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EXPLOSIVE FORMING OF SOLID PROPELLANT ROCKET MOTOR END CLOSURES

J. R. Kapp

THIOKOL CHEMICAL CORPORATION
Wasatch Division
Brigham City, Utah

Technical Publication AFML-TR-70-136

June 1970

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ROCKET MOTOR END CLOSURES

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FOREWORD

This Technical Report covers the work performed under Contract F33615-69-C-1081 from 1 February 1969 through 30 April 1970.

This contract with the Thiokol Chemical Corporation, Wasatch Division, Brigham City, Utah, was initiated under Manufacturing Methods Project 780-8, "Advanced Explosive Forming." It was accomplished under the technical direction of Mr. Kenneth Love, Fabrication Branch (LTF), Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

Mr. D. G. Jensen was the Program Manager and Mr. J. R. Kapp was the Project Engineer. Hardware development was directed by Mr. O. N. Thompson, Supervisor, Metallurgical Section. Other Thiokol Chemical personnel cooperating on the program included Mr. D. Cunningham and Mr. R. Robbins, Metallurgical Section.

Explosive Fabricators Division of Tyco Industries was the major subcontractor assigned the responsibility of the explosive forming demonstration. Mr. R. Agricola was the Program Manager and Mr. G. Lemonds, the Project Engineer.

This project has been accomplished as a part of the Air Force Manufacturing Methods Program, the primary objective of which is to develop, on a timely basis, manufacturing processes, techniques and equipment for use in economical production of USAF materials and components.

Your comments are solicited on the potential utilization of the information contained herein as applied to your present or future production programs. Suggestions concerning additional manufacturing methods development required on this or other subjects will be appreciated.

This technical report has been reviewed and is approved.


JACK R. MARSH
Chief, Fabrication Branch
Manufacturing Technology Division

ABSTRACT

This report describes the manufacturing processes developed as a preliminary step in establishing a lower cost production capability for large solid rocket motor end closures. The objective of the program was to evaluate two new approaches to the use of explosive energy for forming large, high strength steel hemispheres suitable for fabrication into SRM end closures and subsequently to analyze the overall processing costs. The two approaches, which are complementary in nature, consist of (1) a die developed from ring segments suitable for production use after successful demonstration, and (2) use of welded truncated conical preforms in place of flat blanks as starting material. The data derived from the program provide an insufficient basis upon which to base definite conclusions. However, despite numerous unexpected difficulties in preform fabrication and limited success in explosively forming them, it is concluded that the segmented subscale die could be scaled to full size without undue difficulty. Strain calculations verified by limited experimental results indicate that the target configuration is within the formability limits of a properly fabricated, thermally conditioned, and suitably restrained preform.

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SECTION I INTRODUCTION

The manufacturing methods utilized over the past 10 to 15 years have resulted in high quality, reliable hardware for use in launch vehicle and weapons systems. Improvements in technique of manufacture and the development of new methods for forming and joining components have further enhanced the production of close tolerance, man rated structures. The main emphasis over the past several years has been in optimized performance and reliability, not at any cost, but at whatever cost that was commensurate with the desired results. Experience in the flight testing of numerous vehicles has permitted the assessment of manufacturing methods and performance characteristics. It has become apparent that less expensive methods for the production of launch vehicle and solid rocket structures can be adapted to specific segments of the systems to effect significant cost reductions without sacrifice in performance or structural integrity.

One of the most expensive items in a solid rocket motor is the end closure or dome necessary to encapsulate the solid propellant grain and permit pressurization to achieve greater burning efficiencies. The present methods of manufacture include the hot forming of one piece domes and subsequent welding of various attachment members. Because of the need for uniform, thin walled units, extensive machining is required after forming to produce a suitable end closure. The high costs associated with the past and present methods of manufacture formed the incentive for conducting a program to select a more efficient technique of producing relatively low cost, high quality hardware. Explosive forming was selected as the process most likely to satisfy the desired program objectives.

Three general methods of explosively forming domes are currently being utilized within industry: (1) deep drawing; (2) compression forming; and (3) sizing, using a developed preform. These methods were studied with regard to cost, reliability, versatility of tooling, and explosive charge requirements. The third method, using a developed preform to the finished hemispherical thickness, was selected for the program.

This new concept was proposed whereby a welded preform could be produced, placed in a segmented die, filled with water, and explosively formed to hemispherical shape. Igniter boss members and Y-frame sections could be welded to the preform prior to forming. The preform concept permitted the use of constant thickness material which, when properly selected, would eliminate the requirement for subsequent machining. Thus, the only machining needed would be for the igniter boss and Y-frame. If the preform itself was used as the container for water, a large pool or body of water would probably not be necessary. Charge requirements could be significantly reduced if preforms were used. Segmented sections for die construction would permit the use of low capacity cranes for lifting and would allow ground level

working conditions. Consequently, the preform and segmented die concepts could easily result in reduced costs and equivalent reliability of fabricated domes.

One of the major purposes of this program was to verify the usefulness of explosive forming for the production of close tolerance domes by use of the preform concept. Subscale parts were formed to substantiate parameters and determine die performance characteristics. The data obtained from this subscale work could be scaled to larger diameter components.

In summary, the primary objectives in this Air Force Manufacturing Technology program were to:

1. Establish a method wherein acceptable preforms could be fabricated for forming into subscale domes.
2. Demonstrate the suitability of segmented forming die hardware.
3. Apply explosive forming techniques necessary to form the various preform configurations into subscale hemispherical domes.
4. Generally advance the state-of-the-art of explosive forming of domes, and make recommendations and conclusions concerning the practicality of the process.

The intent of the program was to accomplish the above objectives by conducting a 24 in. diameter subscale program. The initial effort was to consist of explosively forming simple truncated conical preforms into hemispherical domes. As the program progressed, the design was changed to include a semifinished igniter boss. Based on the success of this step, a third configuration was to have been fabricated which would include enough material for a stub skirt and cylindrical extension. The major effort was to be completed using D6AC material. However, a minimum effort was to be conducted using HP9-4 preforms which had been heat treated prior to welding.

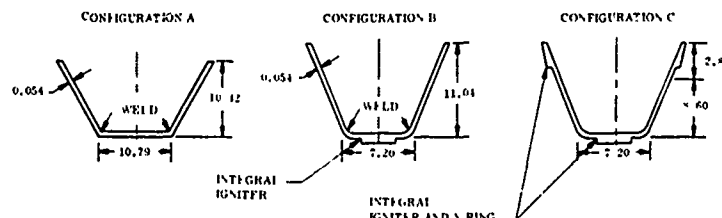
The original program was to consist of forming nine subscale models. The structure of the original program is shown in Table I, which also shows the purpose of each individual preform.

Program complications required that this model matrix be substantially modified. The final test matrix along with specific objectives and results is summarized in Table II.

The forming of each individual preform is discussed in detail in Section VII.

TABLE I
ORIGINAL SUBSCALE FORMING MATRIX

Unit No.	Configuration	Material	Objectives and Data
1	A	D6AC	a. Form essentially constant thickness dome from preform. b. Verify subscale forming die performance. c. Obtain postforming dimensional data from formed dome. d. Obtain residual stress data from sections of formed dome. e. Measure basic physical properties of formed material.
2	B	D6AC	a. Form dome with preattached polar boss reinforcement. b. Verify subscale forming die performance. c. Obtain postforming dimensional data from formed dome. d. Obtain residual stress data from sections of formed dome. e. Measure basic physical properties of formed material.
3	A	HP9-4	a. Form essentially constant thickness dome from heat treated preform. b. Verify weld integrity (welded after heat treatment). c. Obtain postforming dimensional data from formed dome. d. Obtain residual stress data from sections of formed dome. e. Measure basic physical properties of formed material.
4	B	D6AC	a. Duplicate of Unit No. 2 to provide reproducibility data. b. Verify subscale forming die performance. c. Obtain postforming dimensional data from formed dome. d. Obtain residual stress data from sections of formed dome. e. Measure basic physical properties of formed material.
5	B	HP9-4	a. Form dome with preattached polar reinforcement from heat treated material. b. Verify subscale forming die performance. c. Obtain postforming dimensional data from formed dome. d. Obtain residual stress data from sections of formed dome. e. Measure basic physical properties of formed material.
6	B	HP9-4	a. Duplicate of Unit No. 5 to provide reproducibility data. b. Verify subscale forming die performance. c. Obtain postforming dimensional data from formed dome. d. Obtain residual stress data from sections of formed dome. e. Measure basic physical properties of formed material.
7	B	D6AC	a. Determine effects of thermal stress relief* on: 1. Post forming dimensions, 2. Residual stresses, 3. Physical properties.
8	C	D6AC	a. Form dome with preattached polar boss and Y-joint reinforcements. b. Verify subscale forming die performance. c. Obtain postforming dimensional data from formed dome. d. Obtain residual stress data from sections of formed dome. e. Measure basic physical properties of formed material.
9	C	D6AC	a. Duplicate of Unit No. 8 for reproducibility data. b. Verify subscale forming die performance. c. Obtain postforming dimensional data from formed dome. d. Obtain residual stress data from sections of formed dome. e. Measure basic physical properties of formed material.



NOTE: *This unit is identical to Units 2 and 4, except that it will be thermally stress relieved before determining dimensional data and physical properties.

TABLE II
FINAL SUBSCALE FORMING MATRIX

<u>Unit No.</u>	<u>Configuration</u>	<u>Material</u>	<u>Objectives and Results</u>
1	A	D6AC	a. Fabrication technique and tool checkout. b. Formed after numerous circumferential weld repairs; no longitudinal weld repairs required.
2	A	D6AC	a. Forming attempt resulted in circumferential weld failure. b. Failure analysis resulted in preform design change and weld processing change.
3	A	HP9-4	a. Fabricated from annealed plate to gain some familiarity with welding and rolling HP9-4. b. Subsequently used in subprogram to verify that buckling problem had been eliminated.
4	A	D6AC	a. First preform from modified design and process technique. b. Forming attempt made using circular Primacord charge. c. Buckling occurred.
5	A	HP9-4	a. Hardened HP9-4 preform. b. Failed in forming with circular Primacord charge. c. Preform was completely restrained during forming. d. Failure analysis indicated basic overstrained condition; no weld or material flaws. e. A great deal of work hardening noted in some areas.
1	B	D6AC	a. First Configuration B preform. b. Circular charge Trojamite explosive; preform completely restrained. c. Failed, longitudinal rupture. d. Preform left intact for possible repair.
2	B	D6AC	a. Point TNT charge substituted for circular charge; preform completely restrained. b. Longitudinal rupture near welds; origins of failure pinpointed by electron fractography. c. No material defects; overstrained condition.
3	B	HP9-4	a. Rolled and heat treated. b. Work discontinued.
4	B	HP9-4	a. Rolled and heat treated. b. Cone half sections straightened out during heat treatment. c. Work discontinued.
5	B	D6AC	a. Completed preform annealed in furnace prior to forming. b. Point TNT charge with preform completely restrained. c. Failure near longitudinal weld. d. Failure analysis showed 15 percent elongation capability in material; grain structure with not quite desired uniformity.

TABLE II (Cont)
FINAL SUBSCALE FORMING MATRIX

<u>Unit No.</u>	<u>Configuration</u>	<u>Material</u>	<u>Objectives and Results</u>
1 (R)	B	D6AC	a. Repaired Preform 1B. b. Allowed to slip under die during forming. c. Normalized and double tempered prior to forming. d. Two inprocess repairs required in area of original repair. e. Circumferential weld and good longitudinal weld fully formed. f. Grain uniformity very good across weld; 19+ percent elongation noted.
6	B	D6AC	a. Completely fabricated. b. Work discontinued due to end of program.
1	C	D6AC	a. Rolled and longitudinally welded. b. Work halted; end of program.
2	C	D6AC	a. Rolled and one longitudinal weld made. b. Work halted; end of program.

SECTION II SUMMARY

Originally, the program encompassed three different preform designs: (1) Configuration A, having a flat plate of constant thickness at the small end of a truncated cone; (2) Configuration B, replacing the flat plate with a premachined igniter boss; and (3) Configuration C, designed with provisions for both an igniter boss and a Y-ring. The original program plan was considerably altered due to difficulties which were encountered in the forming of preforms of the first two configurations. Therefore no forming was attempted on the final configuration.

Preform 1A (D6AC steel) was restrained by fifteen 0.75 in. bolts torqued to 80 ft-lb (which allowed the preform to slip in the die) and with the weld positioned on the knuckle. Although the weld (and its repaired areas) fractured several times, the part was completely formed with a series of nine central point TNT shots. Preform 2A (D6AC steel) was similarly restrained, with torque increased to 90 ft-lb. The circumferential weld cracked on the first shot (10 gm TNT, point charge). The preform was subjected to a failure analysis which yielded the following conclusions: (1) the welds should be given a final stress relief after weld repair, and (2) the weld location should be shifted off the knuckle to decrease strain requirements.

These ideas were incorporated for the next preform (4A, also of D6AC steel). The restraint and torque were the same as for 2A, but a Primacord ring charge was used and the weld was shifted 0.25 in. from the knuckle. The first shot produced a severe longitudinal buckle near the knuckle. At this point it was reasoned the 80 and 90 ft-lb torques used thus far were allowing the slippage from under the clamping ring which was causing buckling. In an attempt to verify this theory, a Cor-ten steel subprogram was conducted. Although there was one weld failure, two Cor-ten preforms were successfully formed using increased torque. One Cor-ten preform with torque reduced again to 90 ft-lb buckled similarly to 4A. The Cor-ten subprogram seemed to substantiate the theory that complete restraint would eliminate the buckling problem. Preform 3A, an annealed HP9-4 steel which had been shelved because of the weld-on knuckle problem, was used to back up the total restraint theory.

Preform 5A (HP9-4 fully hardened steel) was restrained with 27 (1.0 in. dia) bolts torqued to 475 to 500 ft-lb. The explosive for the first shot was a 9 in. Trojamite circular charge, with the weld shifted 0.25 in. from the knuckle. Despite these changes, the preform split into two pieces on the first shot. Republic Steel performed a failure analysis, concluding that fracture was due to a basic overstrained condition and not to a flaw in the metal, and recommending a post-tempering of the weld for 1 hr at 900° to 1,000° F.

Preform 1B (the first Configuration B unit) was D6AC annealed steel, restrained with 27 (1.0 in. dia) bolts and 580 ft-lb torques, and shaped with a 6 in. Trojamite circular charge. A longitudinal rupture was caused on the first shot.

The failure was again attributed to a basic overstrained condition. It was observed that the circular charge configuration provided greater charge efficiency. However, the repeated failures while using this charge configuration led to the conclusion that the centrally located TNT charge configuration would be a more conservative approach.

Preform 2B (D6AC steel) was restrained with 27 (1.0 in. dia) bolts and 580 ft-lb torque. The forming attempt utilized TNT point charges. The welds were subjected to local heat treatment. On the second shot, fractures occurred in the weld and the parent material. The failure analysis showed hardness to be high in certain areas and low in other areas, suggesting different responses to the stress relief. Again, a basic overstrained condition seemed responsible.

A special study on D6AC steel heat treatment showed that a local weld thermal treatment at 1,250° F for 1.5 hr (and then treatment of the entire preform at 1,550° F for 2 hr) would reduce R_c hardness to the 25 to 30 range.

Preform 5B (D6AC fully hardened steel) was stress relieved according to findings of the special study. The preform was completely restrained again and formed with TNT point charges. The preform fractured on the fourth shot. Failure analysis revealed no material defect and showed that good ductility had been achieved by the heat treatment. The preform had only achieved one half necessary deformation when failure occurred. Because Preform 1A (which had been allowed to slip in the restraining ring) had been successfully formed with a series of shots, it seemed logical to assume that if the preform was allowed to slip and an R_c hardness of 25 to 30 achieved, successful forming might be achieved. A special strain requirement analysis conducted on the computer was used to verify that D6AC steel did not have the strain capability for forming with complete restraint.

Impending program termination necessitated that the previously fractured Preform 1B be repaired and used. This was done to test the theory that properly stress relieved D6AC steel could be completely formed with a point charge arrangement if the preform was allowed to slip in the restraining ring. The weld repair was of questionable quality, but time limitations necessitated that this preform be used. The preform was subjected to stress relief, normalization, and double tempering. A series of TNT point charges was used for forming. Two to four shots are envisioned for production, but the series was used to permit observation of the blank movement. Fifteen 1.0 in. dia bolts were torqued to permit slippage in the restraining ring. Despite cracks adjacent to the previously repaired weld on two of the shots, the preform was completely formed by the series.

Table III presents a summary of all preforms including those used in subprograms and those in various stages of completion when the program was terminated.

SUMMAR

Preform	Material	Cerro Plug	Torque (ft lb)	Bolts		Explosive Type	Size (gm)	Stand Distance (in)
				No.	Dia (in.)			
1A	D6AC (standard mill rolled)	No	80	15	0.75	TNT (point charge)	10	3 1/2
							10	3 1/2
							10	4
							10	4
							10	5
							15	6
							20	7
							30	8
2A	D6AC (standard mill rolled)	No	90	15	0.75	TNT (point charge)	40	8
							10	8
4A	D6AC	Yes	90	15	0.75	Primacord (ring charge)	20 (TNT) (EQUIV)	6 3 in from side
SUBPROGRAM								
	Cor-ten No. 1	Yes	250	15	0.75	Primacord (ring charge)		6
	Cor-ten No. 2	Yes	250	15	0.75	Primacord (ring charge)	20	6
	Cor-ten No. 3	Yes	90	15	0.75	Primacord (ring charge)	20	6
	Cor-ten No. 4	Yes	125	15	0.75	Primacord (ring charge)	20	6
3A	HPF-4 Annealed	Yes	250	15	0.75	Primacord (ring charge)	20 20 10 20	6
5A	HP9-4 (fully hardened) FTU ≈ 200 Ksi	Mach Alum Plug	475-500	27	1.0	Trojamite (3/8 in. Tygon tubing) 9 in. circular charge (equivalent to 20 gm of Primacord) Four blasting caps at 90 deg intervals	43	6 in from bottom 5 in from wall
1B	D6AC	NA (Igniter Boss)	580	27	1.0	Trojamite (6 in. circular charge) single centrally located blasting cap	31	6 in from bottom and side
2B	D6AC	NA	580	27	1.0	TNT (point charge)	10	3
						TNT (point charge)	10	3

TABLE III
SUMMARY OF SUBSCALE FORMING RESULTS

Explosive	Size (gm)	Standoff Distance (in.)	Weld Position	Stress Relief		Results
				Time (hr)	Temp (°F)	
Large)	10	3 1/2	On knuckle	1.5	960 (Longitudinal)	Weld fractured. Formed at apex. Circumferential weld fractured at areas near repaired areas. No further weld failures.
	10	3 1/2		2.0	800 (Circumferential)	
	10	4				
	10	4				
	10	5				
	15	6				
	20	7				
	30	8				
Large)	40	8	On knuckle	1.5	960 (Longitudinal)	Completely formed with no cracks in longitudinal weld.
				2.0	800 (Circumferential)	
	20	6	0.025 in. from knuckle	2.0	1,350 (Longitudinal)	Circumferential weld cracked. Failure analysis revealed: weld over-strain condition, cracks originated in repair areas not stress-relieved (R _C of 58 to 60). Coarse grained martensitic microstructure in crack initiation areas. Incomplete blend radius contributes to crack susceptibility. No cracking where no repairs were made and proper blending existed. Difficulty in maintaining constant material thickness when weld is located on knuckle. Longitudinal welds intact even in weld repair areas. Stress relieved weld areas with R _C of 40 to 50 (too high for required elongation). Failure analysis conclusions: weld stress relief, weld blending, and shift circumferential weld off knuckle to decrease strain requirements.
	(TNT) 3 in. from sidewall			1.5	1,250 (Circumferential)	
		6	Knuckle	None	None	Severe longitudinal buckle near the knuckle area. Preform had slipped in the restraint ring and attenuated elastic wave caused buckle. Circumferential weld remained intact. Increased charge efficiency. Two to three shot production forming sequence shown to be realistic. Failure analysis X-rays showed weld rupture due to buckling (not to defect in or near weld). Conclusion: to increase clamping force. Conclusions to be verified by relatively low grade steel (Cor-ten) subprogram.
	20	6	Knuckle	None	None	Part formed in three shots. No buckling nor tendency to buckle.
	20	6	Knuckle	None	None	Longitudinal weld failure. Buckling (adjacent to weld failure) attributed to weld failure rather than insufficient restraint.
	20	6	Knuckle	None	None	Buckling similar to preform 4A.
	20	6	Knuckle	None	None	Forming completed with no buckling. Program seemed to indicate that complete restraint should eliminate buckling. However, weld on knuckle experienced failure.
	20	6	Knuckle	1.5	960 (Circumferential)	Preform 3A formed as verification of Cor-ten subprogram. Cerro plug crushed after second shot and was removed. Circumferential weld failed on third shot, was repaired, and forming was completed. Decision was made to replace Cerro plug with aluminum plug.
	20			2.0	800 (Longitudinal)	
	10					
	20					
	43	6 in. from bottom	0.25 in. from knuckle	None	None	Preform split longitudinally into two pieces on the first shot, sent to Republic Steel for analysis. Conclusion: failure did not originate from area of flaw or inclusion but was result of basic overstrained condition.
		5 in. from wall				
	31	6 in. from bottom and sidewall	0.25 in. from knuckle	1.5	1,250	Republic Steel failure analysis showed: R _C hardness of weld 49 to 50. Parent material R _C at 46 to 47. R _C in heat affected zones varying from 52 to 57. Recommendations: post-tempering of 1 hr at 900° to 1,000°F, and use of low carbon steel (HP9-4-20) in place of high carbon (HP9-4-25).
	10	3 1/2	0.25 in. from knuckle	1.5	1,250	Longitudinal rupture in parent material on first shot 0.080 to 0.160 in. away from and parallel to weld. No material defect could be found. Attributed to basic overstrained condition.
	10	3 1/2				
						Decision was made to return to central charge on subsequent shots.
						Approximately 0.25 in. uniform deformation on first shot.
						Second shot fractures adjacent to longitudinal weld, and in parent material and along circumferential weld. Behavior typical of alloy with very limited ductility. Failure analysis showed: fracture origins 0.090 and 0.040 in. from weld. Microhardness transverse were high in circumferential weld and heat affected zone (49 to 51 R _C) and low elsewhere suggesting different response to stress relieving treatment. More precisely controlled processing procedures may be required. Failure analysis indicates overstrained condition and not material defect.

SU

Preform	Material	Cerro Plug	Torque (ft lb)	Bolts		Explosive								
				No.	Dia (in.)	Type	Size (gm)							
5B	D6AC	NA	580	27	1.0	TNT	10							
						TNT	10							
						TNT	10							
						TNT	10							
1B(R)	D6AC	NA		15	1.0	Powdered TNT								
							3B	HP9-4						
4B	HP9-4													
1C	D6AC													
2C	D6AC													
6B	D6AC													

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TABLE III (Cont)
SUMMARY OF SUBSCALE FORMING RESULTS

Explosive	Size (gm)	Standoff Distance (in.)	Weld Position	Stress Relief		Results
				Time (hr)	Temp (°F)	
NT	10	3 1/2	0.25 in. from knuckle	Weld: 1,250°F for 1 1/2 hr		Fracture adjacent to longitudinal weld in parent material originating 0.200 in. from weld edge and a vertical distance of 3.35 to 3.50 in. from inside surface of igniter boss. Failure analysis showed no parent material defect, weld hardness of 98.7 R _p , parent material hardness of 98.1 R _p . Since good ductility was apparently present and rupture occurred with only one half deformation achieved, it was concluded that total restraint would not work, and that the part must be allowed to slip under the restraining ring.
	10	3 1/2		Entire Preform: 1,550°F for		
	10	4		2 hr		
	10	4				
			0.25 in. from knuckle	Weld repair: 1 hr at 1,050°F. Weld undercut and repaired, 1 hr at 1,000°F. Entire Preform: Normalized and double tempered by Pyromet Industries		The Tresca theory confirmed that D6AC steel does not have strain cap- ability for forming in complete restraint. For material to form under complete restraint, it must possess 28 percent strain capability in uniaxial tension. Ladish Co recommends change from anneal to normalization treatment followed by double temper, to realize best ductility from D6AC. This preform was the repaired preform previously used as 1B. It was used despite a bad weld condition because program time limitations pre- vented use of 6B, 1C, or 2C preforms. Stress relief, normalization, and double temper operations were performed in attempt to obtain 18 to 20 percent elongation and uniform grain structure across the weld. Hard- ness value of the weld was R _p 98 but weld area was of questionable quality. An ultra conservative sequence of 16 shots was devised to permit obser- vation of blank movement and weld deformation. (Production sequence is anticipated to require 2 to 4 shots.)
	10	3 1/2				
	10	3 1/2				
	10	4				
	10	4				
	10	5				
	15	6				
	5	4 1/2				
	5	5				
	10	5				
	15	5 1/2				
	20	6				
	20	7				
	30	8				
	40	8				
	40	7				
	40	7				
						Small crack adjacent to longitudinal weld previously repaired. Crack repaired.
					Longitudinal crack adjacent to same repaired weld. Crack repaired.	
					Preform formed to final contour.	
					Rolled and heat treated. Work discontinued.	
					Rolled and heat treated. Sections straightened out in heat treatment. Work discontinued.	
					Rolled and longitudinally welded. Work discontinued.	
					Rolled and longitudinally welded. Work discontinued.	
					Extra preform from Thiokol furnished material. Preform is complete through welding.	

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SECTION III SUBSCALE FORMING DIE

A. DIE DESIGN

During the first quarter of the program, a 24 in. subscale segmented die was designed. The individual segments were designed so that extrapolation of dimensions to the full scale, 120 in. diameter die would result in sections weighing approximately 20 tons or less. The die would thus contain 10 segments. Dimensions of full scale die segments are listed in Table IV. A detailed drawing of the assembled die is presented in Figure 1. The dimensions for the die, details of preform fit at the top of the die cavity, restraint rings and inserts for accommodation of Y frame and igniter boss members were dictated by final end closure configuration as discussed in Section VI. Outer skin line dimensions for Titan III SRM end closures were used to develop die configuration.

A survey was made of suitable materials for use in die construction. The ground rules established for selection of die material were the following:

1. Surface hardness should be adequate to prevent excessive wear during the forming of numerous parts. This requirement is not quite as important when a preform blank is used as it is when forming a flat blank since the relative movement between the die and blank is very minimal.
2. Machinability of the material should be good.
3. Impact resistance of 20 ft-lb at +20° F should be withstood.
4. Alloy cost should be as low as possible to minimize die costs.
5. Wrought material should be used if possible because of desirable grain size characteristics and deformation properties.

One of the problems encountered when considering low to medium carbon steels was the hardenability limitations when processing 8 to 10 in. thick plate necessary for the full scale die. Hardness levels on the Rockwell C scale ranging from 26 to 30 R_C were desirable as a minimum, since the material to be formed would be about R_C 30 in the annealed condition. The carbon steel satisfying all of the ground rules was 1035 steel. The Metals Handbook* gives the results of end quench tests for 1037 steel. This steel is very similar to 1035, falling in the same carbon range (0.32 to 0.38) and differing only slightly in manganese content (0.60 to 0.90) for 1035 compared to 0.70 to 1.00 for 1037. The handbook shows

*Metals Handbook, Volume I, 8th Edition, Metals Park, Ohio: American Society for Metals, 1961.

TABLE IV
SEGMENT SIZES FOR FULLSCALE FORMING DIE*

<u>Outside Diameter (in.)</u>	<u>Inside Diameter (in.)</u>	<u>Segment Weight (lb)</u>
156	121.50	18,050
156	115.00	20,944
156	110.75	22,755
156	101.00	26,646
156	88.50	31,109
146	72.50	30,329
136.75	44.50	31,576
128.00	--	30,838
119.00	--	26,691
109.25	--	22,499
Total		261,437

*All segments are eight inches thick.

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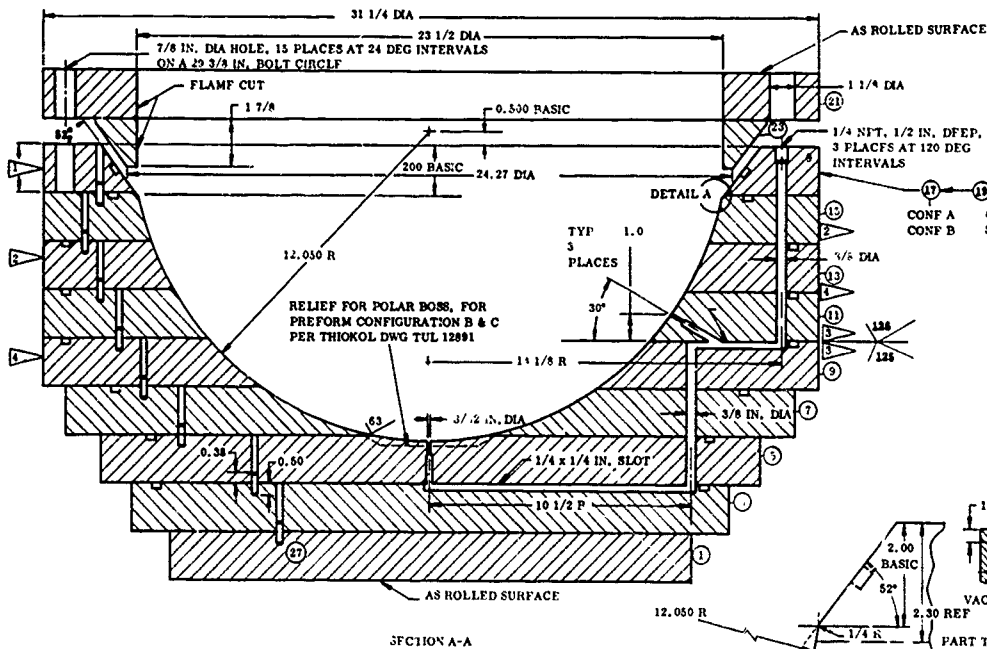
DETAIL DIMENSIONS TABULATED

SEG NO.	DETAIL	THICKNESS (IN.)	O.D.	I.D.	RADIUS TO O-RING GROOVE ϕ	RADIUS TO DOWEL PIN ϕ	RADIUS TO EYEBOLT
23	(23)	1 7/8	27	23 1/2	--	--	--
21	(21)	1 7/8	31 1/4	23 1/2	--	--	13 5/8
17	(17)	1 7/8	31 1/4	32	GROOVE LOCATED ON TREATED I.D.		14 1/2
15	(15)	1 7/8	31 1/4	21	12 3/4	13 7/8	13 1/2
13	(13)	1 7/8	31 1/4	19	14 5/8	13 1/4	13 1/2
11	(11)	1 7/8	31 1/4	16 1/2	14 5/8	12 1/2	13 1/2
9	(9)	1 7/8	31 1/4	12	14 5/8	11 1/2	12 1/2
7	(7)	1 7/8	29 1/4	--	12 5/8	10	11 1/2
5	(5)	1 7/8	26 1/2	--	11 1/4	7	10
3	(3)	1 7/8	24	--	11	6	8 1/2
1	(1)	1 7/8	21	--	--	--	8

(See Detail C)

DRAWING NOTES

1. DOWEL PINS (PER ASA B5.20-1958) WILL HAVE THE FOLLOWING FIT
LOWER SEGMENT - USA STANDARD FORCE FIT, CLASS FN2
UPPER SEGMENT - USA STANDARD CLEARANCE LOCATIONAL FIT, CLASS LC3
2. O-RING GROOVE DIMENSIONS WILL BE
WIDTH $0.360^{+0.010}_{-0.000}$ INCH, DEPTH 0.210 ± 0.005 IN. WITH ALL CORNERS BROKEN
0.005 RADIUS OF GROOVE ϕ SHOWN IN COLUMN 5.
3. THREE EYEBOLT LOCATIONS TO BE PROVIDED AT 120° INTERVALS ON EACH DIE SEGMENT ON RADII SHOWN IN COLUMN 7.
4. HARDENED AND GROUND DOWEL PINS ARE TO BE LOCATED AT 185° INTERVAL BETWEEN THE DIE SEGMENTS ON RADII SHOWN IN COLUMN 6
5. INSIDE DIAMETERS OF THE SEGMENTS AS SHOWN IN COLUMN 4 ARE TO BE FLAME CUT $\pm 1/8$ IN. AN ALLOWANCE FOR CLEAN UP MACHINING OF THE CAVITY HAS BEEN MADE.
6. THE OUTSIDE DIAMETERS OF THE SEGMENTS ARE TO BE FLAME CUT TO THE DIAMETERS SHOWN IN COLUMN 3, $\pm 1/8$ IN., WITH ALL SHARP EDGES BROKEN.
7. ALL MATING SURFACES ARE TO BE FLAT AND PARALLEL WITHIN 0.005 IN. T.I.R. AND A SURFACE FINISH OF 125 RMS
8. DIE SEGMENTS TO BE FLAME CUT FROM AISI 1045 ALLOY PLATE 2 IN. THICK. DETAILS 1 THROUGH 21 ARE TO BE QUENCHED AND TEMPERED TO A R. RANGE OF 30-32 PRIOR TO MACHINING.
9. DIE SEGMENT DIMENSIONS ARE GIVEN IN TABULAR FORM IN THE ABOVE TABLE.



3/4-10 UNC THREADS, THROUGH SEGMENT NO. 10, 15 PLACES AT 24° INTERVALS ON A 29 3/8 IN. DIA BOLT CIRCLE

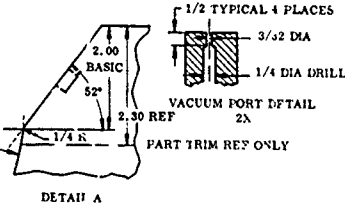
7/8 IN. DIA HOLES, THROUGH CLAMP RING, 15 PLACES AT 24° INTERVALS ON A 29 3/8 IN. DIA BOLT CIRCLE

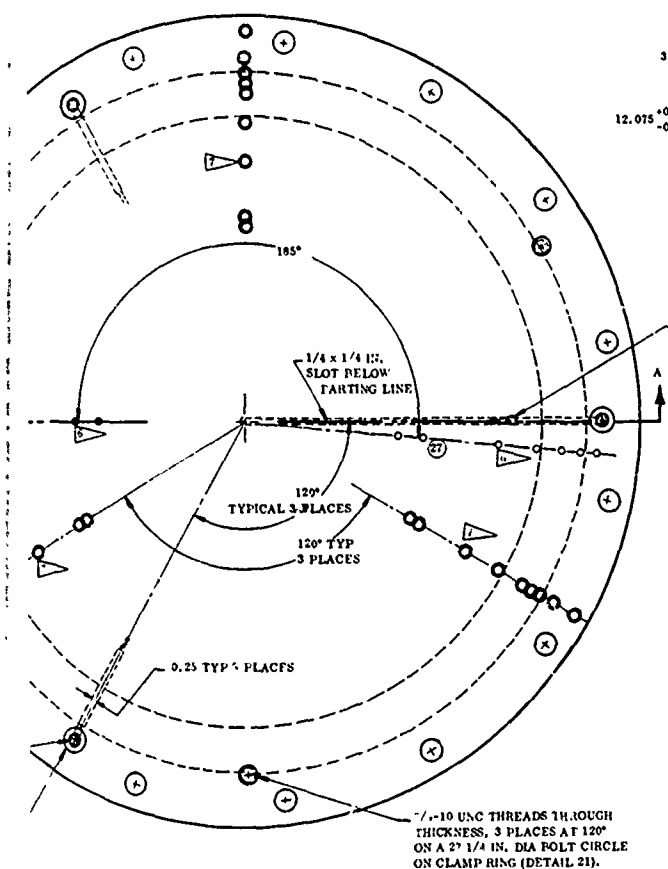
1/4 NPT, 1/2 IN. DEPTH, 3 PLACES AT 120° INTERVALS
CONF A
CONF B
CONF C
SEE DETAIL B

1/2-13 UNC THREADS FOR FULL SEGMENT THICKNESS, TYPICAL 9 PLACES EACH AT 120° INTERVALS (TOTAL OF 36) AT RADII SHOWN IN COLUMN 7 ABOVE

1/2 NPT, 1/2 IN. DEPTH, 3 PLACES AT 120° INTERVALS

1 1/8 IN. DIA HOLE THROUGH HOLDOWN RING, 3 PLACES AT 120° INTERVALS ON A 28 1/2 IN. DIA





TOLERANCES - UNLESS OTHERWISE STATED	
SURFACE FINISH	125
FRACTION	$\pm 1/16$ ANGULAR $\pm 1/4^\circ$
DECIMAL	.X $\pm .050$
	.XX $\pm .025$
	.XXX $\pm .005$

REVISION A	
CHANGES MADE ARE AS FOLLOWS:	
1	9 SEGMENTS USED DUE TO THE 2.0 IN. THICK MATERIAL REQUIRED FOR HOT ROLLED SURFACE CLEANUP.
2	2 DOWEL PINS FOR SEGMENT LOCATION TO FACILITATE EASY DIE ASSEMBLY.
3	INCORPORATION OF DETAIL 19 WHICH WILL REPLACE DETAIL 17 FOR THE CONFIGURATION C FORMING.
4	RELIEF FOR THE POLAR BOSS, SHOWN ON DETAIL 6, WILL BE MACHINED AFTER CONFIGURATION A TESTS ARE COMPLETE.

27	16	DOWEL PINS, 1/4 IN. DIA x 7/8 IN. LONG, HARDENED AND GROUND (ASA 5.20-1948)	
25	15	HEX HEAD CAPSCREW, 3/4-10 UNC x 3 IN. LONG, GRADE 8	
23	1	HOLDDOWN RING, 47 IN. O.D. x 23 1/2 IN. I.D. x 2.0 IN. THICK	2
21	1	CLAMP RING, 31 1/4 IN. I.D. x 23 1/2 IN. x 2.0 IN. THICK	2
19	1	DIE SEGMENT 9 FOR CONFIGURATION C, 31 1/4 IN. O.D. x 24 IN. I.D. x 2.0 IN. THICK	2
17	1	DIE SEGMENT 9, 31 1/4 IN. O.D. x 22 IN. I.D. x 2.0 IN. THICK	2
15	1	DIE SEGMENT 8, 31 1/4 IN. O.D. x 27 IN. I.D. x 2.0 IN. THICK	2
13	1	DIE SEGMENT 7, 31 1/4 IN. O.D. x 19 IN. I.D. x 2.0 IN. THICK	2
11	1	DIE SEGMENT 6, 31 1/4 IN. O.D. x 16 1/2 IN. I.D. x 2.0 IN. THICK	2
9	1	DIE SEGMENT 5, 31 1/4 IN. O.D. x 12 IN. I.D. x 2.0 IN. THICK	2
7	1	DIE SEGMENT 4, 29 1/4 IN. O.D. x 2.0 IN. THICK	2
5	1	DIE SEGMENT 3, 26 1/2 IN. O.D. x 2.0 IN. THICK	2
3	1	DIE SEGMENT 2, 24 IN. O.D. x 2.0 IN. THICK	2
1	1	DIE SEGMENT 1, 21 IN. O.D. x 2.0 IN. THICK	2
DET	QUANT	DESCRIPTION	MATERIAL

Figure 1. Laminated Forming Die

on page 267 that the minimum hardness remains above R_c 30 for 1/8 in. from the surface with proper quenching techniques. Since surface hardness is the primary concern, 1035 should be an adequate material for the full scale die also.

The alloy steels such as 4140, 4340, T1 and maraging steels are all excellent candidates for die material and at the required hardness level possess the necessary impact resistance and other characteristics desired. However, the cost of alloy steel is almost twice that for 1035 steel. The maraging steels are prohibitively expensive in the tonnage being considered. The total die weight has been calculated to be about 261,437 lb, prior to cavity machining. One can see that for every one cent increase in the cost of plates or forgings, a die cost increase of \$2,614.37 results.

One criterion that dictates the necessity for a particular alloy is the production quantity and tolerance control. For a relatively small quantity of parts, i.e., less than 100, one can select a less durable alloy. However, for large production runs of 1,000 or more a consideration must be given to die material, irrespective of cost. Thus, although 1035 steel offers the best characteristics combined with low cost, an alloy steel may be the ultimate answer for extended die life.

For the subscale program, 1035 steel was selected to permit evaluation of die performance, tolerance control, and resistance to repeated loading. Since material properties are non-scalable functions, a substitution of alloy steel, if deemed necessary, could be made with no effect on die details or characteristics. Sonic velocities, acoustic impedance values, and other properties for a large variety of steels are essentially constant, which permits interchange of alloys without concern for effects by shock reflection, etc.

B. DIE FABRICATION

The specific details for die fabrication can be presented as follows.

1. All of the ring segments were flame cut from flat, rectangular plate two in. thick.
2. Each flame cut segment was stress relieved, quenched and tempered to a Brinell hardness of 264 to 286 (R_c 27 to 30). All of the effects of flame cutting were removed by the thermal treatments.
3. Both surfaces of each plate segment were ground flat and parallel within 0.010 in. TIR.* Out of flatness condition produced by either initial plate rolling or heat treatment was removed during this procedure.
4. Grooves to accept a rubber O-ring for segment sealing were machined in the upper surfaces of die segments 2 thru 9.
5. Dowel pins were made and placed in suitable holes at the die segment interfaces. These pins provide for positive segment location during machining and for all subsequent operations using the tool.

*Total indicated reading

6. Vacuum ports and interconnecting vacuum passages in the die segments were laid out and drilled.
7. All of the die details were assembled and the die cavity was machined to a 12.025 in. radius.
8. During the same time that operations 4 thru 7 were being accomplished, the preform clamping rings were fabricated. At the conclusion of operation 7, the top die segment was drilled and tapped to permit attachment of the clamping rings to the die.
9. A plaster cast was made from the die cavity once the die was completely machined to permit the accurate measurement of die contour. Sixteen stations were measured on two radial sections. The tolerance on the radius of the spherical cavity was found to be 12.024 ± 0.010 in.

Before emplacement of the die in the concrete pad, the machined segments were disassembled and individually sealed using calvacene vacuum grease and rubber O-rings (durometer hardness of 40). Since the weight of each subscale die segment was quite low, natural O-ring sealing due to segment weight could not be easily achieved. To effect a 15 to 20 percent compression on the O-ring material, a pressure of 8 to 10 lb/in. was required. An O-ring constructed from closed cell foam was used with satisfactory results. Sealing could be accomplished to levels of 1 to 5 mm Hg once sealing details were established. Pump down rates were also determined once the die was completely sealed. A time of 15 to 20 minutes was sufficient to obtain desired vacuum levels (<5 mm Hg). The rates were determined using a flat blank. Thus, when a preform is used, pump down rates should be much less.

Once the sealing techniques were determined, the die was disassembled and prepared for emplacement in the forming pad. Figure 2 is a view of the assembled die configuration.

C. PAD CONSTRUCTION

The forming pad was constructed from concrete and steel reinforcing bar or sheet. Figure 3 shows the initial installation after concrete has been poured. The completed pad is shown in Figure 4. Once the concrete had cured sufficiently, the die emplacement hole was prepared to receive the die segments. Each segment was lowered into the hole individually and sealed. A vacuum was pumped on each segment or segments as the die was built up. Figure 5 shows the initial segment emplacement. The segments were installed in order and the procedures repeated until segment four was in place. At this point, concrete was poured around the die segments while the cavity was evacuated and the concrete allowed to set. The procedure was repeated as the die was built up until the die was completely assembled



Figure 2. Assembled Subscale Die

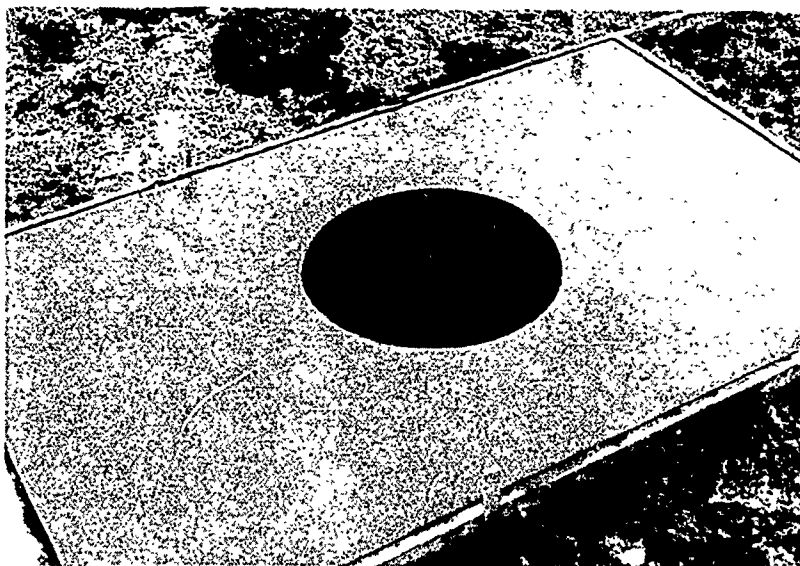


Figure 3. Initial Forming Pad Installation Showing Circular Reinforcing Sheet and Concrete Backing

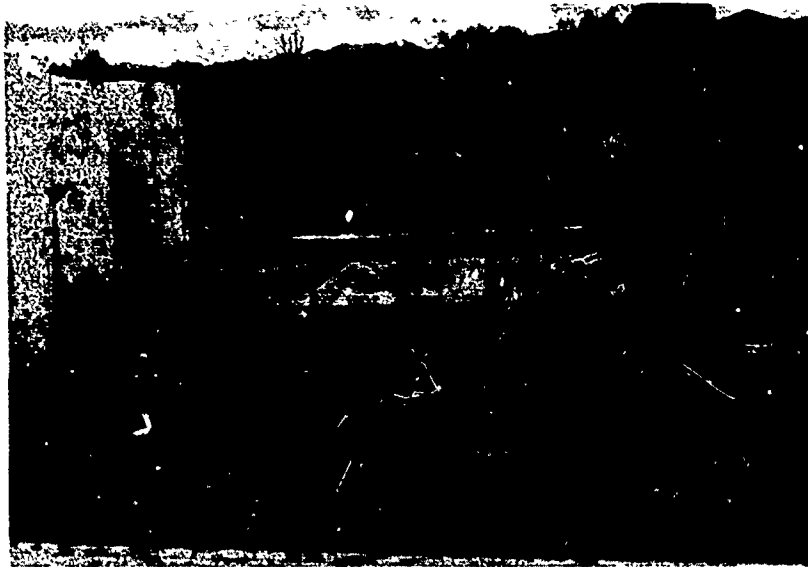


Figure 4. Completed Forming Pad Showing Concrete Installation



Figure 5. First Die Segment Emplacement with Vacuum Pump and Gage Attached

to the last two segments. Figure 6 illustrates the final assembly prior to completed grouting. Concrete was then finally grouted in around the die to complete the installation. Figure 7 shows the finished die emplacement with a two ton portable electric hoist for handling of segments and preforms, and Figure 8 shows the restraint ring being lowered into place.

The completed die could be sealed and pumped down to the 1 to 2 μ range in less than 20 minutes.

D. DIE MODIFICATIONS

Upon conclusion of the Preform 4A analysis and the ensuing Cor-ten buckling program, it was decided that to preclude buckling, the forming die would have to be modified to contain more bolts so that sufficient holding force could be applied to completely restrain the preform. The total number of bolts was therefore increased from 15 to 27 and the bolt size was increased from 3/4 to 1 in. diameter. This modification required rework of the upper segment of the die and clamping ring. No problems were encountered in removing and replacing the upper die segment for this modification.

During the month of October 1969, the last forming experiment on Configuration A preforms was completed. In order to accommodate the Configuration B preforms, it was necessary to machine details 5, 7, 17, and 23 (called out in drawing number NR-1035-002A, Figure 1). The die was first disassembled by removing each segment in order. Although release agents were applied to the exterior of the die segments, some difficulty was experienced in disassembly of the segmented die. Concrete in immediate contact with the metal rings had to be fragmented to allow extraction of the last few die sections.

Once the die was removed from the concrete, the apex segment was machined so as to accommodate the igniter boss necessary as part of the Configuration B preform. Because of the preform design features which included the igniter boss, it was necessary to change the preform cone angle. This resulted in a change of the top die segment to accept the new cone angle so that efficient clamping of the preform could be accomplished. The top die segment was machined for the change in preform configuration. After machining and dimensional checks had been made on the affected die segments, each segment was drilled and tapped to permit bolting of each adjacent segment. Thus, positive sealing was assured between die segments to prevent water or air from becoming entrapped behind the preform. On the sub-scale die, the segment weight is insufficient to compress the rubber O-rings used to effect sealing between segments; thus, the bolting step was required. This will not be necessary on the full scale die since segment mass would be adequate to obtain full compression of the O-ring seals.

