to perfect a third fabrication, duplicating the Yankee element more exactly.

3. More characterization work is necessary. At this point, however, it can be said that UO_2 densities of at least 10.4 g/cc are available with oxygen to uranium ratios of less than 2.10, and that surface smoothness and interface roughness are not so good as obtained in usual metal-over-metal coextrusions.

VI. OTHER WORK

Limited study has been given during the period to a number of items of preliminary status, but potentially great importance. Included are:

1. The probable irradiation behavior of the subject kind of fuel element, especially ratcheting.

2. An economic comparison with the conventional element made from sintered and ground pellets.

3. Steps necessary for elimination of the graphite intermediate layer, namely the design of an inductively-heated device combining the operations of hot pressing, core heating, and core ejecting, and establishment of the conditions for electrical heating of UO_2 dense bodies.

4. Nondestructive evaluation of pickled rods with high voltage radiography.

VII. REFERENCES

1. J. Williams, 4th International Electronics and Nuclear Conf., 1957, Vol. 1, Nuclear Session.

2. R. Schettig and R. King, YAEC-148, August, 1959.

3. Frederik Gronvold, J. Inorganic and Nuclear Chemistry, 1955, Vol. 1, pp. 357-370, p. 357.

Table I - Pre-extrusion Experimental Conditions for All UO_2 Extrusions* (August 1 - October 31, 1959)

Date	Extrusion No.	Oxide Mat'l Type (1)	Oxide Mat'l Wt. (gms)	Can Design No.	Can (Incl. Foil Liner) Mat'l	Can (Incl. Foil Liner) Wall (in.)	Shell (Incl. Sleeve) Mat'l	Shell (Incl. Sleeve) Wall (in.)	Can Temp. (°F)	Shell Temp. (°F)	Die ID (in.)	Reduction (X)	Lubricant	Cut-off Mat'l
8-13	21446	HP	180	I	SS	0.063	CR	0.775	2450	1750	1.000	7.8	Glass	Gr
	21447	Ceramic	85	I	SS	0.063	CR	0.775	2050	1750	1.000	7.8	Glass	Gr
	21448	Ceramic	85	I	SS	0.063	CR	0.775	1750	1750	1.000	7.8	Glass	Gr
	21449	Ceramic	85	I	SS	0.063	CR	0.775	1450	1750	1.000	7.8	Glass	Gr
8-19 and 8-20	21474	HP	158	III	Gr	0.375	CR	0.525	3182	1750	0.900	9.6	Gr+Oil	Gr
	21475	Shot	175(2)	III	Gr	0.375	CR	0.525	3182(2)	1100	0.900	9.6	Gr+Oil	Gr
	21476	HP	178	III	Gr	0.375	CR	0.525	3182	1400	0.900	9.6	Gr+Oil	Gr
	21477	Ceramic	250	III	Gr	0.375	CR	0.525	3360	1400	0.900	9.6	Gr+Oil	Gr
10-2	21806	HP	202	V	Gr Ta	0.125 Foil	CR SS	0.463 0.250	3182	1400	0.900	9.6	Gr+Oil	Gr
	21807	HP	216	V	Gr Ta	0.125 Foil	CR SS	0.463 0.250	3676	1400	0.900	9.6	Gr+Oil	Gr
	21808	HP	189	V	Gr Ta	0.125 Foil	CR SS	0.463 0.250	4172	1400	0.900	9.6	Gr+Oil	Gr
	21809	HP	203(3)	V	Gr	0.125	CR SS	0.463 0.250	3182(3)	1400	0.900	9.6	Gr+Oil	Gr
	-	HP	165(4)	V	Gr	0.125	CR SS	0.463 0.250	3676(4)	1400				
10-14	21860	None	None(5)	-	None	None	CR SS	0.463 0.250	None(5)	1200	0.900	9.6	Gr+Oil	Gr
	21861	HP	221	IV	Ta	0.060	CR SS	0.463 0.250	3632	1200	0.900	9.6	Gr+Oil	Gr
	21862	HP	162	IV	Ta	0.060	CR SS	0.463 0.250	4172	1200	0.900	9.6	Gr+Oil	Gr
	-	HP	168(4)	IV	Ta	0.060	CR SS	0.463 0.250	4532(4)	1200				
10-20	21880	HP	168	IV	Ta	0.060	CR SS	0.463 0.250	4532	1200	0.900	9.6	Gr+Oil	CR
	21881	HP	168(4)	IV	Ta	0.060	CR SS	0.463 0.250	4802(4)	1200				
	21882	Fused	148	V	Gr	0.125	CR SS	0.463 0.250	3182	1200	0.900	9.6	Gr+Oil	CR
	21883	HP	138	V	Gr	0.125	CR SS	0.463 0.250	3632	1200	0.900	9.6	Gr+Oil	CR
	21884	Fused	114	V	Gr Ta	0.125 Foil	CR SS	0.463 0.250	4172	1200	0.900	9.6	Gr+Oil	CR

(Cont'd. on next page)

Table I (Cont'd.)

Date	Extrusion No.	Oxide Mat'l		Can Design No.	Can (Incl. Foil Liner)		Shell (Incl. Sleeve)		Can Temp. (°F)	Shell Temp. (°F)	Die ID (in.)	Reduction (X)	Lubricant	Cut-off Mat'l
		Type (1)	Wt. (gms)		Mat'l	Wall (in.)	Mat'l	Wall (in.)						
10-27	21923	HP	201	VI	Gr	0.055	CR	0.744	3182	1200	0.900	9.6	Gr+Oil	CR
							SS	0.063						
	21924	Fused	140	VI	Gr	0.031	CR	0.744	3182	1200	0.900	9.6	Gr+Oil	CR
							SS	0.063						
	21925	HP	204	VI	Gr	0.022	CR	0.744	3182	1200	0.900	9.6	Gr+Oil	CR
							SS	0.063						
	21926	HP	205	VI	Gr	0.055	CR	0.744	2822	1200	0.900	9.6	Gr+Oil	CR
							SS	0.063						
	21927	Fused	140	VI	Gr	0.031	CR	0.744	2822	1200	0.900	9.6	Gr+Oil	CR
							SS	0.063						
	21928	HP	215	VI	Gr	0.022	CR	0.744	2822	1200	0.900	9.6	Gr+Oil	CR
							SS	0.063						
	21929	HP	169	VI	Ta	0.060	CR	0.463	3182	1200	0.900	9.6	Gr+Oil	CR
							SS	0.250						
	21930	HP	192	I	SS	0.063	CR	0.775	2400	1200	0.900	9.6	Gr+Oil	CR
	21931	Fused	140	I	SS	0.063	CR	0.775	2400	1200	0.900	9.6	Gr+Oil	CR

* Liner Temp., 900°F; Liner ID, 2.800 inches; Die Land, 0.200 inch.

(1) All hot-pressed bodies were approximately 0.875 inch in diameter. Oxide powders or aggregates were cold-pressed in a can of 0.875-inch ID.

