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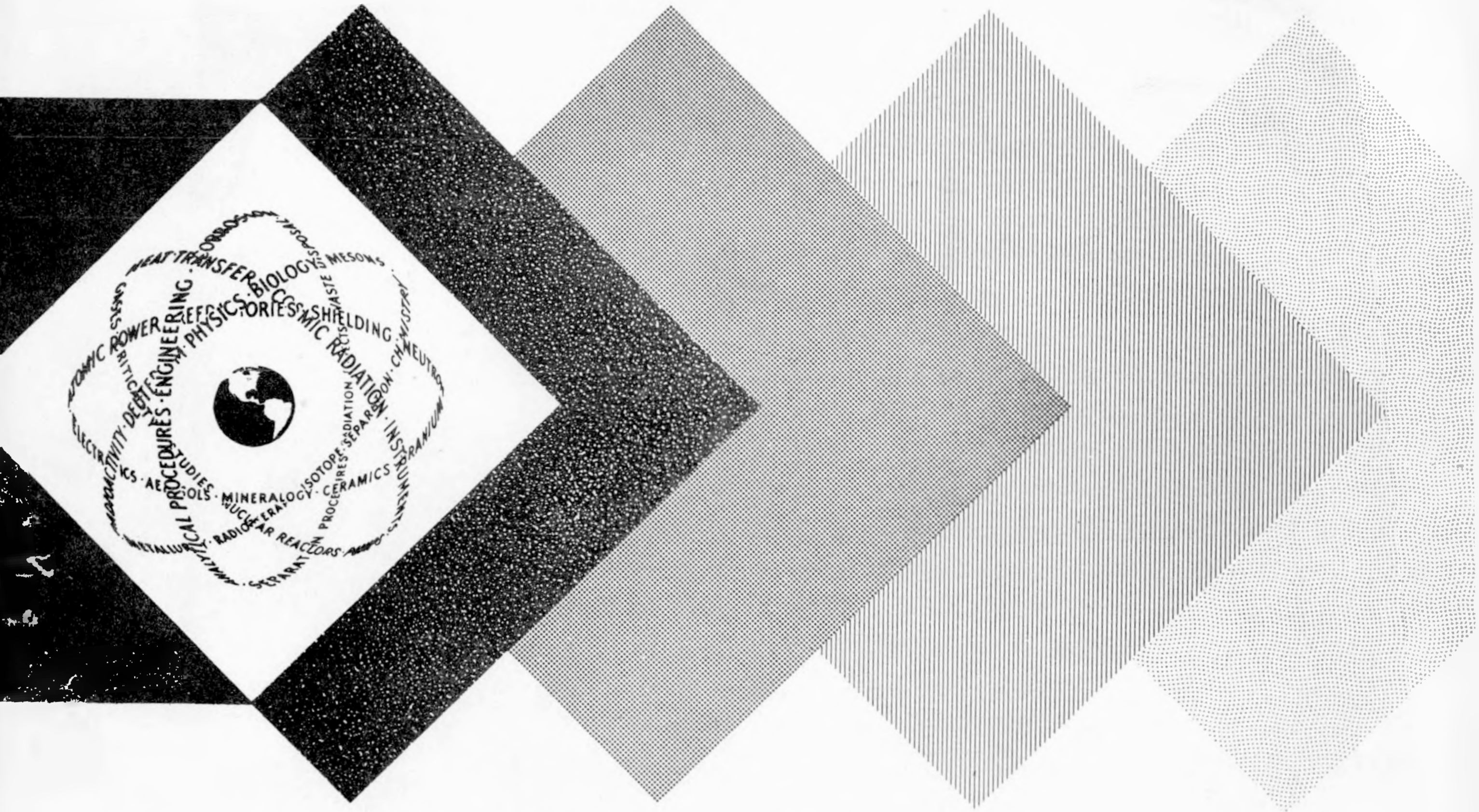
METALLURGY AND CERAMICS

TEXTURE OF EXTRUDED ZIRCONIUM AND ZIRCALOY-2 TUBING

By
V. Nerses

July 11, 1960

Nuclear Metals, Inc.
Concord, Massachusetts



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Nuclear Metals, Inc.
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A. R. Kaufmann
Technical Director

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ABSTRACT

Texture of Extruded Zirconium and Zircaloy-2 Tubing

The textures developed in extruded thin-wall zirconium and Zircaloy-2 tubes were studied for materials with two different fabrication histories. The two primary fabrication methods used were extrusion cupping and rolling. In all cases, the textures were similar with the [10.0] poles parallel to the extrusion direction. The results of burst strength tests, conducted on the extruded thin-wall tubes, and coextrusion experiments were also independent of the primary fabrication history.

I. INTRODUCTION

The combination of low neutron cross section, excellent corrosion resistance, good ductility and moderate strength makes zirconium attractive for use as a nuclear reactor fuel element cladding material. With the large amount of zirconium and Zircaloy-2 tubing and cladding being used, it is important to be aware of properties that might determine their behavior in fabrication or in use in a nuclear reactor. One such property, preferred orientation, which has not been studied extensively on zirconium and Zircaloy-2 tubing and cladding, may play an important role in their corrosion behavior and strength.

II. PLAN OF WORK

The texture of thin-walled extruded zirconium and Zircaloy-2 tubing was determined for materials with two different fabrication histories. The two primary working methods used, extrusion cupping and rolling, followed the usual casting and forging operations. Materials produced by these two techniques were then extruded under similar conditions. The texture and mechanical properties of the final thin-walled tubes were studied to evaluate the effect of fabrication history. Coextrusion experiments with large-grain cast uranium clad with zirconium or Zircaloy-2 were carried out in order to determine if the fabrication history of the cladding material would affect the appearance of the core-cladding interface.

III. MATERIALS

The material used in this work was double-consumable-electrode arc-vacuum melted, reactor-grade zirconium and Zircaloy-2. The zirconium was a 12-inch diameter cast ingot which had been heated to 1650°F and forged to about 6-inches in diameter. The Zircaloy-2 was a 12-inch diameter cast ingot which had been heated to 1630°F and forged to 6-1/4 inches in diameter.

IV. PROCEDURE AND APPARATUS

A. Preparation and Extrusion of Billets

A flow sheet for the processing of zirconium and Zircaloy-2 tubing is given in Fig. 1. A brief description of each step in the processing of the zirconium tubing will be given. The processing of the Zircaloy-2 tubing was identical except for the working temperatures, as indicated in Fig. 1.

1. Extrusion Cupping

Following forging, a 3-inch long section of the 6-inch diameter billet was machined to a cylinder of 5.860-inch diameter which was then canned in a copper tube along with a copper cutoff and extruded at 1350°F with a 3:1 reduction ratio. The copper sheath was pickled off, the zirconium machined to 3.360-inch diameter, and prepared for another 3:1 extrusion at 1350°F. Limitations of press capacity required that the total 9:1 reduction extrusion be carried out in two steps. A section of the extruded rod was machined to 1.856-inch OD and cupped at 1350°F with a 1.5 reduction. Part of the cupped piece was machined to 1.856-inch OD and 1.242-inch ID and then canned in copper. The final extrusion at 1350°F resulted in the formation of a 20-mil wall tube with a 1.050-inch OD.

2. Rolling

A 1-inch thick slab cut off perpendicular to the cylindrical axis of the 6-inch OD zirconium or Zircaloy-2 forging was canned and evacuated in copper and rolled unidirectionally to a thickness of 51 mils. The rolled sheet was annealed at 750°F for one hour and furnace cooled. The sheet was grit blasted, cleaned in acetone, and coiled into a tube around a 1.242-inch OD mandrel with the tube axis perpendicular to the rolling direction. The coiled tube was machined to 1.856-inch OD, canned and evacuated in copper, and extruded at 1350°F into the final 20-mil tube with 1.050-inch OD.

3. Coextrusion

Three coextrusions of each cladding material, zirconium and Zircaloy-2, with as-cast ingot uranium cores were made. The fabrication history of each of the three sets of cladding materials is described below. In the first set, a section of the extruded zirconium and Zircaloy-2 rod after the second 3:1 reduction (see Fig. 1) was machined to 1.856-inch OD and bored to 1.242-inch ID, and coextruded with a piece of large-grain uranium casting at 1175°F with a 23:1 reduction. In the second and third sets, sections from the cupped zirconium and Zircaloy-2 (see Fig. 1) and the rolled zirconium and Zircaloy-2 coiled into a tube were machined to the same dimensions as above and coextruded in the same manner.

The preparation for all the coextrusions was as follows.

a. After machining, the zirconium and Zircaloy-2 were paper polished, cleaned in Lakeseal, followed by a rinsing in acetone.

b. The uranium was paper polished after machining, etched in 50:50 nitric acid:water.

c. The uranium core was placed into the zirconium or Zircaloy-2 clad, and both of these into a copper container which had been etched clean. The copper container was sealed by welding, and the billet was then evacuated for five hours at 0.1 micron vacuum at room temperature.

4. Extrusion Technique

In all the extrusions carried out in this investigation, the surfaces of the billets were painted with a colloidal suspension of graphite powder in alcohol and the billet heated in a graphite container to the desired temperature. The die, cone, extrusion press liner, and mandrel (when used) were heated to 900°F. The extrusion tools were swabbed with a graphite powder and oil mixture before extrusion. Table I gives the temperatures, reduction ratios, and extrusion loads, along with other pertinent data for the processing of the zirconium and Zircaloy-2. The samples were air cooled after each extrusion.