The completely assembled die was lowered into the prepared hole in the forming pad. Concrete was again poured and allowed to cure. The die cavity was blanked

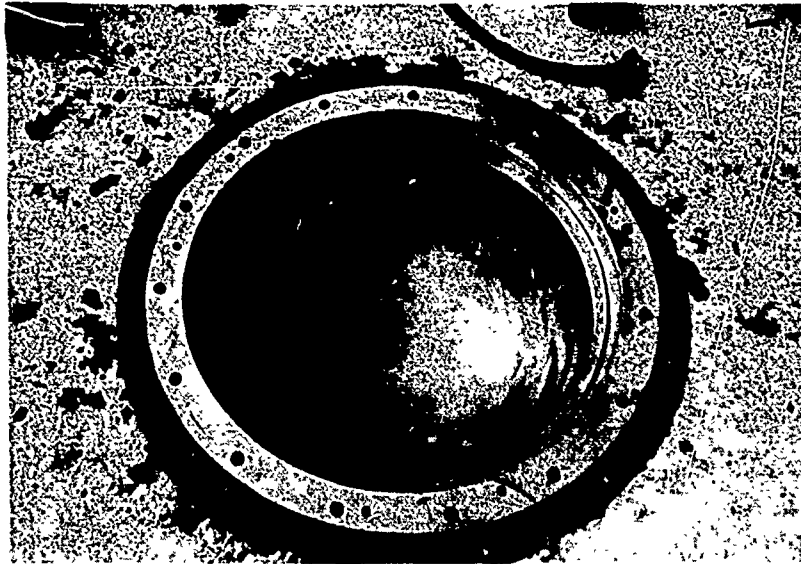


Figure 6. Finished Forming Die Ready for Concrete Grouting

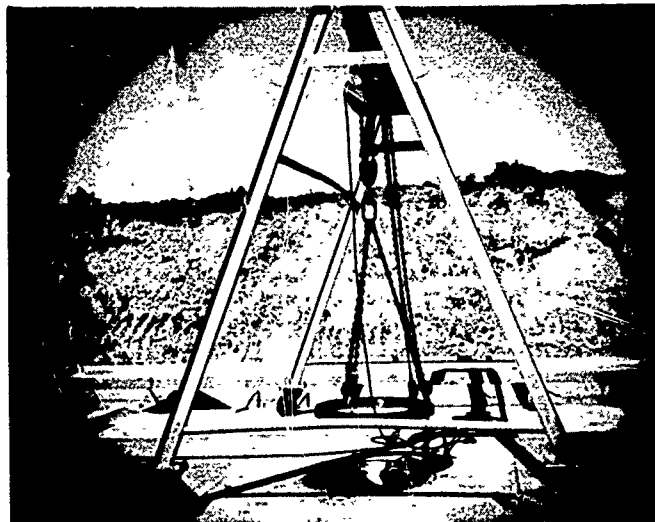


Figure 7. Finished Die Emplacement with Two Ton Portable Crane

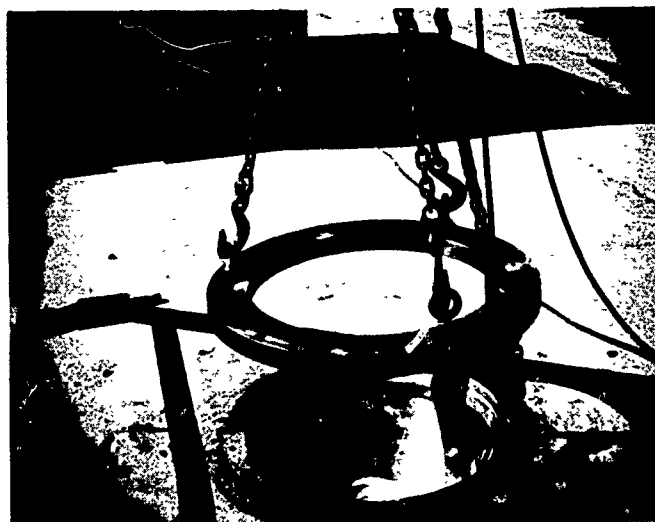


Figure 8. Subscale Die and Restraint Ring

off and a vacuum of less than 2 mm was achieved in the cavity. The die was thus ready to receive the first Configuration B preforms. Figure 9 shows a view of the assembled die after modification.

E. CONFIGURATION A DIE DIMENSIONAL CHECK

In order to evaluate the stability of the subscale forming die, plaster casts of the die cavity were made and inspected periodically during Configuration A forming experiments.

Die contour was checked by placing a plaster cast of the die cavity on the inspection fixture and measuring actual dimensions using an offset template. Figure 10 delineates die contour measurements made on the Configuration A die cavity.

Following the first two die inspections, an error was discovered in the template location on the inspection fixture. This was corrected prior to measuring the last Configuration A plaster mold. The vertical location of the template was incorrect, and the effect of the error in template location is apparent in the polar region of the die.

The evaluation was that the die contour has not been changed by explosive forming.

F. DIE PERFORMANCE

Overall performance of the forming die was exceptional throughout the test. One slight problem was noted at the conclusion of the effort. Upon completion of the explosive forming of Preform 1B (R), examination of the die revealed a gap between the fifth and sixth die segments (Figure 1) details -7 and -0. The gap was noted to be approximately 0.100 in. wide.

After disassembly the concrete grout under the die was found to have given way slightly and it is presumed that this allowed the relative movement described above. The small bolts used to assure sealing between the segments were found to have loosened and did not, therefore, offer any resistance to the separation.

This problem would not be expected to occur in a full scale die because of the weight of the individual die segments.



Figure 9. View of Explosive Forming Die Showing Modifications
of Top and Bottom Segments

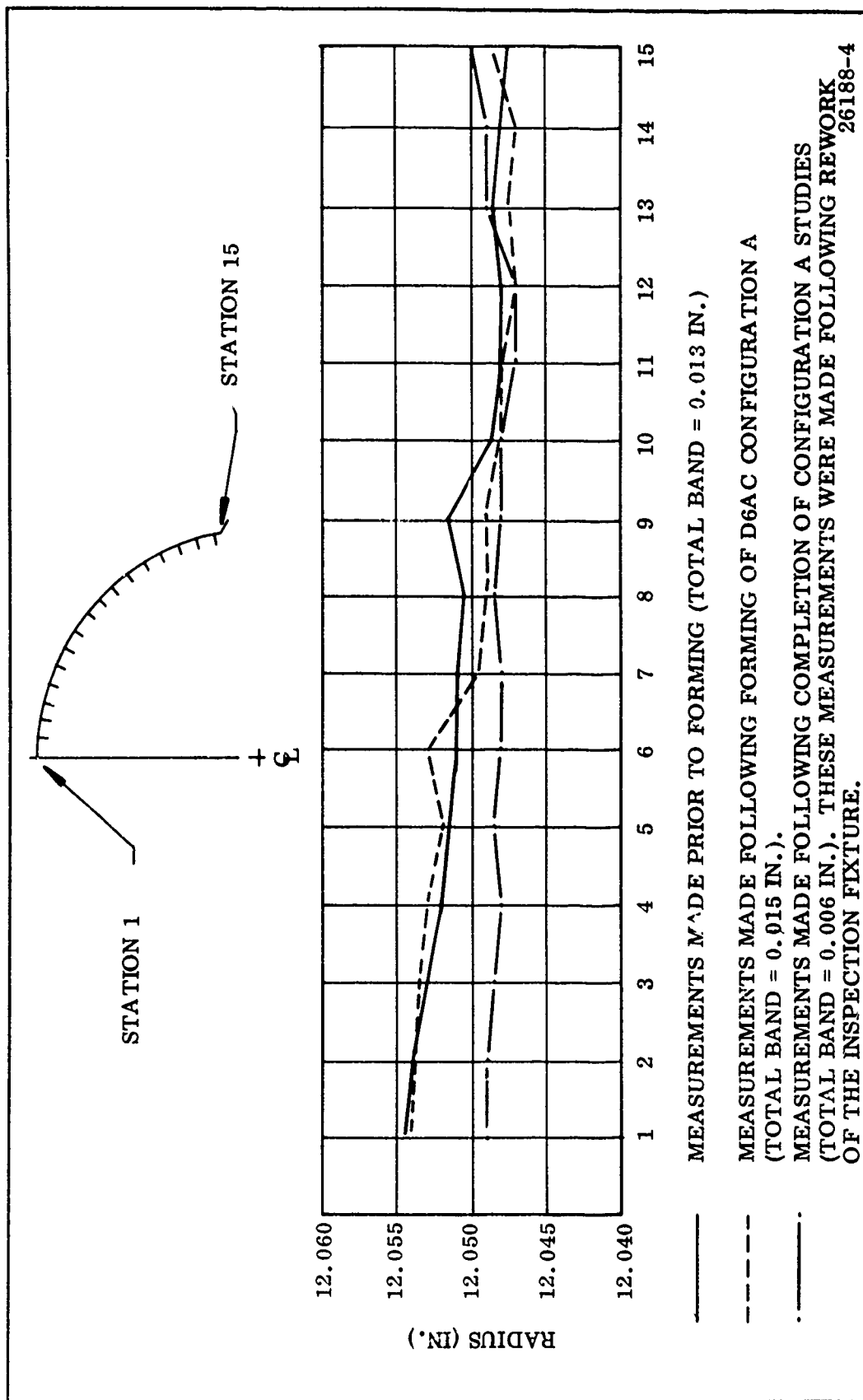


Figure 10. Contour Measurements of 24 In. Subscale Forming Die

SECTION IV SPECIAL TOOLING

In order to permit the accurate measurement of formed parts, it was necessary to design and construct an inspection fixture. Figure 11 shows a view of the fixture in position for dome measurement. Diameters and contour on the fixture were machined to within ± 0.001 in. The fixture will be utilized to measure the contour deviations of the processed domes.

The longitudinal welding could be accomplished directly without the use of extra fixturing; however, the circumferential welds required a special fixture (Figure 12) to hold the preform cone and polar plate during joining. This fixture also provided the inert gas track backup for the welding process. Longitudinal adjustment was accomplished by use of the center screw and lock nut; however, separate plates were required for the A and B, and C configurations. The fixture was necessary for either a hand or machine welding operation. However, the tool was made to fit an automatic welding machine, and every attempt was made to machine weld the part.

One of the tools developed during the program was the circumferential clamping ring shown in Figure 13. This tool was originally designed for use during the circumferential welding operation, but proved to be extremely valuable for drawing the preform onto an aluminum conical mold so that the small diameter could be machined in the round condition.

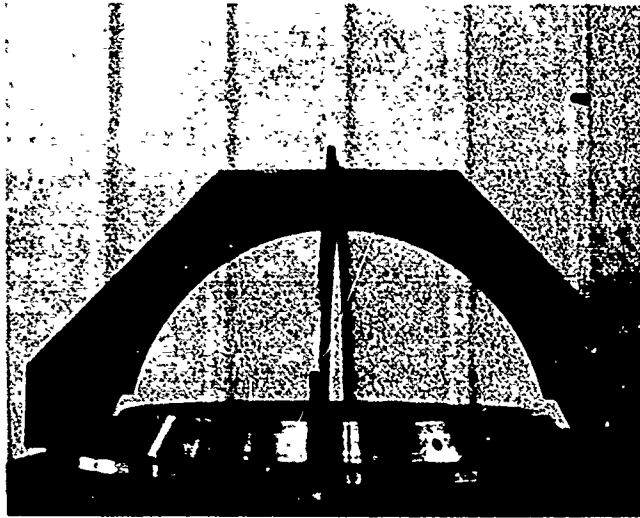


Figure 11. Inspection Fixture for Contour Measurements of Formed Domes



Figure 12. Circumferential Weld Fixture

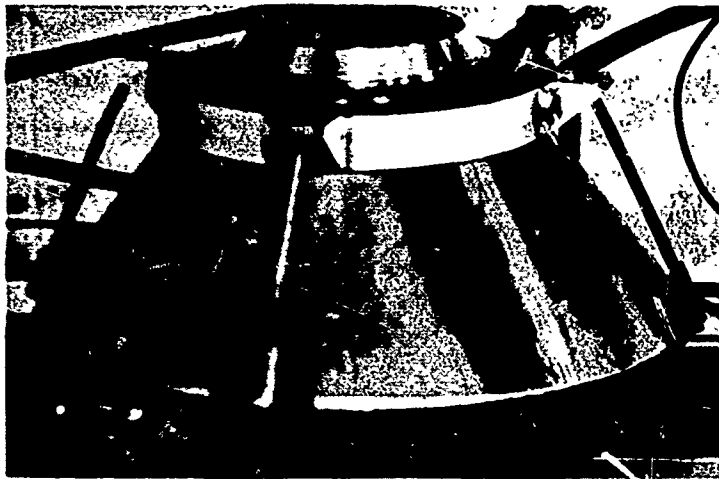


Figure 13. Circumferential Clamping Ring

SECTION V

GENERAL PREFORM DESIGN AND FABRICATION

Upon conclusion of 1A, 2A, and 3A preform fabrication together with the forming attempts on 1A and 2A, it was apparent that some basic changes in preform design and fabrication would be necessary if future program success was to be achieved. This section describes both the original design and fabrication plan, and the subsequent modifications.

A. ORIGINAL DESIGN AND FABRICATION TECHNIQUE (METHOD 1)

A detailed outline from the original plan of the step-by-step procedure to be used to fabricate the first three subscale preforms is presented below.

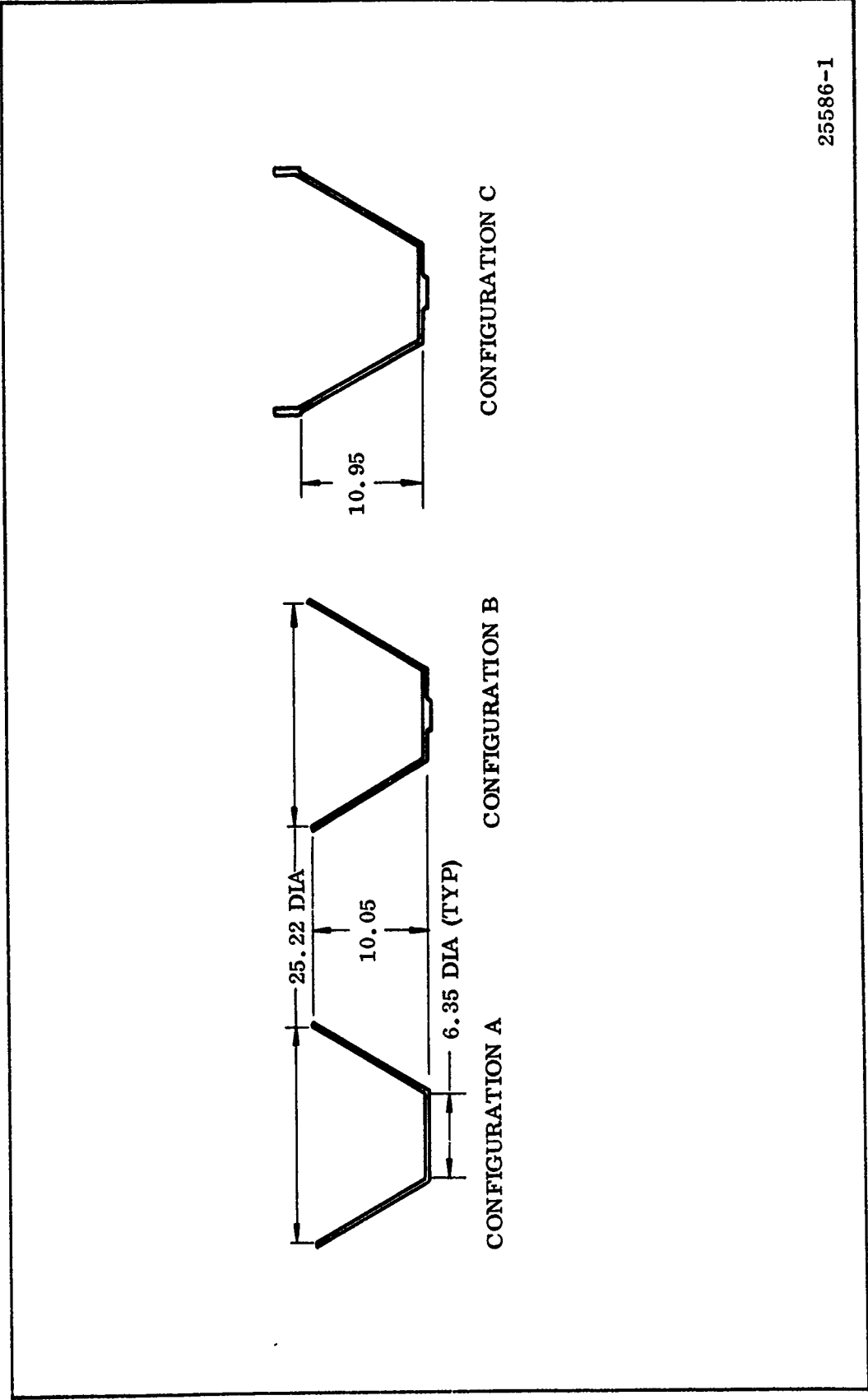
Figure 14 shows the shape and dimensions of the three different subscale configurations. Detailed drawings of the original design planned for Configurations A, B, and C are shown in Figures 15, 16, and 17, respectively. The first three preforms were fabricated according to Figure 15 (TUL 12941) in the following manner.

1. The material was received in sheet form, in the annealed condition, and was visually inspected for conformity to standards of good workmanship and quality. The original material for the first three preforms was not 100 percent cross rolled for either the HP9-4 or the D6AC material.

The individual material dimensions were as follows:

D6AC	0.090 by 24.0 by 42.0 in.
HP9-4	0.090 by 24.0 by 42.0 in.

2. The sheets were then ground to a thickness of 0.054 ± 0.002 in. The surface finish after the grinding operation was estimated to be a nominal 63 finish. The surface was again inspected for visual defects and checked for thickness with a Vidagage.
3. Standard 2 in. gage length tensile specimens were cut from the plate edge for material specification strength and toughness compliance testing. Specimens were taken in both the direction of primary rolling and transverse to it.
4. The preform pattern was laid out and scribed onto the ground sheet. The actual size preform cone sections, as well as the oversized sections, were



25586-1

Figure 14. Preform Configurations

8 7 6 5

H

G

F

E

D

C

B

A

26.70 DIA.

10.52

10.57 DIA.

PERFORM CONSTRUCTION A

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DRAWING NOTES

- 1. 26.70 DIA. MATERIAL PER AMS-4428, 44030 ROLLED PLATE, .034 INCH MATERIAL THICKNESS.
- 2. 10.57 DIA. MATERIAL PER AMS-4428, 44030 ROLLED PLATE, .034 INCH MATERIAL THICKNESS.
- 3. WELD DIA. PER TW-370-33A
- 4. WELD DIA. PER TW-370-33A
- 5. INSPECT ALL WELDS PER TW-370-33A BEFORE AND AFTER FORMING.

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B

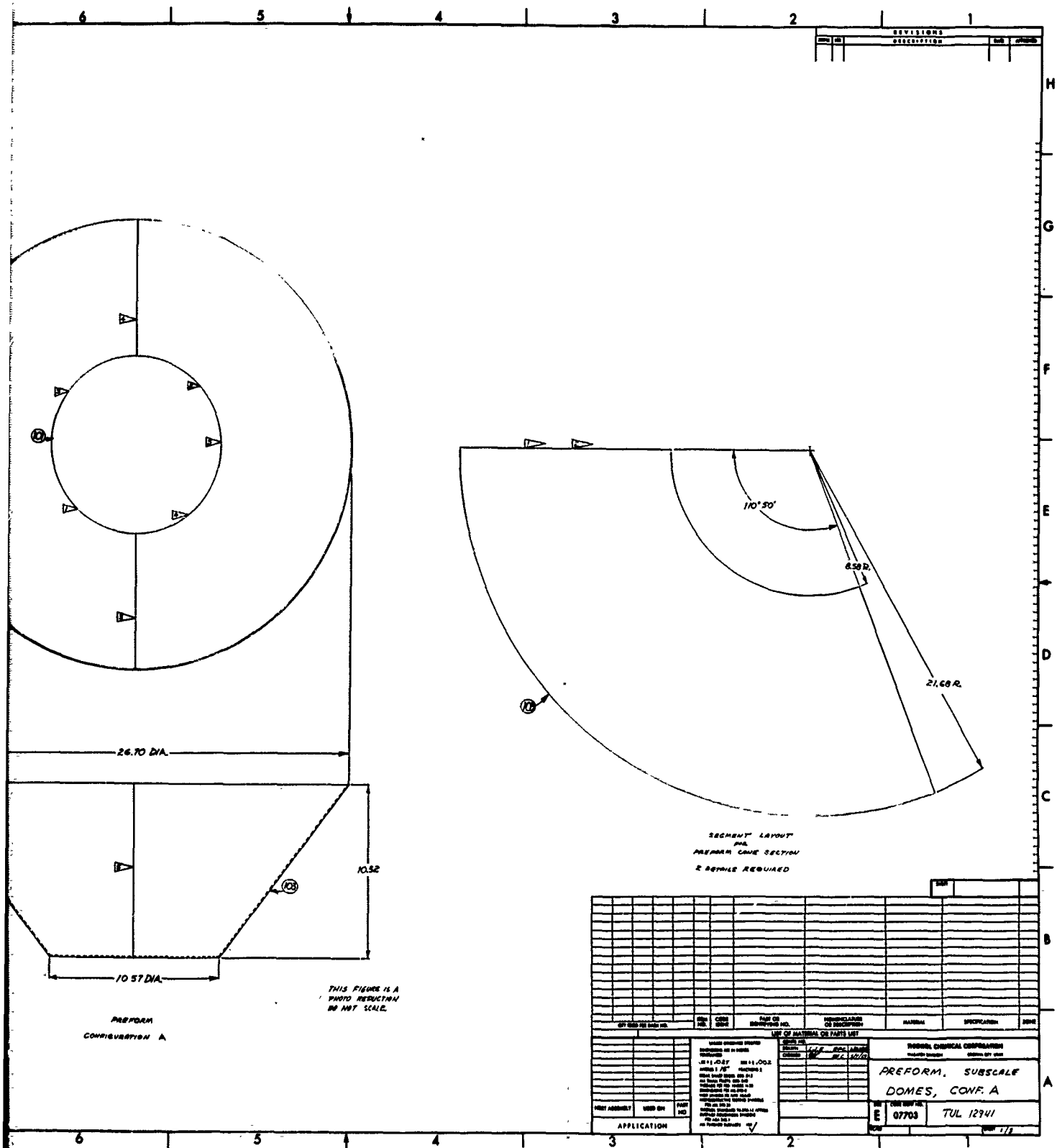
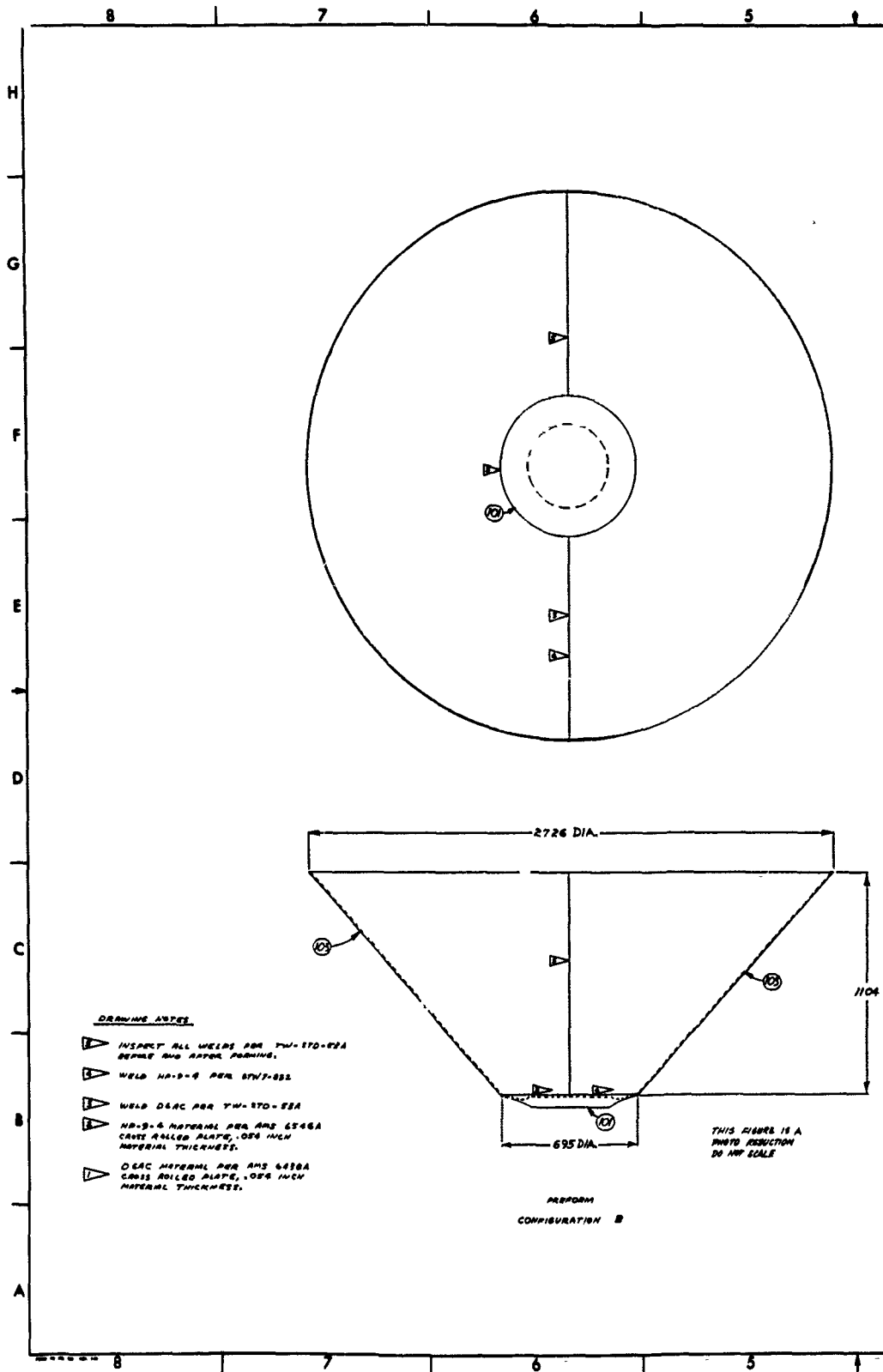


Figure 15. Preform Subscale Dome, Configuration A

A



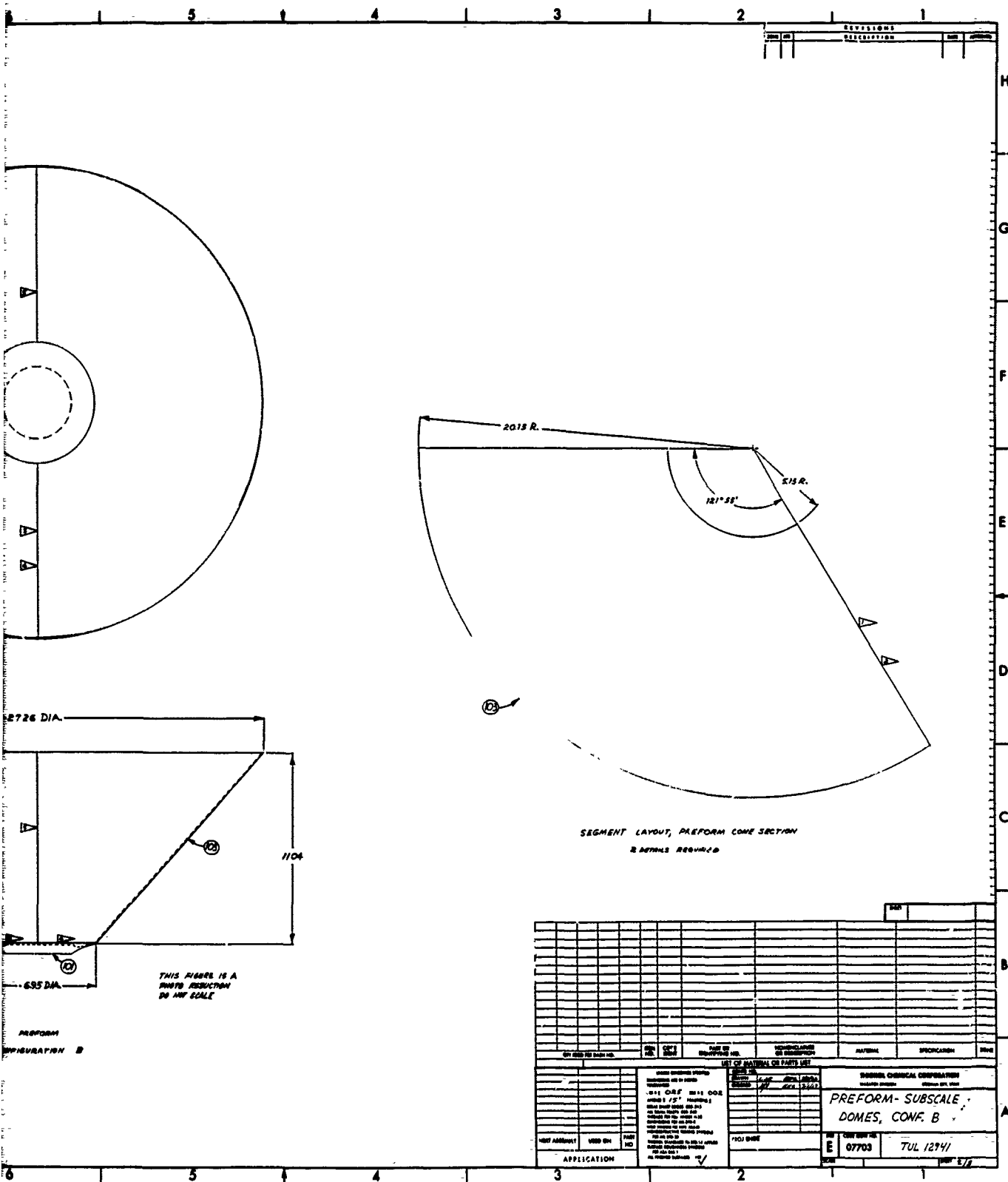


Figure 16. Preform Subscale Dome, Configuration B

8 7 6 5

H

G

F

E

D

C

B

A

INSPECTION SHEET

INSPECT ALL WELDS FOR TWIST-OUTS, SPALLS AND ADDED FORMING.

WELD NO. 5-6 PER STW7-002

WELD 066C PER TWIST-OUTS

NO. 5-6 MATERIAL PER AMS 6266A, 0.075 INCH MATERIAL THICKNESS.

066C MATERIAL PER AMS 6266A, CROSS ROLLED SLIPS, 0.075 INCH MATERIAL THICKNESS.

105 V-RING PERFORM PER TH. DWS. TUL12849

106 POLAR DWS PER TH. DWS. TUL12849

0.392 REF.

6.95 DIA.

25.44 DIA.

PREFORM CONFIGURATION C

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scribed on the ground sheets. The oversized template dimensions were as follows.

- a. The small radius was at least 1.0 in. less and the large radius at least 1.0 in. larger than the actual cone section radius.
- b. At least 3.0 in. beyond either side of the actual cone sections.

Figure 18 shows the preform pattern and oversized configuration which was used.

5. The oversized preform pattern was then cut from the plate. The straight edges were sheared and the curved portions cut with a bandsaw.
6. The oversized cone sections were rolled to the appropriate radius of curvature as shown in Figure 19. The 3.0 in. oversized dimension on either side of the cone sections allowed for flat spots which occur during runout of the rolling operation; i.e., the areas at the edges of the sections after rolling generally had larger radii of curvature than the rest of the section.

Figure 20 shows the half sections subsequent to the rolling operation.

7. The straight cone edges of the preform were cut close to the desired scribed line and then smoothed to the desired dimension with a weld shaver and hand file.
8. The longitudinal seams of the D6AC steel preforms were welded according to Thiokol Specification TWS-STD-53, and the HP9-4-25 preforms according to Thiokol Specification STW-7-832. Welding was performed automatically. Figure 21 shows the preform in position in the automatic welder. The tungsten inert gas process was used in this operation.
9. The longitudinal welds on the D6AC material were then subjected to a stress relief of 960° F for 1.5 hr. This operation was accomplished by clamping opposing Calrod units on each side of the weld. The temperature was monitored by three thermocouples which were spot welded to the weld at three stations along the weld length. This stress relieving operation was omitted on the HP9-4 preforms.

Figure 22 shows the Calrod units in place, prior to the stress relieving operation on the

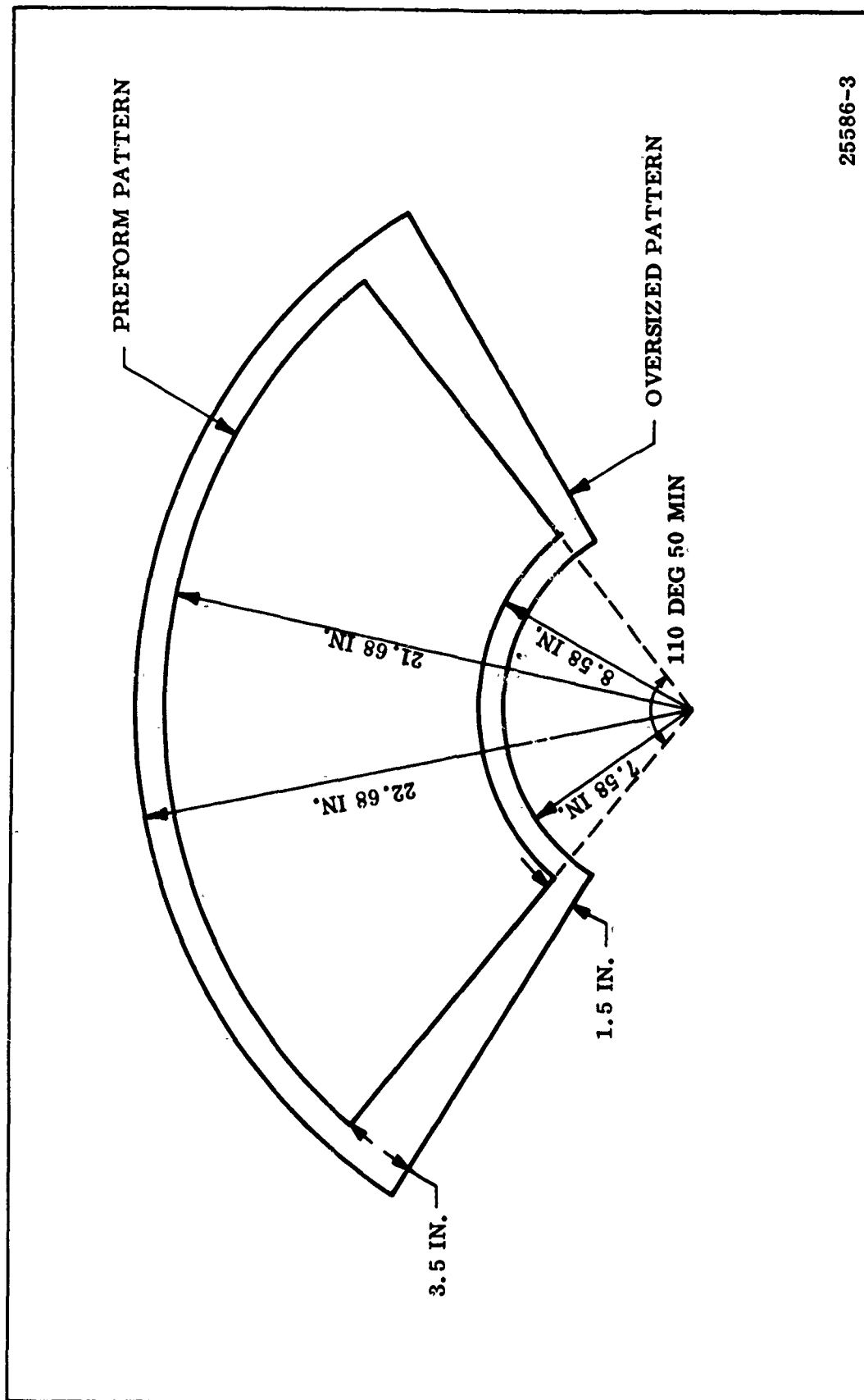
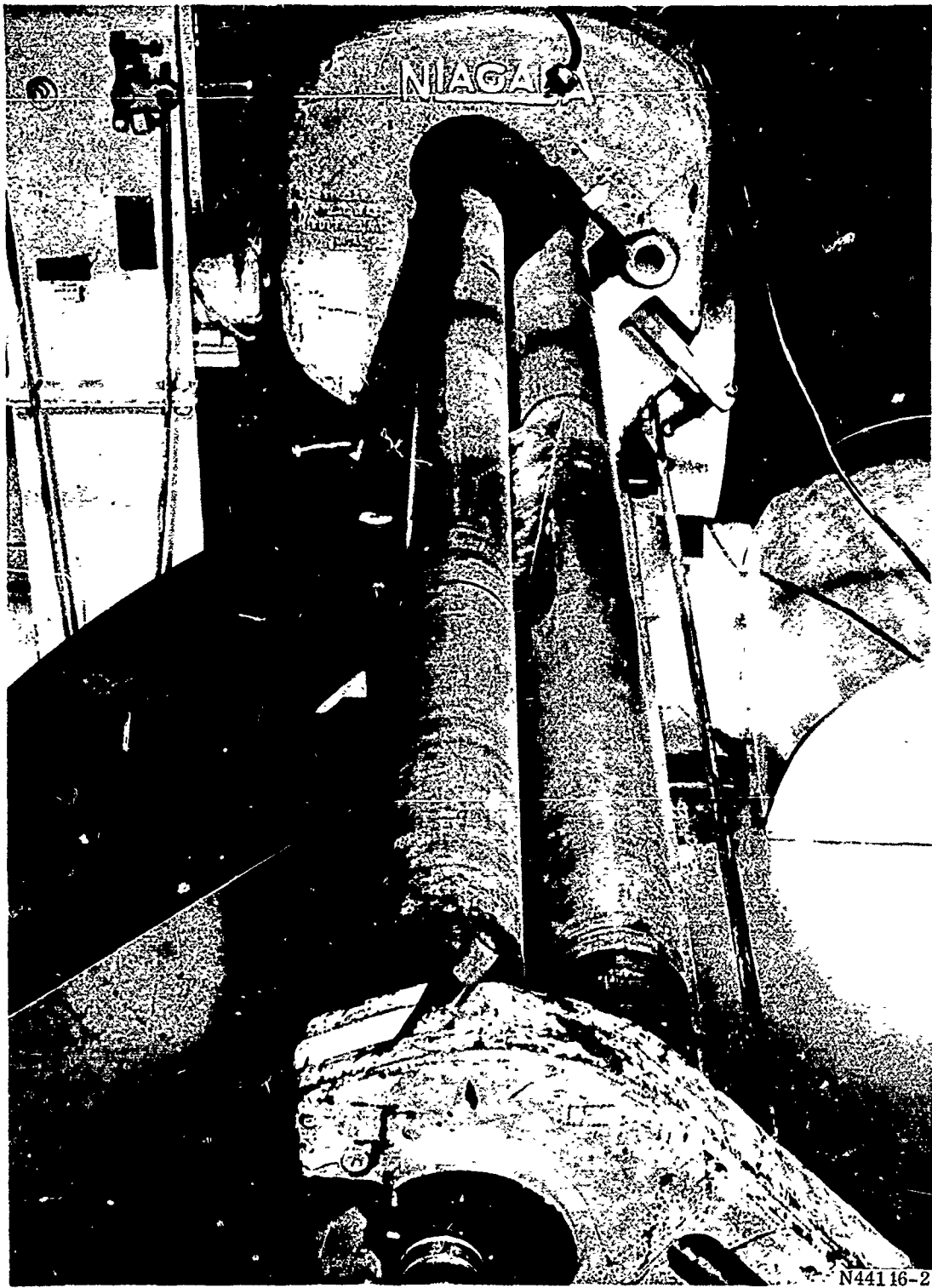


Figure 18. Preform Pattern and Oversized Configuration of Template



N44116-2

Figure 19. Cone Half Section Being Rolled to Contour



N44146-3

Figure 20. Oversized Rolled Cone Half Sections

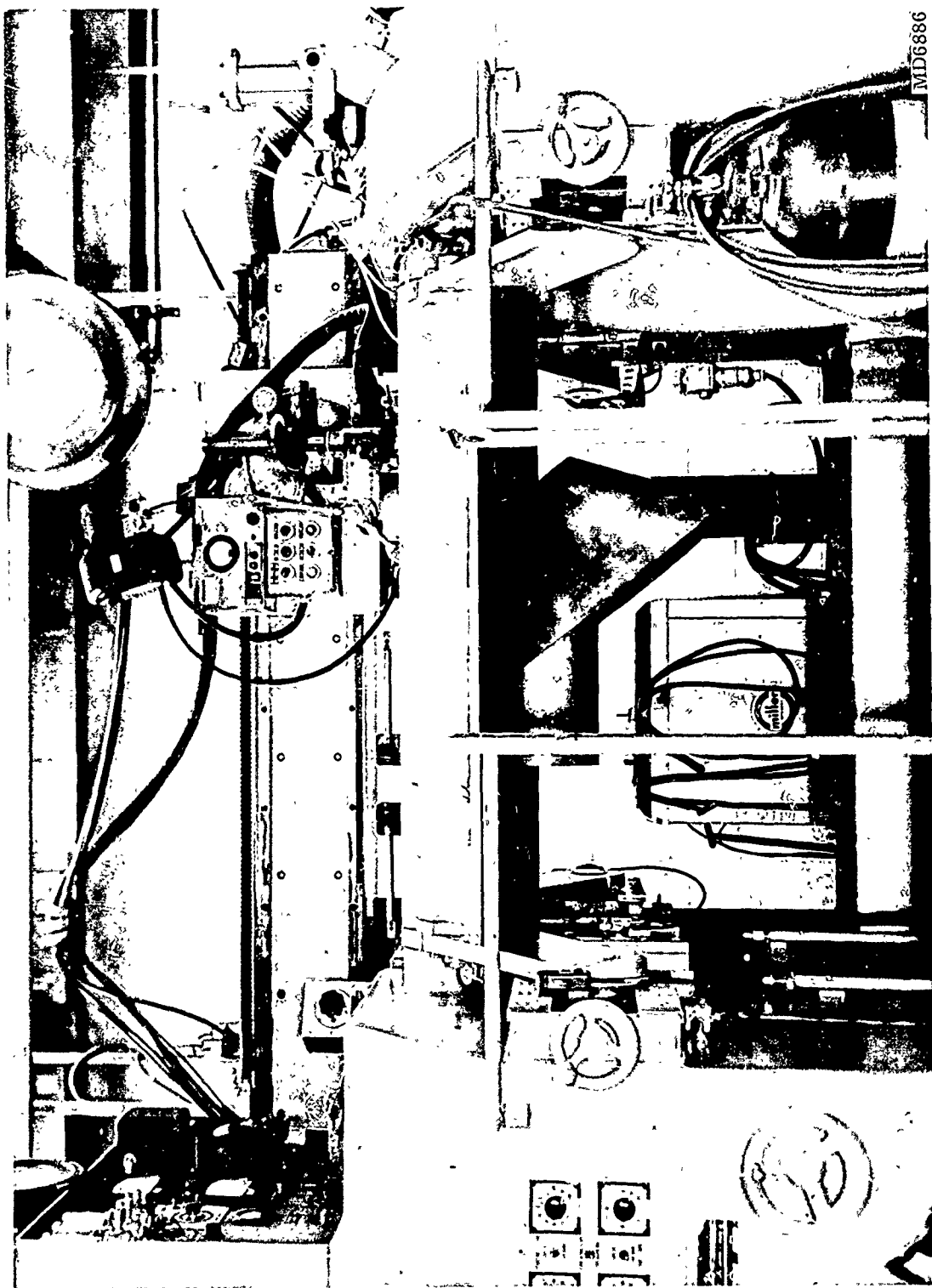


Figure 21. Cone Half Sections in Position for Automatic Longitudinal Welding

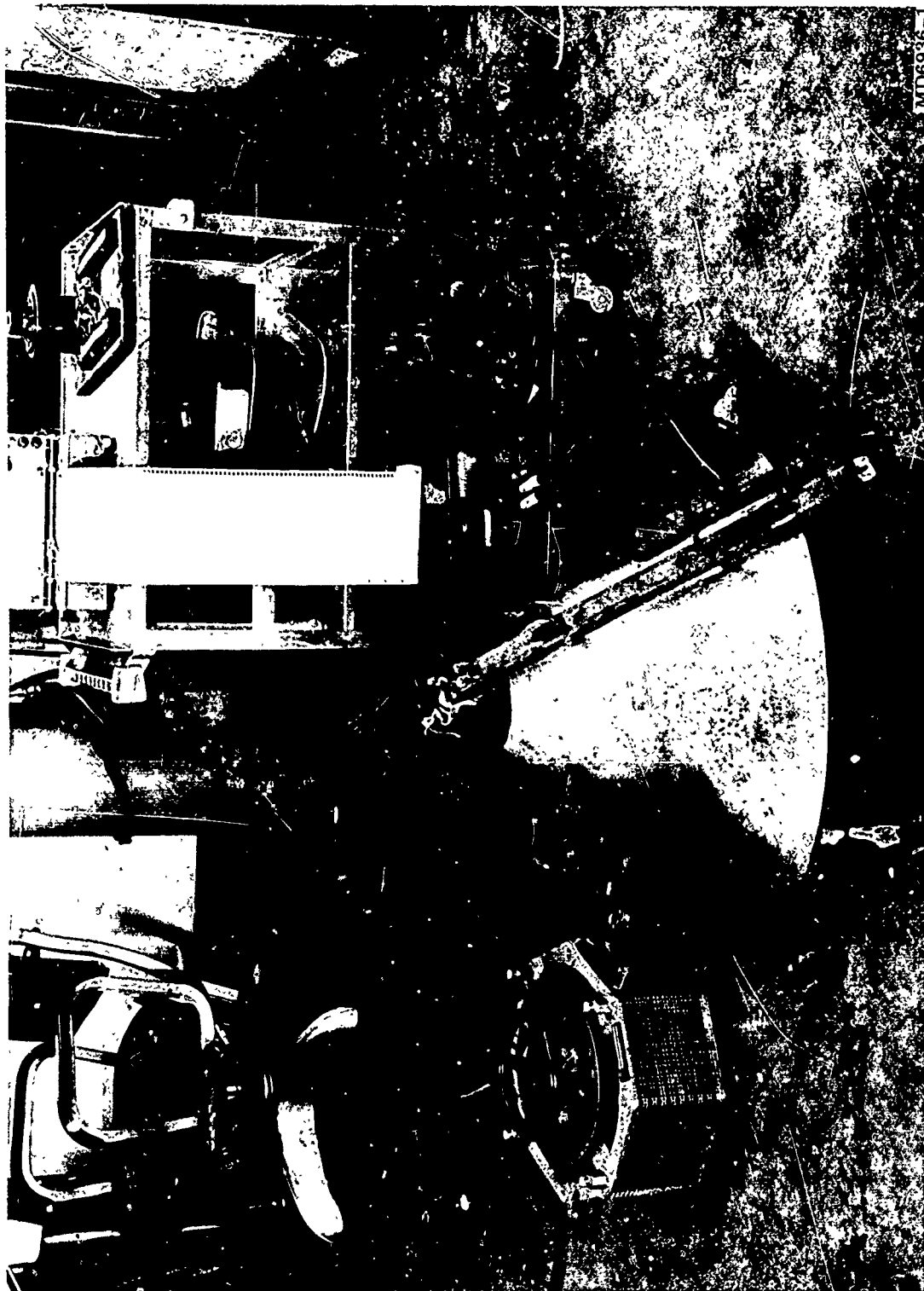
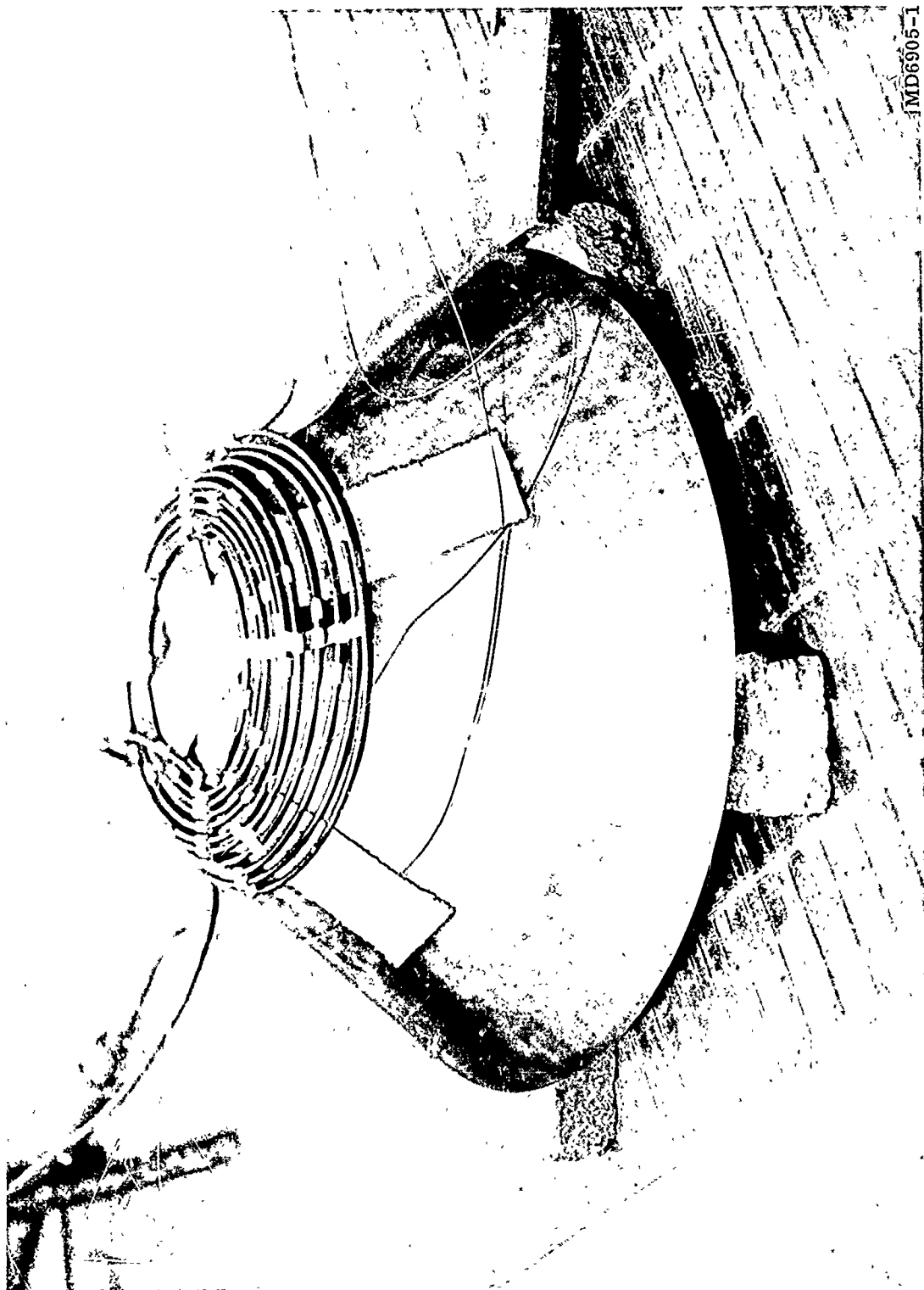


Figure 22. Stress Relieving Apparatus for Longitudinal Welds

- longitudinal welds. In actual operation the Calrods were covered with insulation.
10. The longitudinal welds were then inspected by standard X-ray and dye penetrant techniques. Any defects were noted, and the preform was weld repaired and returned to inspection until an acceptable weld was obtained.
 11. The preforms were fitted on an internal tool, and the large and small diameters were trimmed.
 12. The polar plate was then cut and joined to the preform. The welding was performed according to the previously mentioned Thiokol specifications. The TIG process was used to make the weld and, when possible, the welding was performed automatically. (In the case of the first three preforms being discussed here, it was not possible to machine weld the circumferential welds and hand welding was required.)
 13. The circumferential welds of the D6AC preforms were given a stress relief of 800° F for 2 hr. This operation was omitted on the HP9-4 preform. Figure 23 shows the induction coil in place subsequent to the stress relieving operation. The temperature was monitored by three thermocouples around the circumference.
 14. The circumferential welds were given the same inspection as described for the longitudinal welds in Step 10. Any indicated repairs were made, and the weld was reinspected until an acceptable weld was obtained.
 15. The circumferential weld was then hand worked to provide a blend radius on both the inside and outside surface.
 16. The preforms were then gridded in preparation for inspection.

