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Metals, Ceramics,
and Materials

EFFECT OF EXPLOSIVE IMPACTING ON URANIUM

R. B. Burditt
W. T. Carey
C. P. Coughlen

Y-12 PLANT
Oak Ridge, Tennessee

UNION CARBIDE

UNION CARBIDE CORPORATION
NUCLEAR DIVISION

Operating the

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TID-4500 (27th Edition)

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ABSTRACT

The tensile and yield strengths of both cast and wrought uranium discs were substantially increased by explosively impacting them at room temperature and at 375° F. However, the room-temperature impacting caused gross damage in the cast material and slight internal damage in the wrought material at the highest impacting pressures. Impacting at 375° F, which is just above the brittle-ductile transition temperature for uranium, was the most effective method for increasing the strengths with no damage to either the cast or wrought material. This impacted material retained some of its increased strength after a low-temperature (425° C) vacuum anneal that greatly increased the elongation. A salt anneal caused a partial recrystallization in the impacted cast uranium.

CONTENTS

INTRODUCTION

The Y-12 Plant of Union Carbide Corporation, Nuclear Division, has been fabricating cast and wrought uranium for many years by conventional processes and has demonstrated that this material, if heated to over 375° F, can be explosively formed.[1] However, the potential strengthening effect of explosively impacting uranium without plastic deformation was not known. Laboratories throughout the country have made numerous theoretical and empirical explosive studies, primarily on common materials such as steel, copper, and brass. Much of this work has been reported by Rinehart and Pearson,[2] Shemon and Zackay,[3] C. S. Smith,[4] and Rice, McQueen, and Walsh.[5]

A program was initiated to determine the strengthening effect of an explosive impact upon both cast and wrought uranium that was constrained to prevent plastic deformation. The impacting was done at both room temperature and at 375° F, since at the higher temperature uranium has a much lower yield strength and much higher elongation.

One purpose of impacting cast uranium was to determine if weld metal (essentially a casting) between two wrought parts could be strengthened and recrystallized to have tensile properties nearer to the parent material. One purpose of impact testing wrought uranium was to determine if local areas of a part, fully annealed for good machinability and uniform tensile properties, could be strengthened.

A final purpose of this program was to learn how to use explosives to impact materials. This impacting was done at the National Northern Division of Atlantic Research Corporation for Y-12. Union Carbide now operates an explosive-forming facility at Y-12. The explosive impacting was done with much higher forces than are normally used to explosively form or size metal parts.

SUMMARY

GENERAL PROCEDURE

Five-inch-diameter discs of wrought and cast uranium in thicknesses of 1/16, 1/8, 1/4, and 3/8 inch were explosively impacted at pressures estimated to be 1.1×10^5, 2.4×10^5, and 5.3×10^5 psi, and at two temperatures, ambient (about 75° F)[6] and 375° F.[7] The discs were slightly dished and thinned by the impacting.

RESULTS

Ambient-Temperature Impacting

Both wrought and cast uranium were damaged by the impacting at ambient temperature. The surface of the cast uranium after impacting had a rough, grainy appearance with surface ruptures extending deep into the plate. Internal voids were present in the cast uranium but these did not act as crack initiators. Damage to the wrought uranium was visible only under magnification. The surface of the wrought uranium was not visibly changed by the impacting, but some of the wrought uranium discs developed small internal cracks that lay in what appeared to be planes parallel with the impacted surface of the disc.

The tensile strength of the impacted uranium increased rapidly at the low impact levels (1.1×10^5 psi), reached a maximum at the intermediate level (2.4×10^5 psi), and stayed at this level, or decreased, at the high impact level (5.3×10^5 psi). The typical tensile properties of the salt-annealed wrought uranium impacted at ambient temperature were: ultimate tensile strength, 112,000 psi; 0.2% offset yield strength, 72,000 psi; elongation, 5%; and reduction in area, 5%.

Typical tensile properties of the cast uranium impacted at ambient temperature were: ultimate tensile strength, 75,000 psi; and yield strength, 55,000 psi.

Both of these materials had visible internal strains that accounted for their increased strength.

Warm-Temperature Impacting

Impacting at 375° F did not damage either material and was more effective in increasing the tensile properties. Typical tensile properties of the salt-annealed wrought uranium impacted at 375° F were: ultimate tensile strength, 112,000 psi; 0.2% offset yield strength, 78,000 psi; elongation, 12%; and reduction in area, 12%. Typical tensile properties of the cast uranium impacted at 375° F were: ultimate tensile strength, 87,000 psi; and 0.2% offset yield strength, 56,000 psi.

Vacuum Heat Treatment

When these impacted materials were vacuum heat treated for 30 hours at 425° C, the ductility increased and much of the strength remained. Typical tensile properties of the wrought uranium impacted at ambient temperature and then vacuum heat treated were: ultimate tensile strength, 112,000 psi; 0.2% offset yield strength, 45,000 psi; elongation, 40%; and reduction in area, 40%. Typical tensile properties of the wrought material impacted at 375° F and vacuum heat treated were: ultimate tensile strength, 112,000 psi; 0.2% offset yield strength, 45,000 psi; elongation, 40%; and reduction in area, 55%. Typical tensile properties of the cast uranium impacted at 375° F and vacuum heat treated were: ultimate tensile strength, 92,000 psi; 0.2% offset yield strength, 40,000 psi; elongation, 10%; and reduction in area, 15%.

CONDUCT OF THE STUDY

SPECIMEN PREPARATION AND IMPACTING

Specimen Preparation

The test program was laid out to compare the effect of various impact pressures (three pressure levels) on four thicknesses of wrought uranium (1/16, 1/8, 1/4, and 3/8 inch) and three thicknesses of cast uranium (1/8, 1/4, and 3/8 inch).

All wrought specimens were obtained from a 10-inch-thick uranium billet, induction cast from recycle material. The billet was heated in a 630° C salt bath and cross rolled to one-inch thickness.

The one-inch-thick plate was sheared into four pieces which were reheated and hot rolled with about equal cross rolling to thicknesses of 3/8, 1/4, 1/8, and 1/16 ±0.005 inch. Each piece was salt annealed at 600° C and hot sheared into pieces six inches square. A five-inch-diameter disc was machined from each square and X rayed. A chemical analysis of the plate was obtained and is reported in Table 1. The carbon content reported is lower than would be expected for hot-rolled uranium plate.

Table 1

CHEMICAL ANALYSES OF IMPACTED URANIUM

Element (ppm)	Wrought Plate	Cast Log 1	Cast Log 2
Al	3	9	10
C	40	136	112
Cu	6	6	6
Fe	35	65	15
Mg	4	< 2	< 2
Mn	20	20	4
Mo	< 4	20	4
Ni	6	10	12
Pb	1	3	2
Si	<10	170	175
Ti	6	10	15
Others(1)			

(1) All the other elements showed less than the minimum detectable spectrographic limit.

The amount of material required for performing the test on cast uranium made it necessary to use two eight-inch-diameter logs. The logs were induction cast from recycle material and machined to five inches in diameter. The 1/4 and 3/8-inch-thick discs were obtained from Log 1; the 1/8-inch-thick discs were obtained from Log 2. The discs were examined and those with gross visible defects were discarded and replaced. A few discs which showed substantial internal porosity were retained in the program and impacted as scheduled to evaluate the interaction between impacting stresses and local defects. Chemical analyses of the two logs were obtained and are included in Table 1. As can be seen, there were small composition differences between the two logs in carbon, iron, molybdenum, and manganese; however, these differences would not be expected to produce significant differences in the tensile properties of the material. Both analyses are indicative of better-than-average purity castings.

Impacting

Discs to be impacted were recut to a diameter of 4 1/2 inches to fit the tooling requirements at Atlantic Research[a] which did the impacting work. Six discs of each category were impacted at ambient temperature and six at 375° F. In each case, two discs were impacted at 1.1×10^5 psi, two at 2.4×10^5 psi, and two at 5.3×10^5 psi. Four discs of each category were held for control specimens. The impacting was done outside in the summer at which time the ambient temperature was 75 to 80° F. To work out the impacting techniques, preliminary ambient-temperature impacting tests were run on cold-worked Type 430 stainless steel; preliminary 375° F temperature impacting tests were run on a beryllium-copper alloy. Special care was taken in these tests to hit these relatively large samples in a uniform, predictable, and reproducible manner that would not damage either the impacted or the supported surfaces. The details of this impacting work are given in two reports by National Northern.[6,7] Pertinent excerpts from these reports are presented as Appendixes A and B.

The method used to impact these parts appeared to give a uniform effect on the relatively large disc. The advantages of this method were:

1. The surface was not rutted, as was the case when explosives were placed directly against the metal.

2. The impacted material could be at almost any temperature with minimum hazard of predetonation of the explosive.

3. The impacted material could be encased to prohibit corrosion or contamination.

4. The impact was dependable and could be reproduced.

The disadvantages of this method were:

1. The explosive charge was large and somewhat expensive.

2. The near air shot made a lot of noise which may be objectionable, depending upon the location of the site.

(a) US Flare-National Northern Division, Atlantic Research Corporation.

3. The steel driver often flew up in the air and, for more than occasional use, a special bunker was needed to confine these parts.

4. Because of the large forces involved, the adaptation of this method to a shaped part that is large and practical would require some ingenuity, particularly in the design of the tooling. Also, this shooting would require a special bunker to contain the tools, should they rupture.

5. If the sample to be impacted was not flat, this method did not hold it tight between the driver and backup die.

EVALUATION OF THE IMPACTING

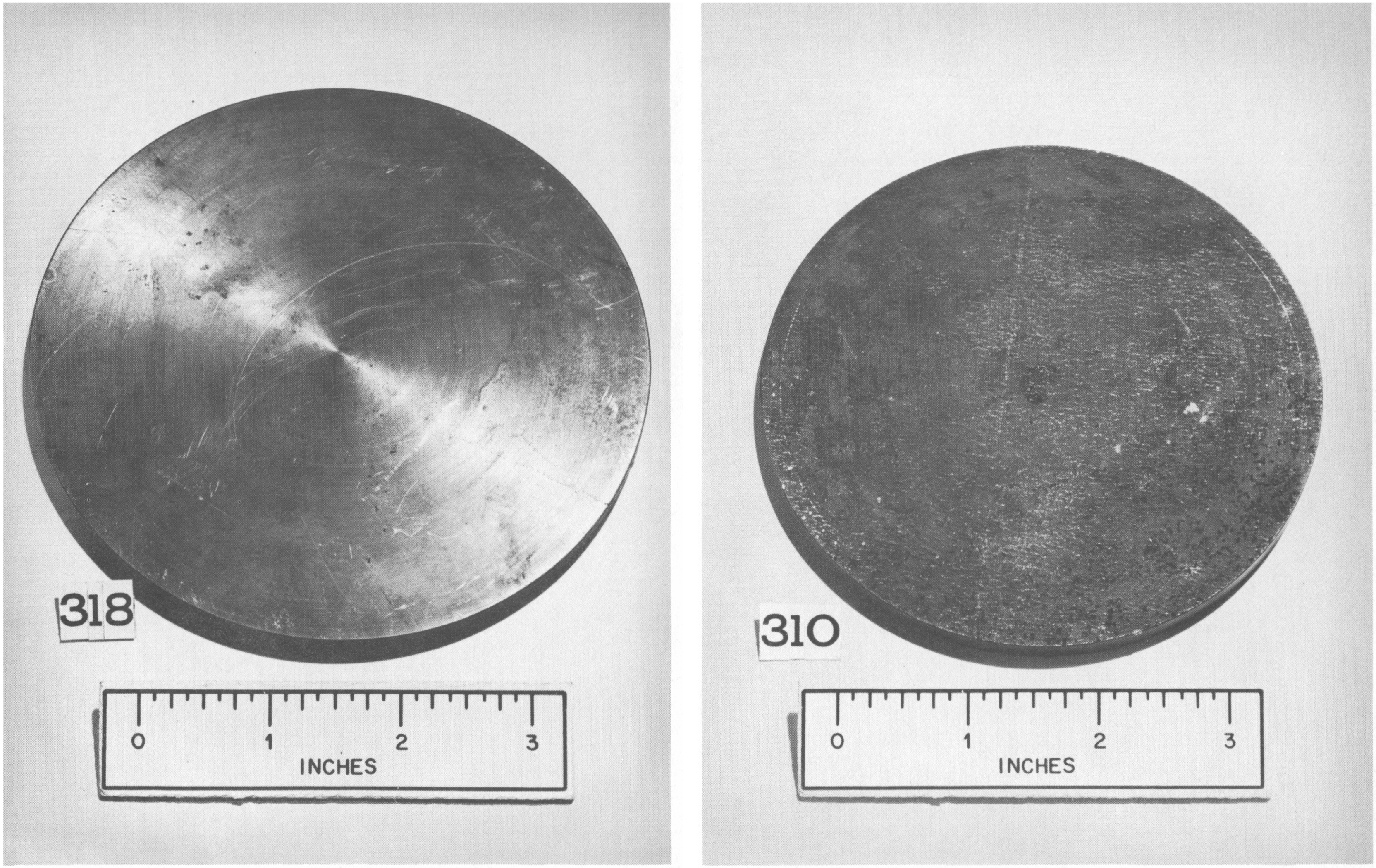
Visual Inspection

All of the discs after impacting were examined for surface damage. Figure 1 presents photographs of the cast and wrought discs before impacting. The cast material was machined and shows a visible pattern of casting flaws. The wrought plate has the typical hot-rolled surface. Figure 2 contains photographs of cast discs that were impacted under 5.3×10^5 psi at ambient and 375° F temperatures. The ambient-impacted disc was cracked and has a grainy surface appearance. The 375° F impacted disc has an even more grainy appearance but no visible flaws. This grainy appearance is typical of the large-grained uranium cast structure. Figure 3 shows photographs of the top (impacted) and bottom (supported by die) sides of a wrought disc that had been ambient impacted at 2.4×10^5 psi and shows no visible damage. Figure 4 is a photograph of the top of a wrought disc impacted under 5.3×10^5 psi at 375° F and shows a smooth surface with no visible damage.

Radiographic Inspection

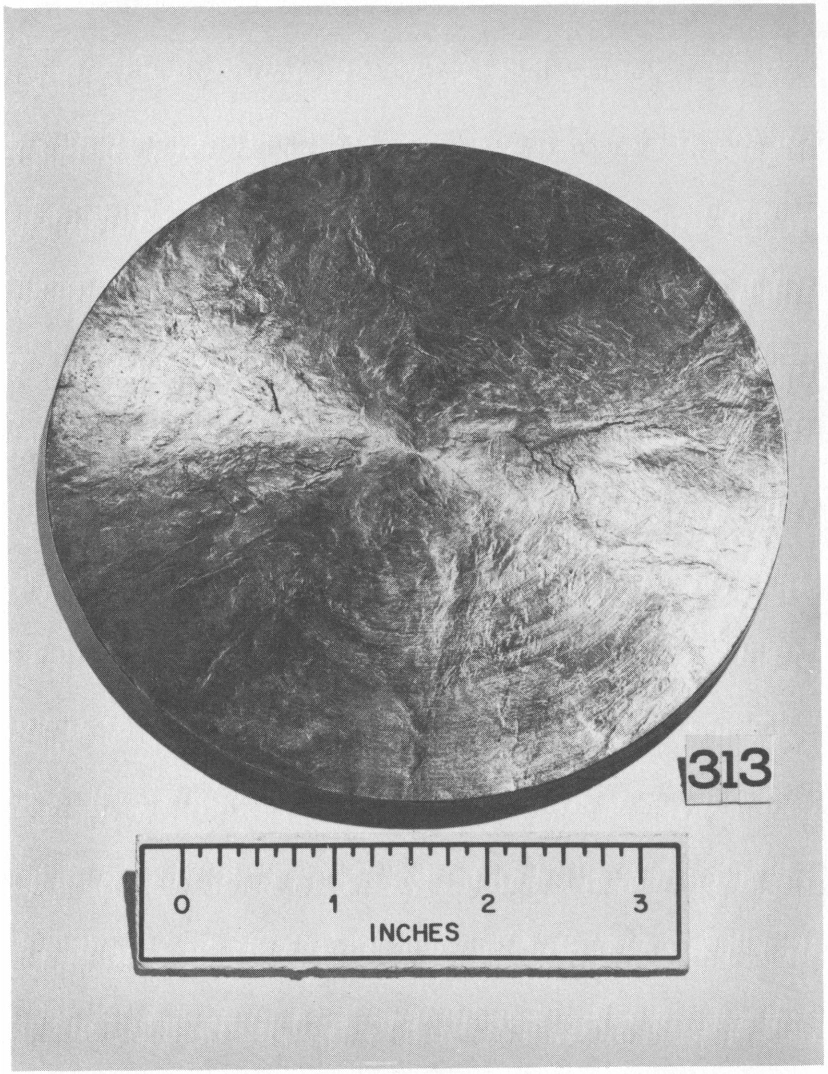
The discs were radiographed and two of the wrought discs, impacted at ambient temperature, showed at least one small crack. One of these (Disc 301) was impacted at 3.5×10^5 psi; the other (Disc 304) was impacted at 1.1×10^5 psi. One cast disc (405) showed surface welts; several others showed some surface roughening or damage. One wrought disc (505) which was impacted at 375° F showed a small crack at the stamped number, apparently due to the marking which was too deep.

Radiographic results of the cast material are summarized in Table 2 and show that cracking was characteristic of all of the discs that were impacted at ambient temperature but was not present in the discs that were impacted at the elevated temperature. In Y-12 terminology, a "negative" radiographic inspection means that no voids or low-density areas were observed. Internal voids which were present in the discs did not generally act as crack initiators. These voids in some cases appeared smaller and not as well defined after impacting. This difference is presumed to be due to a mechanical change in the shape of the void and not to the annealing process.

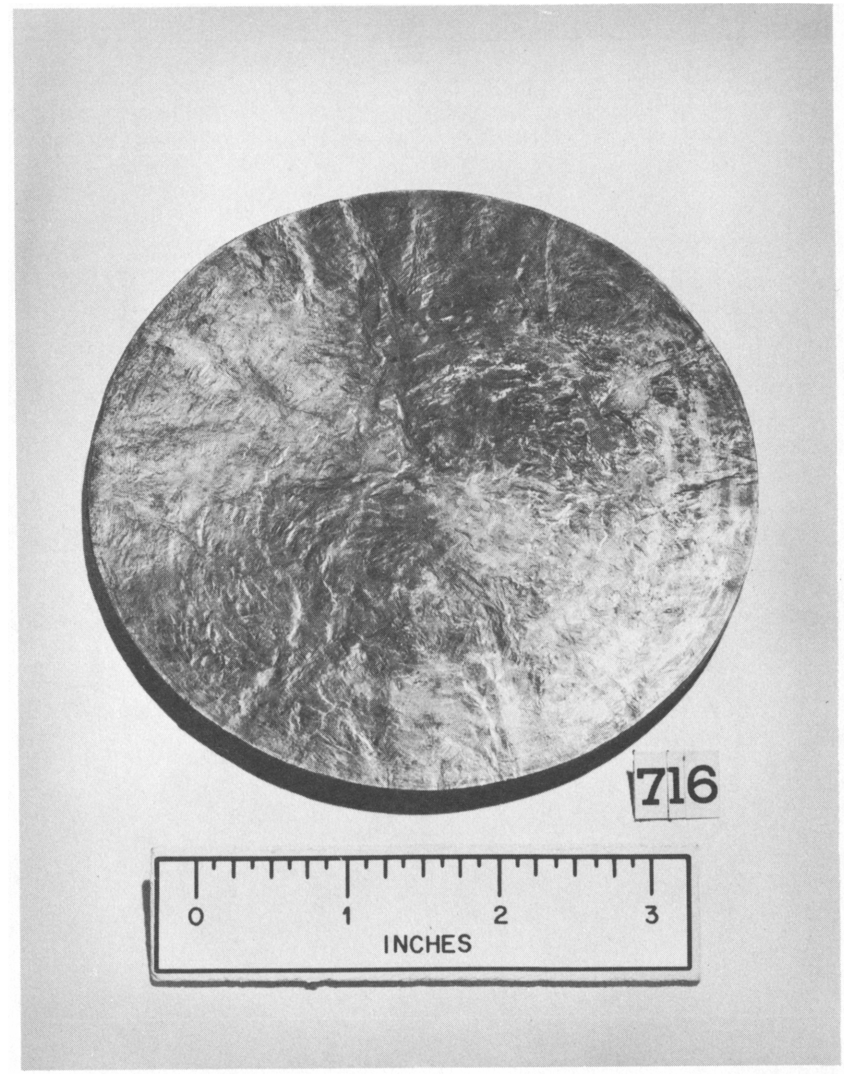


(a) Cast 107073(U) (b) Wrought 107071(U)

Figure 1. URANIUM DISCS BEFORE IMPACTION. (¼-Inch Thick)

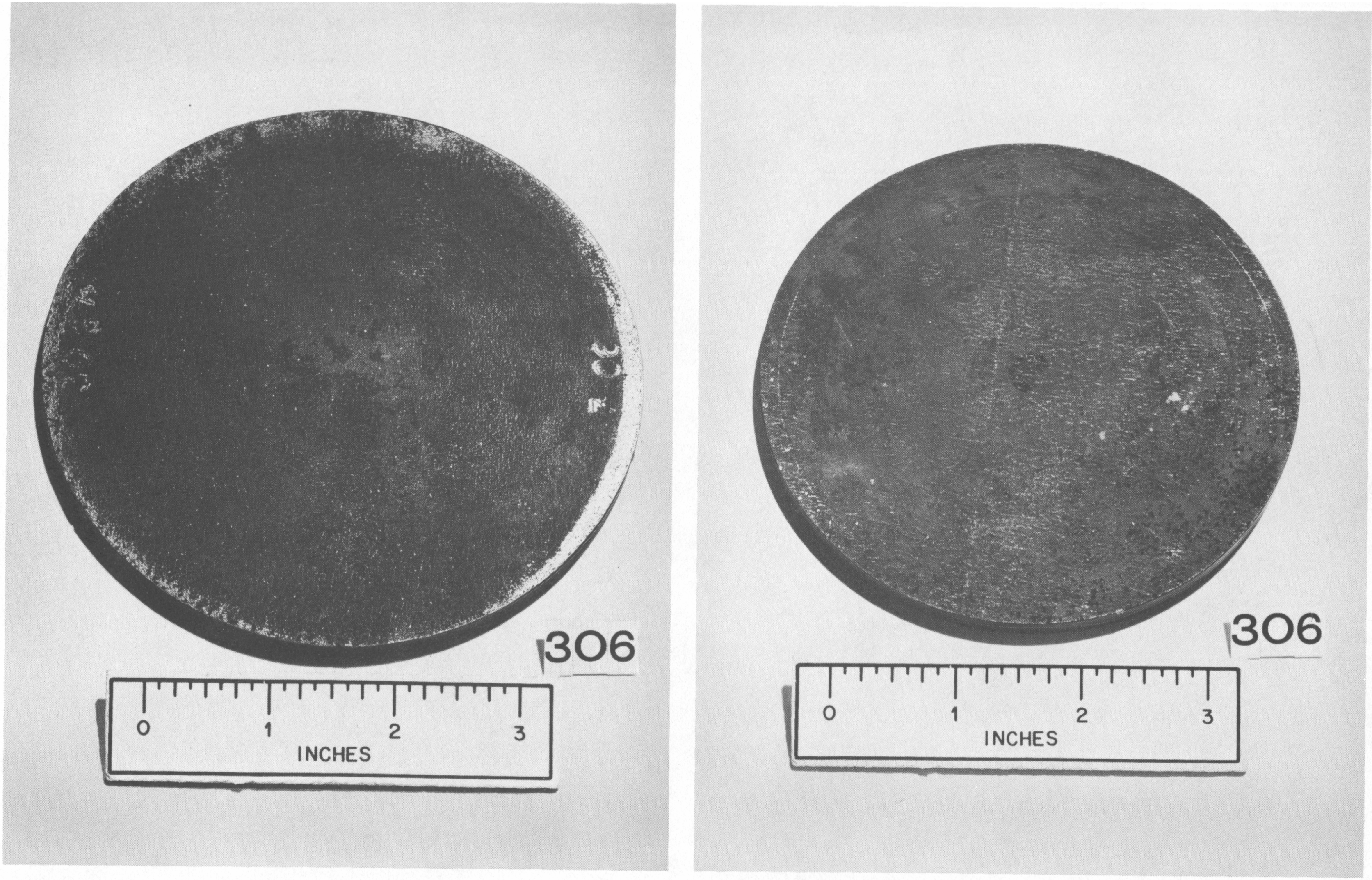


(a) Ambient Temperature at 5.3×10^5 psi. 107072(U)



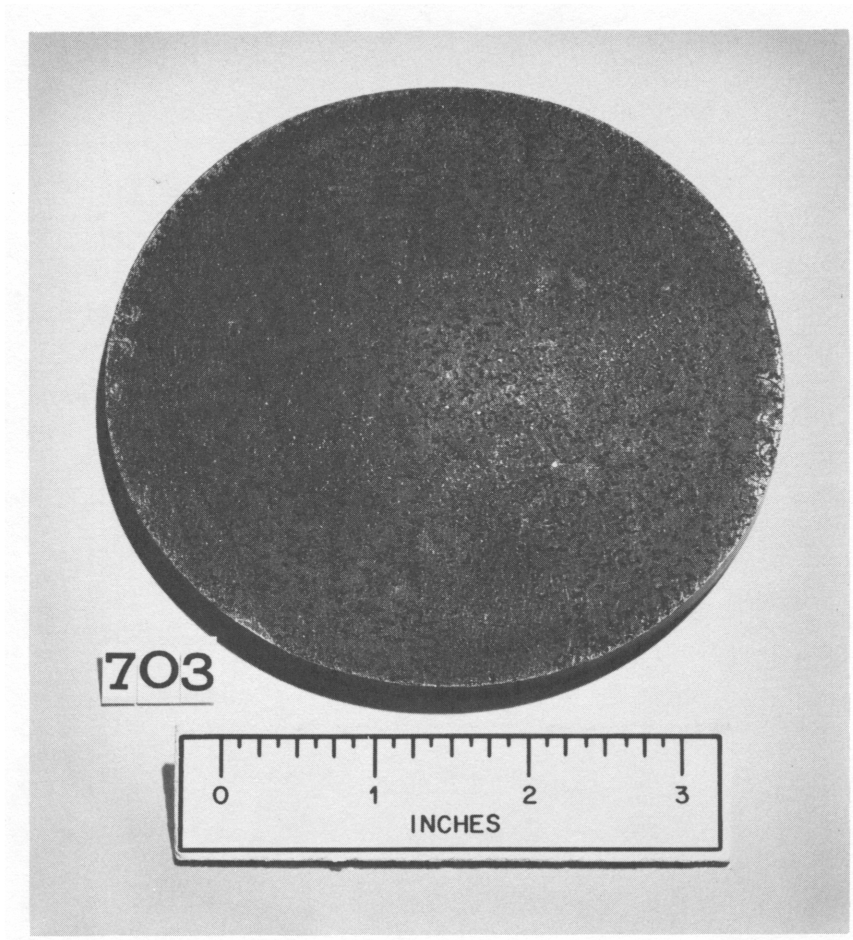
(b) 375° F at 5.3×10^5 psi. 107075(U)

Figure 2. CAST URANIUM DISCS AFTER IMPACTION. (¼-Inch Thick)



(a) Top of Disc 107069(U) (b) Bottom of Disc 107070(U)

Figure 3. **WROUGHT URANIUM DISC AFTER IMPACTION.** (Ambient Temperature at 2.4×10^5 psi; ¼-Inch Thick)



107074(U)

Figure 4. WROUGHT URANIUM DISC IMPACTED UNDER 5.3 × 10^5 PSI AT 375° F. (Top of Disc)

Except for the two wrought discs mentioned, all wrought impacted discs were radiographed with negative results. Some small internal flaws were found later under metallographic examination. Selected radiographs of discs before and after impaction are presented in Appendix C.

