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SUBJECT: A STUDY OF THE FORMING OF ZIRCALOY-2 HEMISPHERES BY POWER SPINNING

TO: Distribution

FROM: F. W. Cooke

ABSTRACT

Twelve Zircaloy-2 sheets, with thicknesses between 1/8- and 5/16-in., were successfully formed into 15-in.-diam hemispheres by power spinning in an effort to determine the feasibility of using such a method to fabricate core vessels for the Homogeneous Reactor Project.

The fabrication of an entire hemisphere as a unit is of interest because it would reduce the number of welds required to form a vessel. This in turn, would reduce the chance of weld contamination and consequent impairment of corrosion resistance and mechanical properties.

A number of difficulties, such as laps and earing, were encountered but were overcome by modifications of the procedure. The maximum percentage reduction in thickness of the shells was between 30 and 40%. The springback on the equatorial radius increased with thickness from 0.040 in. to 0.175 in., while the diametral ellipticity varied between 0.016 in. and 0.100 in.

The average springback was highly reproducible for a given starting thickness, and could therefore be compensated for by die allowance. Thinout and ellipticity were not as highly reproducible so that the demands of weld fitup and sphericity would require a considerable machining allowance and careful fitting of the shells. Although the variations were somewhat larger then had been expected originally, it has nevertheless been demonstrated that power spinning could be used at least as the primary step in the fabrication of Zircaloy-2 hemispheres adequate for HRP applications.

Three complete spheres were successfully welded in a vacuum chamber using a technique developed by the vendor. While the welding was not quite of HRP quality, it did demonstrate that the spun shells could be assembled into vessels.

A STUDY OF THE FORMING OF ZIRCALOY-2 HEMISPHERES BY POWER SPINNING

INTRODUCTION

On October 22, 1958, a study was begun by Titanium Fabricators, Inc., of Burbank, California, to determine the feasibility of forming thin-walled Zircaloy-2 hemispheres by power spinning. This process was under investigation as a possible method of fabricating future core vessels for the Homogeneous Reactor Project (HRP). The fabrication of an entire hemisphere as a unit is of interest, because it would reduce the number of welds required to form a spherical vessel. Reduction in the number of welds is desirable because it would reduce the chance of undetectable weld contamination which impairs corrosion resistance and mechanical properties. Furthermore such a procedure would probably be more economical than a multistep process. The Homogeneous Reactor Test (HRT) core tank required 13 weldments, which could be reduced to 3 if the hemispheres could be made as units. The work was done by Titanium Fabricators, Inc., under subcontract.[1]

EQUIPMENT AND MATERIALS

The spinning equipment on which titanium had been successfully formed was designed specifically for the fabrication of hemispheres in the size range of interest (15 to 30-in. in diameter). The 15-in.-diam die was used to conserve material. The machine consisted, essentially, of a hemispherical die which rotated about a vertical axis. The forming tool, a hardened-steel roller, was supported by a yoke which spanned the die. The roller could thus traverse a great circle path from the pole to the equator of the die. The roller, which was forced against the blank and die hydraulically, spun or rolled blanks bolted to the die at the pole (Fig. 1).

The Zircaloy-2 sheet used in the study was produced by a commercial fabricator according to an Oak Ridge National Laboratory (ORNL) fabrication schedule which produced somewhat lower preferred orientation than is usual

[1] Subcontract No. 93Y-16317 under W-7405-eng-26.

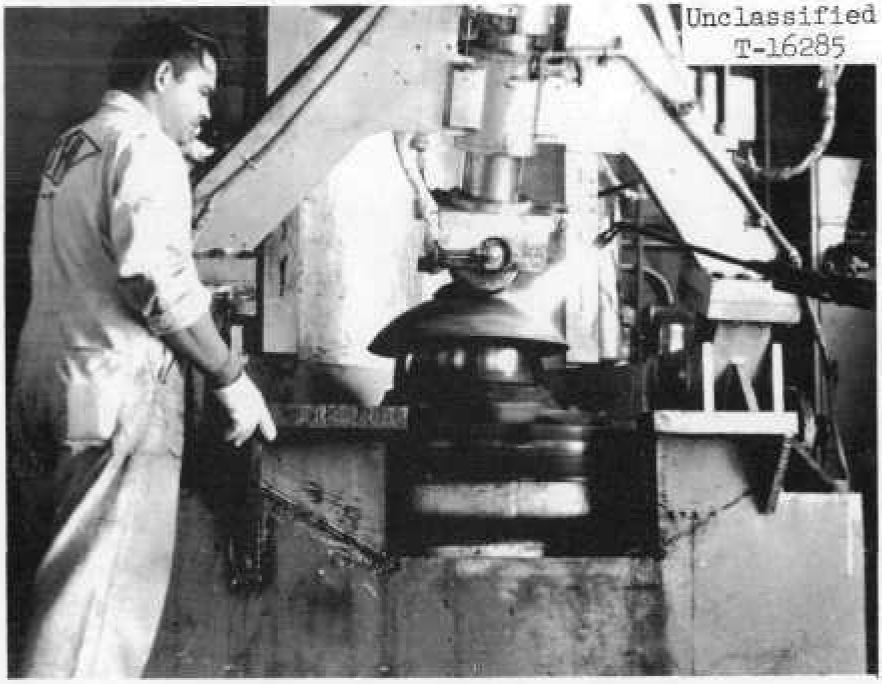

Fig. 1 Spinning Machine, Torch at Right is Heating 30-in. Diameter Sphere about to be Spun on a 15-in. Diameter Die.

in Zircaloy-2 sheet. This sheet was supplied to Titanium Fabricators in the form of two-foot squares cut from the same original plates. There were 12 such blanks, six of nominal 5/16-in. thickness, two of nominal 1/4-in. thickness, and four of nominal 1/8-in. thickness. Two of the 5/16-in. plates were hot (1000°F) rolled 8% and annealed (1400°F) at ORNL to improve their surface condition. The exact thickness of each plate is recorded in Table I.

Table I. Thickness of Zircaloy-2 Sheet Prior to Spinning

Shell Number	Thickness (in.)
1	0.312 ± 0.004
2	0.310 ± 0.004
3	0.312 ± 0.003
6	0.289 ± 0.016
11	0.285 ± 0.002
12	0.285 ± 0.001
5	0.218 ± 0.003
4	0.218 ± 0.003
7	0.126 ± 0.001
8	0.126 ± 0.002
9	0.126 ± 0.002
10	0.126 ± 0.002

PROCEDURE

All surface defects were removed by Titanium Fabricators using a small belt sander. Each sheet was cut into a 22.80-in.-diam disk with a hole, approx 2.5-in. in diameter, cut in the center to allow passage of the hold-down bolt.

To reduce surface oxidation, an organic material (Turko No. 4367), was painted on the blanks prior to heating. It was a proprietary material and its composition could not be learned. No detectable carburization had been attributed to its use on titanium and it was felt that any which might occur on the Zircaloy-2, during the few minutes at temperature, would be removed by pickling.

After application of the coating, a 12-in. diameter circular area in the center of each disk was heated to about 1200°F, with a large oxyacetylene torch. The temperature was sensed by a contact thermocouple immediately after removal of the flame. The disk was then placed in a small press and a 6-in.-diam dimple formed. Thirty to sixty seconds elapsed between removal of the torch and completion of the dimpling operation. The temperature of the dimpled area immediately after dimpling was much lower for the Zircaloy-2 than was normal for titanium. This rapid cooling was due to the higher thermal diffusivity of Zircaloy-2 compared to that of titanium. Wrinkling of the disk below the dimple was noted also; however, this proved to be no problem in spinning.

The blanks were bolted to the die using a 6-in.-diam hold-down washer. The general spinning procedure was to first form the blank to a 30-in.-diam die with 2 or 3 passes of the roller. The shell was then placed on the 15-in.-diam die and formed with 2 to 4 passes of the roller. Final sizing required 1 to 3 additional passes. Because the original blanks were too large, due to calculations based on experience with titanium, the shells usually extended below the equator of the 15-in. die and had to be trimmed before the final sizing passes could be made. The heat was applied to the work during all spinning operations by two large oxyacetylene torches (Fig. 1). The dies and plates were preheated with a removable electric hood. The temperatures during spinning were 1150 to 1350°F as sensed by an electronic pyrometer.

RESULTS AND DISCUSSION

The study was evaluated in terms of such readily observable effects as ears, ridges, and laps on the shells and by the more quantitative results of wall thickness and sphericity measurements. An attempt was made to relate these parameters to the spinning procedures.

Physical Appearance Related to Spinning Procedures

As the roller was brought in contact with the shell at the beginning of each pass it remained stationary, just below the washer, for several revolutions of the die. This caused a groove to be formed at this point, which was about

25 deg from the pole. Also, the circular cross section of the roller made it impossible to fit it up closely to the washer. This left about a 1/4-in. wide band between the washer and the groove that was never in contact with the roller. Back extrusion of the metal from the groove caused this band to become a ridge. A similar ridge formed on the inside of each shell in the same general area.

Ears were usually produced during the initial forming operations (Fig. 2), but were removed by the trimming operation. Only slight earing occurred during the final stages. Rippling near the equator was a more serious phenomenon, which also occurred during the first forming step (Fig. 3). These ripples were removed by further rolling at the expense of the wall thickness. Rippling was most acute in the 1/8-in. shells. Another problem which recurred several times was misalignment of axis of the die and the axis of rotation. This caused rough operation of the machine and a variation in thinout at the equator with azimuthal angle. Excessive heating (several hundred degrees Fahrenheit above the 1200°F requested by ORNL) occurred on two occasions, but had no apparent ill effects on the final shells. During the formation of shell No. 2 on the 30-in. die, the control mechanism failed, and the roller remained at one latitude for many revolutions of the die. This produced a groove about 0.030-in. deep which was reduced to about 0.010-in. by subsequent passes.

Another deviation from the normal was the attempt to form shell No. 1 (0.312 in.) directly on the 15-in.-diam die. This was prompted by the hope of avoiding the $1,500 cost of the extra die and by the earlier success with shells of the same thickness. Numerous deep laps were formed in this shell (Fig. 4), which could not be completely removed by a combination of further rolling and machining. The one-step procedure was abandoned because of the strain it placed on the machine and the amount of development which would have been required to produce a good shell in this way.

The study was divided into two parts. In the first part three 5/16-in., one 1/4-in., and three 1/8-in. shells were spun. In the second period three 5/16-in., one 1/4-in., and one 1/8-in. shells were spun. This interruption, which was due to a delay in shipping some of the blanks, afforded an opportunity to evaluate the work done to that point and to consider means of improving the results in the second period. Furthermore, it served as a natural point of division for observing whether the results did improve as the operators gained experience with the material.

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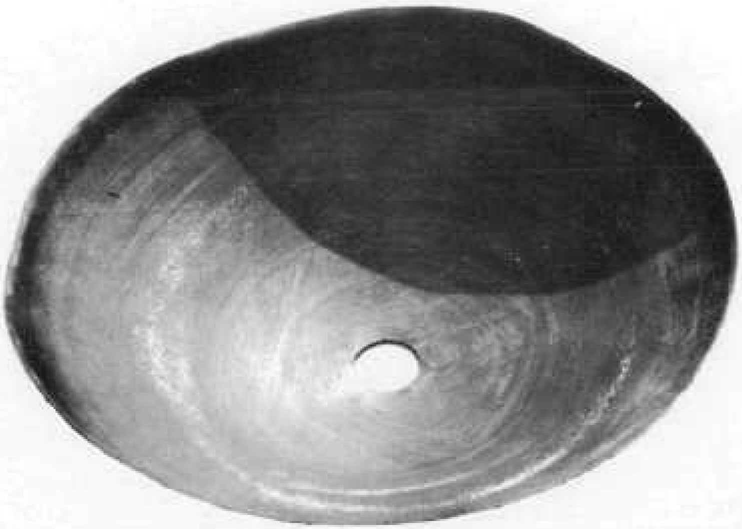

Fig. 2 1/8-in. x 30-in. Diameter Shell Showing Ears.

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Fig. 3 1/8-in. x 15-in. Diameter Shell Showing Ripples.

Fig. 4 5/16-in. Shell Spun Directly to 15-in. Diameter. (Unmachined)

Figure 5 is a picture of a successfully completed 5/8-in.-thick shell. A complete description of the fabrication of each shell is included in the Appendix.

Measurements

The quantitative evaluation of the shells consisted of thickness and diametral measurements made by both Titanium Fabricators and ORNL.

Thickness Measurements (Titanium Fabricators). — Thickness measurements were made by Titanium Fabricators each time a shell was removed from the die. These measurements were made at 2-in. intervals along 4 or 8 longitudes with a dial gage mounted on a special frame. The results of these measurements are summarized in Table II and are recorded in their entirety in Table AI of the Appendix.

Diametral Measurements (Titanium Fabricators). — After the forming operations were completed, diametral measurements were made at Titanium Fabricators' plant. Vernier calipers were used to make measurements near the equator and at points about 2 in. above the equator.

Because the determination of the location of the measurements, as well as the measurements themselves, depended very heavily on the eye and judgment of the inspector, these data are not considered very reliable, and they do not correspond to the ORNL measurements. For the sake of consistency, these data are summarized in Table III and are recorded in their entirety in Table AII of the Appendix.

Thickness Measurements (ORNL). — The thickness measurements were repeated at ORNL, using a Vidigage ultrasonic thickness measuring device. Checks made at the pole and equator of each shell showed that the Vidigage readings were usually identical with those of the micrometer and in only two instances did they differ by more than 2%. At the equator of shell No. 11 the average of 6 micrometer readings showed that the Vidigage was off by 3%, and at the same location on shell No. 1 a similar number of readings indicated that the Vidigage was off by 4%. Thus, the greatest variation encountered in the thickness, averaged for one latitude, was only ± 0.010 in.

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Fig. 5 Completed and Trimmed Shell, 5/16-in. x 15-in. Diameter.

Table II. Shell Thickness (Titanium Fabricators)

Shell No.	Original Thickness ($in. x 10^{-3}$)	Run	Die Size (in.)	No. of Passes	Time Run (Min.)	Maximum* Thickness ($in. x 10^{-3}$)	Maximum Thickness ($in. x 10^{-3}$) (spun area)	Minimum Thickness ($in. x 10^{-3}$)	Equatorial Thickness ($in. x 10^{-3}$)
1	308–316	1	15	3	20	306	284	229	275
		2	15	2	20	--	--	--	--
2	306–314	1	30	2	3	314	306	280	--
		2	15	4	5	308	236	198	--
		3	15	1	4	315	222	190	218
3	309–315	1	30	3	12	308	308	299	--
		2	15	2	9	307	281	246	257
		3	15	2	7	--	--	--	--
6	273–304	1	30	2	5 1/2	306	286	272	--
		2	15	2	9	299	252	210	--
		3	15	2	8 1/2	--	--	--	--
11	284–287 (cold rolled)	1	30	--	7	285	283	265	--
		2	15	2	9	--	--	--	--
		3	15	1	4 1/2	282	206	185	194
12	286–284 (cold rolled)	1	30	--	6 1/2	284	276	264	--
		2	15	2	10	--	--	--	--
		3	15	1	5	290	235	225	230
5	215–221	1	30	3	10	213	206	201	--
		2	15	3	12	212	163	178	--
		3	15	1	5	215	172	160	166
4	216–221	1	30	--	--	214	208	195	--
		2	15	3	--	213	187	174	--
		3	15	--	--	--	--	--	--

Table II (Cont'd)

Shell No.	Original Thickness (in.x10^{-3})	Run	Die Size (in.)	No. of Passes	Time Run (Min.)	Maximum* Thickness (in.x10^{-3})	Maximum Thickness (in.x10^{-3}) (spun area)	Minimum Thickness (in.x10^{-3})	Equatorial Thickness (in.x10^{-3})
7	125-127	1	30	--	3	128	130	122	--
		2	15	3	14	126	110	90	108
		3	15	2	11	--	--	--	--
		4	15	1	3	--	--	--	--
8	125-127	1	30	1	3	129	118	103	106
		2	15	2	4 1/2	--	--	--	--
		3	15	3	11	--	--	--	--
9	Nominal 1/8	--	--	--	--	--	--	--	--
10	125-128	1	30	--	3	132	108	91	103
		2	15	3	12	128	92	65	87
		3	15	2	10	--	--	--	--

*The maximum thickness always occurred in the area under the hold-down washer.

Table III. Diametral Measurements (Titanium Fabricators)

Shell No.	Original Thickness (in.)	Average Inside Diameter (in.) — Equator: Before Sand Blasting	Equator: After Sand Blasting	2 in. Below Equator: Before Sand Blasting	2 in. Below Equator: After Sand Blasting
1	0.312	15.082	15.112	14.446	14.431
2	0.310	15.107	--	14.450	--
3	0.312	15.109	15.113	14.406	14.432
6	0.299	15.083	15.092	14.308	14.409
11	0.285	15.124	15.126	14.412	14.384
12	0.285	15.116	--	14.606	--
5	0.218	15.123	--	14.408	--
4	0.218	--	--	--	--
7	0.126	15.110	--	14.473	--
8	0.126	--	15.091	--	14.223
9	0.126	--	--	--	--
10	0.126	--	15.138	--	14.814

Thinout is defined as:

$$\frac{\text{Original Thickness - Final Thickness}}{\text{Original Thickness}} \times 100$$

and is expressed as a percent analogous to the method of expressing the reduction due to standard rolling operations. Consideration of the maximum thinout will give an indication of the thinout allowances which would have to be provided to obtain a given final thickness.

Table IV is a summary of these thicknesses and thinout data which are presented in detail in the Appendix (Table AIII).

It should be noted that thinout varies widely for the same starting thickness. It is obvious that thinout is primarily a function of the spinning procedure (number of passes, temperature, and loading on the roller). Since this procedure depends upon the whims and touch of operator, the poor reproducibility of thinout is not surprising.

Figures 6 to 8 show how the thinout varies with distance from pole at various stages of fabrication and for various starting thicknesses. In all cases, the portion of the shell which was beneath the washer (i.e., dimpled only) suffered little or no thinout (0 to 5%).

Figure 9 shows the variation of thickness with azimuthal position at the equator of shell Nos. 6 and 11. The thin spots on shell No. 6 are opposite each other and at positions 90 deg from the thick spots. This may be explained in terms of the increased thinout below the ears, which formed at positions of two-fold symmetry on this shell. The thin spot on shell No. 11, however, formed at a point 180 deg from the thick spot. This is explainable in terms of the displacement of the die axis from the axis of rotation. One or the other of these phenomena, or a combination of both, is present to some degree on every shell and causes a maximum thickness variation of about 0.010 in. at any latitude.

Radial Measurements (ORNL). — The ORNL radial measurements were made to determine the distance from various points on the inside of each shell to a point corresponding to the geometric center of the hemisphere to which the shell was spun. The method of determining the center point is explained in the Appendix. The difference between these measurements and 7.5 (the die radius) is the springback. The measurements were made with an indicator gage attached to a sweep arm on a horizontal milling machine, the bed of which could be moved in three directions as well as rotated. The error is believed to be less than 0.010 in.