Figure 24 shows a completed preform fabricated to the original design (Figure 15) using the process just described.



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Figure 23. Stress Relieving Circumferential Weld with Induction Coil

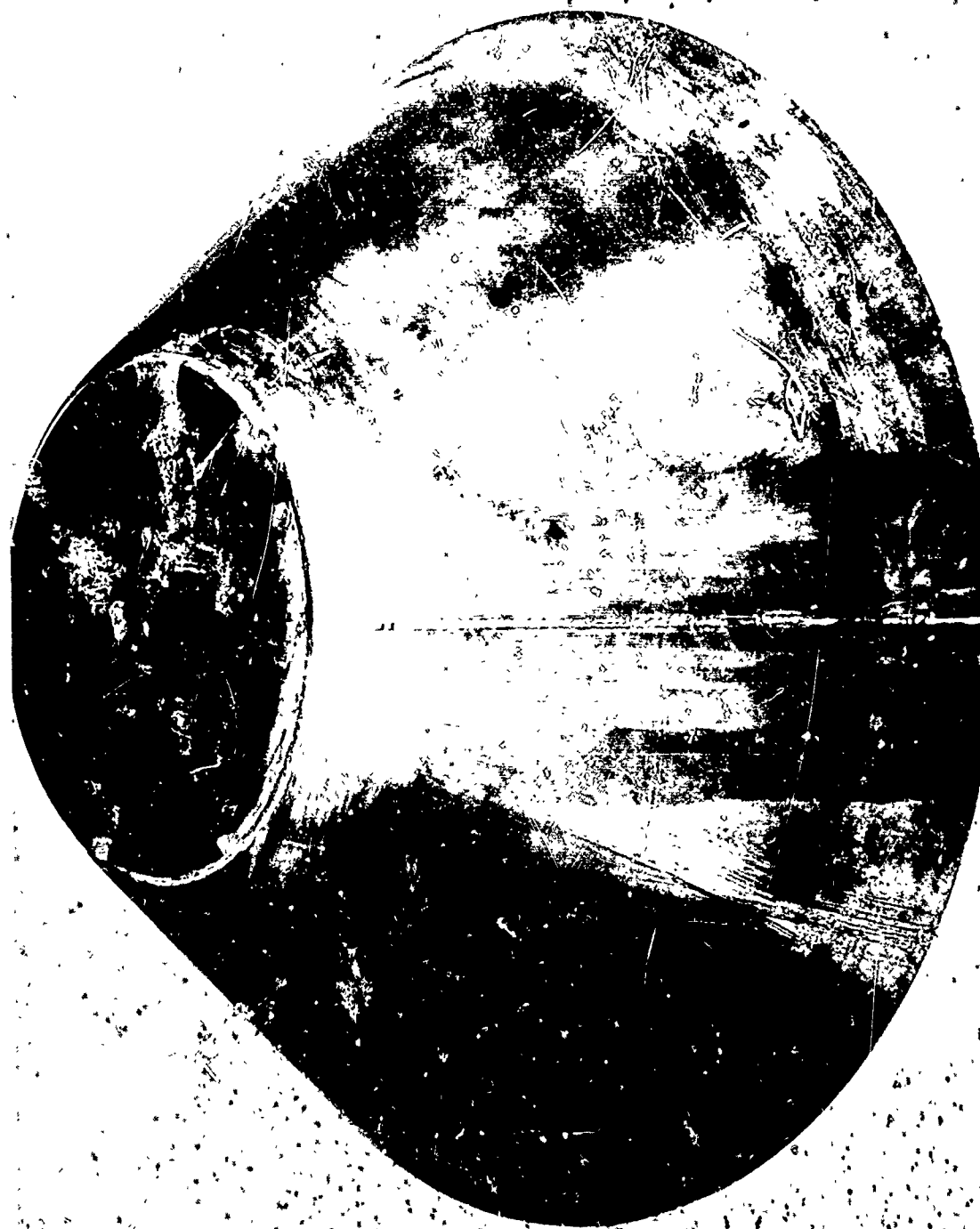


Figure 24. Configuration 2A Preform Fabricated to Original Design from
Original Fabrication Technique

B. MODIFIED DESIGN AND FABRICATION TECHNIQUE (METHOD 2)

As a result of the weld stress relieving study and a reevaluation of the problems encountered during previous preform fabrication efforts, it was concluded that two major changes were required in subsequent preforms: (1) a complete overhaul of the stress relieving technique, and (2) a relocation of the circumferential weld location. Several minor modifications were also incorporated in order to insure a more acceptable preform.

The original procedure through the rolling operation was considered to be acceptable. This part of the processing is covered in Steps 1 thru 8 as previously described. From this point, the technique was substantially modified as follows.

9. The longitudinal weld was subjected to a low temperature (550° to 600° F) stress relief for 20 minutes. The purpose of this operation was to protect the weld until the time that a more complete stress relief can be effected.
10. The partially stress relieved seam was then ground as near to flush with the parent material as was reasonably prudent.
11. The part was then subjected to X-ray and dye penetrant inspection to determine if any defects existed. If required weld repairs were made, the part was ground flush and resubmitted to inspection.
12. When an entirely acceptable weld was obtained, both longitudinal seams were subjected to a rigorous stress relief (1,250° F for 1.5 hr). By following this procedure, it was insured that all longitudinal weld repairs were stress relieved and no section subjected to high temperature more than once, to minimize decarburization.
13. The preform was then forced into a round shape on a premachined conical aluminum forming tool (Figure 25). The small radius was machined.
14. The polar cap was machined from 0.75 in. thick plate. The knuckle area was machined integral with the cap, placing the weld joint approximately 0.14 in. back from the plate face. Figures 26 and 27 are the revised TUL-12941 drawings showing the polar cap detail for Configurations A, B, and C. The drawing for Configuration B is not shown because in this area it was identical with Configuration C.

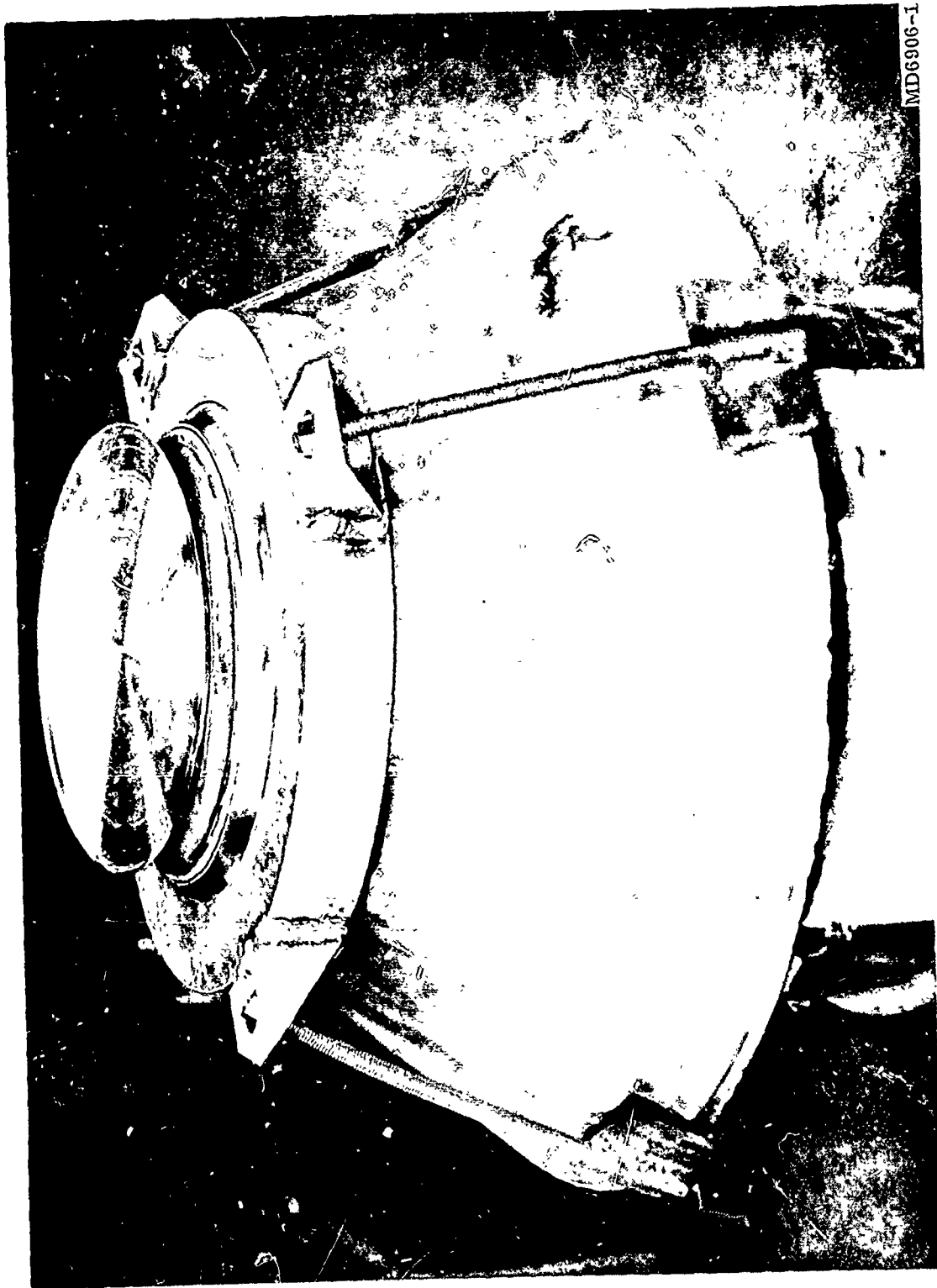
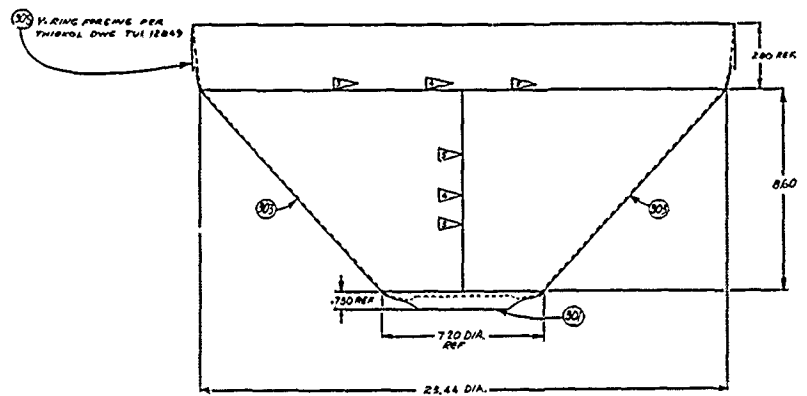
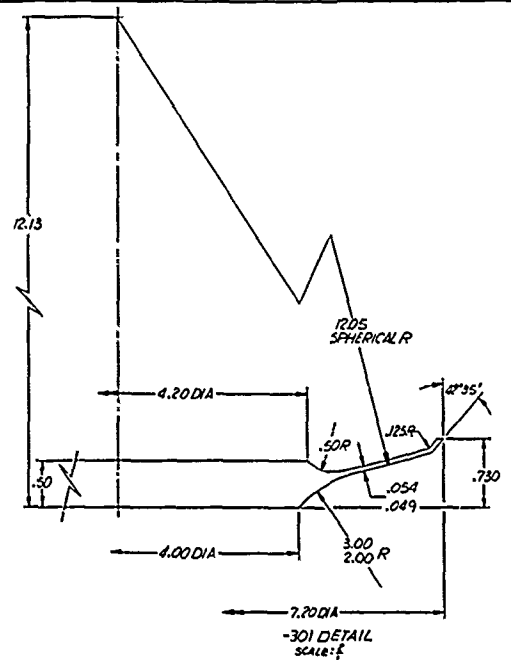


Figure 25. Conical Preform Stretched on Forming Cone with Small Diameter
Machined (Premachined Polar Plate Also Shown)

11

PREFORM NOTES

- ▽ INTERPOLATE ALL WELDS FOR TWO-STEP TEST
- ▽ WELD HA-3-0 PER SNT-011
- ▽ WELD Q-4-0 PER TWO-STEP TEST
- ▽ HA-3-0 MATERIAL FOR THE SEVERE CASES ROLLED PLATE, .075 INCH NOMINAL THICKNESS.
- ▽ Q-4-0 MATERIAL FOR THE SEVERE CASES ROLLED PLATE, .075 INCH NOMINAL THICKNESS.



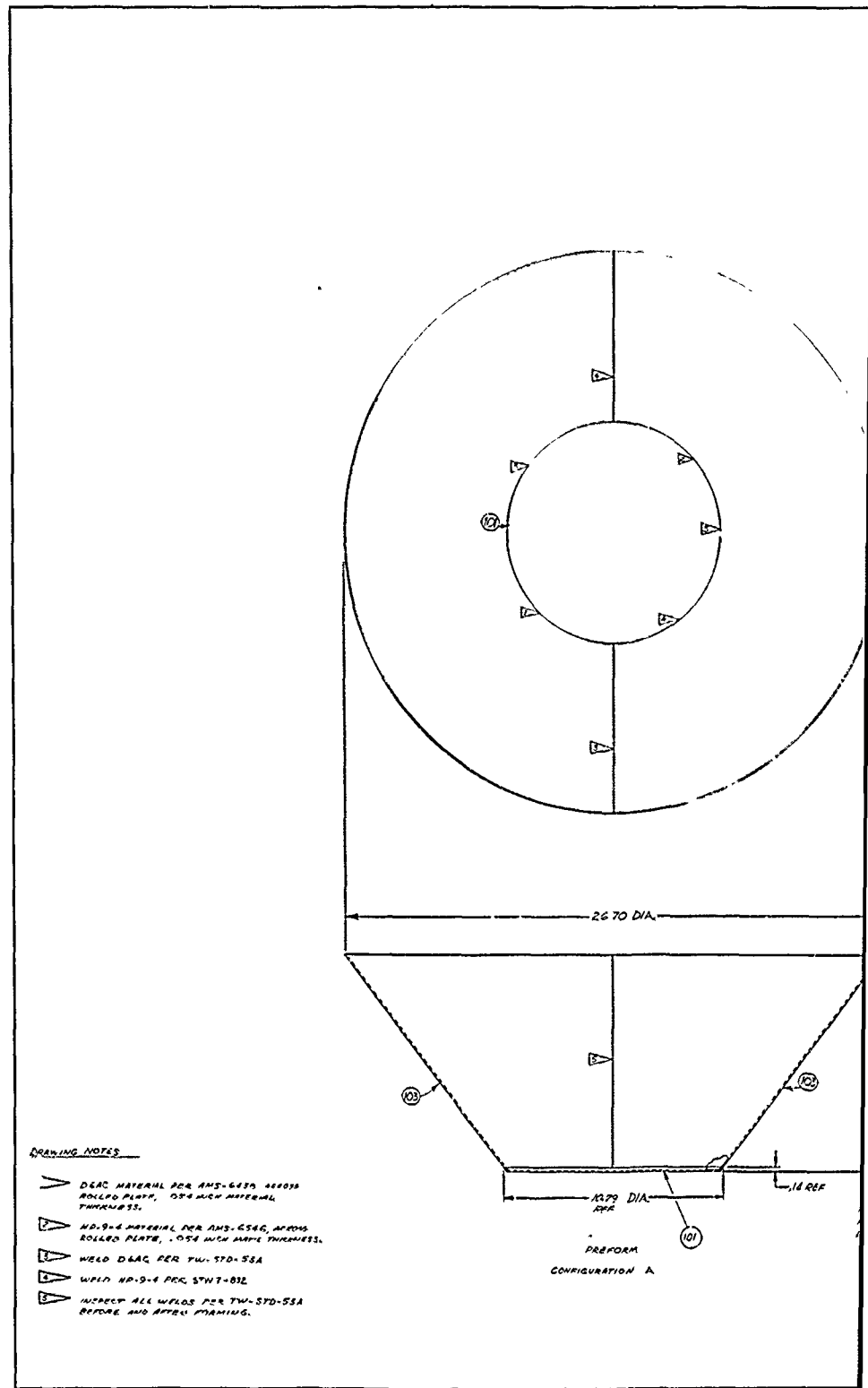
PREFORM
CONFIGURATION C

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Technical drawing of a dome structure, showing preform configuration, segment layout, and details.

PREFORM CONFIGURATION A

Diagram showing the overall preform configuration. Dimensions include 26.70 DIA. and 10.32. A note states: "THIS FIGURE IS A PHOTO REDUCTION DO NOT SCALE."

SEGMENT LAYOUT FOR PREFORM CONF. SECTION

Diagram showing the segment layout for the preform configuration. Dimensions include 10.79 DIA. and 10.32. A note states: "2 DETAILS REQUIRED".

DETAILS

Diagram showing details of the dome structure. Dimensions include 10.79 DIA. and 10.32. A note states: "2 DETAILS REQUIRED".

DETAILS

Diagram showing details of the dome structure. Dimensions include 10.79 DIA. and 10.32. A note states: "2 DETAILS REQUIRED".

53

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15. The polar cap was then machined to the small diameter of the preform.
16. The same circumferential welding procedures were followed as listed in Subsection A.
17. Following the circumferential welding operation, the weld was subjected to a low temperature (550° to 600° F for 20 min) stress relief.
18. The welds were ground flush, inspected, repaired, and inspected as necessary until an acceptable weld was obtained.
19. The circumferential weld was then given the high temperature (1,250° F) stress relief.
20. The grid pattern was inscribed on the preform, and indicated thickness and diameter measurements were taken.
21. The entire processing history was reviewed by the program manager, project engineer, supervisor of the Metallurgical Section, and the responsible engineer to insure that all necessary steps had been completed prior to shipping for explosive forming.

The procedure outlined was for D6AC material. Only slight modifications were made to make it applicable to HP9-4.

1. Prior to the longitudinal welding operation, HP9-4 parts were heat treated to a minimum ultimate strength of 185,000 psi.
2. All stress relieving steps were omitted.

Figure 28 shows a completed Configuration B preform which incorporated the modified design and was fabricated from the modified fabrication procedure just described. All preforms subsequent to 3A were fabricated using this procedure. Preform 5B received an additional full anneal thermal treatment as described in Section VII. After Preform 1B was weld repaired and became Preform 1B (R), it was subjected to a renormalization and double temper operation, which is also described in Section VII.

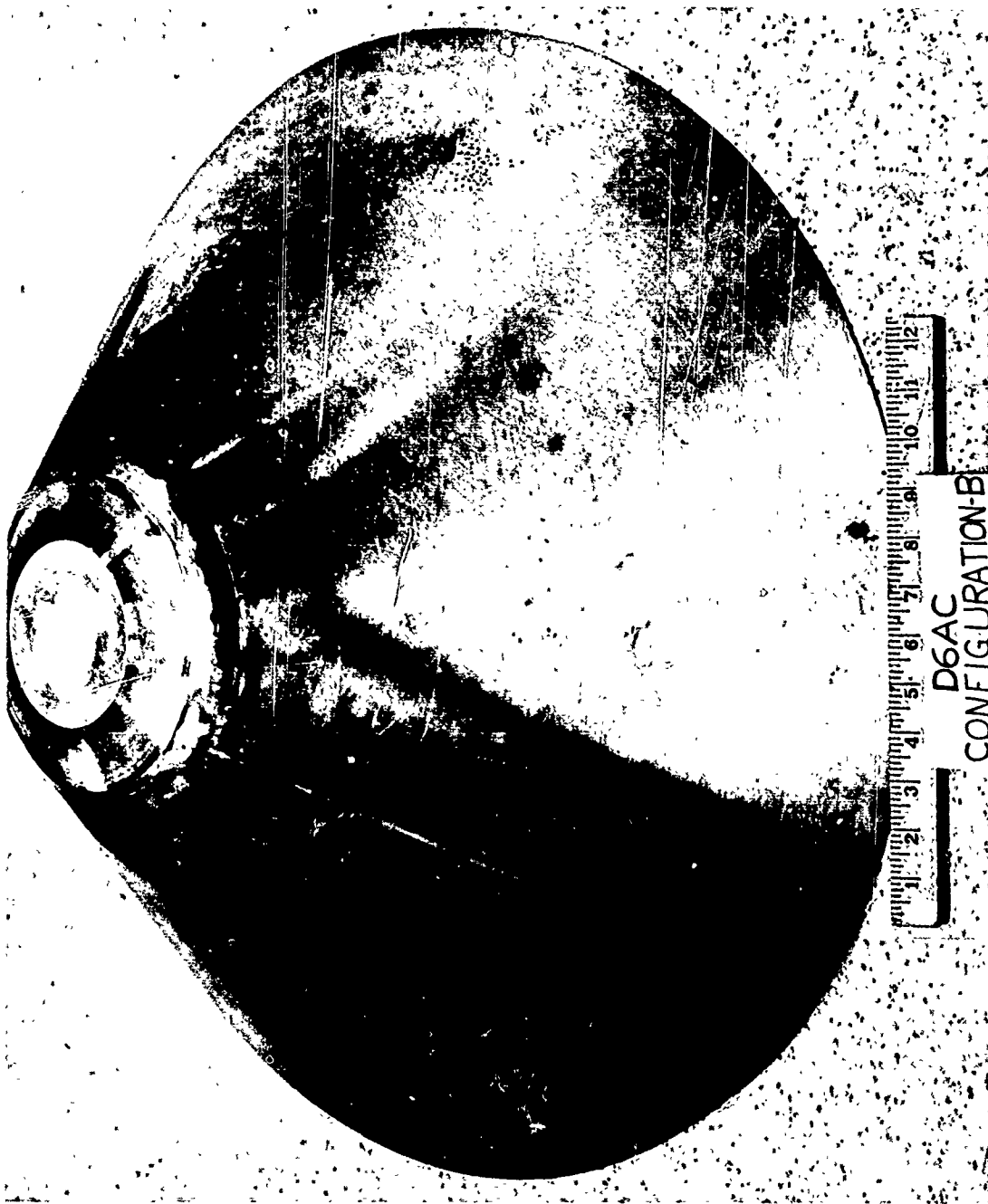


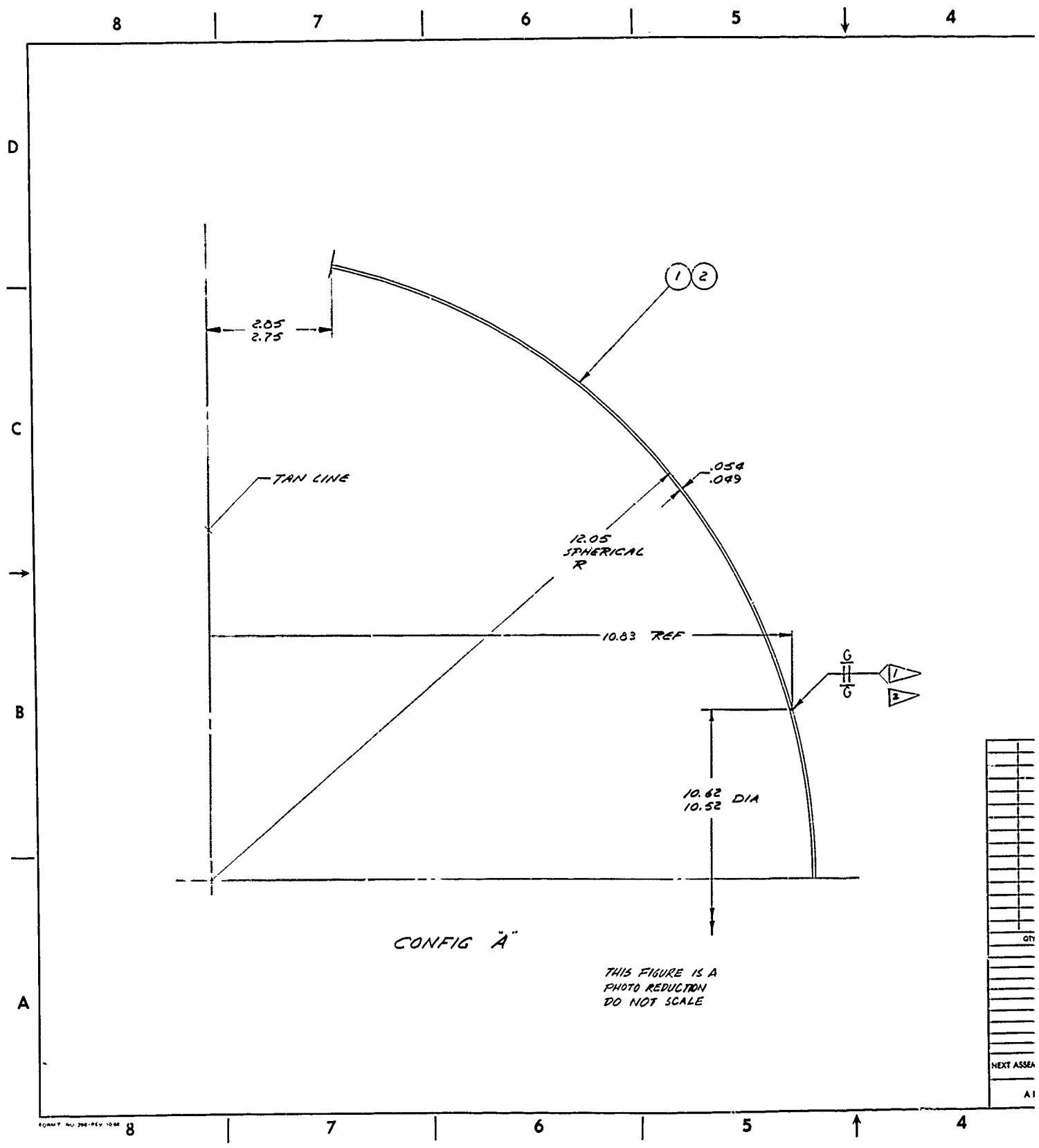
Figure 28. Configuration B Preform of Modified Design from Modified Fabrication Procedure

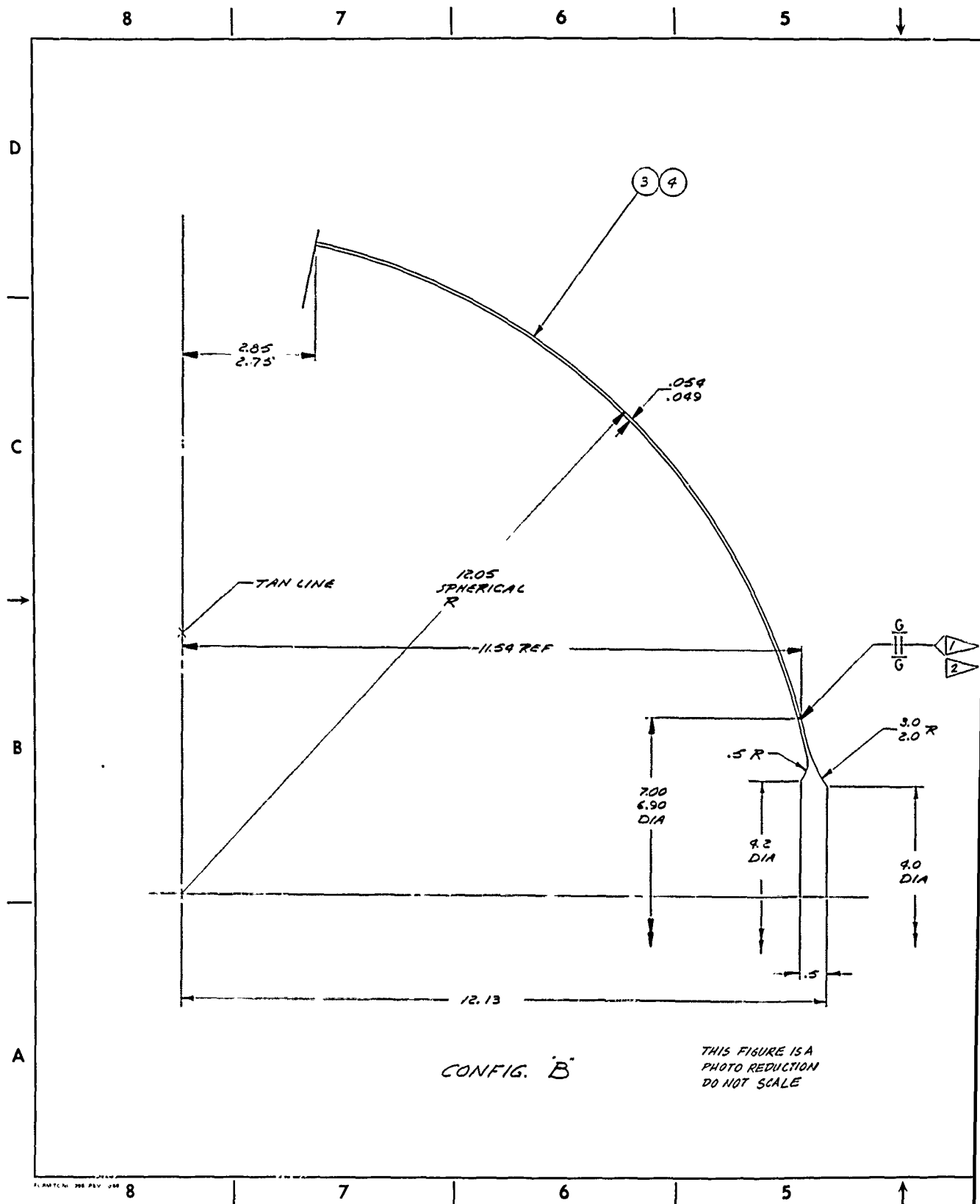
SECTION VI END ITEMS DESIGN

One of the basic objectives of the program was to develop a subscale design of the Titan SRM forward dome. Figures 29 thru 31 are end item drawings of the design selected for the program. These drawings represent 1/5 scale versions of the Titan SRM with respect to diameter and wall thickness. They are not finished machine drawings but end item with respect to the explosive forming operation.

The position of the igniter boss weld is for the original fabrication technique with the weld on the knuckle. For preforms fabricated from the modified technique, the weld radius dimension should be 7.25 to 7.40 inches.

17





B

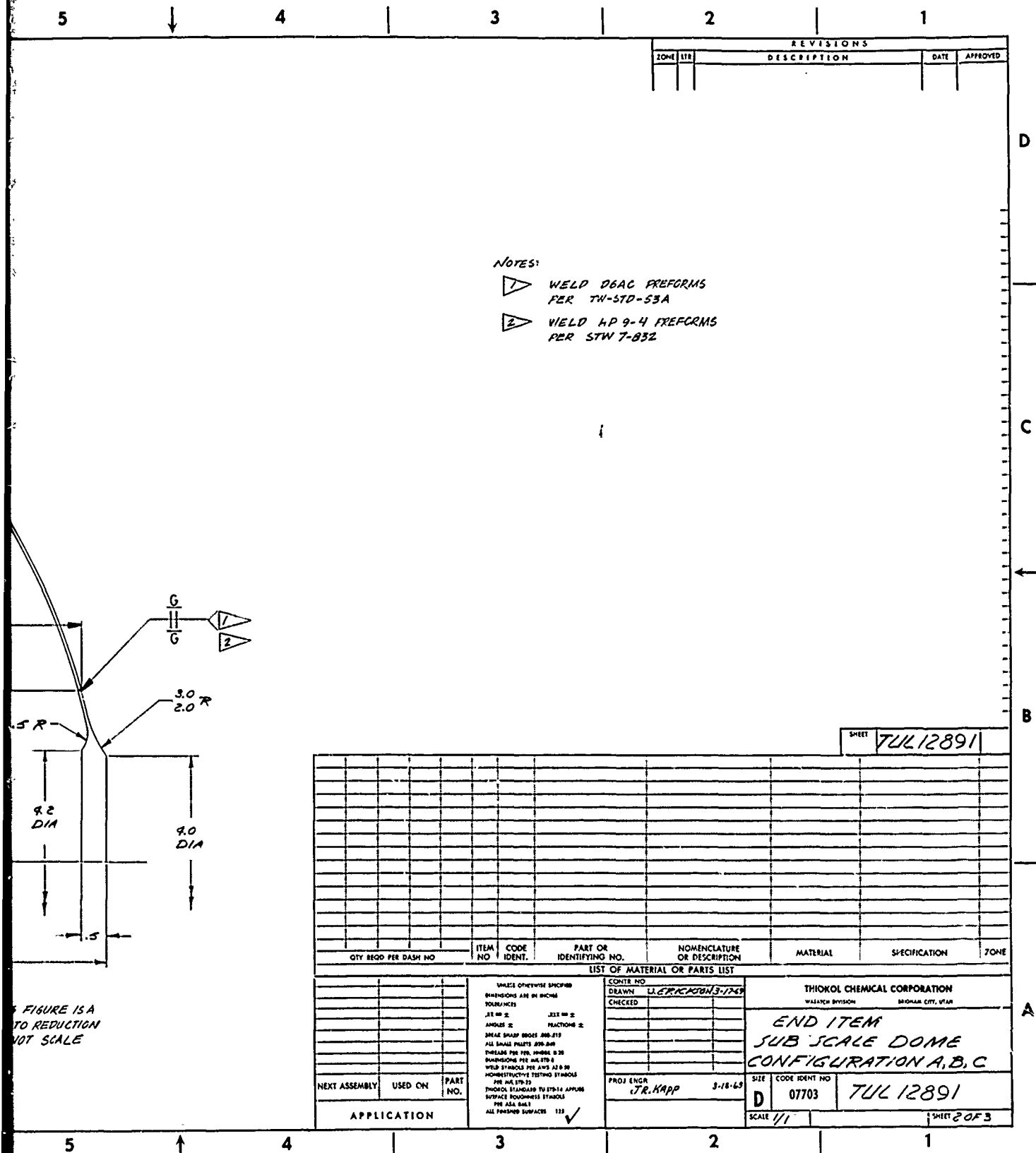
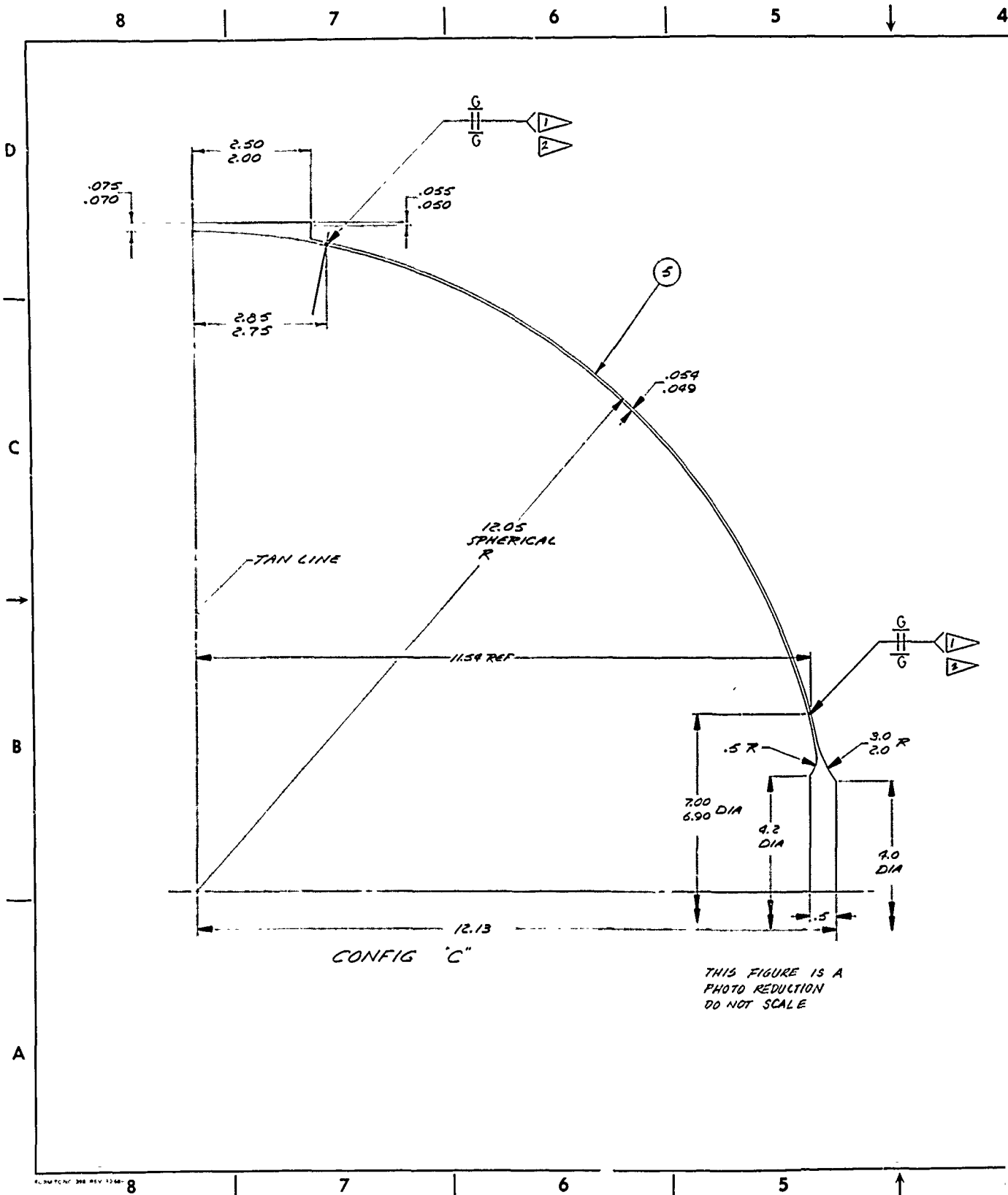


Figure 30. End Item Subscale Dome, Configuration B

P



5 ↓ 4 | 3 | 2 | 1

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SECTION VII DISCUSSION OF INDIVIDUAL PREFORMS

This section presents a detailed discussion of each preform involved in the revised program plan as presented in Table II. The discussion is complete except for those process decisions which were made based on the results of special study efforts. These results are summarized in this section and presented in detail in Section VIII (Special Studies).

In order to facilitate the discussion, preform fabrication is presented in combined form when a group of preforms were fabricated concurrently.

A. FABRICATION OF PREFORMS 1A, 2A, AND 3A

The preceding section details the fabrication procedure for the first three preforms as Method I.

The two D6AC steel preforms (1A and 2A) were the first to be fabricated. Cone sections, larger than required for the finished preform, were laid out on the ground plate material. The amount of excess material on the sides of the sections was not constant, varying from about 3.5 in. at the large end (diameter) to about 1.5 in. at the small end. The large and small diameters of the oversized sections were 1.0 in. larger and 1.0 in. smaller, respectively, than required. After shearing and cutting, the oversized sections were rolled to the approximate radius of curvature of the finished preform. Figure 32 shows how the trailing edge of the cone half sections was guided through the rollers with vice grips. This procedure, although necessary, did induce slightly irregular radii of curvature at the edge.

It should be noted that the D6AC material used for these two preforms was not 100 percent cross rolled material, but rather standard mill roll.

The longitudinal seams were then automatically TIG welded, after which it was noted that the preforms were considerably out of round. The major axis of the somewhat elliptical preform was across the weld seams. All longitudinal welds were stress relieved for 1.5 hr at 960° F. Several weld repairs were required on both preforms. Circumferential welds were stress relieved at 800° F for 2 hours.

After welding and X-ray inspection of the welds, the preform diameters were trimmed to size, beginning with the large diameters. During trimming of the small diameter of the first D6AC steel preform (1A), it was thrown off the machine. The preform was badly dented, and material was gouged from the small diameter. Figure 33 shows the gouge.

The gouged area was filled with weld metal and ground back to thickness. It was determined that the mishap was caused by improper machining techniques with respect to machining tool and cutting speed.



Figure 32. Guiding the Trailing Edge of the Half Section Through the Roller



Figure 33. Machining Gouge on Small Diameter of Preform 1A

This repair was not considered critical since the primary purpose of the preform was for die fit checkout. With new machining procedures implemented, both diameters of the second preform (D6AC 2A) were trimmed without incident.

After the preforms were removed from the internal holding fixture, the diameters appeared to be cut unevenly. This was probably due to the fact the preforms were forced onto the inside fixture and thus assumed nonequilibrium shapes. The diameters were then trimmed, and when the preforms were allowed to relax, the diametral cuts were found to be not even. In addition, the D6AC 2A preform diameters were oversized beyond the tolerance limits. In fact, it was necessary to completely section one side of the preform, pull it together, and weld a longitudinal seam. Thus, this preform contained three longitudinal seams.

Due to the fact that the small diameters of the preforms were out of round and unevenly cut, welding of the polar cover plate was extremely difficult. Moderate gaps existed between the cover plates and preforms. The circumferential welds had to be made manually using the TIG process, and weld beads were drawn on both the outside and inside circumference of the preforms. In those areas of poor match, three and four weld passes were required to close the gaps. Stress relief of the welds for 2 hr at 800° F was accomplished by setting the small ends of the preforms on Nichrome wound furnace heating elements. Subsequent X-ray inspection revealed several large defects (cracks and pores) in the welds. These defects were probably the result of the multipass welding, subsequent smoothing of the welds by grinding, or both. All cracks in the welds were ground out, but only those pores larger than 0.030 in. were removed. After rewelding, the entire weld was again X-rayed. In some instances, two weld repairs were required on a given area.

Figure 34 shows the finished Preform 2A with the three longitudinal weld seams.

Preform diameter and material thickness measurements were taken on each preform. These measurements were accomplished by lightly scribing a grid on each preform with an aluminum scribe and measuring the diameter and thickness at particular points.

Attention was then turned to the fabrication of the first HP9-4 preform (3A). The material which was available was not 100 percent cross rolled. The preform was completely fabricated in the annealed condition. This was done partly because of the trouble encountered in the fabrication of the first two preforms and partly to gain some limited experience with the alloy. At this time we did not feel confident of our capability to build a preform of hardened material until we had demonstrated better capability in the annealed condition. It was planned that an additional HP9-4 configuration preform in the hardened condition would be added to the program plan (5A).

After cutting, the oversized cone sections were rolled to radii of curvature less than those required by the finished preform. The reason for rolling smaller was to attempt to keep the preform more in round. The longitudinal seams were automatically TIG welded according to Thiokol Specification STW-7-832, after which it was observed that the preform was not too badly out of round. It was much better than the previous D6AC preforms. After X-ray inspection and repair of the welds,



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Figure 34. Finished Preform 2A

the preform diameters were then trimmed to size, the small (more critical diameter) being trimmed first. Again, both diameters appeared unevenly cut, but not as bad as the previous preforms. The circumferential weld was thus much easier to make. Welding still had to be performed manually, but only one weld pass was required. Minor repair of the circumferential weld was required. Figure 35 shows the completed 3A preform.

General comments on the final condition of the first three preforms can be made as follows.

1. Final dimensional condition of the preforms was relatively good, and it was anticipated that there should be no problem with die fit.
2. Several weld repairs had to be made on all longitudinal and circumferential seams although final X-ray inspection indicated good quality welds.
3. It was extremely difficult to blend the inside of the circumferential weld since it was located right at the junction of the cone and polar cap. Consequently, there were areas where the weld bead stood out from the parent material. Although it was recognized that this was not a desirable condition from the standpoint of stress concentration, it was felt that the possibility of undercutting the weld was too great to continue blending.

B. EXPLOSIVE FORMING OF PREFORMS 1A AND 2A

1. CHARGE CALCULATIONS

Earlier in the program, EFD had made numerous calculations to determine the starting point for the deformation of the steel preform. A number of equations have been developed for charge estimation; however, the accuracy obtained is basically a function of the assumptions made in the use of available equations. A recent equation which includes the prime parameters and depends on several reasonable assumptions is shown in Equation (1) below.

$$W_e (1 - \cos \phi) = \frac{\pi D_o^2 t_o K}{12 (n+1)} \left[21n \left\{ 1.5 - \frac{1}{2 \left(1 + 4 \frac{w^2}{D^2} \right)} \right\} \right]^{n+1} \quad (1)$$



Figure 35. Finished Preform 3A

where:

- W = charge weight (lb)
- e = specific energy (ft-lb/lb)
- ϕ = subtended angle between charge at a given standoff and the blank surface (deg)
- D = diameter of die opening (in.)
- t_0 = initial blank thickness (in.)
- K = strength coefficient at a true strain of 1.0 (psi)
- n = strain hardening exponent for the material being formed
- w = draw depth required (in.)

Actually, the above equation was developed for use in an open pool with circular blanks in a conventional explosive forming die. Thus, the accuracy of the equation was unknown for the conical preform case with which we are concerned. For example, the die opening diameter is not reasonable to use since the charge is located well below the maximum diameter. Thus, we have used an effective diameter based on the position of the charge within the cavity. In addition, the amount of water over the die in open pool forming is substantial compared with that used in preform fabrication. Although these effects are not analytically accountable, Equation (1) illustrates details considered in the estimation of charge weight.

As indicated, Equation (1) takes into account the important parameters associated with explosive standoff techniques. The strain hardening coefficient was taken from available data on D6AC material. A value of 0.35 was used in the calculations. Strength coefficient values from about 95,000 thru 110,000 psi have been reported for D6AC in the annealed condition. For the purpose of charge estimation, a value of 105,000 psi was used. The explosive chosen for the forming work was trinitrotoluene (TNT). The specific energy of the explosive is in the range of 1.2 to 1.4 x 10⁶ ft-lb/lb, based on granular material. One of the problems that is confronted in the use of central charges for preform fabrication is the difference in standoff from the charge to the base closure and from the charge to the sloping wall at a given charge placement. There is only one point that can be selected for a central charge where the two distances are equal. That point is at the center of the sphere defined by the die cavity. However, because this point is located essentially in the plane of the clamping ring at the top of the preform there would be little or no water head above the charge. This would necessitate the construction of a water container above the die surface to permit greater efficiencies in forming. From economic and logistic standpoints this is undesirable. Consequently the choices one has are to use a "spoked ring" type charge to permit equal standoffs from the sides and bottom or to deform the part in two stages. The latter route is considered the desirable approach for minimization of charge requirements, and because it could possibly provide greater control of material flow during deformation. The greatest reason for consideration of a central charge is that it can be more easily scaled to the 120 in. end closures.

2. PREFORM 1A

The first preform shipped to EFD was essentially an extra blank supplied for tool tryout. The primary purpose of this preform was to check the die for dimensional fit-up, assembly techniques, and vacuum. Although the part was out of round when free standing, it presented no problem in sealing or fit-up when placed in the die with the restraint ring. Contact of the circumferential weld with the die was verified by coating the weld with Hi-spot bluing and then placing the preform in the die. The bluing was transferred to the die, indicating the weld was stabilized prior to forming. It was decided to proceed with forming this blank to verify the initial charge calculations.

Since the preform is stabilized at the bottom by contact with the die surface and assuming a sound, ductile weld (i. e., weld nugget exhibiting similar ductility to that of the parent metal), it is logical from a forming standpoint to form the hemisphere dome cap first to fully stabilize the preform and then fill out the part by a second charge. Using this philosophy, the first preform was shot using a standoff of 3.5 in. Equation (1) indicated a charge of 19.05 gm to permit total deformation of the preform. However, because of the questionable weld repair, it was felt wise to reduce the required charge to enhance weld performance during forming. A charge of 10 gm was selected and used. Table V is a schedule of the charge and standoff sequence used on Preform 1A.

It should be pointed out that because of the thin blank membrane (0.054 in.) a very small pressure at the blank surface will cause yielding of the material. When considering the side wall which is 7.5 in. from the charge, a pressure of 8,800 psi theoretically results in an underwater explosion from a 10 gm charge. Since only partial deformation was achieved from the 10 gm charge, it is obvious that the theories established for pressure due to underwater explosions do not hold true for our case. It is felt that because of the immediate exit of the water from the preform cavity governing equations for pressure, P , as a function of distance might be more closely approximated by those given for blasts in air.