Thickness Measurements

Thickness measurements were made at two points (one inch from the edge) on all of the discs before and after impaction. Average changes in thickness for various thicknesses and impact loads are listed in Table 3.

Thickness changes generally increased with disc thickness, impact pressure, and temperature of impacting. The relative change in thickness is graphically presented in Figures 5 and 6 and the graphs show that, in terms of a change in thickness per inch of thickness, the relative thickness change increased with both increasing temperature and impact pressure. The discs were forged so hard that their laternal confinement was not sufficient to prevent their spreading. The slightly dished shape of the impacted discs showed that one surface was forged more than the other. The roughness of the cast discs after sizing made their thickness measurement of questionable value.

Table 2

RADIOGRAPHIC RESULTS ON CAST URANIUM DISCS

Disc Number	Impact Temperature (° F)	Impact Pressure (psi x 10^{-5})	Inspection Before Impact	Inspection After Impact
			1/8-Inch Thick	
211	Ambient	1.1	One void.	Two very large cracks; complete network of cracks or welts.
216	Ambient	1.1	Negative.(1)	Three small cracks; network of cracks or welts.
213	Ambient	2.4	Negative.	Two medium cracks; network of cracks or welts.
217	Ambient	2.4	Negative	Twelve small cracks; network of cracks or welts.
215	Ambient	5.3	Negative.	Fifteen cracks; network of cracks or welts.
218	Ambient	5.3	Negative.	Ten cracks; network of cracks or welts.
			1/4-Inch Thick	
311	Ambient	1.1	Six small voids.	Twenty-four large cracks; voids not visible.
314	Ambient	1.1	One large 1/4-inch void; two small voids.	Nine cracks; void appears as smaller with cracked edge.
312	Ambient	2.4	Negative.	Major cracking.
315	Ambient	2.4	Negative.	Ten cracks.
313	Ambient	5.3	Negative.	Major cracking.
316	Ambient	5.3	Negative.	Four cracks.
			3/8-Inch Thick	
411	Ambient	1.1	Void (1/4 inch).	Void smaller and X shaped.
414	Ambient	1.1	Negative.	Twelve small cracks.
412	Ambient	2.4	Negative.	About 12 cracks.
415	Ambient	2.4	Negative.	Many large cracks.
413	Ambient	5.3	Negative.	Ten large cracks.
416	Ambient	5.3	Negative.	Twelve small cracks.
			1/8-Inch Thick	
611	375	1.1	One spot (1/32 inch) 1 1/2 inches from edge.	Surface damage; no cracks.

(1) By "negative" is meant that no voids or low-density areas were observed.

Table 2 (Continued)

Disc Number	Impact: Temperature (° F)	Impact: Pressure (psi x 10^{-5})	Inspection: Before Impact	Inspection: After Impact
614	375	1.1	Negative.	Surface damage; no cracks.
612	375	2.4	Six small and many tiny spots.	Holes still present; surface damage.
615	375	2.4	Negative.	Surface damage.
613	375	5.3	Hole in center.	Hole still present; surface damage.
616	375	5.3	Negative.	Surface damage.
			1/4-Inch Thick	
711	375	1.1	Much porosity.	Fewer holes; surface damage.
714	375	1.1	Negative.	Surface damage.
712	375	2.4	Three large spots; one small spot on surface	Spots smaller and surface damage.
715	375	2.4	Negative.	Surface damage.
713	375	5.3	Two small holes.	Spots as before and surface damage.
716	375	5.3	Negative.	Surface damage.
			3/8-Inch Thick	
811	375	1.1	Negative.	Surface damage.
814	375	1.1	Negative.	Surface damage.
812	375	2.4	Negative.	No X ray.
815	375	2.4	Negative.	Surface damage.
813	375	5.3	Three large; many small spots.	No X ray.
816	375	5.3	Negative.	Surface damage.

Tensile Measurements

The impacted discs were cut into four pieces, as shown in Figure 7. One of the large pieces was vacuum annealed at 425° C for 30 hours. Two flat tensile specimens, of the type shown in Figure 8, were machined from the annealed and unannealed large

Table 3

EFFECT OF IMPACT ON SPECIMEN THICKNESS

	Ambient Impact				375° F Impact			
	Wrought		Cast		Wrought		Cast	
Nominal Pressure (psi x 10^{-5})	Average Change in Thickness (mils)	Change in Thickness per Inch (mils)	Average Change in Thickness (mils)	Change in Thickness per Inch (mils)	Average Change in Thickness (mils)	Change in Thickness per Inch (mils)	Average Change in Thickness (mils)	Change in Thickness per Inch (mils)
				1/16-Inch Thick				
1.1	- 1.5	-24			- 1.6	-25.6		
2.4	- 1.7	-27.2			- 3.0	-48.0		
5.3	- 2.2	-35.2			- 3.1	-49.6		
				1/8-Inch Thick				
1.1	- 2.1	-16.8	- 2.9	-23.2	- 3.6	-28.8		
2.4	- 3.0	-24.0	- 0.5	- 4.0	- 5.5	-44.0	- 4.0	-32.0
5.3	- 3.5	-28.0	- 3.7	-29.6	- 6.5	-52.0	- 6.6	-52.8
				1/4-Inch Thick				
1.1	- 5.9	-23.6	- 4.6	-19.2	- 9.4	-39.6	- 6.5	-26.0
2.4	- 8.4	-34.4	- 6.3	-25.2	-12.8	-51.2	- 7.9	-31.6
5.3	- 9.6	-38.4	- 7.3	-29.2	-13.6	-54.4	- 9.7	-38.8
				3/8-Inch Thick				
1.1	- 8.5	-22.7	-11.2	-29.9	-14.8	-39.5	-10.8	-28.8
2.4	-13.0	-34.7	- 9.9	-26.4	-17.6	-47.0	-13.6	-36.3
5.3	-11.6	-30.9	-12.3	-32.4	-23.0	-61.4	-15.9	-42.4

pieces.[b] All specimens except the 1/16-inch-thick specimens were machined to a nominal 0.100-inch thickness and tested using a strain rate of about 0.005 inch/inch-minute up to yield and a crosshead speed equivalent to about 0.15 inch/inch-minute after yield. The yield strength was determined by the use of a constant 26,000,000-psi modulus. The tensile properties of the wrought uranium as salt annealed and as vacuum annealed are given in Table 4 and appear to be typical of hot-rolled, high-purity material that has been given a marginal to inadequate vacuum heat treatment to develop maximum properties. The tensile properties of this wrought material in the as-impacted and impacted-plus-vacuum-heat-treated conditions are given in Tables 5 and 6 for ambient and 375° F impacting, respectively. Again, the amount of vacuum heat treatment was insufficient to fully develop the high-elongation properties.

(b) When comparing the tensile data taken from these flat specimens with other uranium data taken from round specimens, the yield strengths of the flat specimens should be reduced by 3000 psi (for a fixed 26,000,000-psi modulus) and the percent elongation increased 4% to compensate for the known bias between the round and flat uranium specimens for 0.100-inch-thick flat specimens.

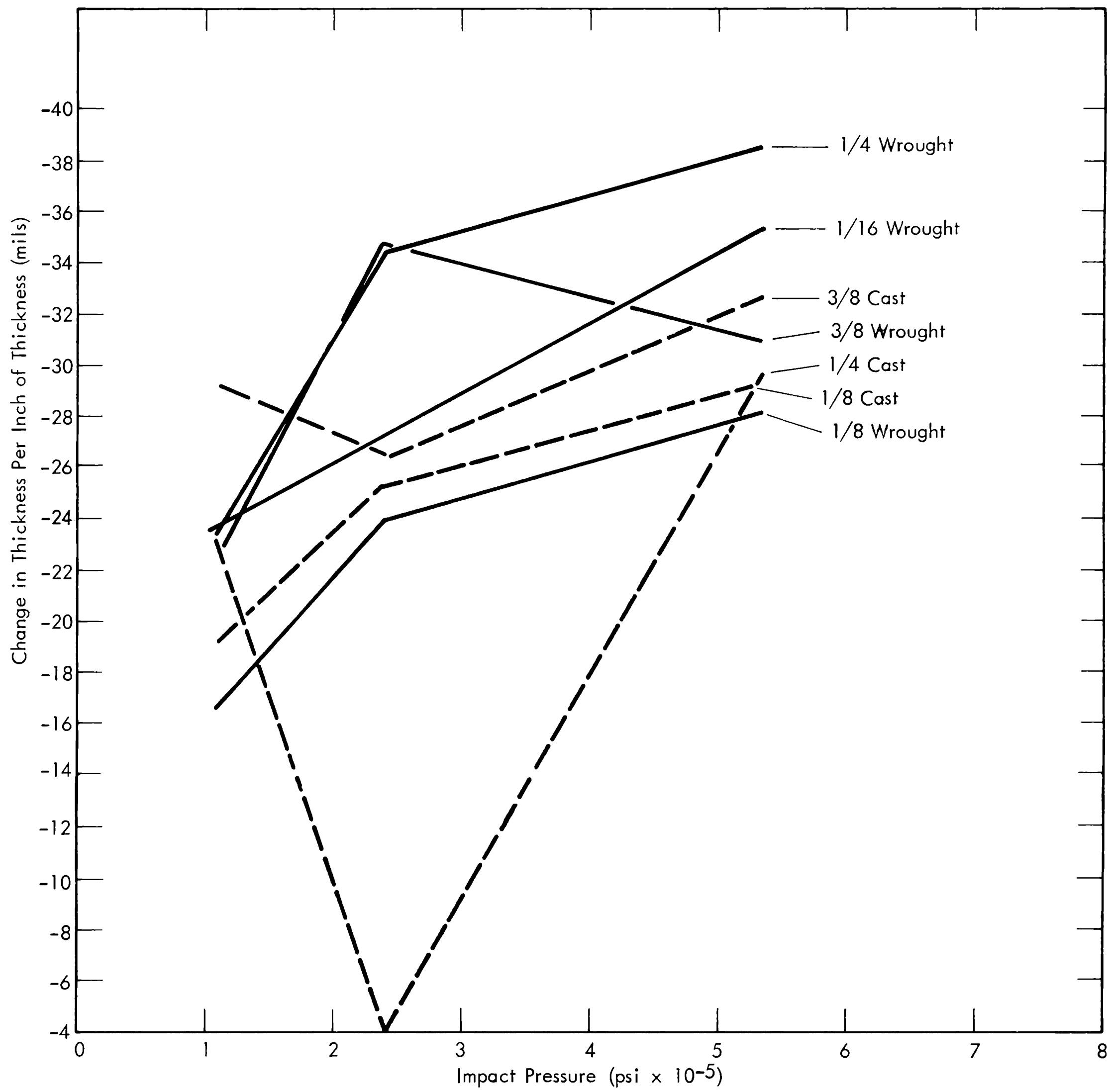


Figure 5. RELATIVE CHANGE IN URANIUM THICKNESS WHEN IMPACTED AT AMBIENT TEMPERATURE. (Data Taken from Table 3)

The tensile properties of the cast uranium used in the experiment in both the as-cast and the vacuum-heat-treated conditions are listed in Table 7. The tensile properties of the cast uranium in the as-impacted and the impacted-plus-vacuum-stress-relieved conditions are listed in Tables 8 and 9 for ambient and 375° F impacting, respectively. The more significant of this data are presented as graphs on the pages that follow. These graphs also illustrate the effect of the impact pressure upon the tensile test results.

Wrought Uranium

Figures 9 and 10 show that the tensile strengths of the wrought uranium increased rapidly as the impact pressure increased and reached a maximum at the middle impact pressure with little change at the highest impact pressure.

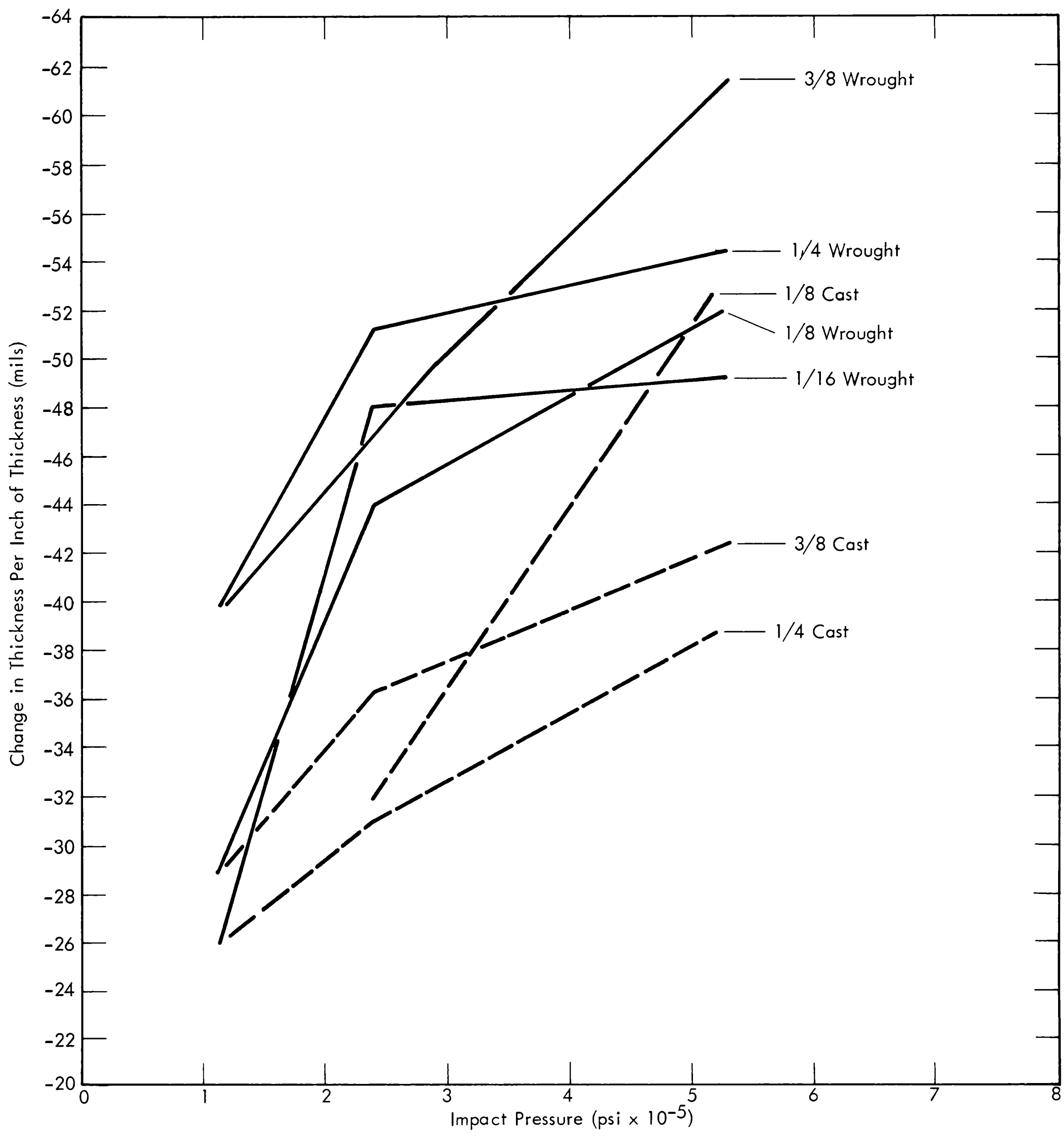


Figure 6. RELATIVE CHANGE IN URANIUM THICKNESS WHEN IMPACTED AT 375° F. (Data Taken from Table 3)

When wrought uranium was vacuum annealed it was dehydrogenated. Elongation of high-purity uranium increases as the hydrogen content decreases. Hydrogen is removed from the metal by diffusion through the metal and, therefore, the time required to produce high-elongation uranium is roughly dependent upon the second power of the plate thickness. The variability in the elongation of the annealed wrought uranium indicated that the 1/16-inch sheet was at the maximum elongation, the 1/8-inch sheet was approaching it, the 1/4-inch plate was definitely marginal, and the 3/8-inch plate was well under the maximum elongation.

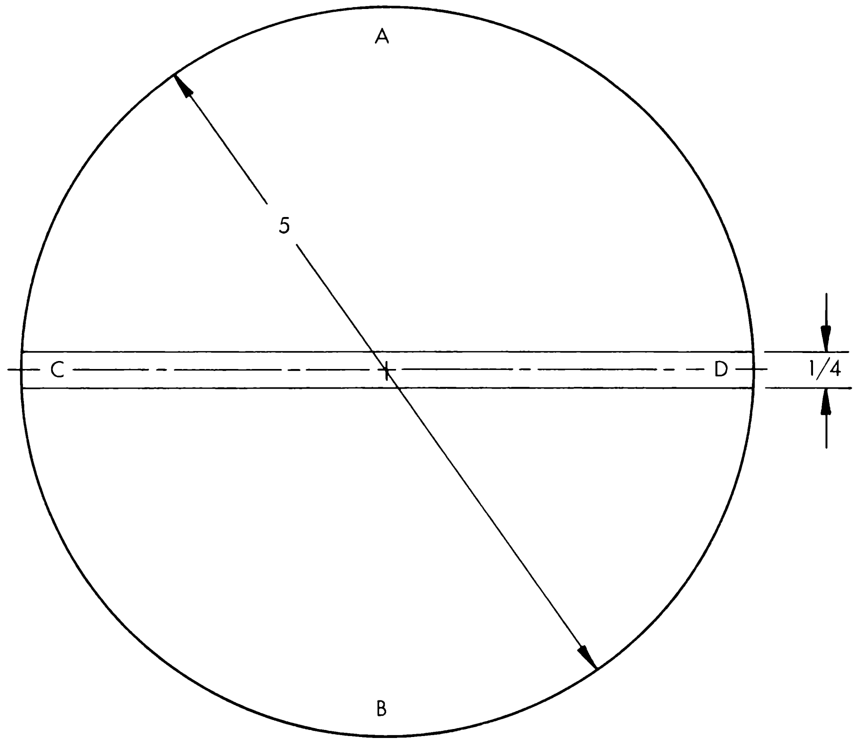


Figure 7. DISC LAYOUT PATTERN.

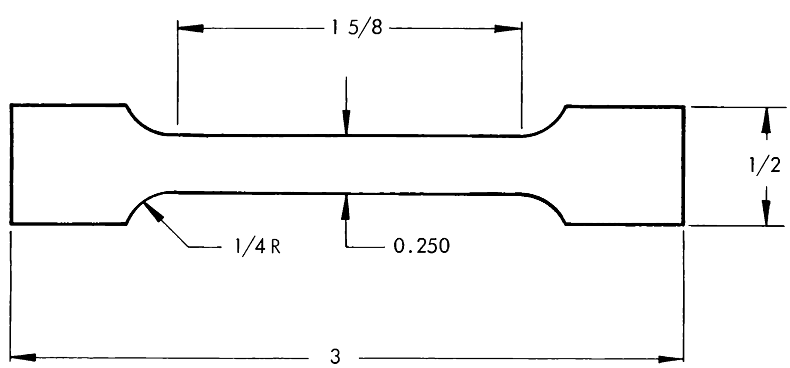


Figure 8. THREE-INCH FLAT TENSILE SPECIMEN. (Thickness – 0.100 Inch)

Figures 11 and 12 show the effect of the 375° F impacting and subsequent vacuum heat treatment upon the ultimate and yielded strengths of wrought uranium. The origins on these curves are for vacuum-annealed material. As shown, the yield strength of the annealed material is lower than the impacted yield strength. The behavior of the 1/16-inch material was strange throughout this work. First, compared to the other material, it had a low strength which may be partially attributable to the test specimens used. Also, it did not impact to as high a strength as the rest.

Table 4

TENSILE PROPERTIES OF WROUGHT URANIUM BEFORE IMPACTING

Disc Thickness (inch)	As Salt Annealed Average(1)	As Salt Annealed Range	As Vacuum Heat Treated Average(1)	As Vacuum Heat Treated Range
		Ultimate Tensile Strength (psi x 10^{-3})		
1/16	92.62	89.5 - 95.2	108.10	106 - 110.3
1/8	95.02	92.0 - 98.5	112.77	108.1 - 120.5
1/4	91.50 (6)	71.2 - 116.6	116.71	108.6 - 124.9
3/8	93.23 (6)	88.0 - 99.8	102.70 (6)	93.0 - 108.4
		Yield Strength (psi x 10^{-3})		
1/16	26.23	20.6 - 31.1	20.82	15.3 - 26.6
1/8	32	15.7 - 47.8	28.35	19.3 - 33
1/4	41.67 (6)	38.1 - 45.5	37.07	28.3 - 42.7
3/8	31.31 (6)	22.3 - 41.3	34.71	26 - 49.9
		Elongation (%)		
1/16	15.5	12 - 19.5	40.9	38 - 45
1/8	12	6 - 17	37.5	29.5 - 43
1/4	8.5 (6)	5 - 12	36.5	24.5 - 47
3/8	10.5 (6)	4 - 16	13	4 - 20
		Reduction in Area (%)		
1/16	15.4	11.3 - 18.9	43.8	38.3 - 51
1/8	11.6	9.2 - 13.8	45	39.2 - 51.4
1/4	8.3	5 - 12.7	40.1	27.9 - 53.6
3/8	8.8	3.3 - 12.2	11.5	3.5 - 18.7

(1) Based on average of eight tests, unless otherwise indicated.

Figures 13 and 14 show the effect of ambient temperature and 375° F impacting on the ductility of uranium both with and without vacuum annealing. The salt anneal reduced the elongation and reduction in area from 10 to 15%, and is used on parts for improved machinability. Vacuum annealing is used where ductility is important. The impacting of this material at low pressure decreases both the elongation and reduction in area, but at the higher impact pressures the structure is strained and these properties are at least partially recovered. This situation is true for the warm impacting. Although the vacuum heat-treating time was insufficient to demonstrate this conclusively on the thicker parts, the vacuum heat treatment produced high ductility at all impact levels.

Evaluation of Impacting Uranium

While each plate thickness had different starting properties, for convenience in comparing the data, property values have been selected from each figure that are typical for all plate thicknesses. These values are listed in Tables 10 and 11 for wrought

Table 5

TENSILE PROPERTIES OF WROUGHT URANIUM IMPACTED AT AMBIENT TEMPERATURE

Disc Thickness (inch)	Impacted at 1.1×10^5 psi: As Impacted, Average(1)	Impacted at 1.1×10^5 psi: As Impacted, Range	Impacted at 1.1×10^5 psi: Plus Vacuum Heat Treatment, Average(1)	Impacted at 1.1×10^5 psi: Plus Vacuum Heat Treatment, Range	Impacted at 2.4×10^5 psi: As Impacted, Average(1)	Impacted at 2.4×10^5 psi: As Impacted, Range	Impacted at 2.4×10^5 psi: Plus Vacuum Heat Treatment, Average(1)	Impacted at 2.4×10^5 psi: Plus Vacuum Heat Treatment, Range	Impacted at 5.3×10^5 psi: As Impacted, Average(1)	Impacted at 5.3×10^5 psi: As Impacted, Range	Impacted at 5.3×10^5 psi: Plus Vacuum Heat Treatment, Average(1)	Impacted at 5.3×10^5 psi: Plus Vacuum Heat Treatment, Range
Ultimate Tensile Strength (psi $\times 10^{-3}$)												
1/16	104.87	101.6 - 110.8	111.18	106.9 - 114.5	110.62	109.2 - 112.5	110.97	107.9 - 112.7	110.11	106.8 - 112.2	112.17	111.2 - 113.4
1/8	108.24	104.2 - 112.2	116.93	113.5 - 120.3	113.40	108.0 - 117.2	119.26	116.9 - 120.7	113.14	106.4 - 123.9	110.63	100.8 - 115.4
1/4	95.51(3)	94.4 - 97.5	110.24	107.4 - 112.2	113.00	103.5 - 122.0	117.01	110.6 - 121.7	109.35	93.4 - 126.0	115.75	110.4 - 121.7
3/8	101.44(3)	94.9 - 105.9	105.29	95.3 - 112.9	102.34	96.5 - 106.9	104.76(3)	102.1 - 108.2	102.36(3)	100.8 - 103.8	110.24	103.1 - 114.6
Yield Strength (psi $\times 10^{-3}$)												
1/16	60.53	49.5 - 70.8	30.08	27.1 - 34.9	65.30	59.0 - 76.9	26.75	22.1 - 31.3	65.83	59.7 - 70.8	34.66	33.6 - 36.8
1/8	74.35	62.7 - 88.7	42.56	36.9 - 45.5	76.98	61.1 - 89.9	42.36	39.1 - 51.0	70.52	61.8 - 77.6	44.13	41.3 - 46.8
1/4	65.62(3)	59.2 - 71.7	45.88	43.7 - 48.8	82.67	75.3 - 89.0	44.27	39.5 - 46.6	76.53	66.0 - 85.5	44.60	37.9 - 51.6
3/8	93.07(3)	83.6 - 98.4	46.81	42.5 - 50.0	76.08	72.5 - 81.1	49.59(3)	46.1 - 53.7	56.79	52.5 - 80.3	45.45	37.1 - 52.9
Elongation (%)												
1/16	10.5	6.5 - 16.5	39.5 (3)	34 - 48.5	12	7.5 - 16	44	34 - 48	8	7 - 10	44.5	40.5 - 46.5
1/8	5	3.5 - 8	42	40 - 44	2.5	1.5 - 4	31.5	28 - 38	8	4 - 10.5	42.5	33 - 48
1/4	6.5(3)	5 - 8.5	27	19 - 36.5	1.5	0.5 - 2.5	39.5	35.5 - 42	3.5	1 - 8	34	23 - 40
3/8	1.5	0.5 - 2.5	12.5	3.5 - 4.5	1.0	0 - 3.0	12.0	7 - 17	3	1.5 - 4	22.5	14.5 - 37.5
Reduction in Area (%)												
1/16	9.6	8.6 - 10.4	41.3	31.5 - 48.2	11.9	7.2 - 15.5	48	41.1 - 57.2	8.4	4.8 - 11.9	47.8	44.0 - 52.6
1/8	4.8	1.8 - 6.4	51.5	46.7 - 58	3.2	1.3 - 5.8	32	27.6 - 37	8.5	4.8 - 11.4	42.1	29 - 47.5
1/4	6.4	4.6 - 8.8	23.9	18.6 - 34.1	3.1	2.5 - 4.1	41.8	38.4 - 47.1	3.9	1.7 - 5.6	36.5	20.9 - 53.9
3/8	1.8	0.7 - 4.0	14.3	7.4 - 20.9	0.8	0.4 - 1.3	12.6	9.4 - 17.1	2.5	0.4 - 4.6	23.3	14.0 - 43.4

(1) Based on average of four tests, unless otherwise indicated.