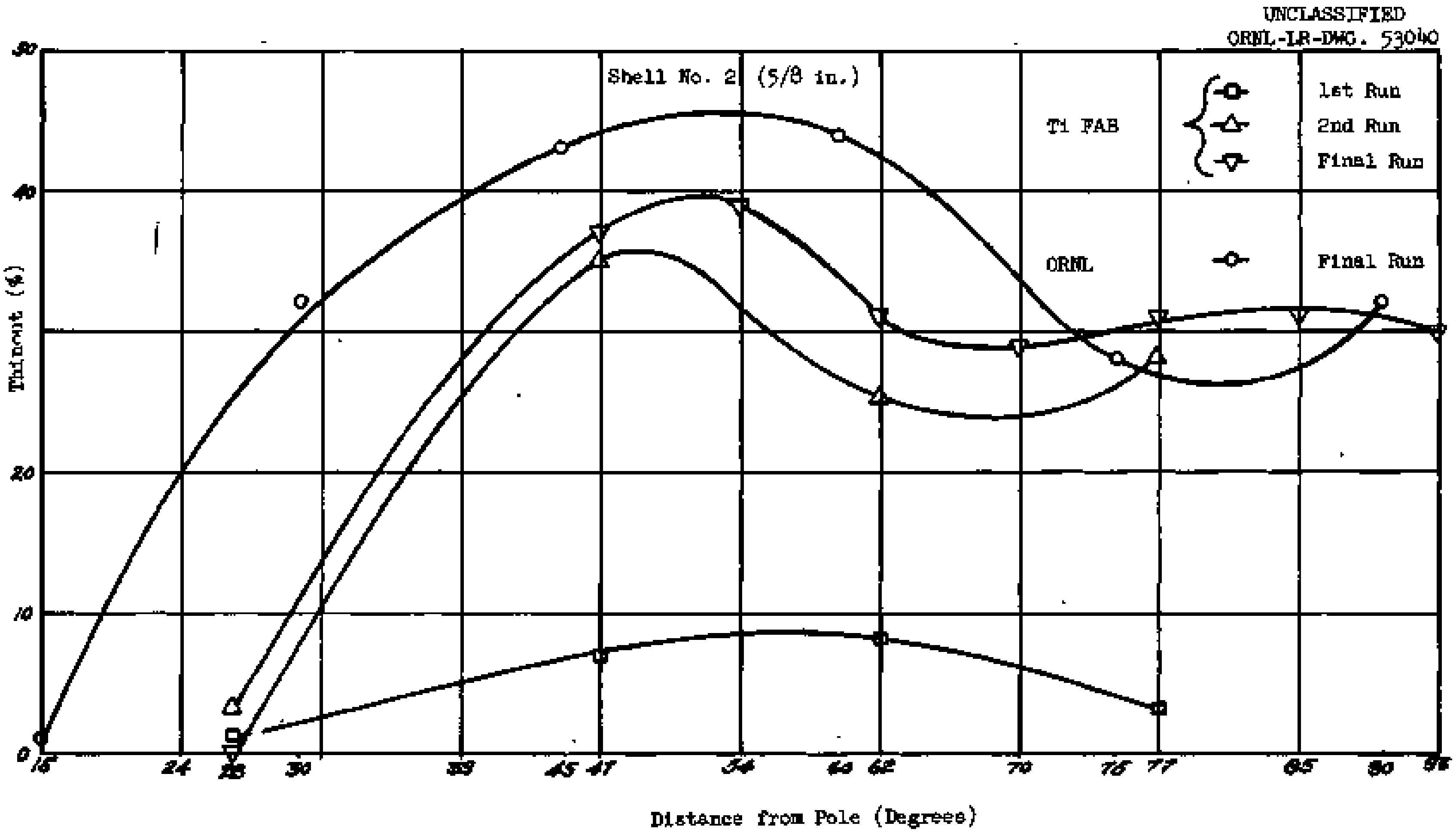

Fig. 6 Distance from Pole vs Thinout

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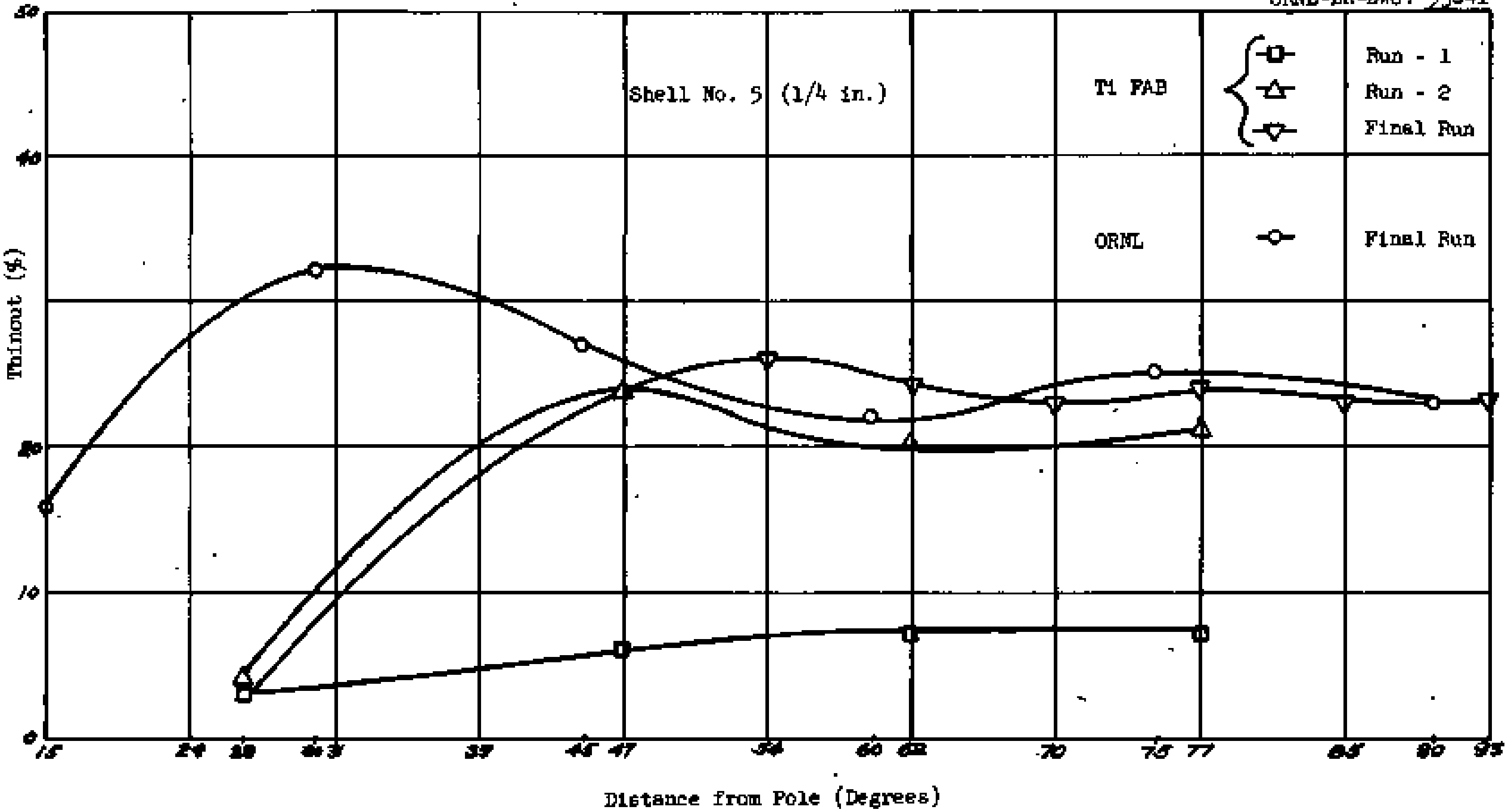

Fig. 7 Distance from Pole vs Thinout

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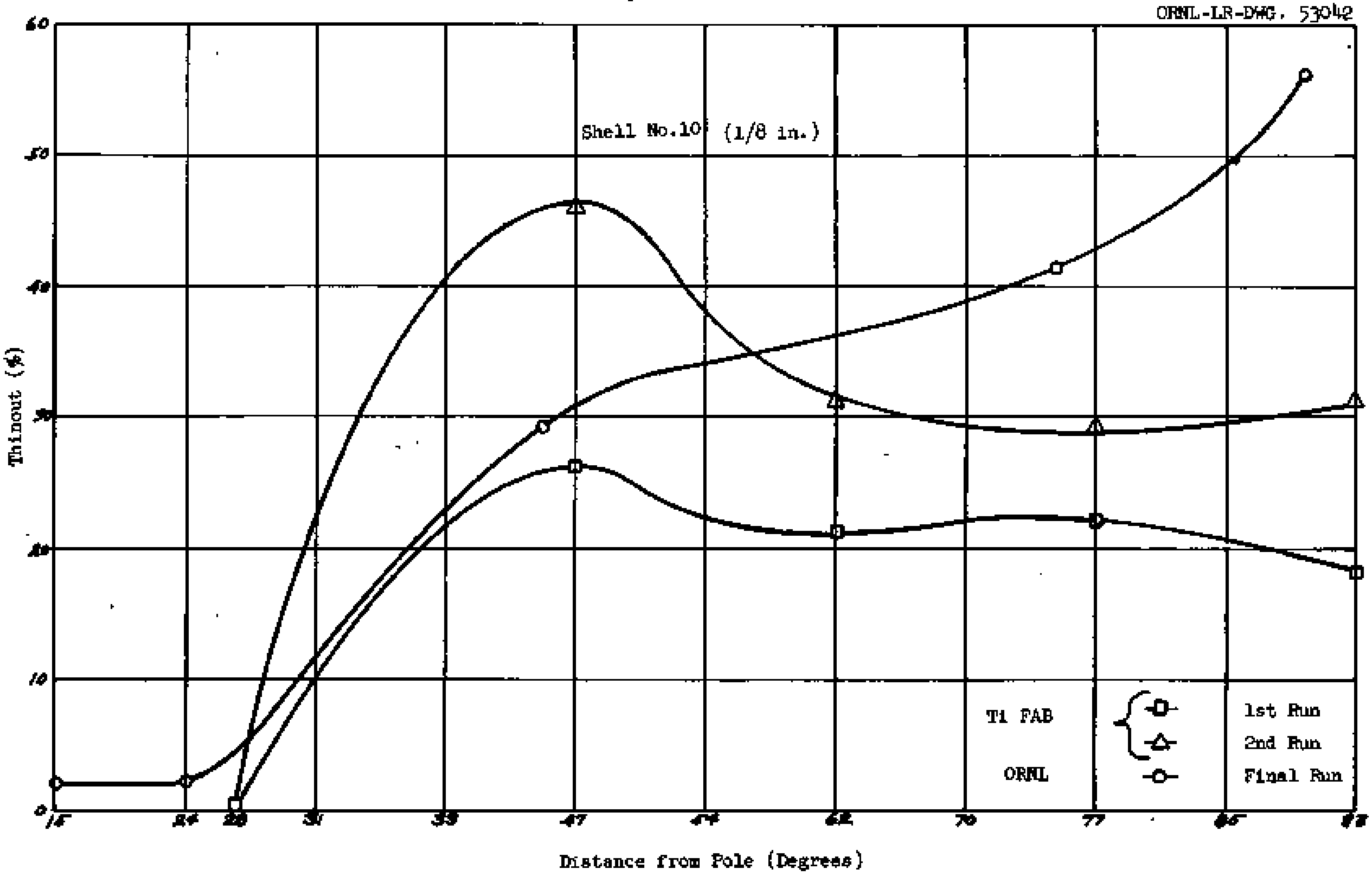

Fig. 8 Distance from Pole vs Thinout

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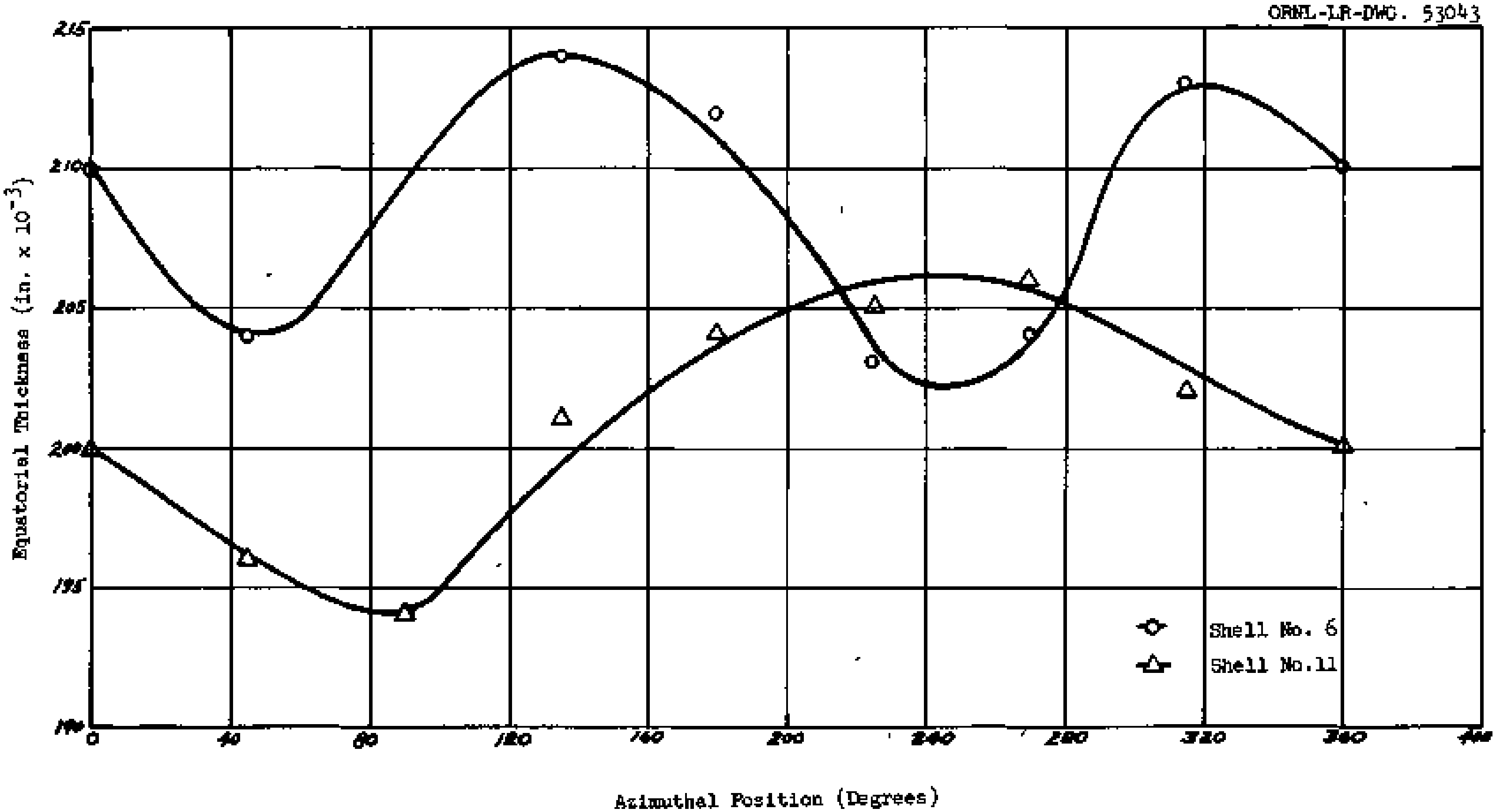

Fig. 9 Equatorial Thickness vs Azimuthal Position

Table IV. Final Shell Thickness (ORNL)

Shell No.	Original Thickness (in.x10^{-3})	Maximum Thickness* (in.x10^{-3})	Maximum Thickness Spun Area (in.x10^{-3})	Minimum Thinout Spun Area (%)	Minimum Thickness (in.x10^{-3})	Maximum Thinout (%)	Equatorial Thickness (in.x10^{-3})	Equatorial Thinout (%)
1	312	240	226	27	168	46	221	29
2	310	310	230	26	172	44	210	32
3	312	269	258	17	218	30	weld	--
6	299	304	230	22	203	31	209	30
11	285	278	209	27	196	31	201	29
12	285	270	240	14	220	23	234	18
5	218	200	170	22	158	28	167	23
4	218	--	192	12	170	22	189	13
7	126	125	92	27	82	35	95	25
8	126	128	95	25	60	52	66	48
9	126	124	96	24	82	35	86	33
10	126	124	92	21	53	58	56	56

*The maximum thickness always occurred in area under hold-down washer. Shells 1, 3, 11, 12, and 5 were surface machined prior to shipment to ORNL, which accounts for the relatively large amount of thinout in the hold-down area of these shells.

and was such as to produce values smaller than the true ones, i.e., reduce the observed springback.

A summary of the springback data for each shell is presented in Table V. Table AIV of the Appendix contains the entire ORNL radial-measurement data.

Because of the requirements of weld fitup at the equator, as well as general dimensional tolerances for the vessel, springback, and ellipticity are of prime importance. Figure 10 is a plot of the radial springback, averaged at each latitude, against the distance from the pole. Only the unwelded shells Nos. 2, 12, 5, 7, and 9 were evaluated for springback, since jigging and welding distorted the welded shells so that a true picture of the as-spun condition could not be obtained for these. It should be noted, however, that the springback was sufficiently reproducible to permit the welding of these other shells. Shell No. 4 was excluded also because a premature alteration of the polar area at ORNL made it impossible to obtain the radial measurements.

It may be seen (Fig. 10) that the springback of the thicker shells (0.310-in. and 0.285-in.) increased more or less uniformly from the pole to the equator. The 0.218-in. shell exhibited a decrease in springback at about 45 deg from the pole, followed by a further increase. The thinnest shells (0.126-in.) exhibited an even sharper decrease in springback at about 60 deg from the pole again followed by a further increase. There is no obvious explanation of this behavior.

It should be noted also that springback was fairly consistent for shells of the same starting thickness, which indicates that this effect may be satisfactorily reproducible.

Figure 11 is a plot of the average radial springback at the equator against the starting thickness of the shell. It is obvious that springback increases with the thickness of the shells. This results from the fact that the surface strains developed during spinning are greater in the thicker shells, since these strains are roughly proportional to the thickness.

The springback at 30-deg intervals around the equator is plotted in Figs. 12–16. In general, the springback alternates between a maximum and a minimum at about 90-deg intervals. These variations are not related to die misalignment which is indicated by the thickness plot on each graph.

Table VI shows the maximum difference in diametral springback (maximum diameter minus minimum diameter) at the equator of each shell. This difference in springback is an index of the out-of-roundness of the shells and varies rather widely and unpredictably.

Table V. Average Springback (ORNL)

Shell	Original Thickness (in.x10^{-3})	Average Radial Springback (in.x10^{-3}) 15°	30°	45°	60°	75°	90° (Equator)	Diametral Springback (in.x10^{-3}) 90° (Equator)
1	312	0	3	35	60	93	--	--
2	310	0	29	38	40	103	176	331
3	312	0	17	31	77	127	--	--
6	299	0	0	17	77	160	--	--
11	285	0	0	1	62	93	--	--
12	285	0	5	24	57	111	173	347
5	218	0	29	23	36	71	118	232
4	218	--	--	--	--	--	--	--
7	126	0	38	20	10	18	32	64
8	126	0	--	11	4	31	--	--
9	126	0	17	13	4	12	51	102
10	126	0	6	17	39	78	--	--

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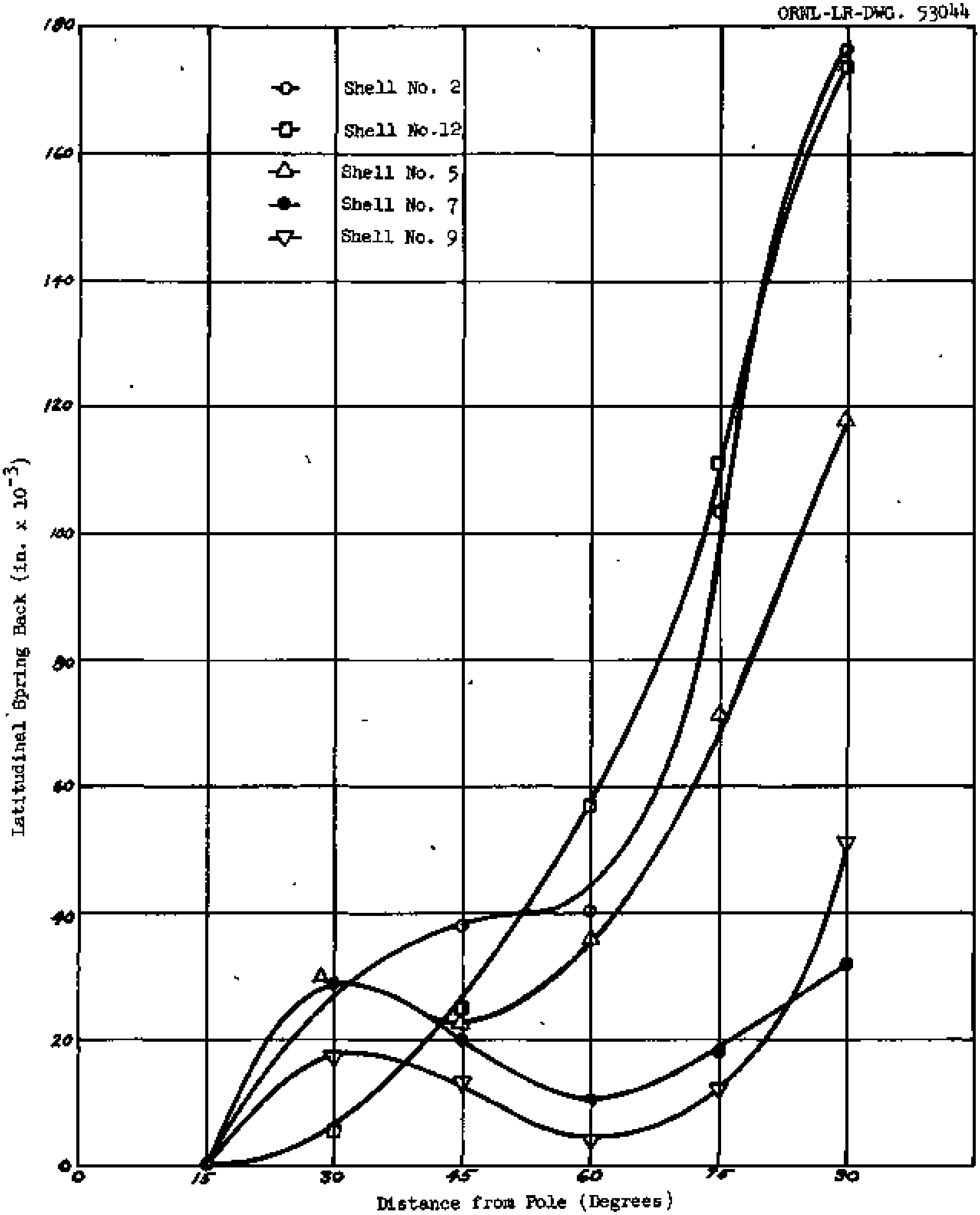