(2) Press stalled.

(3) Can dropped in furnace. Shell extruded empty.

(4) Can dropped in furnace. Shell not extruded.

(5) Test extrusion of shell only.

List of Abbreviations: HP = Hot-pressed; CR = Cold-rolled steel; NR = Not recorded; SS = Stainless steel; Gr = Graphite

Table II - Extrusion Pressures and Constants

Extrusion No.	Force (tons)			Pressure (tsi) on 6.15 in.^{2}			Reduction (X)	2.3 log R	Composite $K = \frac{P}{2.3 \log R}$ (tsi)			Can Temp. (°F)	Shell Temp. (°F)
	Upset	Oxide	Final	Upset	Oxide	Final			Upset	Oxide	Final		
21446	305	290	270	50	47	44	7.8	2.05	24	23	21	2450	1750
21447	335	345	280	55	56	46	7.8	2.05	27	27	22	2050	1750
21448	305	305	260	50	50	42	7.8	2.05	24	24	20	1750	1750
21449	250	290	235	41	47	38	7.8	2.05	20	23	19	1450	1750
21474	NR	NR	NR	NR	NR	NR	9.6	2.26	NR	NR	NR	3182	1750
21475	575	(Stall)		94	(Stall)		9.6	2.26	42	(Stall)		3182(1)	1100
21476	480	375	300	78	61	49	9.6	2.26	35	27	22	3182	1400
21477	505	375	295	82	61	48	9.6	2.26	36	27	21	3360	1400
21806	420	380	-	68	62	-	9.6	2.26	30	27	-	3182	1400
21807	365	330	330	59	54	54	9.6	2.26	26	24	24	3676	1400
21808	370	315	325	60	51	53	9.6	2.26	27	23	23	4172	1400
21809	400	370	-	65	60	-	9.6	2.26	29	27	-	3182(2)	1400
-	-	-	-	-	-	-	9.6	2.26	-	-	-	3676(3)	1400
21860	505	450	-	82	73	-	9.6	2.26	36	32	-	None(4)	1200
21861	485	-	-	79	-	-	9.6	2.26	35	-	-	3632	1200
21862	480	430	-	78	70	-	9.6	2.26	35	31	-	4172	1200
-	-	-	-	-	-	-	9.6	2.26	-	-	-	4532(3)	1200
21880	460	400	425	75	65	69	9.6	2.26	33	29	31	4532	1200
21881	-	-	-	-	-	-	9.6	2.26	-	-	-	4802(3)	1200
21882	425	400	470	69	65	76	9.6	2.26	31	29	34	3182	1200
21883	480	430	510	78	70	83	9.6	2.26	35	31	37	3632	1200
21884	455	390	525	74	63	85	9.6	2.26	33	28	38	4172	1200
21923	470	430	540	76	70	88	9.6	2.26	34	31	39	3182	1200
21924	450	400	485	73	65	79	9.6	2.26	32	29	35	3182	1200
21925	420	390	495	68	63	80	9.6	2.26	30	28	36	3182	1200
21926	535	460	530	87	75	86	9.6	2.26	39	33	38	2822	1200
21927	510	455	500	83	74	81	9.6	2.26	37	33	36	2822	1200
21928	475	410	500	77	67	81	9.6	2.26	34	30	36	2822	1200
21929	500	460	490	81	75	80	9.6	2.26	36	33	36	3182	1200
21930	475	410	470	77	67	76	9.6	2.26	34	30	34	2400	1200
21931	460	415	450	75	67	73	9.6	2.26	33	30	32	2400	1200

(1) Press stalled. (2) Can dropped in furnace. Shell extruded empty. (3) Can dropped in furnace. Shell not extruded. (4) Test extrusion of shell only.

Table III - Extrusion Numbers Arranged by Billet Design and Oxide Temperature

Core Design No.	Core Mat'l	Shell Mat'l	Heating Temperature							
			°C	788/1121	1315/1343	1550	1750	2000	2300	2500
			°F	1450/2050	2400/2450	2822	3182	3632	4172	4532
I	SS	CR		21447(a) 21448(a) 21449(a)	21446(a) 21930(b) 21931(c)					
III	Gr	CR					21474(b) 21476(b) 21477(a)			
IV	Ta	SS+CR					21929(b)	21861(b)	21862(b)	21880(b)
V	Gr	SS+CR					21806(b,d) 21882(c)	21807(b,d) 21883(b)	21808(b,d) 21884(c)	
VI	Gr	SS+CR				21926(b) 21927(c) 21928(b)	21923(b) 21924(c) 21925(b)			

Footnotes:
(a) Heating can loaded with ceramic oxide.
(b) Heating can loaded with hot-pressed ceramic oxide.
(c) Heating can loaded with fused oxide.
(d) Heating can lined with 0.003-inch tantalum foil.

Table IV - Results of Visual Examination

Extrusion No.	Est'd Oxide Length Tip-to-tip (in.)	Approx. Oxide Length Increase Factor	Oxide Dia. Min (1/16)	Oxide Dia. Max (1/16)	Oxide Dia. Rating	Extruded Can				Extruded Sleeve				Oxide Soundness Rating			Actual Macro Appearance	Potential Rating (**)
						Mat'l	Thickness 1/64" (Min)	Thickness 1/64" (Max)	Rating	Mat'l	Thickness 1/64" (Min)	Thickness 1/64" (Max)	Clad Rating	Cracks	Pores	Shape		
21446	7-1/2	3.8	4	7	Poor	SS	1	7	Poor	None				Fair	Poor	Poor	Fig. 7	
21447	4	2.0	4	6	Poor	SS	2	5	Poor	None				Fair	Poor	Poor	Fig. 7	
21448	4-1/4	2.1	4	7	Poor	SS	0	7	Poor	None				Poor	Poor	Poor	Fig. 7	
21449	4-3/4	2.4	2	9	Poor	SS	1	8	Poor	None				Poor	Fair	Poor	Fig. 7	
21474	12-3/4	7.3	4	10	Poor	Gr	2	16	Poor	None				Poor	Poor	Poor	Fig. 8	
21476	15-1/2	8.8	3	5	Fair	Gr	5	9	Fair	None				Good	Good	Good	Fig. 8	Good
21477	13-1/4	4.4	6	9	Poor	Gr	1	12	Poor	None				Fair	Fair	Good	Fig. 8	
21806	16	7.1	4	5	Fair	Gr TA	2	6	Poor	SS	4	8	(*)	Fair	Good	Fair	Fig. 10	Fair
21807	15-3/4	7.0	5	5	Poor	Gr TA	1	2	Fair	SS	4	8	(*)	Fair	Fair	Good	Fig. 10	Fair
21808	17	7.5	4	6	Poor	Gr TA	2	7	Poor	SS	6	8		Fair	Poor	Poor	Fig. 10	
21861	18-1/2	8.2	4	4	Good	TA	2	2	Good	SS	7	7	(*)	Fair	Good	Good	Fig. 9	Good
21862	19-1/2	8.7	4	4	Good	TA	2	10	Fair	SS	7	15	(*)	Fair	Fair	Fair	Fig. 9	Fair
21880	15	6.7	3	4	Fair	TA	0	2	Fair	SS	7	7	(*)	Fair	Poor	Fair	Fig. 9	
21882	17	7.5	4	4	Good	Gr	2	3	Good	SS	7	7	(*)	Fair	Fair	Good	Fig. 10	Fair
21883	14-1/4	6.3	3	4	Fair	Gr	2	3	Fair	SS	6	8	(*)	Poor	Poor	Poor	Fig. 10	
21884	18-1/4	8.1	4	4	Fair	Gr TA	2	4	Fair	SS	7	8	(*)	Poor	Poor	Fair	Fig. 10	
21923	18	8.0	5	5	Good	Gr	1	1	Good	SS	1	2	Good	Good	Good	Good	Fig. 11	Good
21924	13	5.8	4	5	Good	Gr	1	2	Fair	SS	1	2	Fair	Fair	Fair	Fair	Fig. 11	Fair
21925	15-1/2	6.9	4	5	Good	Gr	1/2	3	Poor	SS	1	2	Poor	Fair	Fair	Poor	Fig. 11	
21926	14-1/4	6.3	4	6	Good	Gr	0	1	Good	SS	1/2	2	Good	Fair	Good	Fair	Fig. 11	Fair
21927	12-3/4	5.7	4	5	Good	Gr	0	1/2	Fair	SS	1	2	Fair	Fair	Fair	Fair	Fig. 11	Fair
21928	16-1/4	7.2	5	6	Good	Gr	0	1/2	Poor	SS	0	2	Poor	Fair	Fair	Poor	Fig. 11	
21929	14-1/2	6.4	4	5	Good	Ta	2	2	Good	SS	7	9	(*)	Fair	Good	Good	Fig. 9	Good
21930	14-1/4	6.3	5	6	Fair	SS	1	2	Fair	None				Poor	Poor	Fair	Fig. 7	
21931	8-1/4	3.7	5	6	Poor	SS	1	3	Poor	None				Poor	Poor	Poor	Fig. 7	