B. X-ray Analysis

1. Preparation of Zirconium and Zircaloy-2 Composites

An 8-inch length of tubing was carefully sectioned into 1/4-inch wide rings perpendicular to the tube axis. The rings were placed into circular clamps to hold them firmly in place while eight equal pieces were carefully cut from the ring with a 10-mil cutoff wheel.* About 40 of these cut pieces were used for making up a composite. A flat ground block was used to line the faces of the pieces to be x-rayed in the same plane (reference plane). The pieces were clamped into place and mounted in Casto-Mold. To fit in the flat sample spinner attachment in the Norelco x-ray diffractometer, the mounted pieces were enclosed by a metal ring 1-inch ID and 1-inch high and the ring filled with Casto-Mold. Composites of the transverse and longitudinal planes of the extruded tubes were made in this manner. The mounted pieces which were removed from the enclosed metal ring were carefully ground on emery papers and swab etched in a 45:45:10 nitric acid:distilled water:hydrofluoric acid mixture for about seven seconds. Photographs of typical composite samples are shown in Fig. 2. After x-ray scanning and recording three prominent plane reflections, the sample was re-etched and rescanned until the previous traces were reproduced within 5 percent. The sample was now ready to be scanned for experimental data. A micrometer was used to check the variation of the reference plane in the composite after polishing and etching. The maximum variation measured between any two points on the composite was about 0.001 inch. It was estimated that the reference plane of the samples was within $\pm 2^{\circ}$ of the transverse or longitudinal planes of the extruded tubes.

2. X-ray Diffraction Equipment

A Norelco x-ray diffractometer with Geiger counter and recorder was used. Beam collimation was achieved by soller slits on the incident and reflected beams, an 0.003-inch receiving slit, a 1° divergence slit, and 1° scatter slit. To increase the total number of grains contributing to the x-ray intensity, a flat sample spinner attachment rotated the sample at 77-1/2 rpm in a plane containing the goniometer axis.

---

* Precautions were taken to insure that the cut faces of the sample were parallel to a diameter.

A molybdenum target x-ray tube was used for all Bragg angle reflections. For the detection of molybdenum radiation, a krypton gas-filled Geiger tube was used. Zirconium foil, 0.0035-inch thick, was placed in the incident beam to filter out the incident molybdenum K_β beam.

3. Calculation of Pole Intensities

In general, Harris' analysis(1) (later corrected by Mueller, Chernock and Beck (2)) gives an expression which determines a quantitative inverse pole figure from a large number of planes parallel to the specimen surface. The inverse pole figure represents a comparison of population density, P, of (hkl) poles in the indicated direction with respect to a chosen fabrication direction. The pole density is approximated by

$$P_{hkl} = \frac{(\frac{I}{I^o})_{hkl}}{\frac{1}{n}\sum(\frac{I}{I^o})_{hkl}} \qquad (1)$$

where $(\frac{I}{I^o})_{hkl}$ is the ratio of the integrated intensity of the unknown to a random sample for the reflection (hkl) and n is the number of reflections examined.

4. Pole Intensity Traces

Increasing the number and distribution of poles examined and the number of grains included in the x-ray beam increases the accuracy of the texture as described by an inverse pole figure. Fifty-seven reflections were scanned, indexed, and integrated with a planimeter between a 2θ angle of 14 to 95°. A slow scan of 0.25° per minute through particular 2θ positions was used. The locations of all particular reflections scanned are given in Appendix I.

The ratio of each plane's experimental intensity to its theoretical random intensity was calculated and the arithmetic mean of these ratios was found. The value of the theoretical random intensity used for the particular planes scanned was calculated by Roll,(3) who investigated the texture in extruded zirconium rod. The P value of each plane is found by dividing each $\frac{I}{I^o}$ ratio by the average $\frac{I}{I^o}$ ratio.

5. Inverse Pole Figure Plots

The P values obtained as described above refer to the preferred orientation in the direction being examined. A value of unity represents a total lack of preferred orientation, whereas departures from unity reveal either a depletion or a concentration of poles. The P values were plotted on a standard (00.1) projection for zirconium to make an inverse pole figure. In the inverse pole figure, one plots the population density of one fabrication direction over all directions relative to the crystallographic directions. The orientations of the poles used in the standard projection are presented in Appendix II as the angles between crystallographic planes of zirconium.

The calculated pole intensity, P, of each pole was plotted on the standard projection, and isointensity contour lines of 1/2, 1, 2, 4, 8, etc. random intensity levels were drawn through appropriate positions, taking into account the accuracy of each calculated point. In order to draw the contour lines with a continuous rate of slope change, it was assumed that the pole intensity changes between adjacent poles varied at a constant rate.

C. Burst Testing

Six-inch long burst test specimens were prepared from the as-extruded and annealed (15 minutes at 1350°F) tubes. SR-4 type A7 strain gages were initially used to measure strain on a few specimens, and later SR-4 type A X 7 strain gages were used.

Zircaloy-2 caps were welded to the ends of the Zircaloy-2 tube specimems and zirconium caps to the zirconium tube specimens. The caps had a threaded hole for connecting one end of the specimen to the hydraulic source and the other end to a bleeder valve. Aviation-type hose clamps were placed around the specimens at the end caps to prevent the tubes from breaking near the welds.

Stress-strain curves were obtained by measuring the internal pressure at specific strain increments. Above 0.2 percent offset, the strain gages were not reliable; therefore, only the pressure at rupture was noted. Elongation was determined by comparing the circumference at the point of fracture with the circumference before stressing.

V. RESULTS

A. Texture

The inverse pole figure charts shown in Figs. 3 through 10 give the results of the texture analyses of the over-all axial and tangential direction of the zirconium and Zircaloy-2 tubes. Peak pole intensities are indicated in brackets. Table II lists all of the determined "P" values.

The inverse pole figure charts show that the [10.0] pole is parallel to the extrusion direction. The pole figure charts also show that the [11.6] pole is common and parallel to the tangential direction.

B. Tube Strength

The results of the burst testing of zirconium and Zircaloy-2 tubes are given in Table III. Figure 11 shows typical burst samples of a Zircaloy-2 tube, cupped and extruded, in the as-extruded and in the annealed conditions.

C. Coextrusion

The coextrusion results, shown in Fig. 12, reveal that the core-cladding interfaces produced between the large-grain cast uranium core and zirconium and Zircaloy-2 cladding with varying fabrication history are all highly irregular, independent of primary fabrication history.

VI. DISCUSSION OF RESULTS

A. Texture

The results of this study show that the textures of the as-extruded thin-wall zirconium and Zircaloy-2 were not affected by the prior working methods employed in this investigation. The absence of texture variation is apparently due to the final large reduction used for the tube extrusions.

The texture developed in all the thin-wall zirconium and Zircaloy-2 tubes shows that the [10.0] pole is parallel to the extrusion direction. The zirconium and Zircaloy-2 tubes which were made from the rolled and coiled material showed a less pronounced texture than tubes which were made from the extrusion cupped materials. The texture developed in the extruded thin-wall tubing in this investigation appears consistent with the texture results obtained by Poll(3) on the surface of extruded water-quenched zirconium rods.

B. Other Results

The results of the burst tests, as given in Table III, show that the strength values were independent of the primary working history. This result is consistent with the lack of texture variation in material with different fabrication history. The lack of variation in the appearance of the core-cladding interfaces in the coextrusion experiments further confirms the independence of the behavior of zirconium and Zircaloy-2 and their primary fabrication history.

VII. CONCLUSIONS

It is concluded that variations in primary working history do not give rise to differences in the texture or strength of thin-wall zirconium or Zircaloy-2 tubes produced by high reduction extrusions.

VIII. ACKNOWLEDGMENTS

The author wishes to express his gratitude to the staff at Nuclear Metals, Inc., especially Dr. A. Boltax and R. L. Adams, who contributed significantly to this project.

IX. TABLES AND FIGURES

TABLE I

Extrusion Data on the Processing of Zirconium and Zircaloy-2 Tubing*

NMI Extrusion No.	Billet				Die		Liner		Mandrel		Speed (in./min)	Heating Time (hrs)	Pressure (tons)			Reduction
	Material	Temp. (°F)	Heat Media	Cutoff	Size (in.)	Temp (°F)	Size (in.)	Temp. (°F)	Dia (in.)	Temp. (°F)			Start	Run	End	
20554	Zirconium	1350	Air	Graphite	3.500	900	6.070	900	---	---	13	3	508	797	763	3:1
20584	Zirconium	1350	Air	Graphite	2.000	900	3.545	900	---	---	13	2	288	288	203	3:1
20619	Zircaloy-2	1450	Air	Graphite	3.500	900	6.070	900	---	---	13	3	610	594	356	3:1
20688	Zircaloy-2	1450	Air	Graphite	2.000	900	3.545	900	---	---	13	2-1/2	407	390	390	3:1
20841	Zircaloy-2	1450	Air	Graphite	---	---	2.040	900	1	900	35	2	not recorded			1.5:1
---	Zirconium	1350	Air	Graphite	---	---	2.040	900	1-1/8	900	35	2	not recorded			1.5:1
20917	Zircaloy-2	1450	Graphite and air	Cu	1.061	900	2.040	900	1	900	30	2-1/2	180	150	150	23:1
20924	Zirconium	1350	Graphite and air	Cu	1.061	900	2.040	900	1	900	30	2-1/2	---	154	154	23:1
21198	Zircaloy-2	1450	Graphite and air	Cu	1.061	900	2.040	900	1	900	30	2-1/2	196	164	177	23:1
21199	Zirconium	1350	Graphite and air	Cu	1.061	900	2.040	900	1	900	30	2-1/2	207	179	185	23:1

* For all extrusions:

Canning was 16 gauge Cu; cooling was in air; cone material was cold-rolled steel; core temperature was 900°F.