Because of the shape of the die and, therefore, its confining effect on the explosive blast, an increase in efficiency over open pool forming would be expected. However, the results of the first tests indicate that significant energy is lost because of water exit from the preform cavity, and reloading which accompanies an explosion in pool forming cannot occur.

As was expected, the 10 gm charge selected was insufficient to fully deform the dome cap region. However, the weld fractured, which prevented analysis of forming results. The fracture was found to initiate from a repair area, and little or no deformation occurred in the weld. Since little was learned from the first experiment, continued forming of the preform after weld repair was required. Thus, a second shot was made with a 10 gm charge. This shot completed forming of the part to the die at the apex. However, the weld fractured again at areas near repaired regions. Another repair was made and seven additional shots were made

TABLE V
CHARGE AND STANDOFF SEQUENCE FOR PREFORM 1A

<u>Sequence</u>	<u>Charge (gm)</u>	<u>Standoff Distance (in.)</u>
a.	10	3-1/2
b.	10	3-1/2
c.	10	4
d.	10	4
e.	10	5
f.	15	6
g.	20	7
h.	30	8
i.	40	8

until full die contour was reached by the part. No further weld failures occurred until the final two shots, after which small cracks formed along three repair areas. The forming experience was useful, even though it was not representative of production conditions, since details of sealing, charge effects at various standoffs, and preform deformation behavior were investigated. Figure 36 is a view of preform 1A in the fully formed condition. It is also noted that one small section of the original circumferential weld was still intact after the complete forming operation (Figure 37) and that no weld repairs were required on the longitudinal seams.

A problem observed during the first shot was that of significant pull-in of the preform. The concentrated loading at the preform apex caused excessive draw. This is normally desirable in flat blank deformation, but in fabrication of parts having high D/t ratios, there is a tendency for buckling due to the relatively thin wall of the preform. The excessive draw and resultant buckling of the preform prohibited accurate location of the formed part on the inspection fixture. This problem should be eliminated by increased bolt holddown torque and, therefore, increased restraint. An 80 ft-lb of torque was applied to 15 (3/4 in.) bolts during this forming operation.

3. PREFORM 2A

Based on the results of tests on the first blank, it was decided to form the second blank using a relatively large standoff, 8 in., in addition to increasing the holddown force to 90 ft-lb of torque. The intent here was to crease or pin the preform just below the clamping ring to further stabilize the blank against excessive draw. Subsequent shots would complete the part shape. For conservatism, a charge of 10 gm was chosen. On the first shot (Figure 38), the circumferential weld fractured with some deformation of the base piece. The crease desired at the top of the preform was produced for stabilization. At this stage it was mutually decided by Thiokol and EFD personnel that a detailed investigation be made of the welds to determine characteristics. A detailed study was subsequently conducted by Thiokol personnel.

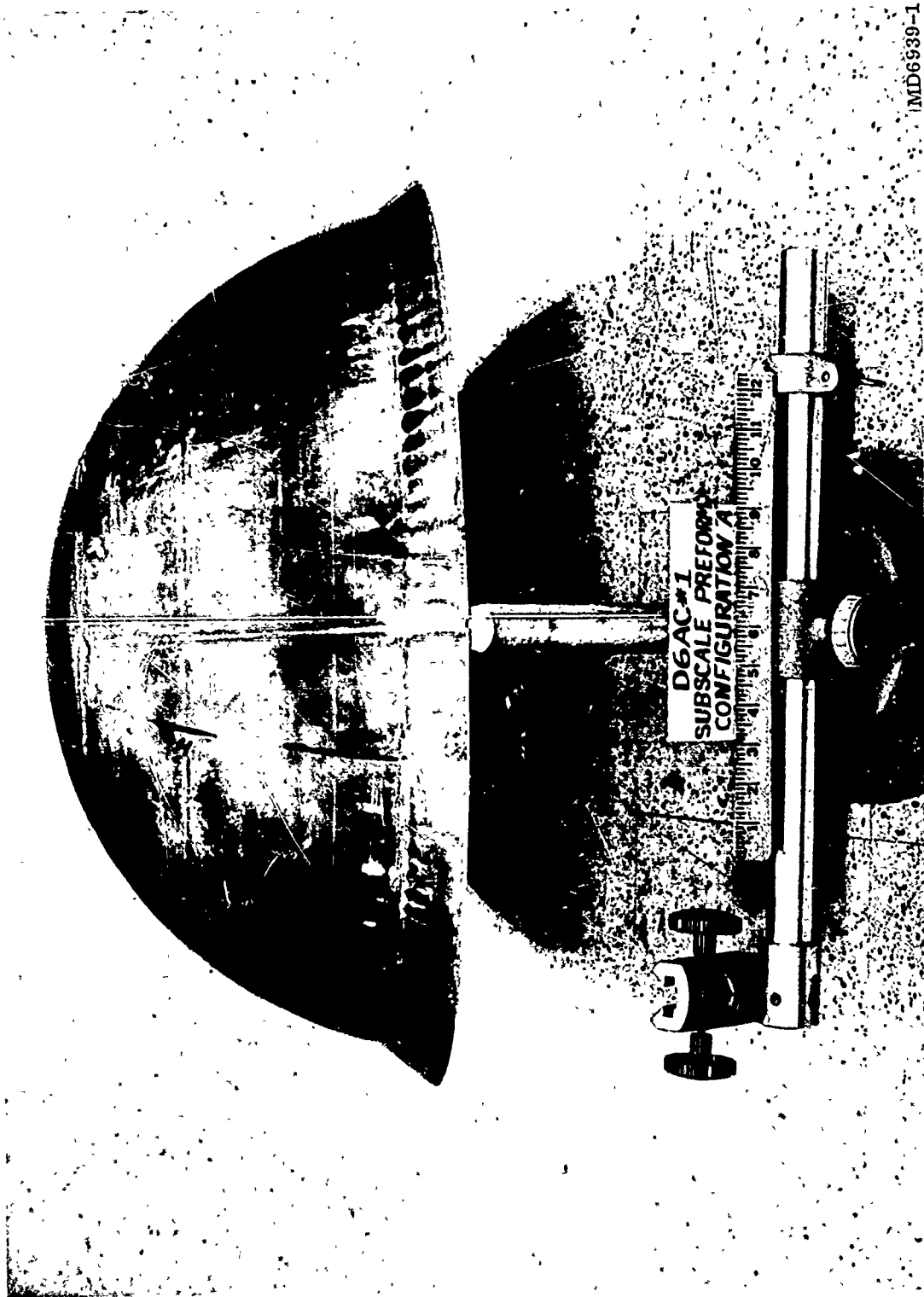
Figure 38 shows the amount of deformation which had taken place in the preform during the first shot.

C. EVALUATION OF PREFORM 2A FAILURE

The second preform, 2A, was shipped to Thiokol for examination.

Figure 39 shows an external view of the large circumferential crack which occurred during the forming operation. No cracking was observed in the longitudinal welds.

The largest crack had a length of about 11.0 in. and was symmetric about the longitudinal-circumferential weld junction as shown by an internal view in Figure 40. A second crack, shown in Figure 41, with a length of about 4.0 in. was located at about 120 deg from the midpoint of the large crack.

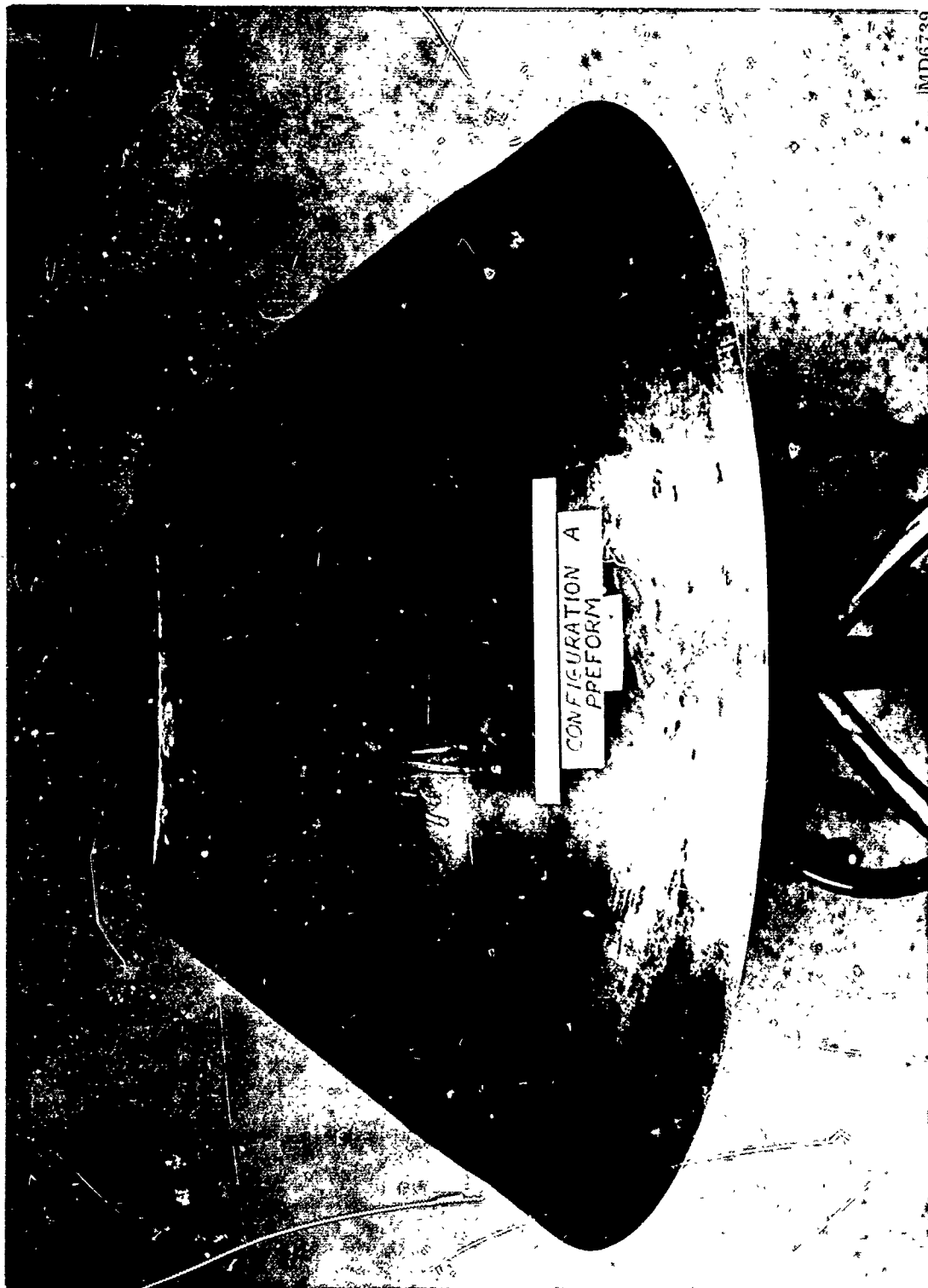


1MD6939-1

Figure 36. Fully Formed Dome 1A



Figure 37. Original Weld Intact After Final Forming Operation (Approx 1 in.)



JMD6739

Figure 38. Preform 2A Subsequent to the First Forming Shot

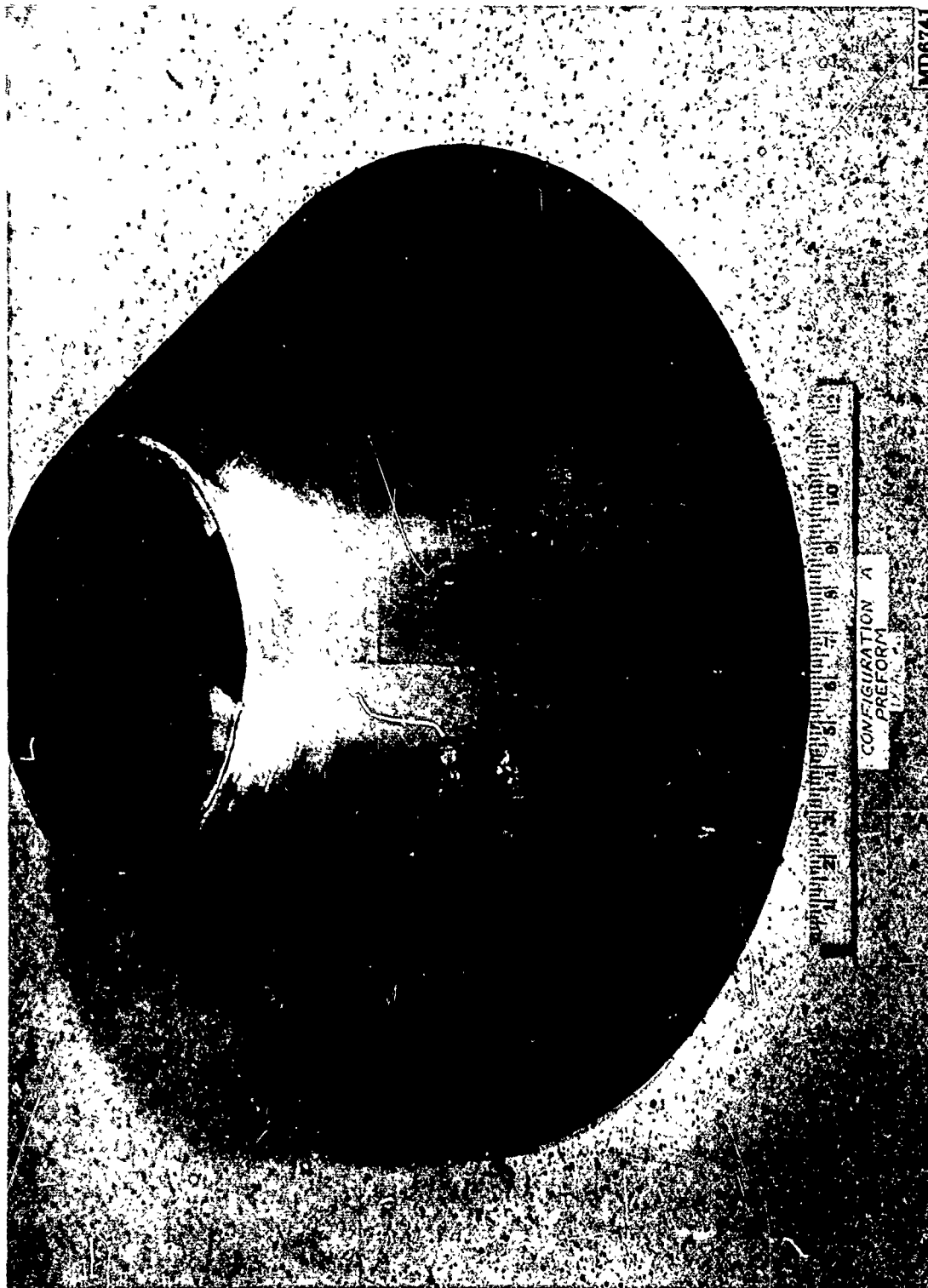


Figure 39. External View of Preform 2A Showing Circumferential Cracking

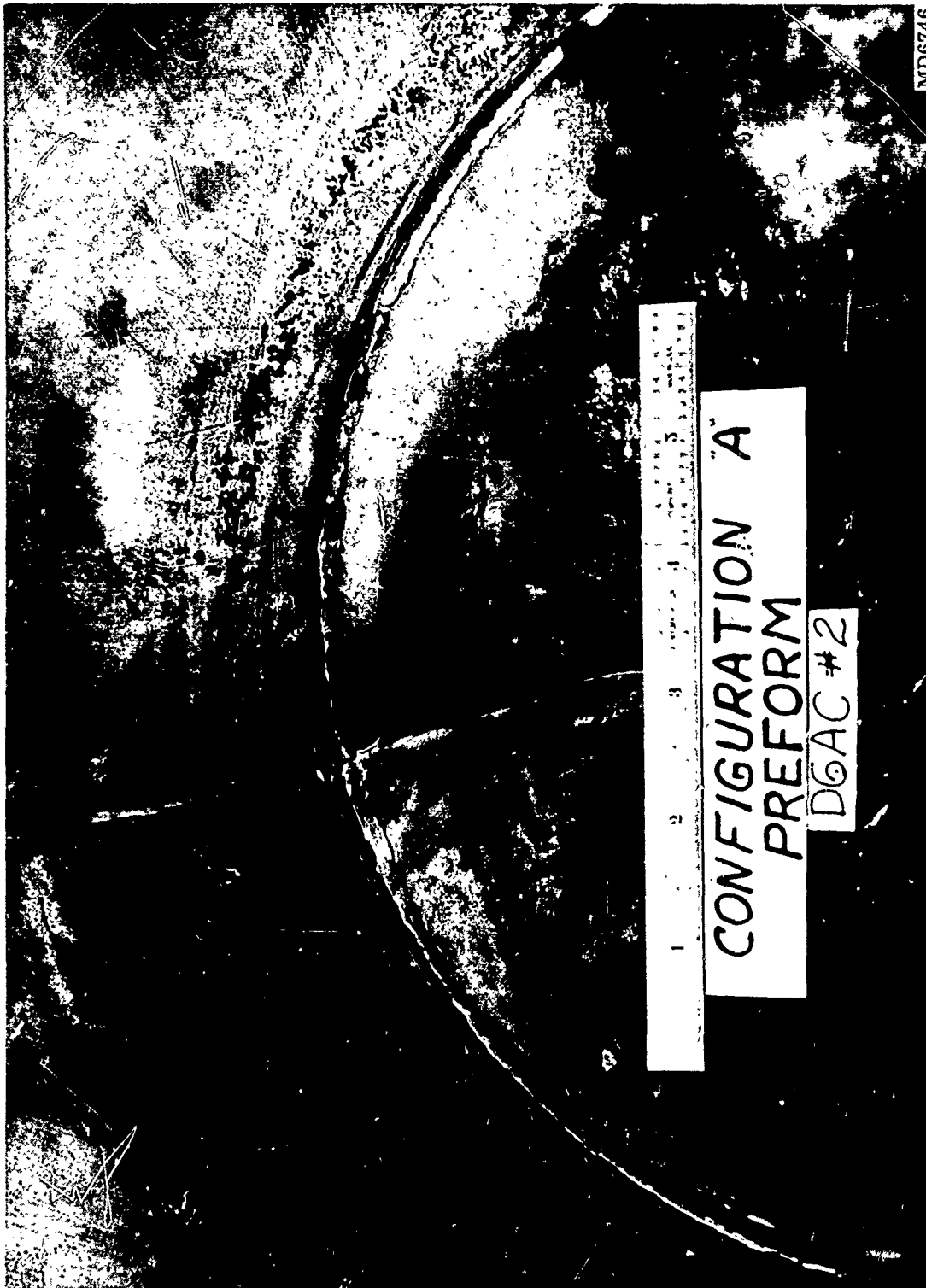


Figure 40. Internal View of Circumferential Crack in Preform 2A

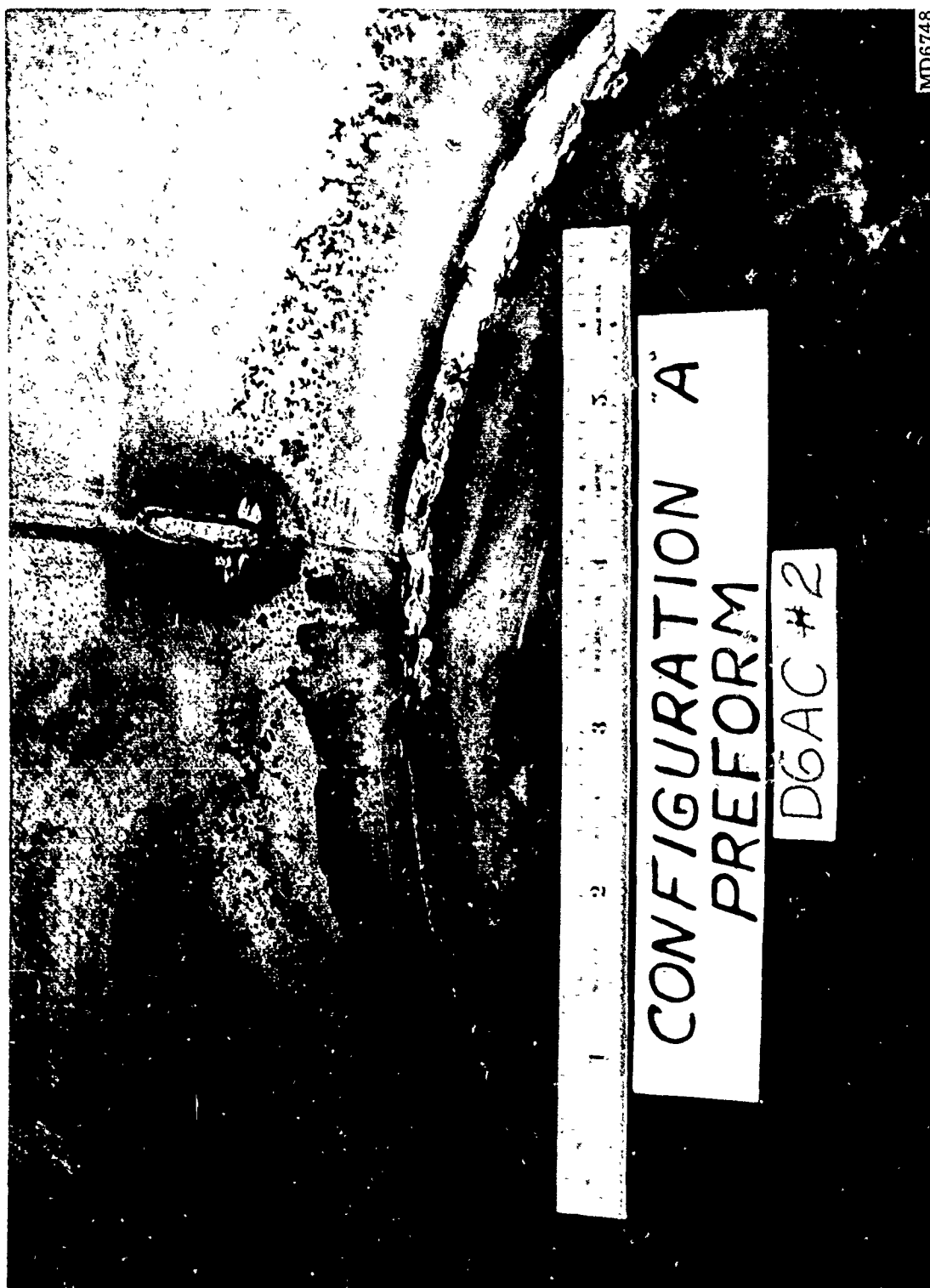


Figure 41. Internal View of Second Largest Circumferential Weld Crack in Preform 2A

A third circumferential crack which had initiated on the inside surface and propagated about three quarters of the way through the thickness was also observed. This crack is shown in cross section in Figure 42. Figure 43 is a scale photo, magnified 250 times, of the tip of the crack shown in Figure 42.

Figure 44 shows the relative position of the three circumferential cracks along with the relative location of metallurgical investigations.

The two open fracture surfaces were examined optically and with an electron microscope (surface replication). Several transverse sections (Figure 45) were taken from the fracture areas and also from intact circumferential weld areas. Longitudinal welds were examined metallographically and checked for hardness. In addition, several tensile specimens were sectioned from the longitudinal welds as shown in Figure 45. Some specimens were cut so that the weld was parallel to the tensile axis, and others had the weld transverse to the pulling direction.

The results of the investigation can be summarized as follows.

1. Optical and electron microscope examinations indicated that the circumferential weld fractures resulted from an overstrain condition; i.e., the areas where the cracks nucleated were not able to accommodate the imposed strain of the explosive forming process, and not from some type of weld defect.
2. All cracks appeared to nucleate in those areas of the weld where repairs had been made and not subsequently stress-relieved. These are areas of high strength (hardness) and low ductility. Rockwell hardness traverses performed in these areas indicated hardnesses in the range of 58 thru 60 R_C .
3. The areas of crack initiation (weld repairs) seemed to exhibit very coarse grained martensitic microstructure. A typical photomicrograph of this martensitic structure is shown in Figure 46. A typical microstructure of the parent D6AC material is shown in Figure 47. The magnification factor is 250 x in both figures.
4. The susceptibility to cracking is further increased in areas where the weld blend is not complete. Figure 48 shows a cross section of the circumferential weld at 10 x magnification. An incomplete blend is readily visible and a crack which is either beginning initiation or is a defect missed by inspection is shown at the weld bead edge. Figure 49 is a 250 x magnification of the defect area.
5. Areas where no weld repairs were made and proper weld blending was accomplished showed no sign of fracture initiation. Figure 50 is a cross sectional view of such an area. This figure also serves to demonstrate the difficulty of maintaining a constant material thickness when the weld is located on the knuckle.

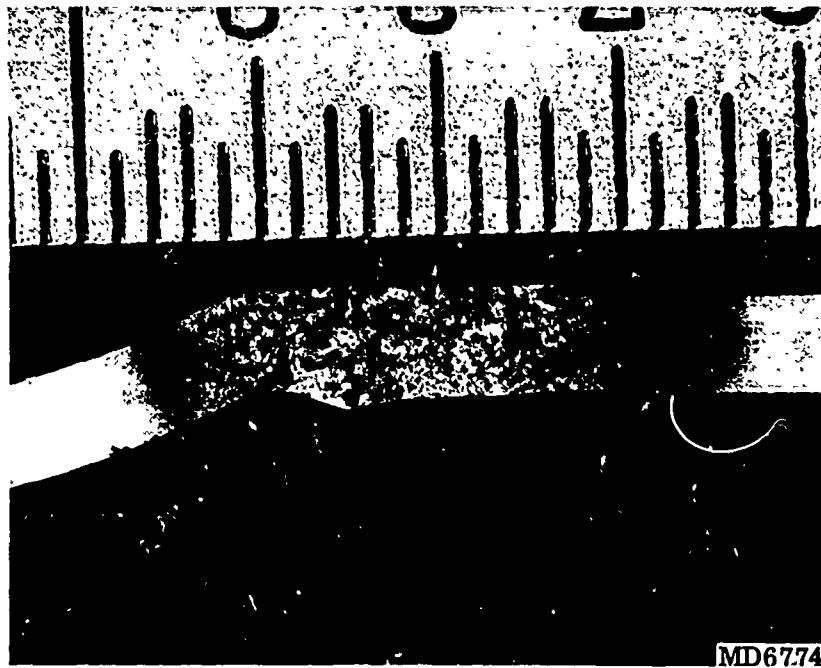


Figure 42. Partial Thickness Circumferential Crack in Preform 2A (10 x)

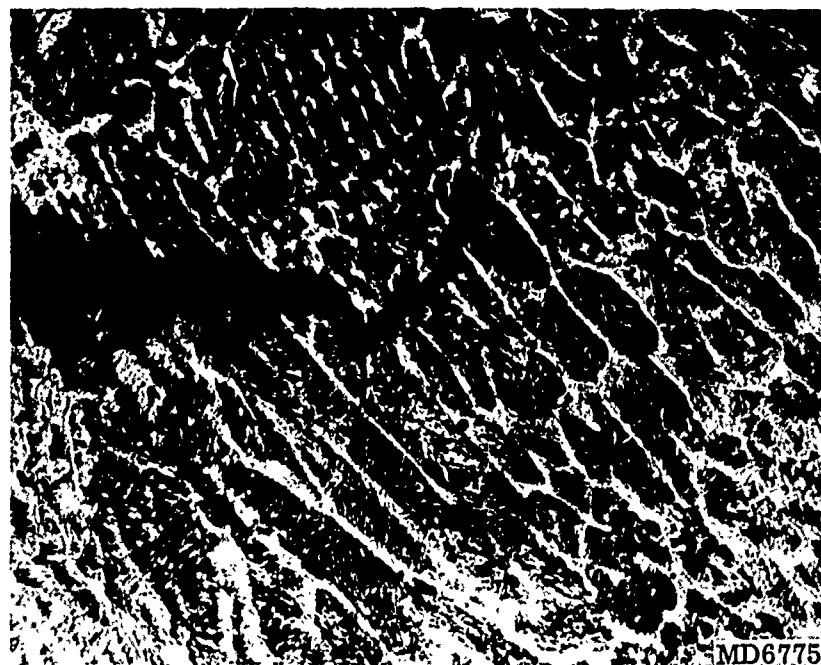


Figure 43. Magnified View of End of Crack Shown in Figure 42 (250 x)

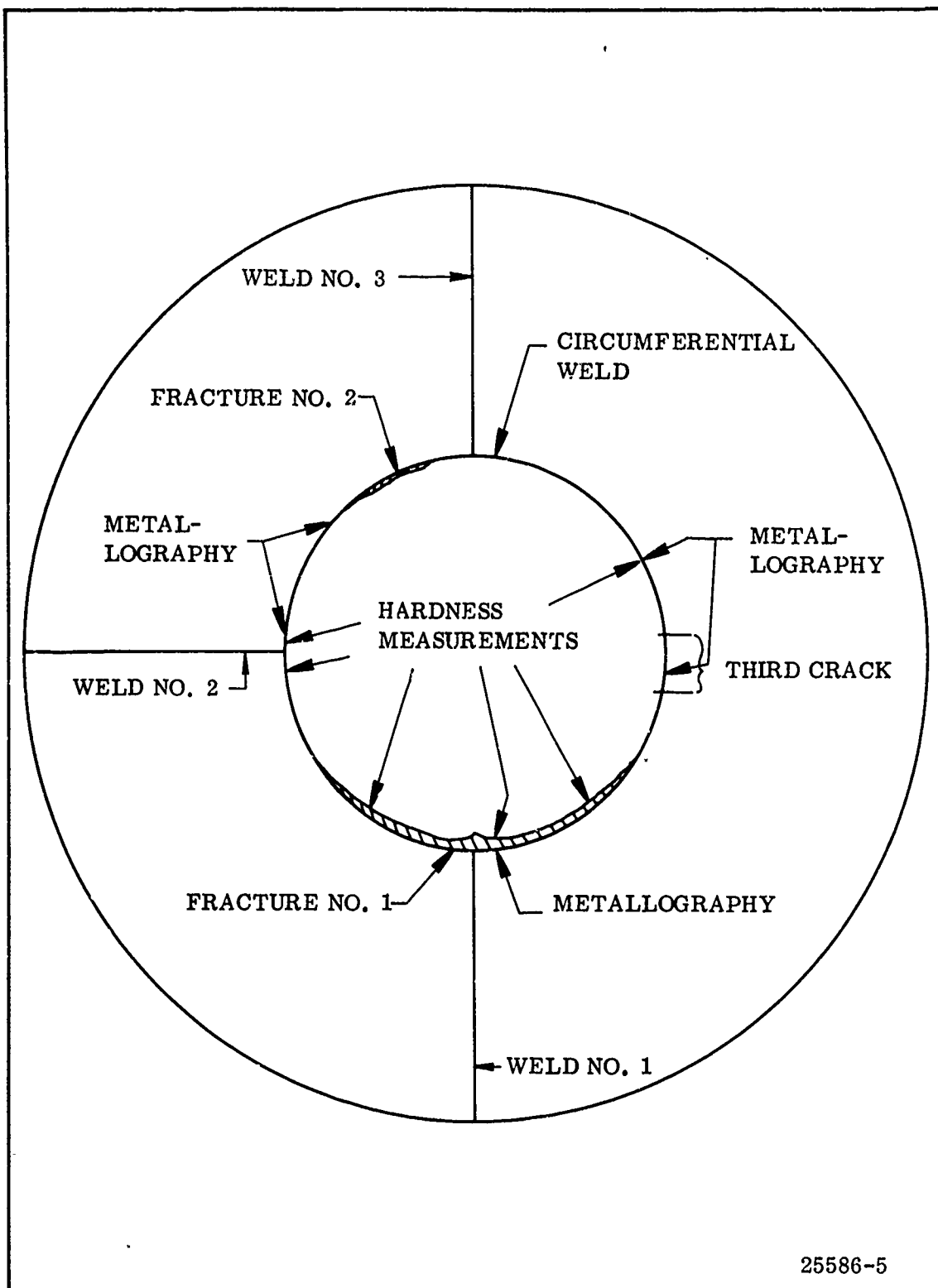


Figure 44. Relative Locations of Fractures and Sites of Metallurgical and Hardness Investigations

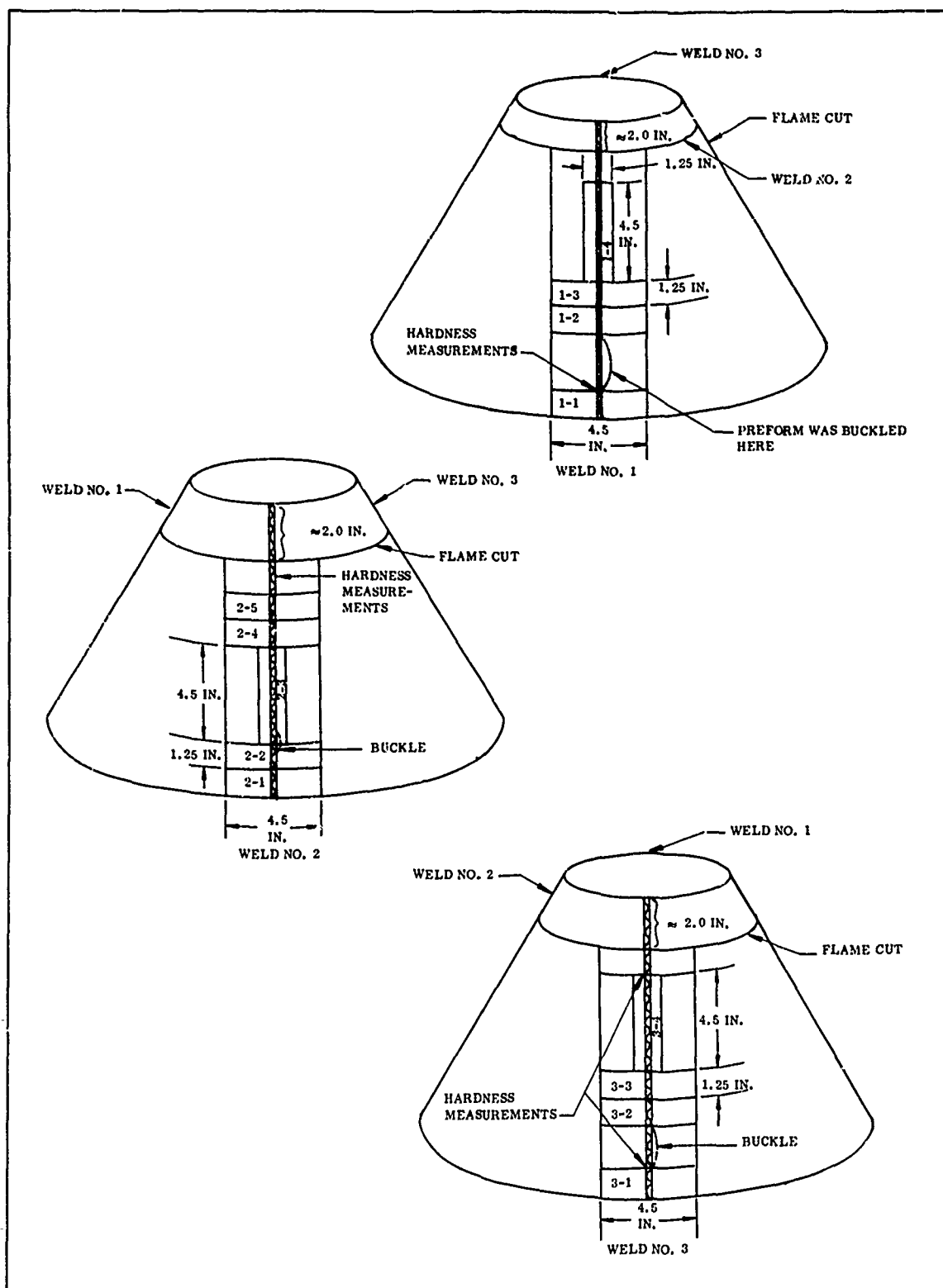


Figure 45. Locations of Tensile Specimen Coupons

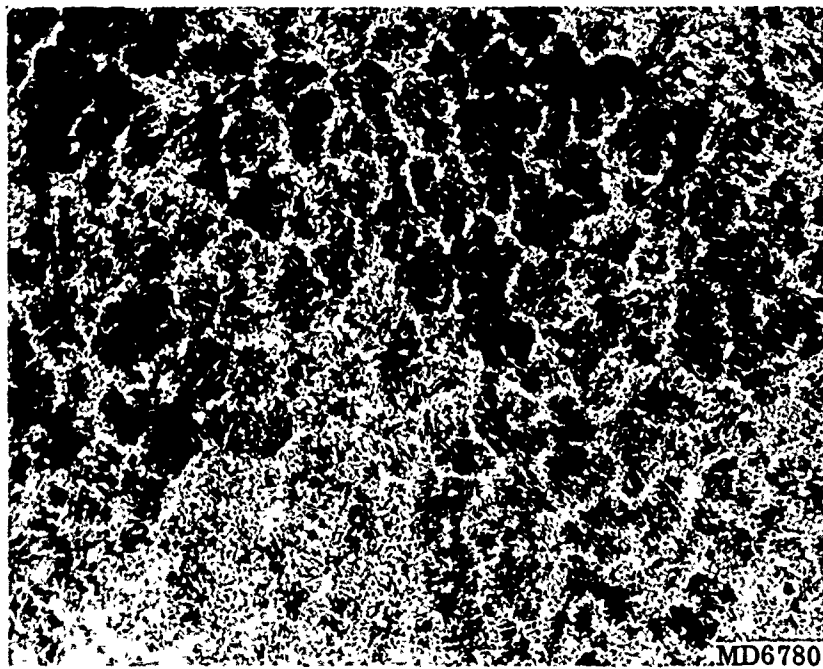


Figure 46. Martensitic Microstructure in Areas of Crack Initiation (250 x)

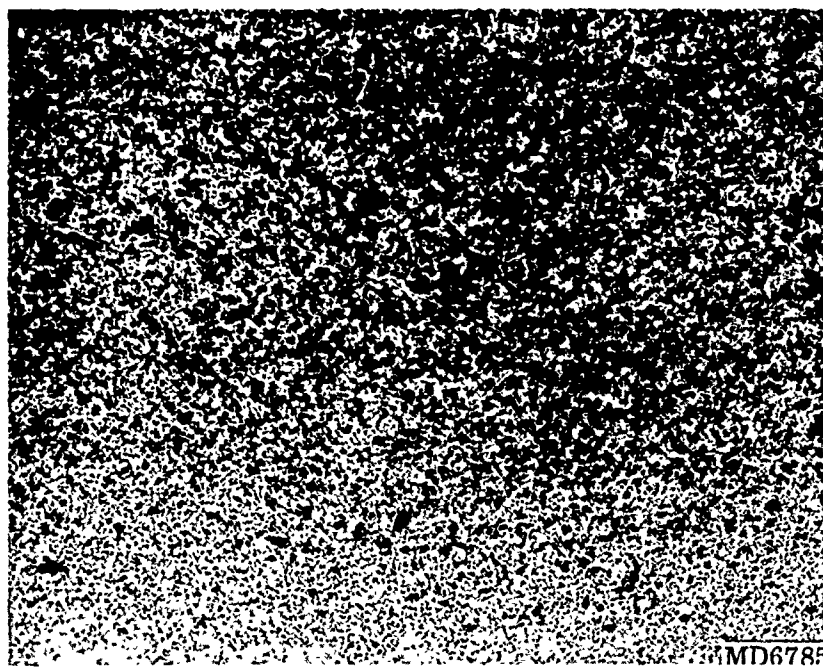


Figure 47. Microstructure of Parent D6AC Material (250 x)

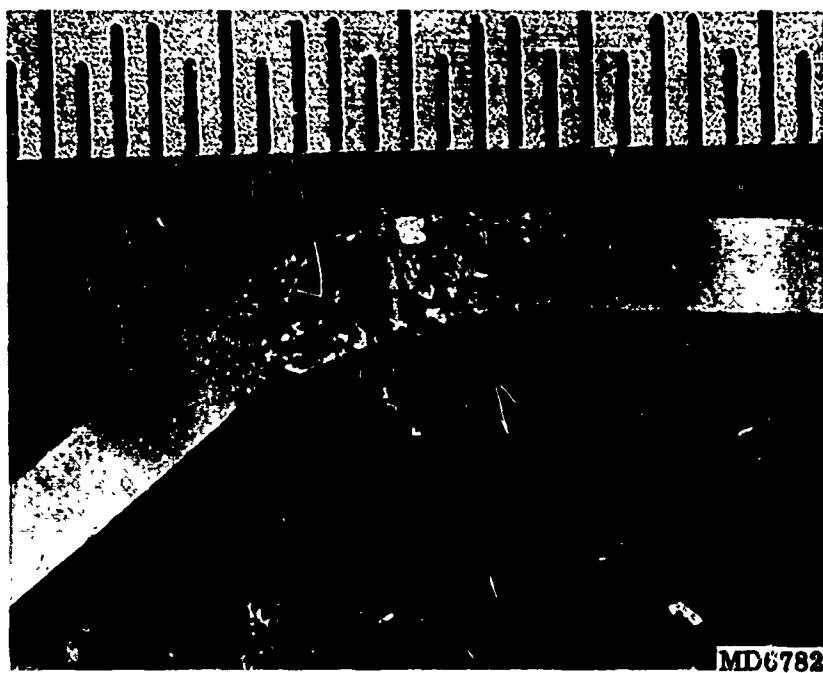


Figure 48. Circumferential Weld Cross Section Showing Incomplete Blend and Edge Defect (10 x)



Figure 49. 250 x Magnification of Edge Defect Shown in Figure 48

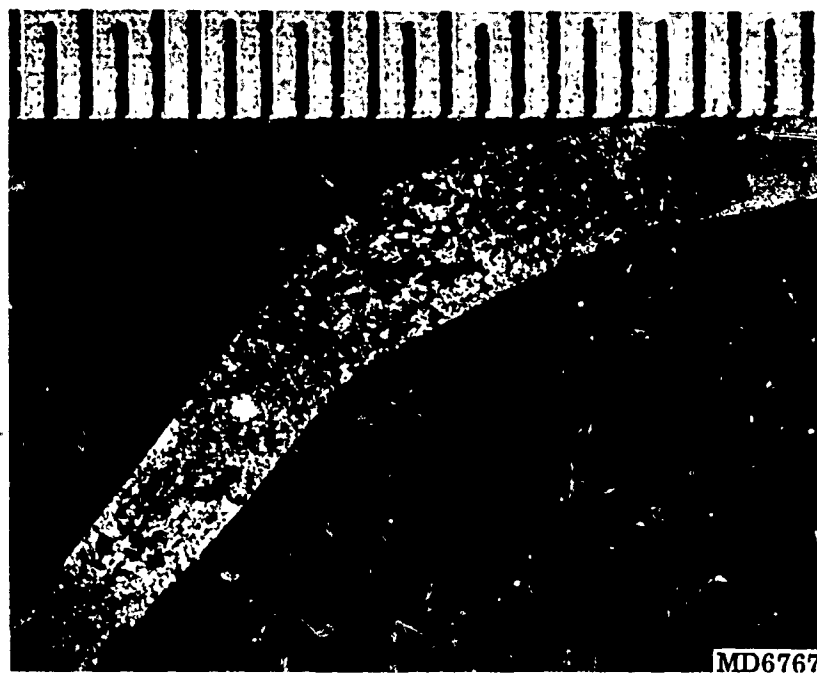


Figure 50. Properly Blended Cross Section of Circumferential Weld (10 x)

6. The longitudinal welds were completely intact even in the weld repair areas.
7. Hardness traverses taken in weld areas which were stress relieved ranged from 40 to 50 R_C, which is too high for the material to have the required elongation.

There are some very important conclusions that were drawn from the results of this investigation.

One major problem was in the area of weld stress relief. All weld repairs, regardless of size, should be stress relieved after repair, and the entire stress relieving process must be reevaluated with respect to time and temperature requirements in order to reduce hardness and grain size in the weld area.

A second major problem was in the area of weld blending. It was felt that something must be done to eliminate the possibility of improper blending causing high stress risers at the weld edge. It also seems to be almost impossible to maintain a constant thickness in the weld blend even when blending has been properly accomplished.

At this time, a modified fabrication technique was developed (described as Method 2 in Section V). The primary advantage of this technique was to move the circumferential weld off the knuckle and thus decrease the strain requirements during forming. At this same time, a weld stress relieving study was initiated in order to determine a better method of local stress relief. The complete results of the study are presented in Section VIII (Special Studies).

D. FABRICATION OF PREFORM 4A

A third D6AC preform, designated as Preform 4A, was fabricated according to the modified procedure. Much of the fabrication process was conducted concurrently with the weld stress relieving study and process review. Therefore, some of the aspects of the modified process came about as a result of experience on this preform.

The conical half sections were rolled to contour. After rolling, it was noted that the radii of curvature did not vary linearly from small end to large as would normally be expected of a true conical shape. It is felt that without rolling equipment with conical rolls, it would be very difficult to roll a true contour.

This slightly discrepant change in curvature resulted in vertical mismatching of the weld edges. A great deal of effort was expended trying to minimize this mismatch. The longitudinal weld beads were successfully made and given a minor (550° F for 20 min) stress relief. Subsequent inspection indicated no need of weld repair on either seam.

At the time of final stress relief, only the 1,350° F for 2 hr portion of the weld study had been completed. The results indicated that acceptable properties could be obtained by this treatment, and the longitudinal welds were processed in this manner.

Completion of the weld study subsequently indicated that a 1,250° F for 1.5 hr stress relief was slightly more acceptable, and future welds (through Preform 2B) were so processed.

An attempt to successfully trim and match the small diameter and polar plate was made. It became evident that it would not be possible to effect a fit which would permit automatic welding.

At this time, it was decided to cut the small radius back and machine it when in the perfectly rounded condition. A conical aluminum mandrel was produced to force the cone on while the diameter trimming was being accomplished. The end mill was allowed to cut right into the aluminum mandrel, and the results of the trimming operation were very good.

The polar cap was machined and mated to the cone for circumferential welding.

At the beginning of the circumferential welding operation, difficulty was encountered with the gas flow rate. The fit between the parts was so close that gas was not allowed to flow out, except at the point of the weld where the material was molten. The flow rate was decreased, and the remainder of the weld was made without incident. Hand repairs were required in the area where the difficulty occurred.

Inspection indicated that one small additional weld repair was required.

The weld was given a 1,250° F for 1.5 hr stress relief.

The general condition of the completed preform was very acceptable. The relocation of the circumferential weld had created a much superior weld and allowed for easy grinding of the weld bead. The knuckle area was now machined instead of hand blended and was in much better condition to accept the strain requirements of the forming operation.

E. FORMING OF PREFORM 4A

A Cerro polar plug was used to support the polar plate of Preform 4A during the initial phase of the forming process. The use of this plug under the apex gave essentially the same conditions as those expected for Configuration B. Thus, all results obtained would be directly applicable to subsequent preform designs. The placement of the metal plug is shown in Figure 51.

At this point in the program, it was evident that the efficiency of the explosive charge was very low. The decision was made to try to increase the efficiency through the use of a ring charge. This configuration would move the charge near to the wall and would consequently be more efficient. Primacord was chosen as the explosive since it had been used successfully by EFD in many previous forming operations. The holding force was 90 ft-lb on 15 (3/4 in.) bolts, the same as Preform 2A.

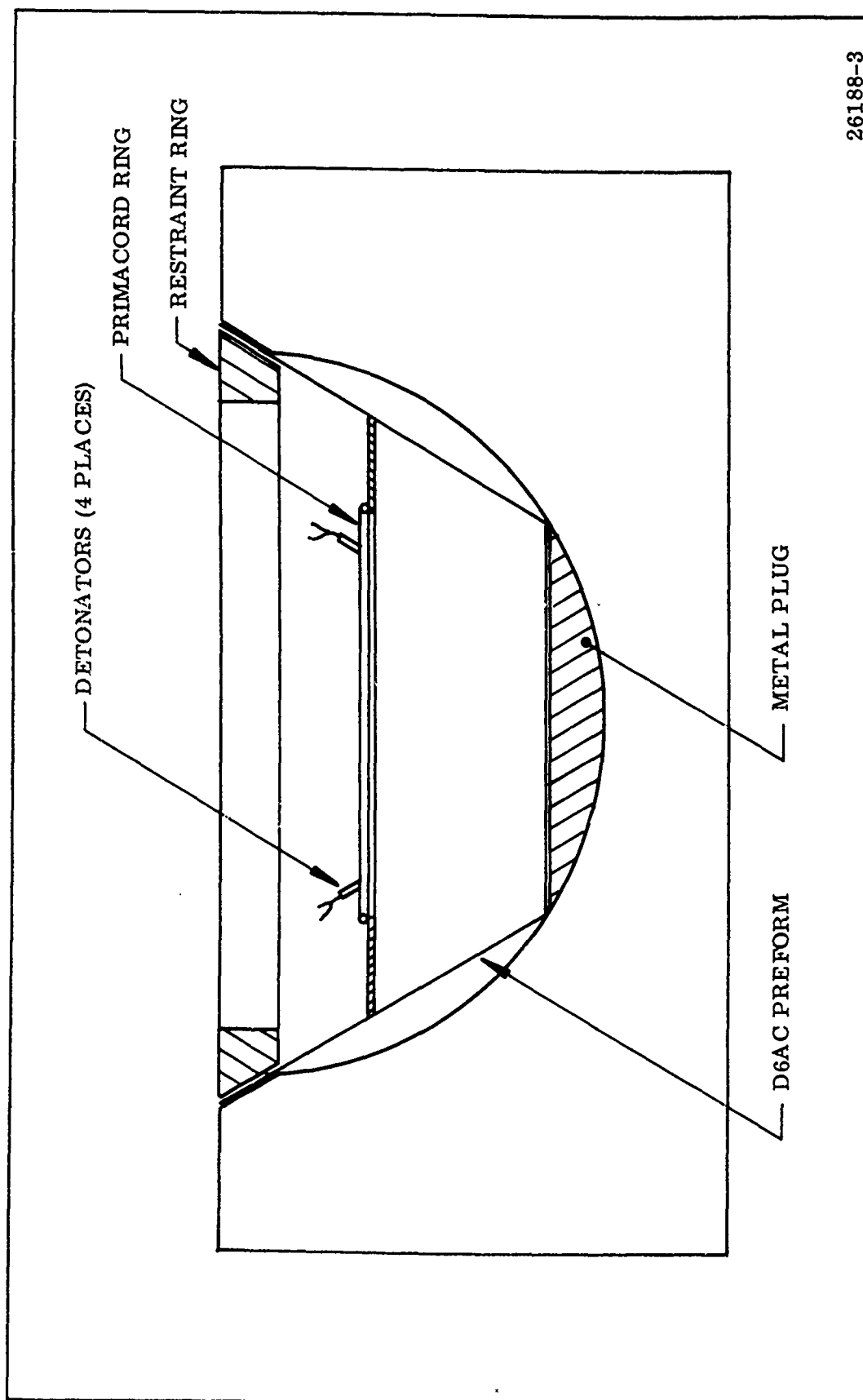


Figure 51. Physical Arrangement for Forming of Preform 4A

The Primacord ring charge was detonated from four points around the periphery of the ring with a standoff of 6 in. from the bottom of the preform and the ring positioned so that a distance of 3 in. from the preform sidewall was maintained. The arrangement shown in Figure 51 with a total charge weight of 20 grams was used.