* Stainless steel sleeve is too thick for potential clad.
** Only Fair and Good extrusions are indicated; the rest are poor.

Table V - Indicated Major and Minor Process Variables, and Two Potential Process Combinations

	Process Variables	Process Combination No. 1*	Process Combination No. 2**
Major	1. Billet Design		
	A. Heating Can Mat'l	Graphite	Tantalum
	B. Heating Can Wall Thickness	0.022 inch	0.063 inch
	C. Heating Can Temperature	3182°F (1750°F)	3632°F (2000°C)
	D. Shell Mat'l and Wall Thickness	0.745-inch Cold-rolled Steel and 0.063-inch Stainless Steel Sleeve	0.463-inch Cold-rolled Steel and 0.250-inch Stainless Steel Sleeve
	E. Shell Temperature	1200°F (649°C)	1200°F (649°C)
	2. Starting Materials		
	A. Type Oxide	Hot-pressed	Hot-pressed
Minor	3. Billet Design		
	A. Cut-off Mat'ls and Designs	Steel	Steel
	B. Front and Rear End Design	Optional at present	Optional at present
	4. Tools and Press		
	A. Lubrication	Graphite and Oil	Graphite and Oil
	B. Ram Speed	130 in./min	130 in./min
	5. Other		
	A. Reduction	9.6X	9.6X
	B. Die Land	0.2 inch	0.2 inch

* Based on billet design VI, extrusion 21923.
** Based on billet design IV, extrusion 21861.

Table VI

Density and Oxygen to Uranium Ratio of Selected Samples

Kind of Sample	Sample Identity	Density				O/U Ratio
		Weight (gms)	No. of Pieces	(g/cc)	Percent Theoretical	
Extrusion	21476	1.0	4 to 5	10.439	95.24	2.04
	21477	1.2	4 to 5	10.391	94.64	2.10
Hot-pressed Body	6 or 8	48.2	1	9.494		
	6 or 8	32.6	1	10.030		
	6 or 8	26.3	1	10.049		
	7	7.6	1	10.231		
	10	59.7	1	10.141		
	12	158.3	1	10.202		
	25	178.8	1	10.539		