TABLE II

"P" VALUES

	Zircaloy-2 Rolled Tang. Dir.	Zircaloy-2 Rolled Axial Dir.	Zircaloy-2 Cupped Tang. Dir.	Zircaloy-2 Cupped Axial Dir.	Zirconium Rolled Tang. Dir.	Zirconium Rolled Axial Dir.	Zirconium Cupped Tang. Dir.	Zirconium Cupped Axial Dir.
hkl	P	P	P	P	P	P	P	P
100	0.67	8.51	0.15	14.80	0.39	9.94	0.21	13.95
002	4.45	0	4.90	0	3.46	0	8.11	0
101	0.71	0.32	0.52	0.20	0.51	0.33	0.78	0.28
102	1.05	0.12	0.70	0	0.80	0.99	0.63	0
110	1.69	0.78	0.71	0.56	1.18	0.99	1.18	0.59
103	1.20	0.10	1.03	0	1.08	0	1.07	0.10
112	3.46	0.14	3.69	0.05	3.42	0.18	3.64	0.20
201	0.48	3.48	0.26	2.57	0.23	3.21	0.33	3.61
104	1.59	0	1.50	0	1.96	0	1.74	0
203	1.00	0.13	0.53	0	0.88	1.37	0.44	0
210	1.18	1.64	0	1.46	0	2.14	0	0.72
211	1.29	1.25	0.48	0.96	0.85	1.40	0.61	1.05
114	5.32	0.13	6.02	0	4.03	0	5.08	0
212	1.31	0.88	1.46	0	1.56	0.45	1.05	0.56
105	1.83	0	2.18	0	1.48	0	1.72	0
213	2.20	0.85	1.58	0	1.98	0.28	1.54	0.46
302	0.84	1.74	0	0.91	0.53	1.50	0.53	1.17
205	0.75	0	0	0	1.08	0	0	0
106	2.57	0	---	0	1.15	0	---	0
214	1.05	0	0	0	0.63	0	2.16	0
310	0	2.62	0	2.05	0	6.54	0	2.61
222	---	0	1.86	0	1.21	0.81	1.23	0
131	0	2.13	3.23	2.23	1.09	2.40	0	1.99
116	4.29	0	5.99	0	4.30	0	8.44	0
132	0	1.46	0	0	0.69	0	0	0.89
125	3.29	0.27	2.43	0	2.44	0	3.88	0
017	0.68	0	2.23	0	2.06	0	3.50	0
133	0.59	0	0.14	0	1.39	0.57	0	0

(Table II Cont'd on next page)

TABLE II (Cont'd)

	Zircaloy-2 Rolled Tang. Dir.	Zircaloy-2 Rolled Axial Dir.	Zircaloy-2 Cupped Tang. Dir.	Zircaloy-2 Cupped Axial Dir.	Zirconium Rolled Tang. Dir.	Zirconium Rolled Axial Dir.	Zirconium Cupped Tang. Dir.	Zirconium Cupped Axial Dr.
HKL	P	P	P	P	P	P	P	P
401	0	8.69	0	14.93	0	4.78	0	10.03
126	0	0	0	0	1.78	0	0	0
134	0	0	0	0	0.96	0	0	0
230	0	0	0	0	0	0	0	0
231	0	1.10	0	0.59	0	0.66	0	0
232	0	0	0	0	---	0	0	0
135	0	0	0	0	0	0	0	0
140	0	4.05	2.00	1.39	0	5.17	0	2.47
127	0	0	2.23	0	1.30	0	0	0
233	1.17	0	0	0	1.14	0	0	0
118	---	0	3.28	0	1.59	0	3.14	0
142	0	1.58	0.90	0.52	0.82	1.87	0	0.99
226	---	0	---	0	---	0	---	0
019	---	0	---	0	---	0	---	0
501	0	12.14	0	13.74	0	8.76	0	13.23
144	0	0	0	0	0	1.45	0	1.10
235	---	0	---	0	---	0.41	---	0
137	0	0	0	0	0	0	0	0
332	---	0	---	0	---	0.81	---	0
241	0	0	0	0	0	0	0	0
243	0	0	0	0	0	0	0	0
129	2.14	0	0	0	1.91	0	0	0
151	0	2.87	0	0	0	0	0	0
146	0	0	0	0	0	0	0	0
153	0	0	0	0	0	0	0	0.99
304	0	0	---	0	0	0	0	0
207	---	0	---	0	1.09	0	---	0
316	0	0	0	0	0	0	0	0
308	3.22	0	0	0	---	0	0	0

TABLE III

Results of the Hydrostatic Burst Testing of Zirconium and Zircaloy-2 Tubes

Material	NMT Extrusion No.	Condition	Yield Strength 0.2% Offset (psi)	Ultimate Strength (Hoop Stress at Rupture) (psi)	Elongation (% at Rupture)	Remarks
Zircaloy-2 cupped and extruded	20917	As extruded	100,500	104,000	3.8	
		As extruded	98,000	102,000	3.7	
		As extruded	98,000	---	2.3	Failure at weld
		Annealed at 1350°F for 15 min.	78,500	79,500	45.9	
		Annealed at 1350°F for 15 min.	75,500	79,500	45.5	
Zircaloy-2 rolled and extruded	21198	As extruded	108,500	113,000	1.9	
		As extruded	105,500	109,400	1.7	
		Annealed at 1350°F for 15 min.	74,500	82,000	--	Pinhole failure
		Annealed at 1350°F for 15 min.	76,500	86,900	5.7	
Zirconium rolled and extruded	21199	As extruded	94,500	---	1.8	Failure at weld
		As extruded	91,000	96,450	1.8	
		As extruded	93,000	99,709	1.7	
		Annealed at 1350°F for 15 min.	---	---	11.2	Strain gage inoperative
		Annealed at 1350°F for 15 min.	61,000	82,100	9.4	
Zirconium cupped and extruded	20924	As extruded	83,000	91,800	3.4	
		As extruded	89,500	92,700	6.7	
		Annealed at 1350°F for 15 min.	60,000	65,700	22.9	
		Annealed at 1350°F for 15 min.	62,500	65,600	22.8	

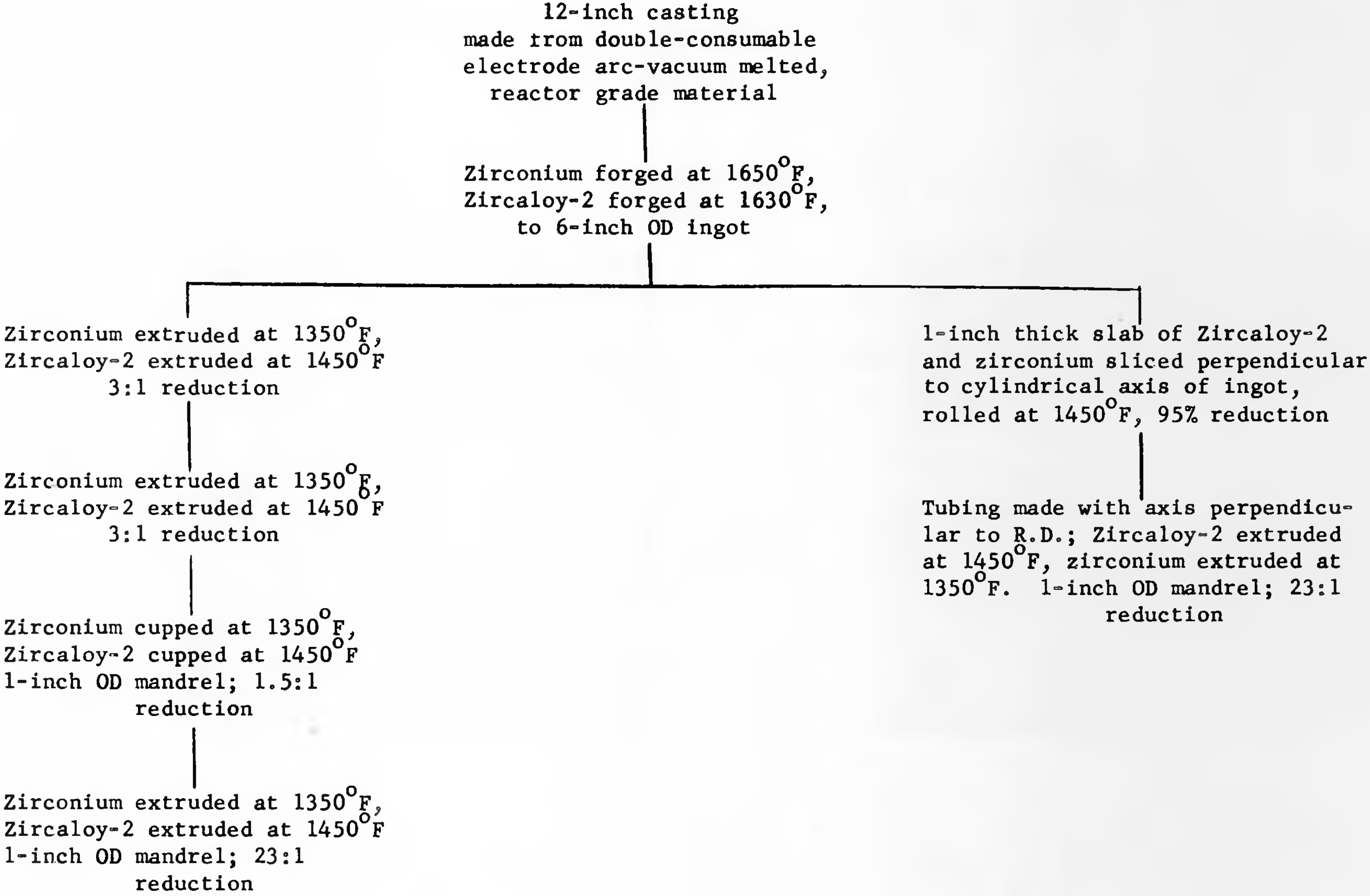
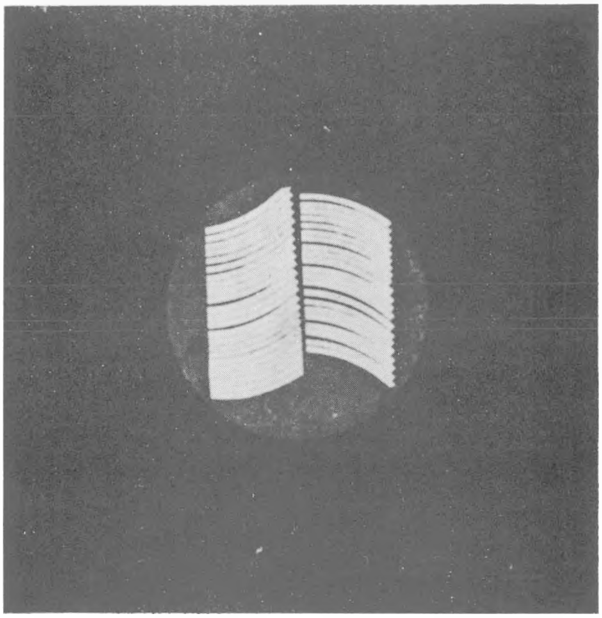