Fig. 10 Latitudinal Spring Back vs Distance from Pole

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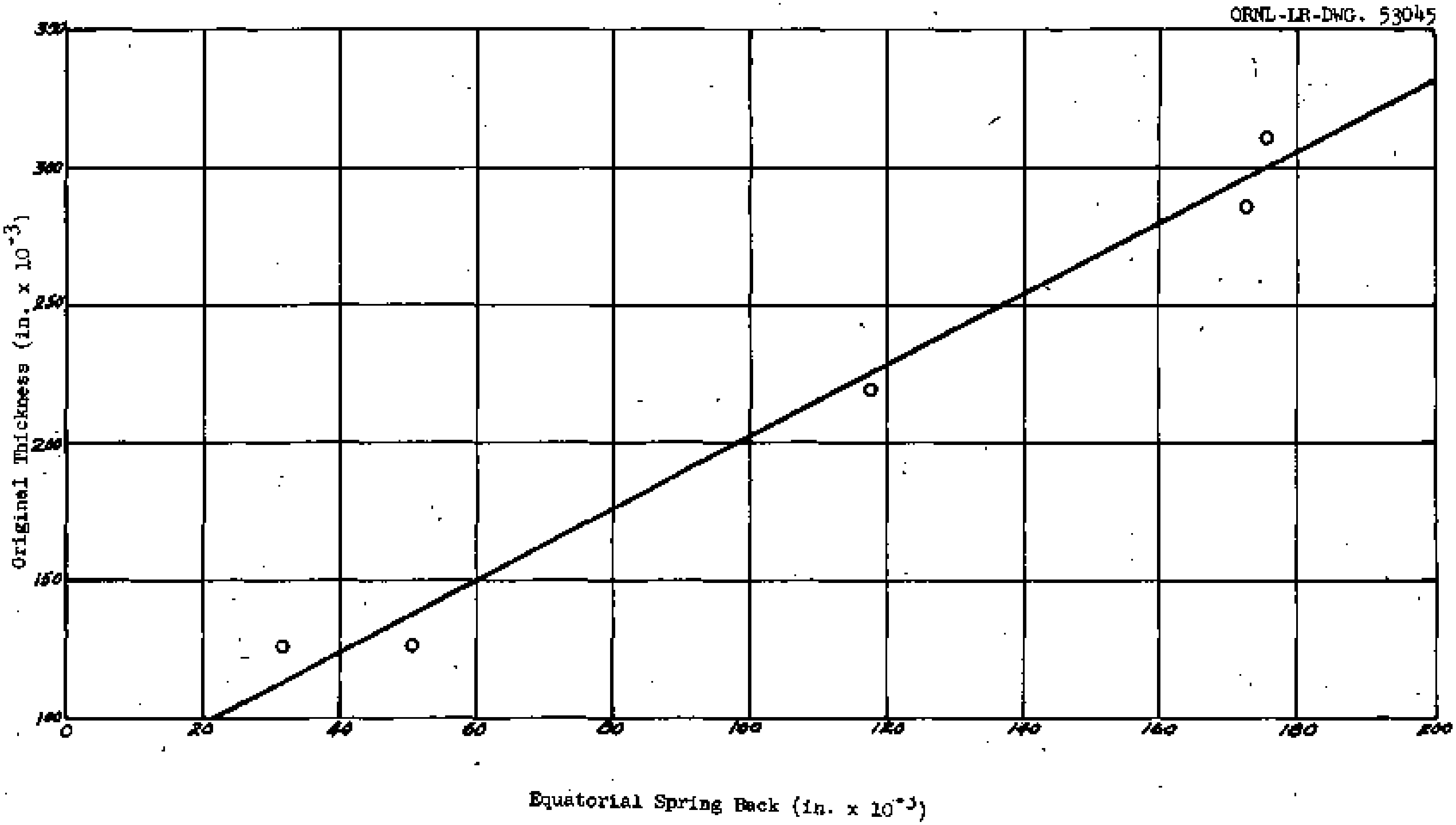

Fig. 11 Equatorial Spring Back vs Original Thickness

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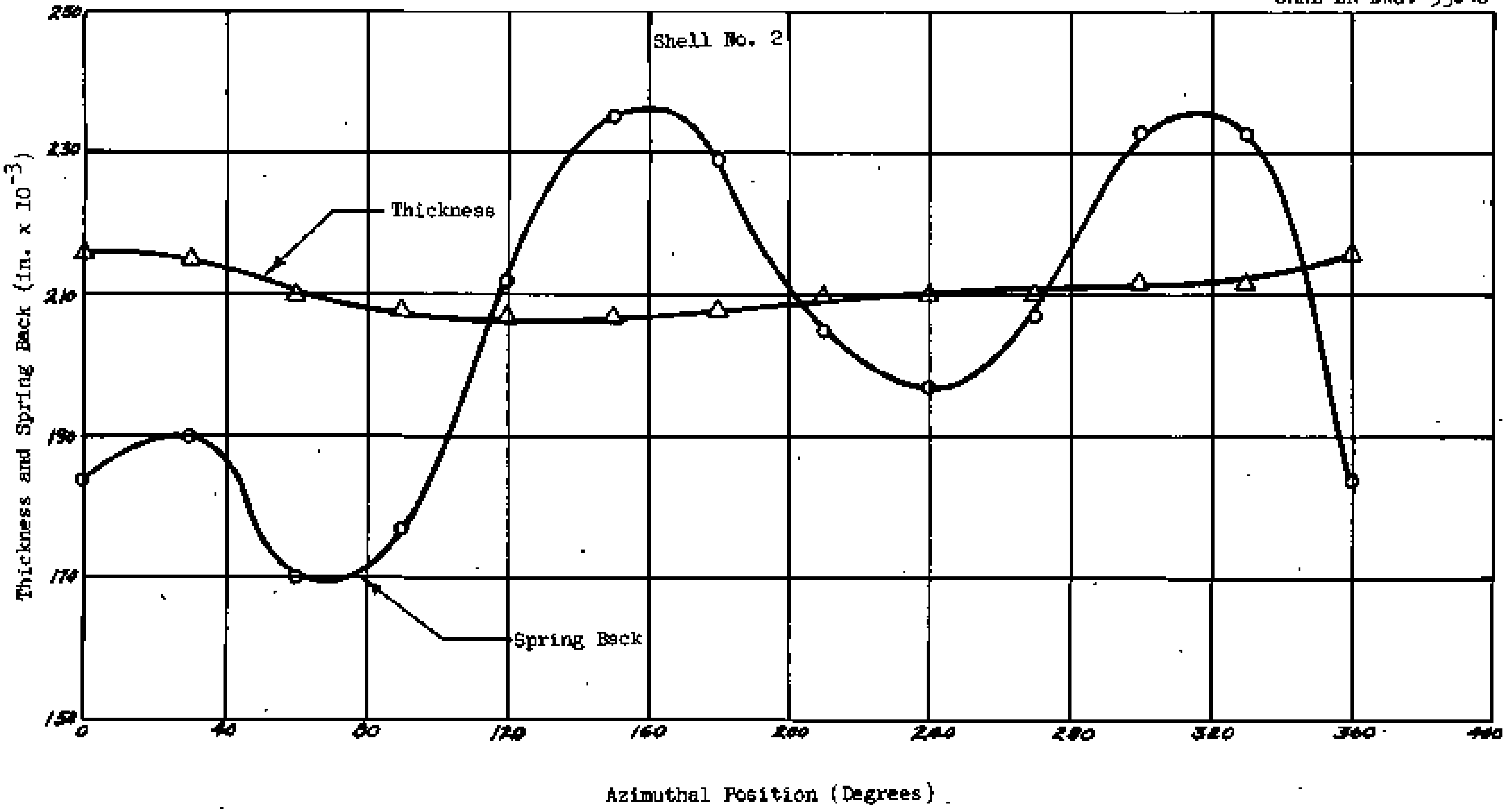

Fig. 12 Equatorial Thickness and Spring Back vs Azimuthal Position

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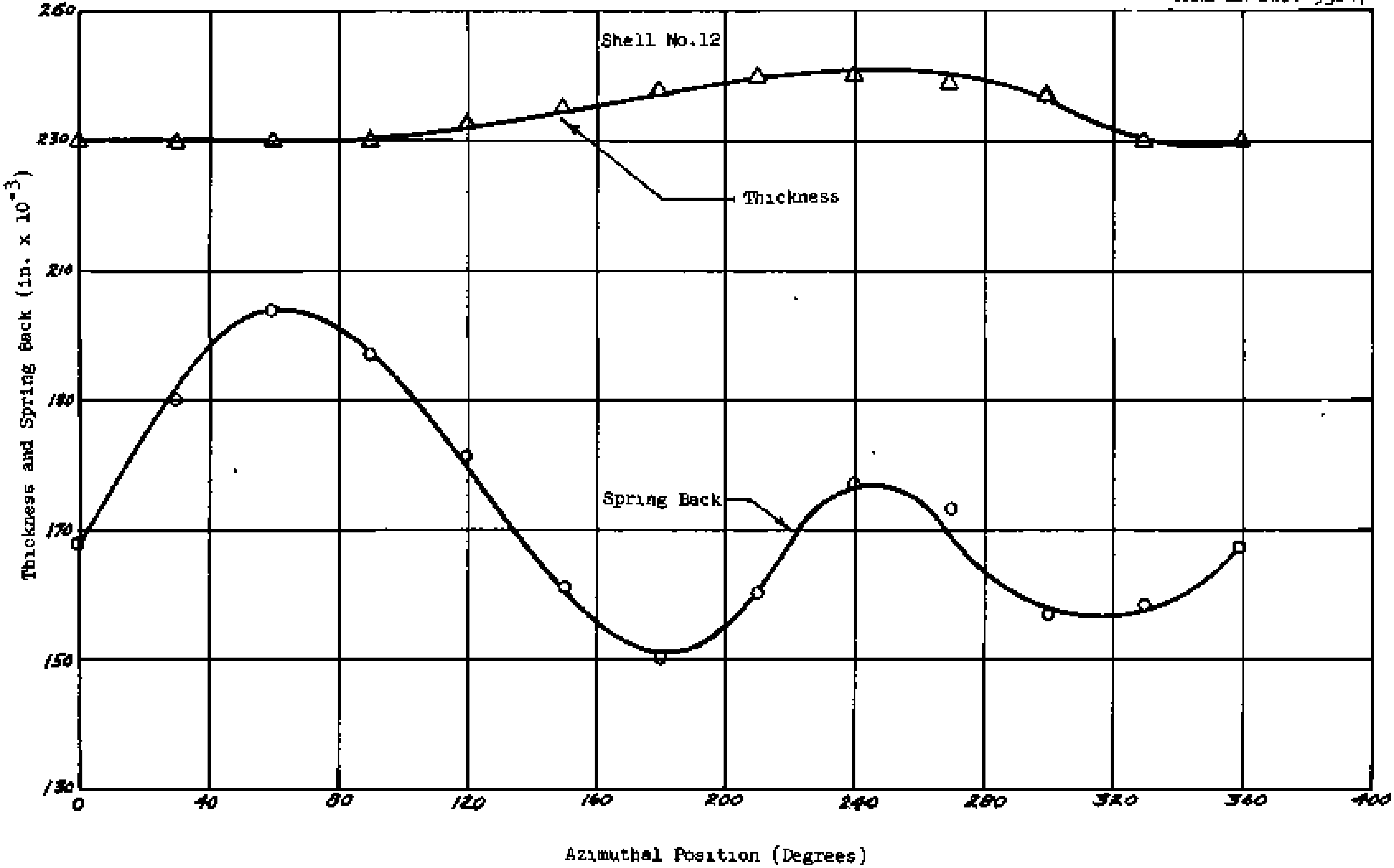

Fig. 13 Equatorial Thickness and Spring Back vs Azimuthal Position

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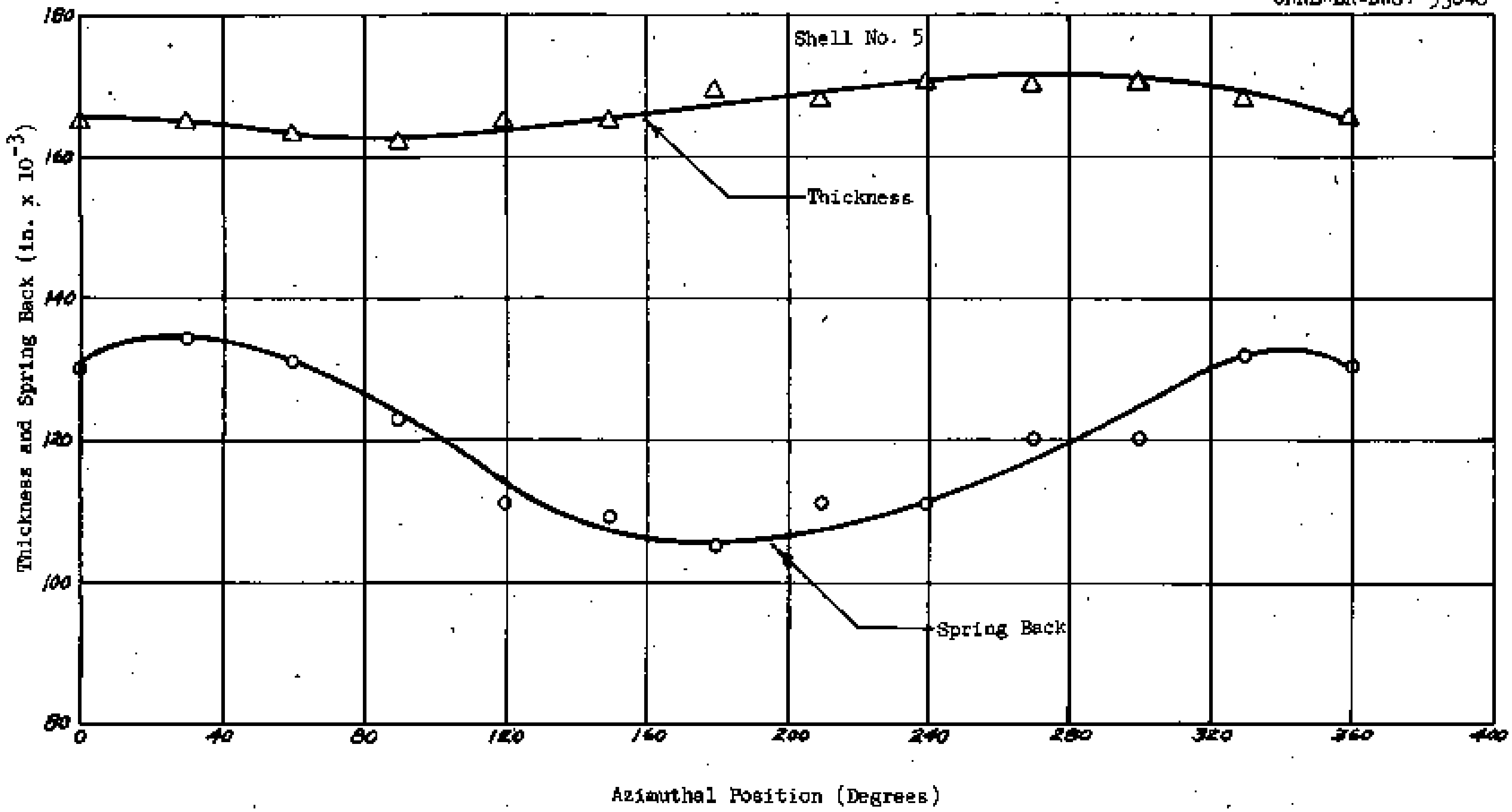

Fig. 14 Equatorial Thickness and Spring Back vs Azimuthal Position

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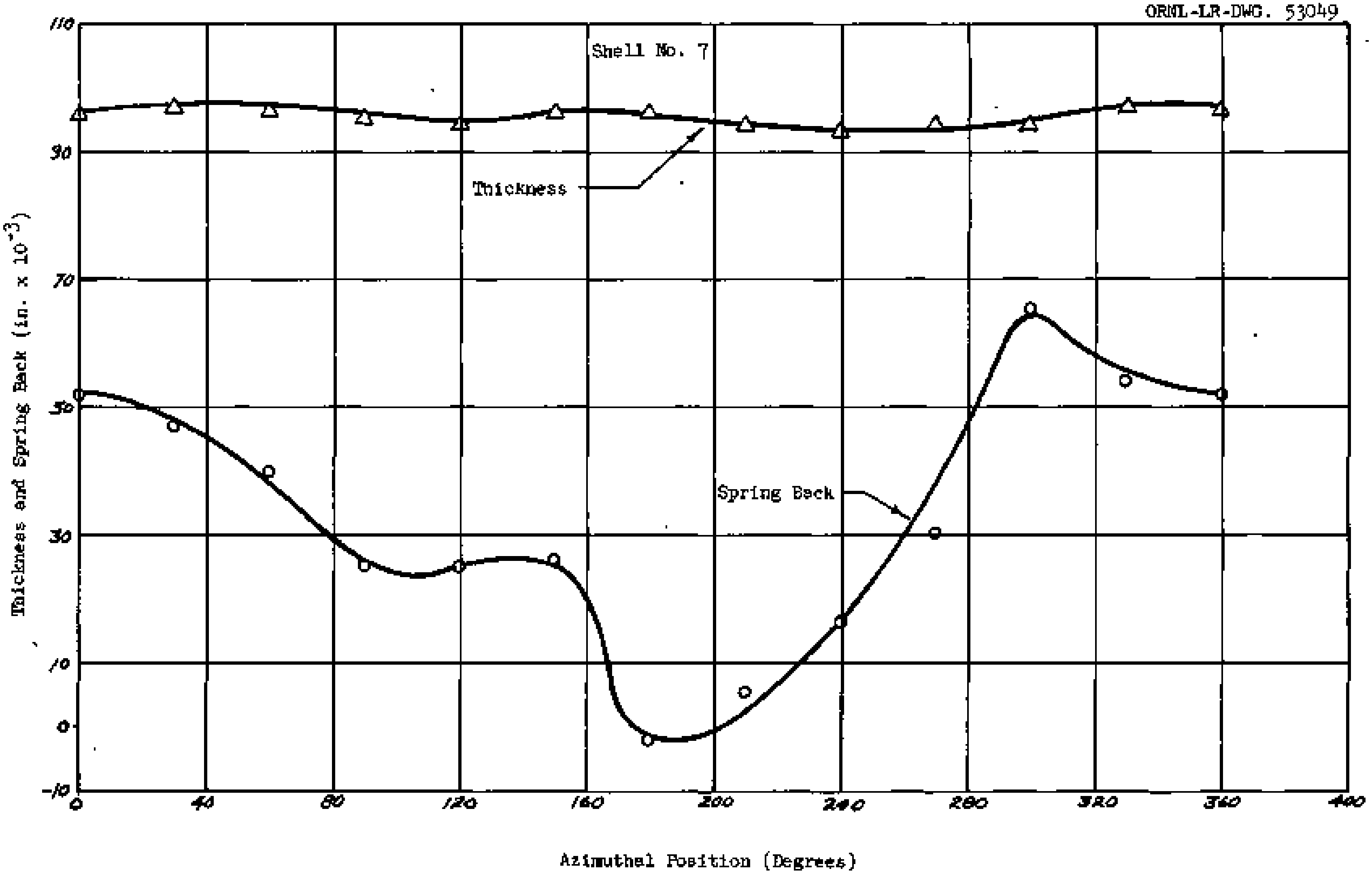

Fig. 15 Equatorial Thickness and Spring Back vs Azimuthal Position

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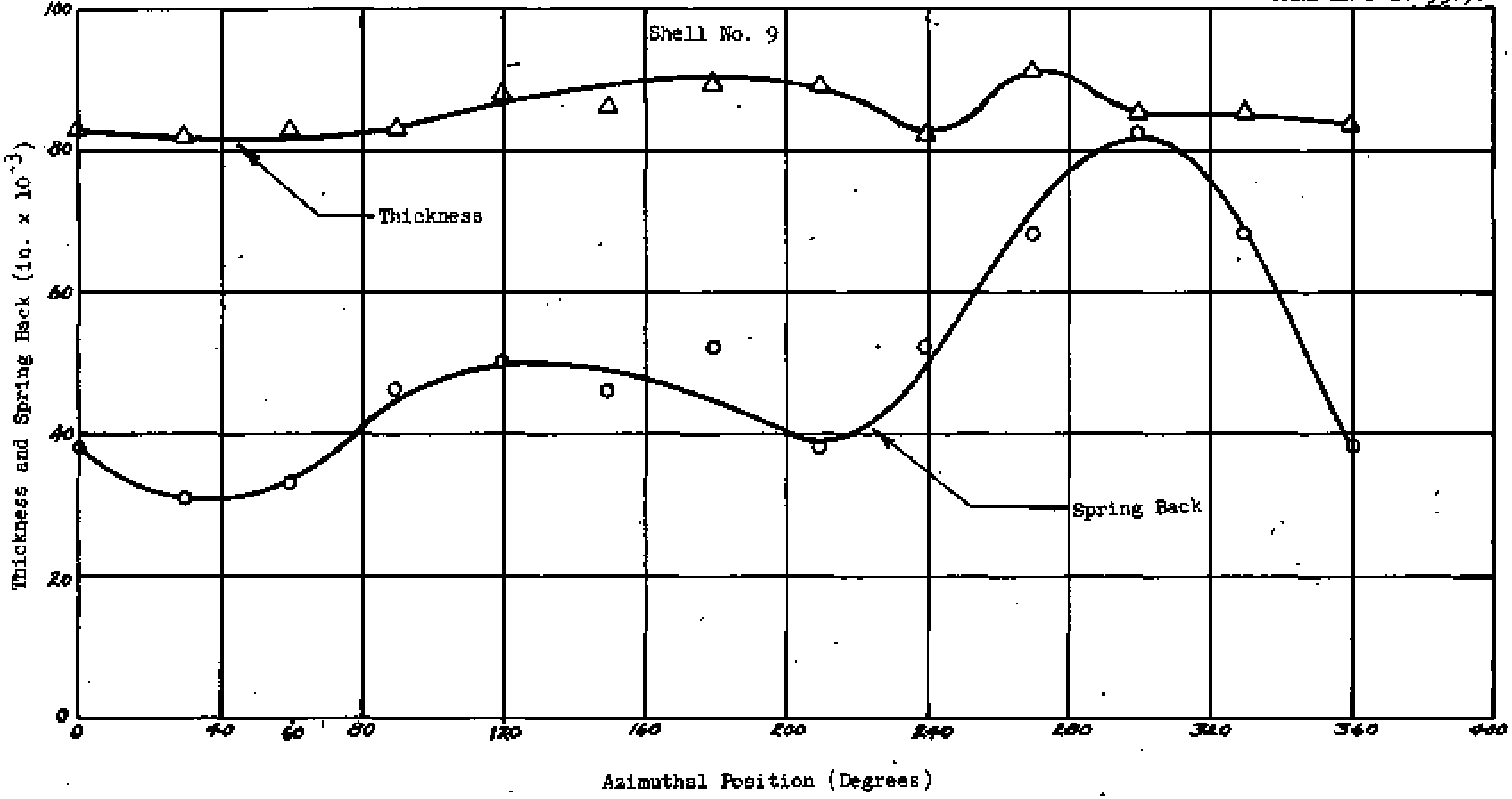

Fig. 16 Equatorial Thickness and Spring Back vs Azimuthal Position

Table VI: Out-Of-Roundness

Original Thickness (in.)	Ellipticity (in.)
0.310 (Shell No. 2)	0.101
0.285 (Shell No. 12)	0.062
0.218 (Shell No. 5)	0.016
0.126 (Shell No. 7)	0.038
0.126 (Shell No. 9)	0.063

Although hand fitting can mitigate the effects of out-of-roundness on weld fit-up, this is a limited means of compensation and does not improve the over-all sphericity of the vessel. It thus seems likely that some additional machining allowance will have to be provided to compensate for out-of-roundness.