Table 6

TENSILE PROPERTIES OF WROUGHT URANIUM IMPACTED AT 375° F

Disc Thickness (inch)	Impacted 1.1 x 10^5 psi				Impacted 2.4 x 10^5 psi				Impacted 5.3 x 10^5 psi			
	As Impacted		Plus Vacuum Heat Treatment		As Impacted		Plus Vacuum Heat Treatment		As Impacted		Plus Vacuum Heat Treatment	
	Average(1)	Range	Average(1)	Range	Average(1)	Range	Average(1)	Range	Average(1)	Range	Average(1)	Range
Ultimate Tensile Strength (psi x 10^{-3})												
1/16	112.32	110.4 - 115.0	111.33	110.0 - 113.0	117.01(3)	114.0 - 120.5	113.66	112.8 - 115.3	117.11	109.3 - 123.6	112.01	109.6 - 115.3
1/8	114.5 (2)	112.9 - 116.1	120.22	112.2 - 124.4	120.79	118.5 - 123.1	111.96	110.0 - 113.7	118.07	116.7 - 120.7	117.64	114.8 - 126.0
1/4	105.64	101.4 - 111.1	111.42	109.2 - 113.2	107.80	104.9 - 109.2	112.39	109.7 - 114.1	115.07	107.7 - 121.4	113.17	112.9 - 113.7
3/8	103.86	102.3 - 105.6	107.78	105.0 - 108.9	106.72	100.6 - 113.3	105.2	88.1 - 110.6	107.91	104.3 - 110.0	108.52	105.3 - 110.2
Yield Strength (psi x 10^{-3})												
1/16	62.23	57.9 - 65.0	30.33	22.1 - 39.1	61.52(3)	58.2 - 67.0	36.37	32.9 - 39.8	66.34	56.7 - 74.8	33.15	30.6 - 36.9
1/8	83.58(2)	83.3 - 83.9	37.93	31.7 - 40.9	91.38	84.8 - 97.6	42.67	39.5 - 50.4	89.94	86.7 - 94.0	52.26	47.1 - 58.8
1/4	82.84	78.5 - 87.0	48.16	44.5 - 53.3	72.31	66.2 - 77.7	48.07	46.0 - 51.3	94.06	91.3 - 95.7	48.44	45.5 - 52.6
3/8	69.09	65.0 - 75.6	52.11	50.9 - 53.7	73.64	62.1 - 81.2	55.87	48.3 - 62.0	76.42	76.4 - 77.0	53.01	51.0 - 56.9
Elongation (%)												
1/16	10.5	7 - 14.5	44	43 - 45	15.5 (3)	9.5 - 19	42	38 - 44	17.5	15 - 19.5	42	38.5 - 46.5
1/8	8.5 (2)	8 - 9	38	33 - 40	14	9.5 - 16	39	38 - 40.5	17	15 - 19	42.5	38.5 - 46
1/4	11	8 - 17.5	35.5	19 - 44	9.5	7 - 13	41.5	40 - 43	10.5	6 - 16	38.5	38 - 39
3/8	3.5	2.5 - 4.5	25.75	16 - 33	2	1 - 3	29.5	5.5 - 43	5	3.5 - 6.5	24.5	12.5 - 44
Reduction in Area (%)												
1/16	12.3	10.0 - 15.1	59.9	57.5 - 61.9	14.9 (3)	9.1 - 18.0	53.4	46.9 - 57.7	17.4	15.6 - 19.2	55.5	50.2 - 60.1
1/8	10.1 (2)	10.0 - 10.1	54.0	49.7 - 58.6	17	14.3 - 19.7	59.0	57.4 - 61.8	15.2	12.8 - 17.1	52.2	46.9 - 59.5
1/4	10.4	6.4 - 15.7	40	15.4 - 59.3	10.2	7.1 - 14.4	53.3	49.9 - 59.5	9.9	7.4 - 12.8	56.9	50.9 - 63.7
3/8	2.3	0 - 4.2	27.1	17.5 - 37.0	2.5	1.0 - 3.4	38.6	7.8 - 53.1	5.1	4.1 - 6.9	25.6	13.1 - 46.6

(1) Based on average of four tests, unless otherwise indicated.

Table 7

TENSILE PROPERTIES OF CAST URANIUM BEFORE IMPACTING

Disc Thickness (inch)	As Cast Average(1)	As Cast Range	As Vacuum Heat Treated Average(1)	As Vacuum Heat Treated Range
		Ultimate Tensile Strength (psi x 10^{-3})		
1/8	50.76(4)	46.6 - 58.3	74.59(4)	59.8 - 84.2
1/4	61.33	55.5 - 72.6	82.32(5)	59.7 - 96.8
3/8	62.86	52.1 - 77.7	78.59	60.9 - 95.0
		Yield Strength (psi x 10^{-3})		
1/8	24.85(4)	21.2 - 30.3	22.29	18.4 - 26.7
1/4	30.67	25.0 - 37.8	24.27	19.2 - 46.5
3/8	33.61	24.6 - 40.5	27.67	19.4 - 37.7
		Elongation (%)		
1/8	8.5 (4)	5 - 11.5	11	4 - 12
1/4	6.5	4.5 - 10.5	15.5	10 - 19
3/8	6.5	1.5 - 11.5	9	4 - 14.5
		Reduction in Area (%)		
1/8	12.3 (4)	11 - 12.9	20	10.3 - 32.7
1/4	11.1	6.2 - 15.9	27.8	12.4 - 39.2
3/8	8.2	3.9 - 13.7	15.6	9.7 - 35.3

(1) Based on average of eight tests, unless otherwise indicated.

Table 8

TENSILE PROPERTIES OF CAST URANIUM IMPACTED AT AMBIENT TEMPERATURE

Disc Thickness (inch)	Impacted at 1.1 x 10^5 psi Average(1)	Impacted at 1.1 x 10^5 psi Range	Impacted at 2.4 x 10^5 psi Average(1)	Impacted at 2.4 x 10^5 psi Range	Impacted at 5.3 x 10^5 psi Average(1)	Impacted at 5.3 x 10^5 psi Range
			Ultimate Tensile Strength (psi x 10^{-3})			
1/8	76.95(2)	75.5 - 78.4	72.09	66.7 - 79.6	65.88(3)	59.5 - 77.9
1/4	58.85(3)	56.5 - 60.8	74.97	69.8 - 82.9	70.61(3)	55.0 - 84.8
3/8	83.43(3)	63.2 - 109.3	76.27(3)	65.6 - 84.7	70.80(3)	61.4 - 85.0
			Yield Strength (psi x 10^{-3})			
1/8	40.18(2)	35.0 - 40.2	55.41(3)	45.8 - 64.2	42.01	28.4 - 69.1
1/4	52.74(3)	50.4 - 55.1	68.75	55.0 - 77.1	58.06	55.0 - 65.4
3/8	59.77(3)	55.3 - 75.6	54.37(3)	46.9 - 58.2	55.88(3)	44.3 - 63.2
			Elongation (%)			
1/8	4 (2)	4	2.5	1.5 - 3.5	1	0.5 - 1.5
1/4	3 (3)	1 - 4	2.0	0.5 - 2.5	3 (3)	1 - 4
3/8	1.5 (3)	1 - 3	3	2 - 4	1.5	1 - 2
			Reduction in Area (%)			
1/8	4.1 (2)	0.4 - 7.8	6.2	4.8 - 7.1	5.8	1.1 - 10
1/4	3.6 (3)	2.0 - 5.6	4.2 (3)	2 - 6.3	1.7	0 - 3.8
3/8	2.9	0.4 - 4.5	4.6 (3)	1.5 - 8.2	2.8	0.8 - 5.6

(1) Based on average of four tests, unless otherwise indicated.

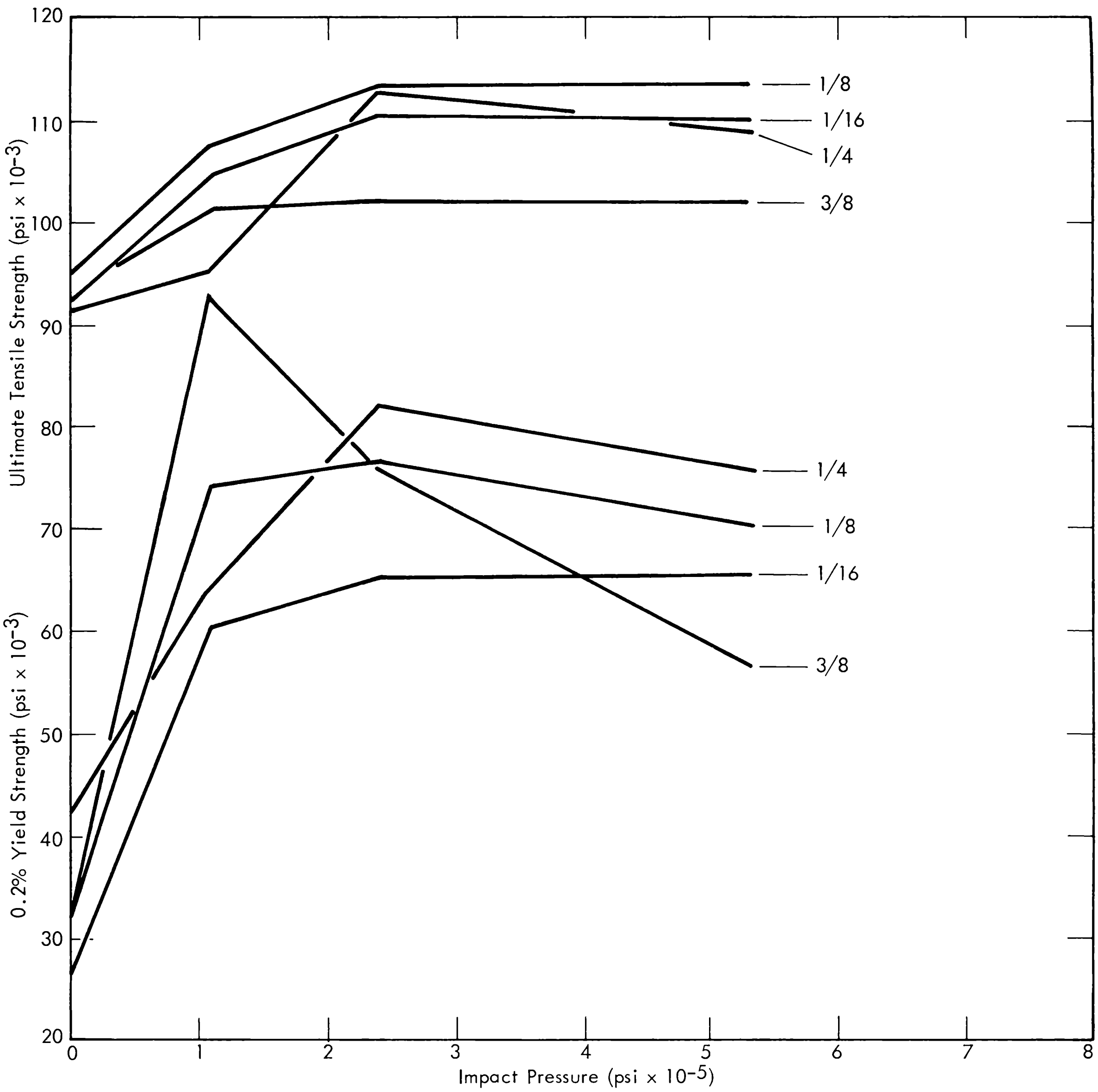


Figure 9. EFFECT OF AMBIENT-TEMPERATURE IMPACT ON THE TENSILE PROPERTIES OF WROUGHT URANIUM. (Data Taken from Tables 4 and 5)

and cast materials, respectively. Tables 12 and 13 compare the effect of the vacuum heat treatment with the original conditions and with the typical warm impacted and vacuum-annealed condition for wrought and cast uranium. These data show that impacting makes a significant increase in the yield strength for both materials. Impacting changed the mechanics of plastic deformation and the reduction in area was significantly increased. The effect is discussed later in the report.

Many wrought uranium parts made at Y-12 are hot rolled, warm formed, and finally recrystallized to make them stable when machined. The wrought plate from which these discs were made was salt annealed to reproduce the standard procedure.

Table 9

TENSILE PROPERTIES OF CAST URANIUM IMPACTED AT 375° F

Disc Thickness (inch)	Impacted at 1.1×10^5 psi				Impacted at 2.4×10^5 psi				Impacted at 5.3×10^5 psi			
	As Impacted		Plus Vacuum Heat Treated		As Impacted		Plus Vacuum Heat Treated		As Impacted		Plus Vacuum Heat Treated	
	Average(1)	Range	Average(1)	Range	Average(1)	Range	Average(1)	Range	Average(1)	Range	Average(1)	Range
Ultimate Tensile Strength (psi $\times 10^{-3}$)												
1/8	80.23	73.8 - 91.3	96.55	84.7 - 111.1	86.36	70.6 - 98.2	100.25	91.7 - 108.0	93.24	84.8 - 101.1	104.56	91.2 - 112.6
1/4	75.94	65.5 - 92.2	77.77	74.5 - 83.4	94.84(2)	93.4 - 96.2	92.52(3)	79.2 - 110.8	93.90	84.6 - 99.8	100.31	94.2 - 107.0
3/8	79.18	66.5 - 91.5	89.09	78.3 - 104.4	78.90	58.8 - 88.7	89.49	77.9 - 102.4	86.83	75.8 - 92.8	90.75	86.1 - 92.5
Yield Strength (psi $\times 10^{-3}$)												
1/8	32.63	17.5 - 56.3	40.11	33.4 - 52.2	53.51	43.3 - 56.8	43.38	39.7 - 48.5	77.41	67.9 - 86.0	43.03	37.8 - 48.4
1/4	67.95	54.3 - 81.8	40.47	35.8 - 45.0	84.17(2)	83.1 - 85.3	44.87	38.1 - 51.7	64.95	52.1 - 84.7	48.88	29.8 - 63.1
3/8	61.17	39.2 - 90.2	36.58	31.2 - 41.8	49.28	40.2 - 56.8	35.49	30.2 - 43.2	61.79	48.6 - 74.8	40.64	32.5 - 47.1
Elongation (%)												
1/8	4.5	1.5 - 7	10	8 - 12.5	3	1 - 5	14	7.5 - 18.5	2.5	2 - 4	8.5	7 - 10
1/4	3	0.5 - 6	7	4.5 - 10	5.5 (2)	3.5 - 7.5	6	2 - 10	4	2.5 - 5.5	9.5	2 - 16
3/8	2.5	1 - 4.5	7.5	5 - 10	2	1 - 3.5	9.25	6.5 - 13	3	1.5 - 5	5.5	4 - 8.5
Reduction in Area (%)												
1/8	9.4	6.8 - 12.8	13.8	11.9 - 15.4	7.3	5.6 - 10.7	25.7	15 - 40.8	5	2.2 - 9.8	20	11.5 - 29.4
1/4	6.1	4.3 - 7.1	10.4	8.9 - 12.1	7.4 (2)	4.4 - 10.4	13.1	2.5 - 25.3	8.6	3.0 - 16.2	16.2	4.5 - 35.5
3/8	6.1	3.2 - 7.7	15.9	7.9 - 24.1	2.6	0 - 7.5	13.1	6.3 - 20.1	9.0	3.2 - 12.2	19.6	10.1 - 37.1

(1) Based on average of four tests, unless otherwise indicated.

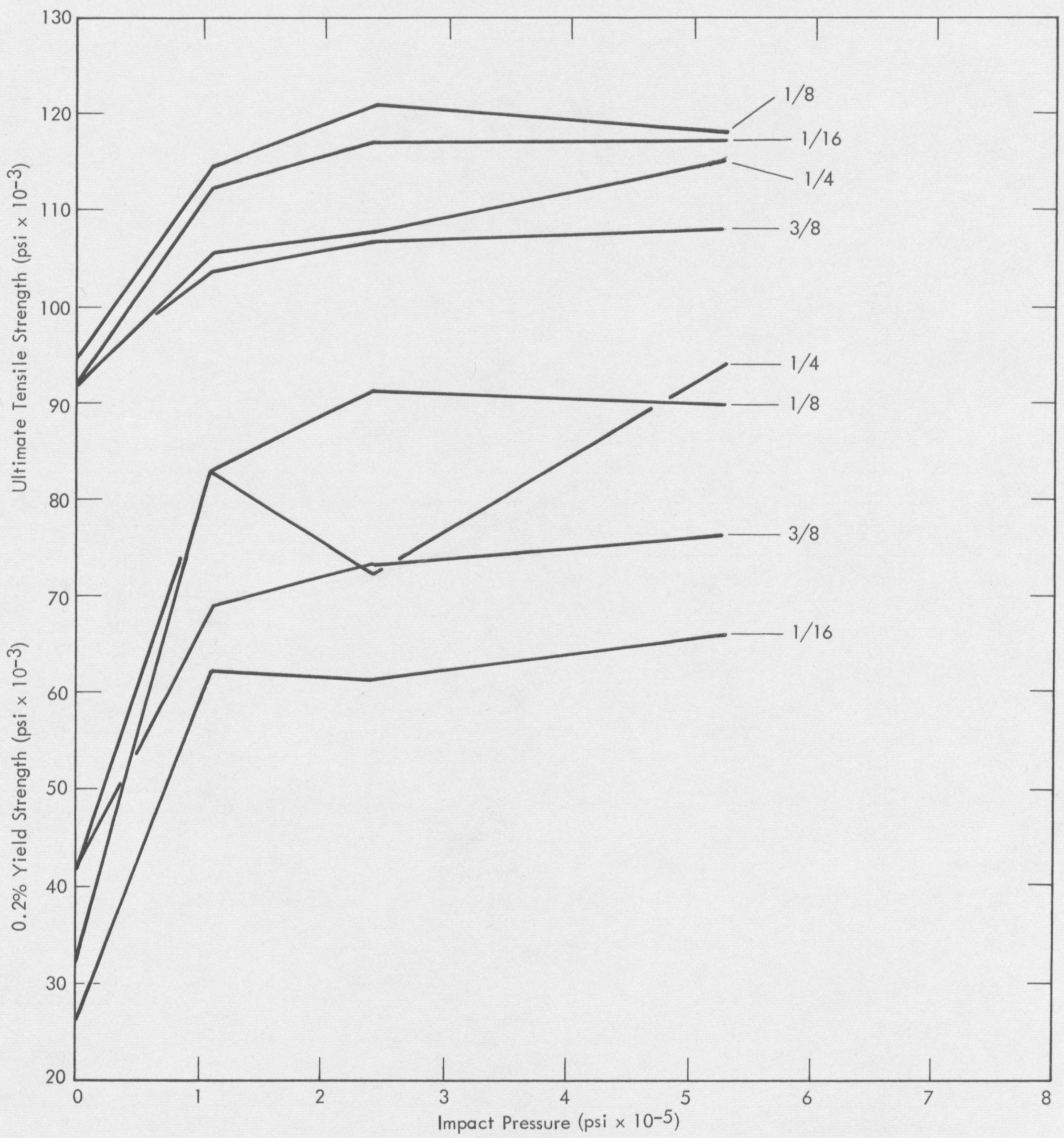


Figure 10. EFFECT OF 375°F IMPACT ON THE TENSILE PROPERTIES OF WROUGHT URANIUM. (Data Taken from Tables 4 and 5)

Cast Uranium

Figures 15 through 18 show that explosive impacting made greater proportional increases in the tensile properties of cast material than in wrought material. Figure 17 shows that the strength of ambient-temperature-impacted, cast uranium increased even though the material was damaged. The decrease in the strength of the cold impacted material at high impacts was believed to be caused by the rupturing. From Figure 16 it can be seen that the ultimate strength of the warm impacted uranium

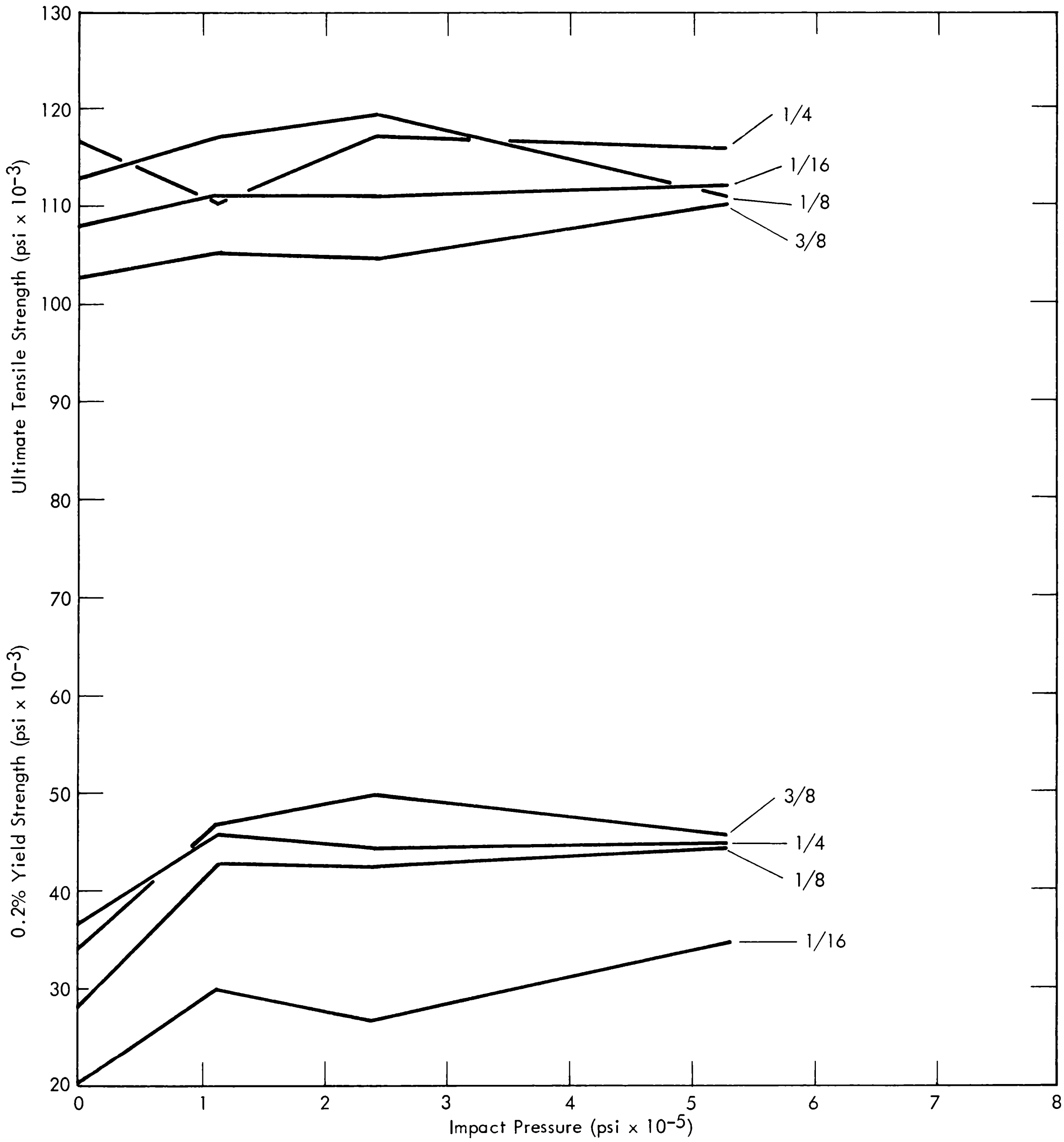


Figure 11. EFFECT OF AMBIENT-TEMPERATURE IMPACT AND VACUUM HEAT TREATMENT ON THE TENSILE PROPERTIES OF WROUGHT URANIUM. (Data Taken from Tables 4 and 5)

continued to increase while the yield strength in two out of three cases peaked. Figure 17 indicates that vacuum heat treatment maintained most of the impacted ultimate strength but reduced the yield strength. A study of Figure 18 reveals that the ductility of the cast material was increased by the vacuum heat treatment, but the material did not absorb enough work to develop the high elongation possible for wrought material.

It has been noted that when a high-elongation uranium tensile specimen ruptures, the cross section of the broken specimens exhibits a marked change in shape. For

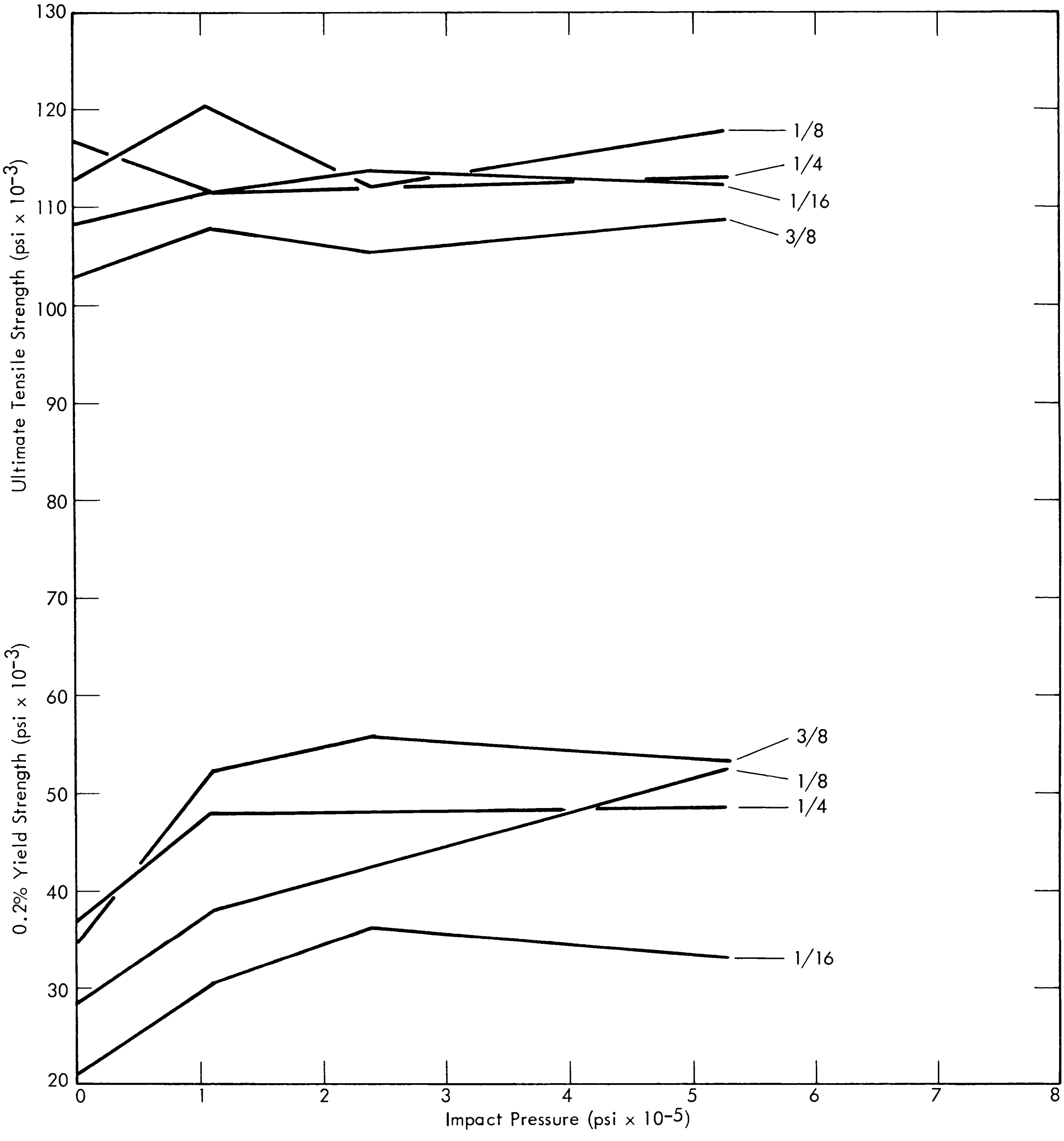


Figure 12. **EFFECT OF 375°F IMPACT AND VACUUM HEAT TREATMENT ON THE TENSILE PROPERTIES OF WROUGHT URANIUM.** (Data Taken from Tables 4 and 6)

instance, a round specimen changes to an oval shape, and, generally, the greater the elongation the greater the ratio of the major axis to the minor axis of this oval. Furthermore, the minor axis is always perpendicular to the surface of the plate. This phenomenon has been observed in Zircoloy-2 and other materials.[8] Beta quenching uranium has, in some cases, reduced this type of directional specimen fracture. Explosive impacting has also reduced this deformation directionality. Table 14 is a tabulation of an analysis based upon a directionality ratio (a ratio of the percent reduction in width at the neck to the percent reduction in thickness).