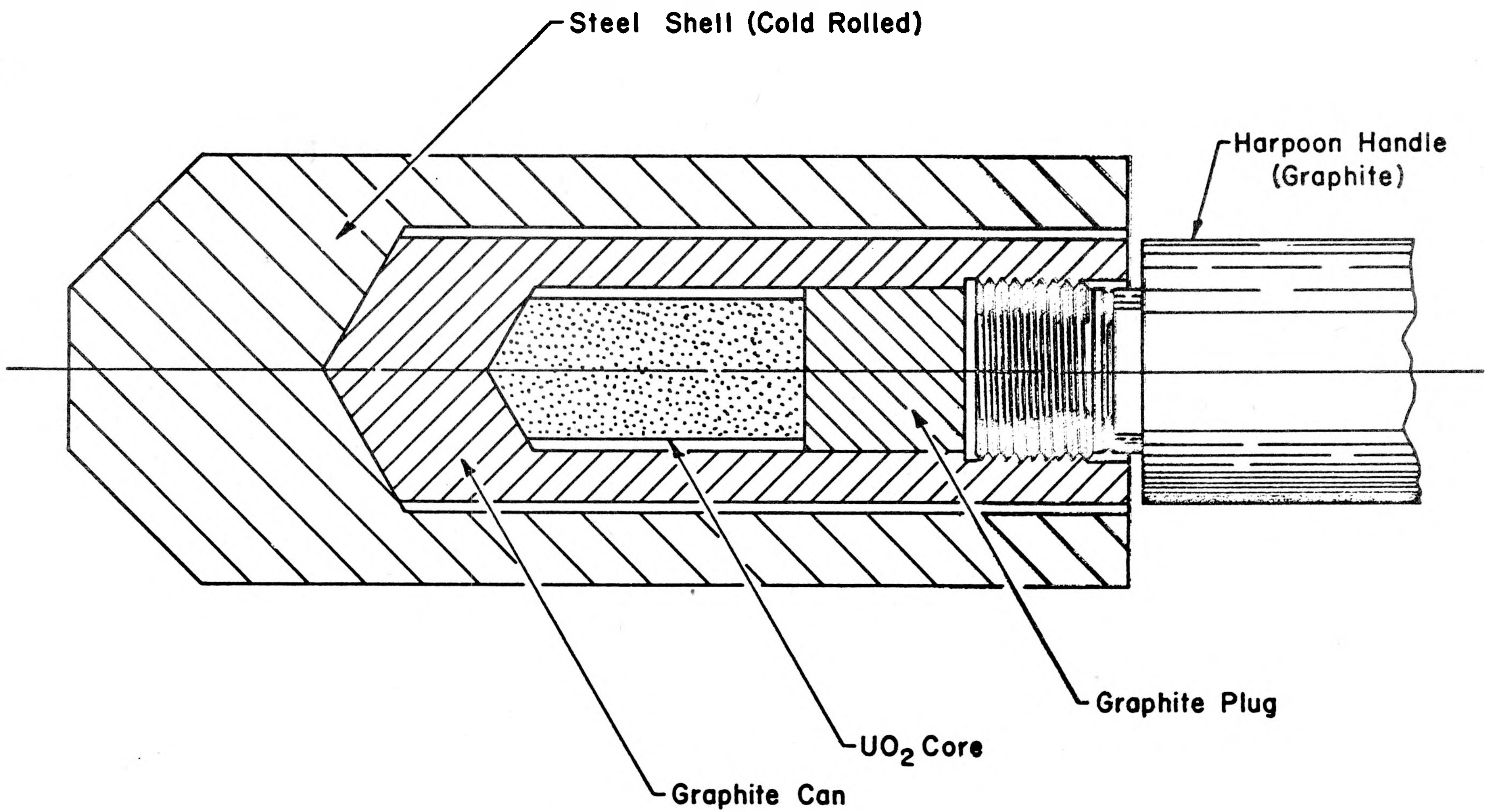

Fig. 1 - Billet design for Design III extrusions.
Drawing No. RA-1399.

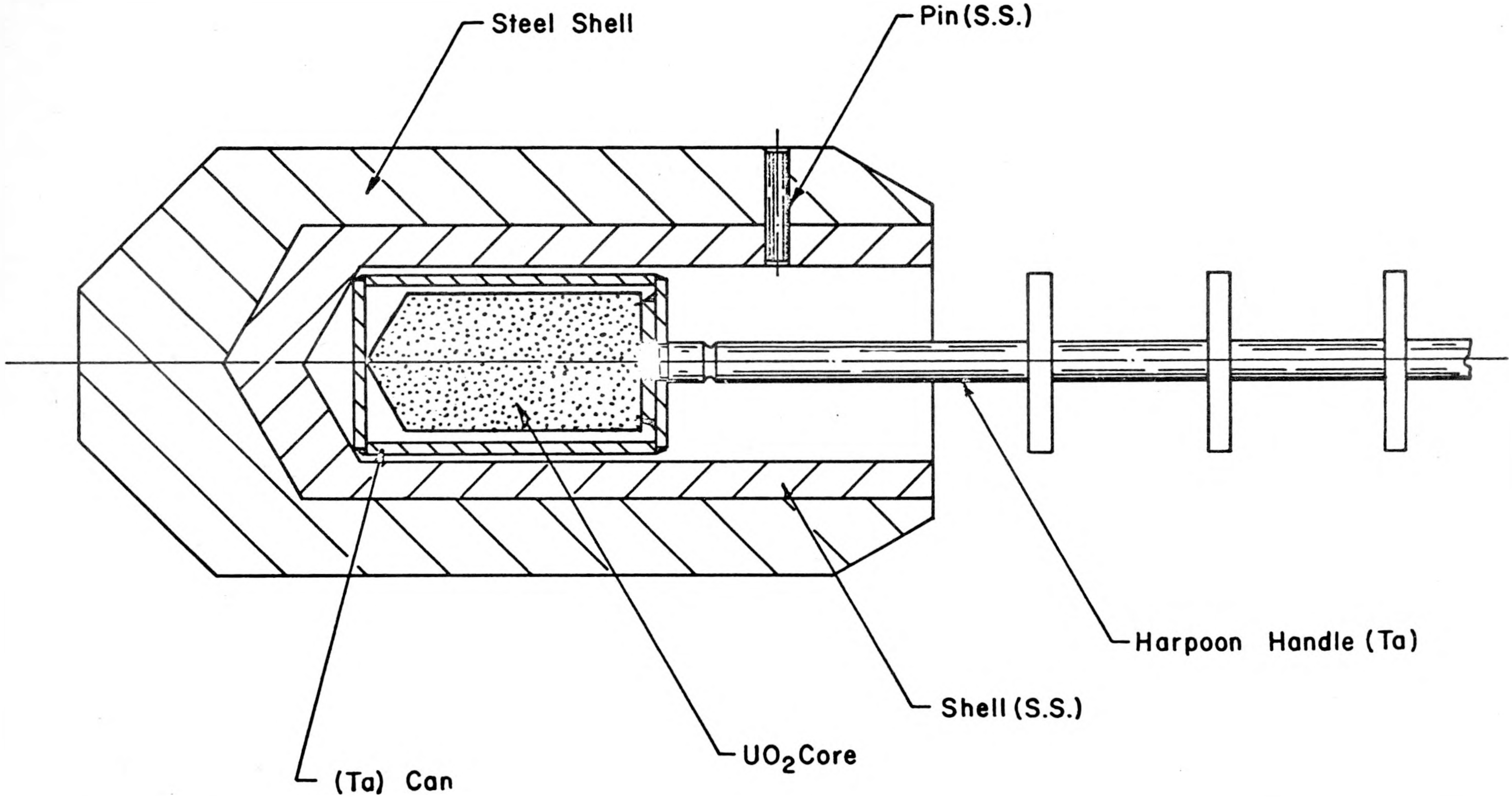

Fig. 2 - Billet design for Design IV extrusions.
Drawing No. RA-1400.