The forming shot was unsuccessful in that a severe buckle was formed near the base of the preform. Figures 52, 53, and 54 indicate the extent of the buckle. This result was caused by insufficient preform stabilization exerted by the clamping ring. This effect had not been experienced in earlier tests, probably due to the fact that the apex was not supported in previous tests and much less deformation had been previously obtained. With bottom support of the preform, there was an increased tendency for buckling, and the clamping force was inadequate to prevent excessive pull-in.

Several important facts were obtained, however, in spite of the appearance of the buckling problem: (1) the circumferential weld remained intact even after severe deformation, thus confirming the improved welding technique and preform fabrication, (2) the greatly increased efficiency predicted by calculation as a result of closer proximity of the charge to the sidewall was substantiated (it is certain that greater use is being made of the water prior to its exit from the preform), and (3) the two to three shot forming sequence anticipated for production forming was shown to be realistic.

F. FAILURE ANALYSIS OF PREFORM 4A

Figure 55 is a closeup view of the split where it crossed one of the longitudinal welds in the buckled section of Preform 4A. It was felt that this split was induced by the buckling problem; however, a metallurgical examination was conducted on the split area in order to insure that no welding or metallurgical problem had escaped detection by X-ray.

Figure 56 shows a strip surrounding the split which was cut from the preform, displaying the cross section of the buckle.

Optical examination of the fracture surface (Figure 57) and examination of the longitudinal weld X-rays indicated that the weld rupture was the result of the preform buckling and not from some defect in or near the weld joint.

Subsequent to the failure of preform 4A, a discussion was conducted between Thiokol and EFD personnel in which it was generally agreed that the lack of clamping force was responsible for permitting the buckling to occur. The loading in the preform wall was allowed to build up to a point where the static clamping capability of the die clamp was exceeded. At this point there was a sudden release of energy in the form of an elastic compression wave which was reinforced in the area of the knuckle resulting in a buckle.

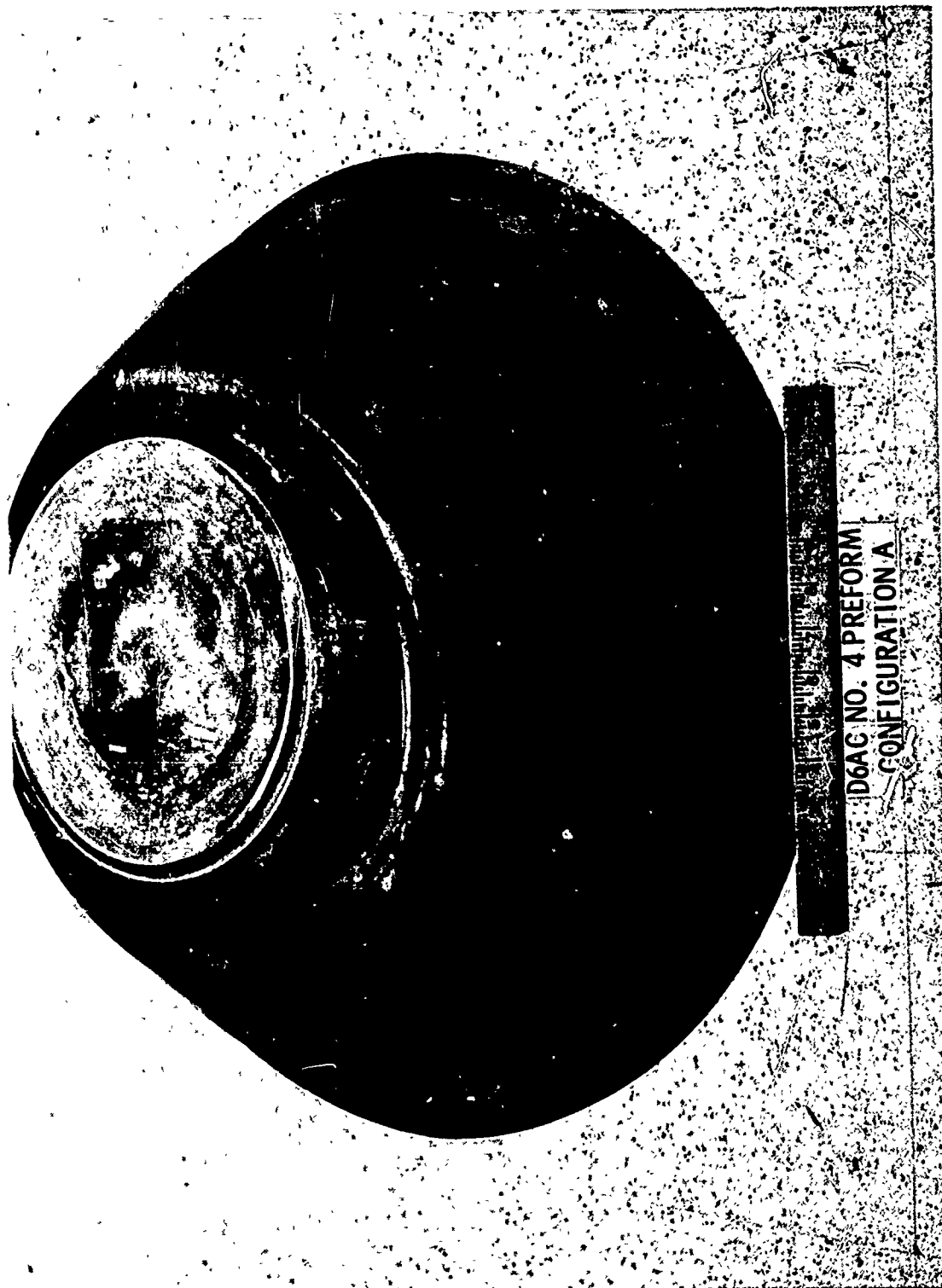


Figure 52. External View of Buckled Preform 4A

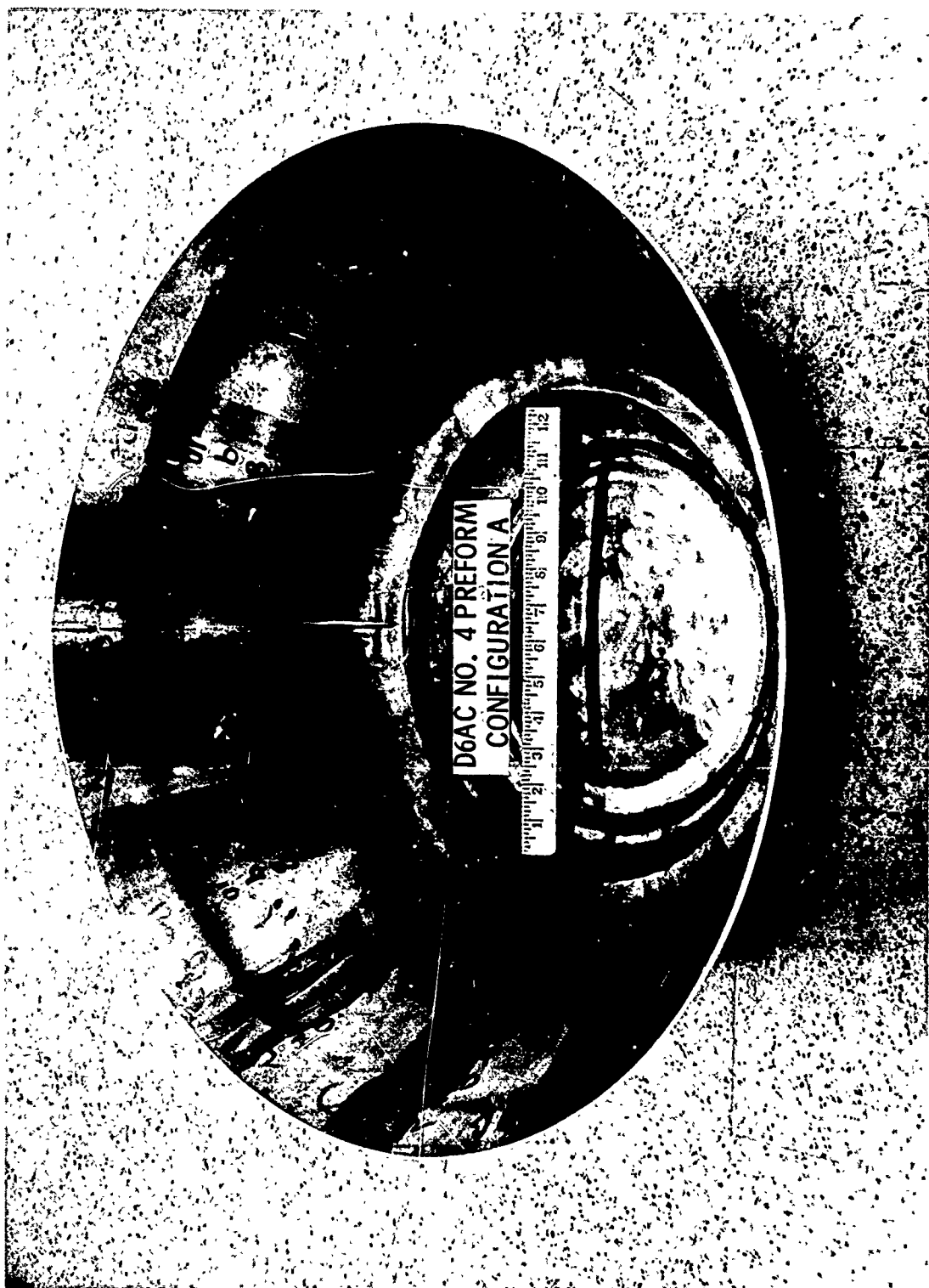


Figure 53. Internal View of Buckled Preform 4A

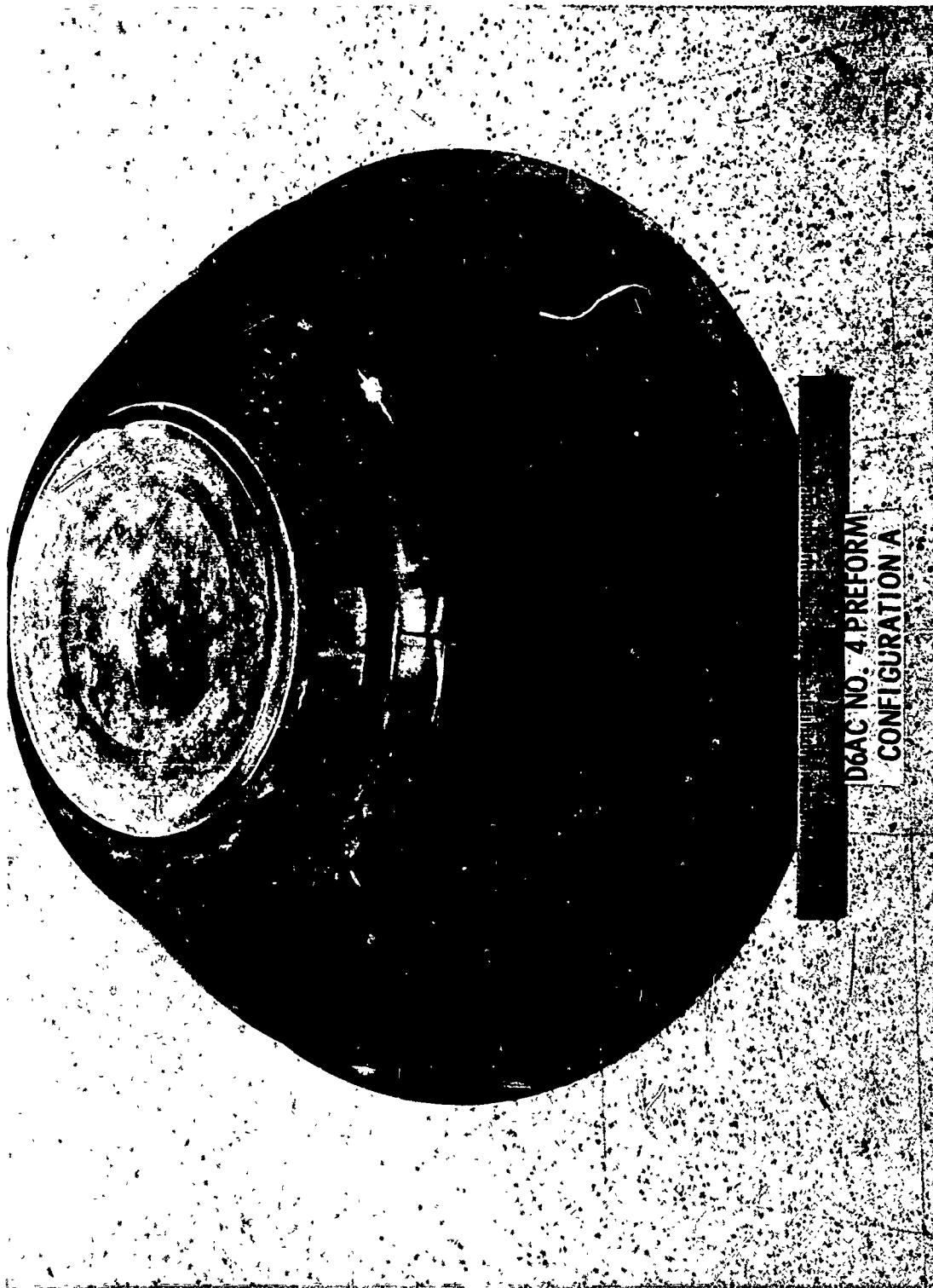


Figure 54. View of Weld Split on Buckle of Preform 4A

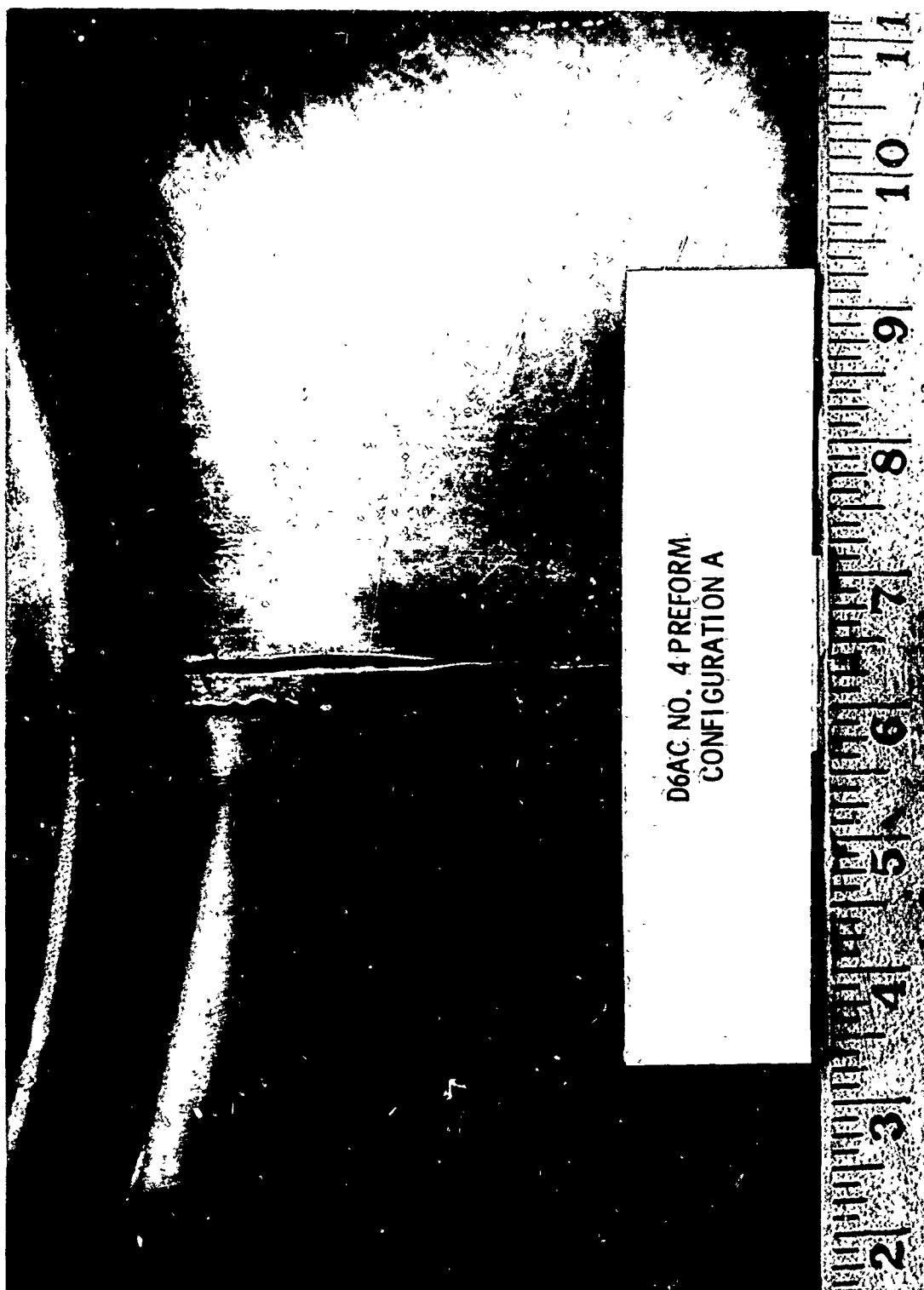


Figure 55. Closeup View of Split in Buckle of Preform 4A



Figure 56. Section of Preform 4A Through Buckle

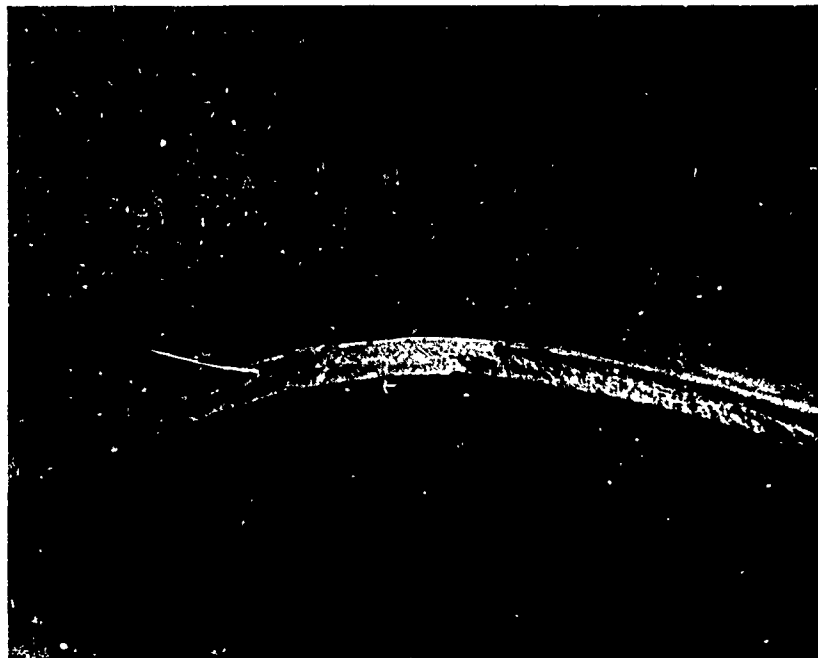


Figure 57. Surface of Preform 4A Split (5 x)

It was mutually agreed that effort was required in the area of clamping force requirements, and it was suggested by EFD that these calculations be verified by an additional subprogram utilizing a relatively low grade steel.

It was subsequently proven in a Cor-ten steel preform forming attempt that buckling could be prevented by complete restraint of the preform under the restraining ring. The ring was modified to accept 27 (1 in.) bolts, which allowed for complete restraint. The holding force calculations as well as the Cor-ten buckling program are described in detail in Section VIII. The detailed die modifications were shown in Section III.

G. FABRICATION OF PREFORM 5A

The general procedure for the fabrication of Preform 5A from fully hardened HP9-4 material is outlined in Section V. Specifications concerning the alloy and heat treatment and welding are contained in the appendixes.

This section presents the specific events encountered in following the outlined procedure.

Several difficulties were encountered, most of which were a direct result of heat treating the cone sections to a tensile strength of nearly 200,000 psi. After heat treating, the contours of the cone sections had changed so that they were no longer in round with deformations similar to that shown in Figure 58, and attempts to bring the cone sections into round by rolling were not successful. Due to the high strength of the material, it was not possible to make the rolling radius small enough to cause any permanent set.

Although the longitudinal weld surface match-up of the cone sections was relatively good, some difficulty was encountered during welding of the longitudinal seams. On the first seam, insufficient penetration was obtained on the first weld pass, and a second weld pass was required along the entire length of the joint. The second weld bead, however, was not wide enough in some places, and additional weld metal was manually deposited in those areas. The second longitudinal weld was accomplished in one pass without notable incident.

The welded preform was badly out of round due to warpage of the cone section, and it was extremely difficult to force it into a round condition in order to trim the small diameter. However, through the use of special clamping tooling, shown in Figure 59, the small diameter was rounded and trimmed. The large diameter had been cut with a bandsaw prior to welding; i. e., the large end of the cone sections had been cut to size. As with Configuration 4A steel preform, a modified cover plate was machined from 3/4 in. material to fit the trimmed preform. This cover plate is shown in an inverted position in Figure 59.

Circumferential welding was performed automatically and without incident except for the last one-fourth of the circumferential distance. Over this distance, the weld bead on the outside surface of the preform was on the preform-cover plate joint, but the weld drop-through on the inside was not on the joint. It appeared



Figure 58. Half Section of HP9-4 Preform After Heat Treatment

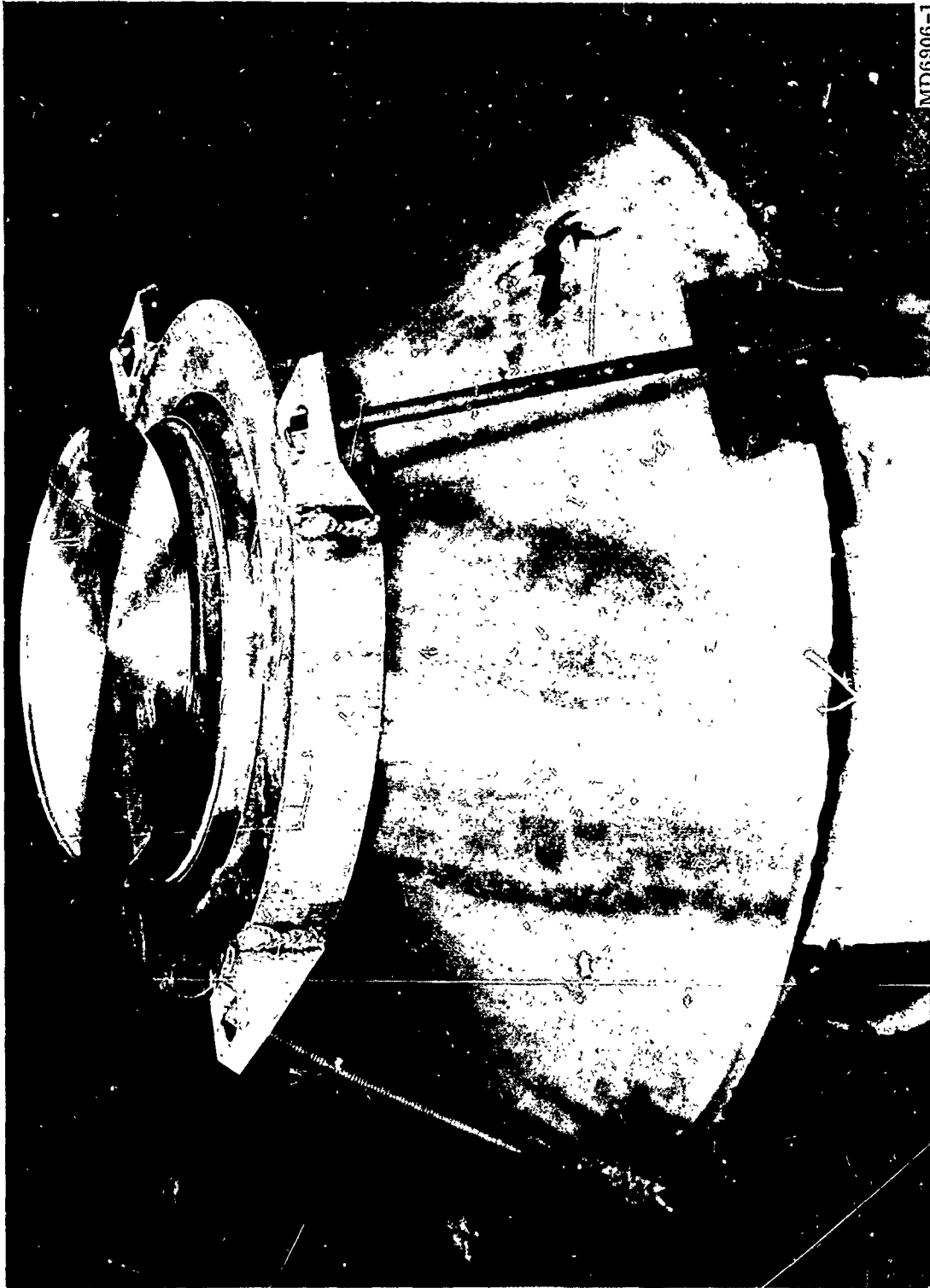


Figure 59. Conical Preform Stretched on Forming Cone with Small Diameter
Machined (premachined Polar Plate Also Shown)

that this situation resulted from a slight jolting of the welding torch which altered the welding angle. The preform was placed back on the circumferential welder, and the area of concern was repaired.

X-ray examination of the circumferential weld bead revealed a number of small cracks which were orientated perpendicular to the weld joint on the inside surface of the weld. The exact cause of this cracking phenomenon was never fully understood. Potential causes include: (1) stresses associated with cooling rates, and (2) residual stresses induced when the welded preform was removed from the welding fixture due to the large amount of force required to hold the preform round during the welding operation.

It was also observed from the X-rays that the cleanliness of the weld with respect to voids and pores was exceptionally good. It was decided to remove the cracks by grinding and manually repair the ground areas. This was accomplished, and the preform was judged to be fully acceptable when final X-ray and magnetic particle inspections indicated a good quality weld.

H. EXPLOSIVE FORMING OF HP9-4 CONFIGURATION 5A PREFORM

Based on the detonation and forming velocity literature survey (explained in Section VIII), the decision was made to use a lower velocity explosive for Preform 5A. Trojamite C was selected for use on the fully hardened HP9-4 part. The minimum diameter required for reliable detonation varies with each individual explosive. The variation is due to the fact that the reaction zone differs from explosive to explosive. The minimum diameter for reliable detonation of Trojamite C was determined experimentally with Tygon tubing used for the charge container. Detonation was inconsistent for diameters tested below 3/8 inch.

A machined aluminum plug was used in the apex of the die instead of a Cerro plug. The die modification was also completed for this test, and the 27 (1 in. diameter) bolts were torqued to 475 to 500 ft lb, which provided a clamping action substantially in excess of that required according to the calculations presented in Section VIII.

The total charge weight selected for preform 5A was 43 grams, which is approximately the same total energy equivalency as the charge used for Preform 3A, (20 grams of Primacord). As a result of the increase in explosive cross section diameter, the ring charge diameter was reduced to 9 in. in order to maintain a conservative charge weight. The charge used is shown in Figure 60. Although the two charges (those for Preforms 5A and 3A) were approximately the same in total energy released, less energy was actually delivered to the blank in 5A as a result of the decreased ring diameter. The charge was initiated by four 25 grain/ft Primacord leads, which were detonated from a common point.

Both longitudinal welds failed on the first shot. The fractures propagated across the polar cap and under the restrain ring. Figure 61 shows both weld failures. The sidewall of the preform experienced very little deformation as compared to the deformation of Preform 3A after the first shot. This was expected, as

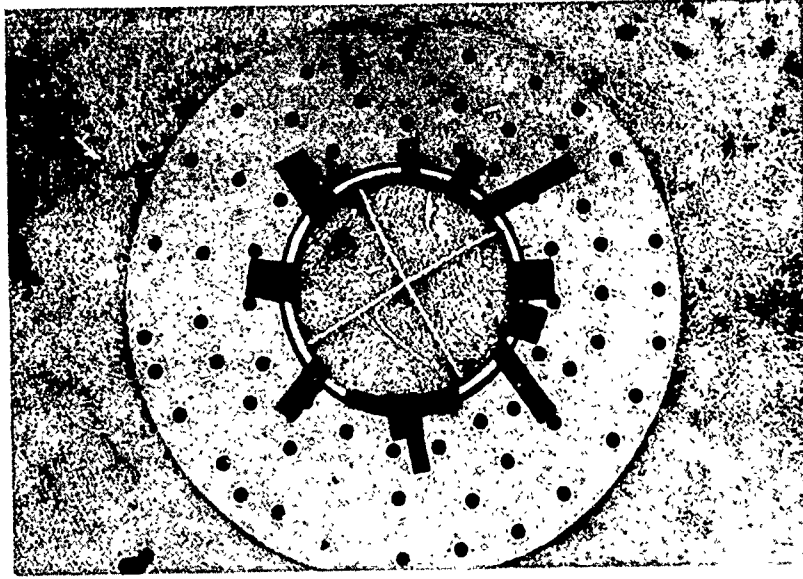


Figure 60. Nine Inch Diameter Ring Charge Initiated by Four 25 Grain/Ft Primacord Leads (Trojamite C Base Charge Packed in Tygon Tubing)

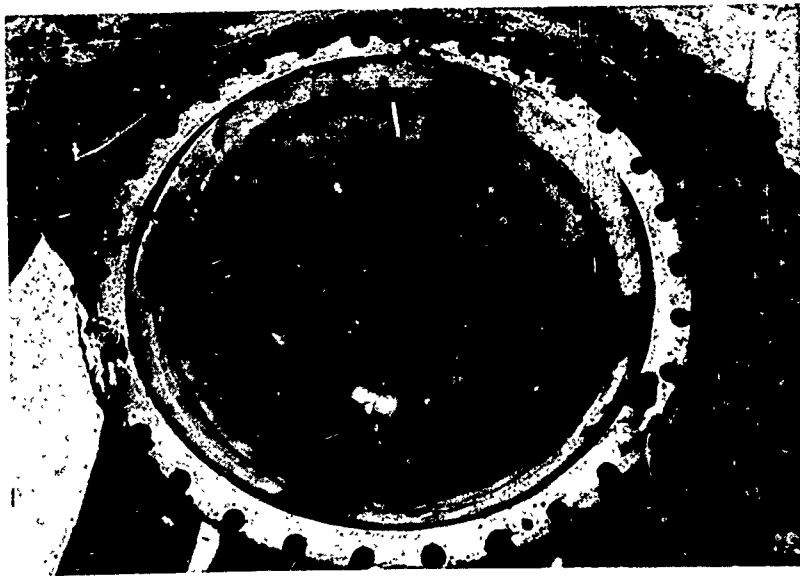


Figure 61. Preform 4A Prior to Removal from Forming Die Showing Failure in Both Welds with Fracture Propagated Across Polar Cup

is discussed above, and was due to the reduced energy delivered to the preform and the increased yield strength of the fully hardened HP9-4 material. The bolt torque used should have been more than sufficient to provide preform stabilization and should have precluded primary buckling. The buckling observed was of the nature of a secondary effect.

At this time, a failure analysis was planned. Thiokol would investigate the fracture surface, and Republic Steel Corporation agreed to perform an analysis on part of the preform which was furnished to them.

I. CONFIGURATION 5A FAILURE ANALYSIS

This section presents the unaltered Republic Steel Corporation failure report:

As we did not have all of the segments of the 24 in. diameter dome preform, we could not determine the location of fracture initiation or the original cause of the failure. Our comments, therefore, can merely describe the nature of the fracture we observed in the two segments received.

The composition and microstructure of both the parent metal and the weld metal are normal and not at all unusual. Metallographic examination of the fractured pieces revealed that the fracture propagated through the weld metal in a region immediately adjacent to the heat affected zone (HAZ). Microhardness surveys on several samples revealed that the weld metal had a R_C hardness of 49/50, and that the parent metal had a R_C hardness of 46/47. The HAZ had a R_C hardness of 52/53 throughout most of the HAZ region, but had a hardened region of R_C 56/57 at the edge of the HAZ. This hardness increase from R_C 47 to 56 from parent metal to HAZ in TIG weldments of light gauge HP 9-4-25 is not unusual and has been observed by ourselves and others. In multi-pass welds in thicker material (1 or 2 in. plate) where more tempering occurs, the typical hardness increase from parent metal to HAZ is 3 to 4 R_C hardness points.

If we assume that no pre-existing flaws were present in the welded 24 in. dome preform, we would speculate that the failure initiated in the hardened HAZ region and propagated through the weld metal adjacent to the HAZ. The 9 to 10 R_C hardness gradient observed represents an ultimate tensile strength gradient of about 90 ksi (225 ksi to 315 ksi) and, hence, a ductility gradient as well. Therefore, to alleviate this hardness gradient observed in one or two pass weldments in thin gauge HP 9-4-25 steel, where sufficient self tempering does not occur, it is recommended that a post-tempering operation be performed. A piece of the failed parent and weld metal from the 24 in. dome segments was tempered at 1,000°F for

1 hr and the following hardness values were obtained: weld metal, R_C 44/45, HAZ R_C 46/47 with a hardened region of R_C 48/49, and base metal of R_C 45/46. It is, therefore, recommended that a post-tempering treatment of 1 hour at 900° to 1,000° F be given to reduce the high hardness gradient in the HAZ region.

As a footnote, it might be mentioned for future work involving TIG welding of thin gauge material that the lower carbon HP 9-4-20 steel (0.17 to 0.19 carbon typical) would not exhibit this sharp hardness gradient to the degree that is observed in the higher carbon HP 9-4-25 grade.

It should be noted that the processing recommendations represent a change from those employed in the actual fabrication of the 5A preform, which were originally coordinated with Republic Steel.

The maximum indicated strength of 315,000 psi suggests the necessity for a great deal of work in the area. This value, along with the absence of any visible porosity or defects, highly suggests an overstrained condition.

It should also be noted at this time that the HP9-4 material was quite hard. There is the possibility that a lower strength level preform could be successful and still give strength levels in the order of 180,000 psi.

J. FABRICATION OF CONFIGURATION B PREFORMS

The fabrication of three Configuration B (1B, 2B, and 5B) preforms were completed using the modified procedure. The as-rolled contours of the cone half sections were considerably better than those obtained during the fabrication of Configuration A preforms. As a result, there was a minimum of mismatch to contend with during the welding of the longitudinal seams. Welding of these joints was somewhat erratic, however, in that enough filler metal would be deposited on some joints and not enough on others, even though the welding conditions appeared to be identical. One seam on each preform thus required a repair in the form of depositing additional filler metal on the existing weld. The repairs were made manually. The welding problem seemed to be associated with the fact that a power source different from that used to weld the Configuration A preforms was employed. The original power source was in need of repair, thus necessitating the change. Attempts to isolate the specific problem were not successful.

After welding, the preforms were not far out of round, and trimming of the small diameters was relatively easy. Again, the large diameters had been roughly cut to size by sizing the large ends of the cone sections prior to welding. The small diameter was cut according to the revised drawing TUL 12941 A. The revised configuration of the igniter boss is shown in a drawing detail in Figure 26. The small diameters of the preforms were trimmed to the low side and igniter bosses machined to the high side of the tolerance so that there were some mismatches (about 0.010 in. on 2 side) between them. The mismatches did not present a welding problem.

Circumferential welding of Preforms 1B and 2B was successful for about three-fourths of the distance around the circumference. For the remaining distance, the weld bead was on the igniter boss preform seam on the outside surface (but not on the inside, drop-through, surface). This problem can best be discussed by referring to Figure 62. This figure, which shows the circumferential welding of a preform, shows the angle the welding torch makes with circumferential weld joint. During welding, the gap between the preform and igniter boss has a tendency to decrease in width. In the area just ahead of the weld bead, the temperature is near the melting point of the steel, and localized material flow is possible under an applied stress. In some cases, depending on the gap width and imposed welding stress, the parts being welded may come together in these areas and force the joint in an outward direction. Under these circumstances, the distance between the torch and the joint is decreased and must be adjusted by backing the torch away from the part. However, the torch moves away along the fixed angle; thus the weld drop-through on the inside surface of the part is shifted so that it is no longer on the joint, but on the outside surface, and the weld bead remains on the joint. Placing the torch in a more vertical position would probably correct this situation.

Preform 2B was put back on the welder and repaired by making another weld bead around the entire circumference. The repair, however, introduced some pores which were removed by grinding. The additional welding required to fill the grinding holes was done by hand. The area around one of the longitudinal-circumferential weld joints was slightly thin after grinding the weld beads and required some weld buildup.

The repair required on the 1B preform was made manually.

Before welding the 5B preform, the welding torch was adjusted to as near a perpendicular position as possible. The result was that the circumferential weld was accomplished in one pass and required no repair. However, additional weld metal was required in both longitudinal-circumferential weld joint areas as they had become somewhat thin during grinding of the weld beads. A completed Configuration B preform is shown in Figure 63.

The cone sections for the two HP9-4 Configuration B preforms (3B and 4B) were rolled and heat treated. The contours after rolling and prior to heat treating were very good--better in fact than those of the previous D6AC cone sections. During the thermal cycling, however, two of the cone sections nearly flattened out as shown in Figure 64. Contours similar to those shown previously in Figure 58 were expected, and the reason for flattening of the sections is not known since all four sections were supposedly treated identically.

At this point in the program, work on both HP9-4 preforms was suspended pending a critical program review of available funding.

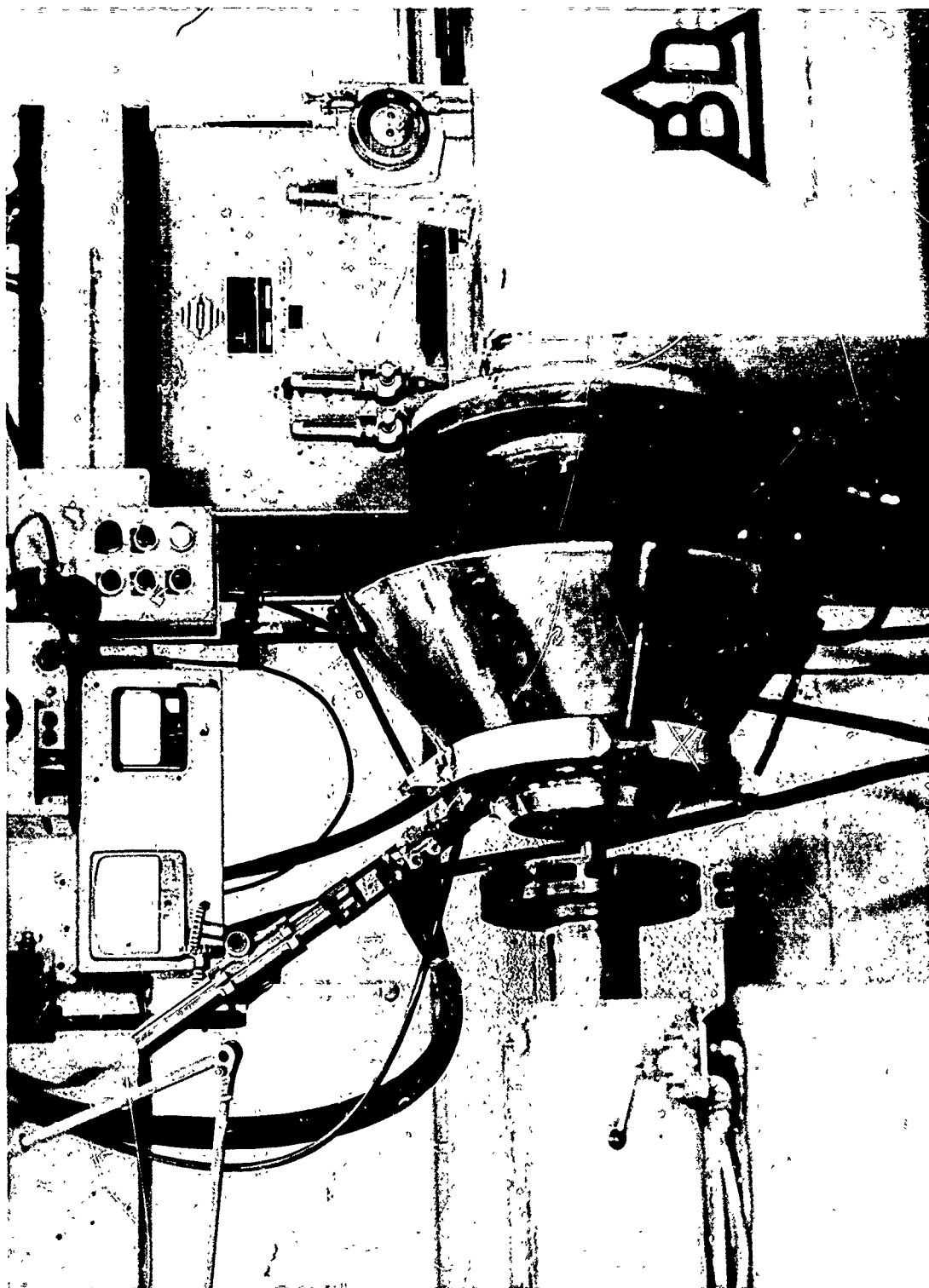


Figure 62. Automatic Circumferential Welding Setup

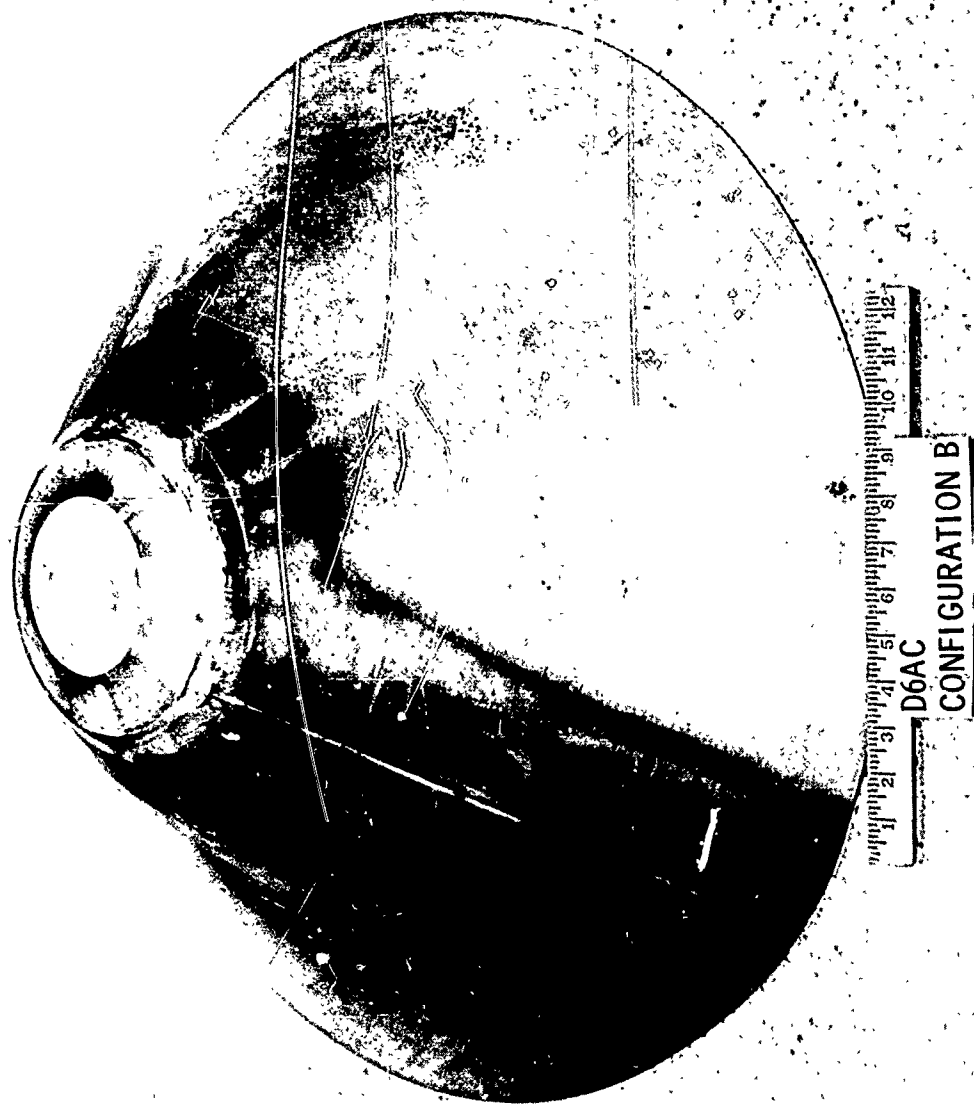


Figure 63. Completed Configuration B, D6AC Preform

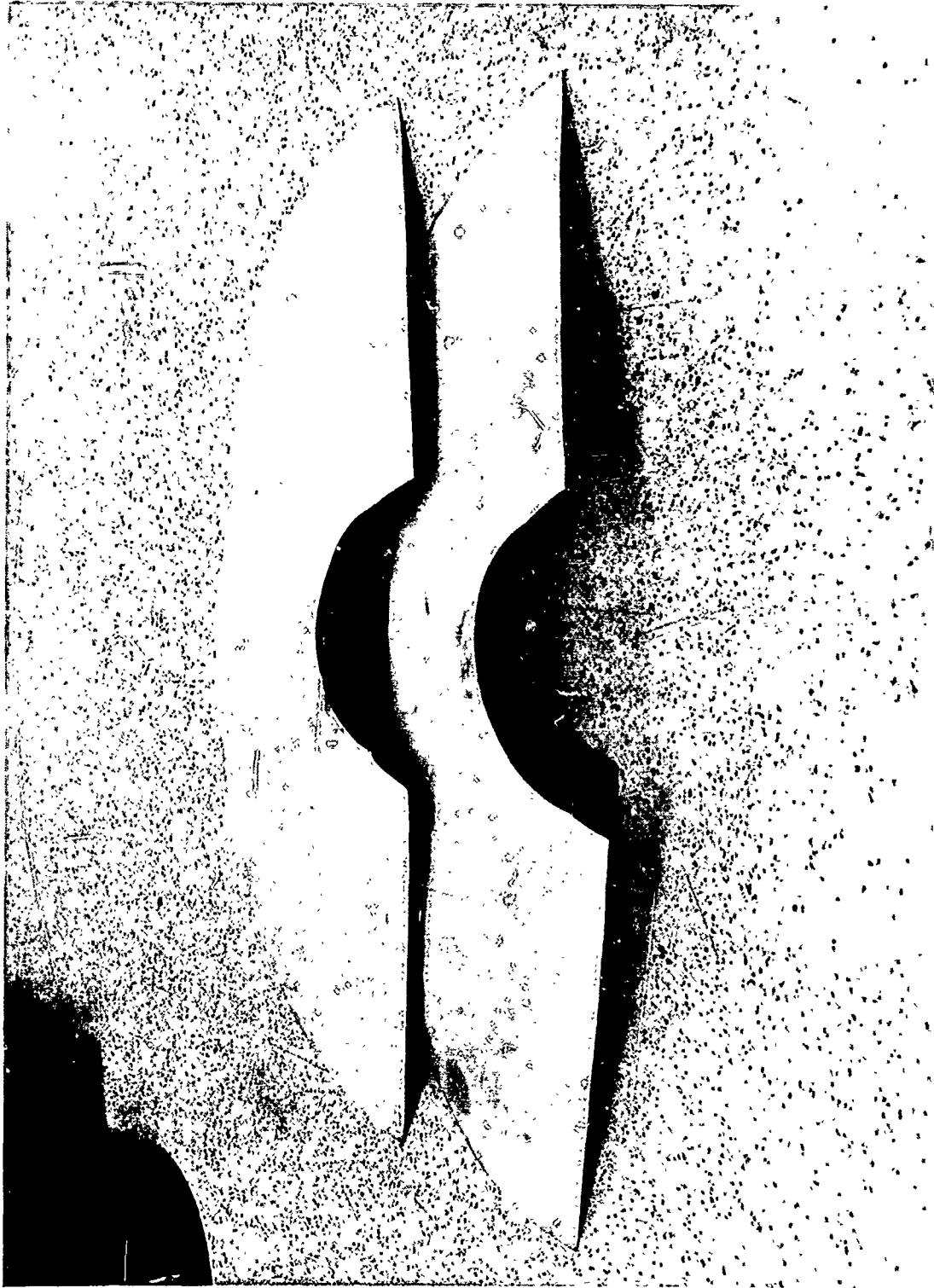


Figure 64. HP9-4 Preforms After Quenching Operations

K. FORMING OPERATIONS--CONFIGURATION 1B PREFORM

The Configuration 1B preform was shipped from Thiokol to Tyco Industries, Explosive Fabricators Division, where it was dimensionally inspected. In general, the dimensional aspects of the preform were good. Some ovality was present in the unrestrained preform; however, when pressure was applied around the clamping ring, the preform "rounded out" and positive sealing was achieved.