WELDING STUDY

Following the fabrication study, a limited welding investigation was conducted using equipment developed for commercial titanium work. The dry box used for all welding was evacuated to about 100 μ pressure and back purged with three volumes of argon. A stationary tungsten-arc torch was used in conjunction with a wire feed mechanism. The work was held on a variable speed, motor-driven turntable controlled from the outside.

Test welds were made on 1/8-in. and 5/16-in. sheet to determine the quality of the welds obtainable with this equipment. Welds were made on the 1/8-in. sheets with and without the use of filler metal. The 5/16-in. sheet was welded with a fusion root pass (no filler metal) followed by three filler passes in which metal was added.

Full penetration silver-colored welds were obtained in all cases. Microscopic examination and weld metal hardness of 150–170 DPH (converted from Rockwell superficial measurements) indicated adequate weld quality. It was determined that a single pass using filler metal was the most desirable procedure for the 1/8-in. sheet. In no case was back welding on the root side found to be necessary though this is the usual practice of Titanium Fabricators when welding titanium.

A welding joint, using an 0.073-in. root face and a 45-deg bevel, which was developed specifically for this application, was machined on the equator of shells Nos. 8 and 10 (nominal 1/8-in.). Another 45-deg bevel, 0.010-in. deep, was also machined on the inside for back welding. The shells were bolted together on the table so that no root gap existed. The linear peripheral speed of the work during welding was 6-in./min. The welding current was 95 to 110 amp at 9 v. Filler wire was added at a rate of 15 to 23-in./min. Only one pass was necessary to effect full penetration. Figure 17 shows the completed sphere.

Shells Nos. 1 and 3 (nominal 5/16-in.) were welded using the same joint design and dry-box setup. The welding current was 110 amp at 9 v for the fusion root pass. The linear peripheral speed was 6-in./min. The filler passes were made at 150 amp and 10 v. The linear peripheral travel was 3-3/8-in./min, and the filler wire was added at the rate of 12 to 16-in./min. A full penetration weld was obtained and no back welding was necessary. A third pair of shells, Nos. 6 (nominal 5/16-in.) and 11 (0.285-in.) were welded in a manner similar to shells Nos. 1 and 3 with similar results.

Metallographic examination of a section cut from the weld between shells Nos. 1 and 3 revealed it to be normal although the heat-affected zone was wider than that usually obtained in hand welding. The average weld metal hardness was 175 DPH determined for 10 kg load (converted from 185 DPH using 1 kg load). The base metal hardness was 168 DPH for a 10 kg load. Radiographic examination revealed that the weld between shells Nos. 1 and 3 was of good quality and uniform thickness, except at the tie-in which was slightly thin. The weld between shells Nos. 6 and 11 was uniform also except at the tie-in where there was a deep crevice and a spot of medium porosity. The weld between shells Nos. 8 and 10 contained some fine, scattered porosity which became quite concentrated in one azimuthal position. The tie-in was also quite thin and there was a pin hole completely through the weld at this point. This work was observed for ORNL by W. J. Leonard of the HRP Metallurgy Group.

CONCLUSION

Although the cooperation of the technical and administrative personnel was good, there was some difficulty in having instructions communicated to the

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Fig. 17. Completed Sphere Formed by Welding Two 1/8-in. Shells Together.

operators. To a large extent, the process depended on the judgment of these operators. This included such basic operations as the control of the roller feed and travel, and the application of heat by the hand-manipulated torches. The temperature-sensing device was also quite inaccurate and little attention was paid to it.

Since thinout is primarily a function of these procedural variables, it is not surprising that it was poorly reproducible. An increase in the starting thickness could compensate for thinout, but this would require some further development, as well as increased machining.

The effect of die misalignment does not seem to be significant and the difficulties with rippling and lapping seem to have been overcome even for the thinnest shells (1/8-in.).

The average springback seems to be reproducible for a given starting thickness and probably can be compensated for by die allowance. Ellipticity also can be compensated for to a large extent by hand fitting. Unfortunately, the ellipticity does not appear to be highly reproducible and consequently will require some extra machining allowance on the thicker shells. Since thinout and springback both increase somewhat with thickness, the addition of a machining allowance to overcome these problems is not straightforward and will require development. It may be necessary to size the spun shells by some process like hot pressing prior to machining unless the spinning technique itself can be improved.

It is encouraging that the thinout of the shells formed during the second period (Nos. 6, 11, 12, 5, and 9) was significantly lower than that for the first shells formed (Nos. 1, 2, 3, 4, 7, 8, and 10). Because of the limited amount of data (five shells), a similar comparison cannot be validly made for springback. Most of the uncontrolled incidents (e.g., ring rolling and overheating) occurred during the first period and the avoidance of such mishaps is probably responsible for the improvement in the second period.

The welding was not quite adequate for HRP requirements, but could be made so by the development of a better tie-in technique and the exercise of a little more care.

In summation, the study has shown that it is possible to form Zircaloy-2 hemispheres by power spinning. While the process shows promise, it did not quite live up to the expectations of the fabricator. If typical reactor-grade close tolerances are placed on sphericity, it is likely that further sizing operations or the use of very large machining allowances will be required.

Acknowledgment is made of the assistance given by Titanium Fabricators and by the ORNL Metallography Laboratory at Y-12 in the preparation of the photographs and by the ORNL Inspection Group in making the measurements.

APPENDIX

APPENDIX

Method of Making Radial Measurements at ORNL

The method of determining the point from which the radial measurements were made at ORNL was as follows:

1. The shell was positioned on the bed of the milling machine so that it was symmetrical with the axis of rotation of the bed. This was done by adjusting the shell position so that the dial gage gave the same reading at the ends of several equatorial diameters. This was checked by similar measurements near the pole to be sure the equatorial plane of the shell was parallel to the bed of the mill.

2. Next, the thickness of the shell around the polar hole (t_p) was measured with a micrometer. The dial gage was then mounted on a sweep arm which rotated about a horizontal axis which, because of the machine design, intersected the vertical rotational axis of the shell and bed (Fig. A1). The gage was adjusted so that it read zero when it was 7.5 in. + t_p from its own axis of rotation. The shell and bed were then raised until the polar area of the shell barely came in contact with the gage (i.e., zero reading). At this point the intersection of the shell axis and sweep axis is assumed to be identical with the geometrical center of the die (Fig. A1). To do this, it must be further assumed that only an insignificant amount of springback occurred near the pole. The subsequent measurements were in terms of 7.5 in. plus the thickness and the springback at the point of measurement.

Detailed Description of the Spinning of Each Shell

The following is a brief description of the spinning of each shell: Blanks Nos. 2 and 3 (0.310- and 0.312-in. thick, respectively) were rolled on the 30-in. die without incident, except that blank No. 3 was worked at somewhat higher temperature (1400°F) than the recommended 1200°F. This seemed to have no ill effect, however, since a good shell was produced. Only slight earing occurred at the equator. Shell No. 3 extended below the die equator after 2 passes on the 15-in. die and had to be removed and trimmed. After this, it was sized to the 15-in. die without incident. The outer surface of the shell was machined to reduce the thickness variations before shipment to ORNL. This precluded thickness measurements of the shell at ORNL in the as-spun condition. Shell No. 2 was trimmed prior to forming on the 15-in. die. During the second pass on this die the

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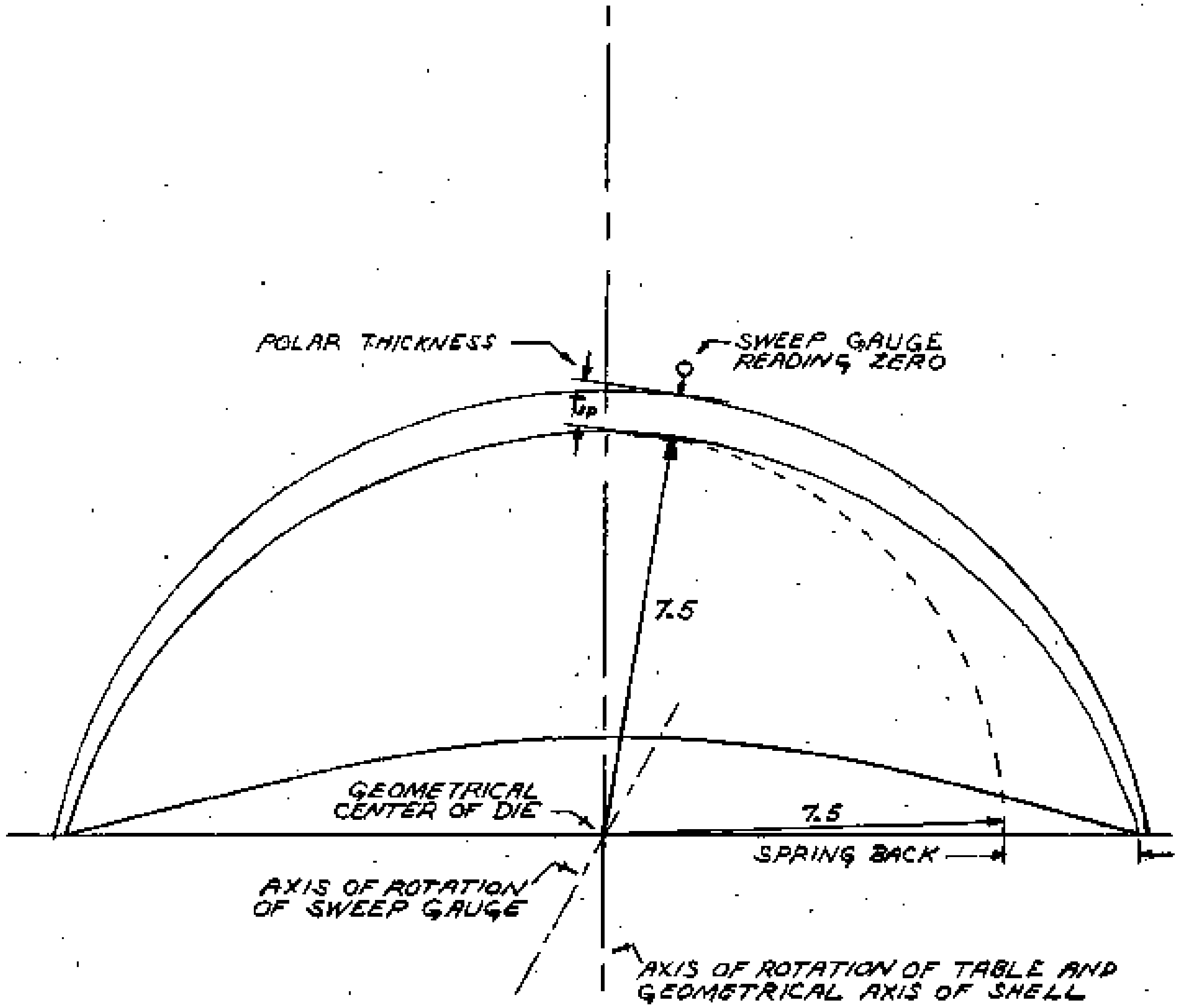


FIGURE - A1

control mechanism failed and the roller remained at a point about 45 deg from the pole for many revolutions of the die (ring rolling). This resulted in the formation of a groove at this point. Three more passes were made in an attempt to smooth out this groove. The groove was found to be more than 0.030 in. deep when the shell was removed from the die. Two more passes sized the shell to the die and reduced the groove to a little more than 0.010 in.

Because of the success with shells Nos. 2 and 3, blank No. 1 (0.312 in. thick) was formed directly on the 15-in. die without benefit of the intermediate die. About a dozen large ripples formed which were rolled into deep laps after three passes. Two more passes partially removed these laps. The surface of this shell was then machined but two deep laps still remained which extended several inches above the equator.

The single-die procedure caused considerable shock loading on the roller and yoke and excessive thinout would also have resulted if the folds had been completely removed by spinning or machining. For these reasons, the cost of the intermediate die (approx $1500) seems justified.

Blank 6 (0.299 in. thick) was spun on the 30-in. die and the initial passes on the 15-in. die were made before trimming. Two large folds and several small ones were present near the equator at this point. After trimming, these were removed during the final sizing passes.

Blank 11 (0.285 in. thick) was dimpled at a higher temperature than intended but this had no observably deleterious effect. The shell was spun on the 30- and 15-in. dies without incident. Following the spinning, the 15-in. die was found to be slightly off center. The die was centered, and the shell was trimmed and sized to the die without incident.

Except for the overheating during dimpling, blank 12 (0.285 in. thick) was treated and behaved the same as shell No. 11. The spinning temperature, however, appeared to the eye to be somewhat higher than the 1175°F indicated by the pyrometer. The die may also have been off center. This shell was surface machined prior to shipment to ORNL.

Blank No. 5 (0.218 in. thick) was rolled on the 30- and 15-in. dies and some folds occurred. The die, which was off center, was realigned and the shell trimmed. The folds were removed and the shell sized by the final passes.

This shell was machined before shipment to ORNL. Similarly, blank No. 4 (0.218 in. thick) was rolled on the 30-in. die, trimmed, and rolled on the 15-in. die without incident.

Considerable earing occurred on shell No. 7 (0.125 in. thick) during spinning on the 30-in. die. The initial passes on the 15-in. die resulted in the formation of a great many ripples. The shell was trimmed and re-rolled, removing most of the ripples. Blank No. 8 (0.126 in. thick) behaved in a similar manner, but extra care in spinning reduced the rippling.

No data or notes were supplied for blank No. 9 (0.126 in. thick) by Titanium Fabricators. The ORNL observer reported that earing occurred on this shell during the first pass on the 30-in. die and was partially removed by subsequent passes. The shell was trimmed and formed on the 15-in. die. During the first pass on this die folds and flats formed but were partially removed by subsequent passes. Blank No. 10 (0.120 in. thick) was trimmed before any forming was performed. Rippling occurred and was removed as in the case of shell No. 7. After forming, all shells were sand blasted and pickled.

Table AI

Thickness

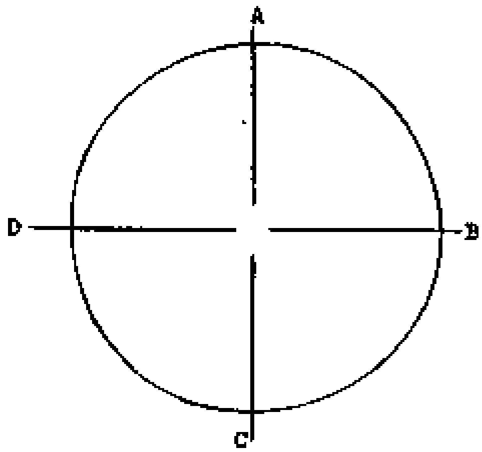
(Titanium Fabricators)

SPINNING RECORD

BLANK NO. 1 MATERIAL Zr-2 BLANK SIZE 22.80 in.

DATE SPUN ______ TEMPERATURE ______ TIME AT TEMP. 20 min.

15 in. STAGE DIE INSPECTOR # ______



2" Stations

Thickness (inches x 10^{-3})

	A	B	C	D
1	305	304	306	304
2	278	288	291	293
3	229	230	230	230
4	237	238	235	235
5	246	243	250	243
6	270	269	277	284

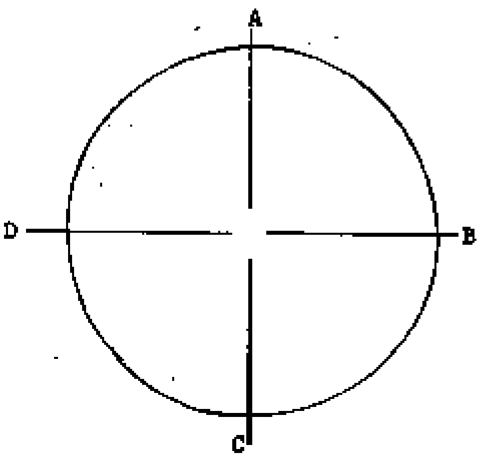
3 passes 20 min. at 1150-1250

SPINNING RECORD

BLANK NO. 2 MATERIAL Zr-2 BLANK SIZE 22.80 in.

DATE SPUN ______ TEMPERATURE ______ TIME AT TEMP. ______

30 in. STAGE DIE INSPECTOR # ______



2" Stations

Thickness (inches x 10^{-3})

	A	B	C	D
1	312	314	310	311
2	304	302	306	304
3	285	284	292	288
4	285	283	292	280
5	306	299	308	297
6				

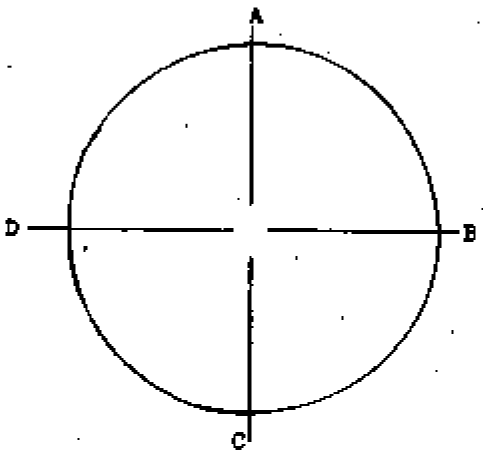
0.306–0.314-in. starting thickness

SPINNING RECORD

BLANK NO. 2 MATERIAL Zr-2 BLANK SIZE ______

DATE SPUN ______ TEMPERATURE ______ TIME AT TEMP. ______

15 in. STAGE DIE INSPECTOR # ______



2" Stations

Thickness (inches x 10^{-3})

	A	B	C	D
1	305	306	308	308
2	299	300	298	293
3	203*	198*	200*	204*
4	235	225	234	236
5	224	222	224	226
6				

4 Passes Trimmed

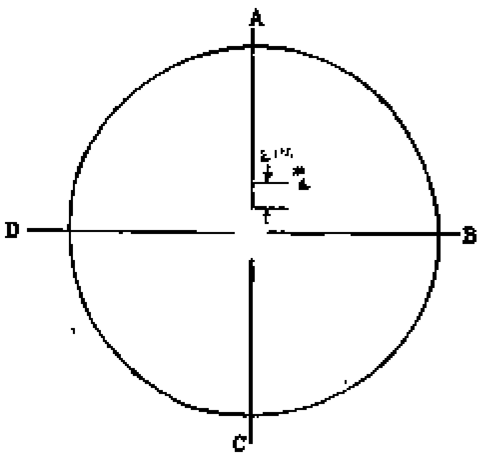
*Ring Rolled

SPINNING RECORD

BLANK NO. 2 (1st sheet) MATERIAL Zr-2 BLANK SIZE ______

DATE SPUN ______ TEMPERATURE ______ TIME AT TEMP. ______

15" STAGE DIE INSPECTOR # ______



2" Stations

Thickness (in. x 10^{-3})

	A	B	C	D
1	305	305	308	307
2	195	192	200	198
3	213	210	215	217
4	213	212	215	215
5	220	213	220	218
6				

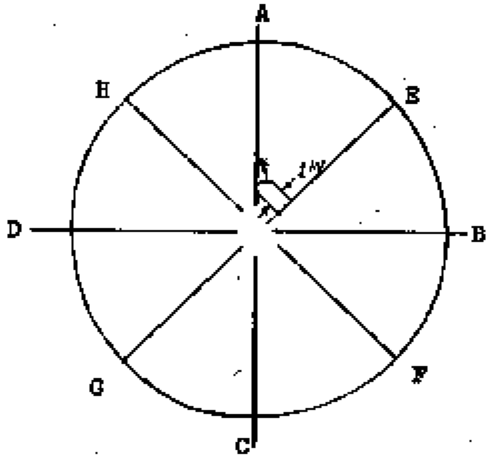
12-10-58

SPINNING RECORD

BLANK NO. 2 (2nd sheet) MATERIAL Zr-2 BLANK SIZE ______

DATE SPUN ______ TEMPERATURE ______ TIME AT TEMP. ______

15" STAGE DIE INSPECTOR # ______



2" Stations

Thickness (inches x 10^{-3})

	E	F	G	H
1	310	310	310	312
2	315	305	310	307
3	190	190	190	190
4	215	220	220	222
5	210	213	220	218
6				

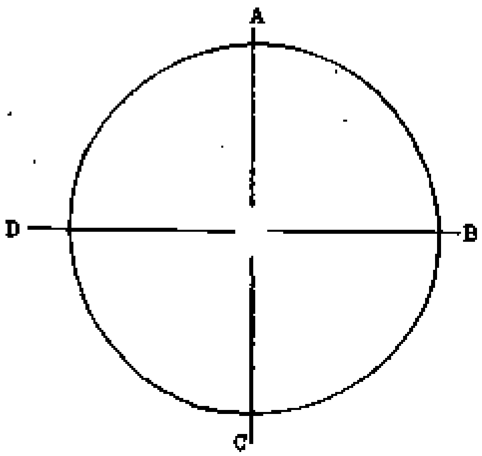
12-10-58

SPINNING RECORD

BLANK NO. 3 MATERIAL Zr-2 BLANK SIZE 22.80 in.