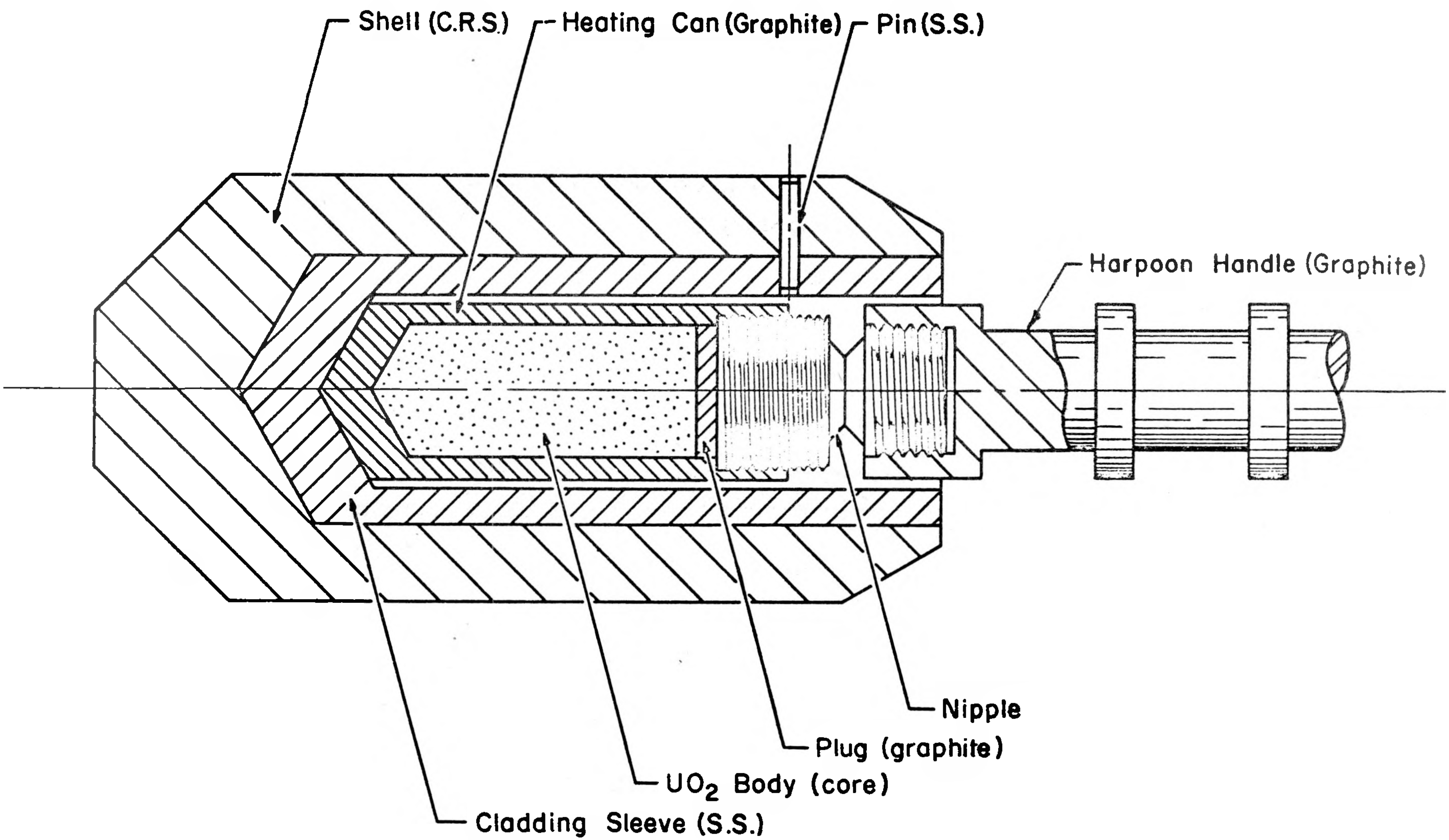

Fig. 3 - Billet design for Design V extrusions. Drawing No. RA-1398.

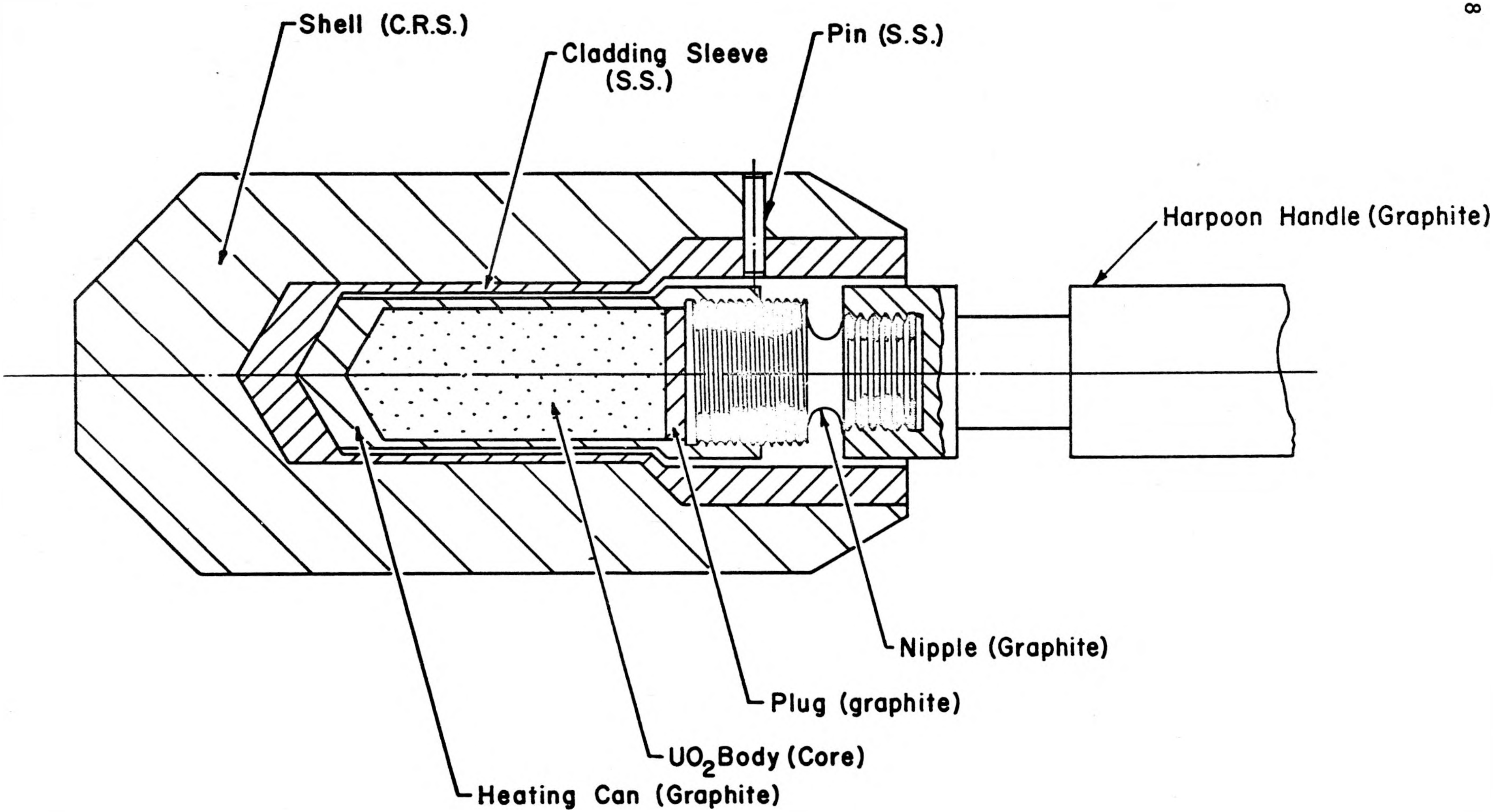

Fig. 4 - Billet design for Design VI extrusions. Drawing No. RA-1397.