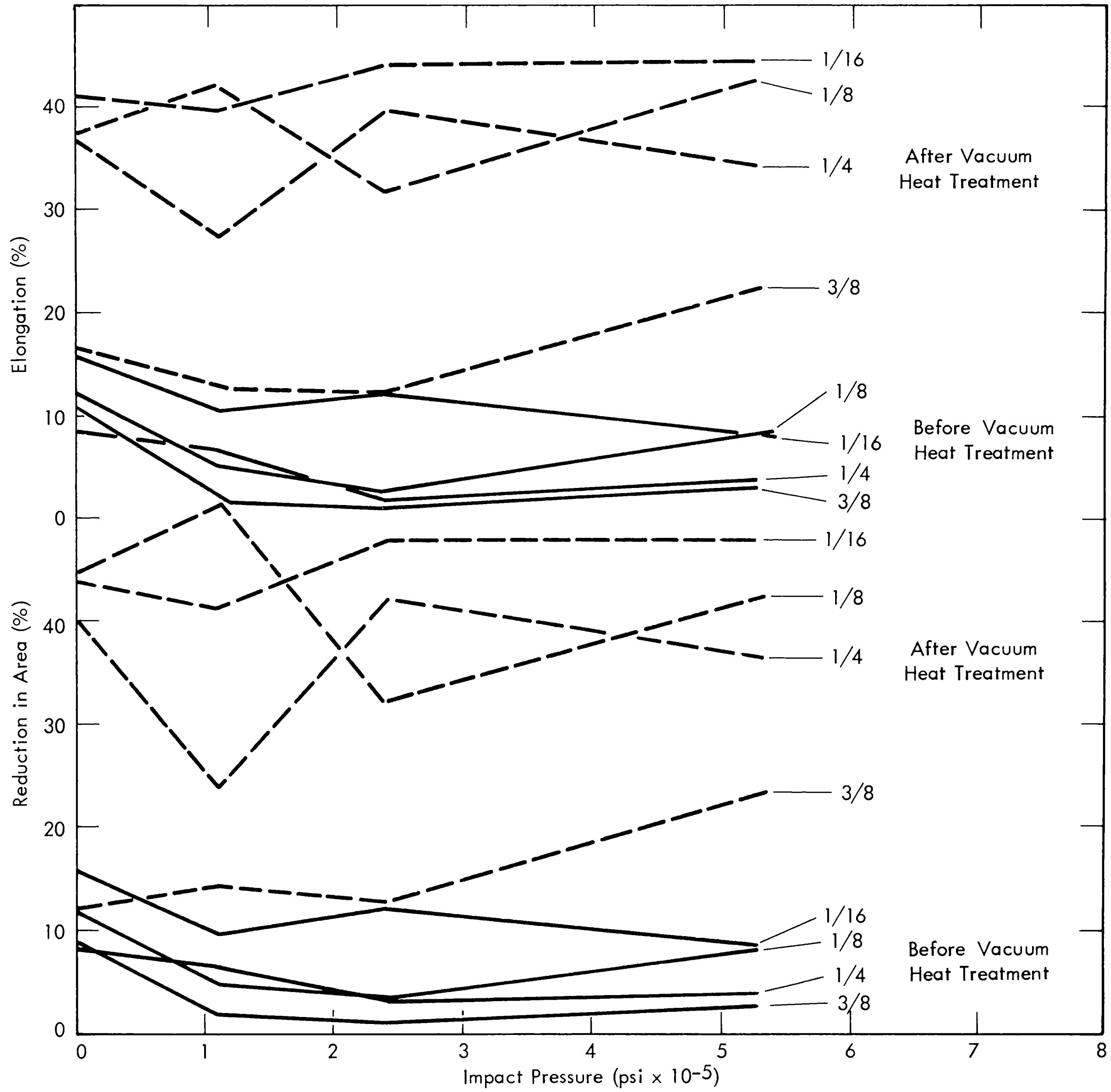


Figure 13. **EFFECT OF AMBIENT-TEMPERATURE IMPACT ON THE DUCTILITY OF WROUGHT URANIUM.** (Data Taken from Tables 4 and 5)

Only the vacuum heat-treated material, 1/16 to 1/4 inch in thickness, where substantial ductility was found was analyzed. As shown in the table, the ratio was found to be about 3:1 for unimpacted material and about 2:1 for impacted material. There was little difference between the material impacted at 2.4 x 10^5 psi and that impacted at 5.3 x 10^5 psi. The effect was more consistent at the 1.1 x 10^5 psi impact level, and a lower directionality ratio was accompanied by a higher percent reduction in area. This effect was more consistent for the warm impacted specimens.

Metallographic Studies

The photomicrograph in Figure 19 shows the typical wrought salt-annealed structure at 250X magnification. The structure is equiaxed with some internal strain lines.

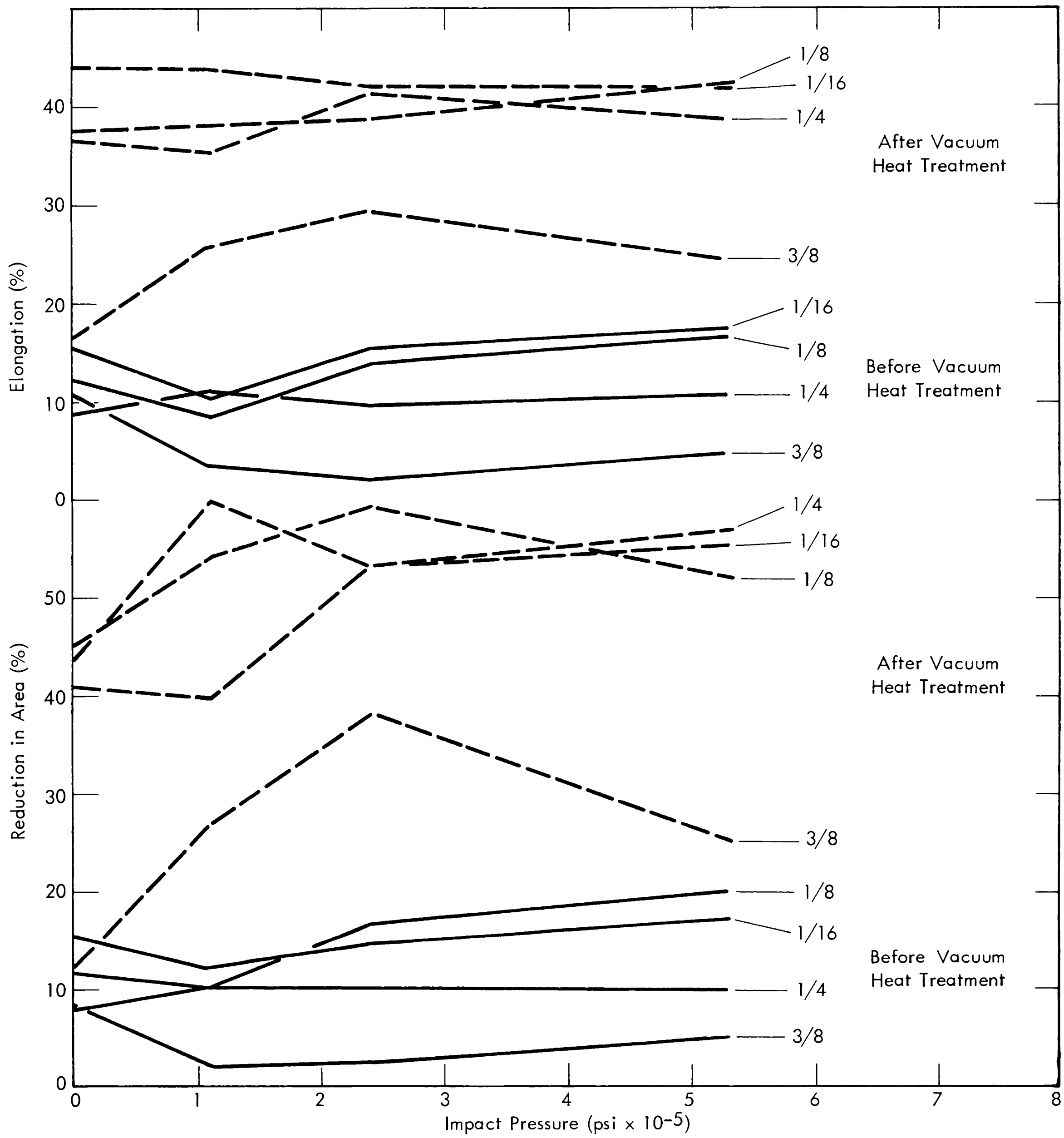


Figure 14. EFFECT OF 375°F IMPACT ON THE DUCTILITY OF WROUGHT URANIUM. (Data Taken from Tables 4 and 6)

Figure 20 reveals that impacting appreciably increased the twinning in this material while Figure 21 shows that an anneal at 620° C essentially recrystallized the material with slight grain growth. It was, therefore, assumed that the induced strain generally exceeded the critical strain of 2 to 6% which would have produced large grain growth.

Figures 22 through 24 are photomicrographs that show the structure of the impacted cast material after salt annealing. As indicated, the salt anneal isolated patches of small-grain recrystallized material. These grain sizes appear smaller than those of

Table 10

TYPICAL TENSILE PROPERTIES FOR IMPACTED WROUGHT URANIUM

	Original	Ambient Impacted		Warm Impacted	
	Salt Annealed	As Impacted	Vacuum Heat Treated	As Impacted	Vacuum Heat Treated
Ultimate Tensile Strength (psi)	92,000	112,000	112,000	112,000	112,000
0.2 Percent Yield Strength (psi)	32,000	72,000	45,000	78,000	45,000
Elongation (%)	12	5	40	10	40
Reduction in Area (%)	11	5	40	10	55

Table 11

TYPICAL TENSILE PROPERTIES FOR IMPACTED CAST URANIUM

	Original	Ambient Impacted		Warm Impacted	
	Salt Annealed	As Impacted	Vacuum Heat Treated	As Impacted	Vacuum Heat Treated
Ultimate Tensile Strength (psi)	57,000	75,000	-	87,000	92,000
0.2 Percent Yield Strength (psi)	30,000	55,000	-	56,000	40,000
Elongation (%)	7	-	-	-	10
Reduction in Area (%)	11	-	-	-	15

Table 12

COMPARISON OF WROUGHT URANIUM

	Salt Annealed	Vacuum Annealed	Typical Maximum Warm Impacted and Vacuum Annealed
Ultimate Tensile Strength (psi)	92,000	110,000	112,000
0.2 Percent Yield Strength (psi)	32,000	30,000	45,000
Elongation (%)	12	38	40
Reduction in Area (%)	11	43	55

Table 13

COMPARISON OF CAST URANIUM

	Cast	Vacuum Annealed	Typical Maximum Warm Impacted and Vacuum Annealed
Ultimate Tensile Strength (psi)	57,000	78,000	92,000
0.2 Percent Yield Strength (psi)	30,000	24,000	40,000
Elongation (%)	7	12	10
Reduction in Area (%)	11	21	15

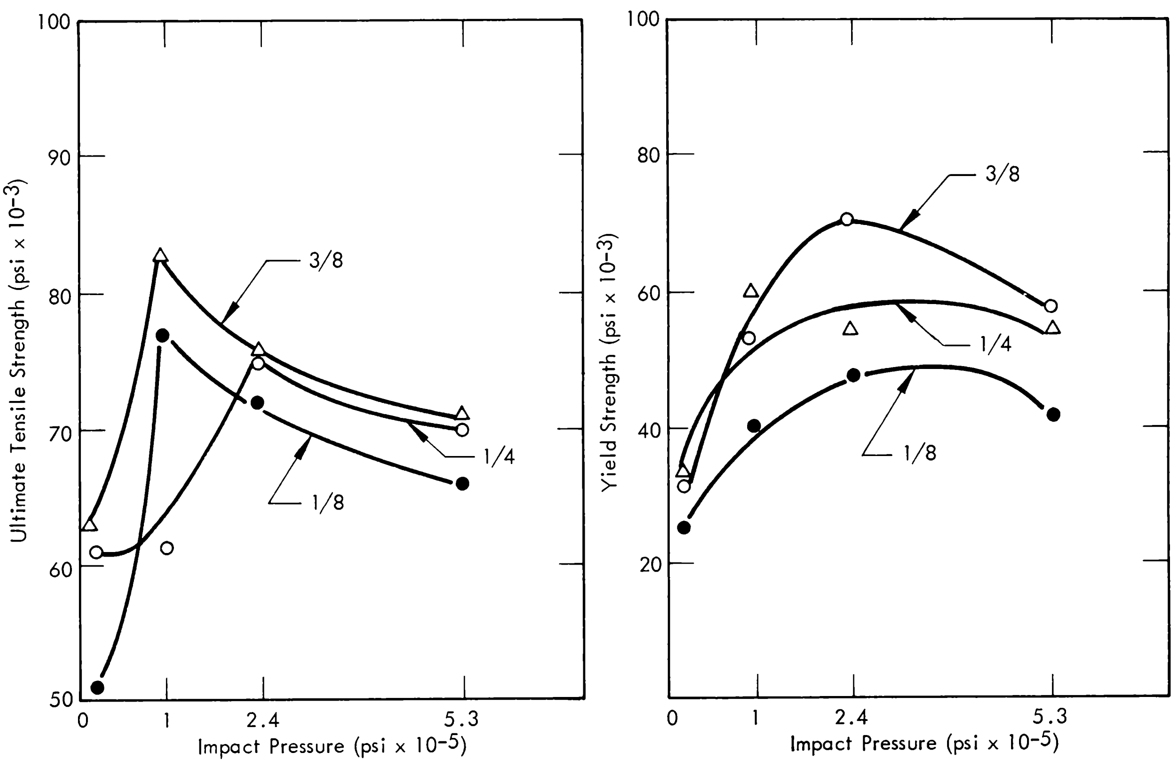


Figure 15. EFFECT OF AMBIENT-TEMPERATURE IMPACT ON THE TENSILE PROPERTIES OF CAST URANIUM. (1/8, 1/4, and 3/8-Inch Thick)

wrought uranium. Orientation of the patches did not show any consistent relation to the impacting direction. Surface areas of the cast impacted and annealed specimens frequently showed this effect, with patches of irregular locations in the cross section as well. From 20 to 40% of the area of cast discs was apparently worked sufficiently by impacting to recrystallize by annealing. The larger areas were found in the thinner discs. No effort was made to investigate the effect of repeated impacting and annealing.

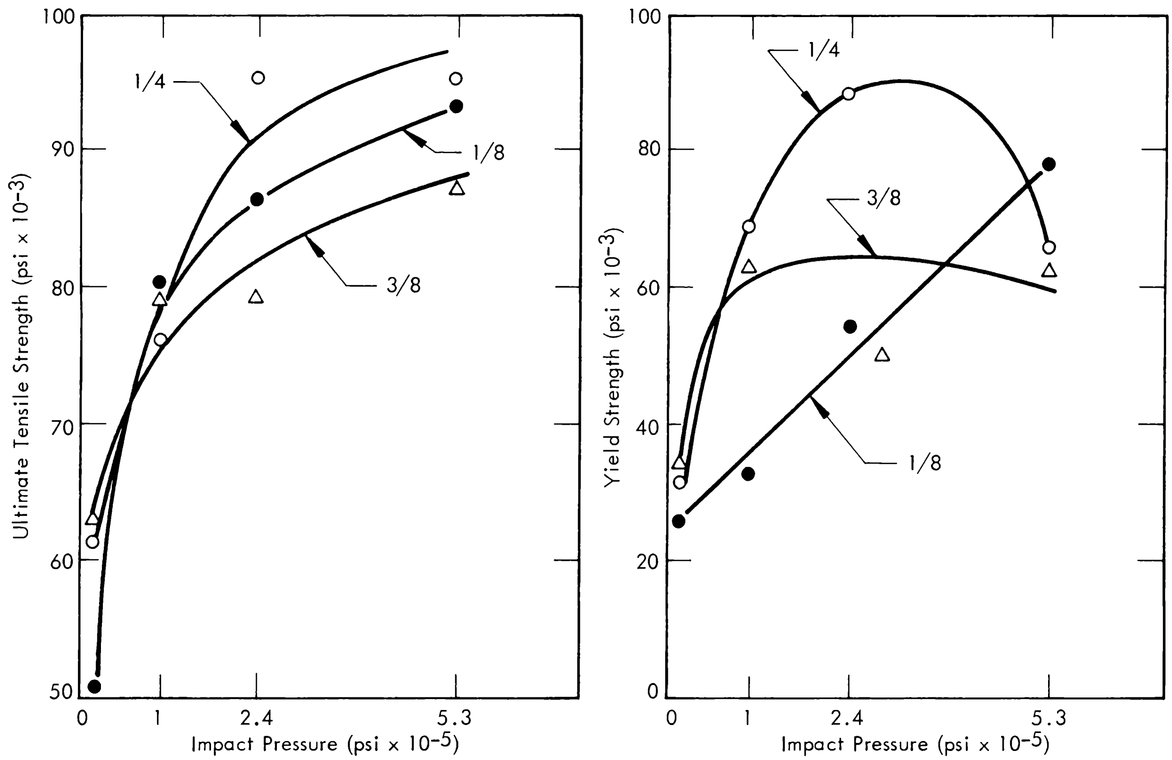


Figure 16. EFFECT OF 375°F IMPACT ON THE TENSILE PROPERTIES OF CAST URANIUM. (1/8, 1/4, and 3/8-Inch Thick)

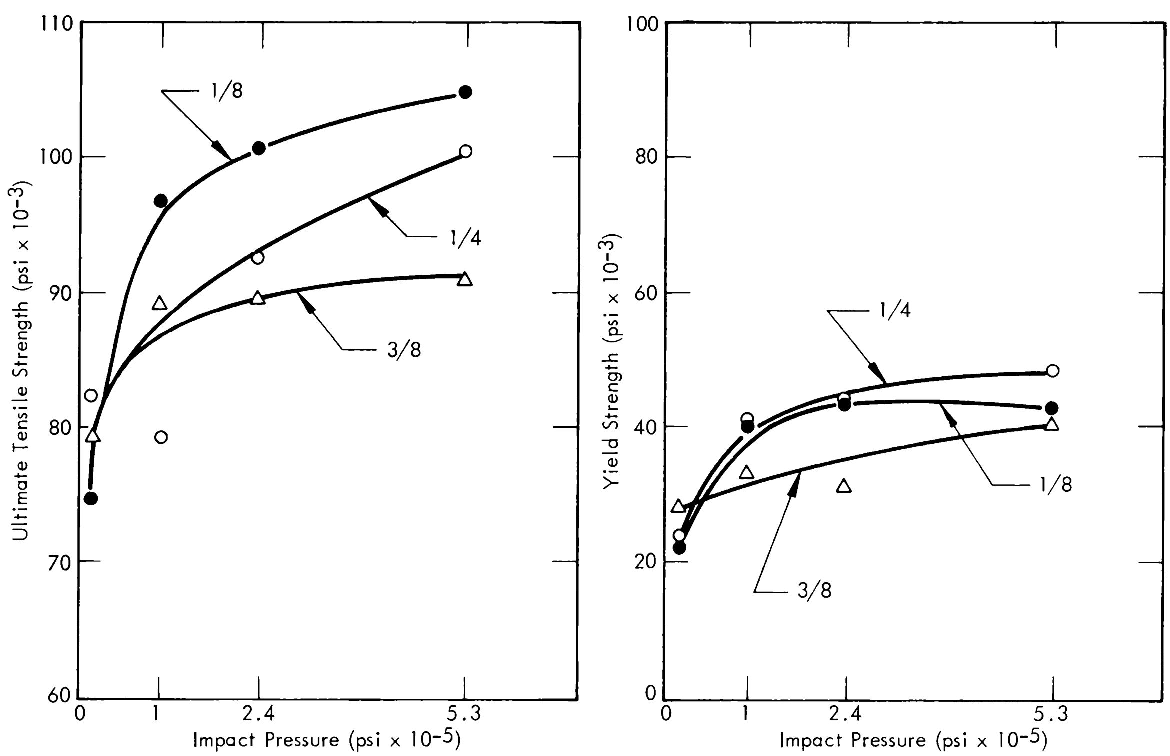


Figure 17. EFFECT OF 375°F IMPACT AND VACUUM HEAT TREATMENT ON THE TENSILE PROPERTIES OF CAST URANIUM. (1/8, 1/4, and 3/8-Inch Thick)

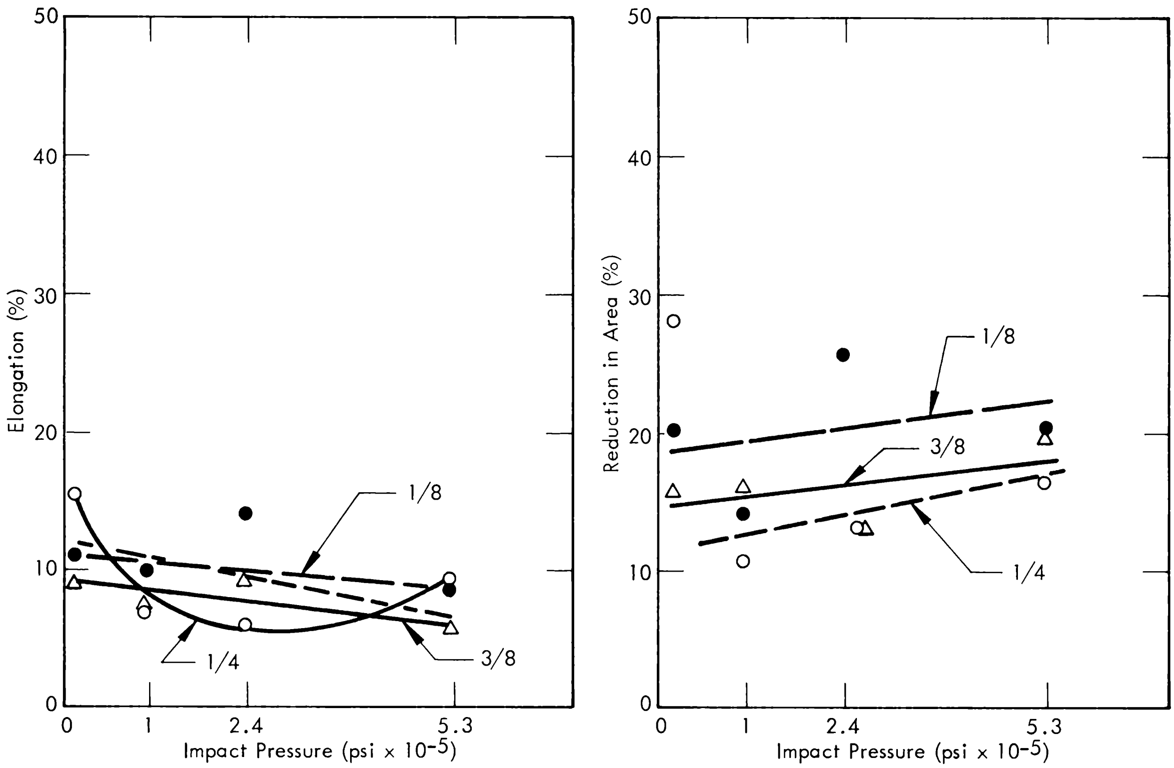


Figure 18. EFFECT OF 375°F IMPACT AND VACUUM HEAT TREATMENT ON THE DUCTILITY OF CAST URANIUM. (1/8, 1/4, and 3/8-Inch Thick)

Table 14

EFFECT OF IMPACTING ON THE DIRECTIONALITY RATIO AT THE IMPACTS GIVEN

Material Thickness (inch)	Impact Pressures (psi x 10^{-5}) 0	1.1	2.4	5.3
		Ambient Temperature		
1/16	3.3(1)	2.1	2.3	1.9
1/8	3.2	1.8	2.1	3.2
1/4	3.0	3.3	1.9	1.9
		375° F		
1/16	-	1.8	1.5	1.4
1/8	-	2.2	1.7	1.6
1/4	-	2.1	1.9	1.6

(1) Directionality ratio is defined as the percent change in width at the neck divided by the percent change in thickness.