Fig. 1 Flow sheet for processing zirconium and Zircaloy-2 tubing.



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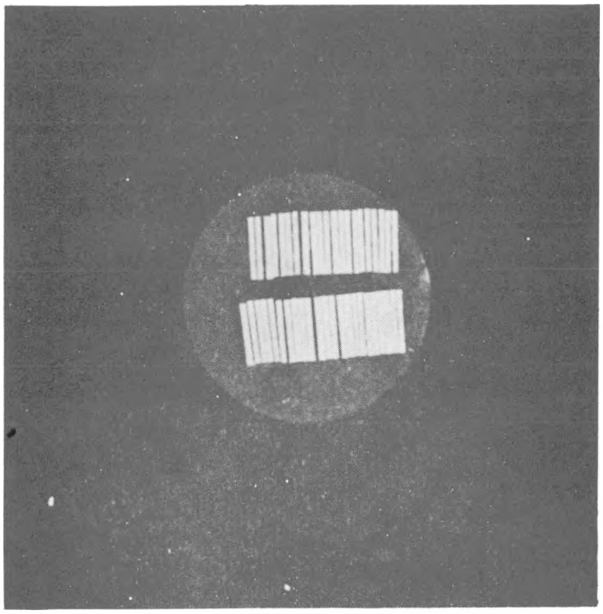
a) Transverse plane (axial direction)

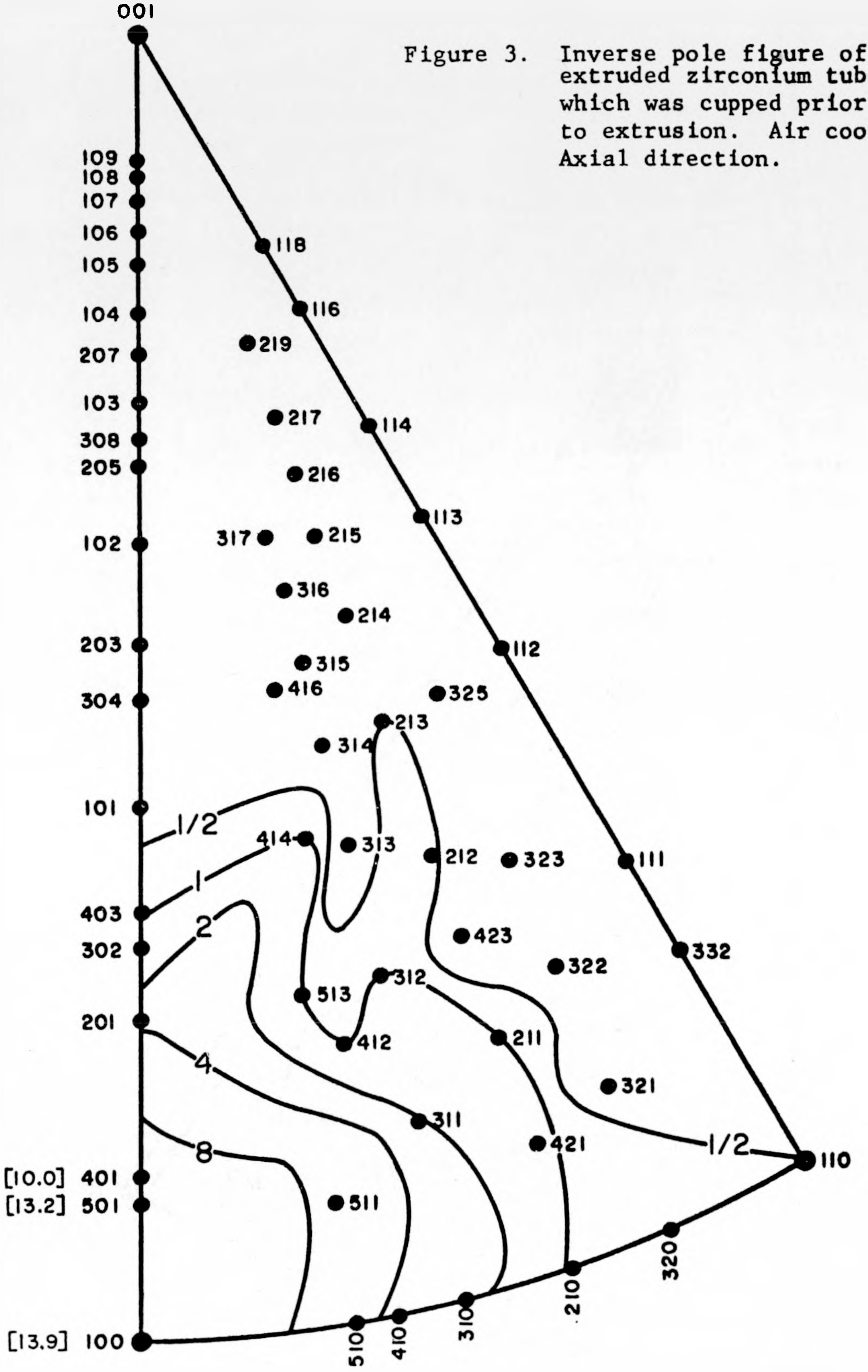


RF-6827

b) Longitudinal plane (tangential direction)

Fig. 2 - Composite samples for analysis.

Figure 3. Inverse pole figure of extruded zirconium tube which was cupped prior to extrusion. Air cooled. Axial direction.