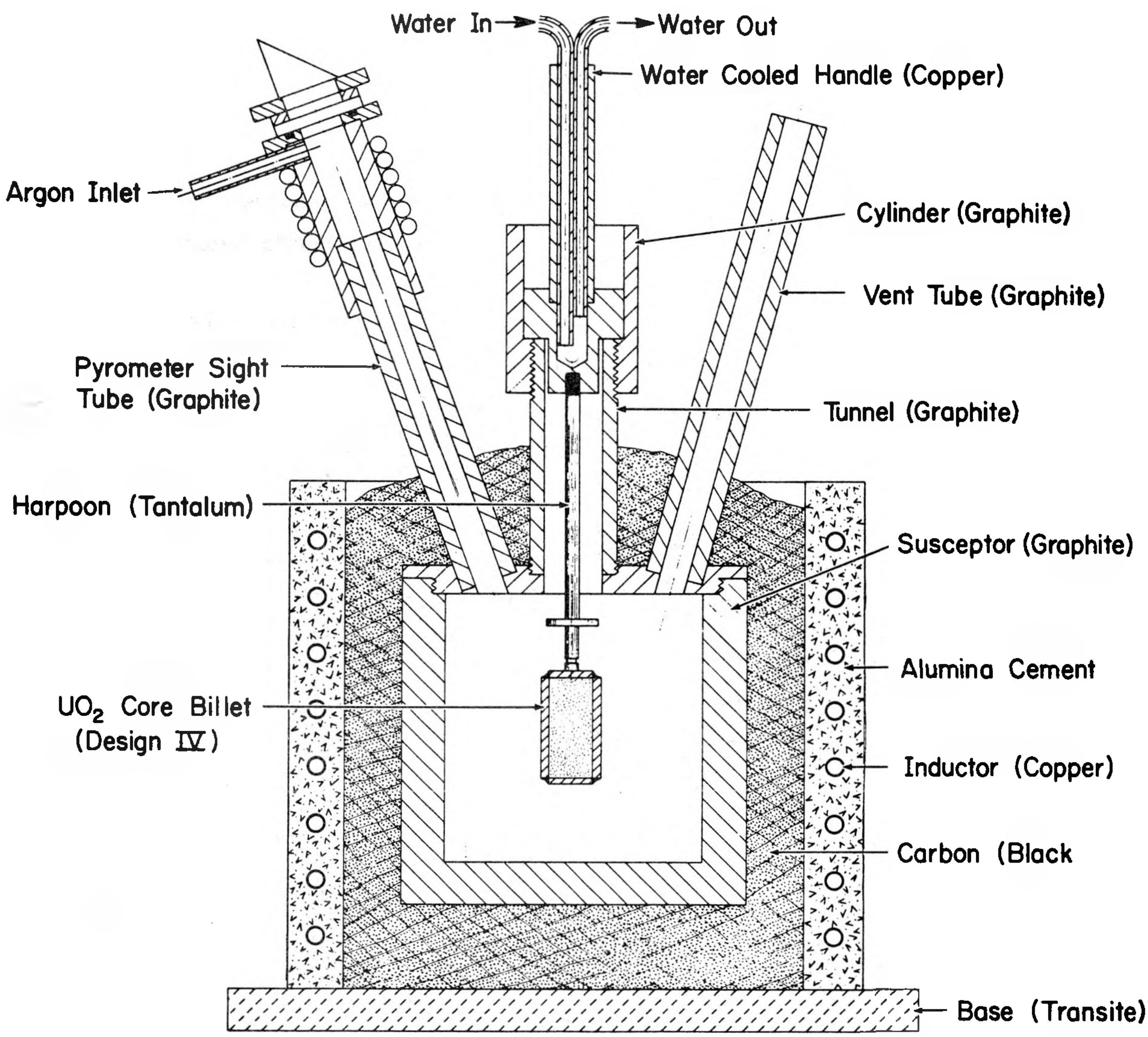

Fig. 5 - First furnace to heat UO_2 to high temperatures.

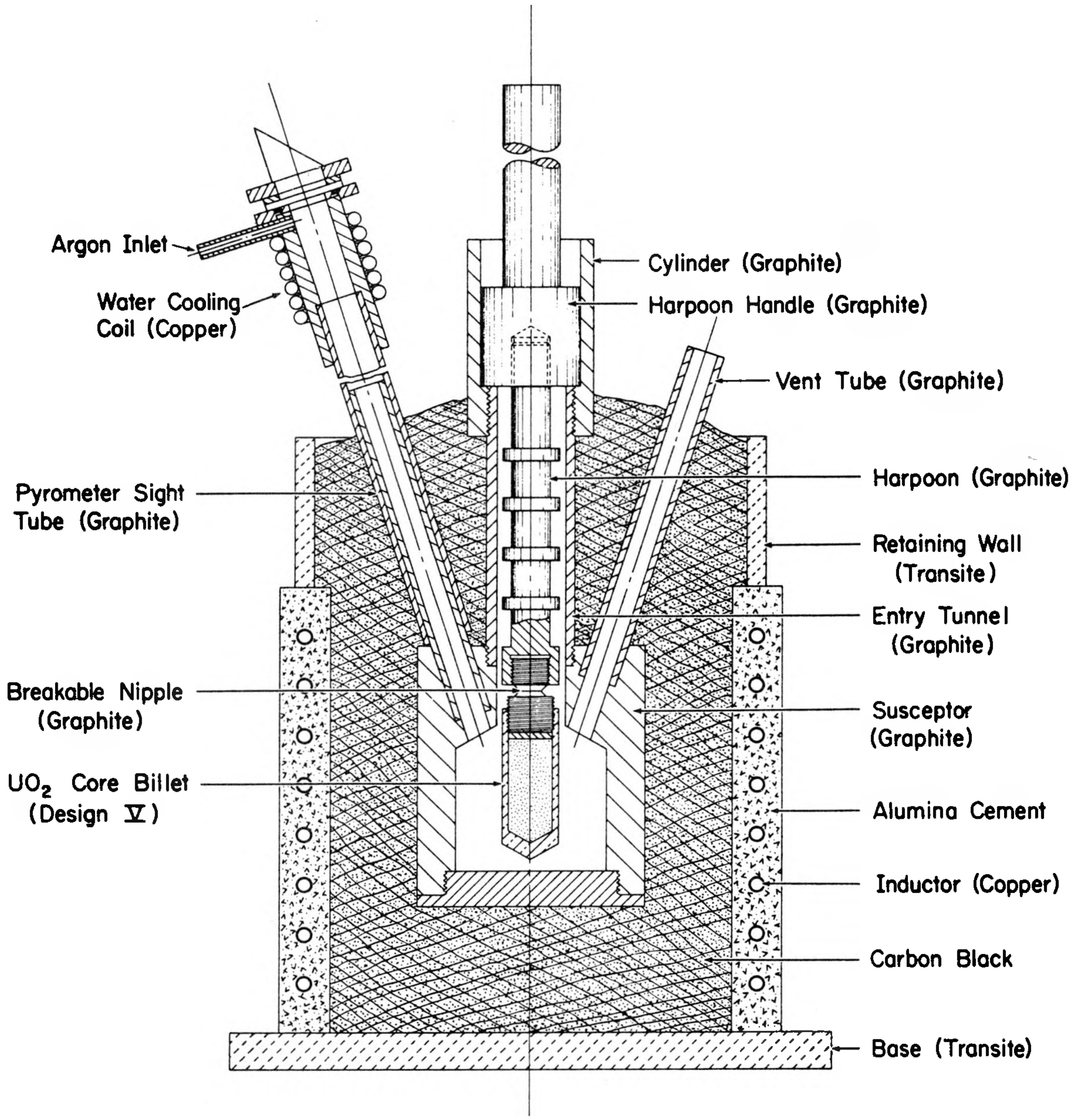

Fig. 6 - Second furnace to heat UO_2 to high temperatures.