Several of the wrought discs that were impacted at ambient temperature were found to have small internal cracks. These ruptures were small dish-like flaws that were parallel to the impacted surface and lay in layers or bands that were parallel to the impacted surface. Since metals fail in tension at lower stresses than in compression,

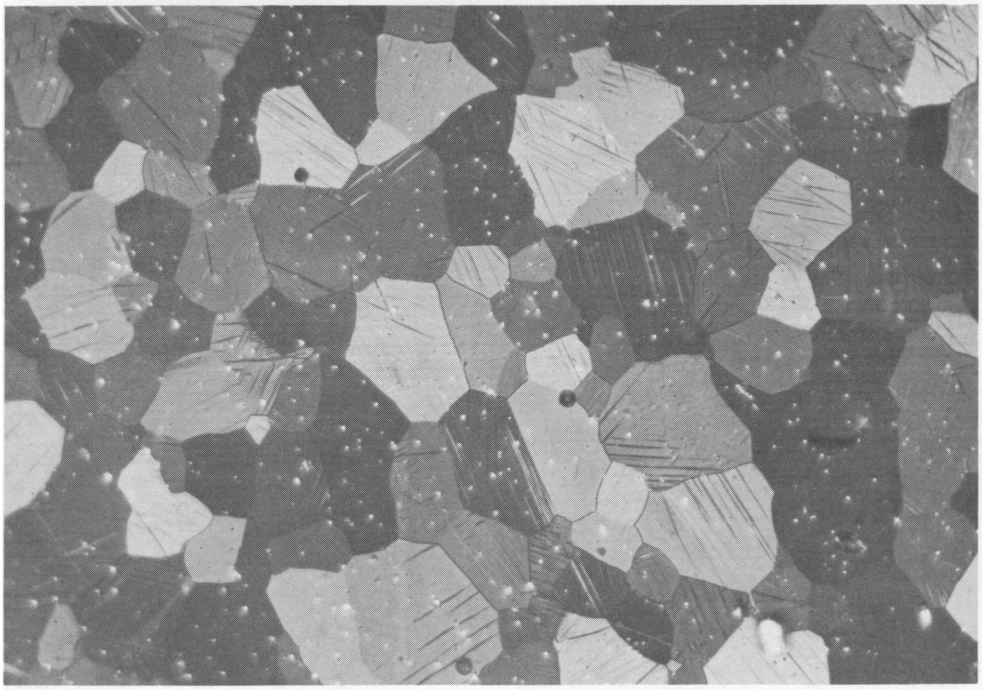


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Figure 19. MICROSTRUCTURE OF A 3/8-INCH SALT-ANNEALED WROUGHT URANIUM DISC. (Not Impacted)

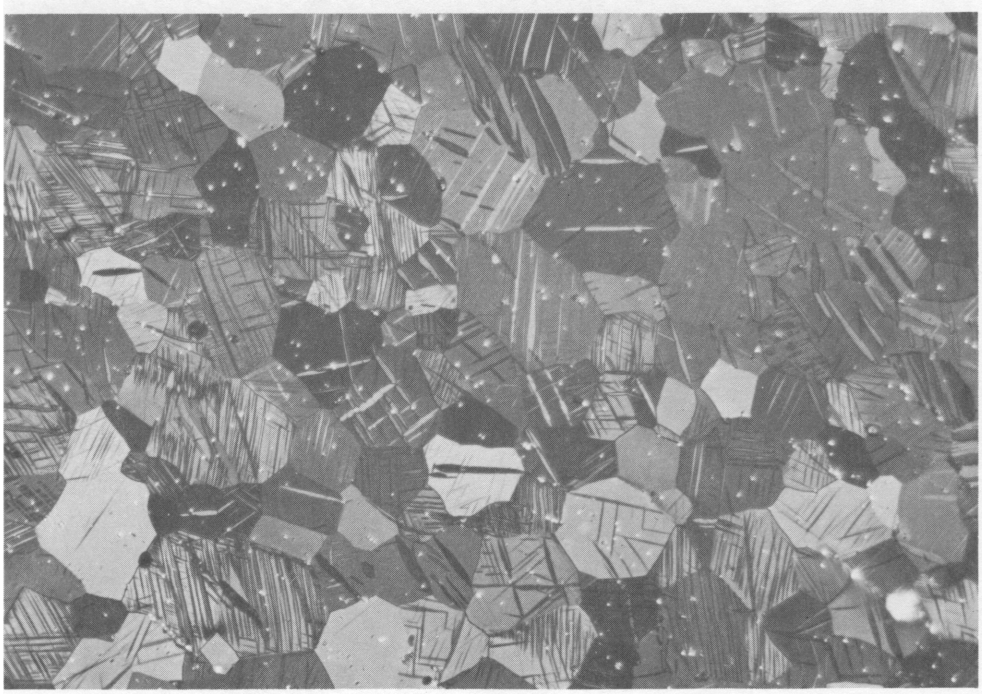

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Figure 20. MICROSTRUCTURE OF A 3/8-INCH COLD IMPACTED WROUGHT URANIUM DISC. (Estimated Impact Pressure – 5.3×10^5 psi)

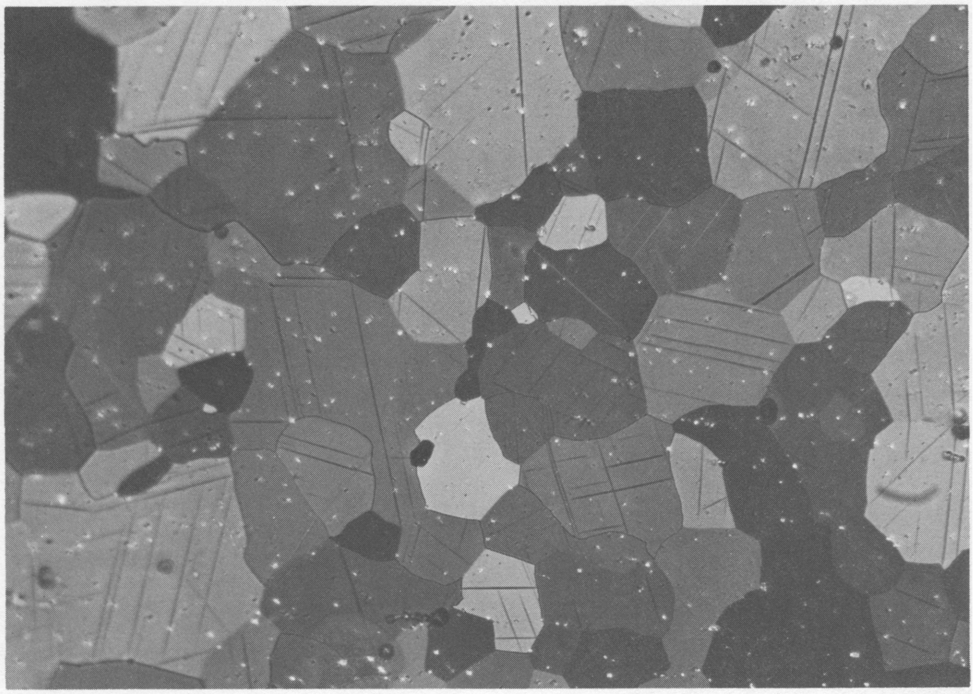

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Figure 21. MICROSTRUCTURE OF A 3/8-INCH COLD IMPACTED AND REANNEALED WROUGHT URANIUM DISC. (Estimated Impact Pressure – 5.3×10^5 psi)

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Figure 22. MICROSTRUCTURE OF A 3/8-INCH WARM IMPACTED AND ANNEALED CAST URANIUM DISC. (Estimated Impact Pressure – 5.3×10^5 psi; End View)

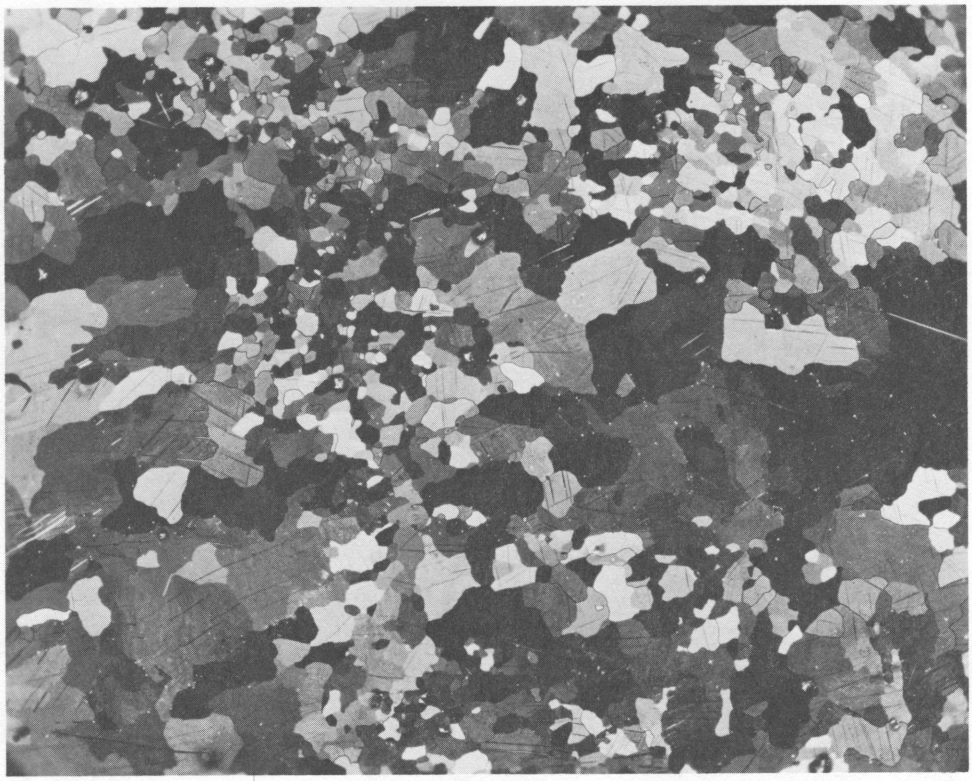

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Figure 23. MICROSTRUCTURE OF A 1/8-INCH WARM IMPACTED AND ANNEALED CAST URANIUM DISC. (Estimated Impact Pressure – 5.3×10^5 psi; Surface View)

the presumed cause of the rupture was not the initial compressive impact wave but rather resonance of the tension refraction waves generated at the bottom surface of the metal when the compressive pressure wave was transferred to the supporting die. These internal cracks were not found in the warm impacted material. At the warm impact temperature, the metal was able to plastically deform and absorb the energy involved.

CONCLUSIONS

This program confirmed the original assumption that explosive impacting without plastic deformation would increase the strength of uranium; and to avoid metal damage, this impacting should be done with the metal above the ductile-brittle transition temperature.

This program did not generate sufficient data to determine the relationship between part wall thickness and required explosive impact to maximize the tensile properties, nor was the technique used completely applicable to a cup-like part.

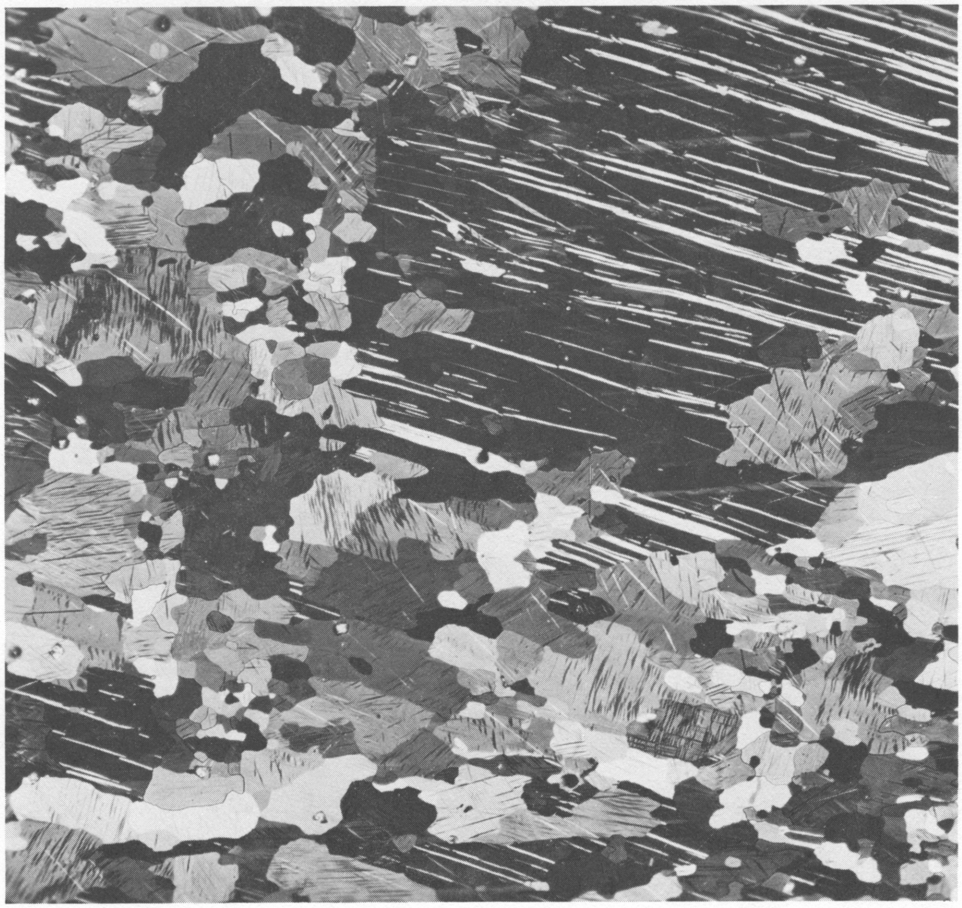

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Figure 24. MICROSTRUCTURE OF A 1/8-INCH WARM IMPACTED AND ANNEALED CAST URANIUM DISC. (Estimated Impact Pressure – 5.3×10^5 psi; Cross-Section View)

Impacting and heat treating cast uranium initiated grain refinement. It is not known whether repeated impacts and heat treatments would complete the transformation of the cast material into wrought material with corresponding improvement in tensile properties.

ACKNOWLEDGEMENTS

This work was greatly helped through the interest shown by J. L. Williams of Mechanical Operations.

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APPENDIX A

AMBIENT-TEMPERATURE IMPACTING

This impacting was done by National Northern Division of Atlantic Research Corporation for Y-12, Union Carbide Corporation, Nuclear Division (Subcontract 24Y-17262C).[6] Herein is a presentation of this report, with only minor editorial changes and changes in the figure and table numbers.

SUMMARY

Preliminary Tests

Tests at various shock levels were conducted on Type 430 cold-worked stainless steel to: (1) determine fracturing level of shock to a metal having properties similar to uranium, and (2) determine the technique and explosive-charge shapes for introducing a plane shock wave to the surface of the metal.

Both shock-impact levels and explosive geometry were determined in these tests. The shock levels induced hardening of the Type 430 stainless steel, and all indications were that a plane wave shape had been achieved.

Tests of Uranium

Three shock levels determined in preliminary tests were used in the testing of the uranium samples at ambient temperature. These were applied to the samples listed in Table A-1. A total of 42 uranium tests were conducted at ambient temperatures with the variables being shock level, wrought or cast uranium, and uranium thickness.

TYPICAL TEST PROCEDURE

Explosive charges were cast and assembled as shown in Figure A-1. These charges were utilized in a test arrangement as shown in Figure A-2. Components for the test are laid out in Figure A-3 and assembled in sequence in Figure A-4. Figure A-5 shows the facility used for these tests.

In a step-by-step procedure, the following outline applies:

A. Assemble components; ie, uranium, pressure plate, platen, die, and explosive charge.

B. Record shock level with sample number.

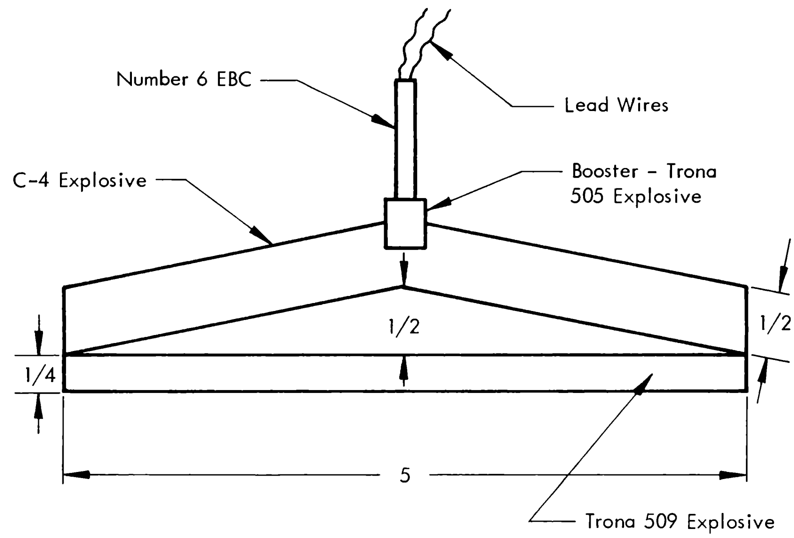
C. Detonate explosive charge with personnel in shelter (100-yard radius was used as the exposed danger area for fragments).

Table A-1

ROOM TEMPERATURE TESTS

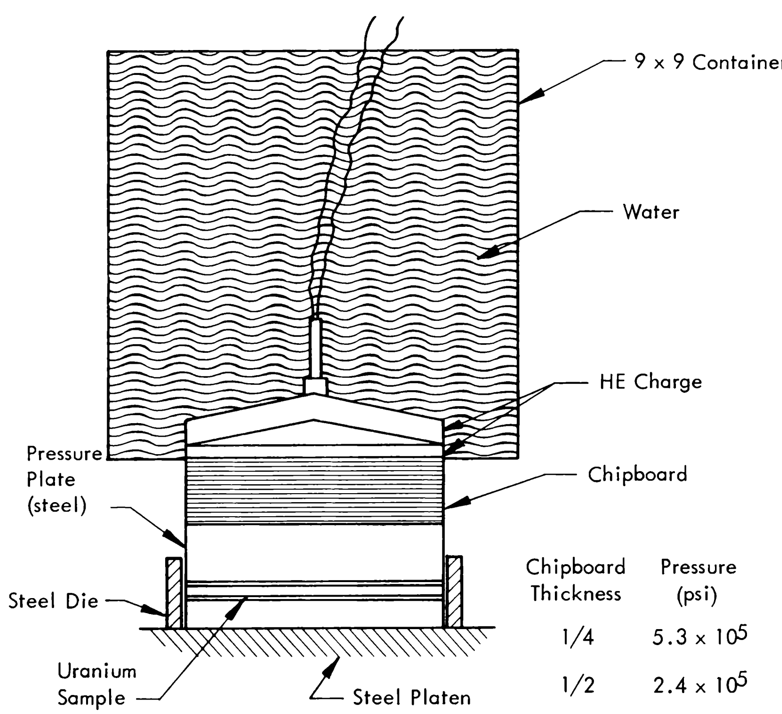
Series	Metal	Condition	Thickness (inch)	Sample Number	Pressure Level(1) (psi x 10^{-5})
A	430	Cold Worked	0.390	1	-
A	430	Cold Worked	0.390	2	-
A	430	Cold Worked	0.390	3	7.3
A	430	Cold Worked	0.275	4	-
A	430	Cold Worked	0.275	5	1.1
A	430	Cold Worked	0.276	6	2.4
A	430	Cold Worked	0.273	7	5.3
A	430	Cold Worked	0.126	8	1.1
A	430	Cold Worked	0.127	9	2.4
A	430	Cold Worked	0.130	10	5.3
1	U	Wrought	1/16	101	1.1
1	U	Wrought	1/16	102	2.4
1	U	Wrought	1/16	103	5.3
1	U	Wrought	1/16	104	1.1
1	U	Wrought	1/16	105	2.4
1	U	Wrought	1/16	106	5.3
2	U	Wrought	1/8	201	1.1
2	U	Wrought	1/8	202	2.4
2	U	Wrought	1/8	203	5.3
2	U	Wrought	1/8	204	1.1
2	U	Wrought	1/8	205	2.4
2	U	Wrought	1/8	206	5.3
2	U	Cast	1/8	211	1.1
2	U	Cast	1/8	213	2.4
2	U	Cast	1/8	215	5.3
2	U	Cast	1/8	216	1.1
2	U	Cast	1/8	217	2.4
2	U	Cast	1/8	218	5.3
3	U	Wrought	1/4	301	1.1
3	U	Wrought	1/4	302	5.3
3	U	Wrought	1/4	303	5.3
3	U	Wrought	1/4	304	1.1
3	U	Wrought	1/4	305	2.4
3	U	Wrought	1/4	306	2.4
3	U	Cast	1/4	311	1.1
3	U	Cast	1/4	312	2.4
3	U	Cast	1/4	313	5.3
3	U	Cast	1/4	314	1.1
3	U	Cast	1/4	315	2.4
3	U	Cast	1/4	316	5.3
4	U	Wrought	3/8	401	1.1
4	U	Wrought	3/8	402	2.4
4	U	Wrought	3/8	403	5.3
4	U	Wrought	3/8	404	1.1
4	U	Wrought	3/8	405	2.4
4	U	Wrought	3/8	406	5.3
4	U	Cast	3/8	411	1.1
4	U	Cast	3/8	412	2.4
4	U	Cast	3/8	413	5.3
4	U	Cast	3/8	414	1.1
4	U	Cast	3/8	415	2.4
4	U	Cast	3/8	416	5.3

(1) Computed, see DISCUSSION.



Booster	4 Grams
C-4	220 Grams
Trona 509	170 Grams
Total Explosives Weight:	394 Grams

Figure A-1. TASK I & II - CONDITIONING URANIUM DISCS. (Expolsive Charge Geometry)



Chipboard Thickness	Pressure (psi)
1/4	5.3×10^5
1/2	2.4×10^5
1	1.1×10^5

Figure A-2. TASK I & II - CONDITIONING URANIUM DISCS. (Test Setup)

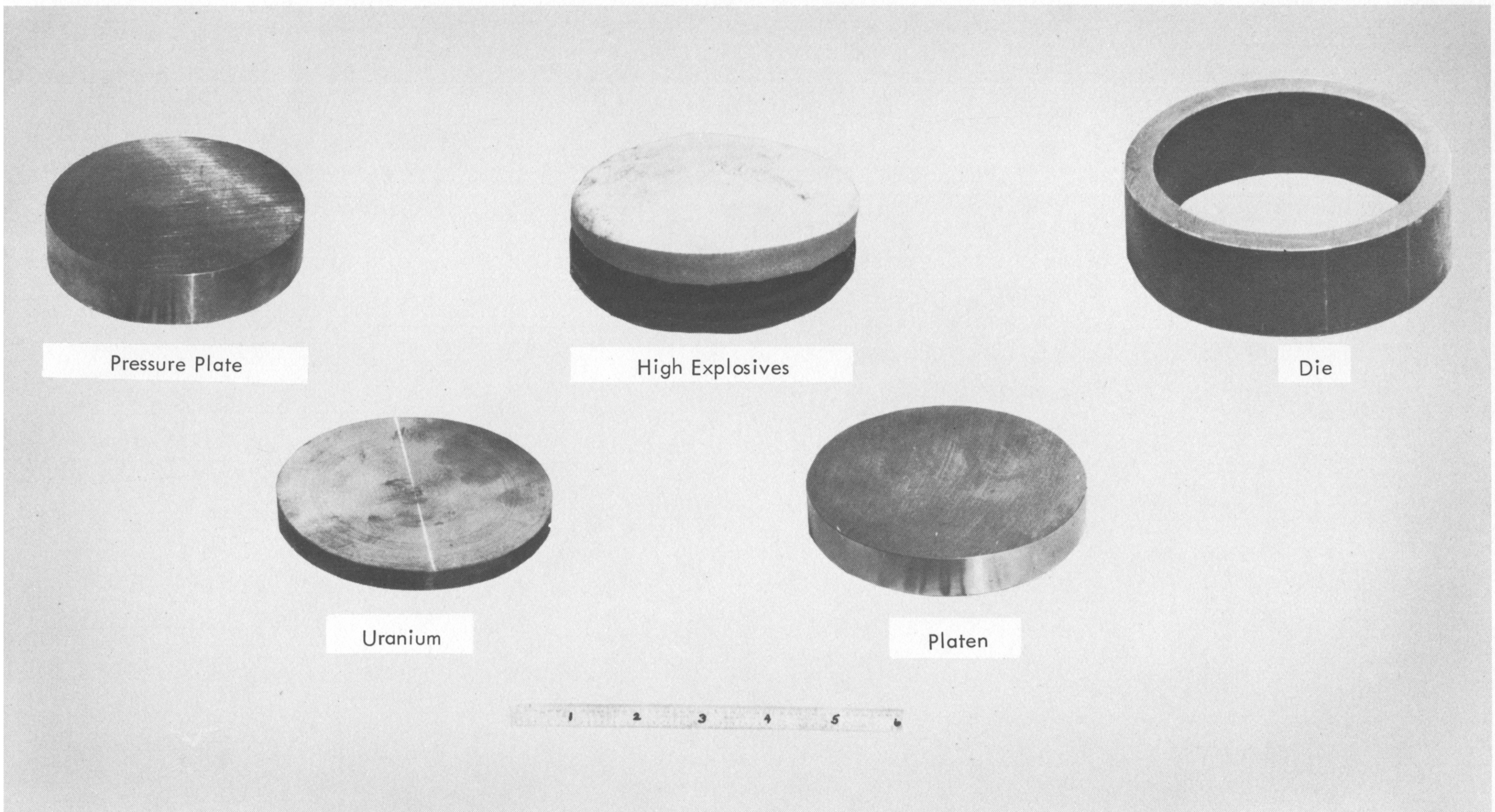


Figure A-3. COMPONENTS FOR EXPLOSIVE TEST.

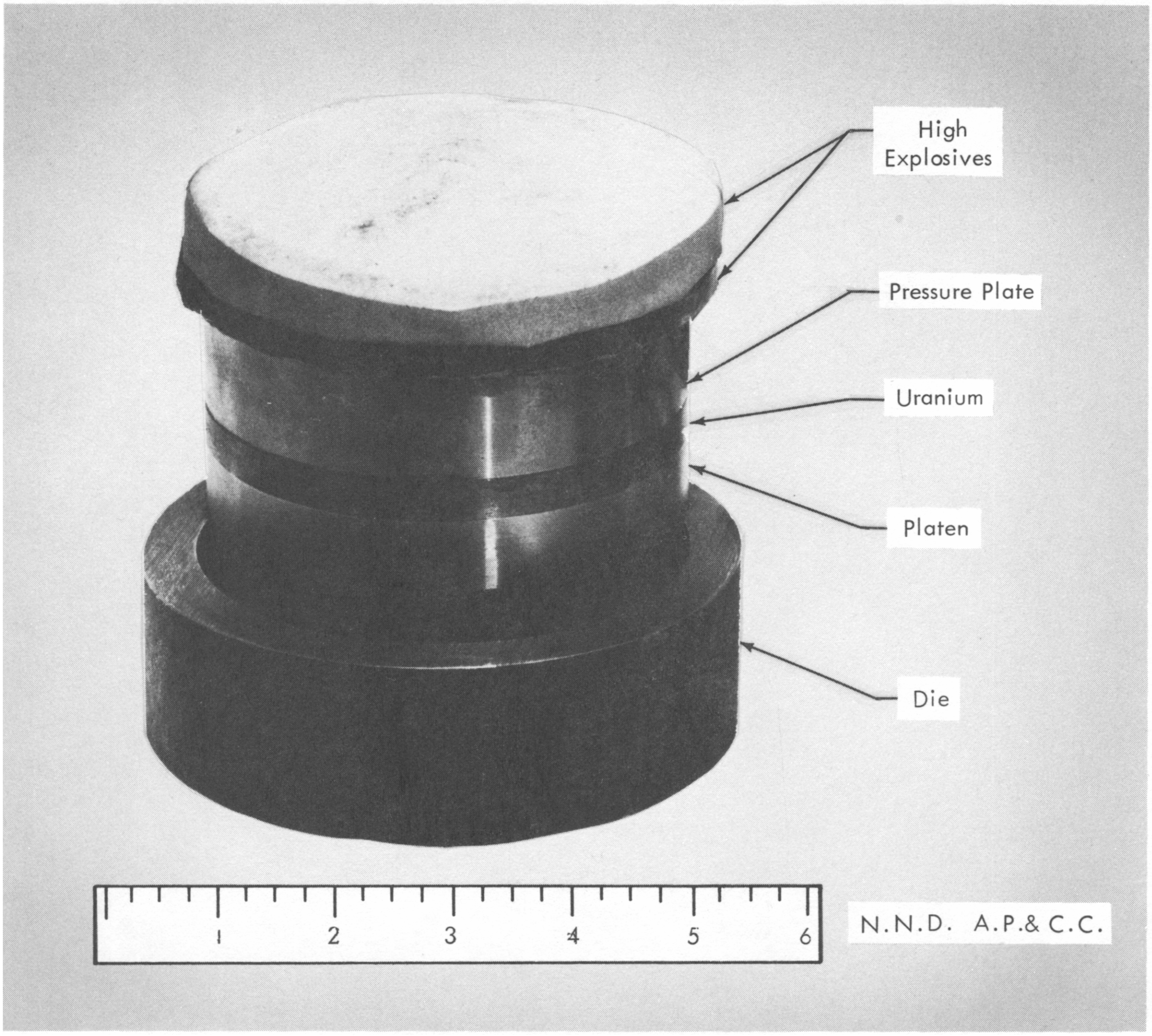


Figure A-4. TEST COMPONENTS ASSEMBLED IN SEQUENCE.

D. Firing personnel were never at less than a 90 degree angle formed by their line of vision to the explosion and the wind direction.

E. Thirty seconds after detonation, the "all clear" was sounded. The uranium sample was cleaned, dimensions and any unusual results recorded, and the sample numbered and boxed.

F. Urine samples of personnel engaged in this program were taken before the start and after completion of the tests. A consultant was used to aid in establishing proper handling procedures and to record radioactivity before, midway, and at the completion of the tests.