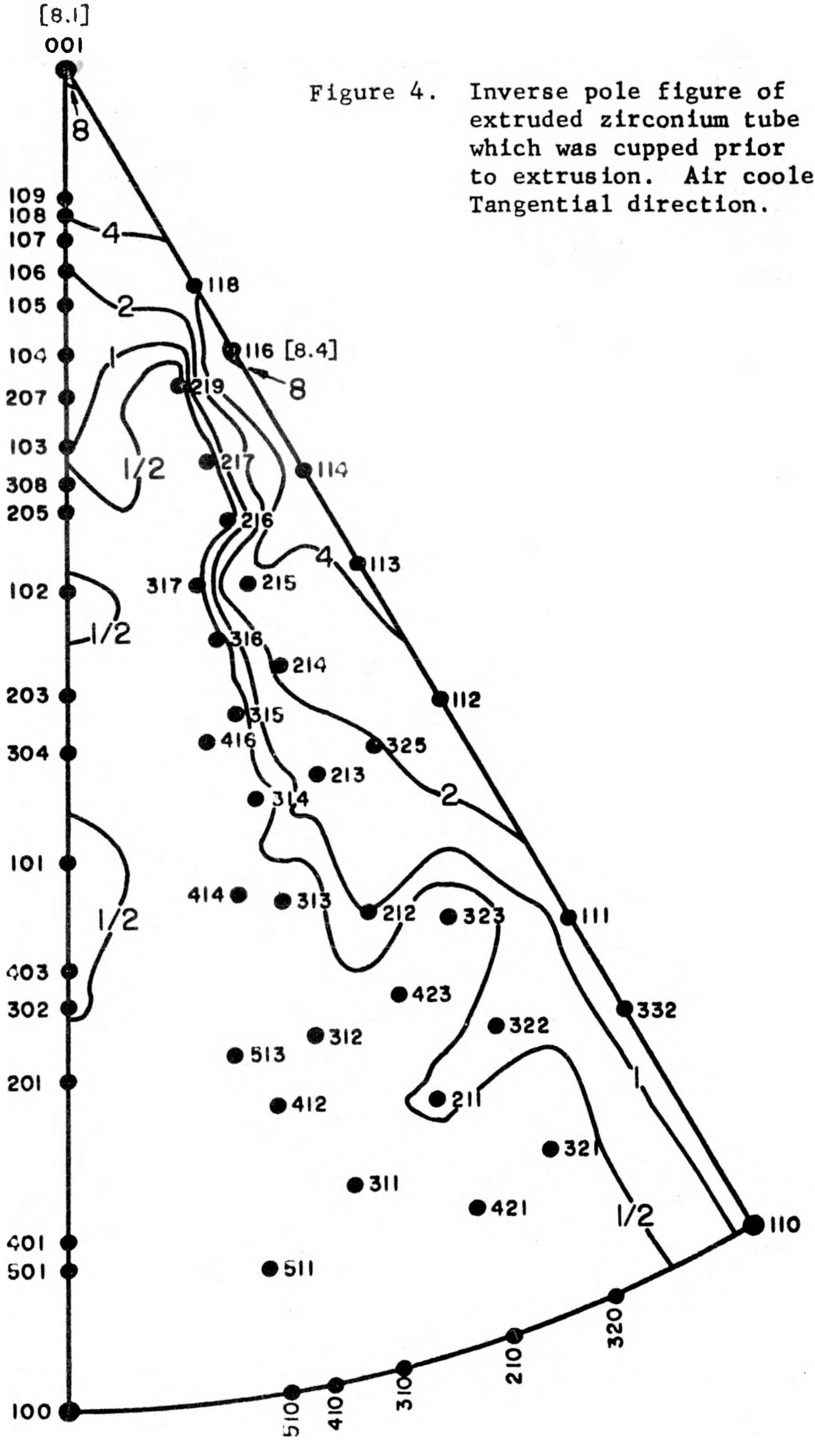


Figure 4. Inverse pole figure of extruded zirconium tube which was cupped prior to extrusion. Air cooled. Tangential direction.

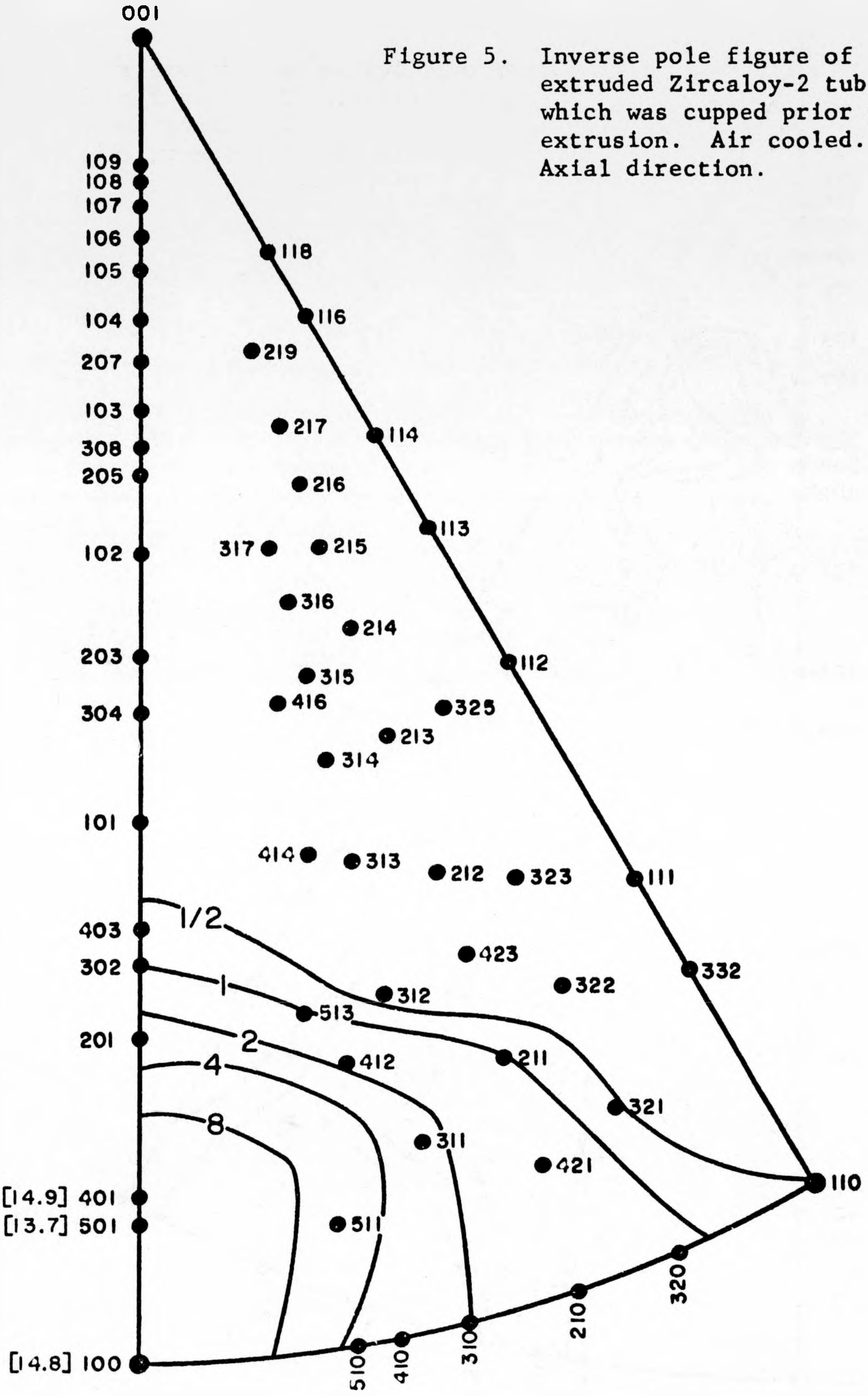


Figure 5. Inverse pole figure of extruded Zircaloy-2 tube which was cupped prior to extrusion. Air cooled. Axial direction.

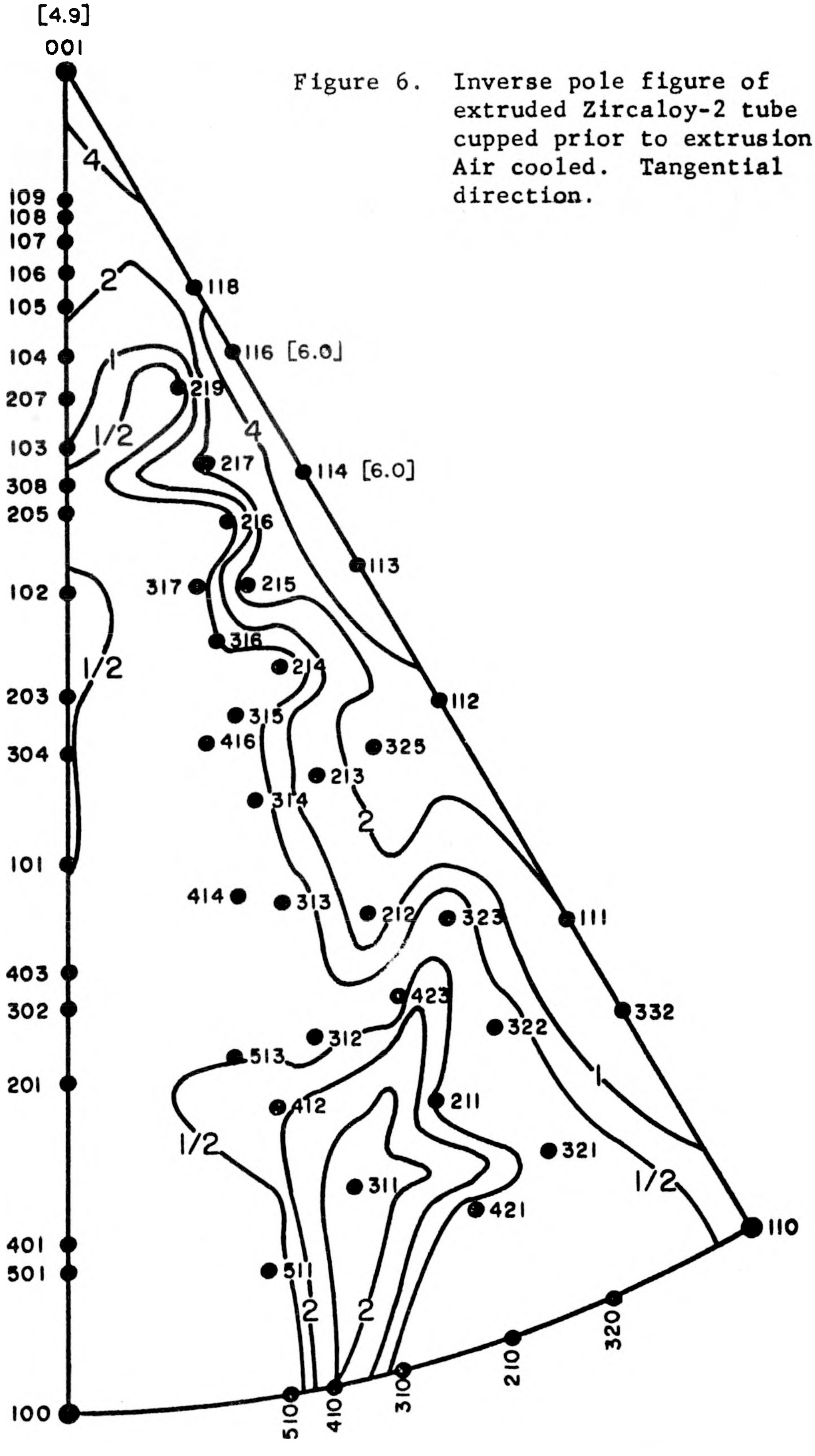


Figure 6. Inverse pole figure of extruded Zircaloy-2 tube cupped prior to extrusion. Air cooled. Tangential direction.