<u>Fig. 7</u> - Longitudinal sections of Design I, extrusions 21447, 21448, 21449, 21446, 21930 and 21931, reading top to bottom. The centrally-located UO_2 is separated by stainless steel from the cold-rolled steel shell. Nital etch. Extrusion 21930 provides a good example of "wafering". Extrusion direction is from left to right. RF-7224.

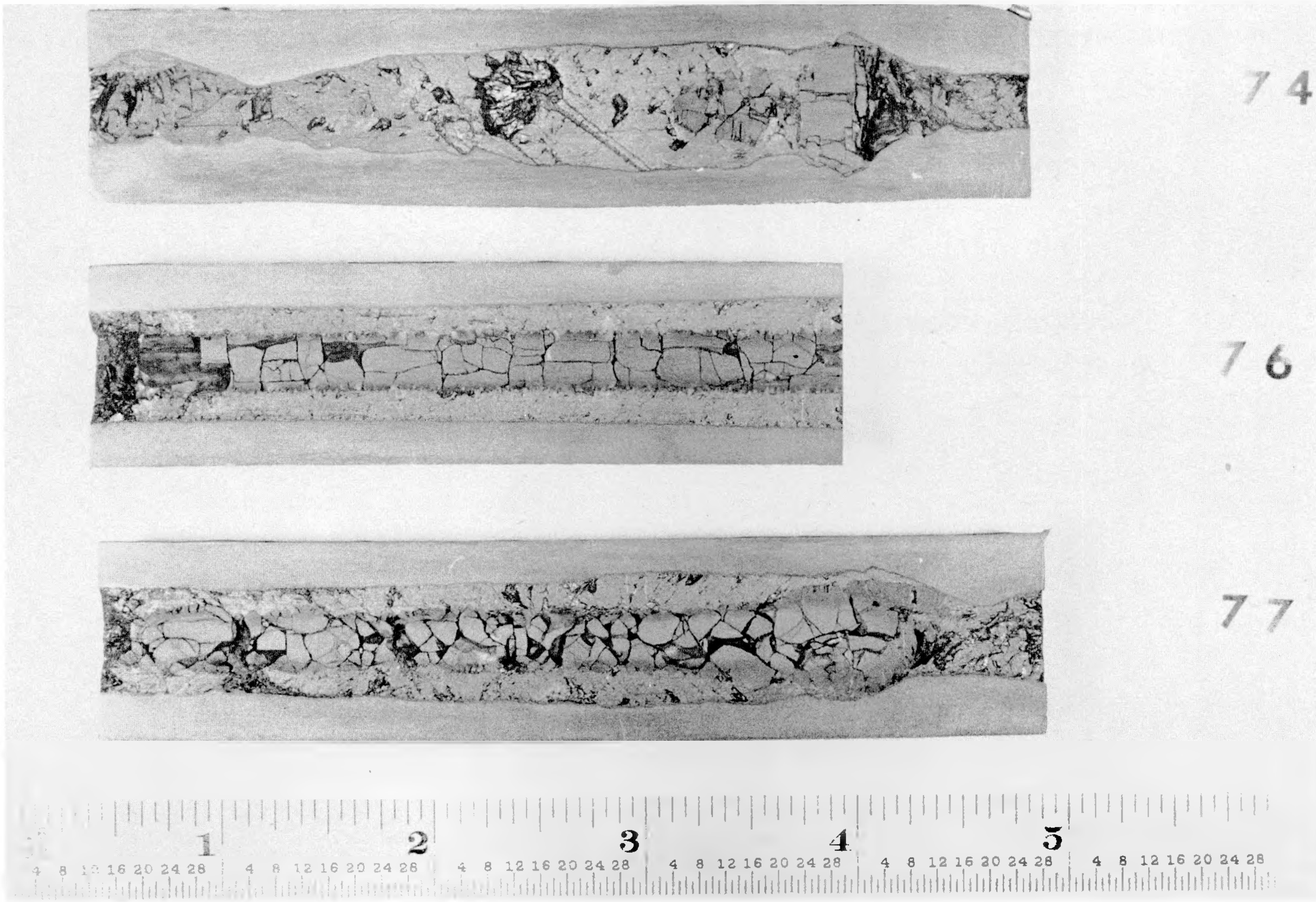

Fig. 8 - Longitudinal sections of Design III, extrusions 21474, 21476 and 21477, reading top to bottom. The centrally-located UO_2 is separated by extruded graphite from the cold-rolled steel shell. Nital etch. Extrusion direction is from left to right. RF-7170.

Fig. 9 - Longitudinal sections of Design IV extrusions 21929, 21861, 21862 and 21880, reading top to bottom. The UO_2 in the middle is surrounded in turn by a thin tantalum cladding, a thick stainless steel sleeve and a thick cold-rolled steel sleeve. The tantalum and stainless steel are unetched, or bright for the Nital etch used. Extrusion direction is from left to right. RF-7225.