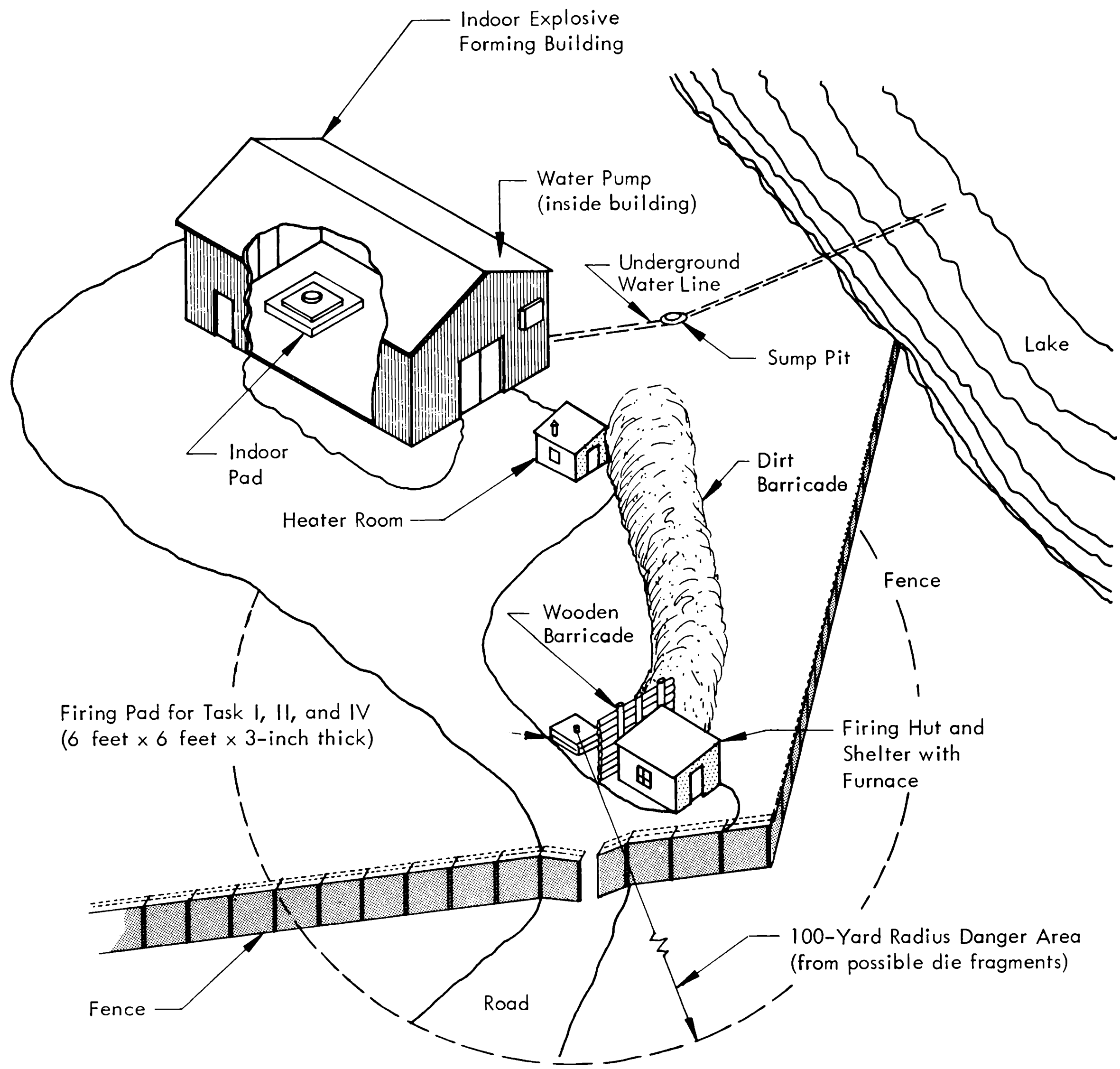


Figure A-5. TASK I, II, & IV - TEST FACILITY FOR EXPLOSIVE CONDITIONING AND COMPACTION.

ITEMS UNDER TEST

Preliminary tests were conducted on Type 430 cold-worked stainless steel. This alloy was chosen because of its similarity in physicals to uranium and availability. Approximate physical properties before test were:

Metal	Condition	Tensile Strength (psi)	Yield Strength (psi)	Elongation (%)
Type 430 Stainless Steel	Cold Worked	85,000	50,000	20
Uranium	Wrought	100,000	30,000	10
Uranium	Cast	80,000	20,000	6

Table A-1 lists the item numbers, condition, thickness, and explosive pressure level to which items were subjected.

EXPLOSIVE CHARGES AND GEOMETRY

The explosive charge, weights, and geometry used for these tests are shown in Figure A-1. They were designed to generate essentially a flat, plane wave to the pressure plate in order to produce simultaneous forces of equal magnitude on the surface of the items under test. Preliminary tests indicated that this design was the best for this purpose. The initiator starts the action on the umbrella-type charge. This charge, in turn, initiates the 1/4-inch wafer of explosive that is parallel to the pressure plate. The explosive charges weighing 394 grams each were the same for all the uranium tests. The pressure levels for all tests were varied by varying the thickness of chipboard between the explosive and pressure plate (Figure A-2). The chipboard acted as an attenuator or control in this case. The four thicknesses and pressure levels are listed in Table A-2.

Table A-2

COMPUTED PRESSURE LEVELS
(Ambient Temperature)

Thickness (inch)	Pressure(1) (psi x 10^{-5})	Pressure Level
0.180	7.3	D
1/4	5.3	C
1/2	2.4	B
1	1.1	A

(1) Pressures computed at National Northern. See DISCUSSION and PRESSURE COMPUTATIONS.

The preliminary tests on Type 430 stainless proved that a 0.180-inch thickness of chipboard (7.3 x 10^5 psi) was insufficient, since circumferential cracking of the metal took place. The next lower pressure level, 5.3 x 10^5 psi (0.250-inch chipboard), was selected as the maximum to be used for the uranium samples. At this level, the highest of three pressure levels, some cracking took place in the cast uranium.

The explosive charges shown in Figure A-1 consisted of the following and were detonated in the listed order during the explosion.

Number 6 Electric Blasting Cap (initiator)
TRONA 505 Booster (initiating explosive)
C-4 Explosive (primarily a rich RDX composition)
TRONA 509 Explosive (underwater blast explosive)

RESULTS

Cracks

In general, no large defects in the uranium were observed after test. Minor cracks occurred in some samples, with the majority being in the cast uranium samples. After test, some small cavities were noted, particularly in the cast uranium, which probably were present just below the surface before test.

Grain

A large grain-type appearance was noted on the cast uranium specimens.

Dishing

Dishing (out of flat) was present on some of the specimens before test and also after test. The final amount of dishing was either all caused by the explosive force or a total of that caused by the explosive force and that which was present at the start. Although some was introduced in certain specimens by the explosive forces, it was not necessarily from an uneven force application. Although forces may be applied uniformly, an "end effect" on discs or tubes usually creates an uneven product at the edges or ends.

Stainless Steel Sheets

The preliminary tests conducted on stainless steel discs of 3/8, 1/4, and 1/8-inch thicknesses resulted in increased hardnesses, as listed in Table A-3.

Table A-3

CHANGE IN HARDNESS AFTER IMPACTING

Sample	Pressure (psi x 10^{-5})	Disc Thickness (inch)	Hardness (Rockwell "C") Before	After
5	1.1	1/4	(7)	13 - 14
6	2.4	1/4	(7)	13 - 14
7	5.3	1/4	(7)	15
8	1.1	1/8	(9)	13 - 17
9	2.4	1/8	(9)	13 - 15
10	5.3	1/8	(9)	12 - 15

The increase in hardness represents a converted increase in tensile strength of from 85,000 to 100,000 psi. The stainless steel discs after test are shown in Figure A-6. Samples 1 through 4 increased in hardness to 25 Rockwell "C" or 126,000 psi tensile.

Uranium Results

Cracking, grain structure, and dishing have been noted. In addition, the samples were sent to Union Carbide, Y-12 Plant, for analysis.

DISCUSSION

Generally, the uranium at ambient temperature reacted in a manner similar to other metals when subjected to high levels of explosive shock. The exact levels of shock are only theoretical at the present time. The exact values are relative to values determined by other facilities.

An increase in hardness and a change in grain structure or size should have taken place in the uranium samples. The amount or degree of change before fracturing occurs can be determined by analysis of the test samples by Union Carbide.

Other shapes of uranium could also be "shock tested" if similar changes in the phyical properties are desired.

The facility used for these tests is shown in Figure A-5.

CONCLUSIONS

The variables that could be expected to result from the explosive shock treatment of the test samples are:

1. Hardness

2. Tensile Strength

3. Yield Strength

4. Percent Elongation

5. Reduction in Area

Plots of the changes from the original physicals along with those created by varying pressure levels would be of interest after analysis of the test specimens by Union Carbide.

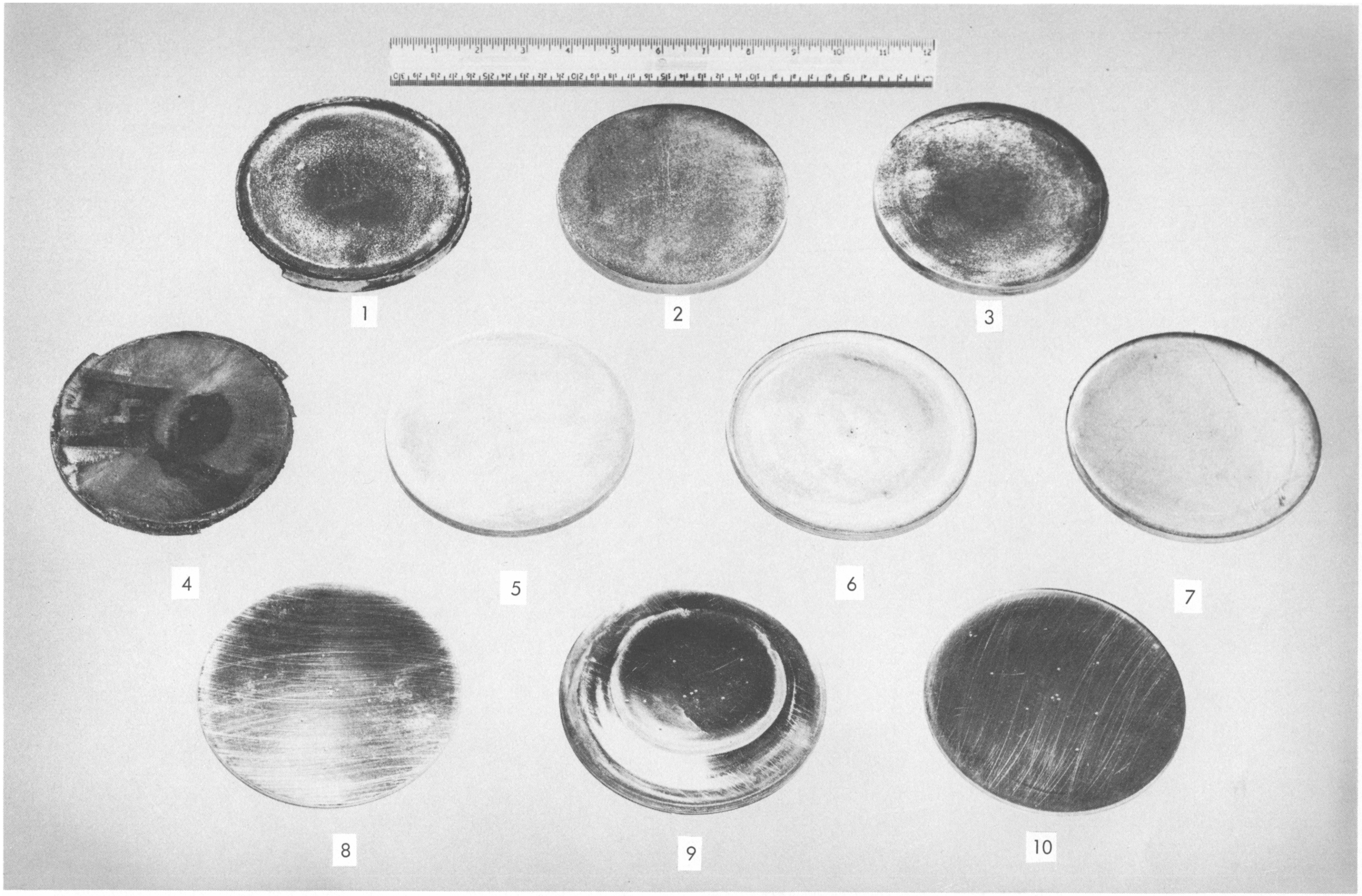


Figure A-6. TYPE 430 STAINLESS STEEL DISCS AFTER TEST.

The work conducted in this program is such that shock pressure can now be applied to practical items and not just research samples. The only changes required would be the geometry of the explosive. This would change with the geometry of the uranium part.

GENERAL

The shock levels determined in this program are essentially theoretical, since no measuring device can establish or record peak pressures in the magnitude encountered in this program. Various facilities can and do differ in their reported values, and National Northern is no exception.

Test data confirm the fact that all metals will fracture when subjected to a sufficiently high pressure-time impulse. The program developed a pressure region that would just fracture a metal (Type 430 stainless) having physicals similar to uranium. This explosive quantity was used and the distance between the part subjected to the pressure and the explosive was varied.

Another contributing factor to nonestablishment of an accurate value of pressure is that a contact-type explosion was used with chipboard as the attenuator, which, we shall assume, behaved as a fluid. The differences in pressure that occur between air or water as the attenuator are enormous (see NAVORD Report 7033 by John Pearson, US Department of Commerce, PB 161828). An example of the difference between air and water as the standoff is that four pounds of TNT produce 4000 psi in air and 40,000 psi in water at a one-foot distance from the charge. In the zero-to-one-foot range from the explosive, the pressures are on an exponential curve, thereby creating wide variations in the differences.

PRESSURE COMPUTATIONS

The formula used by National Northern for computing reported pressures is:

$$P = K \left(\frac{\omega^{1/3}}{R}\right)^{a} .$$

For these tests, the following values were used:

$K = 21{,}500$

$\omega^{(a)}$ = weight of explosive in pounds per square inch

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(a) Only the weight of explosive per square inch (0.04) was utilized for these computations since a total weight would produce an unusually high pressure value.

R = distance in feet between explosive and plate

a = 1.13

Values of R of 1, 0.5, 0.25, and 0.18 inch were used for distances. The 0.18-inch distance fractured the stainless steel and was not used in the uranium tests.

The computed pressures values for the various distances were:

1.0 inch	110,000 psi
0.5 inch	240,000 psi
0.25 inch	530,000 psi
0.18 inch	730,000 psi

Again we state that the values should be considered relative. Values computed by other facilities for these test conditions would vary and go into the multimillion psi range of pressures.

APPENDIX B

ELEVATED-TEMPERATURE IMPACTING

The impacting was done by National Northern Division of Atlantic Research Corporation for Y-12, Union Carbide Corporation, Nuclear Division (Subcontract 24Y-17262C).[7] Herein is a presentation of this report, with only minor editorial changes and changes in the figure and table numbers.

Preliminary Tests

Tests at various explosive shock levels were conducted on beryllium-copper discs at 375° F to determine the: (1) fracturing level, and (2) physical property changes of the metal.

Results indicated an increase in hardness as a consequence of the shock treatment. Hardness values increased from Rockwell B-74 to a range of Rockwell C-13 to C-27 depending upon the shock level. These values represent an equivalent tensile-strength increase from 65,000 psi to a range of 95,000 to 130,000 psi. Thickness loss of the discs ranged from 0.007 to 0.030 inch depending on the pressure level applied.

Uranium Tests at 375° F

Three levels of shock were utilized on both cast and wrought uranium discs at 375° F. None of the 42 samples under test cracked, and the thicknesses were reduced by up to 0.015 inch maximum as a result of the shock pressures. Analyses of the physical property changes are being made by Union Carbide.

TYPICAL TEST PROCEDURE

Explosive charges were cast and assembled. The test material, not including the explosive, was heated and equalized in a 400° F furnace for a minimum of six hours.

A cooling curve for obtaining the 375° F temperature was obtained on the item under test after removal from the furnace. The time was established at 2 1/2 to 3 minutes which was ample to install, hook up, take shelter, and detonate.

In a step-by-step procedure, the following outline applies:

1. Assemble components; ie, uranium, pressure plate, platen, die, and explosive charge. Meltemp 7, a lubricant, was applied in a very thin coat on both sides of the uranium.

2. Record shock level with sample number.

3. Preheat test assembly (minus explosive) in a 400° F furnace.

4. Set explosive in water container with space below for insertion of heated parts.

5. Remove test assembly from furnace, place under explosive setup, hook up detonator, take shelter, and detonate at 2 1/2 to 3 minutes after removal from furnace.

6. Firing personnel were never at less than a 90-degree angle formed by their line of vision to the explosion and the wind direction. This precaution was taken to keep personnel out of the combustion products, which could have contained uranium dust.

7. Thirty seconds after detonation the "all clear" was sounded. The uranium sample was cleaned, dimensions and any unusual results recorded, and the sample numbered and boxed.

8. Urine samples of personnel engaged in this program were taken before the start and after completion of the tests. A consultant was used to aid in establishing proper handling procedures and to record radioactivity before, midway, and at the completion of the tests.

ITEMS UNDER TEST

Preliminary tests were conducted on beryllium-copper alloy. This alloy was chosen because of its similarity in physicals to uranium at 375° F and availability. Approximate physical properties before test at 375° F follow:

Metal	Condition	Tensile Strength (psi)	Yield Strength (psi)	Elongation (%)
Be-Cu	Annealed	70,000	25,000	35 - 50
Uranium	Wrought	50,000	20,000	30 - 40
Uranium	Cast	40,000	15,000	20 - 30

The item numbers, condition, thickness, and explosive pressure level to which items were subjected are listed in Table B-1.

EXPLOSIVE CHARGES AND GEOMETRY

The explosive charge, weights, and geometry were designed to generate an essentially flat plane wave at the pressure plate in order to produce simultaneous forces of equal magnitude on the surface of the items under test. Preliminary tests indicated that

Table B-1

TESTS AT 375° F

Series	Metal	Condition	Thickness (inch)	Sample Number	Pressure Level[1] (psi x 10^{-5})
B	Be-Cu	Annealed	1/4	1	1.1
B	Be-Cu	Annealed	1/4	2	2.4
B	Be-Cu	Annealed	1/4	3	5.3
B	Be-Cu	Annealed	3/8	4	1.1
B	Be-Cu	Annealed	3/8	5	2.4
B	Be-Cu	Annealed	3/8	6	5.3
B	Be-Cu	Annealed	1/8	7	2.4
5	U	Wrought	1/16	501	1.1
5	U	Wrought	1/16	502	2.4
5	U	Wrought	1/16	503	5.3
5	U	Wrought	1/16	504	1.1
5	U	Wrought	1/16	505	2.4
5	U	Wrought	1/16	506	5.3
6	U	Wrought	1/8	601	1.1
6	U	Wrought	1/8	602	2.4
6	U	Wrought	1/8	603	5.3
6	U	Wrought	1/8	604	1.1
6	U	Wrought	1/8	605	2.4
6	U	Wrought	1/8	606	5.3
6	U	Cast	1/8	611	1.1
6	U	Cast	1/8	612	2.4
6	U	Cast	1/8	613	5.3
6	U	Cast	1/8	614	1.1
6	U	Cast	1/8	615	2.4
6	U	Cast	1/8	616	5.3
7	U	Wrought	1/4	701	1.1
7	U	Wrought	1/4	702	2.4
7	U	Wrought	1/4	703	5.3
7	U	Wrought	1/4	704	1.1
7	U	Wrought	1/4	705	2.4
7	U	Wrought	1/4	706	5.3
7	U	Cast	1/4	711	1.1
7	U	Cast	1/4	712[2]	2.4
7	U	Cast	1/4	713	5.3
7	U	Cast	1/4	714	1.1
7	U	Cast	1/4	715	2.4
7	U	Cast	1/4	716	5.3
8	U	Wrought	3/8	801	1.1
8	U	Wrought	3/8	802	2.4
8	U	Wrought	3/8	803[3]	5.3
8	U	Wrought	3/8	804	1.1
8	U	Wrought	3/8	805	2.4
8	U	Wrought	3/8	806	5.3
8	U	Cast	3/8	811	1.1
8	U	Cast	3/8	812	2.4
8	U	Cast	3/8	813	5.3
8	U	Cast	3/8	814	1.1
8	U	Cast	3/8	815	2.4
8	U	Cast	3/8	816	5.3

(1) Computed.
(2) This sample had a small casting cavity in the center before test.
(3) This sample had a rough-edge surface before test.

this design was the best for this purpose. The initiator starts the action on the umbrella-type charge. This charge, in turn, initiates the 1/4-inch wafer of explosive that is parallel to the pressure plate. The explosive charges weighing 394 grams each were the same for all the uranium tests. The pressure levels for all tests were varied by changing the thickness of chipboard between the explosive and pressure plate. The chipboard acted as an attenuator, or control, in this case. The four thicknesses and pressure levels are listed in Table B-2.

Table B-2

COMPUTED PRESSURE LEVELS
(Elevated Temperature)

Thickness (inch)	Pressure(1) (psi x 10^{-5})	Pressure Level
0.180	7.3	D
1/4	5.3	C
1/2	2.4	B
1	1.1	A

(1) Pressures computed at National Northern.

Only pressure levels A, B, and C were used in Task II, since level D was considered too marginal and could result in fracturing some specimens.

The explosive charges consisted of the following and were detonated in the listed order during the explosion:

Number 6 Electric Blasting Cap (initiator)
TRONA 505 Booster (initiating explosive)
C-4 Explosive (primarily a rich RDX composition)
TRONA 509 Explosive (underwater blast explosive)

RESULTS

Cracks

In general, no large defects were observed in the uranium after test. Sample 505 had a small, 1/8-inch-long through crack attributed to a notch effect from the sample number being stamped too deeply. Other than this one minor crack, no other samples showed visible cracks. Therefore, the 375° F condition was of use in making the metal more ductile under explosive shock.

Grain

Large grainy type surfaces were noted on the cast uranium specimens after shock treatment.

Pitting

A number of the wrought samples had a "pitted" appearance after test. The pitting is attributed to defects in the uranium surface that are enlarged upon shock working. Some cast samples had surface cavities which became more obvious after explosive impact. These surface cavities were created by casting voids which were surface or just subsurface upon casting. These are present in practically all metal castings. None were of sufficient magnitude to create failure on impact at 375° F.

Dishing

Dishing (out of flat) was present on some of the specimens before test and also after test. The final amount of dishing was either all caused by the explosive force or a total of that caused by the explosive force and that which was present at the start. Although some was introduced in certain specimens by the explosive forces, it was not necessarily from an uneven force application. Although forces may be applied uniformly, an "end effect" on discs or tubes usually creates an uneven product at the edges or ends.

Beryllium-Copper Alloy Results

The preliminary tests conducted on beryllium-copper discs of 1/8, 1/4, and 3/8-inch thickness resulted in increased hardnesses. The results are listed in Table B-3.

Table B-3

CHANGE IN HARDNESS AFTER IMPACTING

Sample	Pressure (psi x 10^{-5})	Disc Thickness (inch)	Hardness (Rockwell)	
			Before	After
1	1.1	1/4	B-73	C-27
2	2.4	1/4	B-73	C-26
3	5.3	1/4	B-73	C-19
4	1.1	3/8	B-76	C-13
5	2.4	3/8	B-76	C-14
6	5.3	3/8	B-74	C-17
7	2.4	1/8	B-74	C-16

The increased hardness values represent an increase in tensile strength from 65,000 psi to a range of 95,000 to 130,000 psi.

The beryllium-copper discs after test are shown in Figure B-1.

Uranium Results

Grain structure, pitting, and dishing were noted in the uranium samples. In addition, all samples were sent to Union Carbide for analysis. They will report the effect of shock treatment on physical properties.

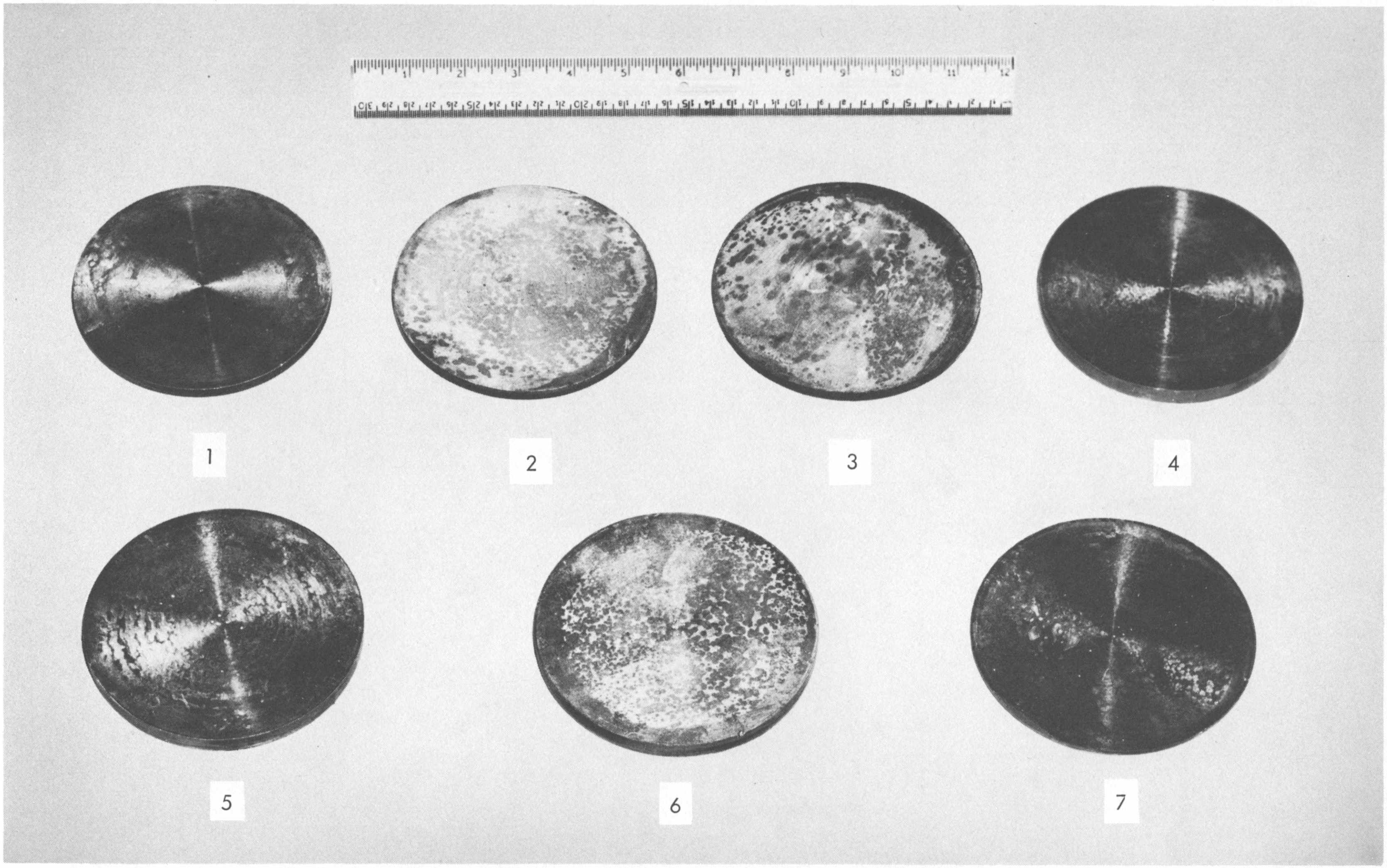

Figure B-1. BERYLLIUM-COPPER DISCS AFTER TEST.

DISCUSSION

Generally, the uranium at 375° F reacted in a manner similar to other metals; ie, more ductile at an elevated temperature, when subjected to high levels of explosive shock.

An increase in hardness and a change in grain structure or grain size should have taken place in the uranium samples. The amount of change at various shock levels is being determined by analysis of the test samples by technical personnel of Union Carbide.

Other shapes of uranium could also be "shock tested" if similar changes in physical properties are desired. The shape utilized in these tests was selected for convenience.

CONCLUSIONS

Judging from data already obtained from impacts on stainless steels and beryllium-copper alloy, certain changes in the physical properties of uranium could be expected as the result of explosive impact. These are:

1. Hardness
2. Tensile Strength
3. Yield Strength
4. Percent Elongation
5. Reduction in Area

The changes should be fairly consistent, since impact levels were controlled. A difference in physicals obtained between ambient and 375° F tests should be evident in the results.