DATE SPUN ______ TEMPERATURE ______ TIME AT TEMP. ______

30 in. STAGE DIE INSPECTOR # ______



2" Stations

Thickness (inches x 10^{-3})

	A	B	C	D
1	308	307	308	306
2	300	297	308	306
3	302	302	301	302
4	302	307	306	308
5	299	303	302	299
6				

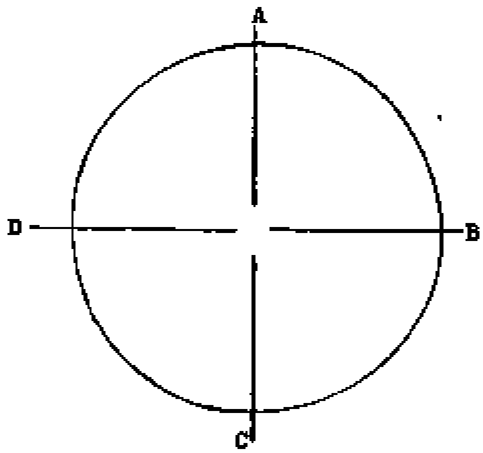
0.309 - 0.315 in. Starting Thickness

SPINNING RECORD

BLANK NO. 3 MATERIAL Zr-2 BLANK SIZE ____

DATE SPUN ____ TEMPERATURE ____ TIME AT TEMP. ____

- 15 in. STAGE DIE INSPECTOR # ____



2" Stations

Thickness (inches x 10^{-3})

	A	B	C	D
1	304	305	305	306
2	304	307	298	302
3	278	277	277	280
4	276	281	278	277
5	281	269	268	269
6	263	261	246	257

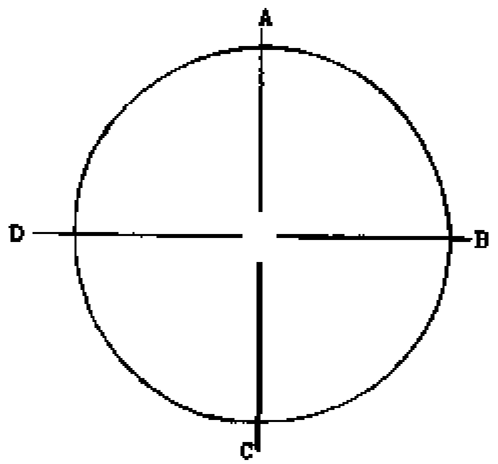
2 Passes Too large to be sized

SPINNING RECORD

BLANK NO. 6 MATERIAL Zr-2 BLANK SIZE 22.800

DATE SPUN 1-2-58 TEMPERATURE 1050° TIME AT TEMP. 5-1/2 min.

30" STAGE DIE INSPECTOR #



2" Stations

Thickness (in. x 10^{-3})

	A	B	C	D
1	203	306	303	301
2	296	296	292	291
3	286	286	283	285
4	275	279	272	276
5	279	282	275	279
6				

Original thickness: 0.273–0.304 in.

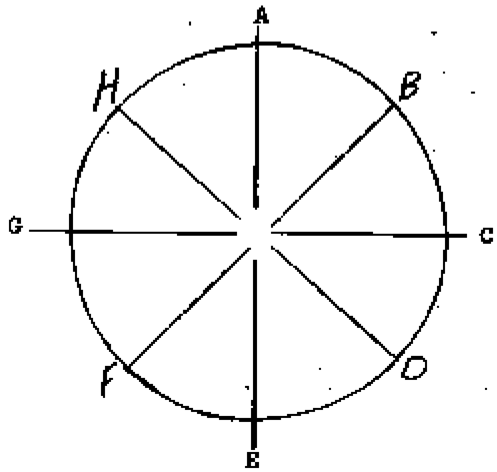
2 passes

SPINNING RECORD

BLANK NO. 6 (1st sheet) MATERIAL Zr-2 BLANK SIZE 22.8

DATE SPUN 12-3 TEMPERATURE 1200 TIME AT TEMP. 9 min.

15" STAGE DIE INSPECTOR #



2" Stations

Thickness (in. x 10^{-3})

	A	B	C	D
1	299	298	299	293
2	295	262	288	264
3	251	246	245	249
4	242	248	239	232
5	225	218	222	222
6				

2 passes

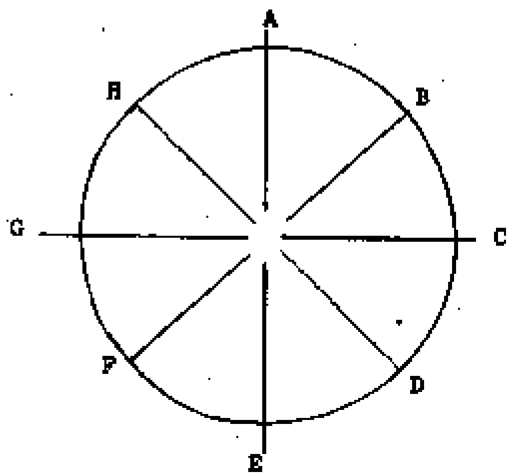
2 large folds several minor ones

SPINNING RECORD

BLANK NO. 6 (2nd sheet) MATERIAL Zr-2 BLANK SIZE 22.8

DATE SPUN 12-4 TEMPERATURE ______ TIME AT TEMP. ______

15" STAGE DIE INSPECTOR # ______



2" Stations

Thickness (in. x 10^{-3})

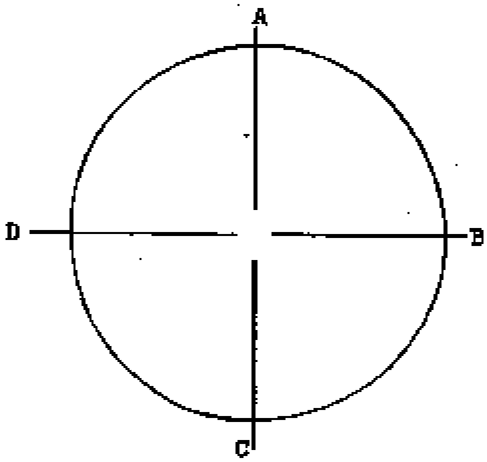
	E	F	G	H
1	299	299	299	297
2	290	262	298	258
3	248	251	251	252
4	240	236	244	235
5	222	217	230	210
6				

SPINNING RECORD

BLANK NO. 11 MATERIAL Zr-2 BLANK SIZE 21.800

DATE SPUN 1-2-58 TEMPERATURE 1200° TIME AT TEMP. 7 min

30" STAGE DIE INSPECTOR #



2" Stations

Thickness (in. x 10^{-3})

	A	B	C	D
1	283	284	285	283
2	278	277	280	280
3	265	270	267	275
4	269	266	271	268
5	281	281	283	281
6				

0.284 - 0.287 original thickness

Hotter than others during dimpling. Intended for 1000°F but got too hot.

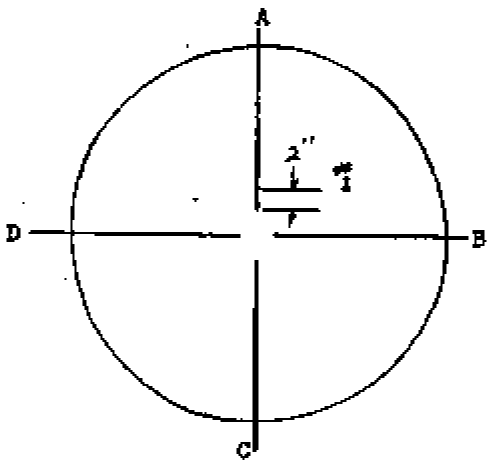
Lip but no folds.

SPINNING RECORD

BLANK NO. 11 (1st sheet) MATERIAL Zr-2 BLANK SIZE ____

DATE SPUN ____ TEMPERATURE ____ TIME AT TEMP. ____

15" STAGE DIE INSPECTOR # ____



2" Stations

Thickness (in. x 10^{-3})

	A	B	C	D
1	280	279	275	278
2	208	200	205	208
3	186	188	190	190
4	189	188	190	192
5	196	190	195	198
6				

12-11-58

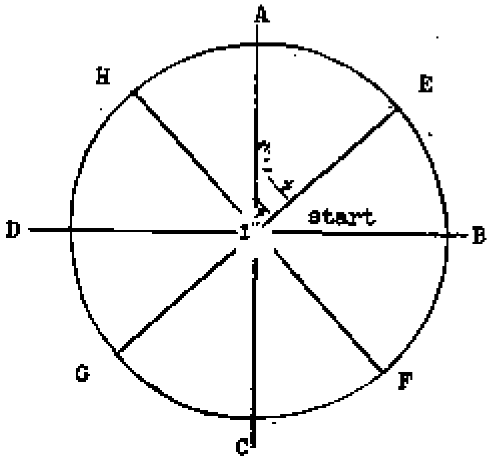
Trimmed after 1 pass and die centered (0.008 in.) prior to this run.

SPINNING RECORD

BLANK NO. 11 (2nd sheet) MATERIAL Zr-2 BLANK SIZE ______

DATE SPUN ______ TEMPERATURE ______ TIME AT TEMP. ______

______ STAGE DIE INSPECTOR # ______



2" Stations

Thickness (in. x 10^{-3})

	E	F	G	H
1	282	280	280	280
2	282	276	270	278
3	192	195	195	195
4	185	195	192	190
5	190	188	195	195
6				

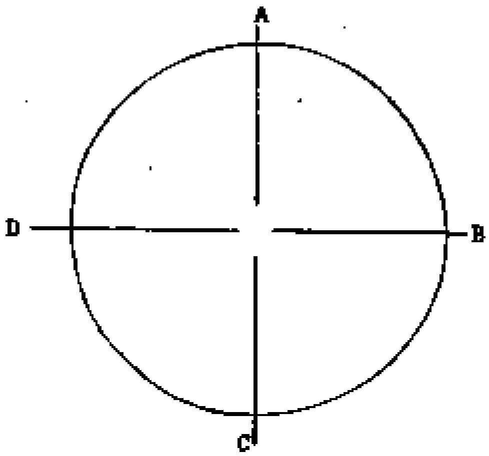
12-11-58

SPINNING RECORD

BLANK NO. 12 MATERIAL Zr-2 BLANK SIZE 21.800

DATE SPUN 12-2-58 TEMPERATURE 1175 TIME AT TEMP. 6-1/2 min.

30" STAGE DIE INSPECTOR #



2" Stations

Thickness (in. x 10^{-3})

	A	B	C	D
1	283	284	284	282
2	278	272	279	278
3	276	274	275	271
4	265	265	270	268
5	264	264	271	270
6				

0.286 - 0.284 thick

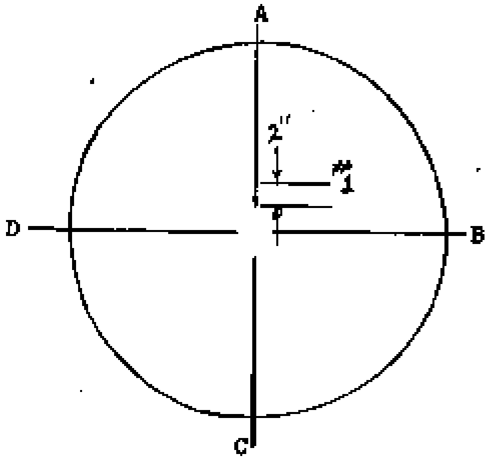
Appeared hotter than above temp. No folds but a small lip was present.

SPINNING RECORD

BLANK NO. 12 (1st sheet) MATERIAL Zr-2 BLANK SIZE ____

DATE SPUN ____ TEMPERATURE 1200 TIME AT TEMP. 5 min

15" STAGE DIE INSPECTOR # ____



2" Stations

Thickness (in. x 10^{-3})

	A	B	C	D
1	280	280	290	275
2	225	230	230	228
3	225	225	230	232
4	228	232	235	228
5	226	235	232	228
6				

12-11-58

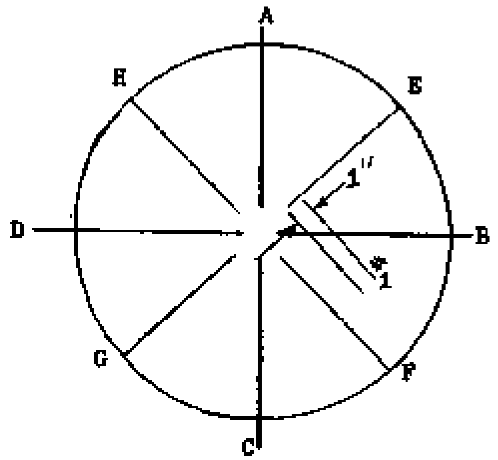
3 passes trimmed; die may have been off center again.

SPINNING RECORD

BLANK NO. 12 (2nd Sheet) MATERIAL Zr-2 BLANK SIZE ____

DATE SPUN ____ TEMPERATURE ____ TIME AT TEMP. ____

____ STAGE DIE INSPECTOR # ____



2" Stations

Thickness (in. x 10^{-3})

	E	F	G	H
1	282	285	282	280
2	280	282	275	278
3	225	228	228	228
4	232	232	228	228
5	228	235	230	225
6				

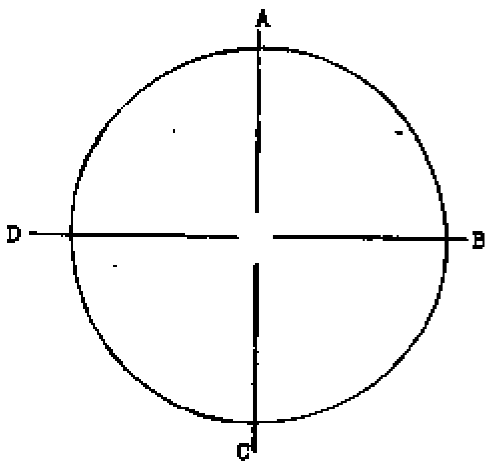
12-11-58

SPINNING RECORD

BLANK NO. 5 MATERIAL Zr-2 BLANK SIZE 22.800

DATE SPUN 12-2-58 TEMPERATURE 1125° TIME AT TEMP. 10 min.

30" STAGE DIE INSPECTOR #



2" Stations

Thickness (in x 10^{-3})

	A	B	C	D
1	212	212	211	213
2	211	210	209	210
3	205	206	205	206
4	201	203	203	205
5	203	203	202	201
6				

Before spin 215-221

3 passes

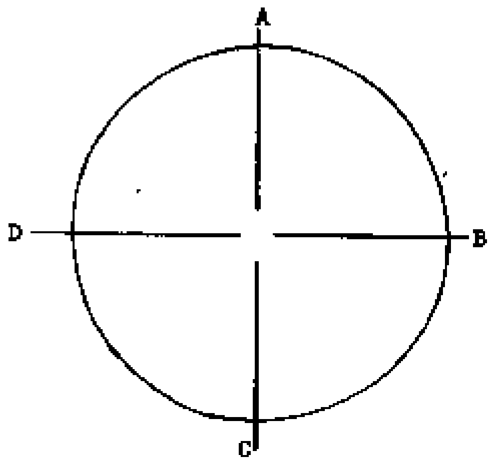
Very good condition after this die

SPINNING RECORD

BLANK NO. 5 MATERIAL Zr-2 BLANK SIZE 22.8

DATE SPUN 12.3 TEMPERATURE 1200^0 TIME AT TEMP. 12 min.

15" STAGE DIE INSPECTOR #



2" Stations

Thickness (in. x 10^{-3})

	A	B	C	D
1	211	212	211	211
2	209	208	210	210
3	163	165	168	166
4	168	175	178	174
5	166	171	175	172
6				

3 passes

First pass only outer half--fair amount of folding but did not interfer

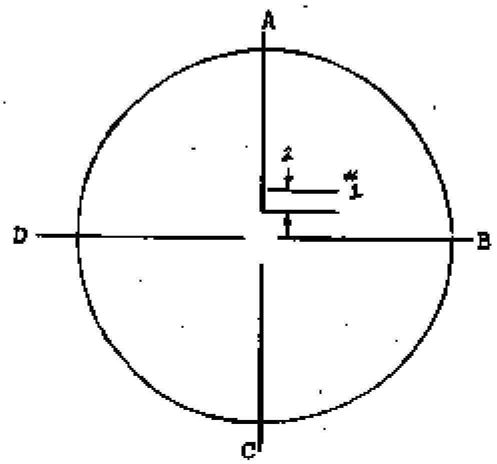
on others. Many 3/4" folds 1" high otherwise o.k.

SPINNING RECORD

BLANK NO. 5 (1st sheet) MATERIAL Zr-2 BLANK SIZE ______

DATE SPUN ______ TEMPERATURE 1175 TIME AT TEMP. 5 min

15" STAGE DIE INSPECTOR # ______



2" Stations

Thickness (in. x 10^{-3})

	A	B	C	D
1	212	210	213	210
2	165	165	168	168
3	164	164	168	168
4	164	166	170	170
5	164	160	172	170
6				

12-10-58

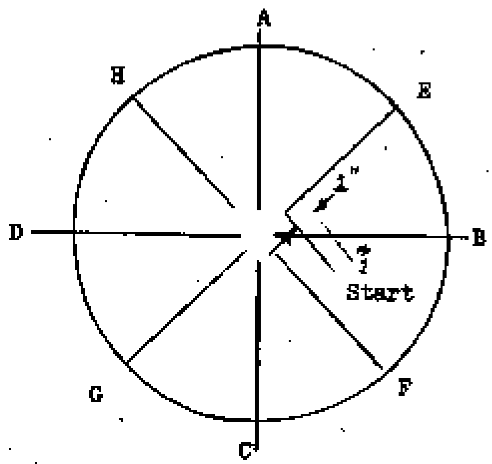
1 pass die centered before spinning.

SPINNING RECORD

BLANK NO. 5 (2nd sheet) MATERIAL Zr-2 BLANK SIZE ____

DATE SPUN ____ TEMPERATURE ____ TIME AT TEMP. ____

15" STAGE DIE INSPECTOR # ____



2" Stations

Thickness (in. x 10^{-3})

	E	F	G	H
1	212	212	213	215
2	210	210	212	210
3	160	160	164	162
4	162	168	172	170
5	165	170	171	168
6				

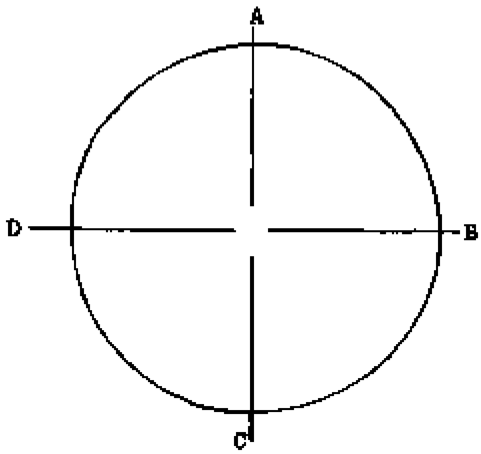
12-10-58

SPINNING RECORD

BLANK NO. 4 MATERIAL Zr-2 BLANK SIZE 22.80 in.

DATE SPUN ______ TEMPERATURE ______ TIME AT TEMP. ______

30 in. STAGE DIE INSPECTOR # ______



2" Stations

Thickness (inches x 10^{-3})

	A	B	C	D
1	213	214	213	212
2	205	212	210	209
3	207	208	200	204
4	203	204	195	199
5	208	205	201	199
6				

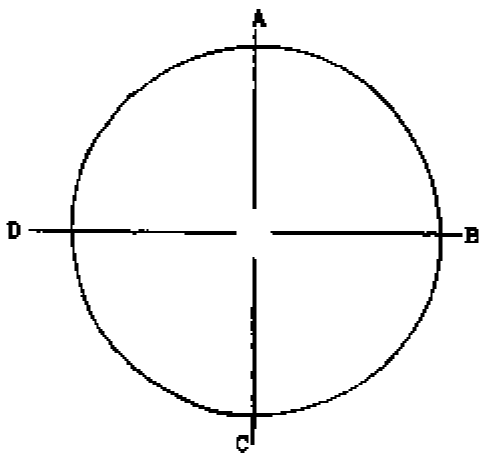
0.216 - 0.221 in. Starting thickness

SPINNING RECORD

BLANK NO. 8 MATERIAL Zr-2 BLANK SIZE 22.80 in.

DATE SPUN ______ TEMPERATURE ______ TIME AT TEMP. ______

30-in. STAGE DIE INSPECTOR # ______



2" Stations

	A	B	C	D
1	129	129	129	128
2	128	128	128	129
3	108	108	110	109
4	110	108	110	112
5	115	114	113	118
6	105	103	107	108

0.125–0.128-in. Starting Thickness

Above followed by 5 passes on 15-in. die, ripples rolled out (1225°F, 11 min).

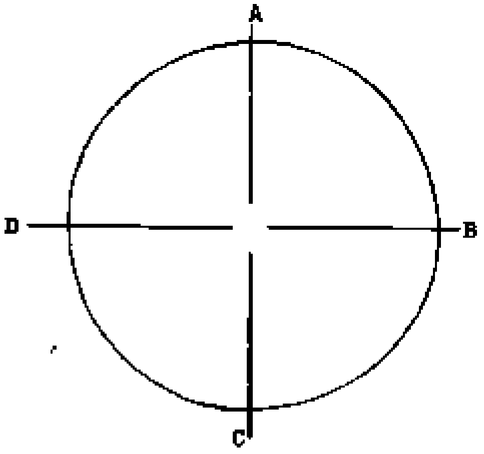
No data.

SPINNING RECORD

BLANK NO. 10 MATERIAL Zr-2 BLANK SIZE 22.80 in.