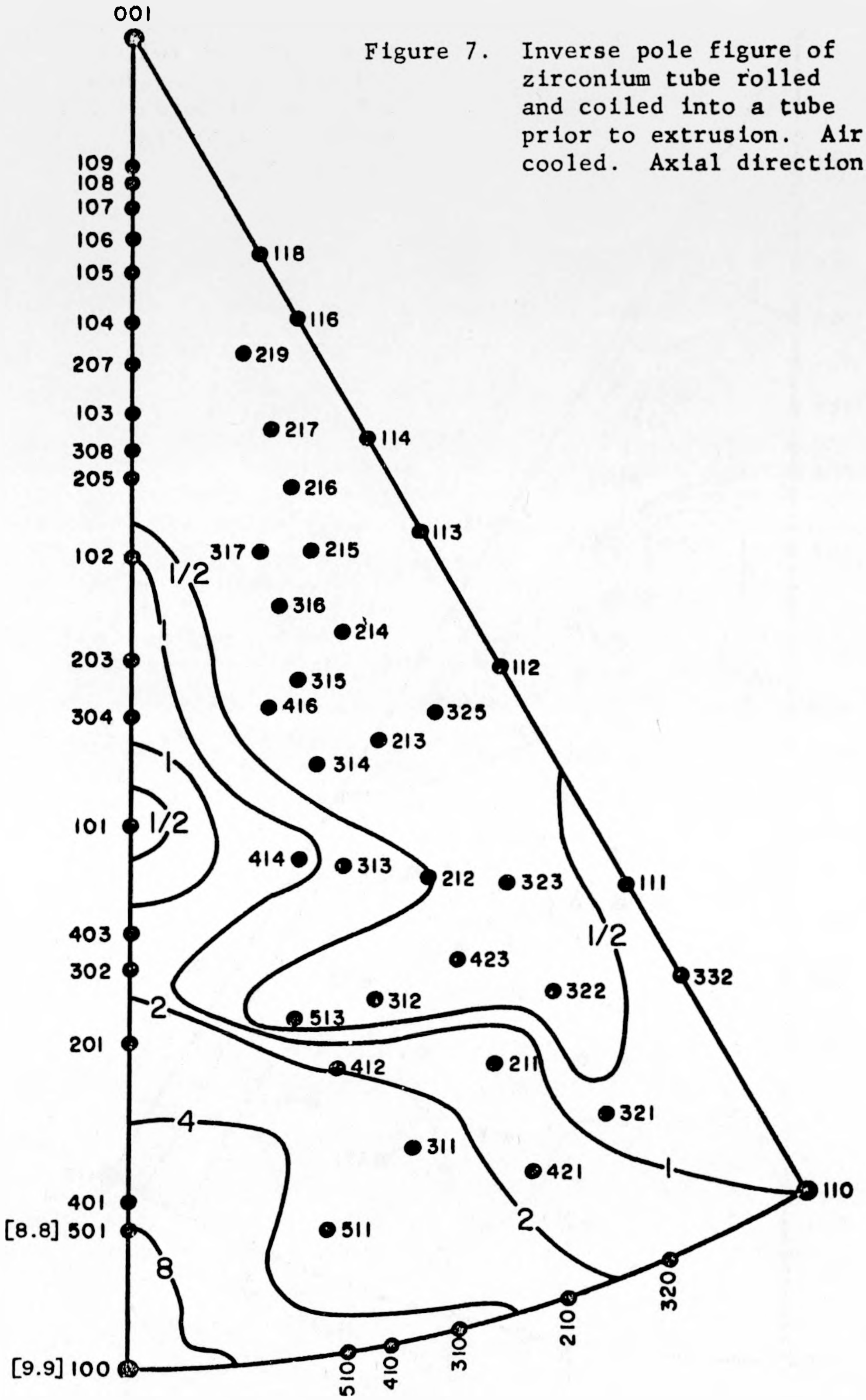


Figure 7. Inverse pole figure of zirconium tube rolled and coiled into a tube prior to extrusion. Air cooled. Axial direction.

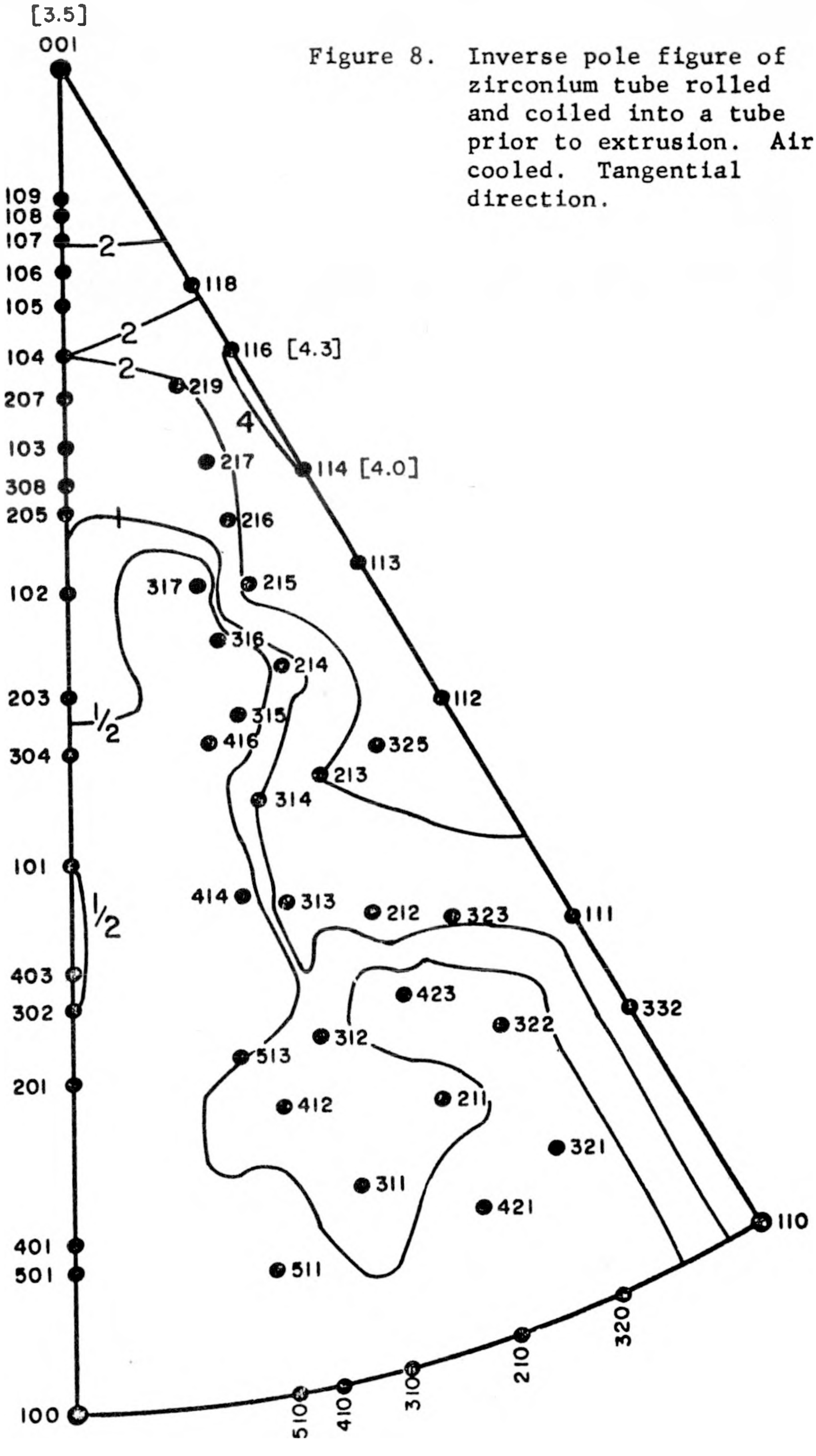
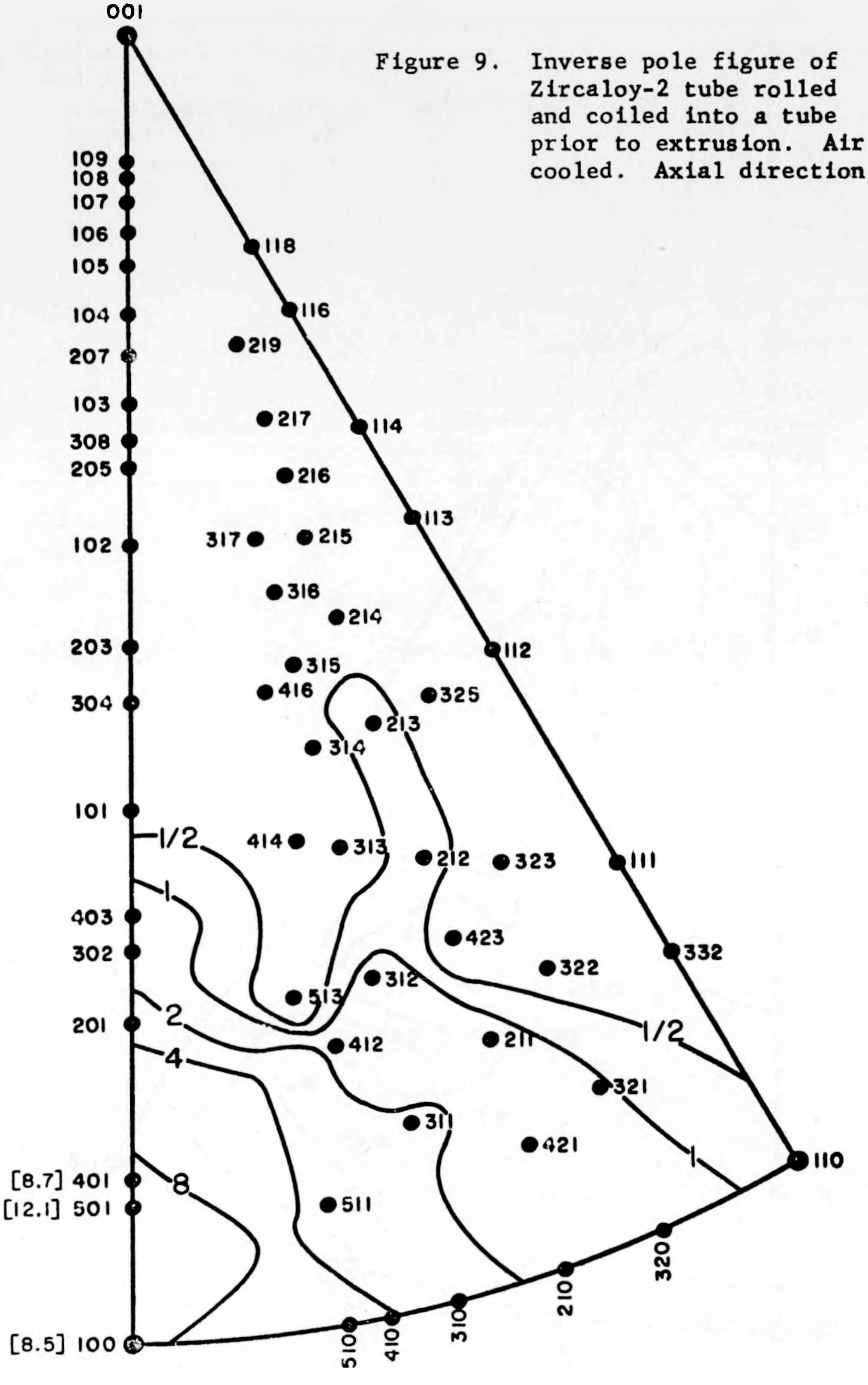