Tests at elevated temperatures presented no major problem. Explosive impacts of uranium at varied impact levels and temperature can be performed with proper procedures.

The techniques developed and controlled impact levels attained can readily be extrapolated to other sizes and shapes.

All samples were returned to Union Carbide for analysis and evaluation.

APPENDIX C

SELECTED RADIOGRAPHS OF DISCS BEFORE AND AFTER IMPACTION

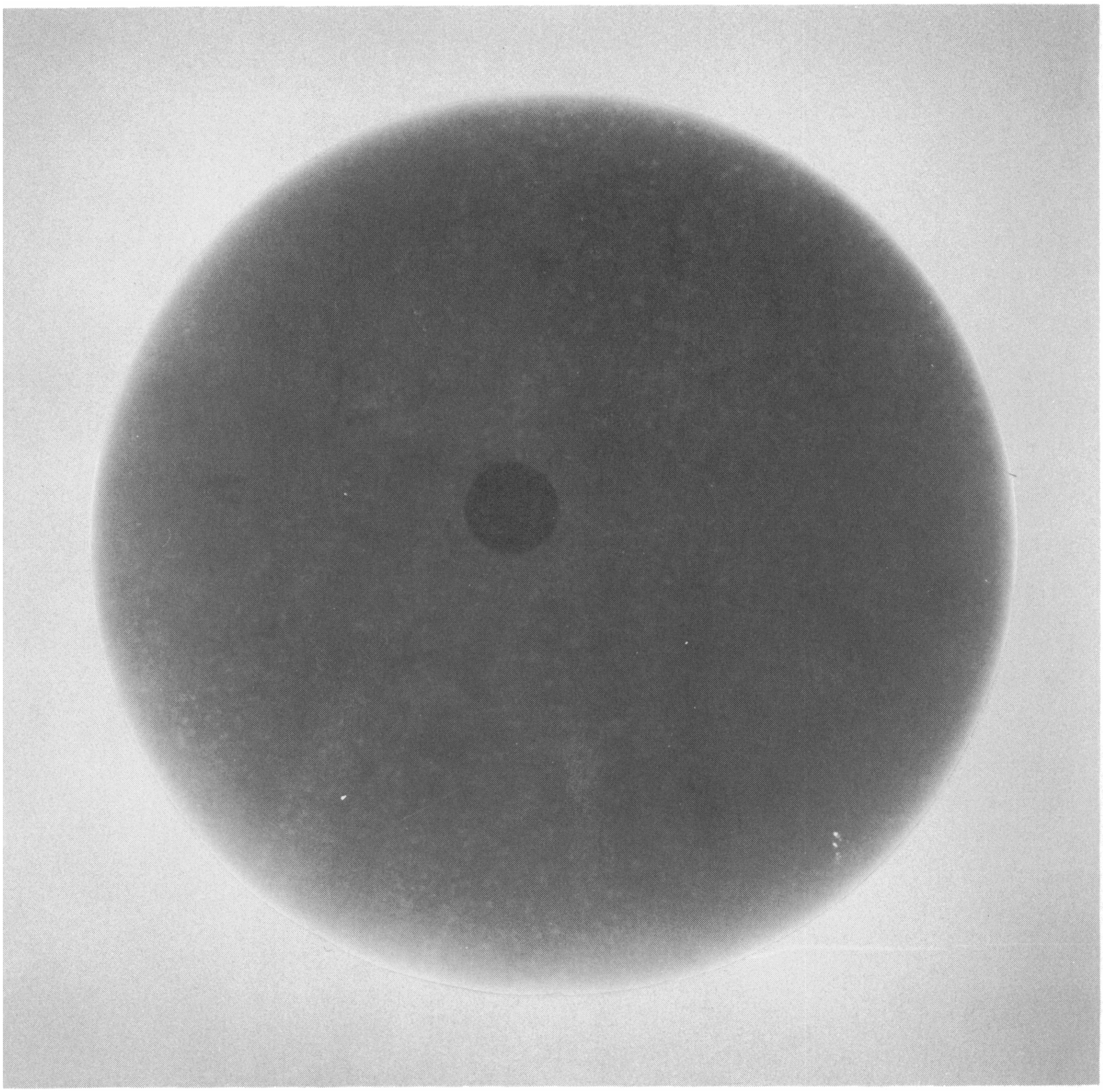

Figure C-1. DISC 301 (1/4-INCH THICK) ROLLED AND SALT ANNEALED; NOT IMPACTED. (Large Marking is a Penetrameter)

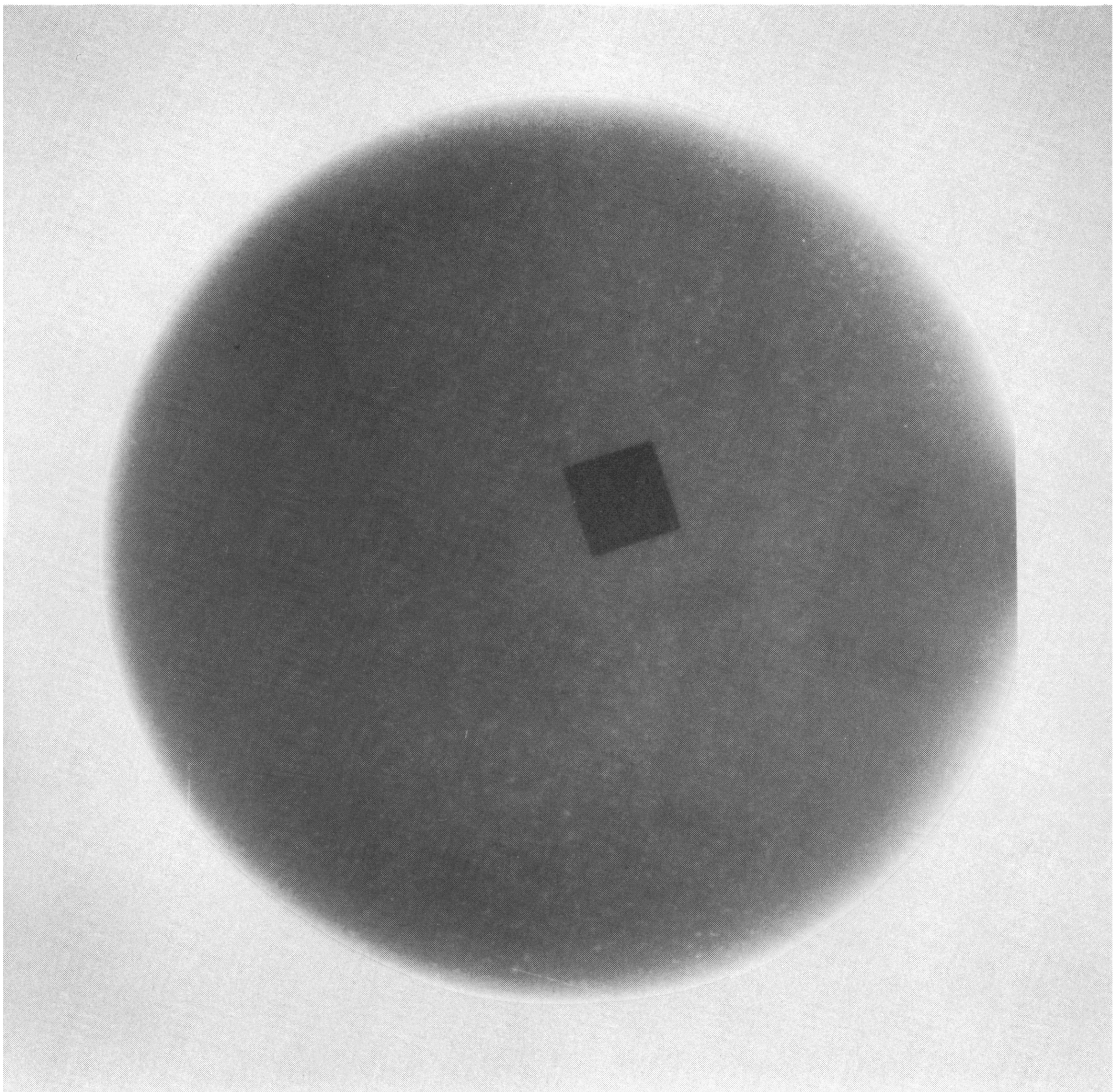

Figure C-2. DISC 301 AFTER AMBIENT-TEMPERATURE IMPACTION AT 1.1 X 10^5 PSI. (Large Marking is a Penetrameter)

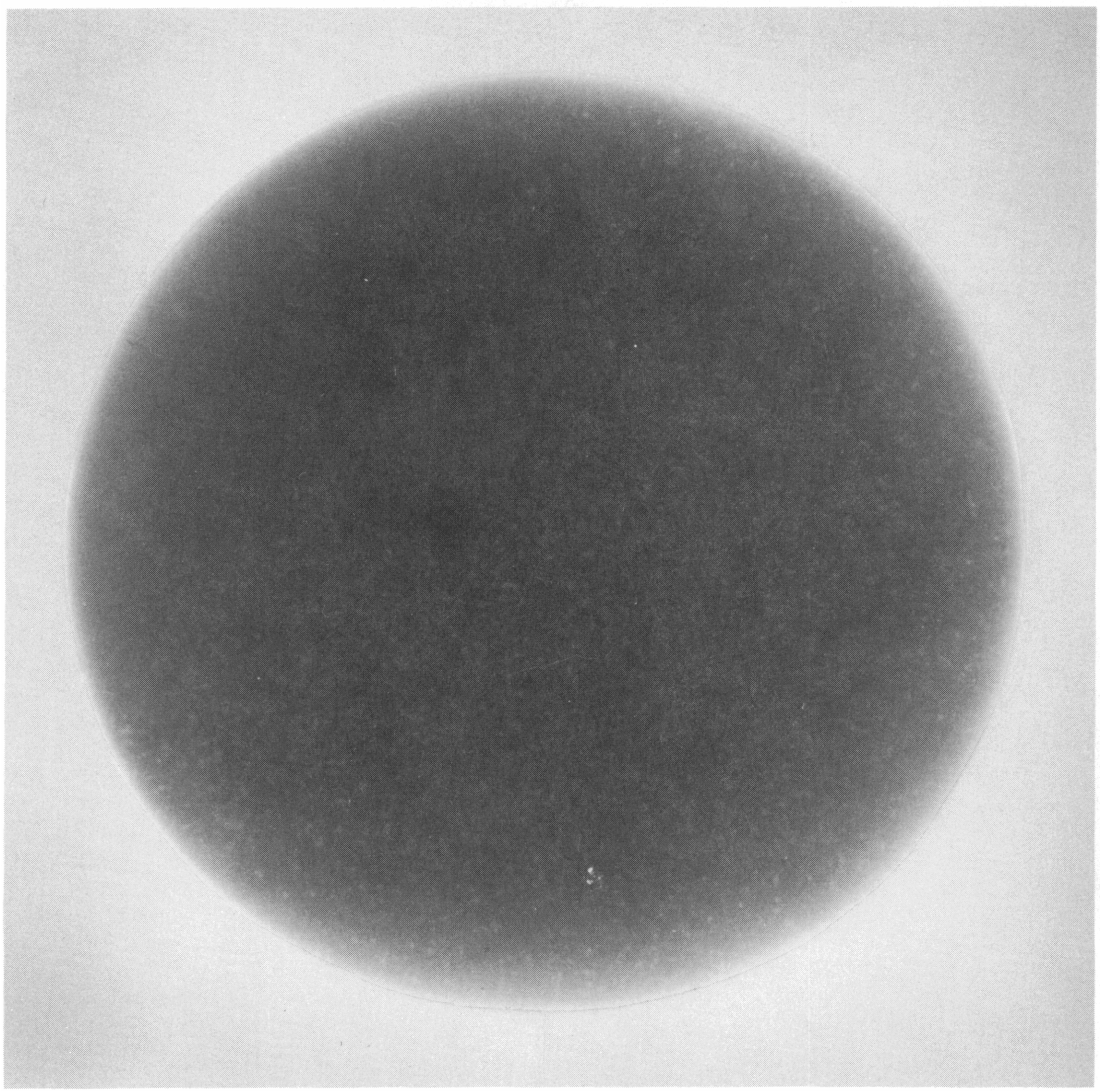

Figure C-3. DISC 304 (1/4-INCH THICK) ROLLED AND SALT ANNEALED; NOT IMPACTED.

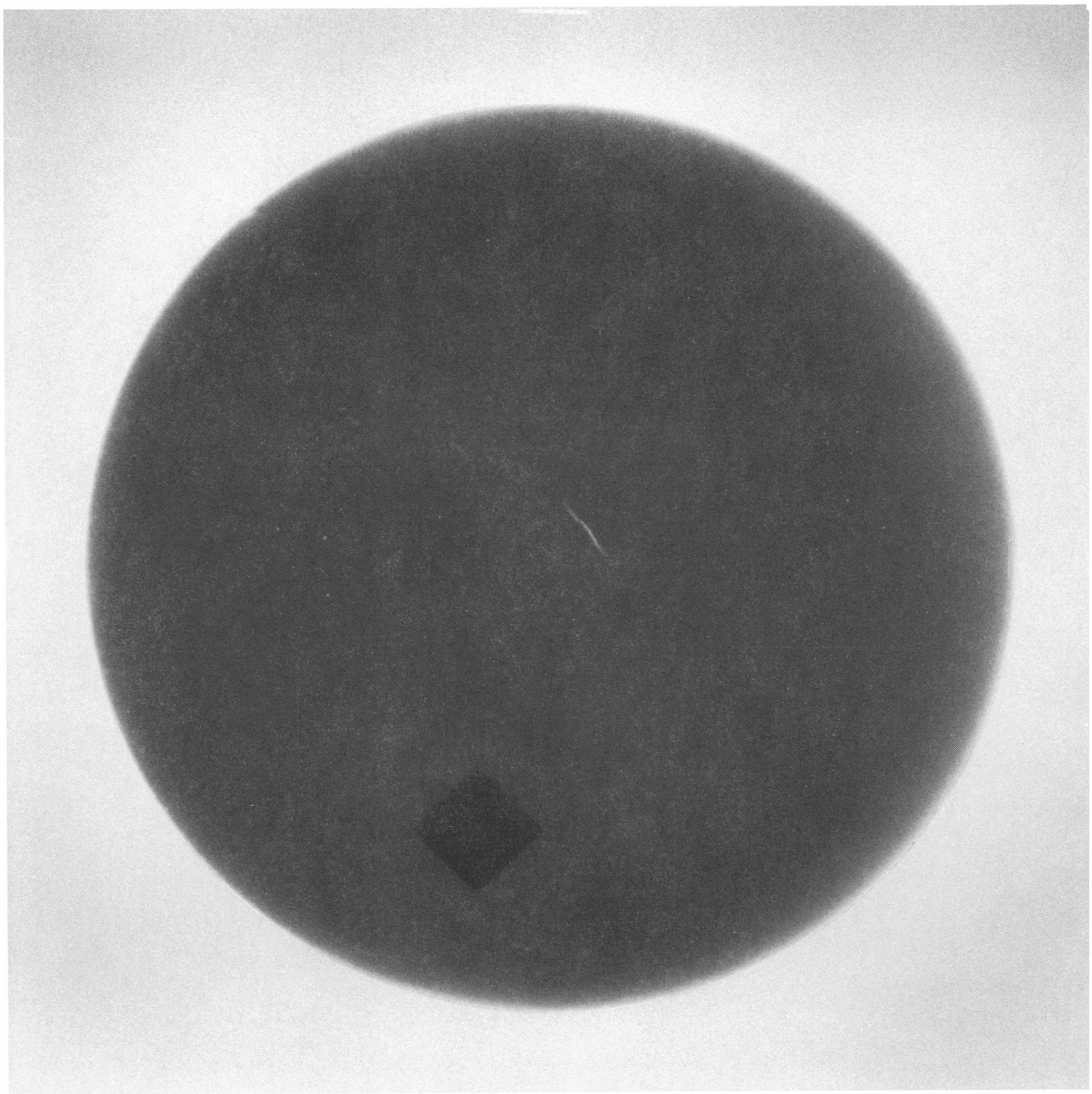

Figure C-4. DISC 304 AFTER AMBIENT-TEMPERATURE IMPACTION AT 1.1 X 10^5 PSI.

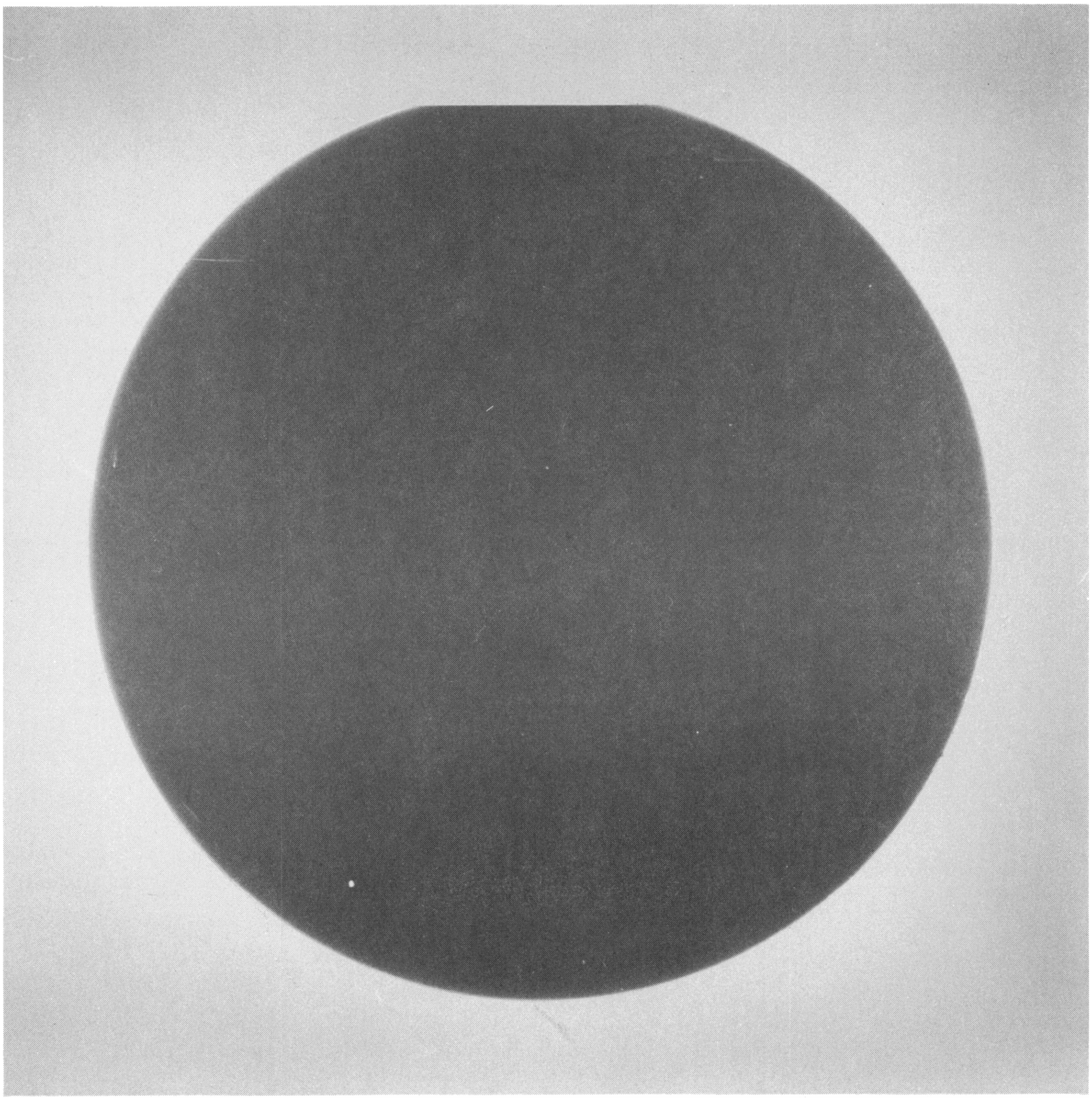

Figure C-5. DISC 502 (1/16-INCH THICK) ROLLED AND SALT ANNEALED; NOT IMPACTED.

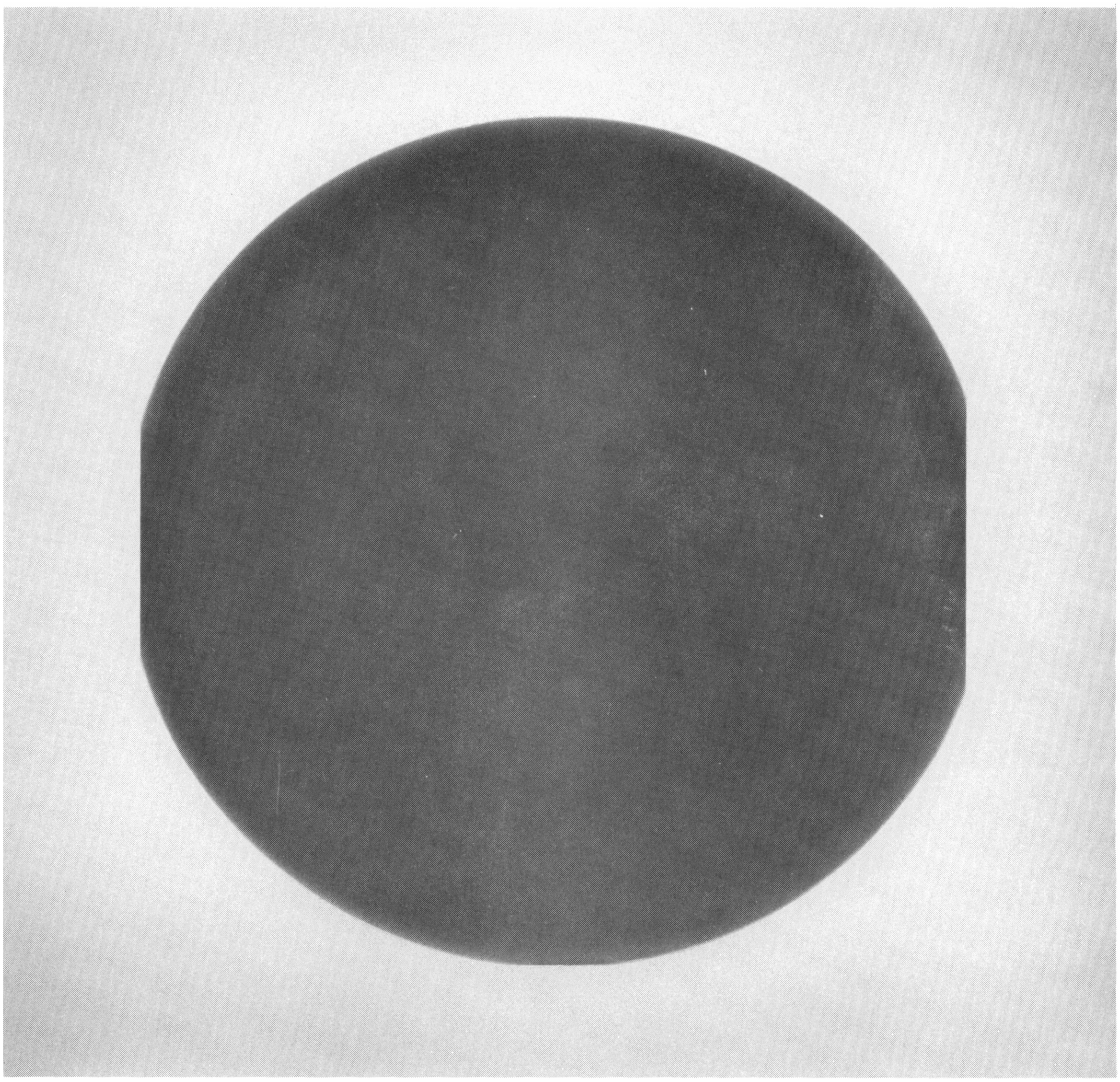

Figure C-6. DISC 502 AFTER 375° F IMPACTION AT 2.4 X 10^5 PSI.

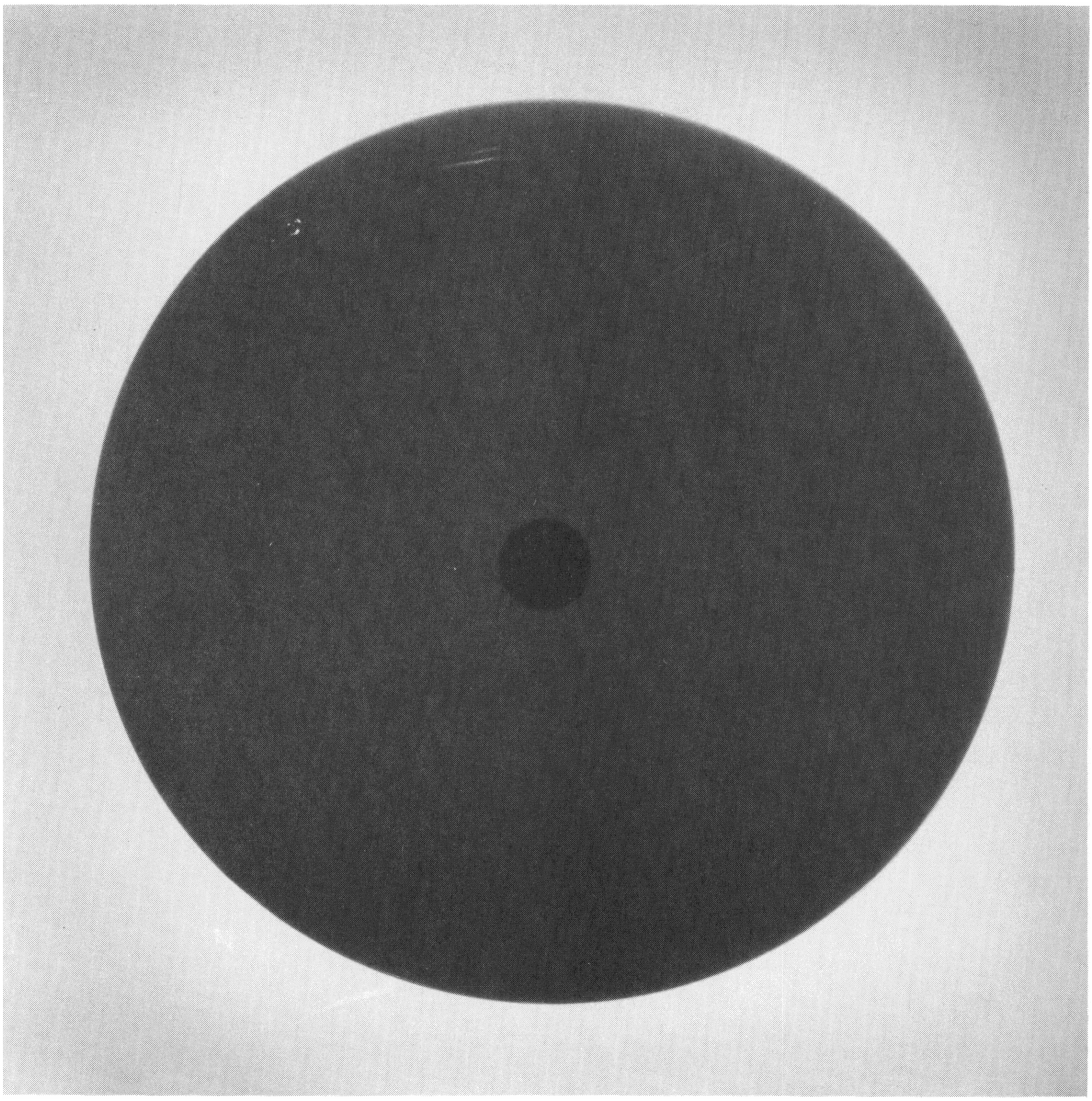

Figure C-7. DISC 505 (1/16-INCH THICK) ROLLED AND SALT ANNEALED; NOT IMPACTED.