In the Configuration A preform design, the cone angle was larger than for Configuration B. The last forming experiment conducted (Configuration 5A with HP9-4 steel) involved a 9 in. diameter ring charge consisting of 43 gm of Trojamite C explosive packed in a 3/8 in. OD plastic tube. The charge was positioned, using a cardboard framework, at a distance of 6 in. from the bottom of the preform. The distance from the charge periphery to the preform side walls was approximately 5 inches. Detonation was achieved by the use of a centrally positioned electric blasting cap which was located at the center point of intersecting Primacord leads. The Primacord was embedded in the plastic tube containing the Trojamite C at four locations about 90 deg apart along the ID of the tube. Thus, an outwardly expanding and essentially uniform shock wave could be produced.

Because of the increasing cone angle for Configuration B preforms, it was decided to use a smaller ring charge to: (1) reduce the pressure to the preform wall, and (2) permit a more conservative set of conditions for forming. Therefore, a 6 in. ring of Trojamite C was used with a setup identical to the last Configuration C experiment. This resulted in a standoff about equal from both the preform bottom and the side walls; i.e., 6 inches. The total charge weight used was 31 gm including about 1.5 gm of Primacord lead-in. A torque of 580 ft-lb was applied to the bolts used to effect total restraint on the preform.

The results of the forming operation were disappointing. After the first forming shot, a longitudinal rupture was noted. Figure 65 shows the failed preform in the die with the restraining ring removed. Figure 66 is an external view of the failed preform.

It can be noted that the 9.5 in. fracture occurred adjacent to the longitudinal weld. Subsequent examinations revealed that the crack seemed to be in the parent material and not in the large grained area associated with the weld area and heat affected zone. The distance between the edge of the weld and the crack varied from about 0.080 to 0.160 inches. The X-rays of the longitudinal weld and areas adjacent to the weld (about 2.5 in. on either side of the weld) prior to the forming attempt were examined for welding defects from which the rupture may have originated. No defects could be found. There was some concern about whether the rupture was actually in the parent material or in the heat affected zone immediately adjacent to the weld edge. A specimen that was used in the study to determine an adequate stress relief temperature was used to supply information regarding this question. This weld specimen had been stress relieved for 1.5 hr at 1,250° F (identical to the stress relief employed on the preform welds). As shown in Figure 67,



Figure 65. Configuration B1 Preform After Removal from Die Showing Crack Along Longitudinal Weld

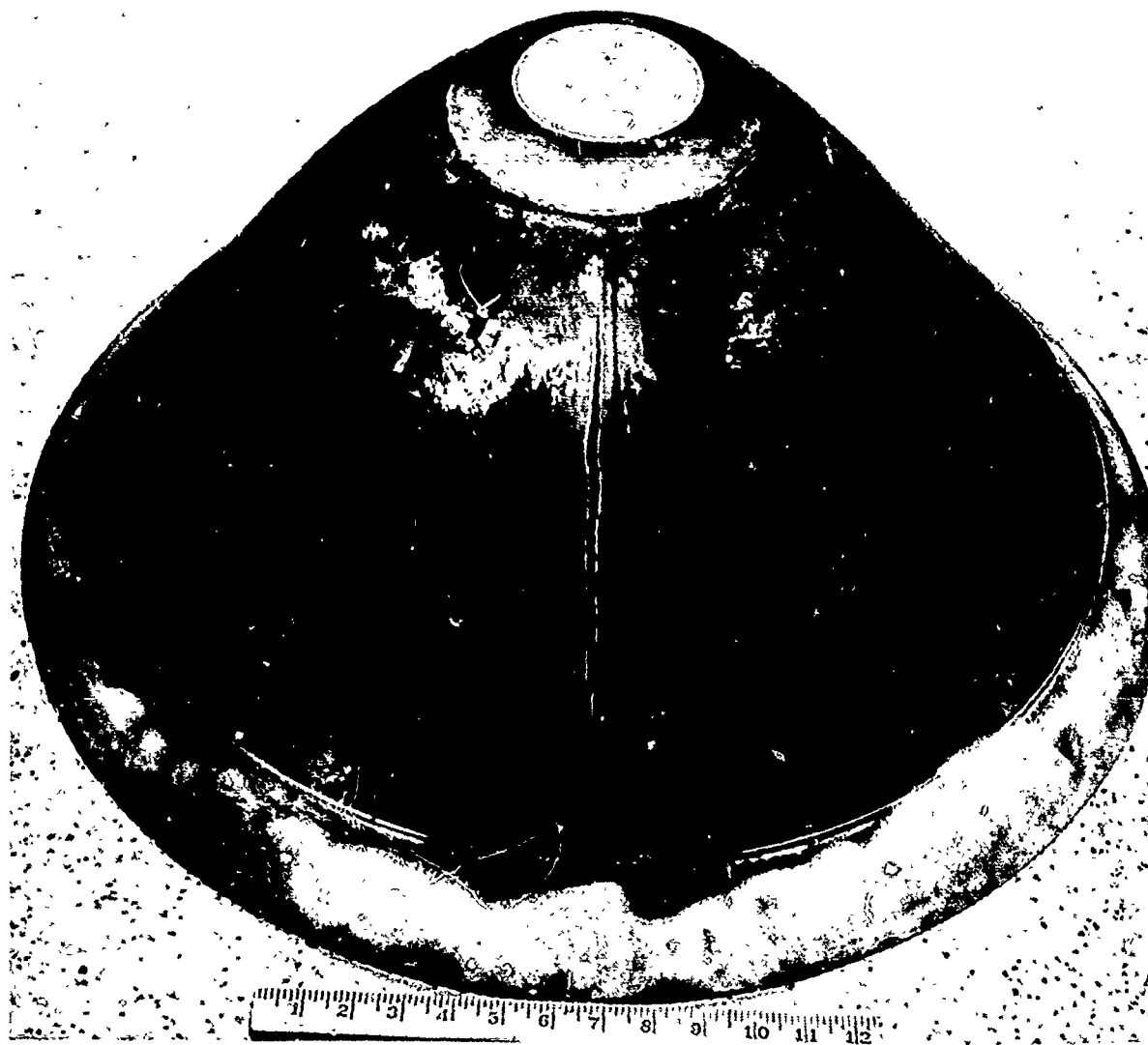


Figure 66. External View of Longitudinal Crack in Configuration B1 Preform

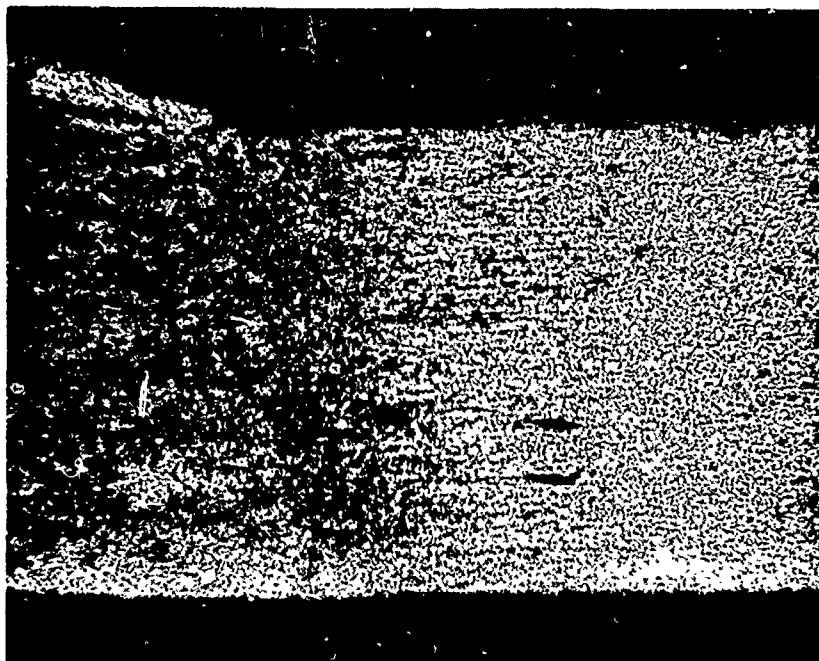


Figure 67. Photomicrograph Showing the Weld Zone, Heat Affected Zone, and Parent Material of a D6AC Steel Weld Specimen After Stress Relieving at 1,250° F for 1.5 Hours (50 x)

the extent of the heat affected zone after the stress relief is quite small: 0.036 inch. Microhardness readings of the stress relief sample and actual hardness measurements on the preform weld substantiate the extent of the heat affected zone after stress relief. It therefore appears that the rupture was in the parent material.

There was a possibility that Preform 1B could be repaired for a second forming attempt; therefore, no metallographic specimens were cut in order to help locate the fracture origin. Consequently, the actual reason for failure of the preform was not known at that time. Photographs were taken of the failure surface which revealed no porosity or gross reason for crack initiation. This evidence, along with X-ray studies, seems to point to the conclusion that the area of the fracture was overstrained and not a result of an initial porosity or crack.

For the purpose of complete reporting, it should be pointed out that the movement of the preform material under the influence of the explosive charge appeared to be nonuniform with respect to the longitudinal axis of the preform. Measurements were made at both longitudinal welds and at points 90 deg from the welds to determine the amount of movement of the preform from its original contour. The measurements were taken at the various points around the circumference at distances of 3.0 to 4.0 in. from the small diameter; the deflections measured are shown in Figure 68. The deflection at the weld nearest the rupture was about 0.650 in. and at the other weld 0.420 inch. At the points 90 deg from the welds, the amount of deflection was 0.230 in. on one side and 0.510 in. on the other side. The points of measurement are shown in Figure 68.

It is realized that this condition could have been a natural result of the failure mode and preform restraint. The condition did exist, however, and is therefore reported.

L. FORMING OPERATION--CONFIGURATION 2B PREFORM

An analysis of all of the forming experiments conducted previous to Preform 2B showed that the only successful results with respect to retention of longitudinal weldment integrity were Configuration 1A Preform (D6AC material) and Configuration 3A Preform (HP9-4-25 material) which was not fully heat treated. In the first test 10 gm central charges of TNT were used, and in the latter case a Primacord ring was used. Irrespective of the vast difference in charge configuration and sequence used, both preforms were taken to full contour without any failures in longitudinal welds. There were failures in the circumferential welds, however, which prevented the successful forming of complete components. At this point, discussions were held with a number of individuals who had various degrees of experience in the field of explosive forming and, it was felt, could lend additional expertise to the operation. The consensus of opinion was that the central TNT charge was at least more conservative and, therefore, the decision was made to use the centrally located 10 gm TNT charges on Preform 2B, and to proceed with the same schedule as Preform 1A (Table V).

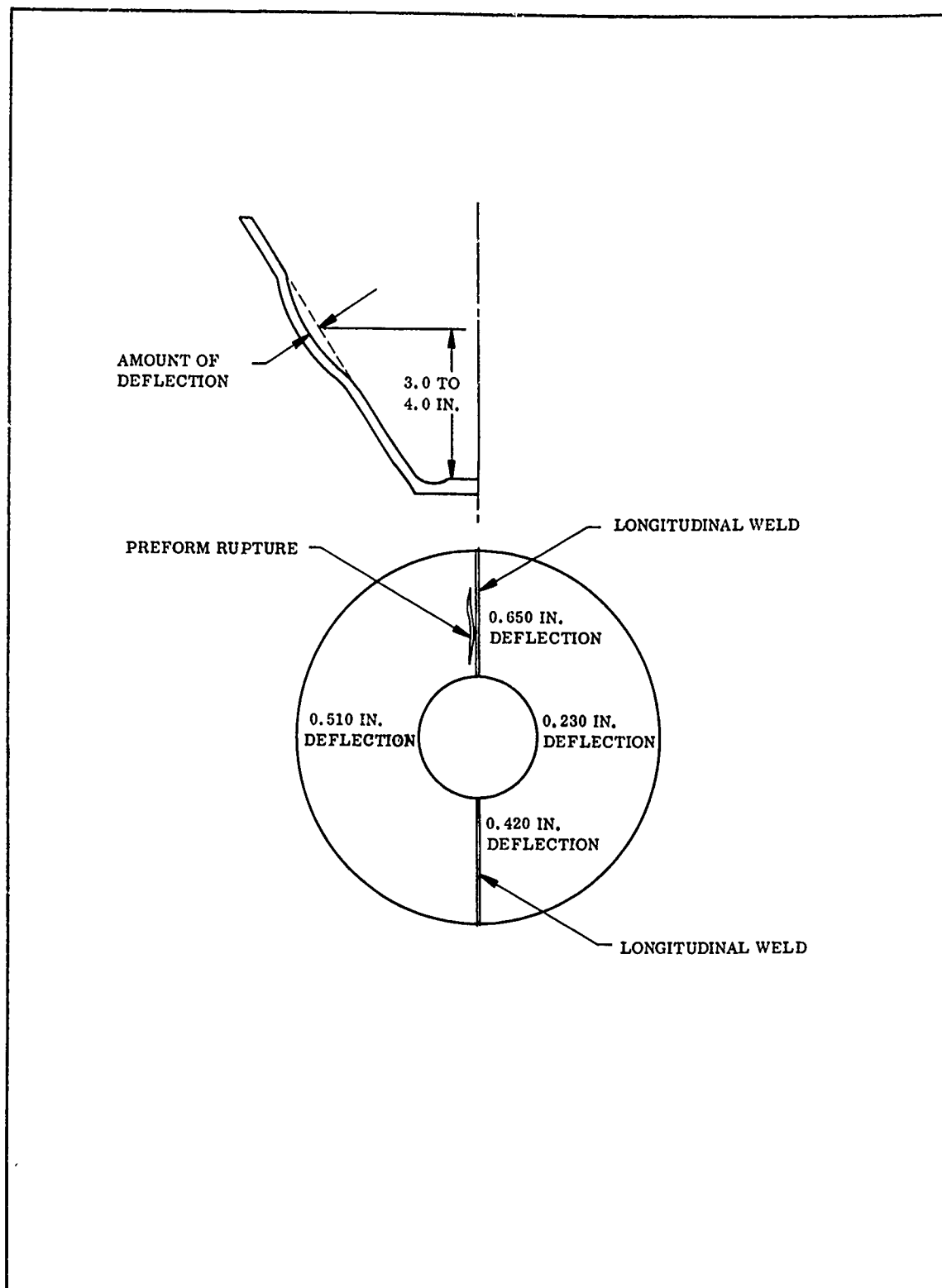


Figure 68. Schematic Showing Preform 1B Deflection Measurements

To prevent any interference between the charge and the preform, a suspension setup was used to place the charge. Figure 69 shows the arrangement prior to the first forming shot which was made without incident. Approximately 0.25 in. of deformation was observed uniformly around the preform, extending from the junction of the igniter boss with the conical preform sides to a position opposite the charge location. No pull-in or other preform movement was observed, and good evacuation of the die cavity was maintained. A second charge of 10 gm was placed in the identical position, and forming continued. However, on the second shot, fractures occurred: (1) adjacent to one of the longitudinal welds, and (2) around part of the circumferential weld and extending for a distance of about two thirds of the preform height into parent material. The greatest amount of deformation took place in the region associated with the fracture in parent material. Figures 70 and 71 show general and closeup views of the weld zone fracture. Figures 72 thru 75 show various views of the second fracture. It should be noted that the material behavior was that normally associated with an alloy of very limited ductility. No explanation could be given for the behavior at the time.

An analysis of the rupture was conducted including both metallographic grain studies and work with the optical and electron microscopes.

One of the primary objectives was to locate the origins of failure, due to the fact that one of the failure lines occurred in a vicinity completely remote from a longitudinal weld.

Figure 76 shows the location of the origins of both fractures. The rupture adjacent to the longitudinal weld is 0.090 to 0.180 in. away from the weld edge. The distance from the origin of this crack to the edge of the weld is about 0.090 inch. The origin of the other crack is about 0.040 in. away from edge of the circumferential weld.

Metallographic specimens were sectioned transverse to both the longitudinal and circumferential welds near the rupture origins. The microstructures, Figures 77 and 78, were examined, and microhardness transverses were made across each weld.

<u>Area</u>	<u>Microhardness Transverse Value (R_C)</u>
Longitudinal Weld	32
Heat Affected Zone	31
Parent Material	26
Circumferential Weld	49
Heat Affected Zone	51
Igniter Boss (Thin Sections)	51
Igniter Boss (Near Center)	18
Parent Material (Opposite Weld)	26

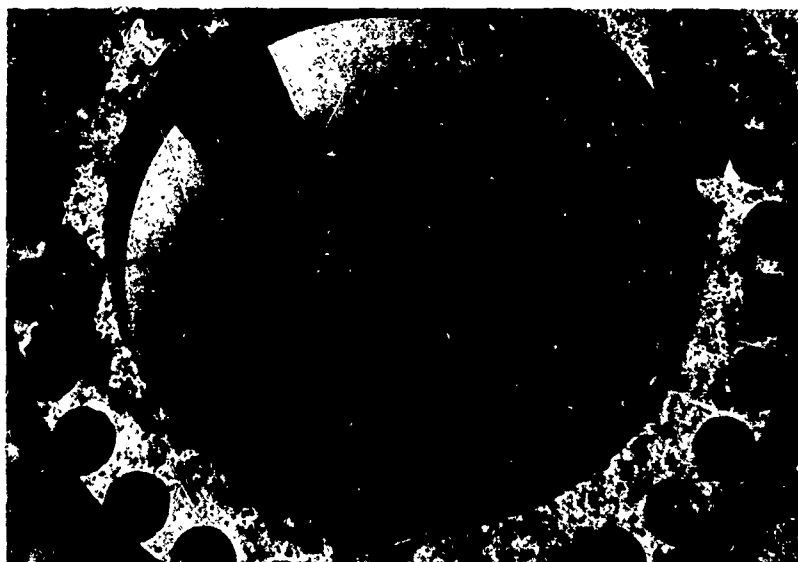


Figure 69. Charge Arrangement for Preform 2B Showing Suspension Device



Figure 70. Closeup of Crack Along Longitudinal Preform Weld (Exterior View)



Figure 71. Closeup of Internal Surface of Crack



Figure 72. Fracture Along Longitudinal Weld on 2B Preform



Figure 73. Second Fracture in Parent Material and Along Circumferential Weldment



Figure 74. Internal View of Fracture in Parent Material and Along Circumferential Weld



Figure 75. Exterior Closeup of Fracture

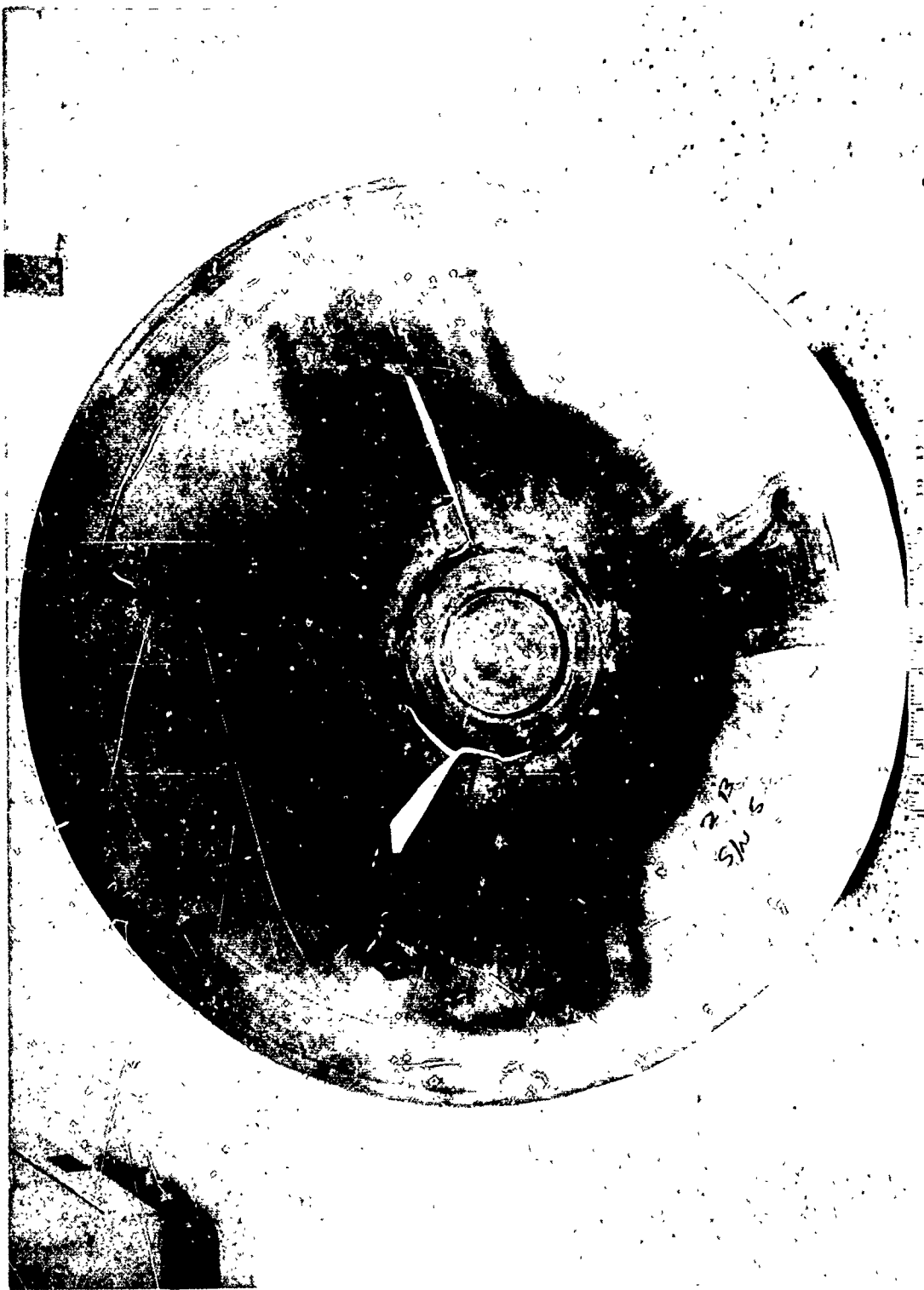


Figure 76. Failure Origins on D6AC Steel Preform 2B

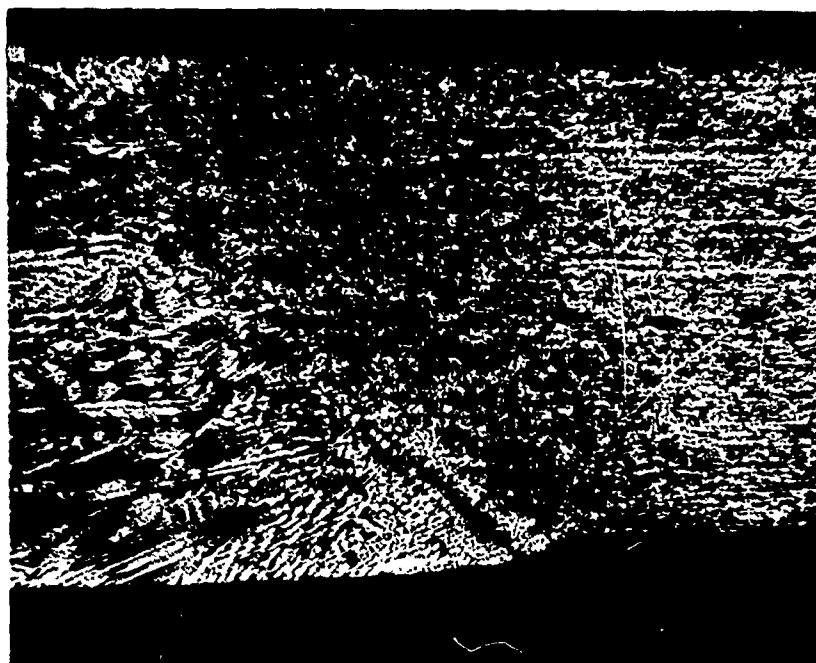


Figure 77. Photomicrograph of a Transverse Section of the Longitudinal Weld Near the Rupture in Preform 2B (50 x)

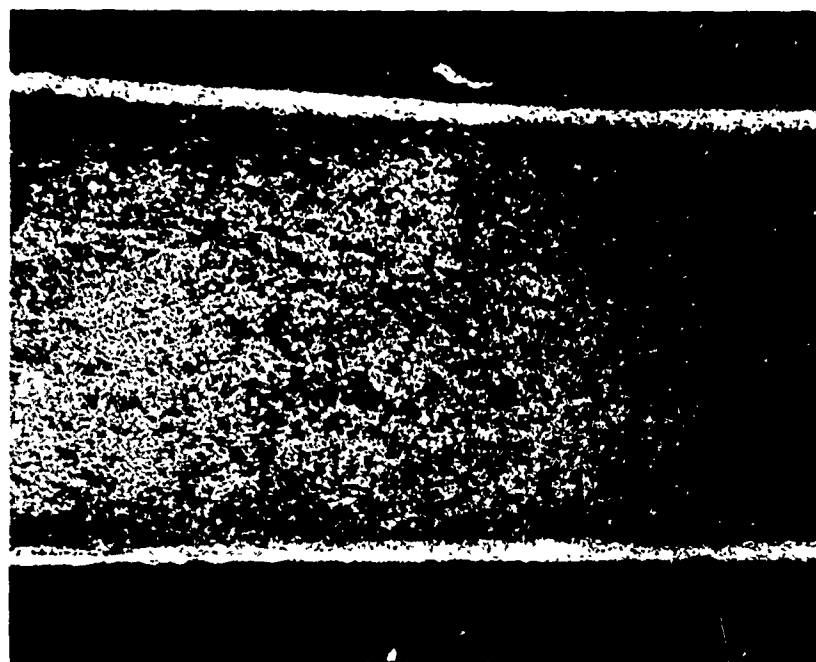


Figure 78. Photomicrograph of a Transverse Section of the Circumferential Weld Near the Rupture in Preform 2B (50 x)

The high hardness values in the weld and heat affected zone suggest that the circumferential weld was not stress relieved. However, decarburization to a depth of about 0.004 in. on each surface, thermal discoloration of the part, and the stress relief record attest to the fact that the part had received a normal 1,250° F stress relief. No definite explanation existed for the high hardness values measured. It was possible that the material on either side of the weld responded differently to the local stress relieving process that is presently employed. If this is the case, then much more precisely controlled processing procedures than originally anticipated will be required.

It was apparent from the weld X-rays taken after fabrication of the preform and from electron microscope examination of the fracture surface that both ruptures were the result of overstress (strain) conditions and not from some material defect. The longitudinal rupture was in parent material near the weld, whereas the circumferential crack lay mainly in the heat affected and weld zones.

M. ANNEALING OF PREFORM 5B

Based on the disappointing results obtained thus far in the program, it was decided that the primary cause of failure was related to the method of local stress relief and an associated lack of ductility. Therefore, in order to enhance the probability of success, the decision was made to treat Preform 5B in some manner which would give greater ductility and a more uniform grain structure. The following thermal treatment was selected:

1. Welds were locally stress relieved as usual, i.e., 250° F for 1-1/2 hours.
2. The entire preform was subjected to 1,550° F for 2 hr, cooled 50° F/hr to 1,000° F, then furnace cooled to room temperature (full anneal).

This treatment resulted in the following nominal material properties:

Ultimate tensile strength	= 85,000 psi
Yield strength	= 53,000 psi
Elongation	= 14 to 15 percent

Figure 79 shows a view of Preform 5B subsequent to the full annealing treatment. In general, the distortion appeared to be minimal with a slight amount of scaling occurring near the small diameter (as shown in Figure 79).

N. FORMING OF PREFORM 5B

The attempt to form Preform 5B with a series of small centrally located charges was unsuccessful. The standoff and charge sequence shown in Table V was used. During the fourth shot, a 10.0 in. crack was formed adjacent to a longitudinal weld. Tensile and microstructure specimens were sectioned from the partially formed dome, and it was determined that the intent of the annealing process; i.e., to increase the weld ductility, was accomplished.

O. FAILURE ANALYSIS OF PREFORM 5B

The first three forming charges were all 10 gm; the first two were located at a vertical distance of 3.5 in. from the inside surface of the igniter boss and the third at a distance of 4 inches. The fourth charge was also 10 gm located at a standoff height of about 4.0 inches. This charge resulted in a 10.0 in. crack adjacent to a longitudinal weld (Figure 80). The fracture origin, shown by the arrow in Figures 80 and 81, was located at a vertical distance of about 3.25 to 3.50 in. from the inside surface of the igniter boss and 0.200 in. away from the longitudinal weld edge. The distance between the rupture and the weld edge varied

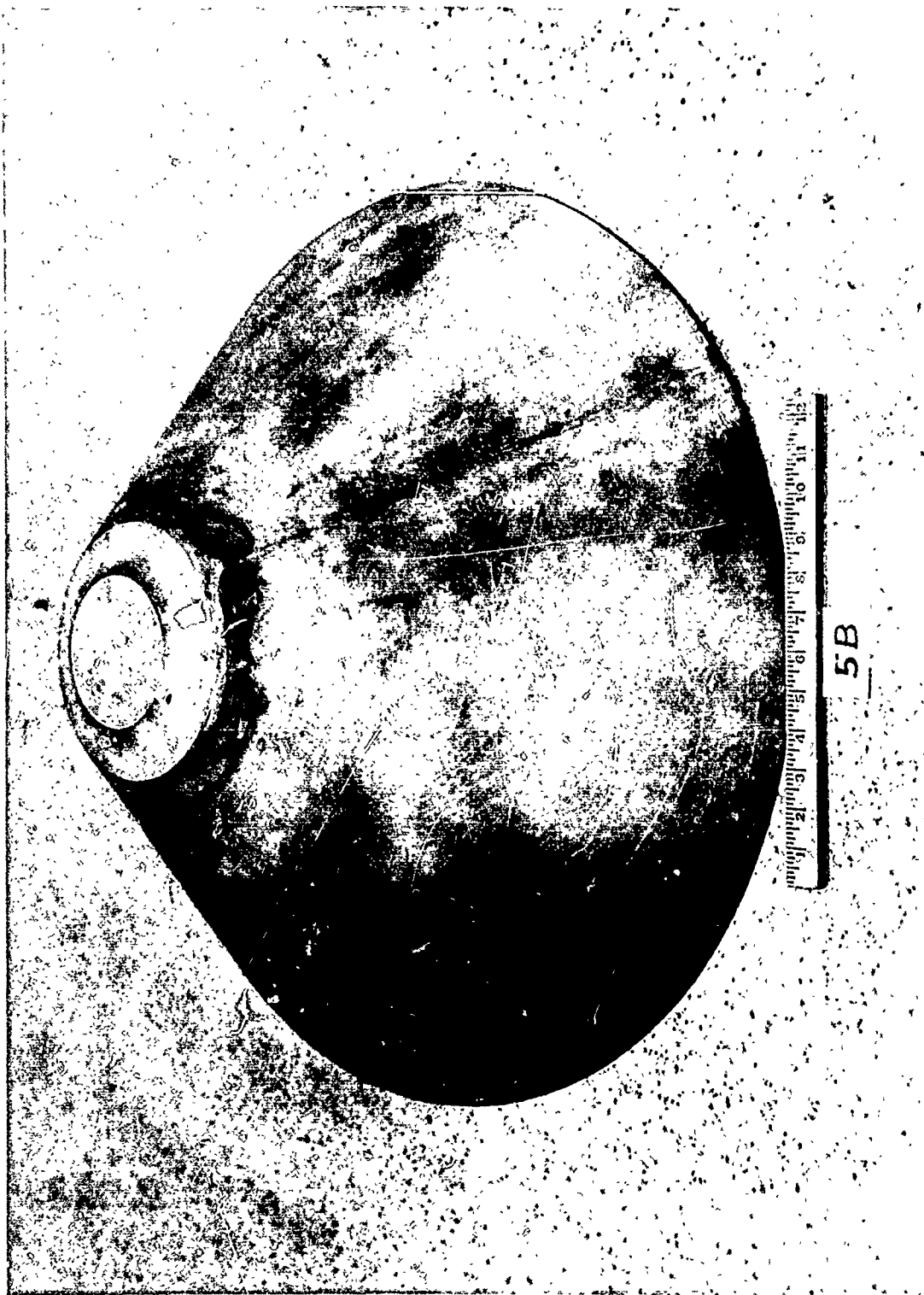


Figure 79. Preform 5B After Full Annealing

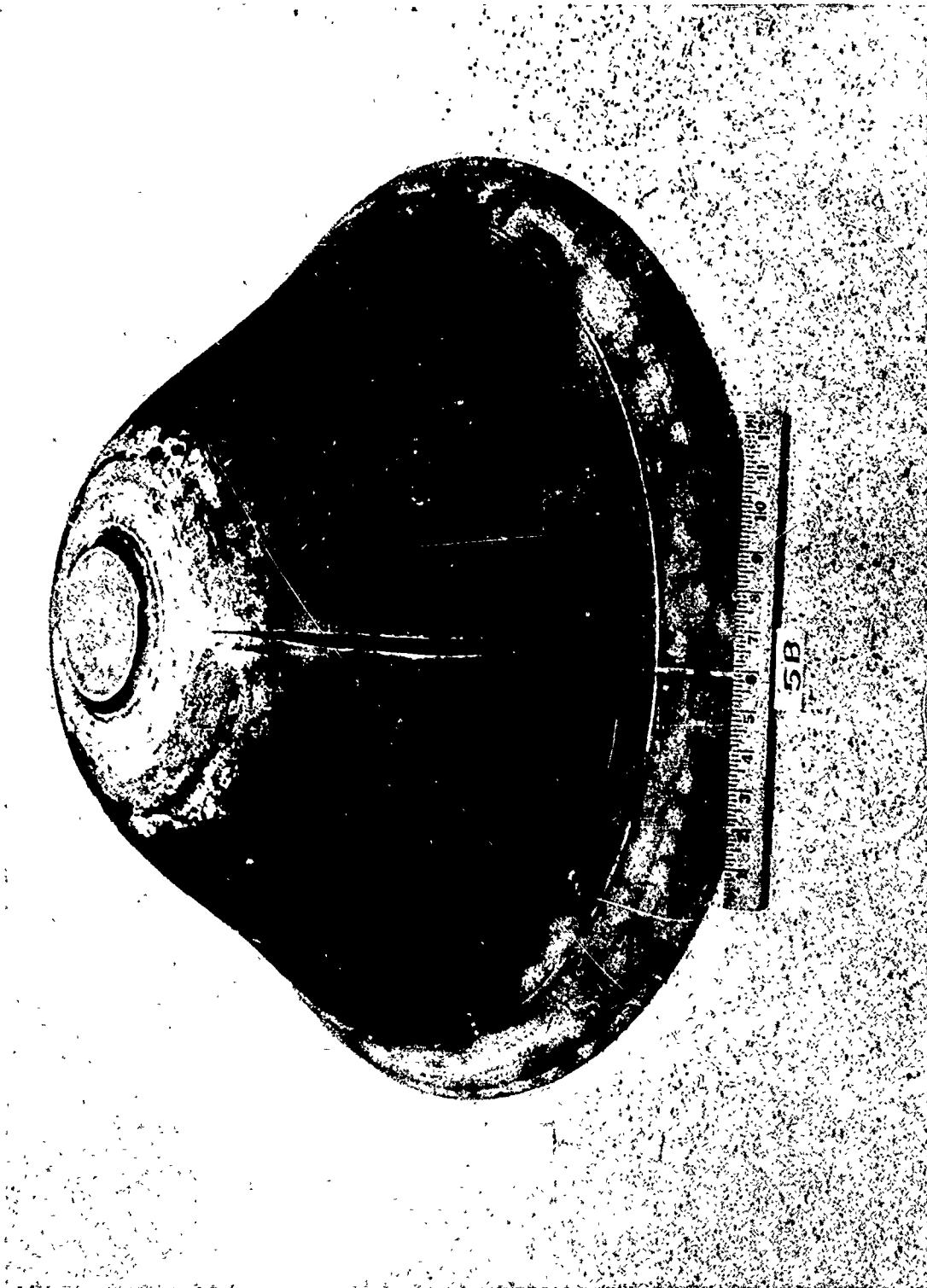


Figure 80. D6AC Steel Preform 5B After Forming Attempt

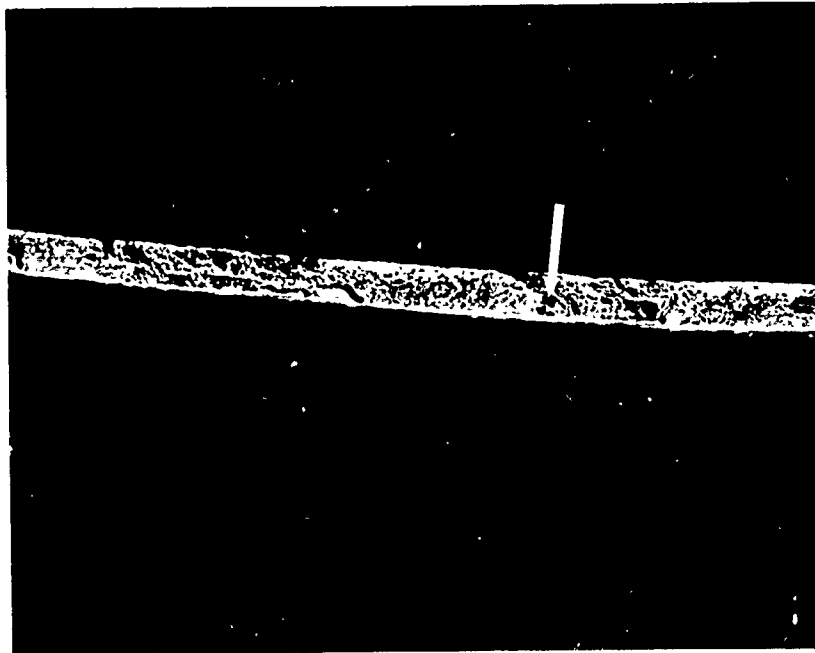


Figure 81. Fracture Surface of Preform 5B Showing the Rupture Origin (8 x)

from about 0.180 to 0.250 inches. The crack was entirely in parent material as shown in Figure 82, which shows a section transverse to the rupture surface near the rupture origin. Review of the longitudinal weld X-rays prior to the forming attempt showed that the rupture was apparently not initiated by some type of microscopic parent material defect.

Tensile coupons were sectioned from the preform at positions shown in Figure 83. One specimen was cut so that the longitudinal weld was parallel to the tensile axis, one specimen had the weld transverse to the tensile axis, and one was a parent material specimen. The transverse weld and parent material specimens were taken from that portion of the preform which was under the die restraining ring during the forming attempt.

Metallographic specimens were also sectioned from the preform in areas shown in Figure 83. From these, the weld microstructures and hardnesses were evaluated.

The tensile and metallographic specimens were considered necessary in order to determine if the preform, and in particular the welds, were in the desired condition due to the annealing process. This was especially important since the preform was annealed for 2 hr at a 1,500°F temperature instead of at the 1,550°F temperature previously selected. This discrepancy was attributed to misinterpretation between Thiokol and the heat treating vendor, and it remained to be verified that satisfactory ductility was still obtained.

Results of the tensile tests are given in Table VI, and it should be noted that all specimens possessed good ductility. The area beneath the restraining ring did not undergo a measurable decrease in thickness, thus the values for specimens 5BT-2 and 5BT-3 should be reasonable. However, specimen 5BT-1 was taken from an area where the thickness had been reduced by about 7.4 percent. This may result in slightly higher strength and lower ductility values. In any case, the uniform and total elongations of the annealed weld have been increased by about 100 percent and 61 percent, respectively, over the weld ductilities after stress-relieving for 1.5 hr at 1,250°F. Thus, in spite of the lower temperature (1,500°F vs 1,550°F), the intent of the annealing process was accomplished; i. e., to increase the ductility of the welds.

The microstructures at two locations along the longitudinal weld adjacent to the preform rupture are shown in Figures 84 thru 87. Figures 84 and 85 are specimen 5BM-3 photomicrographs of the weld and weld-parent material interface, respectively, taken near the rupture origin. The prior cast structure of the weld was still somewhat evident; however, the weld appeared to be entirely ferritic (body centered cubic) rather than martensitic. This was reflected by the low hardness of the weld, R_c 20.9. The parent material hardness was R_c 21.9. Specimen 5BM-2, Figure 86, also revealed evidence of the prior weld structure. The area referred to appeared to be a weld repair made prior to stress-relieving and annealing. Again, the weld appeared to be mostly ferritic and had a hardness of R_b 98.7. The hardness of the adjacent parent material was R_b 98.1. Both specimens show that the microstructure across the weld was not uniform due to a difference in grain size

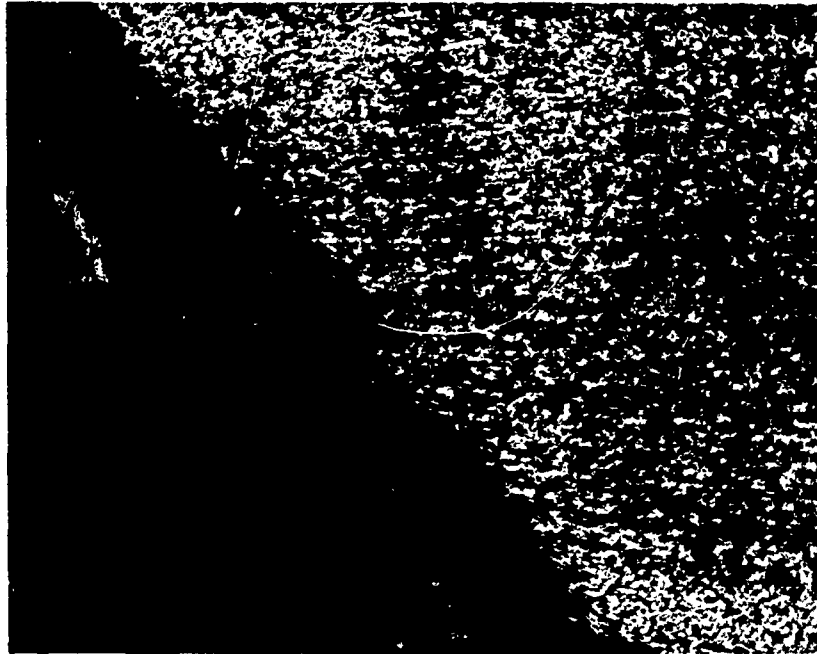


Figure 82. Photomicrograph of a Section Transverse to the Fracture Surface
Near the Rupture Origin (100 x)

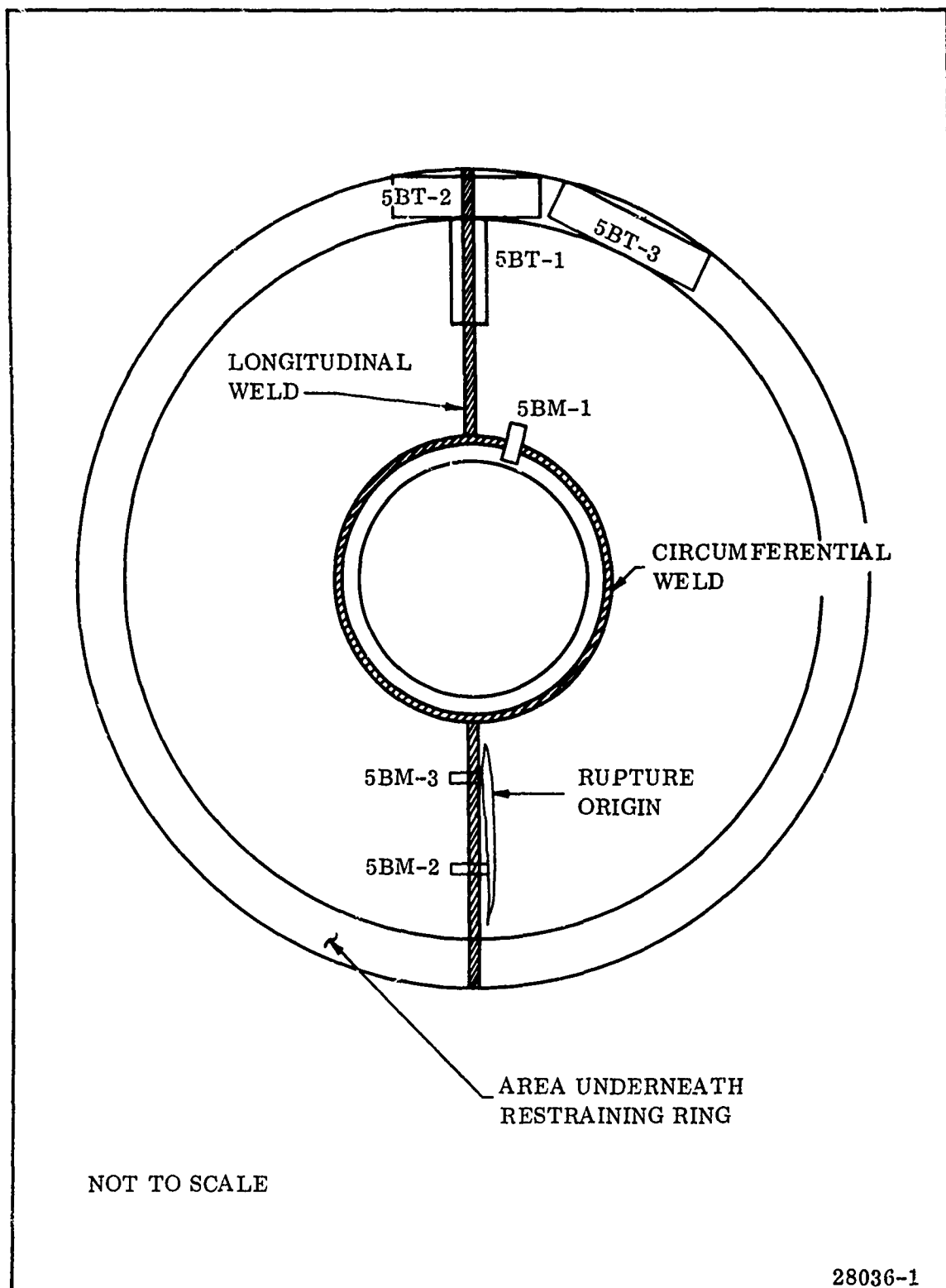


Figure 83. Schematic of the Top View of Preform 5B After Forming Attempt

TABLE VI
TENSILE PROPERTIES OF WELD AND PARENT MATERIAL
SPECIMENS FROM PREFORM 5B

Specimen	Strength (psi)		Uniform	Strain (%)	
	0.2% Y.S.	UTS		Recorded†	Total Measured††
5BT-1*	75,676	96,757	10.2	11.5	13.7
5BT-2**	52,098	80,000	8.3	12.0	13.1
5BT-3***	61,170	96,543	12.4	15.0	19.5

*5BT-1 - Weld parallel to tensile axis.

**5BT-2 - Weld transverse to tensile axis.

***5BT-3 - Parent material.

†Recorded Strain - Strain readout from optical extensometer.

††Measured Strain - Determined by fitting the broken pieces together and measuring the final length.