DATE SPUN ______ TEMPERATURE ______ TIME AT TEMP. ______

30 in. STAGE DIE INSPECTOR # ______



2" Stations

Thickness (inches x 10^{-3})

	A	B	C	D
1	130	132	129	132
2	130	130	128	131
3	094	093	091	095
4	097	099	098	101
5	098	095	098	099
6	108	099	101	104

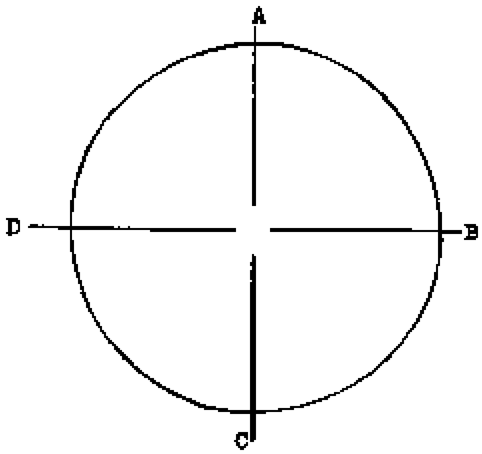
0.125 - 0.128 in. Starting Thickness

SPINNING RECORD

BLANK NO. 10 MATERIAL Zr-2 BLANK SIZE ______

DATE SPUN ______ TEMPERATURE ______ TIME AT TEMP. ______

15 in. STAGE DIE INSPECTOR # ______



2" Stations

Thickness (inches x 10^{-3})

	A	B	C	D
1	128	125	128	125
2	128	128	127	127
3	073	069	065	065
4	089	088	083	088
5	092	089	087	089
6	088	087	086	087

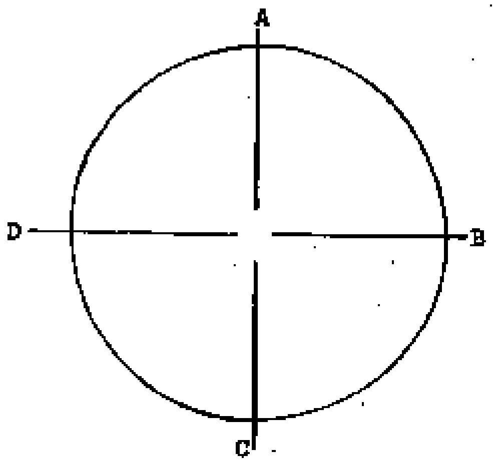
3 Passes Trimmed, Puckered Edge

SPINNING RECORD

BLANK NO. 4 MATERIAL Zr-2 BLANK SIZE ______

DATE SPUN ______ TEMPERATURE ______ TIME AT TEMP. ______

15-in. STAGE DIE INSPECTOR # ______



2" Stations

Thickness (inches x 10^{-3})

	A	B	C	D
1	209	210	213	208
2	208	207	210	207
3	182	187	192	179
4	178	182	178	174
5	185	187	184	181
6				

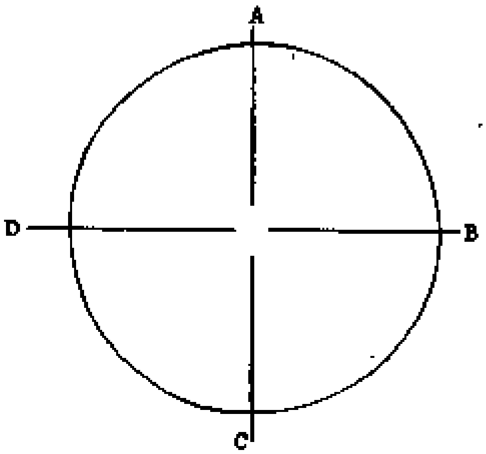
3 Pass Trimmed

SPINNING RECORD

BLANK NO. 7 MATERIAL Zr-2 BLANK SIZE ______

DATE SPUN ______ TEMPERATURE ______ TIME AT TEMP. ______

15-in. STAGE DIE INSPECTOR # ______



2" Stations

Thickness (inches x 10^{-3})

	A	B	C	D
1	125	125	123	123
2	125	126	122	125
3	091	090	090	094
4	097	098	093	095
5	105	107	104	106
6	108	108	107	110

3 Passes

Untrimmed (Large rippled brim)

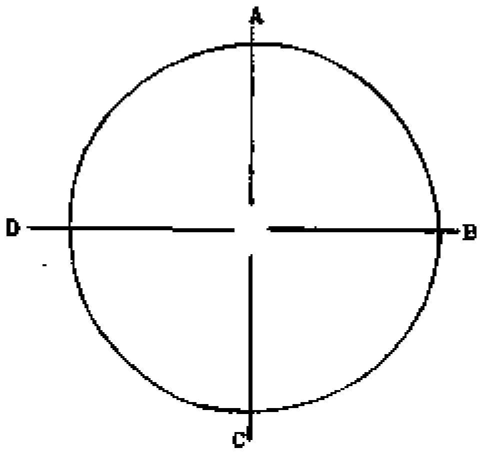
Trimmed after this run, re-rolled 11-25, 2 passes at 1250 (11min), no data.

SPINNING RECORD

BLANK NO. 7 MATERIAL Zr-2 BLANK SIZE 22.80 in.

DATE SPUN ___ TEMPERATURE ___ TIME AT TEMP. ___

30-in. STAGE DIE INSPECTOR # ___



2" Stations

Thickness (inches x 10^{-3})

	A	B	C	D
1	126	125	128	126
2	125	126	128	127
3	122	123	127	124
4	124	124	126	125
5	124	126	130	127
6				

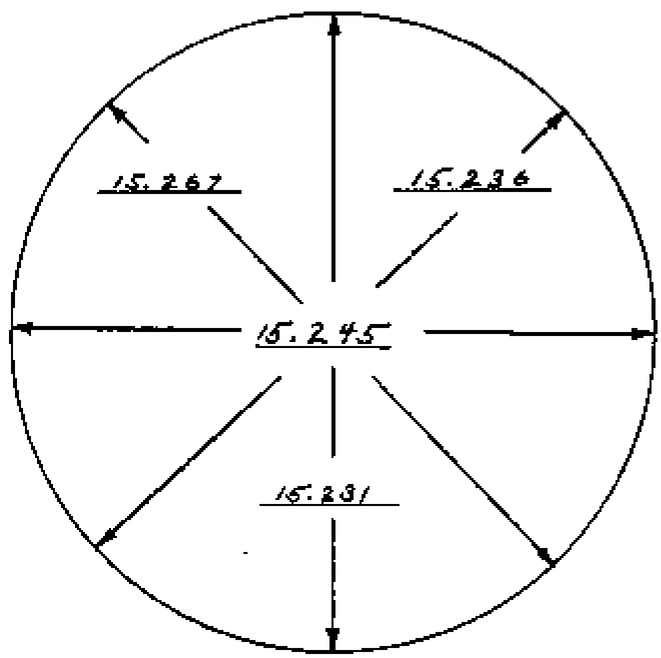
0.125-0.127 in. Starting Thickness

Table AII

Diameter

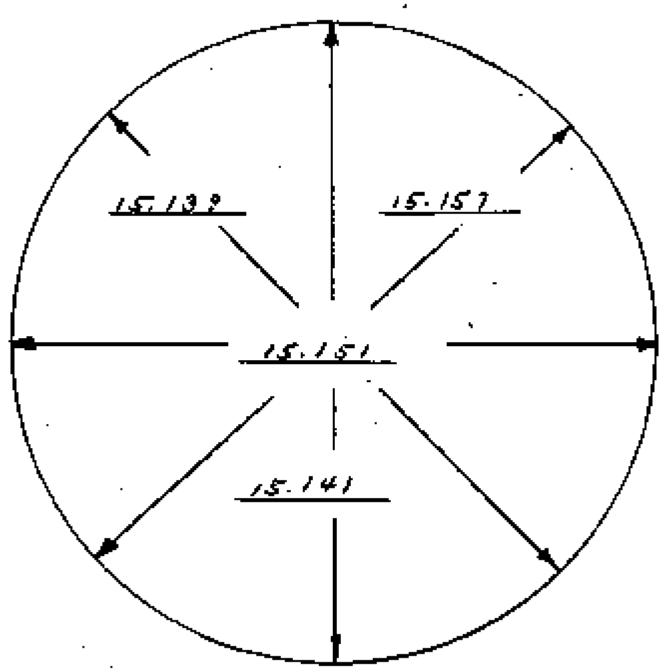
(Titanium Fabricators)

Shell # 11



Shop Measurement

Shell # 12



Shop Measurement

UNION CARBIDE NUCLEAR COMPANY LABORATORY

P. O. # 93Y-1617

Job #252

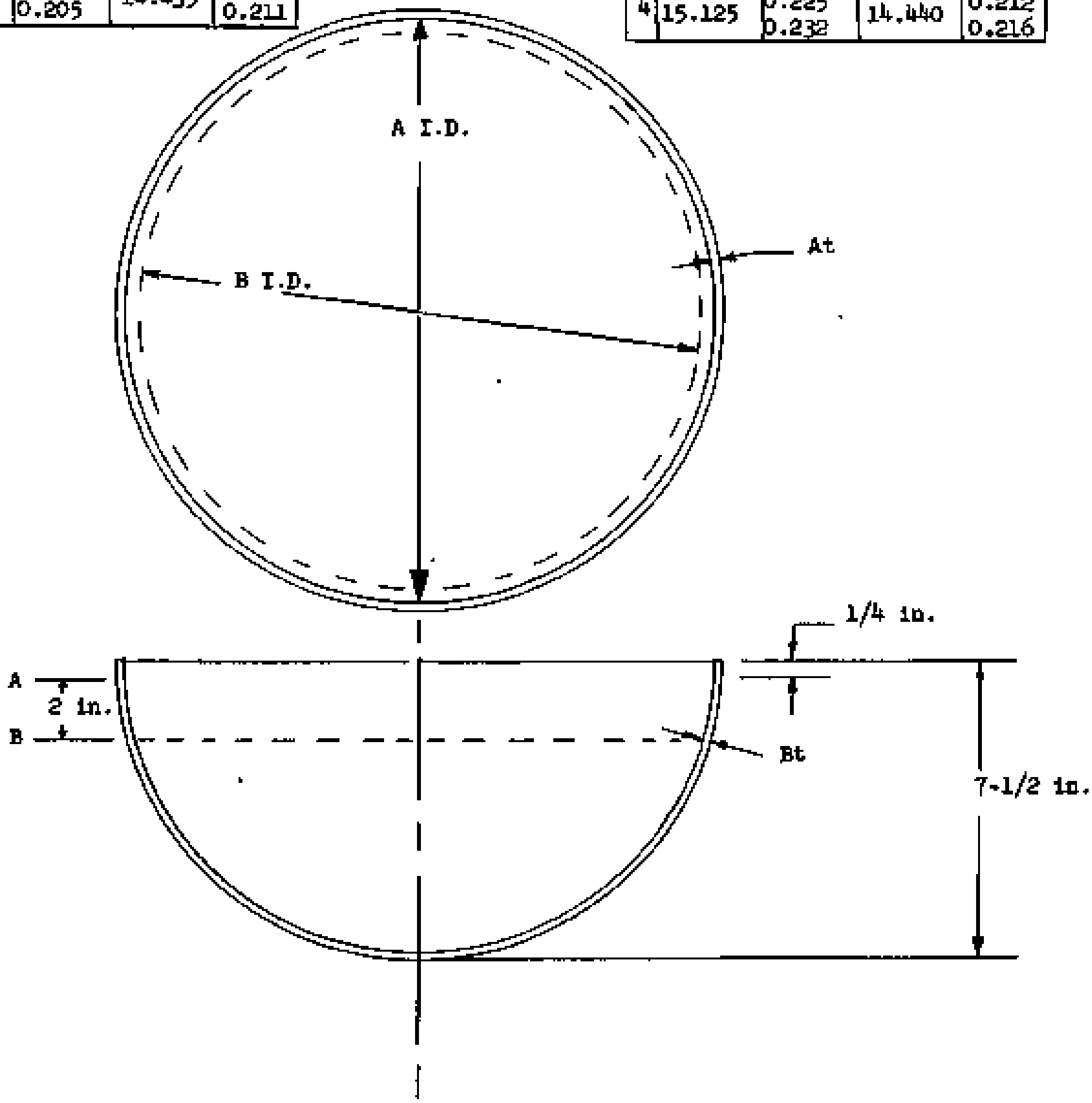
Shell # 1

Before sandblast

	A		B	
#	I.D.	t	I.D.	t
1	15.025	0.200 0.207	14.410	0.210 0.210
2	15.060	0.200 0.205	14.440	0.208 0.212
3	15.140	0.200 0.210	14.500	0.207 0.213
4	15.105	0.200 0.205	14.435	0.208 0.211

After sandblast

	A		B	
#	I.D.	t	I.D.	t
1	15.075	0.236 0.223	14.410	0.221 0.210
2	15.105	0.232 0.222	14.425	0.215 0.212
3	15.145	0.228 0.230	14.450	0.209 0.217
4	15.125	0.225 0.232	14.440	0.212 0.216



UNION CARBIDE NUCLEAR COMPANY LABORATORY

P. O. # 93Y-1617

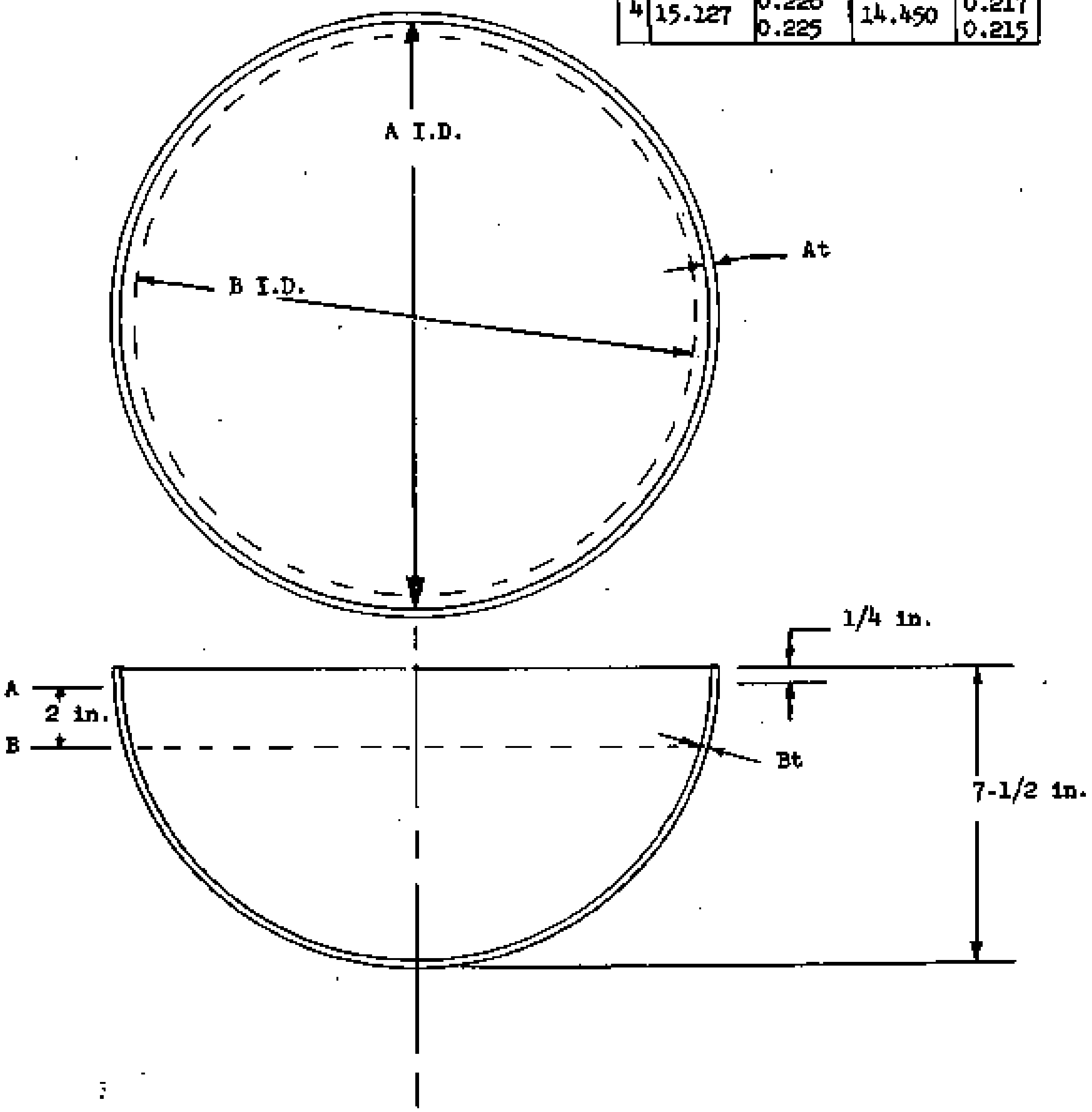
Job #252

Shell # 2

Before sandblast

	A		B	
#	I.D.	t	I.D.	t
1	15.075	0.232 0.232	14.440	0.216 0.222
2	15.095	0.228 0.232	14.450	0.215 0.218
3	15.130	0.227 0.228	14.460	0.216 0.218
4	15.127	0.228 0.225	14.450	0.217 0.215

CORE TANK



UNION CARBIDE NUCLEAR COMPANY LABORATORY

P. O. # 93Y-1617

Job #252

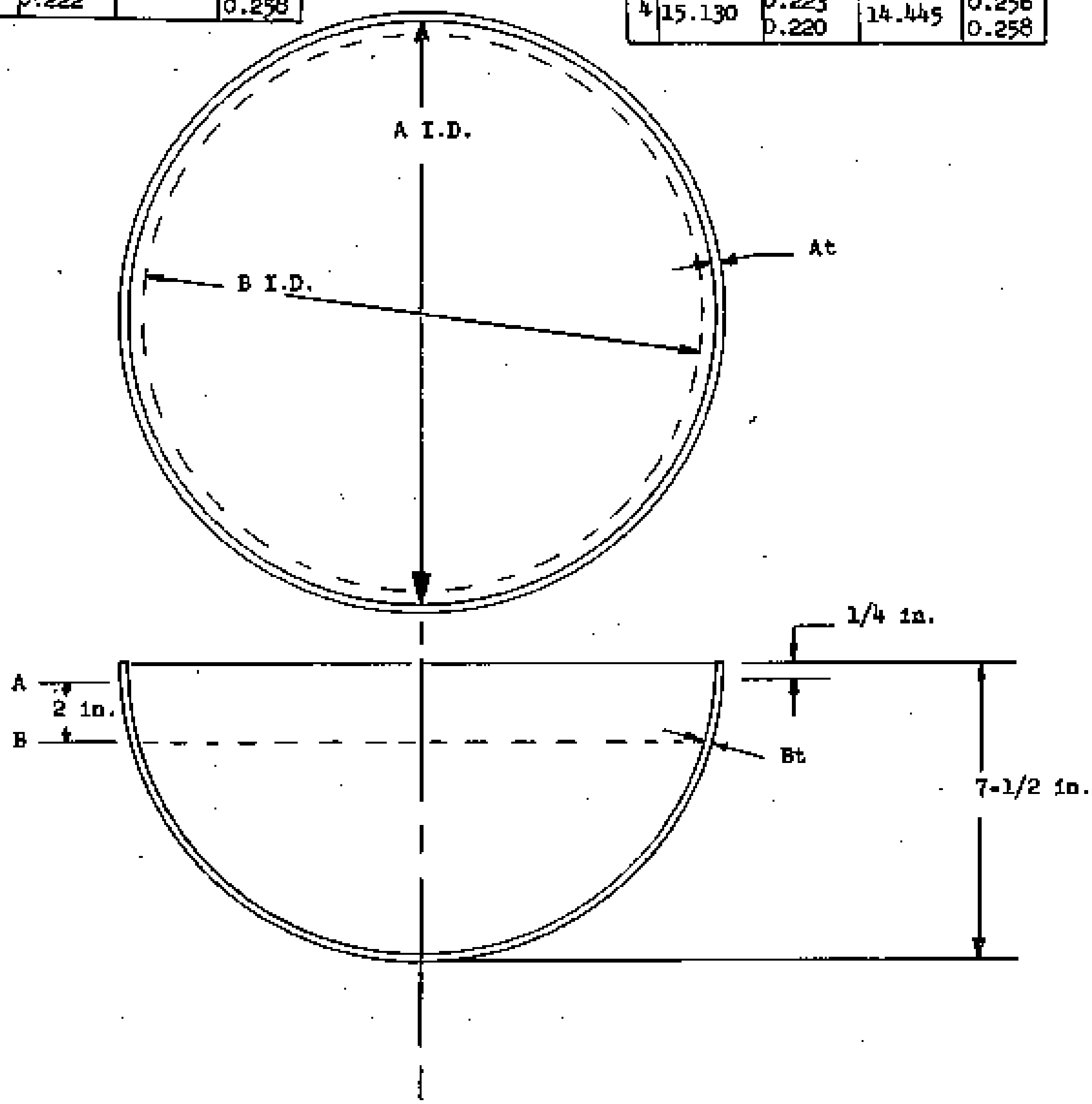
Shell # 3

Before sandblast

	A		B	
#	I.D.	t	I.D.	t
1	15.090	0.235 0.230	14.385	0.260 0.259
2	15.125	0.225 0.222	14.415	0.258 0.258
3	15.115	0.225 0.227	14.425	0.260 0.258
4	15.105	0.235 0.222	14.400	0.260 0.258

After sandblast

	A		B	
#	I.D.	t	I.D.	t
1	15.120	0.222 0.222	14.433	0.252 0.254
2	15.093	0.228	14.420	0.256 0.254
3	15.108	0.230 0.225	14.430	0.257 0.252
4	15.130	0.223 0.220	14.445	0.256 0.258