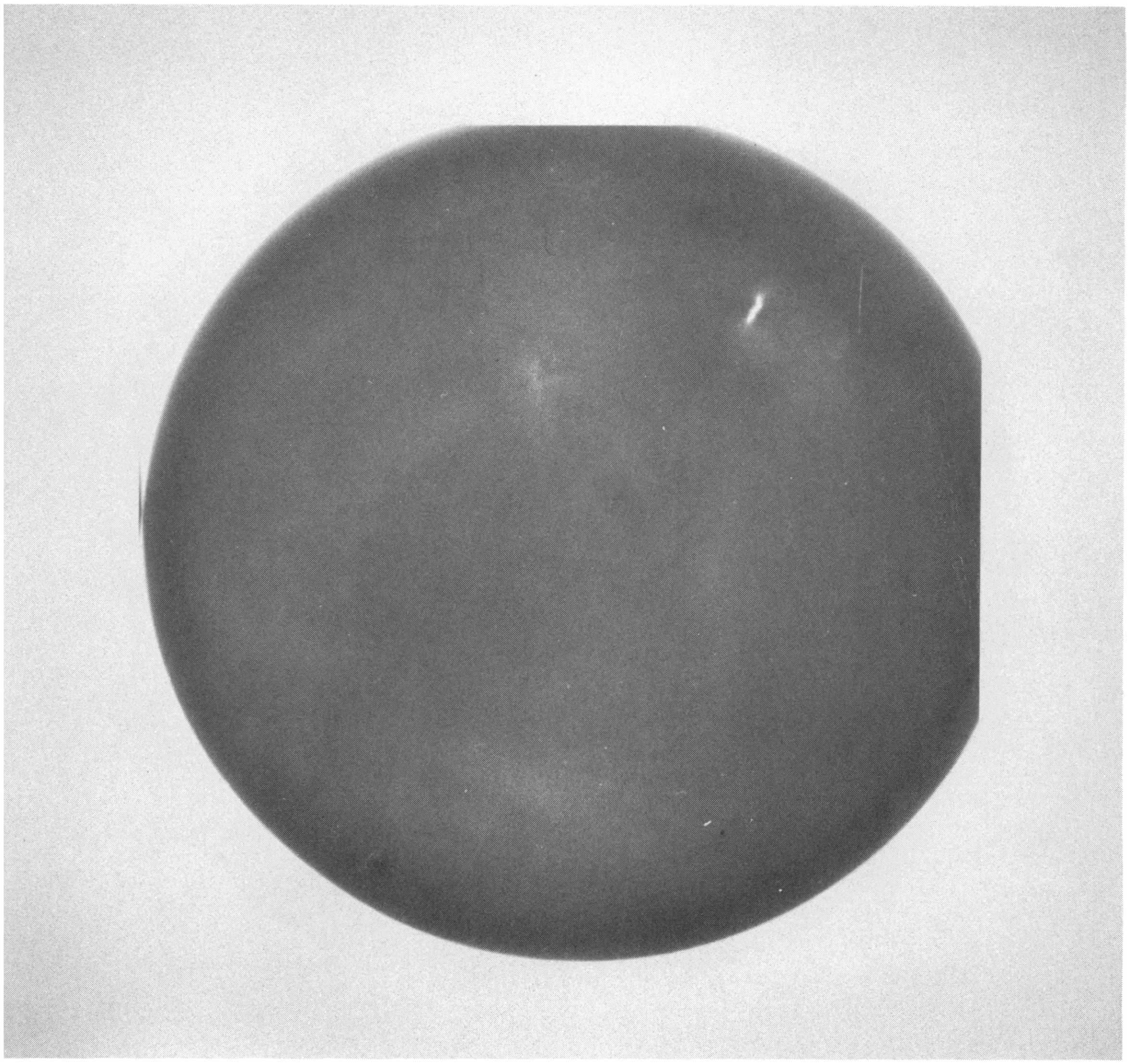

Figure C-8. DISC 505 AFTER 375° F IMPACTION AT 2.4 X 10^5 PSI.

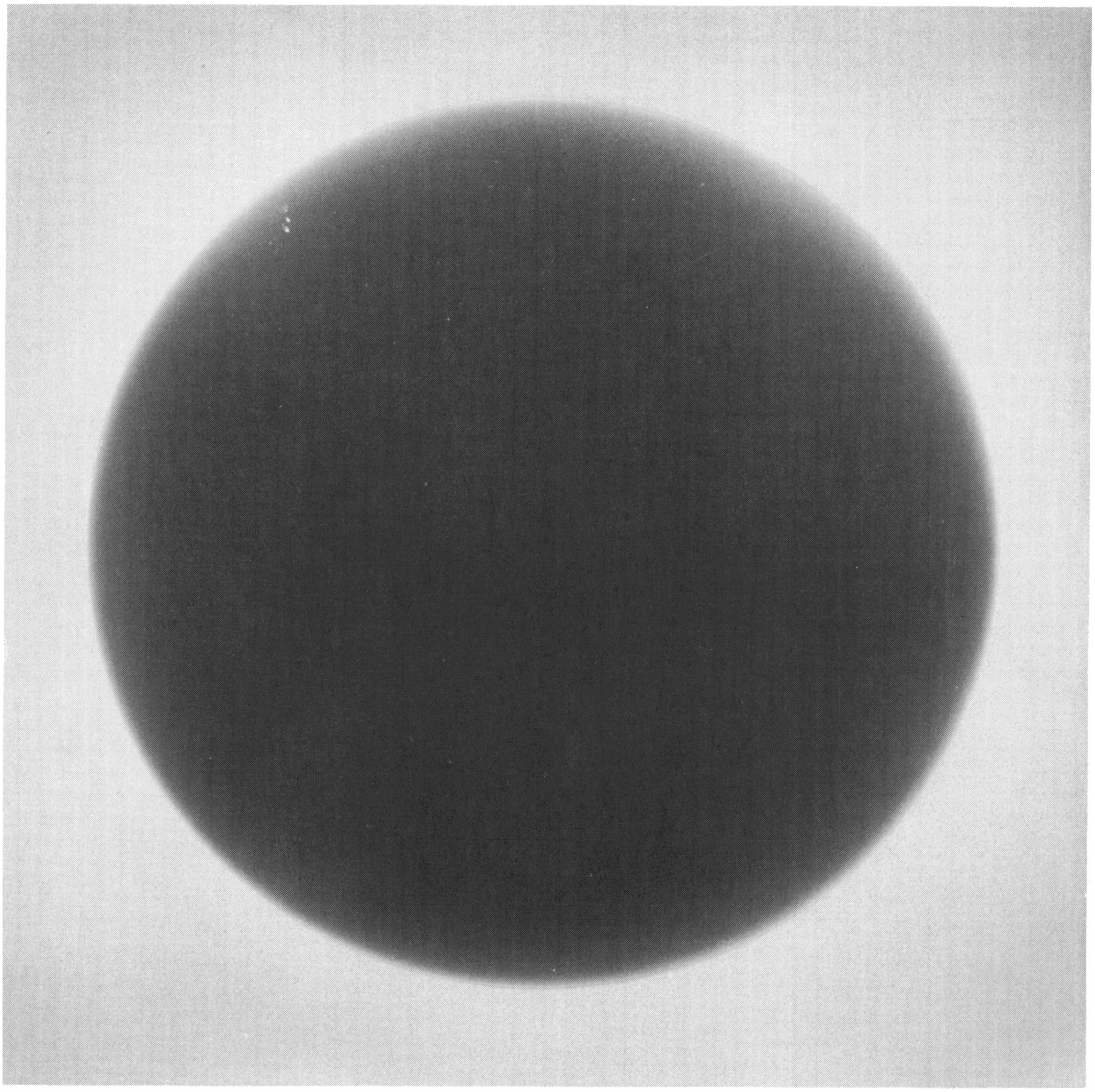

Figure C-9. DISC 313 (1/4-INCH THICK) AS CAST; NOT IMPACTED.

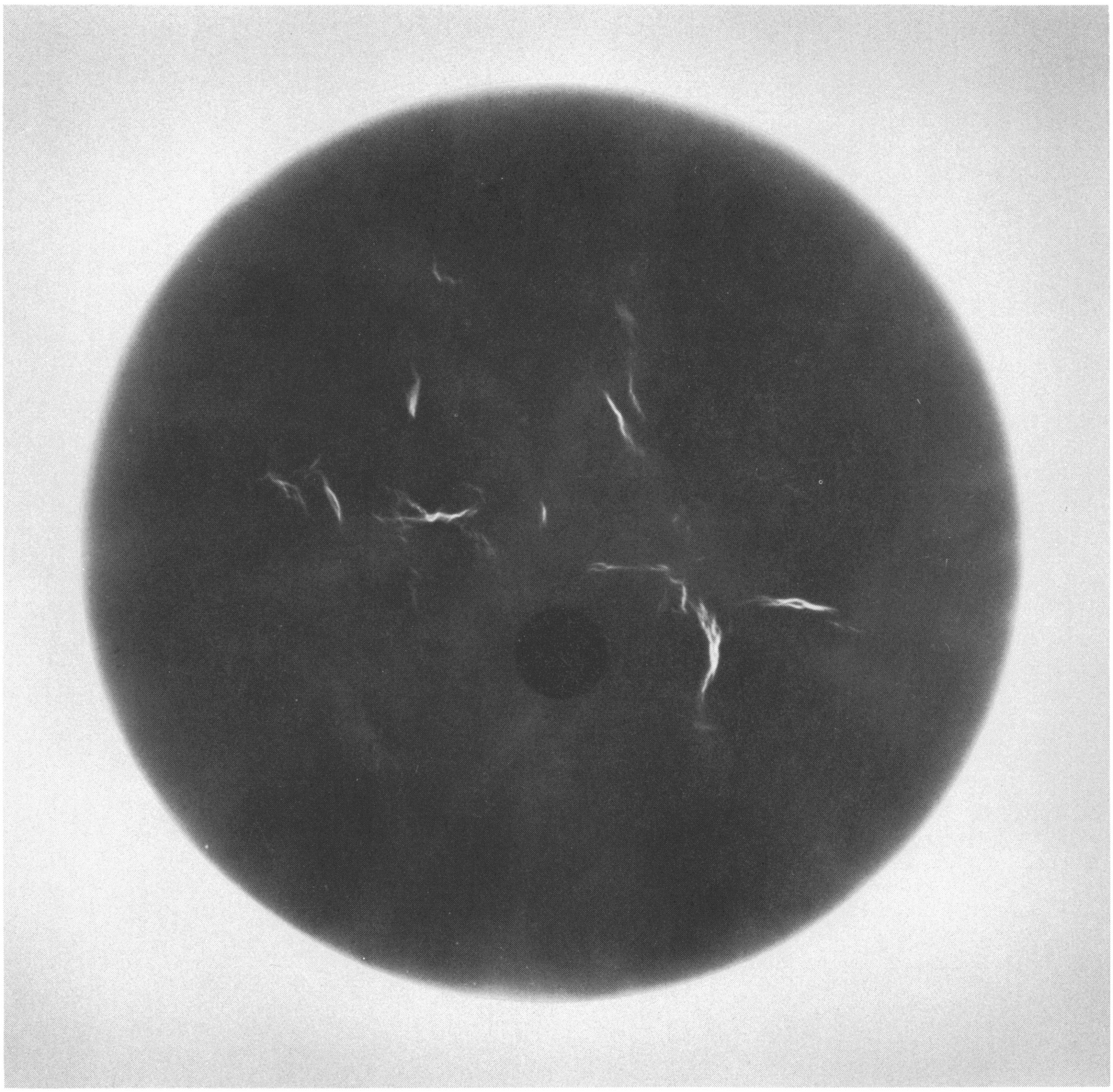

Figure C-10. DISC 313 AFTER AMBIENT-TEMPERATURE IMPACTION AT 5.3×10^5 PSI.

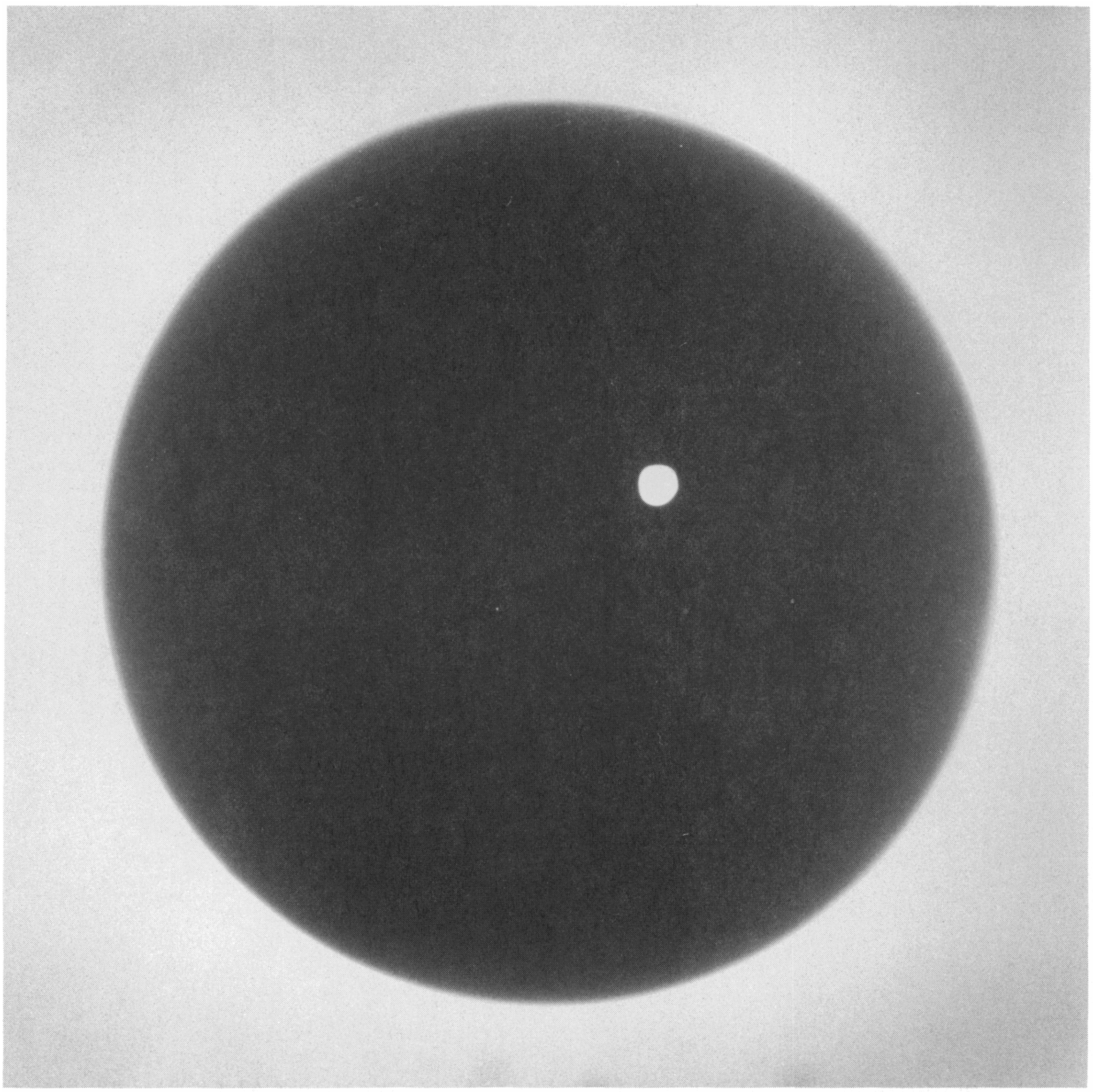

Figure C-11. DISC 314 (1/4-INCH THICK) AS CAST; NOT IMPACTED.

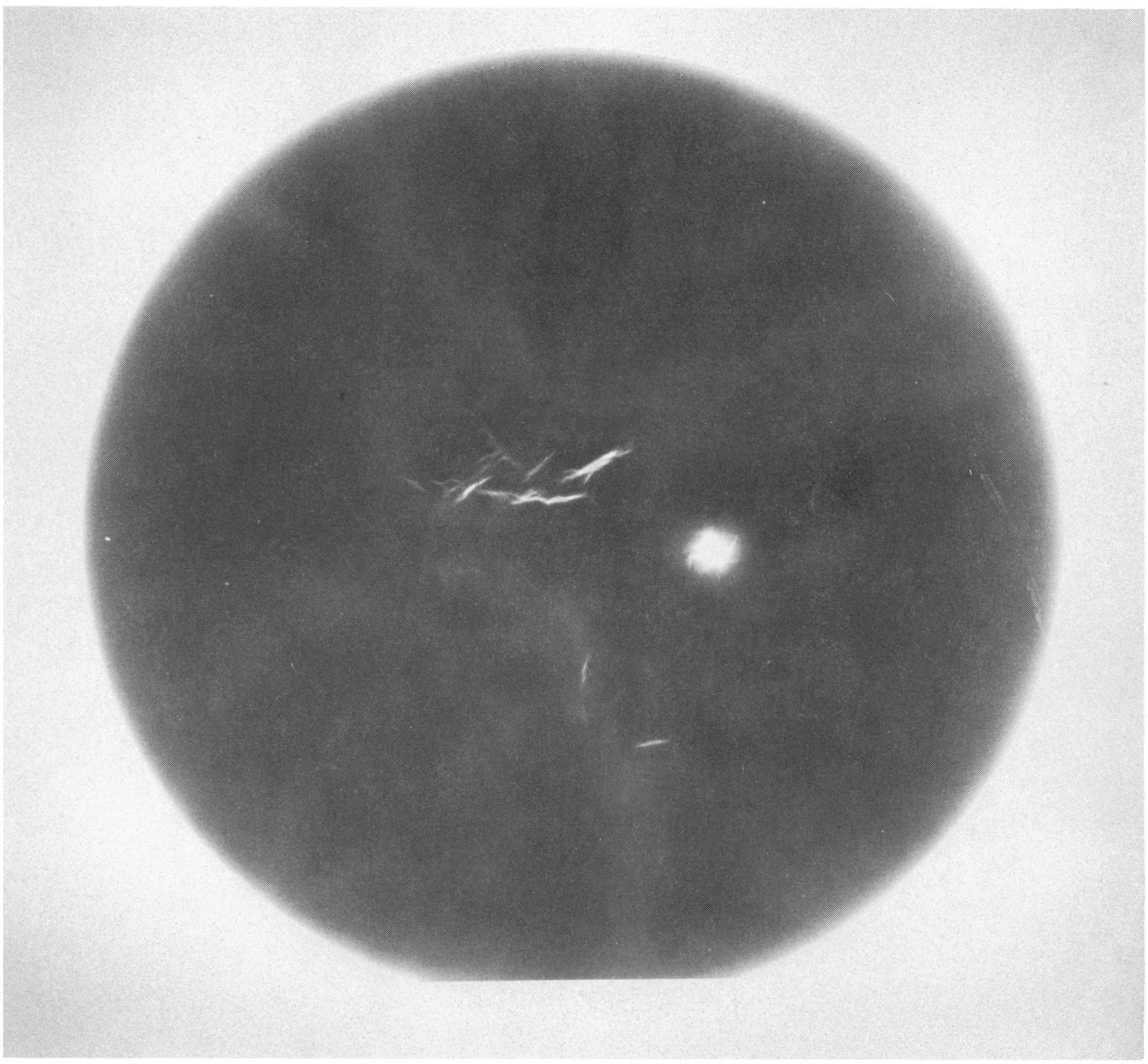

Figure C-12. DISC 314 AFTER AMBIENT-TEMPERATURE IMPACTION AT 1.1×10^5 PSI.

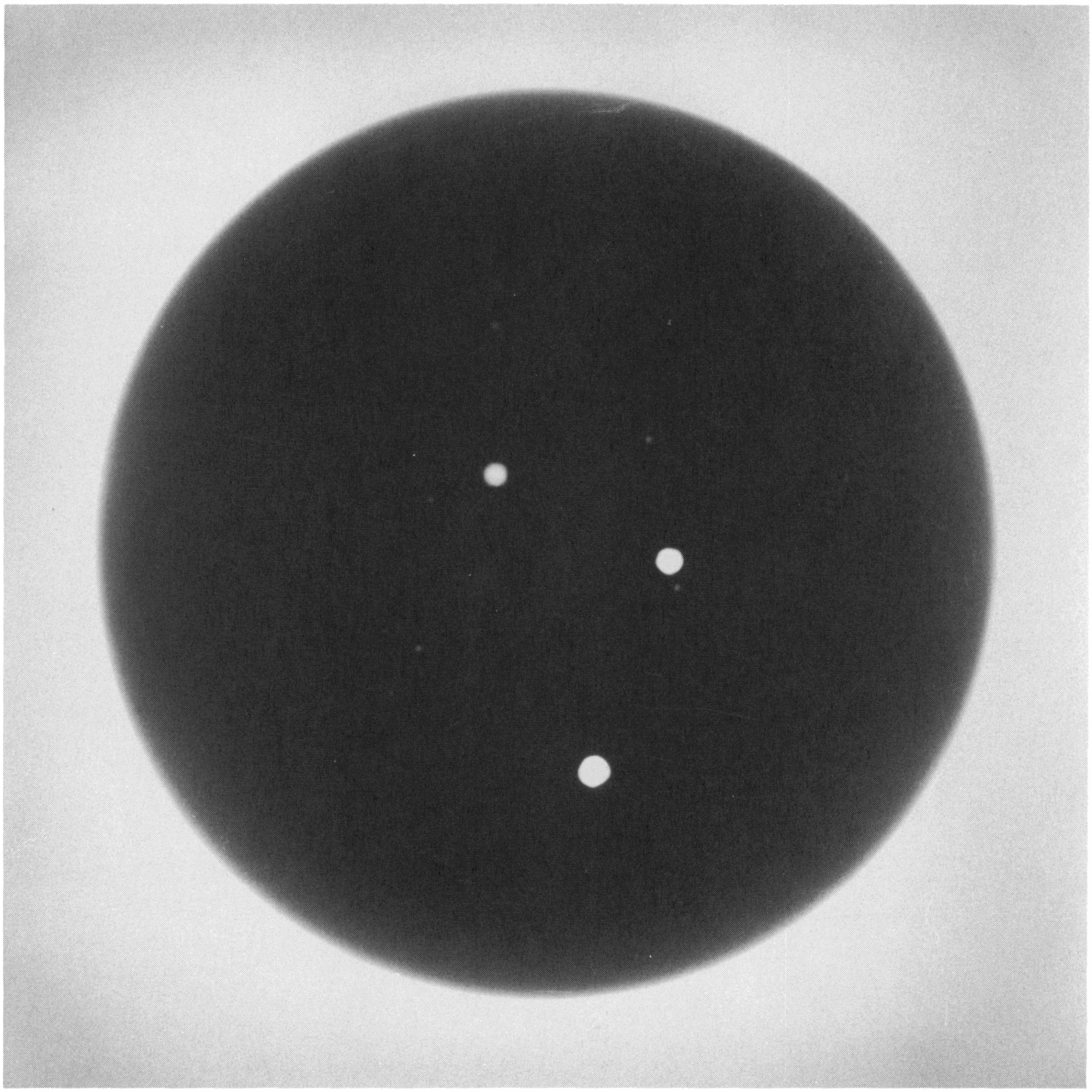

Figure C-13. DISC 712 (1/4-INCH THICK) AS CAST; NOT IMPACTED.

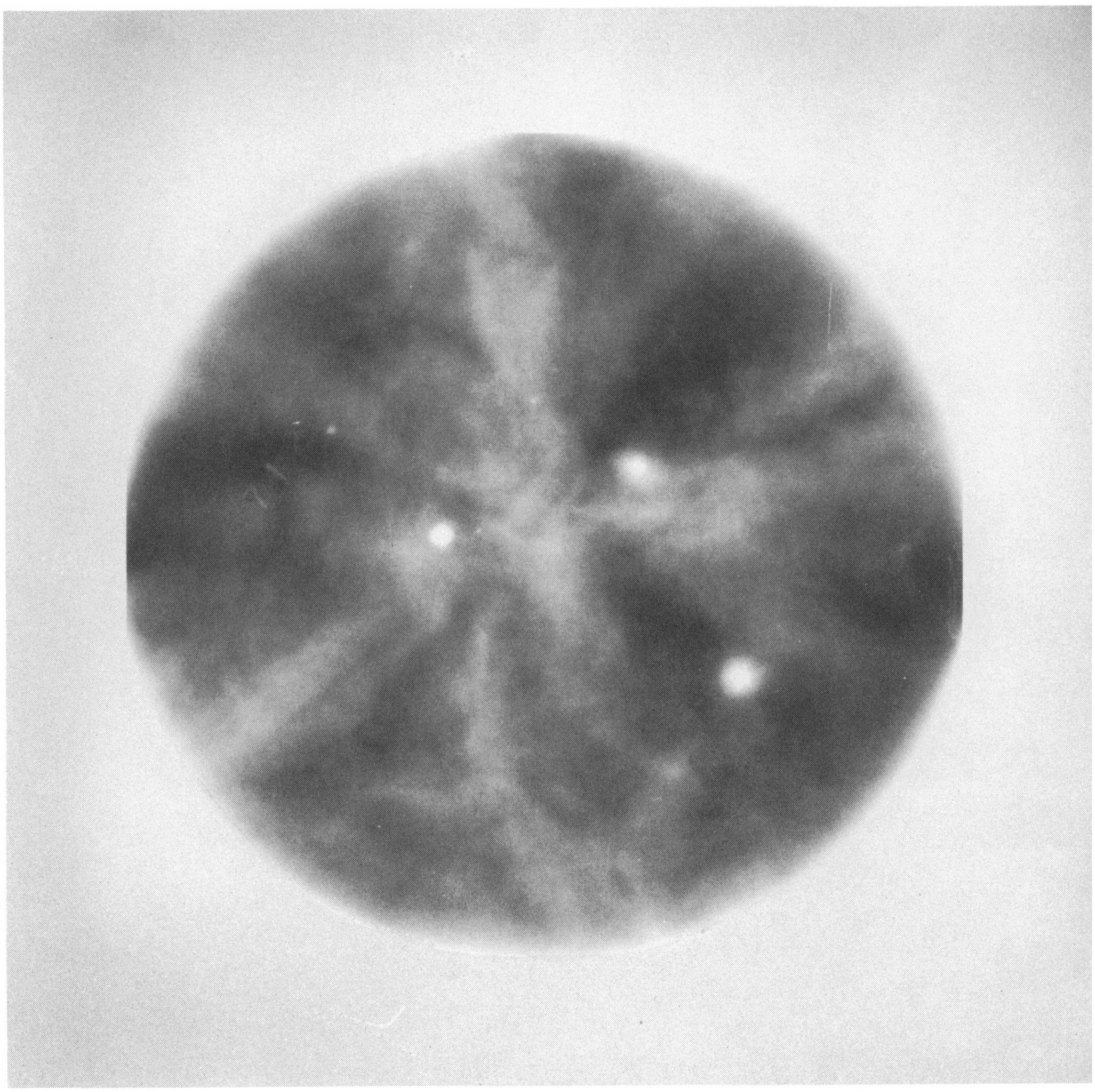

Figure C-14. DISC 712 AFTER 375° F IMPACTION AT 2.4 X 10^5 PSI.