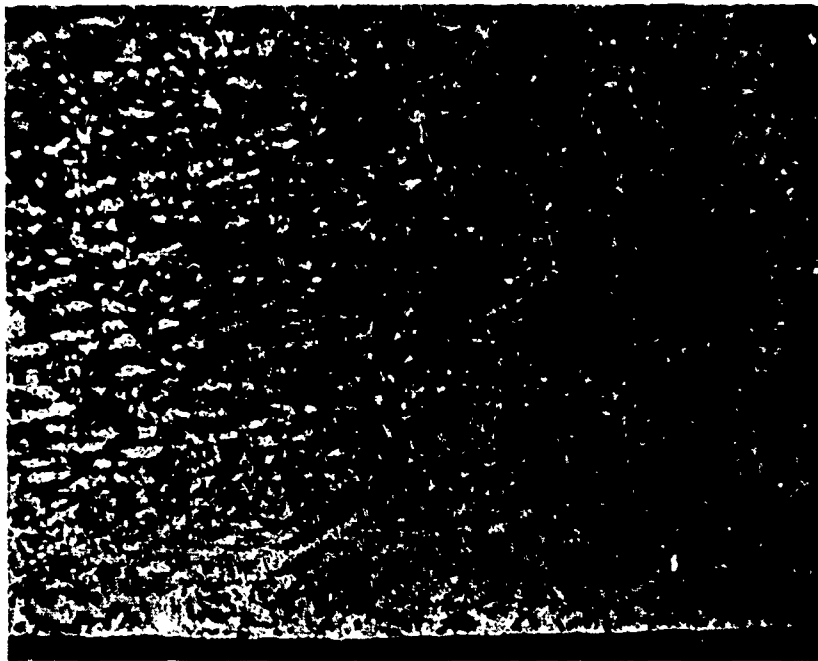


Figure 84. 5 BM-3 Weld Microstructure (100 x)

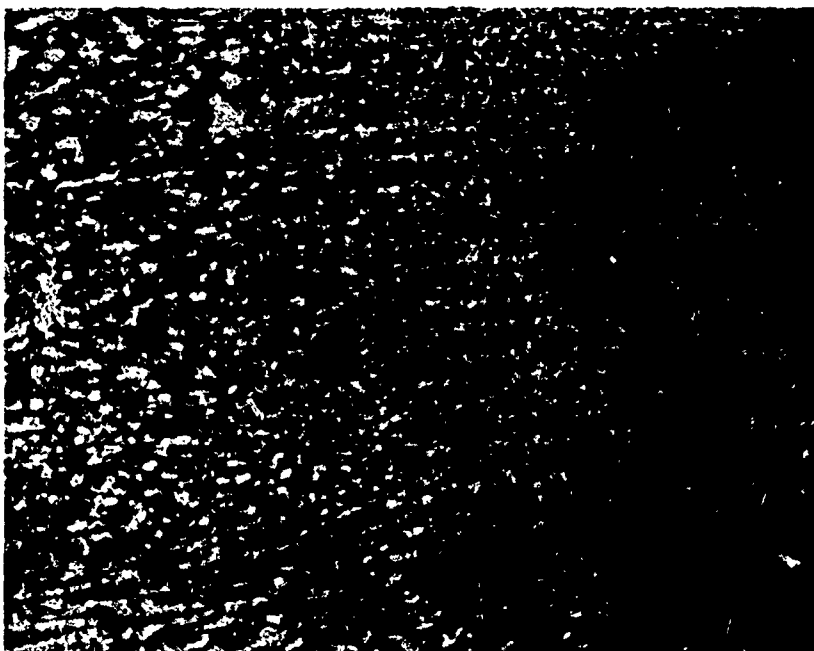


Figure 85. 5 BM-3 Weld and Parent Material Microstructure Interface (100 x)

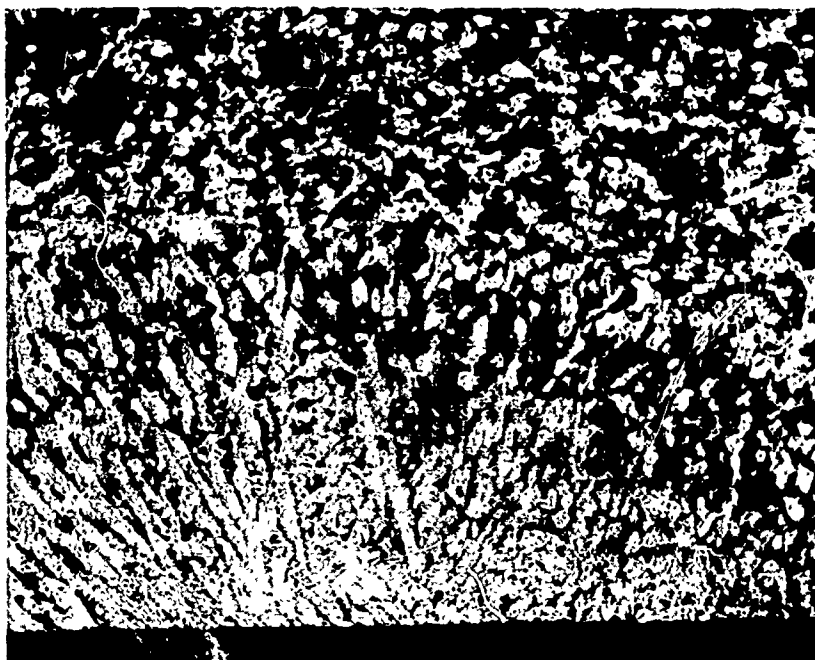


Figure 86. 5 BM-2 Weld Microstructure (100 x)



Figure 87. 5 BM-2 Microstructure of Interface Between Weld and Parent Material (100 x)

between the weld and parent material. According to the cursory thermal treatment study conducted by Thiokol, the microstructure across the weld would have been more uniform if the annealing temperature had been 1,550° F rather than 1,500° F.

After reviewing the analysis of Preform 5B, it was evident that even though relatively good ductility existed in the part, it was not possible to obtain even one-half the deformation required for full forming. And again comparing the conditions that existed in the Preform 1A shot (which was relatively successful) with the recent unsuccessful shots, it became evident that the primary difference was that Preform 1A was allowed to slip under the restraining ring.

Although the original program plan contained no provisions for any computer study effort, company funding was obtained to support a strain study in order to determine the exact strain requirements for a completely restrained preform. The results were compared with a proven strain theory (TRESCA) and it was found that the preforms had been behaving about as should have been expected and that there was no chance of completely forming a fully restrained preform from material with less than about 30 percent elongation capability. This explains why the Cor-ten experiments were successful. A complete presentation of the strain requirement analysis is contained in Section VIII.

With this information, it was decided to conduct the forming operation allowing the material to slip out under the restraint ring, and at the same time to try a new thermal treatment that would give a more uniform grain structure through the weld than had the annealing process used on Preform 5B.

There were three possibilities that existed for obtaining a preform for this effort:

1. Repair and reuse Preform 1B.
2. Use one of the Configuration C preforms (1C or 2C) without the Y ring welded in.
3. Fabricate a new Configuration B preform (6B).

P. REPAIR AND THERMAL TREATMENT OF PREFORM 1B

When calculations indicated that the length of the Configuration C preforms precluded their use, the decision was made to weld-repair Preform 1B and use it as a forerunner with which to establish the exact thermal treatment for a new Preform 6B.

The weld repair was accomplished with quite a bit of difficulty, after which the weld was stress-relieved for 1 hr at about 1,050° F and X-rayed for defects. No pores or cracks were noted, but the weld was undercut in several places. After building up the undercut areas, the weld was again stress-relieved but this time at 1,000° F for 1 hour.

The preform was then shipped to Pyromet Industries to be normalized and double subcritical annealed. The procedure for the thermal cycle was coordinated closely with the Ladish Co. as follows.

1. Hold at 1,750°F for 1 hour.
2. Air cool in retort with gas flowing in retort and fans blowing external air on retort surface.
3. Hold at 1,315° $\pm$ 5°F for 6 hours.
4. Air cool in retort to below 200° F.
5. Hold at 1,315° $\pm$ 5°F for 6 hours.
6. Air cool in retort.

All operations were accomplished with the preform in the retort in dry hydrogen.

It was desired to obtain 18 to 20 percent elongation with this treatment and a uniform grain structure across the weld.

Hardness readings taken on the treated part were R_b 98, indicating a quite soft condition.

However, the weld repair area was still questionable.

Q. FORMING OF PREFORM 1B (R)

When program requirements indicated that it would not be possible to complete a new Preform 6B before contract termination, it was decided to proceed with forming Preform 1B (R) even though a bad situation existed in the weld repair area. It was felt that if the circumferential weld and the one good longitudinal weld could be made to form that it would be a complete vindication of the strain requirement study. The probability of intermittent weld repairs on the repaired weld was recognized.

The schedule below lists the procedure that was followed during the forming of the part.

1. The explosive used was powdered TNT.
2. In each shot, a central charge was used and suspended on a wire frame to the standoff distance.
3. Only 15 of the 27 one in. bolts were used. Torque values are listed in Table VII.
4. The explosive forming sequence is also listed in Table VII.

R. ANALYSIS OF PREFORM 1B (R)

Prior to forming Preform 1B (R), a grid pattern was scribed onto the preform at two longitudinal stations, 0 and 90 degrees. Table VIII lists the hoop strain at each of 12 longitudinal stations. Also listed is the longitudinal strain between stations. After the preform had been sectioned through the 90-270 deg plane, thickness measurements were taken along the edge and are also listed in Table VIII.

The maximum thickness thin-out was about -16.6 percent at Station 12, Section 270. This was considerably more than expected and is particularly strange

TABLE VII
EXPLOSIVE FORMING SCHEDULE FOR PREFORM 1B (R)

<u>Event (Shot No.)</u>	<u>Explosive Load (gm)</u>	<u>Standoff (in.)</u>	<u>Blank Pull-In (in.)</u>	<u>Bolt Torque (ft-lb)</u>
1	10	3.5	0.12 to 0.20	115
2	10	3.5	0.40	115
3	10	4	0.35 to 0.43	115
4	10	4	0.50	115
5	10	5	0.55	115
6*	15	6	0.53 to 0.65	115
7	5	4.5		90
8	5	5		90
9	10	5		90
10	15	5.5		90
11	20	6		90
12	20	7	0.725 to 0.850	90
13**	30	8		90
14	40	8		90
15	40	7		90
16	40	7	0.90	90

*Upon completion of Shot No. 6, a small crack was noted adjacent to the longitudinal weld which had been previously repaired. The crack was approximately 3/4 in. long and appeared to be a ductile failure; i.e., the material had necked down considerably.

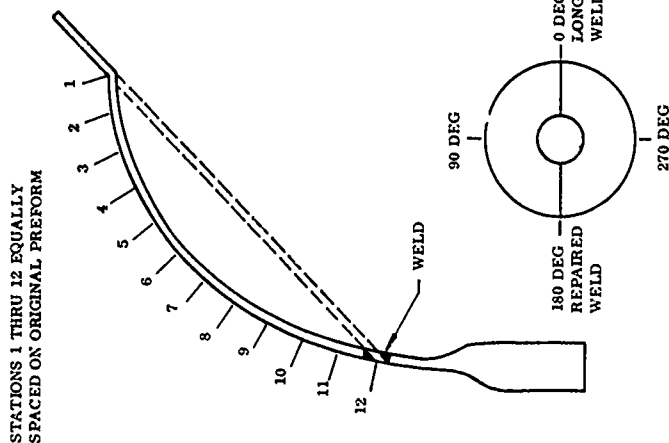
The crack was repaired using Tungsten-Inert-Gas (TIG) welding techniques. Bare 308 stainless steel was used for the filler metal. The welded area of the part was thermally treated immediately after welding by locally heating to 600° to 700°F for 25 minutes. The repaired area was die penetrant inspected prior to additional forming and found to be free of defects.

**A longitudinal crack adjacent to the same repaired weld was noted following Shot No. 13. The same procedure as described for Shot No. 6 was used in repairing the weld. The preform was subsequently formed to final contour.

TABLE VII
 PREFORM 1B (R) HOOP STRAIN AND THICKNESS MEASUREMENTS

	Station No.											
	1	2	3	4	5	6	7	8	9	10	11	12
Hoop Strain Across Weld (in./in.)	0	0.061	0.065	0.090	0.089	0.089	0.094	0.085	0.063	0.050	0.029	0
Hoop Strain in Parent Material 90 deg (in./in.)	0.032	0.053	0.083	0.092	0.111	0.095	0.090	0.089	0.062	0.049	0.024	0
Thickness After Forming, 90 Deg From Longitudinal Weld (in.)	0.0526	0.0536	0.053	0.0528	0.0503	0.0490	0.0490	0.0490	0.0485	0.0480	0.0490	0.0500
Thickness After Forming, 270 Deg From Longitudinal Weld (in.)	0.0522	0.0528	0.0523	0.0513	0.0508	0.0489	0.0472	0.0490	0.0483	0.0472	0.0160	0.0450
Average Hoop Strain (in./in.)	0.016	0.057	0.074	0.091	0.100	0.092	0.092	0.087	0.063	0.049	0.027	0
Average Longitudinal Strain (in./in.)	-0.015	-0.030	-0.030	-0.030	-0.026	-0.035	-0.037	-0.030	-0.025	-0.020	-0.010	

Original material thickness = 0.052 to 0.056 in.; 0.054 in. nominal.



since it occurred in an area where no hoop strain was recorded. One possible explanation was that most of this thickness reduction took place during the original forming attempt (when preform was completely restrained). It must be remembered that in the restrained condition, all of the material used in hoop and longitudinal strain must come from a decrease in thickness. It can be noted that in the area of maximum forming (Station 5) the strain invariant, $\epsilon_1 + \epsilon_2 + \epsilon_3 = 0$, is essentially satisfied.

At this point the thickness strain is -6.8 percent and:

$$+0.010 - 0.068 - 0.026 = 0.006 \sim 0$$

Figure 88 is a plot of average measured strains in the formed part.

Figure 89 shows an internal view of the formed preform. The weld repairs are visible on one longitudinal weld. Figure 90 shows the contour of the preform and the good longitudinal weld. Figure 91 shows the cross section of the sectioned preform. It can be noted that the springback was not symmetrical.

One of the objectives of the new thermal treatment was to obtain a uniform grain structure throughout the part. Figures 92, 93, and 94 show that this condition was obtained. Figure 93 shows this particularly well as it was almost impossible to distinguish between weld and parent material.

After the preform was sectioned, one tensile coupon was cut from the relatively unstrained material under the restraint ring to more exactly determine the actual condition of the material after the thermal cycle. Properties were as follows:

Yield strength	59,375 psi
Ultimate strength	98,958 psi
Elongation	19.4 percent
Uniform elongation	12.0 percent

Upon completion of the explosive forming, examination of the die revealed a gap between the fifth and sixth die segments (Figure 1, Details -7 and -0). The gap was noted to be approximately 0.100 in. wide.

Since the separation was not detected subsequent to removal of the part from the die after Shot No. 13 (and Shots 14, 15, and 16 were thereafter employed to form the part to full contour), the imprint of the discontinuity between segments was readily apparent on the formed piece.

After disassembly, the concrete grout under the die was found to have given way slightly, and it was presumed that this allowed the relative movement described above. The small bolts used to assure sealing between the segments were found to have loosened and did not, therefore, offer any resistance to the separation.

It should be pointed out that the large number of shots used to completely form the preform were not representative of an expected production sequence. An ultra conservative approach was used to permit the observation of blank movement and weld deformation since a reworked preform was processed. The smaller charges also assured controlled deformation and complete formation of the hemispherical

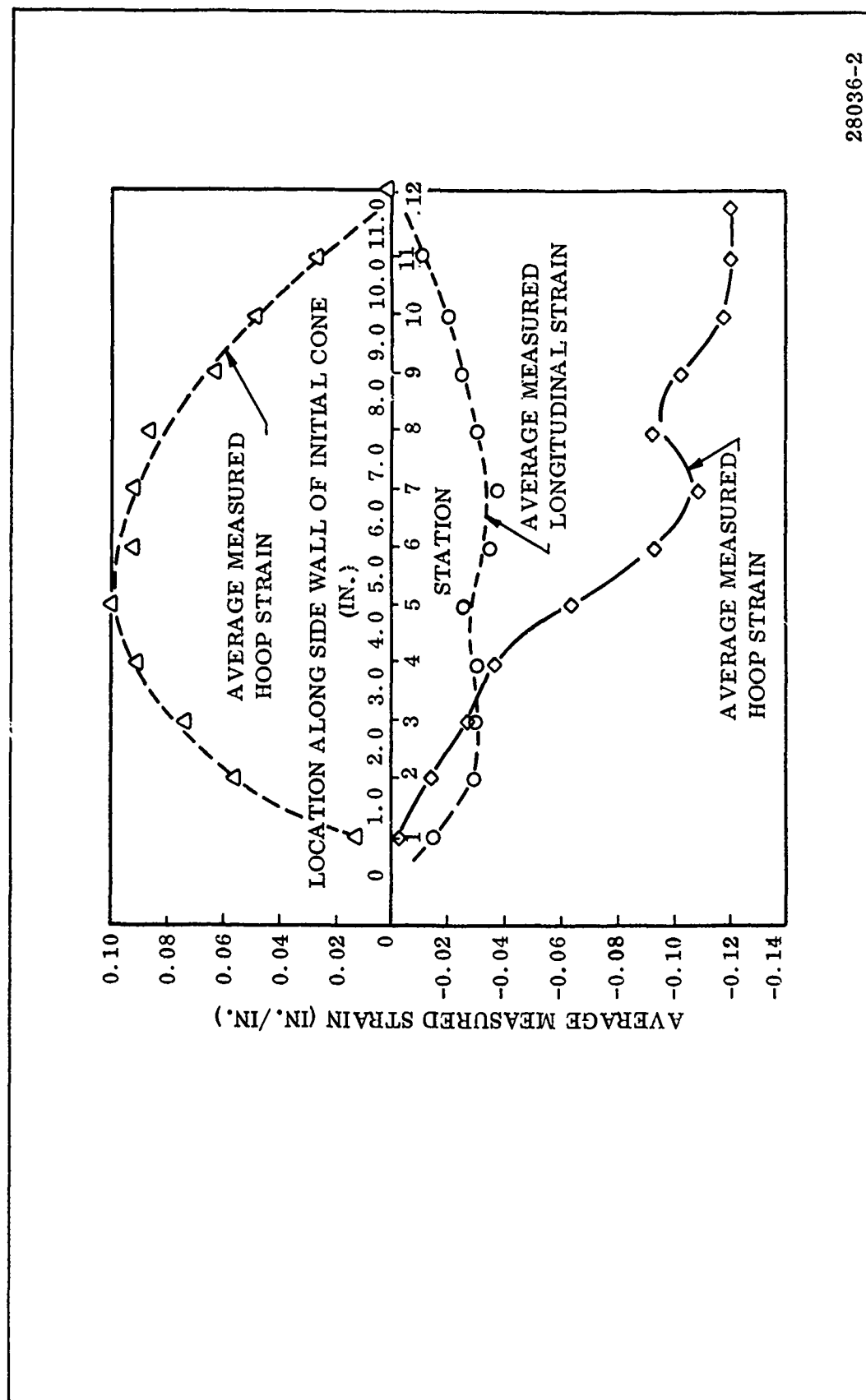


Figure 88. Preform 1B (R) Average Strains

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Figure 89. Internal View of Preform 1B (R) After Forming



Figure 90. Completely Formed Preform 1B (R)

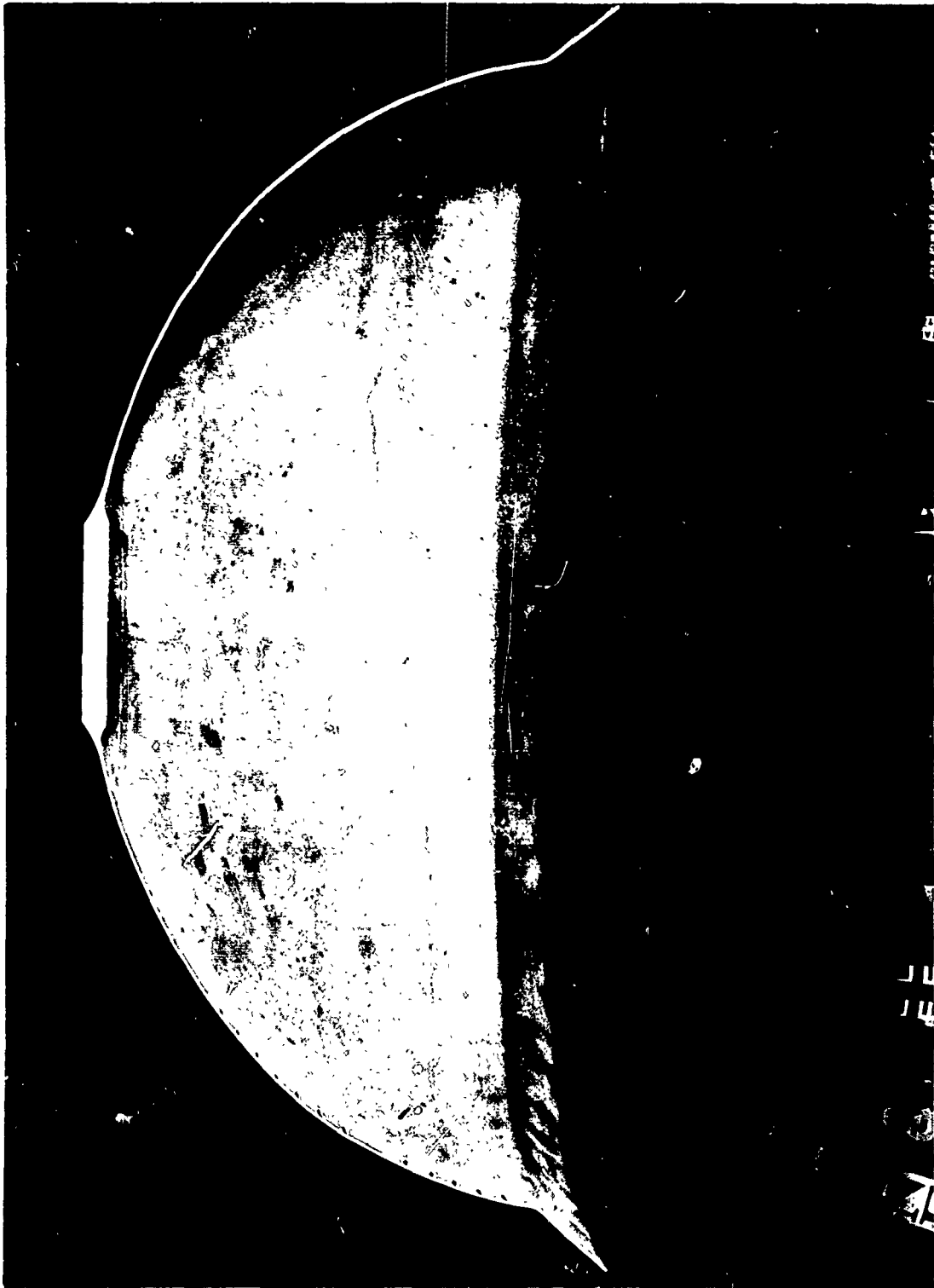


Figure 91. Cross Section of Preform 1B (R) After Sectioning

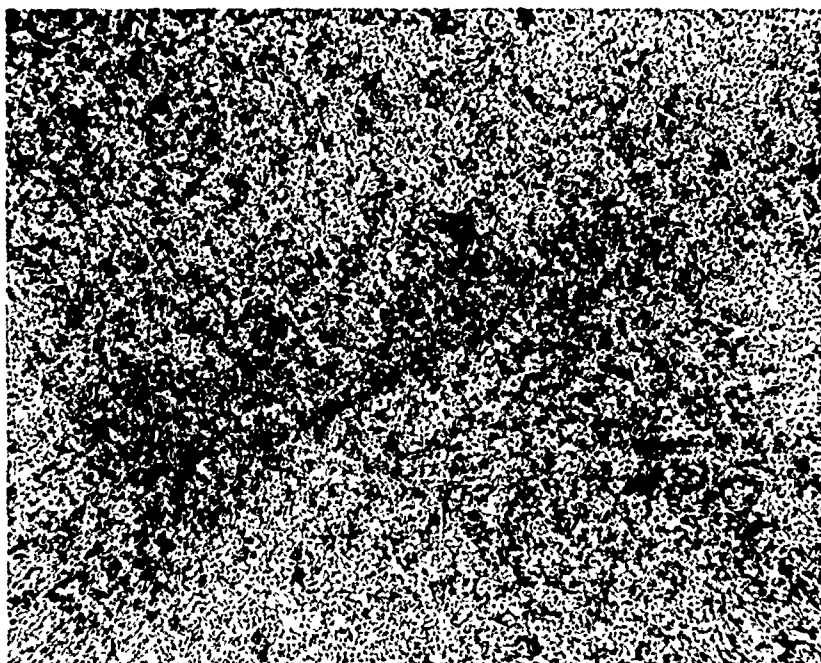


Figure 92. Preform 1B (R) Weld Material Grain Structure After Normalization and Double Temper (100 x)

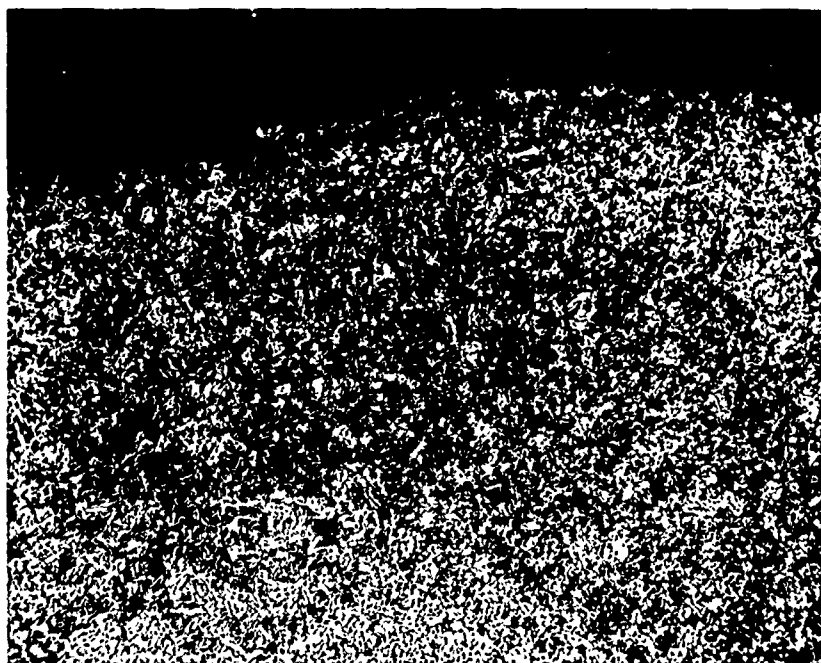


Figure 93. Preform 1B (R) Weld Edge Grain Structure After Normalization and Double Temper (100 x)

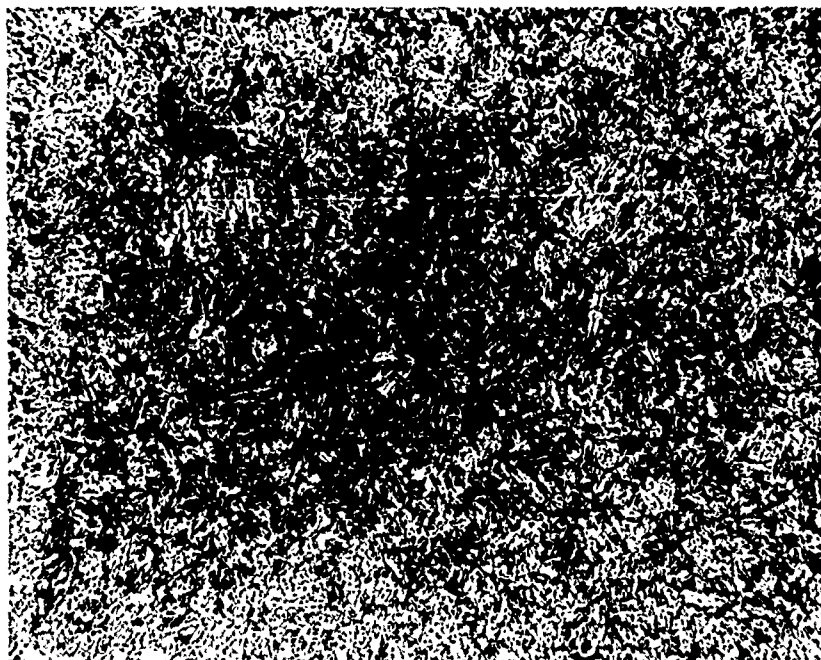


Figure 94. Preform 1B (R) Parent Material Grain Structure After Normalization and Double Temper (100 x)

shape under a modified restraint condition. We would estimate a production forming sequence to involve two to four operations.

S. REMAINING PREFORMS

At the termination of the contract, there remain several preforms in various stages of completion:

3B and 4B	Cones rolled and heat treated; no joining done.
1C	Cones rolled and joined with longitudinal welds; no circumferential welding or trimming.
2C	Cones rolled and one longitudinal weld bead made.
6B	Extra preform made from Thiokol furnished material; preform is complete.

T. CONCLUSIONS

There are numerous conclusions which can be drawn from the experience obtained in the program. The following are the more important.

1. SPECIFIC CONCLUSIONS

1. When using high strength materials with uniaxial tensile strain capability under 28 percent, it is mandatory that the material be allowed to slip under the restraint ring. This fact requires that special initial clearance techniques be used for Configuration C preforms. The initial clearance requirements were established by this program for Configurations B and C at about 0.07 in./in. of slant wall length being formed.
2. One of the major problems associated with the explosive forming process is that of buckling. There are three general methods by which buckling can probably be eliminated.
 - a. By using a small initial charge to "set" the complex curvature in the preform before proceeding with larger forming charges.
 - b. By pulling sufficient vacuum that the part can be almost completely formed by the first shot.

- c. By varying the bolt torque to adjust slippage as the forming progresses.
3. The partial success of Preform 1A with respect to the forming of the longitudinal welds indicates that it might be possible to form D6AC with local stress relief, although the final program success was achieved with a preform normalized and double tempered after welding.

2. GENERAL CONCLUSIONS

1. In its present state of development, the technology of explosive forming is in many aspects an empirical art although there are numerous areas where existing scientific methods can apply.
2. There is an area concerned with dynamic environment of a process and dynamic response of specific materials wherein little data currently exists (except for some of the more simple processes and common materials).
3. There is enough experience and expertise in the explosive forming industry that a successful dome forming program should be possible even though some of the information on dynamic environment and response is not available. This conclusion is enhanced by the final result of this program.

U. RECOMMENDATIONS

1. The level of success of this program has demonstrated the potential of the preform concept. However, it is felt that an additional subscale program should be instituted to verify and extend certain results before a full scale effort is begun.
2. Any additional hardware effort should be preceded by a study phase where the material and processing are more fully characterized. This study phase would consist of collecting existing data and possibly developing a minimum of new data.
3. The ideal material for explosive forming application would be a steel which would not need to be recommit-
ted to an oven after forming. Some prime candidate materials which offer this advantage include: HP9-4, HY-130, HY-150, and the maraging steels.

SECTION VIII SPECIAL STUDIES

This section presents the special efforts and studies conducted in support of the general program. Each study has been referenced previously in appropriate sections of the report, but the details of these studies were grouped here in one section to prevent the interruption in continuity that might otherwise occur.

A. ANALYSIS OF CHARGE REQUIREMENTS FOR FORMING FROM CONICAL PREFORMS

The general method used in the following analysis is an energy balance between the work necessary to form the sidewalls of a conical preform and the energy delivered to the sidewalls by a ring shaped explosive charge. The work required to form the part is determined from an assumed strain distribution at the conclusion of forming and subsequent integration of the stress-strain profile. The energy delivered to the sidewalls by the explosive is determined from a geometry standpoint and is semi-empirical.

The assumed strain profile was determined as indicated in Figure 95.

$$\epsilon_L = \frac{L_2 - L_1}{L_1}$$

$$\epsilon_H = \frac{H_2 - H_1}{H_1}$$

The value for ϵ_t was determined from the constant volume condition:

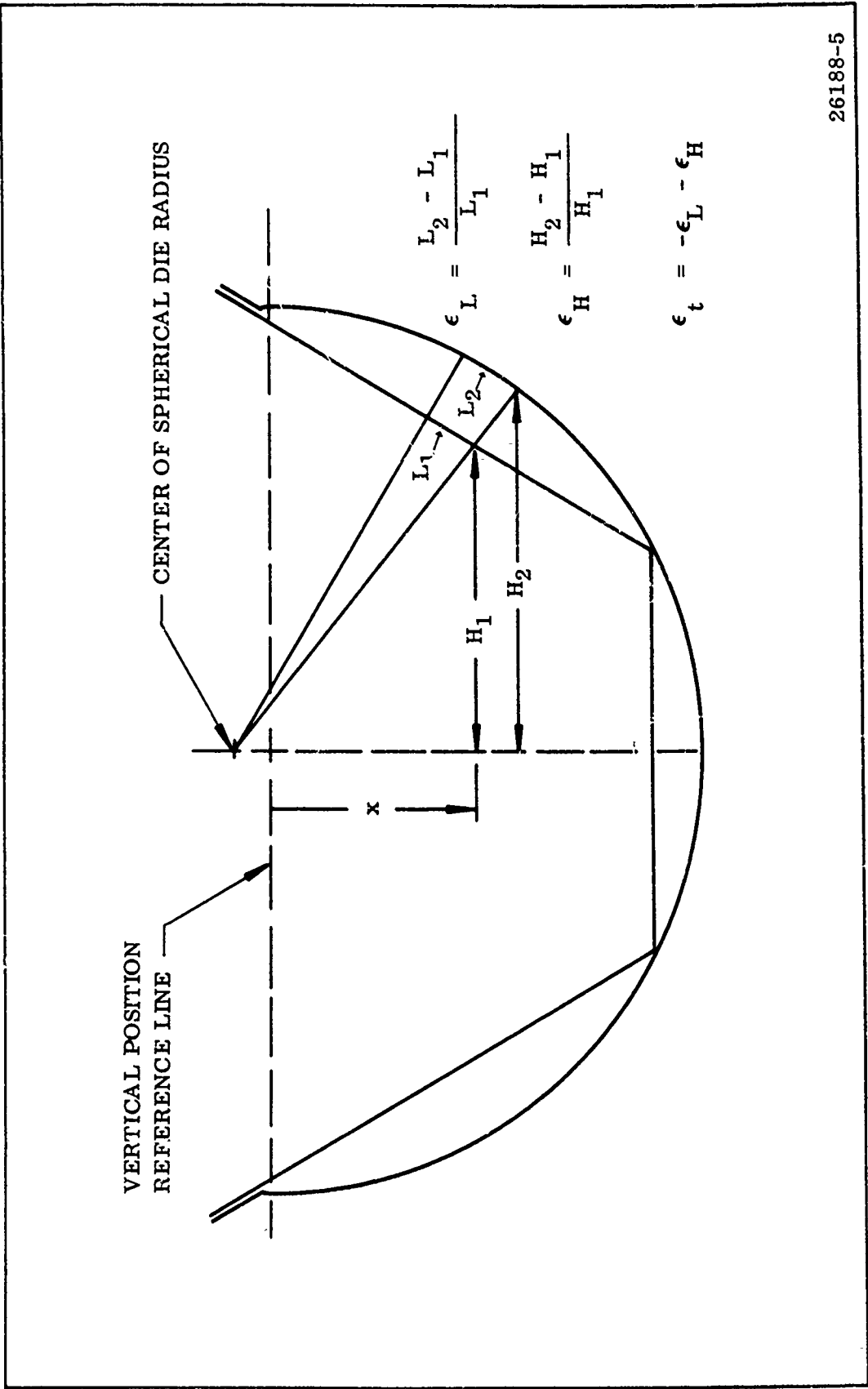
$$\epsilon_t = -\epsilon_L - \epsilon_H$$

where:

- ϵ_L = longitudinal strain
- ϵ_H = hoop or tangential strain
- ϵ_t = thickness strain

Figure 95 illustrates the graphical method used to determine the strain profile. These results are listed in Table IX. Values for longitudinal strain represent average values between points 1 and 2, 2 and 3, 3 and 4, etc.

Table X shows a summary of effective strain calculations.



26188-5

Figure 95. Illustration of Graphical Determination of Strain Profile

TABLE IX
GRAPHICALLY DETERMINED HOOP AND LONGITUDINAL STRAINS

Point	Distance From Vertical Position Reference Line (in.)	H ₁ (in.)	H ₂ (in.)	ε _{Hoop}	L ₁	L ₂	ε _{Long.}
1	0.91	10.98	11.44	+0.042	1.29	1.28	0.0078
2	1.96	10.18	10.95	+0.076	1.35	1.26	0.071
3	2.94	9.39	10.31	+0.098	1.43	1.31	0.092
4	3.96	8.57	9.50	+0.1085	1.43	1.29	0.1085
5	4.96	7.78	8.56	+0.100	1.38	1.28	0.078
6	5.96	6.98	7.55	+0.082	1.32	1.28	0.031
7	6.96	6.17	6.48	+0.050			

TABLE X
SUMMARY OF EFFECTIVE STRAIN CALCULATIONS

Distance From Vertical Position Reference Line (in.)	ε _{Long.}	ε _{Hoop}	ε _t	ε _{eff}
1.435	+0.0078	+0.059	-0.067	+0.037
2.45	+0.071	+0.089	-0.160	+0.054
3.45	+0.092	+0.105	-0.196	+0.066
4.46	+0.1085	+0.107	-0.215	+0.071
5.46	+0.078	+0.092	-0.017	+0.057
6.46	+0.031	+0.068	-0.099	+0.039

The points listed in Table IX were plotted vs position as shown in Figure 96. As was expected, graphically determined hoop strains were more reliable data than the longitudinal strains and, as such, were used for interpolation to give data points for "in-between" stations. This was done to obtain hoop strains at the same distance from the vertical position reference line as for longitudinal strains. The interpolated values are also shown in Figure 96.

Using the constant volume condition:

$$\epsilon_H + \epsilon_L + \epsilon_t = 0,$$

thickness strain (ϵ_t) was calculated for the "in-between" points. Effective strain was calculated, then, using the relationship*:

$$\epsilon_{\text{effective}} = \sqrt{\frac{2}{3}} \sqrt{(\epsilon_H - \epsilon_L)^2 + (\epsilon_L - \epsilon_t)^2 + (\epsilon_t - \epsilon_H)^2}$$

The effective strains were plotted vs position as shown in Figure 97. An equation was determined which does not fit the data exactly but should be satisfactory as an approximation. The plot of this relationship is also shown in Figure 97.

Since the work per unit volume is given by:

$$\frac{W_p}{V} = \int \sigma d\epsilon \quad (2)$$

and the relationship between stress and strain for the material can be assumed to follow the equation:

$$\sigma = K\epsilon^n \quad (3)$$

where:

K = strength coefficient

n = strain hardening exponent

Then:

$$\frac{W_p}{V} = \int K\epsilon^n d\epsilon \quad (4)$$

But:

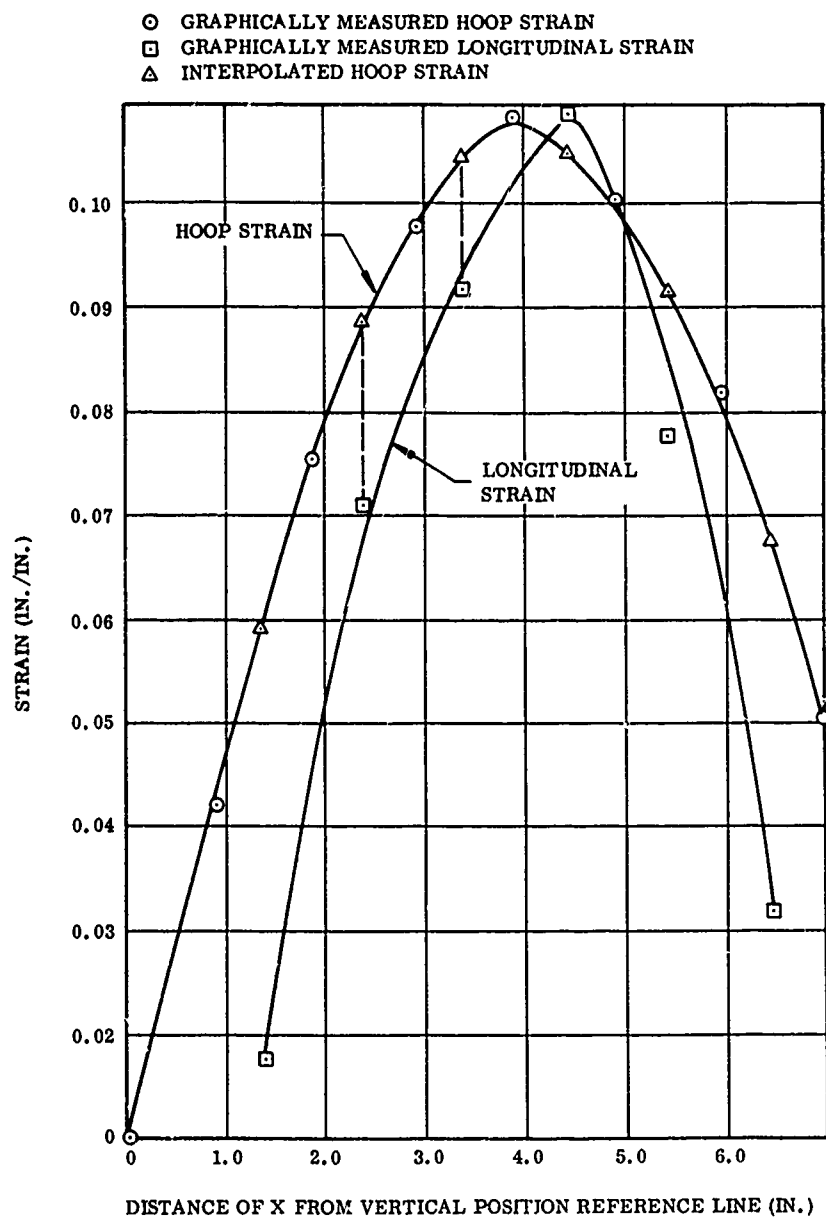
$$\epsilon = \epsilon_{\text{effective}} = 0.07 \left(1 - \frac{x^2}{16}\right)^{1/2} \quad (5)$$

Substituting (5) into (4) and solving the definite integral between the limits for this case:

$$W_p = (0.07)^2 \left(K / \frac{n+1}{2}\right) V$$

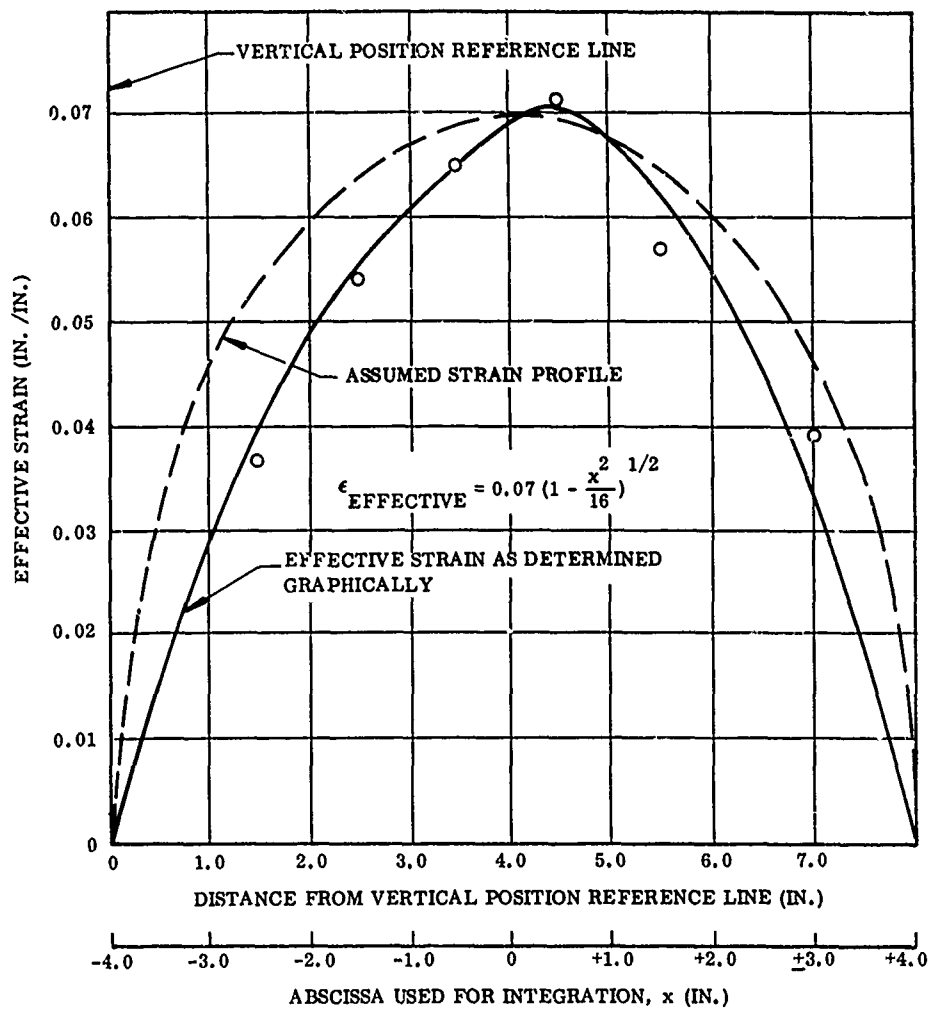
which represents the work necessary to form the sidewalls of the part from a strain energy standpoint.

*See Reference 1.



26188-6

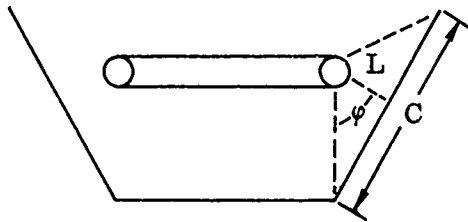
Figure 96. Strain vs Position on Preform



26188-1

Figure 97. Effective Strain vs Position

A relationship is now needed for energy delivered to the work piece by the explosive charge. The sketch below illustrates the geometry of the ring charge placement in the preform.



$$\tan \varphi = \frac{C}{2L}$$

The delivered energy relationship for water is:

$$E_{\text{delivered}} = \frac{W e \eta_g}{4}$$

where:

η_g = efficiency of the configuration

$$= \frac{\text{ratio of solid angle}}{4\pi}$$

$$= \frac{2\pi (1 - \cos \varphi)}{4\pi}$$

W = weight of charge, lb

e = specific energy of explosive, in.-lb/lb

Since initial tests indicated that the energy delivered to the piece was about 1/13 that expected from a pressure standpoint, a factor of 10 is included for conservatism. The unusually low efficiency is attributed to the proximity of the water surface to the charge. Including this factor and performing the energy balance, the relationship for weight of explosive is obtained:

$$W = \frac{80}{e(1 - \cos \varphi)} (0.07)^2 \left(K / \frac{n+1}{2}\right) V \quad (6)$$

B. WELD STRESS RELIEVING STUDIES

As a result of the failure analysis of **Preform 2A**, it was decided to completely reevaluate the entire stress relieving procedure. It was evident that even when treated at 960°F for 1.5 hr the weld hardness was not reduced to a desirable level. Parent material hardnesses were in the nominal 20 R_c range, and the stress relieved weld and HAZ hardness levels were ranging as high as 50 R_c . It was concluded that higher temperatures were required for stress relieving than 800° to 960°F.

A small test program was conducted to gain specific data on stress relief in the temperature range of 1,150° to 1,350°F.

New Calrod units capable of producing temperatures up to 1,500°F were purchased and checked out.

Several pieces of D6AC steel were welded, using the same welding procedure as planned for the preforms. Each piece of material was then stress relieved with the opposing Calrod arrangement at selected temperature and times in order to find suitable stress-relief temperature from the standpoint of hardness and amount of decarburization. One weld was stress relieved for 1.5 hr at 1,150°F, another for 1.5 hr at 1,250°F, and a third for 2.0 hr at 1,350°F for comparison. After stress-relieving, micro hardness measurements were taken of the cross section, and tensile specimens were cut from the plates in a manner so that the weld joints were perpendicular to the tensile axis. The specimens were tested at a strain rate of about 0.03 in./in./min to determine the integrity of the weld.

Figures 98, 99, and 100 show the results of the micro hardness traverses taken through the cross section of the 1,150°, 1,250°, and 1,350°F specimens, respectively.

Because it is believed that the ideal range of weld hardness levels should be 25 to 30 R_C , the 1,250°F stress relief should produce the desired results. The hardness levels of 40 R_C and above produced by the 1,150°F stress relief are considered to be too high.

The hardness levels of 21.6 to 28 R_C produced by the 1,350°F stress relief seemed to be slightly lower than desirable; however, tensile coupons subsequently cut and tested from the 1,350°F material all fractured in areas outside the weld. As would be expected, tensile coupons from the 1,250°F material also fractured outside the weld zone.

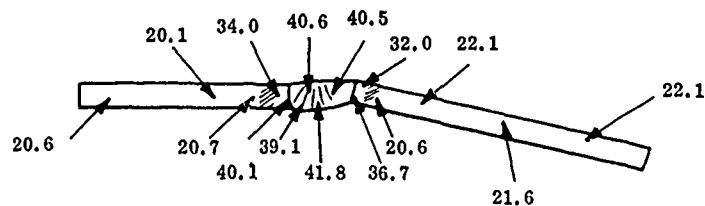
At this point, either the 1,250° or 1,350°F stress reliefs seemed to produce the weld characteristics desired. The 1,250°F results seem more desirable, however, because of the slightly higher hardness and decreased decarburization.

C. CLAMPING FORCE ANALYSIS

This analysis was conducted in three general steps:

1. Calculate pressure necessary to deform cone plastically.
2. Calculate required force on clamp ring necessary to react load due to deforming pressure.
3. Calculate load per bolt required and convert to bolt torque.

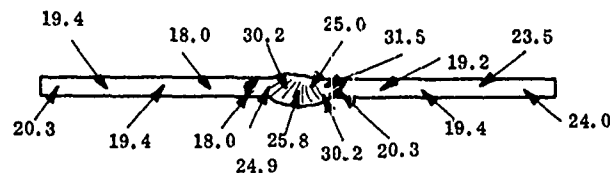
ROCKWELL "C" HARDNESS



TEMP = 1,150°F
TIME = 1.5 HR
NO VISIBLE DECARB NOTED

Figure 98. Micro Hardness Traverse of Weld, Stress Relieved at 1,150°F for 1.5 hr (D6AC Steel)

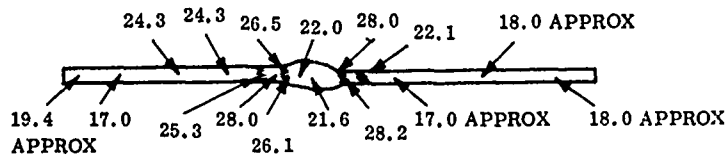
ROCKWELL "C" HARDNESS



TEMP = 1,250°F
TIME = 1.5 HR
DEPTH OF DECARB = 0.0027 IN.

Figure 99. Micro Hardness Traverse of Weld, Stress Relieved at 1,250°F for 1.5 hr (D6AC Steel)

ROCKWELL "C" HARDNESS



TEMP = 1,350°F
TIME = 2.0 HR
DEPTH OF DECARB = 0.0042 IN.