UNION CARBIDE NUCLEAR COMPANY LABORATORY

P. O. # 93Y-1617

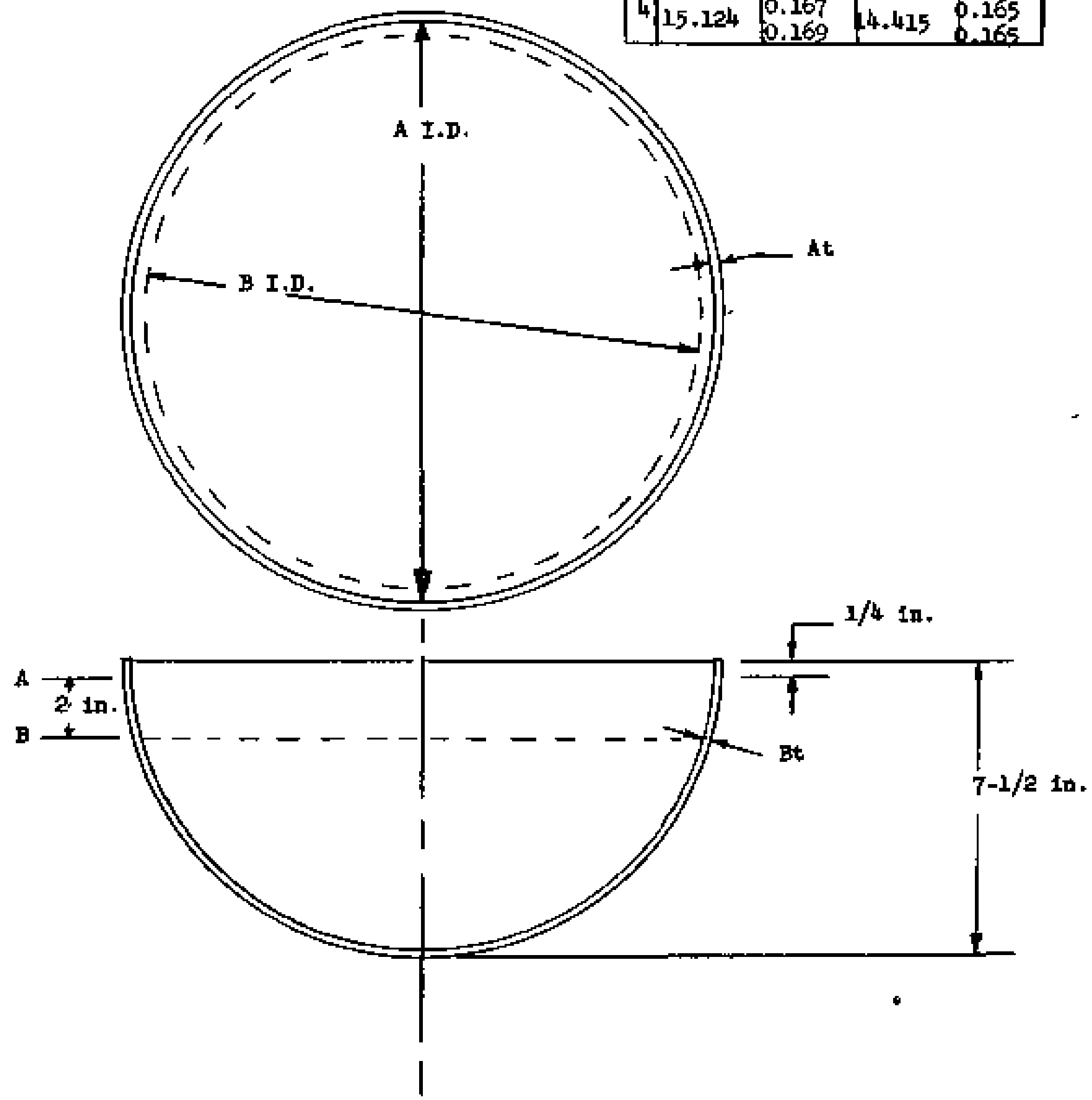
Job #252

Shell # 5

CORE TANK

Before sandblast

	A		B	
#	I.D.	t	I.D.	t
1	15.125	0.168 0.120	14.400	0.162 0.168
2	15.120	0.168 0.175	14.405	0.162 0.173
3	15.123	0.168 0.170	14.410	0.163 0.120
4	15.124	0.167 0.169	14.415	0.165 0.165



UNION CARBIDE NUCLEAR COMPANY LABORATORY

P. O. # 93Y-1617

Job #252

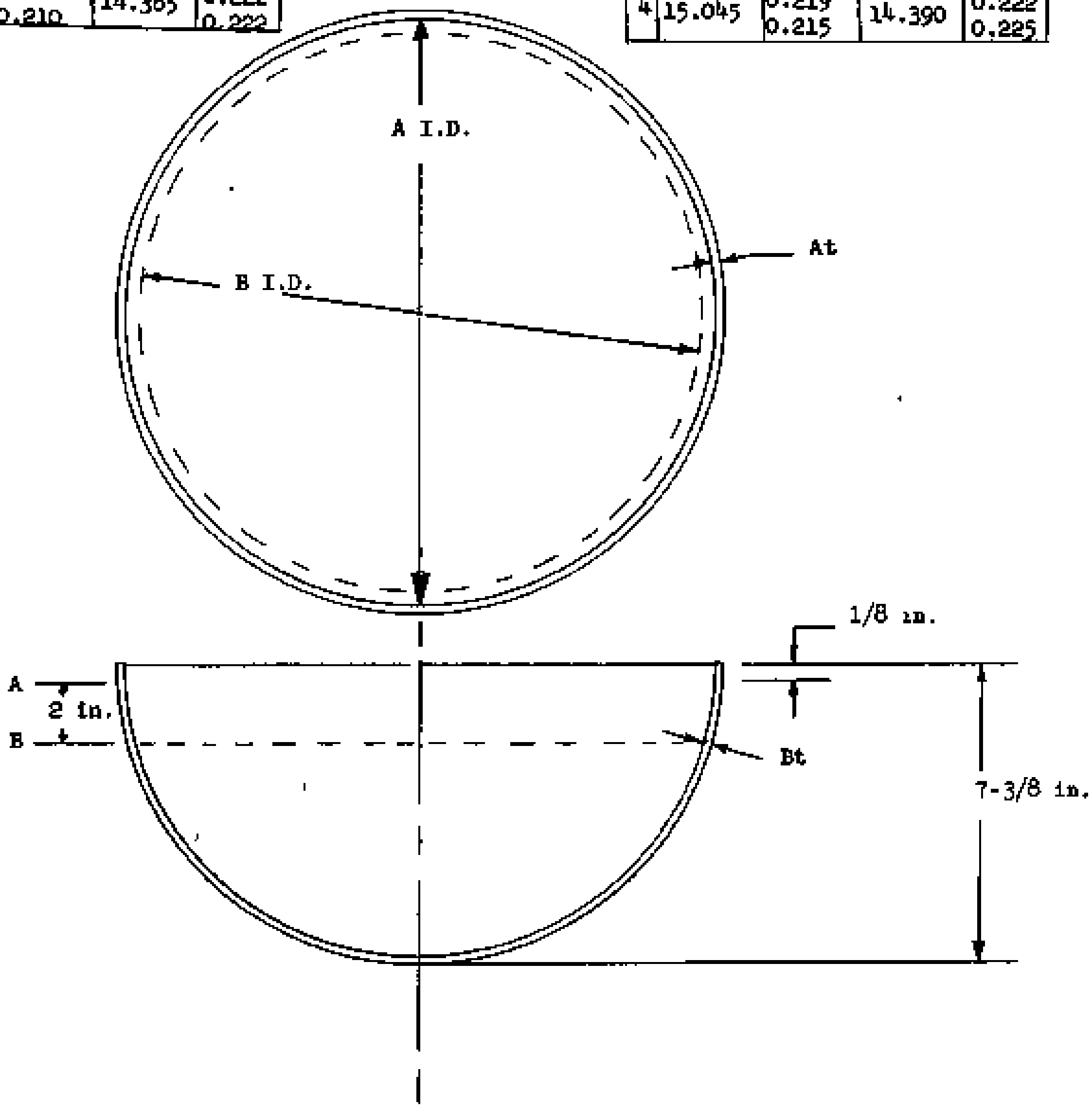
Shell # 6

Before sandblast

#	A I.D.	A t	B I.D.	B t
1	15.045	0.218 0.205	14.365	0.220 0.223
2	15.108	0.218 0.220	14.390	0.225 0.225
3	15.110	0.218 0.215	14.400	0.222 0.225
4	15.070	0.211 0.210	14.365	0.222 0.222

After sandblast

#	A I.D.	A t	B I.D.	B t
1	15.105	0.222 0.217	14.420	0.225 0.220
2	15.130	0.216 0.213	14.425	0.227 0.220
3	15.090	0.210 0.210	14.400	0.220 0.222
4	15.045	0.219 0.215	14.390	0.222 0.225



UNION CARBIDE NUCLEAR COMPANY LABORATORY

P. O. # 93Y-1617

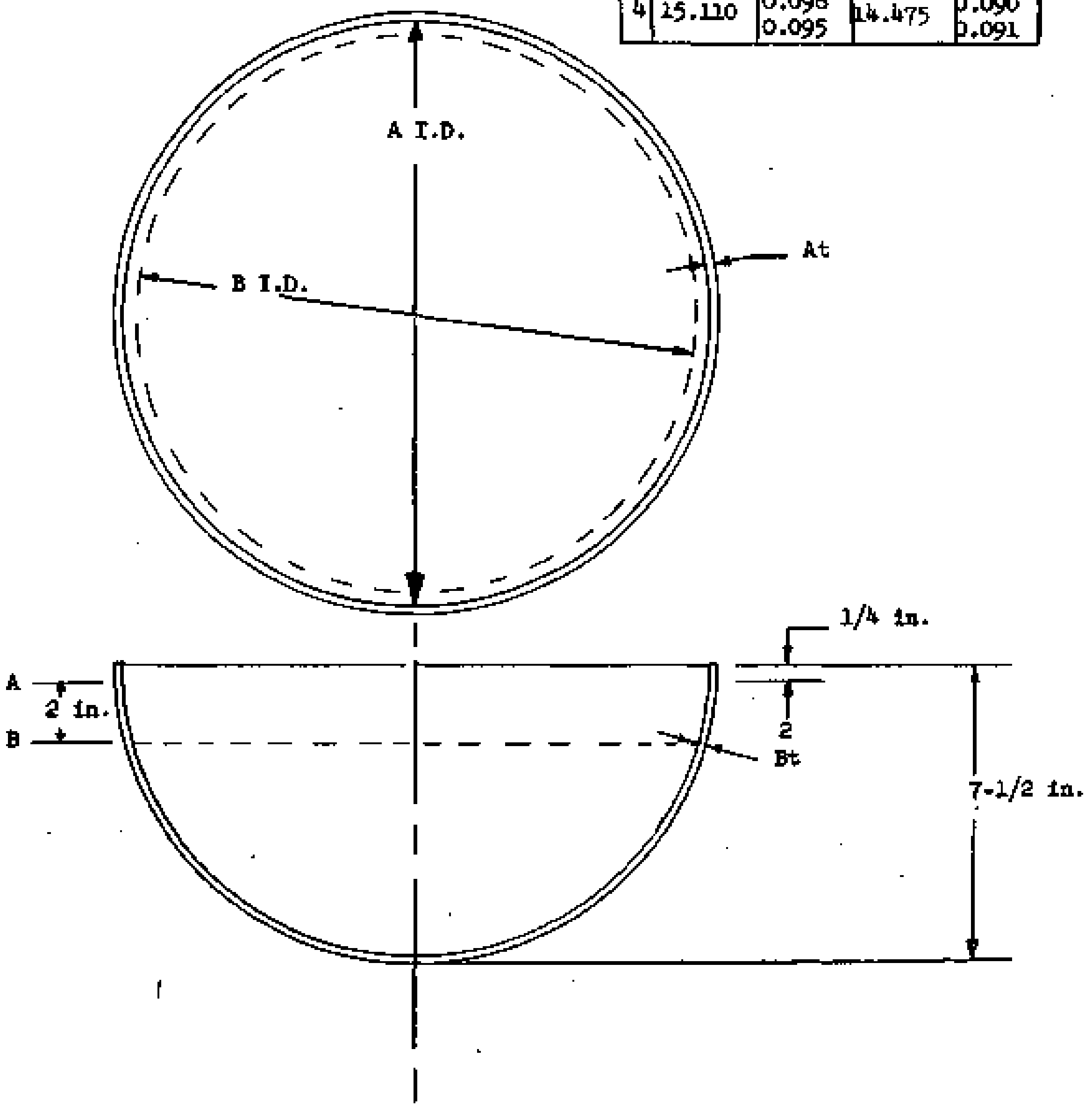
Job #252

Shell # 7

CORE TANK

Before sandblast

#	A I.D.	A t	B I.D.	B t
1	15.120	0.095 0.097	14.480	0.090 0.090
2	15.110	0.095 0.098	14.465	0.090 0.091
3	15.100	0.095 0.097	14.475	0.090 0.093
4	15.110	0.096 0.095	14.475	0.090 0.091



UNION CARBIDE NUCLEAR COMPANY LABORATORY

P. O. # 93Y-1617

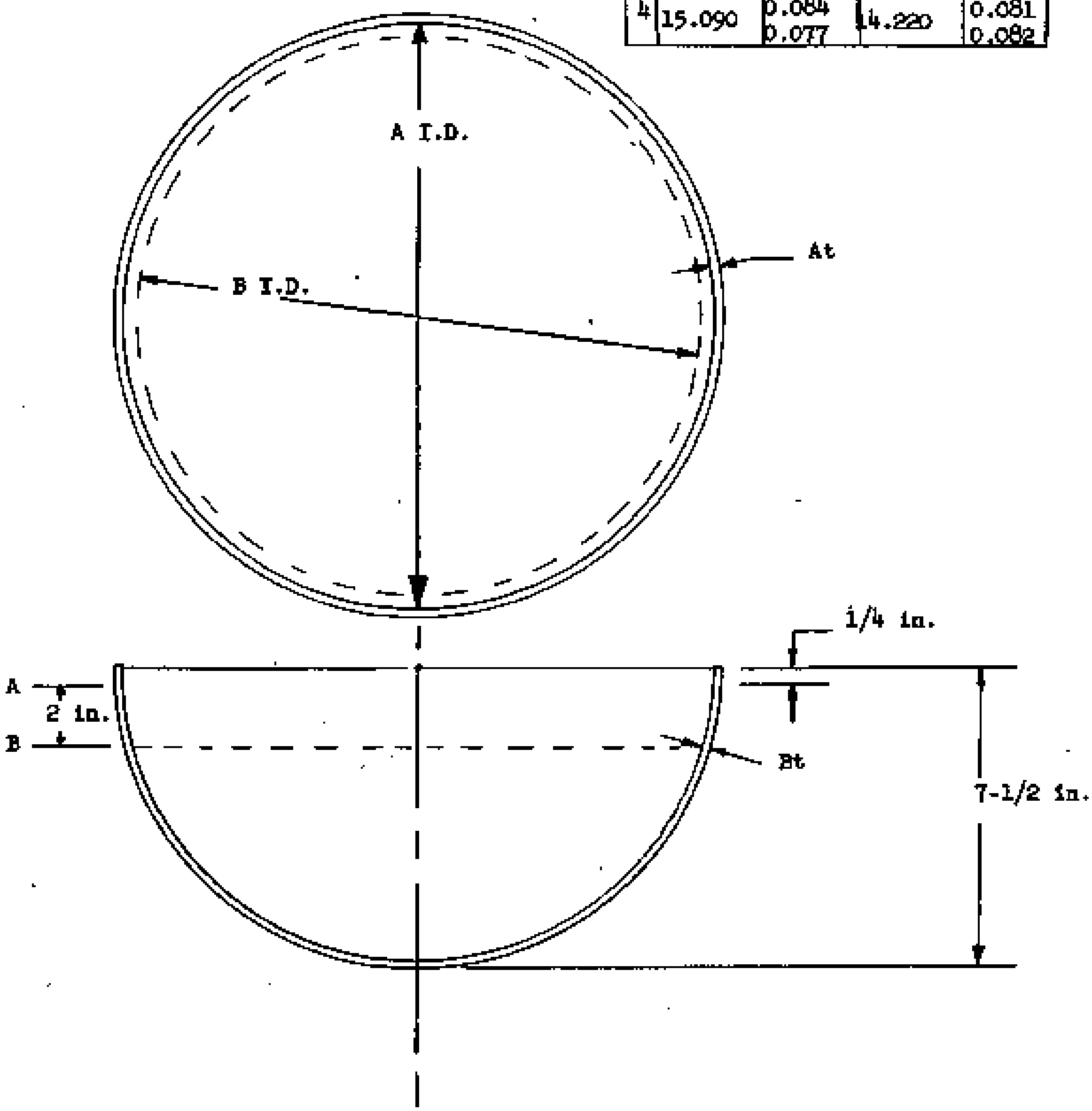
Job #252

Shell # 8

CORE TANK

After sandblast

	A		B	
#	I.D.	t	I.D.	t
1	15.100	0.080 0.085	14.230	0.078 0.082
2	15.090	0.080 0.082	14.220	0.078 0.082
3	15.085	0.081 0.080	14.225	0.078 0.082
4	15.090	0.084 0.077	14.220	0.081 0.082



UNION CARBIDE NUCLEAR COMPANY LABORATORY

P. O. # 93Y-1617

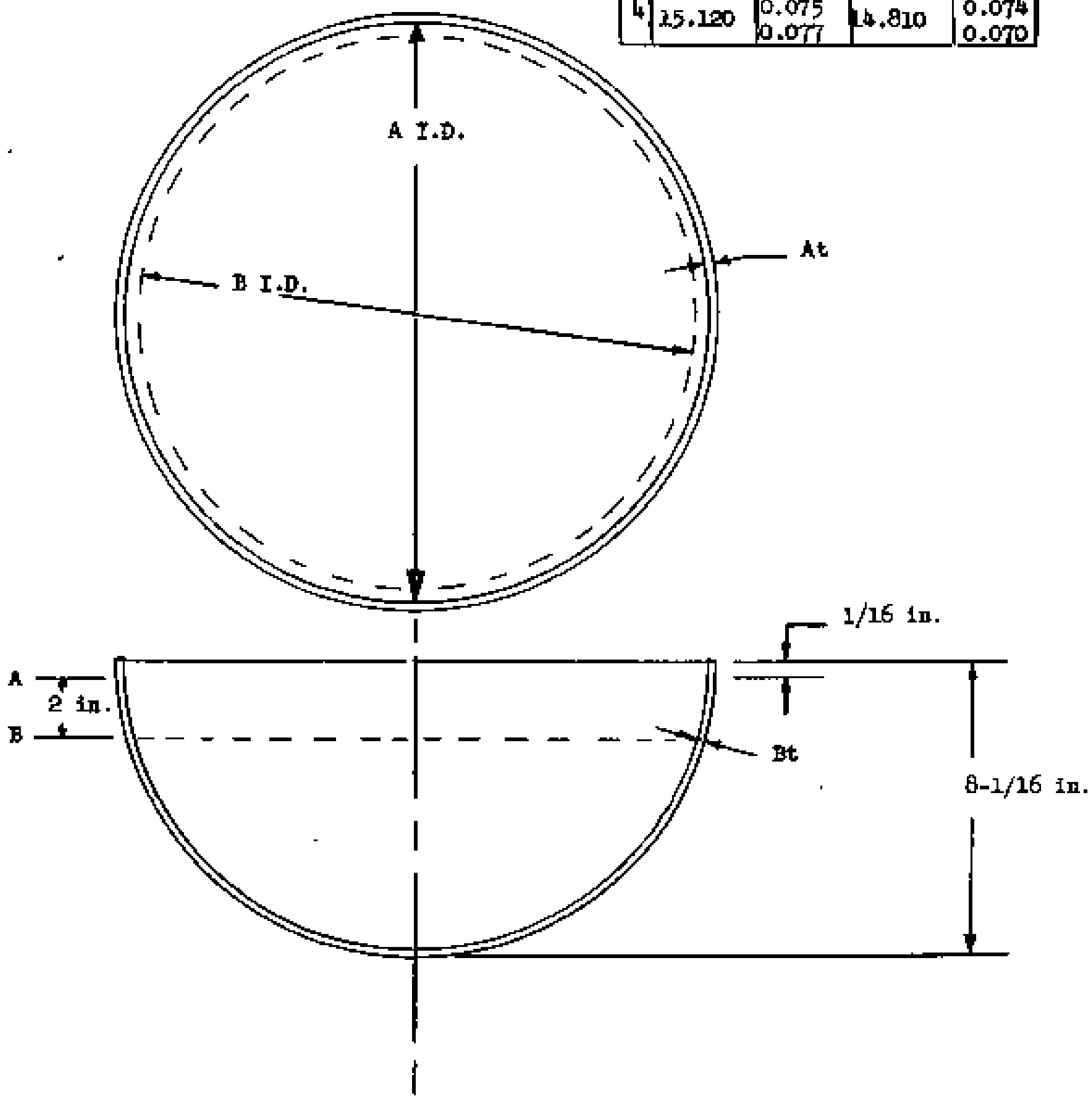
Job #252

Shell # 10

CORE TANK

After sandblast

	A		B	
#	I.D.	t	I.D.	t
1	15.100	0.078 0.074	14.790	0.071 0.070
2	15.162	0.079 0.077	14.820	0.076 0.068
3	15.172	0.078 0.075	14.835	0.080 0.070
4	15.120	0.075 0.077	14.810	0.074 0.070