Figure 8. Inverse pole figure of zirconium tube rolled and coiled into a tube prior to extrusion. Air cooled. Tangential direction.

Figure 9. Inverse pole figure of Zircaloy-2 tube rolled and coiled into a tube prior to extrusion. Air cooled. Axial direction.



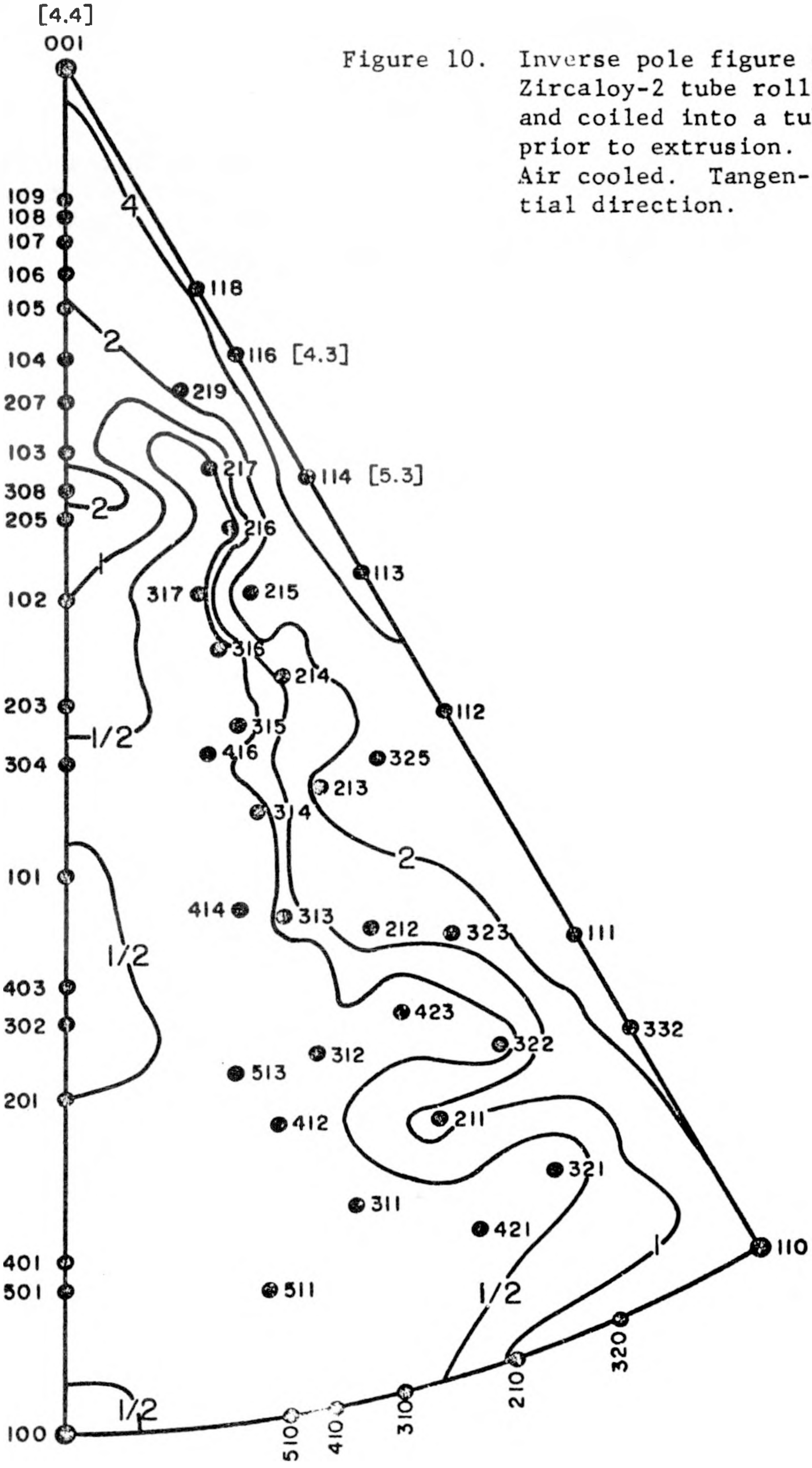
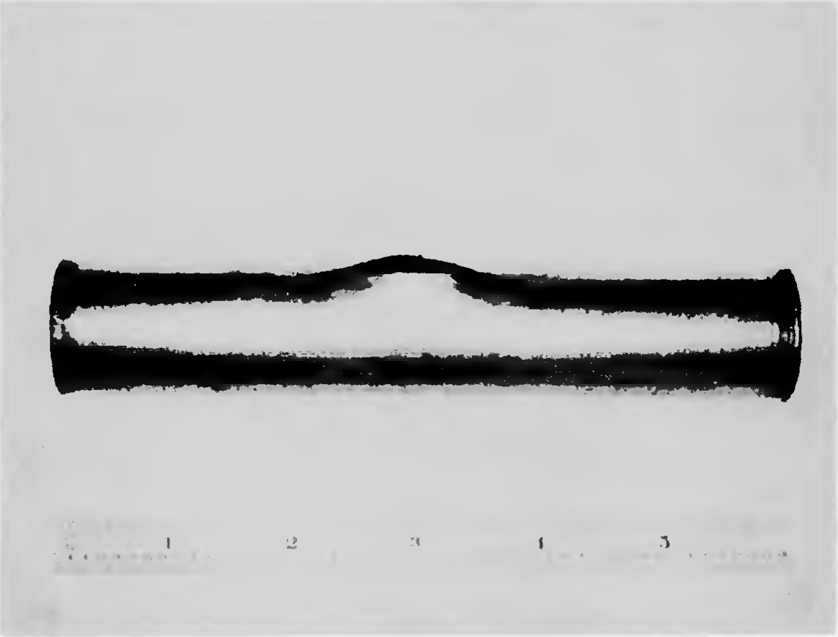
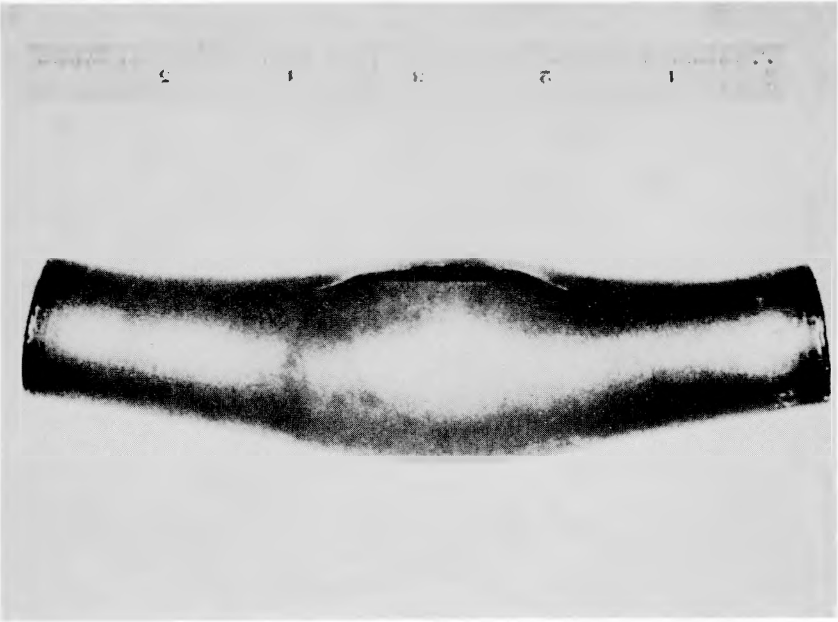