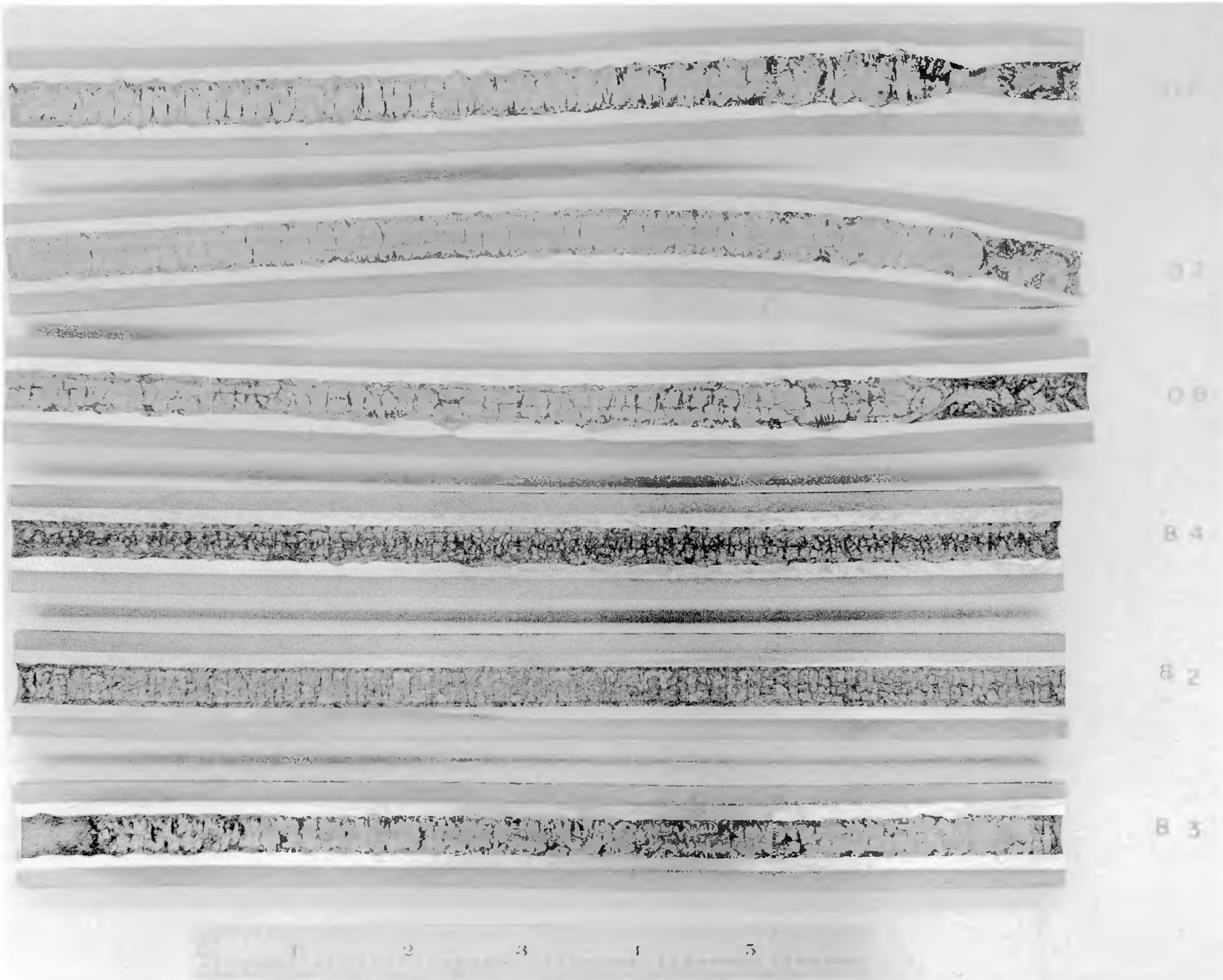

Fig. 10 - Longitudinal sections of Design V coextrusions, 21806, 21807, 21808, 21884, 21882 and 21883, reading from top to bottom. Nital etch. The UO_2 in the middle is bounded in succession by extruded graphite, stainless steel and cold-rolled steel. Scattered remnants of 0.003-inch tantalum foil bound the UO_2 for extrusions 21806, 21807, 21808 and 21884. Extrusion direction is from left to right. RF-7226

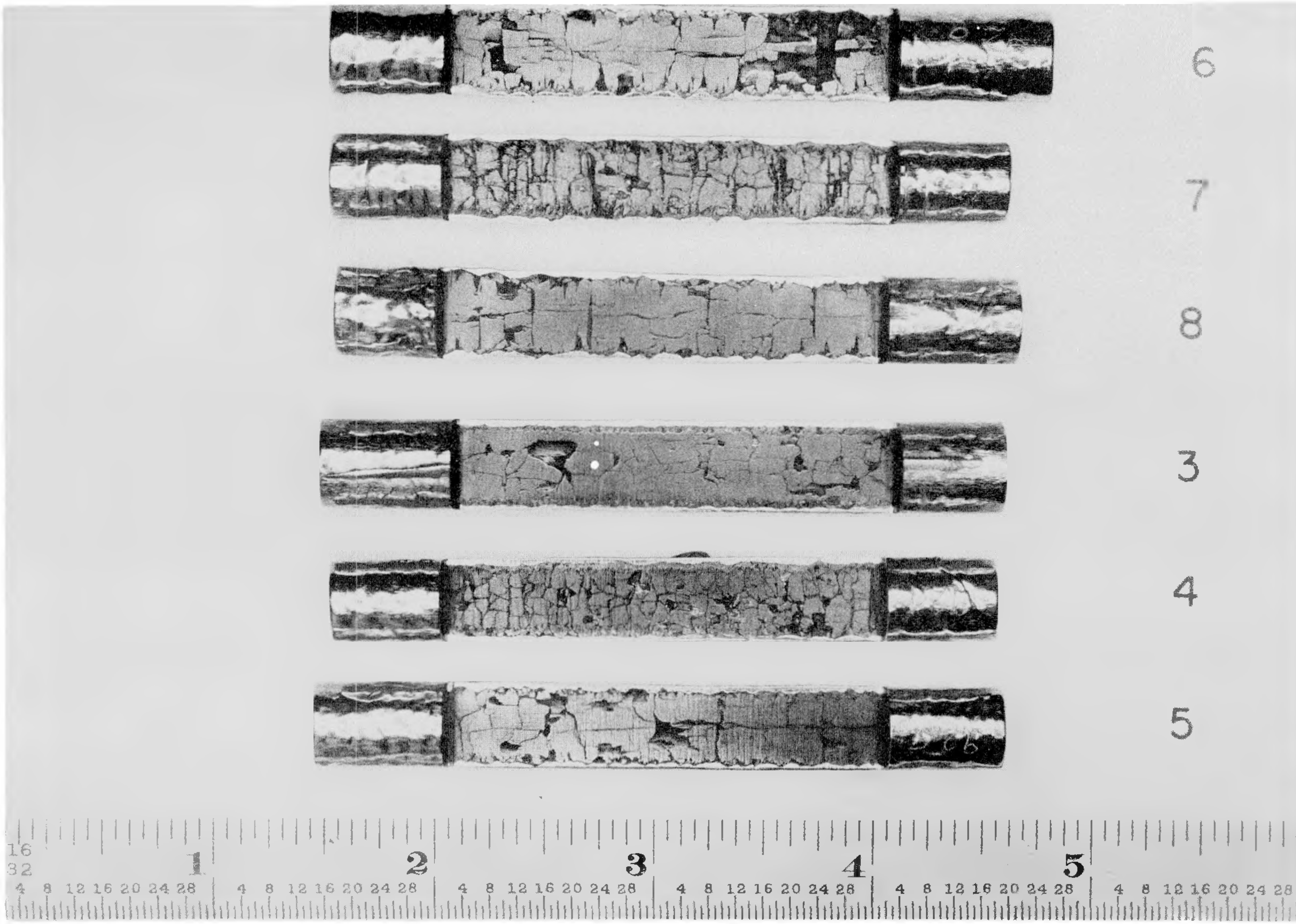

Fig. 11 - Longitudinal sections of Design VI, extrusions 21926, 21927, 21928, 21923, 21924 and 21925, reading from top to bottom. The cold-rolled steel has been previously removed by pickling, and transverse grinding has exposed a full diameter. Nital etch. Here the UO_2 is separated by a thin, extruded graphite interlayer from the stainless steel cladding. Extrusions 21927 and 21924 were loaded with fused UO_2, the others were hot-pressed UO_2 bodies. Note the large voids which most certainly are "pull-out" resulting from the transverse grinding. Observe also the surface of the stainless steel with its "orange-peeling" and "fold marks". RF-7227.