UNION CARBIDE NUCLEAR COMPANY LABORATORY

P. O. # 93Y-1617

Job #252

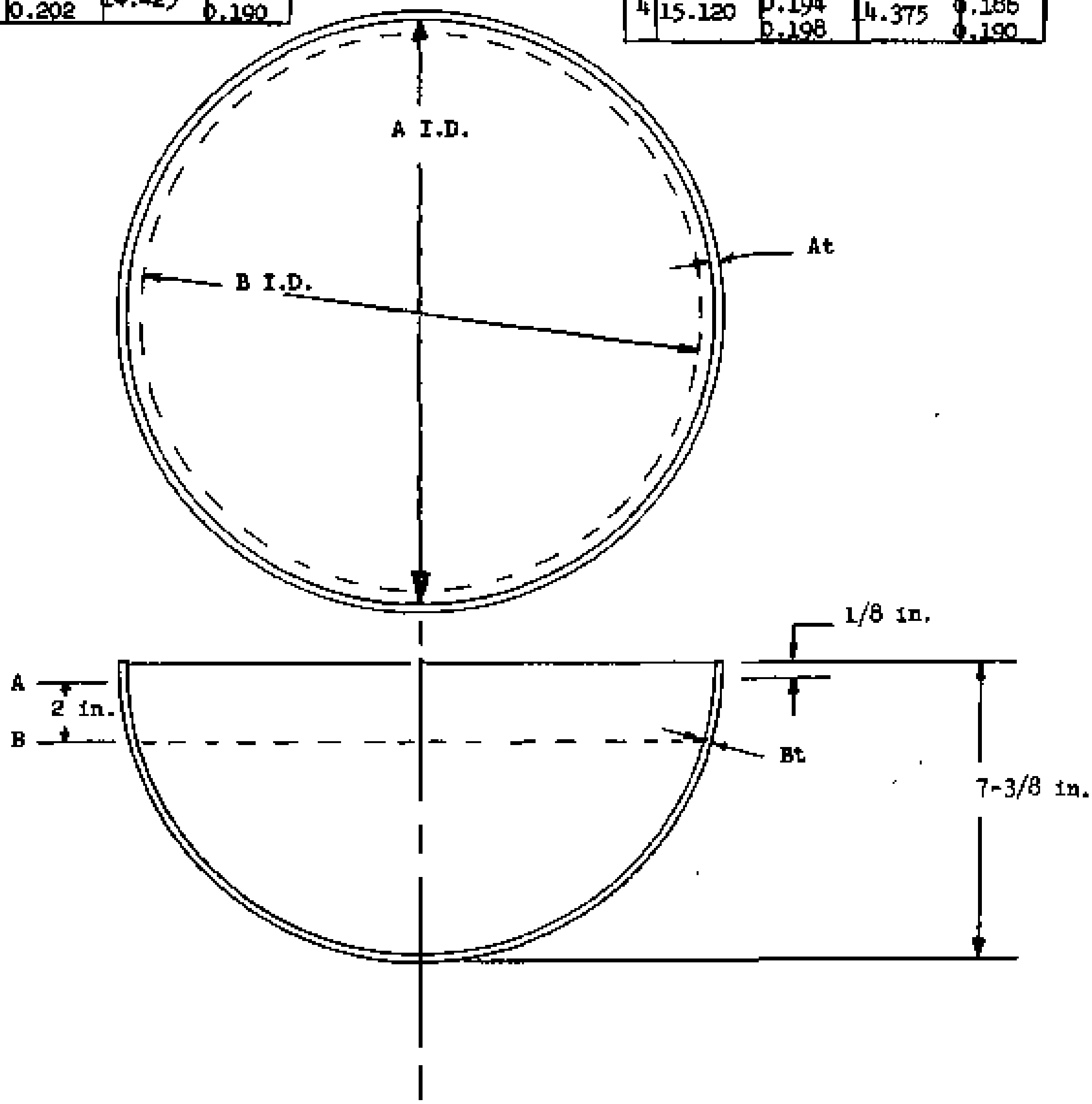
Shell # 11

Before sandblast

	A		B	
#	I.D.	t	I.D.	t
1	15.115	0.210 0.195	14.410	0.192 0.188
2	15.110	0.205 0.196	14.400	0.192 0.185
3	15.130	0.200 0.200	14.415	0.192 0.188
4	15.140	0.198 0.202	14.425	0.190 0.190

After sandblast

	A		B	
#	I.D.	t	I.D.	t
1	15.140	0.195 0.198	14.400	0.191 0.190
2	15.130	0.194 0.199	14.385	0.189 0.193
3	15.115	0.194 0.199	14.375	0.186 0.192
4	15.120	0.194 0.198	14.375	0.186 0.190



UNION CARBIDE NUCLEAR COMPANY LABORATORY

P. O. # 93Y-1617

Job #252

Shell # 12

CORE TANK

Before sandblast

#	A I.D.	A t	B I.D.	B t
1	15.140	0.230 0.245	14.615	0.225 0.235
2	15.135	0.240 0.240	14.610	0.227 0.232
3	15.100	0.240 0.235	14.585	0.228 0.230
4	15.090	0.240 0.230	14.590	0.231 0.226

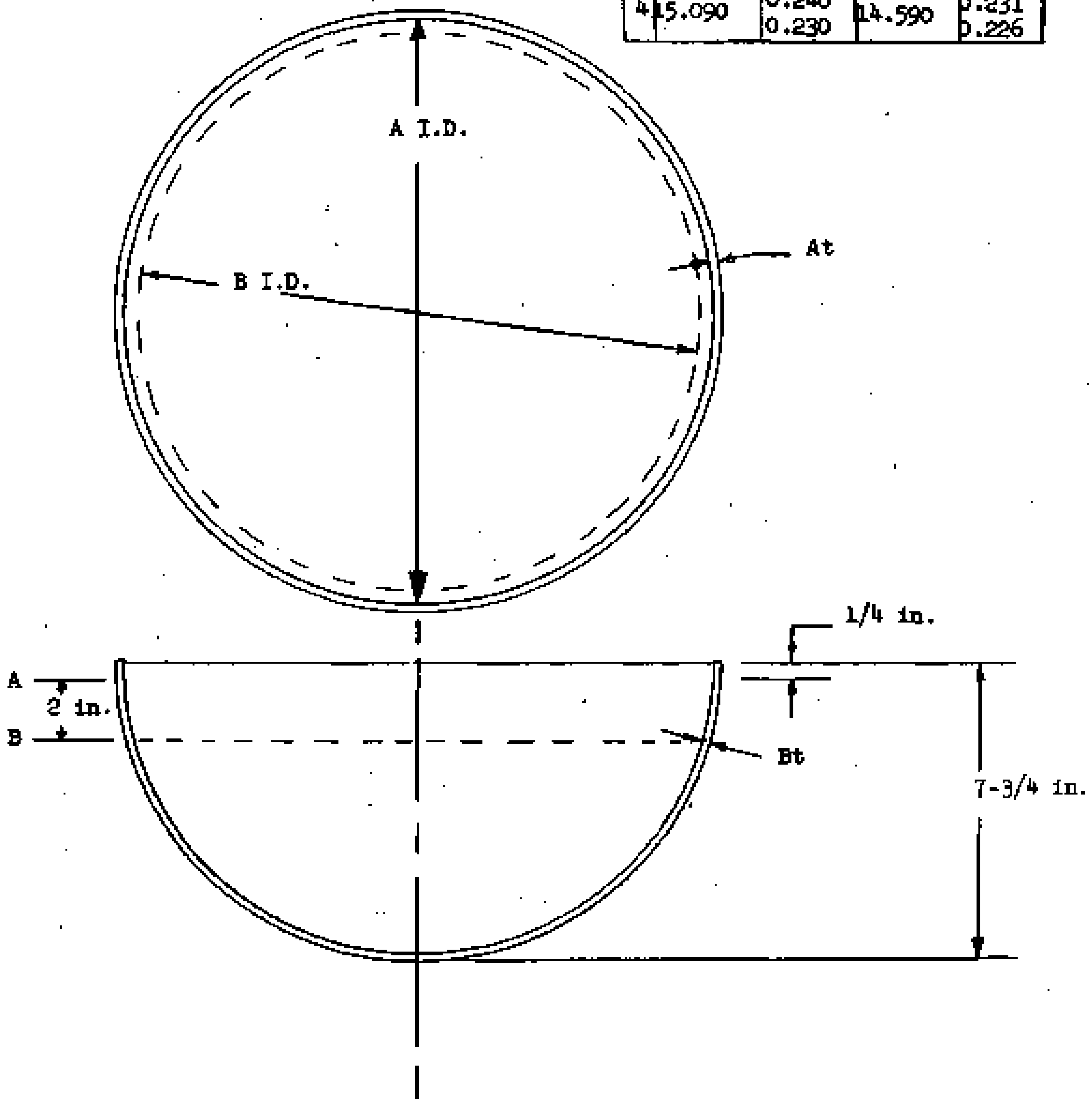


Table AIII

Thickness (ORNL)

Table AIII (a)
Thickness in. x 10^{-3} (ORNL)
Shell No. 1

Azimuthal Position (Degrees)	Degrees From Pole							
	Lip	15	30	35	45	60	75	90
0	234	227	214	150	168	194	218	
45	233	226	209	155	172	198	221	
90	235	230	215	160	180	202	224	
135	238	236	228	160	180	206	222	
180	240	240	235	160	180	204	222	
225	239	234	224	160	128	204	226	
270	233	233	221	158	125	198	216	
315	234	231	222	155	175	197	220	

Table AIII (b)
Thickness in. x 10^{-3} (ORNL)
Shell No. 2

Azimuthal Position (Degrees)	Degrees From Pole						
	Lip	15	30	45	60	75	90
0	306	310	308	180	176	230	216
30	305	308	305	178	175	225	215
60	304	308	307	175	172	217	210
90	306	308	305	176	173	215	208
120	304	305	303	176	174	215	207
150	302	304	300	177	177	217	207
180	301	305	298	180	171	223	208
210	304	307	300	178	176	226	210
240	302	304	310	176	174	266	210
270	301	305	310	178	176	222	210
300	304	307	310	180	176	223	212
330	305	308	306	180	178	226	212

Table AIII (c)
Thickness in. x 10^{-3} (ORNL)
Shell No. 3 (0.312-in.)

Azimuthal Position (Degrees)	Degrees From Pole						
	Lip	15	30	35	45	60	75
0	267	269	250	240	240	253	228
45	268	269	257	240	242	254	227
90	267	268	251	243	245	258	224
135	268	269	251	240	243	255	218
180	265	262	242	236	244	248	219
225	265	261	234	234	238	250	218
270	263	263	239	235	234	252	220
315	264	266	240	233	230	253	218

Table AIII (d)
Thickness in. x 10^{-3} (ORNL)
Shell No. 6

Azimuthal Position (Degrees)	Degrees From Pole						
	Lip	15	30	35	45	60	75
0	292	298	289	225	226	218	210
45	290	301	291	225	230	222	204
90	295	304	298	223	230	226	--
135	293	303	300	224	228	225	214
180	297	302	300	228	230	226	212
225	293	300	296	226	230	225	203
270	293	298	290	224	226	223	204
315	295	298	289	220	226	218	213

Table AIII (e)
Thickness in. x 10^{-3} (ORNL)
Shell No. 11

Azimuthal Position (Degrees)	Degrees From Pole						
	Lip	15	30	45	60	75	90
0	278	275	272	202	196	200	
45	276	274	270	204	196	196	
90	275	273	265	200	196	194	
135	274	275	268	199	198	201	
180	274	275	270	206	198	204	
225	274	273	268	200	200	205	
270	275	276	268	207	198	206	
315	274	277	268	205	196	202	

Table AIII (f)
Thickness in. x 10^{-3} (ORNL)
Shell No. 12

Azimuthal Position (Degrees)	Degrees From Pole							
	Lip	15	30	35	45	60	75	90
0	270	250	227	--	227	223	227	230
30	270	250	228	--	225	222	224	230
60	263	257	228	--	225	223	227	230
90	264	253	228	--	226	225	230	230
120	269	259	239	--	224	224	229	233
150	269	259	237	--	225	227	232	235
180	268	252	236	--	226	227	231	238
210	267	251	229	--	229	229	230	240
240	268	252	226	218	229	230	234	240
270	269	252	222	213	229	230	224	239
300	270	246	220	216	228	230	230	237
330	230	248	220	--	225	224	228	230

Table AIII (g)
Thickness in. x 10^{-3} (ORNL)
Shell No. 5

Azimuthal Position (Degrees)	Degrees From Pole						
	Lip	15	30	45	60	75	90
0	200	188	162	161	169	160	165
30	200	190	155	160	168	165	165
60	200	190	152	158	164	160	163
90	198	184	146	159	165	159	162
120	195	185	146	159	164	160	165
150	189	176	138	159	169	160	165
180	189	175	130	159	168	166	169
210	190	180	131	160	167	164	168
240	190	179	140	162	172	166	170
270	198	187	155	161	173	169	170
300	199	189	166	161	173	166	170
330	200	190	162	161	172	165	168

Table AIII (h)
Thickness in. x 10^{-3} (ORNL)
Shell No. 4

Azimuthal Position (Degrees)	Degrees From Pole						
	Lip	15	30	45	60	75	90
0	--	--	--	180	178	185	190
45	--	--	--	180	176	182	186
90	--	--	--	178	170	176	184
135	--	--	--	180	173	178	184
180	--	--	--	184	174	184	187
225	--	--	--	182	178	186	190
220	--	--	--	184	178	188	192
315	--	--	--	184	178	182	190

Table AIII (i)
Thickness in. x 10^{-3} (ORNL)
Shell No. 7

Azimuthal Position (Degrees)	Degrees From Pole							
	Lip	15	30	35	45	60	75	90
0	123	122	125	57	83	94	95	96
30	123	121	124	55	85	94	90	97
60	122	123	123	56	88	91	93	96
90	123	122	124	52	90	89	93	95
120	123	123	125	51	82	88	93	94
150	122	122	125	51	85	96	92	96
180	123	122	122	52	87	92	88	96
210	122	122	122	52	84	88	92	94
240	122	121	121	52	82	91	92	93
270	122	122	122	52	82	93	94	94
300	122	122	123	58	83	92	97	94
330	122	122	123	57	84	95	95	97

Table AIII (j)
Thickness in. x 10^{-3} (ORNL)
Shell No. 8

Azimuthal Position (Degrees)	Degrees From Pole						
	Lip	15	30	45	60	75	90
0	124	123	126	92	68	66	
45	124	123	125	93	68	69	
90	125	126	128	95	62	64	
135	124	126	128	91	64	62	
180	125	124	128	93	63	60	
225	128	125	127	93	66	69	
270	124	128	127	90	64	70	
315	126	128	126	87	65	68	

Table AIII (k)
Thickness in. x 10^{-3} (ORNL)
Shell No. 9

Azimuthal Position (Degrees)	Degrees From Pole							
	Lip	15	30	35	45	60	75	90
0	118	117	119	80	86	88	85	83
30	119	119	116	79	85	86	84	82
60	120	119	118	79	85	89	85	83
90	118	120	120	80	86	89	87	83
120	117	120	121	80	89	90	86	88
150	118	119	118	81	87	91	88	86
180	119	120	121	83	88	92	91	89
210	120	121	121	85	92	86	82	89
240	119	120	120	86	84	94	90	82
270	118	118	120	82	92	94	92	91
300	122	124	123	81	91	89	87	85
330	124	124	123	81	87	90	87	85

Table AIII (l)
Thickness in. x 10^{-3} (ORNL)
Shell No. 10

Azimuthal Position (Degrees)	Degrees From Pole					
	Lip	15	30	45	60	75
0	123	123	124	90	78	61
45	124	123	121	92	76	58
90	122	123	123	89	76	56
135	122	122	122	90	75	55
180	123	123	124	90	75	53
225	123	122	123	90	74	54
220	120	122	123	89	70	58
315	120	121	123	89	68	55

Table AIV

Radial Measurements (ORNL)

Table AIV (a)
Outside Radius, inches (ORNL)
Shell No. 1

Distance From Pole (Degrees)	Azimuthal Position							
	0°	45°	90°	135°	180°	225°	270°	315°
15	7.727	7.727	7.726	7.724	7.724	7.725	7.725	7.727
30	7.727	7.725	7.724	7.723	7.722	7.722	7.724	7.727
45	7.721	7.723	7.715	7.710	7.698	7.700	7.716	7.721
60	7.770	7.760	7.764	7.760	7.750	7.754	7.761	7.770
75	7.830	7.815	7.816	7.810	7.799	7.806	7.811	7.828

Table AIV (b)
Outside Radius, inches (ORNL)
Shell No. 2

Distance From Pole (Degrees)	Azimuthal Position											
	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
15	7.841	7.808	7.807	7.807	7.807	7.809	7.841	7.810	7.809	7.807	7.809	7.810
30	7.843	7.844	7.823	7.815	7.845	7.845	7.842	7.839	7.818	7.819	7.841	7.840
45	7.751	7.695	7.680	7.688	7.733	7.740	7.748	7.698	7.675	7.700	7.744	7.732
60	7.740	7.666	7.676	7.695	7.744	7.753	7.725	7.659	7.671	7.754	7.741	7.758
75	7.839	7.820	7.780	7.804	7.820	7.831	7.837	7.818	7.823	7.832	7.845	7.845
90	7.895	7.868	7.848	7.853	7.871	7.888	7.888	7.868	7.862	7.874	7.895	7.900
1/4 in. Below Equator	7.900	7.905	7.880	7.885	7.919	7.942	7.937	7.915	7.907	7.919	7.945	7.945

Table AIV (c)

Outside Radius, inches (ORNL)

Shell No. 3

Distance From Pole (Degrees)	Azimuthal Position							
	0°	45°	90°	135°	180°	225°	270°	315°
15	7.764	7.762	7.760	7.760	7.760	7.760	7.761	7.761
30	7.766	7.765	7.764	7.757	7.756	7.757	7.762	7.767
45	7.782	7.780	7.774	7.761	7.756	7.761	7.773	7.780
60	7.864	7.840	7.830	7.816	7.810	7.809	7.822	7.845
75	7.868	7.865	7.846	7.836	7.829	7.832	7.842	7.872

Table AIV (d)

Outside Radius, inches (ORNL)

Shell No. 6

Distance From Pole (Degrees)	Azimuthal Position							
	0°	45°	90°	135°	180°	225°	270°	315°
15	7.770	7.775	7.767	7.774	7.766	7.767	7.766	7.768
30	7.778	7.780	7.781	7.782	7.783	7.773	7.779	7.774
45	7.748	7.749	7.746	7.743	7.751	7.746	7.737	7.736
60	7.804	7.801	7.797	7.803	7.808	7.796	7.793	7.801
75	7.857	7.845	7.837	7.848	7.863	7.849	7.833	7.857

Table AIV (e)
Outside Radius, inches (ORNL)
Shell No. 11

Distance From Pole (Degrees)	Azimuthal Position							
	0°	45°	90°	135°	180°	225°	270°	315°
15	7.751	7.750	7.750	7.747	7.744	7.746	7.748	7.752
30	7.761	7.760	7.758	7.751	7.750	7.752	7.761	7.763
45	7.708	7.712	7.707	7.698	7.692	7.698	7.709	7.710
60	7.752	7.759	7.760	7.775	7.748	7.757	7.763	7.761
75	7.812	7.712	7.712	7.818	7.818	7.830	7.823	7.823

Table AIV (f)
Outside Radius, inches (ORNL)
Shell No. 12

Distance From Pole (Degrees)	Azimuthal Position											
	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
15	7.738	7.737	7.736	7.737	7.735	7.733	7.732	7.733	7.735	7.737	7.738	7.738
30	7.736	7.736	7.735	7.732	7.729	7.728	7.728	7.739	7.731	7.733	7.735	7.735
45	7.748	7.755	7.765	7.754	7.742	7.738	7.740	7.748	7.754	7.756	7.751	7.747
60	7.780	7.789	7.796	7.792	7.782	7.776	7.774	7.785	7.792	7.790	7.782	7.776
75	7.837	7.850	7.860	7.854	7.840	7.830	7.827	7.837	7.849	7.846	7.836	7.829
90	7.898	7.920	7.934	7.927	7.914	7.896	7.888	7.900	7.917	7.912	7.894	7.888

Table AIV (g)
Outside Radius, inches (ORNL)
Shell No. 5

Distance From Pole (Degrees)	Azimuthal Position 0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
15	7.688	7.688	7.686	7.685	7.683	7.681	7.682	7.683	7.685	7.686	7.682	7.687
30	7.681	7.681	7.680	7.677	7.672	7.670	7.671	7.674	7.678	7.675	7.681	7.681
45	7.683	7.685	7.686	7.680	7.677	7.682	7.683	7.687	7.688	7.680	7.681	7.681
60	7.711	7.712	7.684	7.703	7.700	7.698	7.700	7.703	7.705	7.710	7.714	7.715
75	7.738	7.744	7.735	7.730	7.728	7.724	7.730	7.730	7.732	7.741	7.738	7.743
90	7.795	7.799	7.794	7.785	7.776	7.774	7.774	7.779	7.781	7.790	7.790	7.800

Table AIV (h)
Outside Radius, inches (ORNL)
Shell No. 7

Distance From Pole (Degrees)	Azimuthal Position 0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
15	7.624	7.626	7.629	7.631	7.634	7.633	7.624	7.623	7.623	7.623	7.623	7.623
30	7.658	7.642	7.669	7.675	7.679	7.679	7.660	7.655	7.654	7.654	7.654	7.654
45	7.596	7.609	7.621	7.632	7.640	7.629	7.608	7.587	7.585	7.586	7.585	7.586
60	7.606	7.601	7.602	7.610	7.596	7.617	7.588	7.584	7.599	7.606	7.609	7.610
75	7.617	7.614	7.618	7.615	7.617	7.618	7.585	7.594	7.599	7.609	7.620	7.623
90	7.648	7.644	7.636	7.620	7.619	7.622	7.594	7.599	7.609	7.624	7.659	7.651

Table AIV (i)
Outside Radius, inches (ORNL)
Shell No. 8

Distance From Pole (Degrees)	Azimuthal Position							
	0°	45°	90°	135°	180°	225°	270°	315°
15	7.625	7.627	7.625	7.625	7.629	7.631	7.627	7.625
30	7.622	7.620	7.610	7.625	7.629	7.631	7.625	7.619
45	7.593	7.564	7.569	7.582	7.594	7.605	7.585	7.554
60	7.581	7.578	7.552	7.585	7.579	7.565	7.550	7.565
75	7.589	7.592	7.549	7.604	7.614	7.572	7.547	7.565

Table AIV (j)
Outside Radius, inches (ORNL)
Shell No. 9

Distance From Pole (Degrees)	Azimuthal Position											
	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
15	7.623	7.641	7.621	7.620	7.620	7.618	7.617	7.617	7.616	7.618	7.621	7.641
30	7.639	7.640	7.640	7.640	7.634	7.631	7.631	7.631	7.636	7.638	7.643	7.641
45	7.595	7.590	7.592	7.601	7.595	7.585	7.579	7.583	7.596	7.603	7.611	7.609
60	7.595	7.586	7.591	7.596	7.589	7.584	7.579	7.582	7.596	7.605	7.616	7.607
75	7.596	7.587	7.589	7.594	7.597	7.592	7.585	7.588	7.600	7.614	7.625	7.617
90	7.621	7.613	7.616	7.629	7.638	7.632	7.641	7.627	7.634	7.659	7.667	7.653

Table AIV (k)
Outside Radius, inches (ORNL)
Shell No. 10

Distance From Pole (Degrees)	Azimuthal Position							
	0°	45°	90°	135°	180°	225°	270°	315°
15	7.620	7.621	7.622	7.622	7.627	7.626	7.624	7.621
30	7.623	7.625	7.627	7.633	7.635	7.633	7.627	7.624
45	7.601	7.602	7.597	7.608	7.614	7.612	7.613	7.611
60	7.605	7.611	7.606	7.621	7.619	7.618	7.614	7.613
75	7.623	7.639	7.616	7.644	7.652	7.639	7.630	7.644

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