Figure 10. Inverse pole figure of Zircaloy-2 tube rolled and coiled into a tube prior to extrusion. Air cooled. Tangential direction.



RF-6952

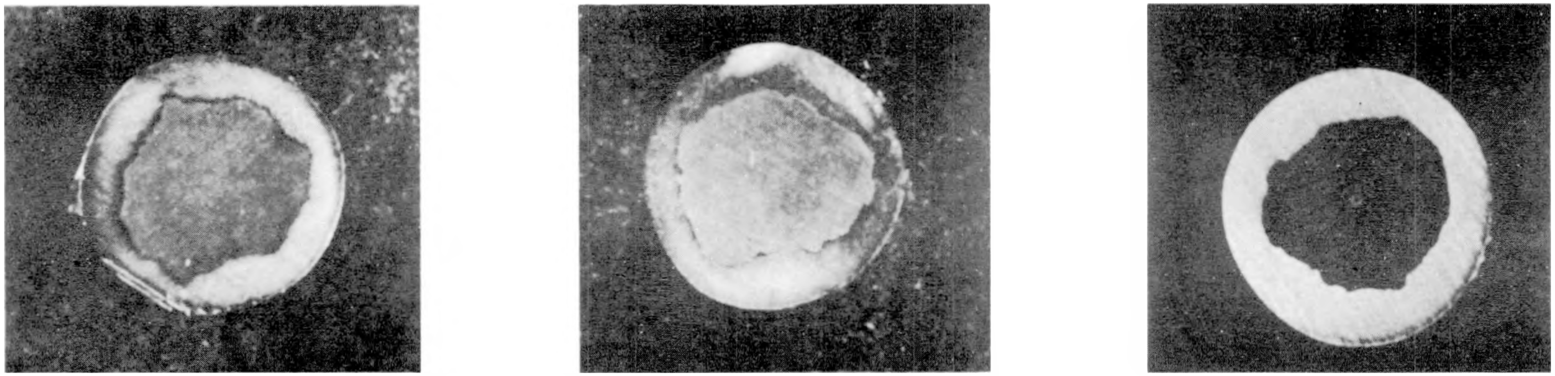
a) As extruded: extrusion No. 20917



RF-6953

b) Annealed at 1350°F for 15 minutes: extrusion No. 20917

<u>Fig. 11</u> - Burst samples of the Zircaloy-2, cupped and extruded, in the as-extruded and in the annealed conditions.



RF-6757

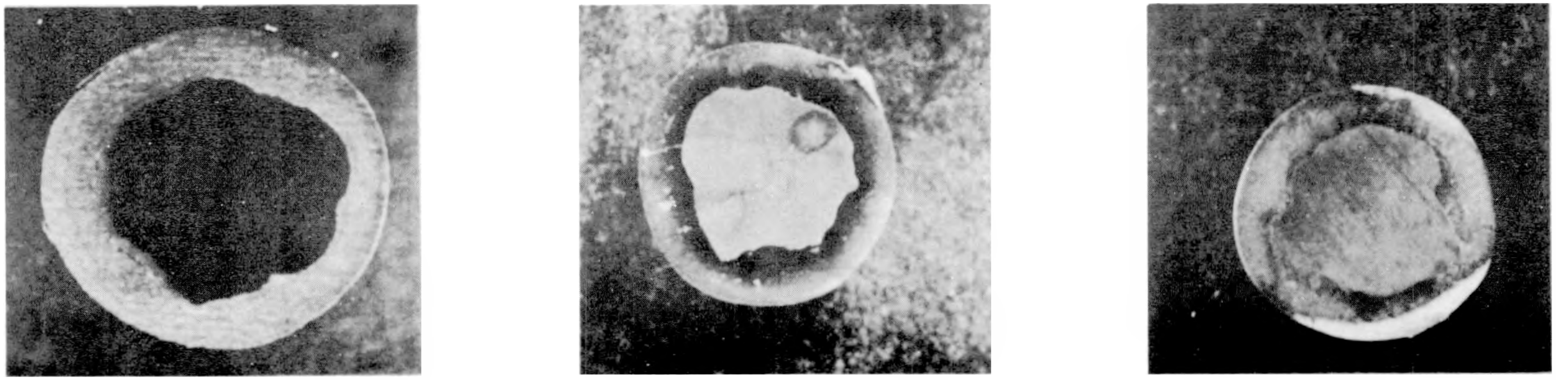
a) Cupped zirconium

RF-6758

b) Cupped Zircaloy-2

RF-6855

c) Rolled zirconium sheet which had been coiled into a tube



RF-6854

d) Rolled Zircaloy-2 sheet which had been coiled into a tube

RF-6755

e) Extruded zirconium rod which had been bored

RF-6756

f) Extruded Zircaloy-2 rod which had been bored

Fig. 12 - Zirconium and Zircaloy-2 with various primary working histories coextruded with large-grain cast uranium at 1175°F, 23:1 reduction.

APPENDIX I

Order of Zirconium Lines

Molybdenum Radiation = 0.70926 Å

hk·l	2θ	θ	hk·l	2θ	θ
100	14.56	7.28	017	59.80	29.90
002	15.84	7.92	133	60.20	30.10
101	16.58	8.29	400	60.88	30.44
102	21.58	10.79	401	61.52	30.76
110	25.36	12.68	126	64.30	32.15
103	28.06	14.03	134	64.48	32.24
200	29.36	14.68	027	66.02	33.01
112	30.04	15.02	230	67.04	33.52
201	30.46	15.23	231	67.62	33.81
004	31.98	15.99	232	69.38	34.69
104	35.32	17.66	135	69.78	34.89
203	38.18	19.09	140	70.98	35.49
210	39.14	19.57	127	71.92	35.96
211	40.04	20.02	233	72.26	36.13
114	41.26	20.63	118	72.76	36.38
212	42.50	21.25	142	73.26	36.63
105	43.08	21.54	226	74.14	37.07
300	44.70	22.35	136	76.06	38.03
213	46.40	23.20	019	78.50	39.25
302	47.70	23.85	501	79.16	39.58
006	48.84	24.42	144	79.98	39.99
205	50.64	25.32	235	81.20	40.60
106	51.24	25.62	137	83.24	41.62
214	51.44	25.72	038	84.04	42.02
310	54.36	27.18	332	84.54	42.27
222	54.78	27.39	241	84.74	42.37
131	55.02	27.51	243	89.10	44.55
116	55.80	27.90	129	89.62	44.81
034	56.00	28.00	151	90.28	45.14
132	57.00	28.50	146	90.90	45.45
125	57.46	28.73	153	94.62	47.31

Appendix II

Angles Between Crystallographic Planes of Zirconium

$h_1k_1{\cdot}l_1 = 10.0$	
$h_2k_2{\cdot}l_2$	ϕ
510	9.05
410	11.02
310	13.97
210	18.98
320	23.46
110	30.04

Angles Between Crystallographic Planes of Zirconium

$h_1k_1{\cdot}l_1 = 00.2$			
$h_2k_2{\cdot}l_2$	ϕ	$h_2k_2{\cdot}l_2$	ϕ
109	11.58	416	54.56
108	13.00	112	57.90
107	14.76	325	58.05
106	17.16	213	58.36
105	20.29	314	58.91
118	21.74	101	61.47
104	24.77	414	64.62
207	27.76	313	65.63
116	27.99	212	67.67
219	28.43	403	67.82
103	31.54	323	69.48
308	34.62	302	70.08
217	34.82	222	72.58
205	36.38	423	72.87
114	38.59	312	73.22
216	39.06	201	74.80
102	42.64	322	75.99
317	43.46	412	76.65
215	44.24	332	78.18
226	46.73	211	78.39
316	47.88	311	81.42
214	50.59	401	82.26
203	50.83	321	82.89
315	53.00	501	83.79
304	54.07	421	84.13
		511	84.42

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