Figure 100. Micro Hardness Traverse of Weld, Stress Relieved at 1,350°F for 2.0 hr (D6AC Steel)

1. PRESSURE TO DEFORM CONE

From membrane theory of shells, applicable to thin wall pressure vessels, the maximum stress in the wall of a truncated cone is given by the expression:

$$\sigma_S = \frac{(P)(S) \cot \theta}{2t} \quad (7)$$

where:

- σ_S = hoop stress, psi
- θ = reference angle, deg
- t = shell thickness, in.
- S = distance from apex to base of cone measured on the edge, in.
- P = pressure, psi

(Figure 101 is a schematic of a preform showing these terms.)

The dynamic strength can be assumed to be approximately twice the static yield strength of the material.* Therefore, to determine the pressure at which the cone wall will yield:

$$P = \frac{4 t \sigma_S}{(S) \cot \theta} \quad (8)$$

2. FORCE ON CLAMP RING TO REACT LOAD

A free body diagram of the forces on the ring is shown in Figure 102 where the vertical component of the pressure force is:

$$F_{PV} = P a = P \pi (R_o^2 - R_i^2) \quad (9)$$

where:

- F_{PV} = vertical component of pressure
- P = pressure at yield from Equation (8)
- a = projected area of cone
- R_o = outside radius of cone
- R_i = radius of frustrum of cone

The tension force in the shell is:

$$T = F_{PV} \sin \theta = 2N \mu \quad (10)$$
$$N = \frac{F_{PV} \sin \theta}{2 \mu}$$

*See Reference 2.

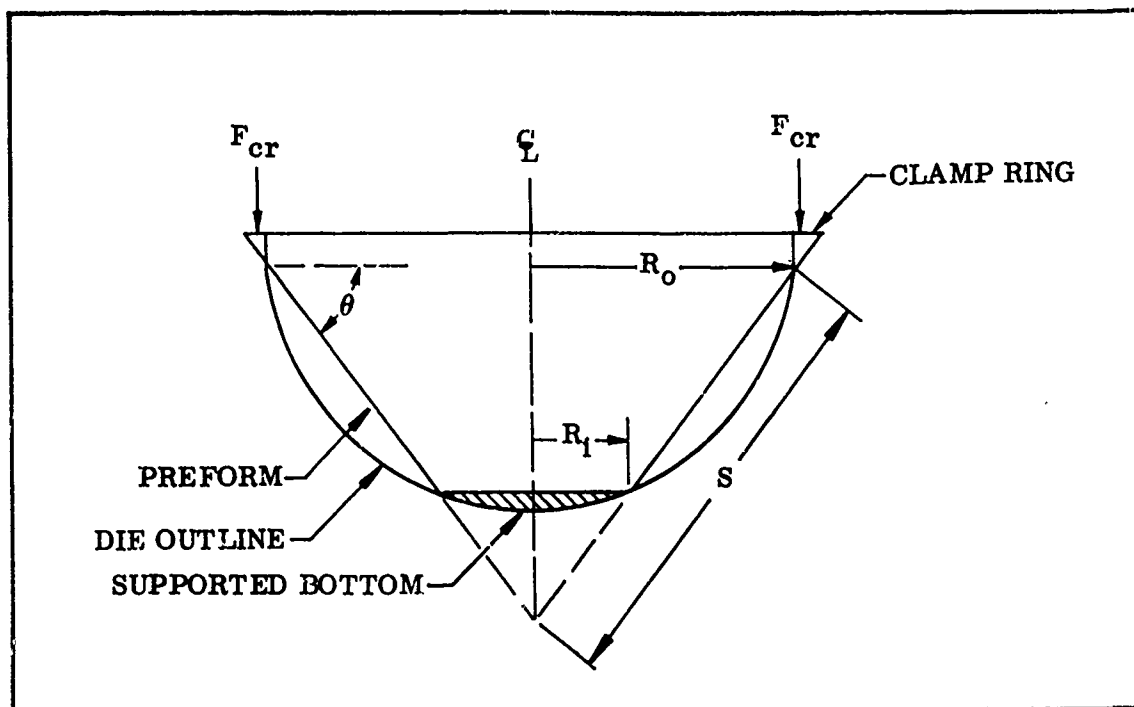


Figure 101. Explanation of Parameters Used in Holding Force Analysis

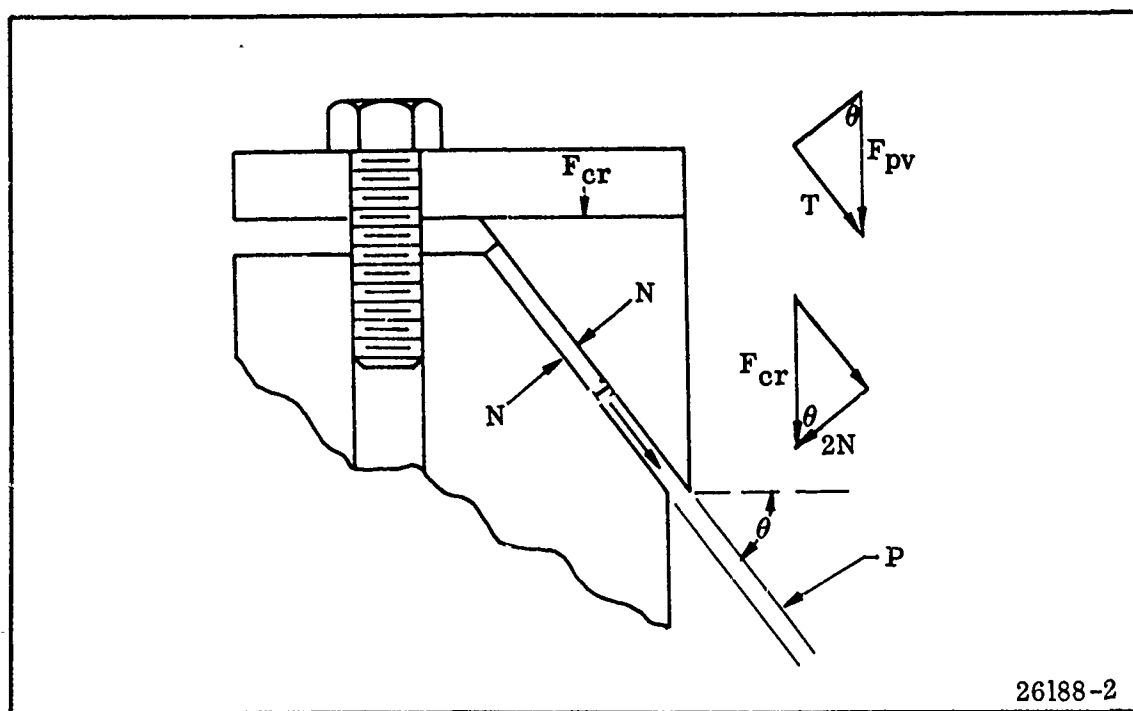


Figure 102. Cross Sectional View of Clamping Ring with Assumed Force Vectors

The clamping ring force is defined as:

$$F_{cr} = \frac{N}{\cos \theta} \quad (11)$$

Now combining Equations (5) and (6):

$$F_{cr} = \frac{F_{PV} \sin \theta}{2 \mu \cos \theta} = \frac{F_{PV} \tan \theta}{2 \mu}$$

where:

T = tension force in shell, lb

N = force normal to shell wall exerted by clamp ring, lb

μ = coefficient of friction for steel on steel

F_{cr} = clamp ring force, lb

3. LOAD PER BOLT AND CONVERSION TO TORQUE

The clamp ring contains 15 bolts, 3/4 in. diameter, 10 UNC; therefore, the load per bolt is:

$$L/b = \frac{F_{cr}}{15} \quad (12)$$

Then the bolt torque is:

$$M = \frac{\mu D L/b}{12} \quad (13)$$

where:

L/b = load per bolt, lb

M = bolt torque, ft-lb

D = nominal diameter of bolt, in.

μ = coefficient of friction (bolt to thread)

The results of these calculations for the three types of preform materials: D6AC, HP9-4, and Cor-ten steel are:

<u>Material</u>	<u>Yield Strength (psi)</u>	<u>Thickness (in.)</u>	<u>Yield Pressure (psi)</u>	<u>Bolt Torque Clamp Rings (ft-lb)</u>
D6AC	105,000	0.054	750	280
HP9-4	160,000	0.054	1,120	410
Cor-ten	55,000	0.047	340	124

D. COR-TEN PREFORM SUBPROGRAM

In order to substantiate the fact that the proper clamping force would prevent buckling and to verify the results of the holding force calculations the decision was made to fabricate and form additional preforms. The material selected was 0.047 in. thick Cor-ten steel. This material had a lower yield and tensile strength than the HP9-4 and the D6AC materials. Buckling characteristics, however, should be very similar to those of the HP9-4 D6AC preforms since the modulus of elasticity remains constant. Dimensional and weld quality were of minor importance since the primary purpose of these verification experiments was to determine the effect of increased restraint on the preform.

The first preform was formed using a bolt torque of 250 ft-lb. This torque was much higher than the calculations indicated would be required, but the purpose of this test was to completely restrain the blank in an attempt to eliminate the buckle. The Cerro plug was used as in the D6AC Configuration 4A test. The only other change was a reduced charge weight made to compensate for the lower yield of the preform material. A Primacord ring charge was used with four lead-in "spokes" to detonate the charge. The charge size was designed for a three-shot sequence in order to duplicate the extent of forming on the previously buckled D6AC Configuration 4A part. The part was formed in three shots. No buckling or tendency to buckle was evident.

The second of these experiments using Cor-ten steel was set up identically to the first with the exception of an increase in load in the Primacord ring charge to demonstrate blank stability in a more severe forming operation. This charge was of the same strength and standoff as the load used on the D6AC Configuration 4A preform that buckled. No indication of buckling was present except in a local area adjacent to the longitudinal weld which failed. Figure 103 shows the localized buckle caused by instability due to the weld failure rather than due to insufficient restraint.

The third experimental preform was shot with identical hold down torque as the D6AC Configuration 4A preform that buckled. The bolt torque was 90 ft-lb, and the explosion charge was a Primacord ring. The same type of buckle appeared as in the D6AC Configuration 4A preform. The only area that did not buckle was across the longitudinal weld where a double thickness of metal was used to reinforce the weld area. Figures 104 and 105 illustrate the results of this experiment.

The fourth Cor-ten preform was used to further verify the accuracy of the bolt torque calculation. The explosive load was identical to that in the second experiment above. The bolt torque was reduced to 150 ft-lb which was 25 ft-lb above the required torque as calculated. The forming was completed without buckling. Figure 106 shows the formed part.

It was apparent that buckling on the D6AC Configuration 4A preform was, indeed, the result of insufficient restraint and that correction of the problem could be effected by increasing the bolt load to the clamping ring. The results of the above four experiments indicated that the method of calculating required torque was valid. The minimum amount of force required for a given material was not pinpointed, but parts were formed slightly above and below the calculated values with results as predicted.

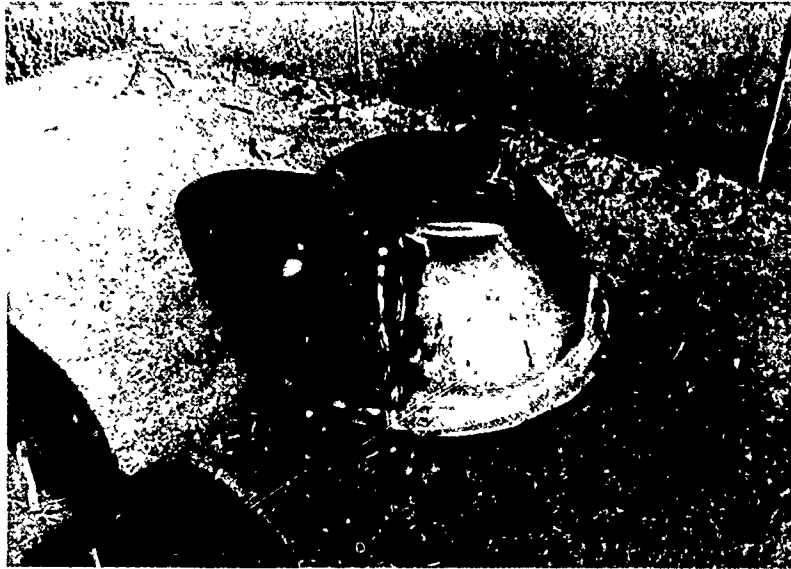


Figure 103. Cor-ten Steel Preform Formed with 250 ft-lb Torque
(Buckled Areas Caused by Weld Failure)

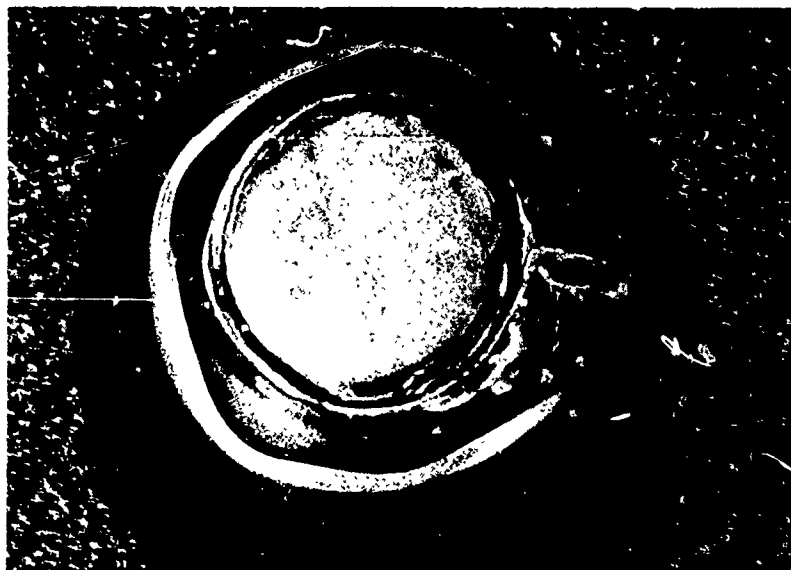


Figure 104. Cor-ten Preform Buckled Due to Insufficient Preform Stabilization



Figure 105. Cor-ten Steel Preform Formed with Identical Charge and Restraint as the D6AC Preform 4A (Buckling Occurred in Same Area as on 4A)

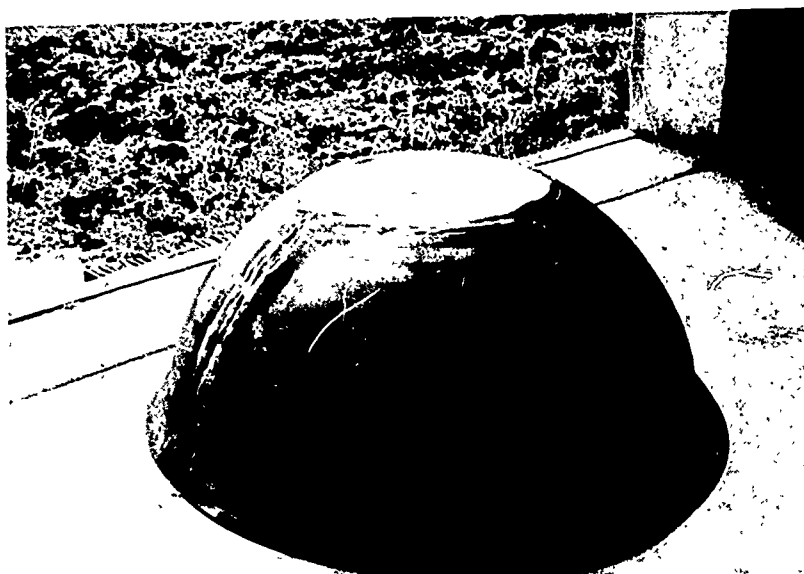


Figure 106. Cor-ten Part Formed by 150 ft-lb Torque with Primacord Ring Charge

E. FORMING OF HP9-4 CONFIGURATION 3A PREFORM

After initial tests of Configuration A preforms had indicated the vulnerability of the circumferential weld when placed right on the knuckle, Preform 3A was recalled from EFD and shelved. This decision was also influenced by the fact that the preform was annealed HP9-4 instead of hardened HP9-4 as initially planned for the program.

At this point in the program, the Cor-ten experiments had strongly indicated that a solution to the buckling problem had been found. The yield strength of the Cor-ten material was, however, much lower than the D6AC (55,000 vs 105,000 psi). It was noted that the yield strength of the annealed HP9-4 Preform 3A was very close to that of D6AC and, therefore, a successful (unbuckled) shot of this preform would provide conclusive evidence that the buckling problem had been eliminated for D6AC preforms.

A metal plug was employed as shown in Figure 107 and a 100 grain/ft Primacord ring charge was used (Figure 108). The part was formed without buckling or failure in the longitudinal weld. Figure 109 shows the formed HP9-4 Configuration 3A part. This preform was not of the improved geometry, and it was expected that problems would occur in the circumferential weld area. After two 20 gram shots, it was noted that the Cerro plug had been crushed under the circumferential weld, and consequently the weld was bent quite badly but had not failed. The Cerro plug was removed and a light (10 gram) charge was used in an attempt to form the polar plate. After this shot, circumferential weld failure was observed as shown in Figure 110. The failure was plugged with sealant in order to pull a vacuum, and an additional 20 gram shot made, which almost completely formed the dome (Figure 109). In future operations, an aluminum plug will be used instead of Cerro in order to preclude failure of the plug.

F. EXPLOSIVE SELECTION FOR FORMING OF HIGH STRENGTH STEELS

There was considerable controversy over the effects of high detonation velocity explosives on the formability of high strength steels. In initial experiments using predeveloped preforms to produce hemispherical solid rocket motor end closures, centrally placed charges of granulated TNT were used. It was difficult to assess the influence of the lower velocity explosive (when compared to PETN in powder or cord form) since preform failures attributable to welding practice or design occurred. The detonation velocity and pressure for the two explosives are shown below:

	Detonation Velocity *	Detonation Pressure *
	(ft/sec)	(psi)
PETN	27,200	3.30×10^6
TNT	22,600	2.25×10^6

*See Reference 3.

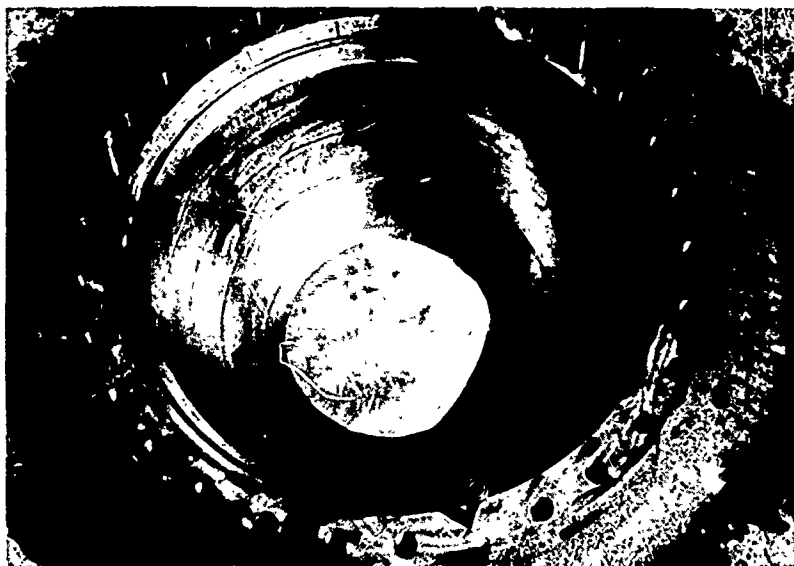


Figure 107. Forming Die with Apex Plug in Position

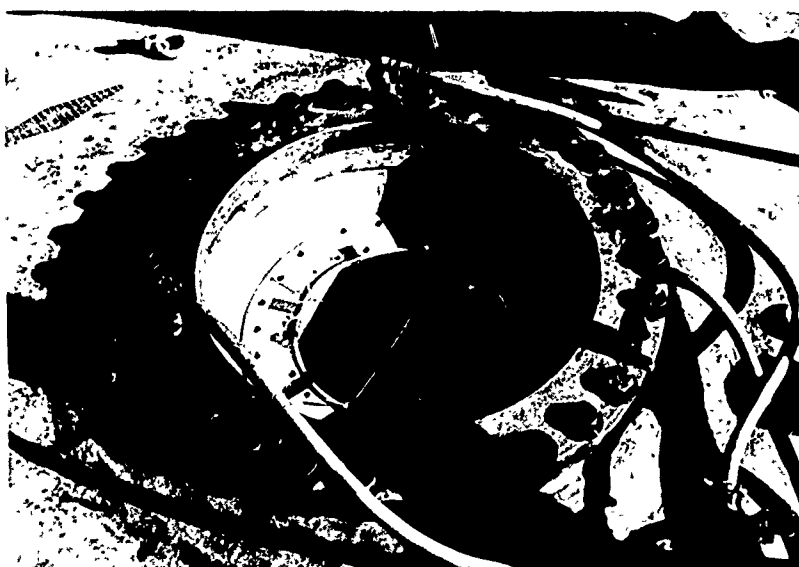


Figure 108. HP9-4 Annealed Preform with 100 Grain/ft Ring Charge
Placed in Subscale Forming Die

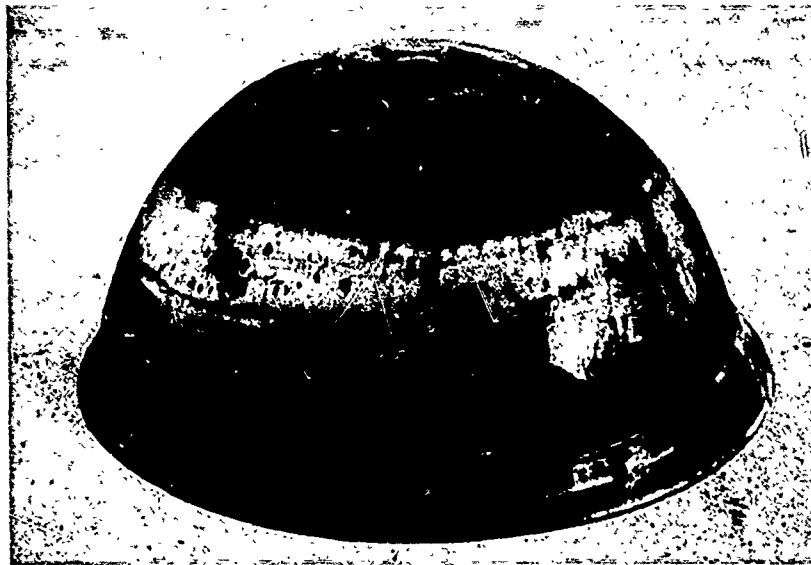


Figure 109. HP9-4 Annealed Preform Formed to Contour by Primacord Ring Charges

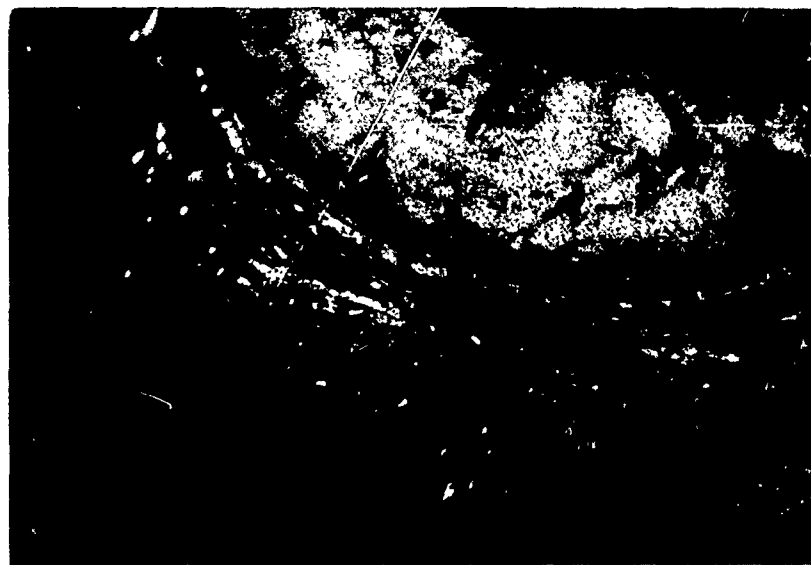


Figure 110. Circumferential Weld Failure on HP9-4 Annealed Preform

Reports from the literature are varied with respect to results obtained using high detonation velocity explosives for high strength steel fabrication. Johnson (see Reference 4) used Composition C-3 explosive, which is based on RDX, to form 4340 alloy steel. He found that "although 4340 steel has lower absolute ductility dynamically than does softer material at any strain rate, the steel exhibits much greater ductility at high strain rates than material in the same hardness condition at low strain rates." Thus, deeper draws were possible by the use of rapid forming rates such as obtained using C-3 explosive. Wood reported (see Reference 5) that the optimum velocity range for forming high strength alloys varied from about 550 ft/sec to 800 ft/sec (except for titanium alloys which were lower). These are forming speeds normally associated with high detonation velocity explosives. In fact, a number of tables are presented for explosive loadings, standoff, and draw-depth which are based on RDX explosives. Douglass (see Reference 6) conducted deep drawing experiments on 0.090 in. thick Vascojet 1000 (5 percent Cr hot work die steel) and obtained good results using stacked discs of EL 506 sheet explosive. Eight ft diameter mild steel heads were also made using EL 506 sheet explosive arranged in a ring form. There have been related results where high detonation velocity explosives were used successfully to form mild steel, stainless steel, and aluminum (see References 7, 8, and 9). However, since these results were obtained with materials of much lower yield strength than D6AC or HP9-4-25, they are only shown here for reference. Probably the most pertinent work that was conducted on high strength alloys was by Hofstatter, et al (see Reference 10). Using Primacord and fully heat treated HP9-4-25, ellipsoidal heads (2:1) were successfully formed from both 0.100 in. and 0.210 in. thick stock. Parts 28 in. and 40 in. in diameter were produced this way. Optimized sequences involved (1) two shots, stress relief at 1,000° F for 2 hours and four additional shots, and (2) three shots, stress relief at 1,000° F for 2 hours, four shots, stress relief for 2 hours at 1,000° F, one shot, stress relief and a final sizing shot, respectively.

Data available from Nemitz and Van Wely (see References 11 and 12) show the value of low brisance and low detonation velocity explosives for deep drawing high strength steels. Elliptical and hemispherical heads were made from N-A-XTRA steel using Carbonit explosive (density 0.036 lb/cu in., velocity 5,000 ft/sec). It was reported that greater draw depth was achieved with less total apex strain than for high velocity explosives. It is known also that the Germans successfully formed heavy armor in the fully heat treated condition over a male die using low detonation velocity explosives in direct contact with the steel.

Based on the review of two dozen separate papers and reports, there does not appear to be any data directly applicable to the formation of parts from pre-developed preforms using high detonation velocity explosives. There are reports of using Primacord or other high velocity explosives for the sizing of high strength parts where very limited deformation is obtained. Thus, the only concrete evidence upon which to base a decision as to the explosive type to use for preform deformation is the data applied to deep drawing. Although many of the available documents present favorable data when high detonation velocity explosives are used, there have been unfavorable results for deep drawing 18 percent nickel maraging steel and high

strength titanium alloys (see References 13 and 14). In addition, much of the work in Europe appears to favor the use of low detonation velocity materials for forming.

Since it is known that there are no adverse effects of low detonation velocity explosives on high strength steels, and since there have been reported cases where high detonation velocity explosives are undesirable, it appears wise to redirect selection of explosive to those that have detonation velocities below 20,000 ft/sec. The availability of such explosives is good, and a number of possible choices is presented in Table XI. It is suggested that detonation experiments be conducted on any of the listed explosives selected to assure stable and consistent detonation when contained in small diameter tubing.

Analyses of results obtained to date on conical preforms dictates the use of a ring charge to minimize charge required and to increase efficiency of energy transfer to the preform. Thus, any of the low detonation velocity explosives selected would have to be packaged in expendable tubes. The tube diameter and detonation means must be such that consistent and complete detonation occurs every time. The above suggested experiments will verify detonation behavior.

G. STRAIN REQUIREMENT ANALYSIS

Prior to the unsuccessful forming attempt on Preform 5B, it was decided that further analytical study was required concerning the state of strain which exists in the preform during forming with the large diameter completely restrained.

Thiokol funds were allocated to perform a finite element (plastic; $\nu = 0.5$) analysis on the preform to determine what maximum principal strains were required for full forming of the preform.

The following results were obtained:

$$\begin{array}{lcl} \epsilon_{\theta} & = & 14.06\% \text{ (circumferential strain)} \\ \epsilon_{\text{Min}} & = & 27.78\% \\ \epsilon_{\text{Max}} & = & 13.85\% \end{array} \left. \vphantom{\begin{array}{l} \epsilon_{\theta} \\ \epsilon_{\text{Min}} \\ \epsilon_{\text{Max}} \end{array}} \right\} \text{strain in R-Z plane}$$

One of the more popular failure theories that presently exists is the TRESCA theory. This theory provides a means of predicting success or failure based on the results of uniaxial test coupons. The strain version of the theory states that when three orthogonal strains are measured during uniaxial testing, that

$$\frac{\epsilon_{\text{Max}} - \epsilon_{\text{Min}}}{2} = \text{constant}$$

This constant can then be used to predict success or failure of a future process with the same material.

TABLE XI

PROPERTIES OF AVAILABLE EXPLOSIVES WITH DETONATION
VELOCITIES BELOW 20,000 FT/SEC

<u>Explosive</u>	<u>Specific Gravity (gm/cc)</u>	<u>Detonation Velocity (ft/sec)</u>	<u>Detonation Pressure (psi)</u>
60% Extra Gelatin	1.4	17,000	1.2×10^6
40% Dynamite	1.4	15,500	0.97×10^6
60% Dynamite	1.3	12,500	0.62×10^6
40% Extra Dynamite	--	10,400	0.5×10^6
70% Gelex Dynamite	1.3	18,400	--
Trojamite A	1.1	10,600	--
Trojamite B	0.95	10,100	--
Trojamite C	0.84	9,600	--
Aerex L-1	1.12	20,500*	--

*Slightly exceeds 20,000 ft/sec maximum desired.

About 15 percent strain has been observed typically in the welded specimens which have been annealed. If fully plastic behavior is assumed, then the transverse strains will be $-(0.5 \times 15)$ or -7.5 percent applying TRESCA.

$$\frac{15 - (-7.5)}{2} = 11.25$$

Referring to the predicted strains from the computer analysis, it can be seen that the strain capability requirements are:

$$\frac{14.06 - (-27.78)}{2} = 20.92$$

since $20.92 \gg 11.25$ failure would be predicted.

This theory proves to be consistent when applied to the Cor-ten experiments and also the flat blank programs performed by other investigators prior to this program.

The indication is that the D6AC material does not have the strain capability required by the fully clamped process. Earlier success (1A) indicates that if the preforms are allowed to slip in the die, success would be predicted.

This study can be extended to predict that for a material to be able to form while fully restrained, it must have about 30 percent elongation in the uniaxial tensile test.

H. METALLURGICAL STUDIES

1. PREFORM FABRICATION (MATERIAL ANALYSIS)

Tensile tests were conducted on specimens from the D6AC and HP9-4 steels. The HP9-4 specimens were tested in both the annealed and heat treated condition. In addition, weld specimens from annealed D6AC steel have also been tested. All tensile tests were conducted on an Instron tensile machine at room temperature and 0.5 in./min crosshead speed. The averaged tensile data are given in Table XII.

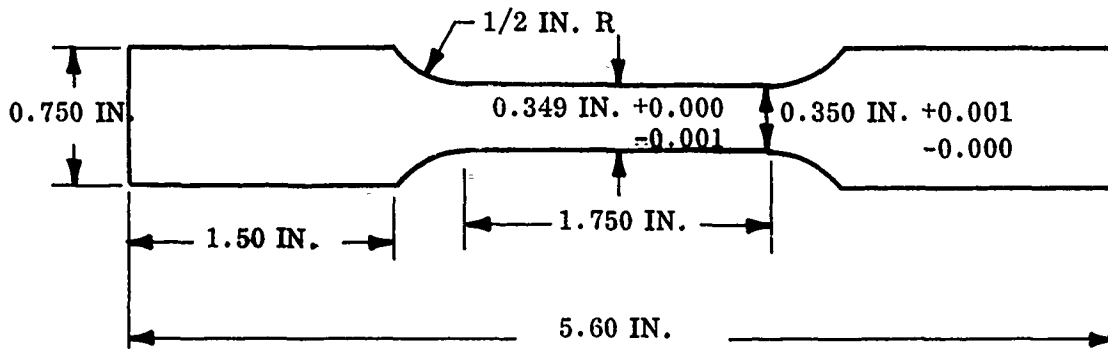
Tensile specimens were sectioned parallel (R.D.) and transverse (T.D.) to the final rolling direction of the sheet stock. Since all the plates had been cross rolled, only minor variations in the annealed and heat treated properties were expected. This is essentially true for all but the yield strength values for the heat treated HP9-4-25 steel. The reason for this larger variation is not known.

The HP9-4-25 steel specimens were heat treated according to AMS Specification 6546A; the tensile values for the heat treated HP9-4-25 steel were above the specified minimum values.

TABLE XII

TENSILE PROPERTIES OF ANNEALED AND HEAT TREATED
D6AC AND HP9-4-25 STEELS

<u>Material</u>	<u>Strength (psi)</u>		<u>Elongation (%)</u>	
	<u>0.2% Offset</u>	<u>Tensile</u>	<u>Uniform</u>	<u>Total</u>
D6AC Steel				
Annealed				
T.D.*	90,351	114,258	11.3	17.0
R.D.**	95,165	115,277	13.2	18.3
HP9-4-25 Steel				
Annealed				
T.D.	110,355	170,157	11.7	17.3
R.D.	105,886	170,687	10.5	14.9
HP9-4-25 Steel				
Heat Treated				
T.D.	179,030	192,002	6.9	13.8
R.D.	168,349	193,198	6.9	13.1



TENSILE SPECIMEN DIMENSIONS

*T.D. indicates transverse to final rolling direction of sheet stock.

**R.D. indicates parallel to final rolling direction of sheet stock.

2. DETERMINATION OF PROCESSING FOR PREFORM 5B

As previously stated, it was decided that the last D6AC configuration (Preform 5B) would be given some type of thermal treatment prior to the forming attempt. Two particular treatments were considered; a full anneal or a renormalizing followed by a high temperature temper. The full anneal would involve holding the part sufficient length of time in the austenitizing region (near 1,550° F), furnace cooling at a prescribed rate (usually 50° F/hr) to 1,000° F, and then furnace cooling to room temperature. The parent material received from Republic Steel Corporation had been normalized, tempered for 48 to 96 hr at 1,275° F, cooled 10° F/hr to 1,000° F, and furnace cooled from there to room temperature. A similar thermal treatment was investigated. The heat treatments investigated were evaluated in terms of tensile properties, uniformity of microstructure throughout the part, hardness, and ease of handling.

Several pieces of the D6AC steel program material were welded together under similar conditions as employed for the previous D6AC steel preforms. The composition of the weld wire being used in the program is given in Table XIII. The welds were stress-relieved for 1.5 hr at 1,250° F using calrods, and the 20 in. long by 5 in. wide plates were sectioned for subsequent heat treating.

Annealing was performed in an inert atmosphere (argon) at 1,550° F for 2 hours. The part was then cooled 50° F/hr to 1,000° F, and then furnace cooled to room temperature. Other parts of the welded sheet were normalized for 2 hr at 1,725° F in an endothermic atmosphere and air cooled. The dew point of the atmosphere was controlled at $24^{\circ} \pm 2^{\circ}$ F. The parts were then heated to 1,275° F for 48 hr, cooled to 1,175° F at 10° F/hr, and finally furnace cooled to room temperature. Metallographic specimens were sectioned and tensile specimens machined from the heat treated plates. The tensile specimens were tested at room temperature at a strain rate of about 0.03 in./in./minute. Strains were measured with an optical extensometer as well as by a photographic technique.

The microstructures of the annealed and the normalized and tempered parts are shown in Figures 111 and 112, respectively, together with associated hardness values. The left margin on both figures is the centerline of the weld.

The inert atmosphere employed for the full anneal was not adequate as evidenced by the large amount of decarburization shown in Figure 111. However, the weld and parent material microstructures are clearly evident. With the exception of a small difference in grain size, the microstructure is fairly uniform throughout the weld and parent materials. The average ASTM grain sizes of the weld and parent materials are estimated at 7 to 8 (0.032 to 0.022 mm grain diameter) and 8 to 9 (0.022 to 0.016 mm grain diameter) respectively.

The microstructure after normalizing and tempering is also quite uniform throughout the part. As can be seen in Figure 112, it is practically impossible to evaluate the grain size. However, it does appear that the overall grain size of this part is smaller than that observed after the full anneal.

TABLE XIII
CHEMICAL COMPOSITION OF THE WELD WIRE EMPLOYED

<u>Element</u>	<u>Percent by Weight</u>
Chromium	2.50
Molybdenum	0.95
Carbon	0.08 to 0.14
Manganese	0.40 to 0.70
Silicon	0.30 to 0.55
Phosphorus	0.02 (maximum)
Sulfur	0.025 (maximum)

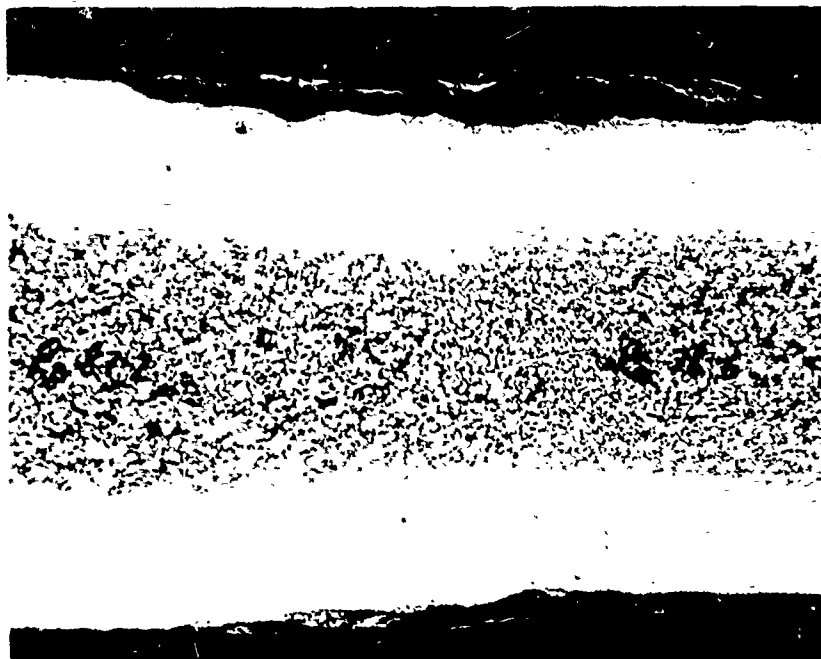


Figure 111. Photomicrograph of the Weld and Parent Material After the Full Anneal (50 x)

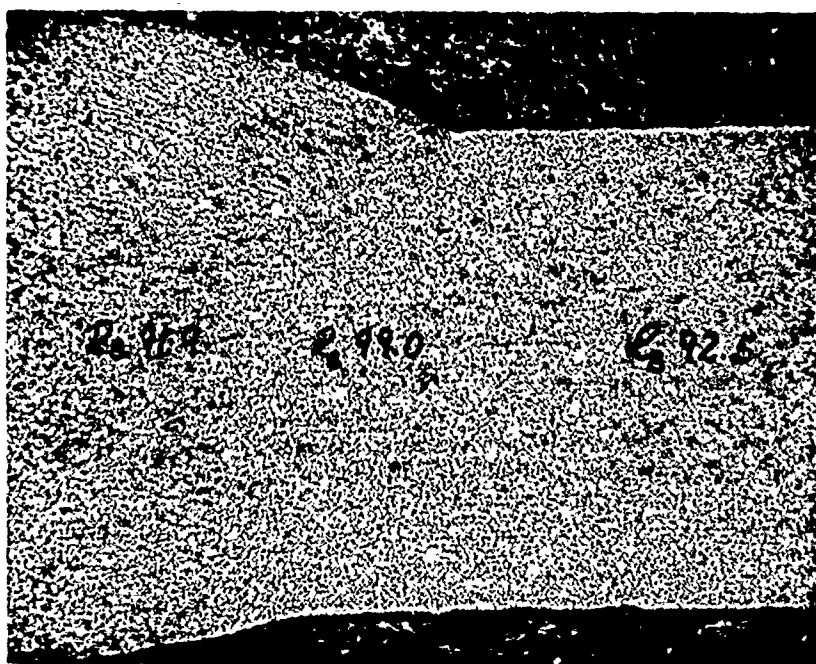


Figure 112. Photomicrograph of the Weld and Parent Material After Normalizing and Tempering (50 x)

The tensile properties of the weld before and after the thermal treatments are shown in Table XIV. The treatments resulted in a decrease in strength and an associated increase in ductility. The data for C-6 (full anneal) is not entirely indicative of the material condition since only about 0.010 in. of the decarburized material was removed from the specimen thickness. It is expected that the yield strength would be higher and the tensile strength slightly lower if the specimen were not decarburized. No change in elongation would be expected. Although the elongation values for the C-6 condition are slightly less than for the C-4 condition (normalized and tempered), it is felt that the average properties of the weld brought about by either condition would be quite similar. Considering this together with the heat treating times (17 hr for the full anneal vs greater than 85 hr for the normalizing and tempering) it would appear that the full anneal would suit the requirements previously described for the last Configuration B preform.

It should be noted that the two general thermal treatments considered in this investigation (the anneal, and the normalize and temper) were modified when applied to actual Preforms 5B and 1B(R), respectively. This was done due to additional information obtained subsequent to this weld coupon study and prior to the preform processing. The exact thermal treatments used for Preforms 5B and 1B(R) are detailed in Section VII, subsections M and P, respectively.

Welded tensile specimens from annealed and heat treated D6AC steel have been tested under identical conditions as the base metal specimens. These data are shown in Table XV. The yield strength values for several of the specimens are not available due to poor strain measurement. All the specimens having the weld joint transverse to the tensile axis ruptured in parent material and thus exhibited lower strengths but higher elongations.

Tensile properties data are presented in Table XVI for annealed specimens from both the D6AC and HP9-4-25 steel igniter boss material. The data appear to be typical of each material.

The toughness data for annealed and heat treated D6AC and HP9-4-25 steels are given in Table XVII.

Plastic work (toughness) represents the amount of energy a material can absorb before failing and comprises both the strength and ductility of a material. From Table XVII, it is obvious that the steels have greater toughness in the annealed than in the heat treated condition, and that the HP9-4-25 steel has greater toughness than the D6AC steel.

TABLE XIV
ROOM TEMPERATURE TENSILE PROPERTIES
OF WELDED D6AC STEEL

<u>Condition</u>	<u>Strength (psi)</u>		<u>Elongation (%)</u>	
	<u>0.2 % Yield Strength</u>	<u>Ultimate Tensile Strength</u>	<u>Uniform</u>	<u>Total</u>
C-1*	98,162	122,525	6.6	8.9
C-4	63,524	76,844	9.1	18.7
C-6	53,246	85,389	7.7	10.0** 14.0

CONDITIONS:

C-1 - Welded + 1.5 hr at 1,250°F (stress relief).

C-4 - C-1 + 1,725°F for 2 hr, air cooled + 48 hr at 1,275°F, cool 10°F/hr to 1,175°F then furnace cool to room temperature (renormalizing process).

C-6 - C-1 + 2 hr at 1,550°F, cool 50°F/hr to 1,000°F then furnace cool to room temperature (full anneal).

*Average of six tests.

**Actual strain was registered at 10 percent; however, some necking (reduction of area) occurred outside control benchmarks. A conservative estimation indicates that at least 14 percent total elongation may be expected in the C-6 condition.

TABLE XV

TENSILE PROPERTIES OF ANNEALED D6AC STEEL
WELDED SPECIMENS IN THE C-1 CONDITION*

<u>Specimen**</u>	<u>Strength (psi)</u>		<u>Elongation (%)</u>	
	<u>0.2% Yield Strength</u>	<u>Ultimate Tensile Strength</u>	<u>Uniform</u>	<u>Total</u>
DWA-1	--	126,682	5.6	10.5
DWA-2	--	98,963	11.5	15.0
DWA-3	102,325	122,558	5.6	10.0
DWA-4	78,865	100,000	19.8	13.6
DWA-5	108,144	118,325	4.7	5.4
DWA-6	79,894	101,322	8.4	16.6
DWA-7	103,097	119,247	4.5	9.3
DWA-8	--	99,479	10.7	14.4
DWA-9	111,848	127,725	4.5	9.5
DWA-10	--	100,000	8.2	11.7
DWA-11	108,771	120,614	5.8	7.5
DWA-12	77,720	98,963	7.1	10.3

*C-1 condition: welded + 1.5 hr at 1,250°F (stress relief).

**Odd numbered specimens are with the weld parallel to the tensile axis.

Even numbered specimens are with the weld transverse to the tensile axis.

TABLE XVI
TENSILE PROPERTIES OF ANNEALED D6AC AND
HP9-4-25 IGNITER BOSS MATERIALS

<u>Material</u>	<u>Strength (psi)</u>		<u>Elongation (%)</u>	
	<u>0.2% Yield Strength</u>	<u>Ultimate Tensile Strength</u>	<u>Uniform</u>	<u>Total</u>
D6AC	103,346	139,844	9.2	16.4
HP9-4-25	94,359	142,564	10.6	17.8

TABLE XVII
PLASTIC WORK (TOUGHNESS) OF ANNEALED AND
HEAT TREATED D6AC AND HP9-4-25 STEELS

<u>Material</u>	<u>Plastic Work (Ft - lb)</u>
D6AC	
Annealed	23.53
Heat Treated	17.34
HP9-4-25	
Annealed	34.76
Heat Treated	29.74

SECTION IX

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APPENDIX I



Society of Automotive Engineers, Inc.
TWO PENNSYLVANIA PLAZA, NEW YORK, N.Y. 1000

AEROSPACE MATERIAL SPECIFICATION

AMS 6438A

Superseding AMS 6438

Issued 6-30-64
Revised 11-1-68

STEEL SHEET, STRIP, AND PLATE
1.05Cr - 0.55Ni - 1.0Mo - 0.11V (0.45 - 0.50C)
Premium Quality, Consumable Electrode Melted

1. **ACKNOWLEDGMENT:** A vendor shall mention this specification number and its revision letter in all quotations and when acknowledging purchase orders.
2. **APPLICATION:** Primarily for ultra-high strength structural applications requiring a through hardening weldable material for use at temperatures up to 600 F (316 C).
3. **COMPOSITION:**

	min	max
Carbon	0.45	0.50
Manganese	0.60	0.90
Silicon	0.15	0.30
Phosphorus	--	0.015
Sulfur	--	0.015
Chromium	0.90	1.20
Nickel	0.40	0.70
Molybdenum	0.90	1.10
Vanadium	0.08	0.15
Copper	--	0.35
- 3.1 **Check Analysis** Composition variations shall meet the requirements of the latest issue of AMS 2259, paragraph titled "Low Alloy Steels" except that the variations for carbon and vanadium shall apply to "over max" only.
4. **CONDITION:** Unless otherwise ordered, the product shall be supplied in the following condition:
 - 4.1 **Sheet and Strip:** Cold finished, bright or atmosphere annealed, and pickled if necessary, or hot rolled, annealed, and pickled; having hardness not higher than Rockwell C 30 or equivalent.
 - 4.2 **Plate:** Hot rolled, annealed, and pickled having hardness not higher than Rockwell C 30 or equivalent.
 - 4.3 When normalized and tempered material is specified, hardness shall be not higher than Rockwell C 30 or equivalent.
5. **TECHNICAL REQUIREMENTS:** When ASTM methods are specified for determining conformance to the following requirements, tests shall be conducted in accordance with the issue of the ASTM methods listed in the latest issue of AMS 2350.
 - 5.1 **Decarburization:**
 - 5.1.1 **Material Under 0.045 In. in Thickness:** The method of test and the allowance shall be as agreed upon by purchaser and vendor.

SAE is not responsible for the accuracy of the information contained herein. The user of this specification is advised that the information is for reference only and should not be used as a basis for design or construction. The user is responsible for the proper use of this specification and for the results of its use. The user is also responsible for the proper use of the information contained herein for the protection of patents.

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5.1.2 Material 0.045 In. and Over in Thickness:

- 5.1.2.1 Specimens Shall be the full thickness of the material except that specimens from plate over 0.250 in. thick shall be slices approximately 0.250 in. thick cut parallel to and preserving one original surface of the plate. Recommended specimen size is 1 x 4 inches.
- 5.1.2.2 Procedure Specimens shall be hardened by austenitizing and quenching; preferably they shall not be tempered but, if tempered, the tempering temperature shall be not higher than 300 F (149 C). During heat treatment, specimens shall be protected by suitable atmosphere or medium or by suitable plating to prevent carburization or further decarburization. Protective plating, if used, shall then be removed from specimens of material 0.045 to 0.250 in., excl, in thickness and a portion of the specimen shall be step ground to a depth of 0.050 in. or half thickness, whichever is less. Specimens from material 0.250 in. and over in thickness shall be ground to remove from the original surface of the plate the amount of metal shown below and a portion of the specimen shall be further ground to a depth of at least 1/3 the original thickness of the specimen. At least three Rockwell hardness readings shall be taken on each prepared step and each group of readings averaged.

Nominal Original Thickness Inches	Surface Depth Removal Inch
0.250 to 0.375, incl	0.020
Over 0.375 to 0.500, incl	0.025
Over 0.500 to 0.750, incl	0.030
Over 0.750 to 1.000, incl	0.035
Over 1.000 to 2.000, incl	0.040

5.1.2.3 Allowance:

- 5.1.2.3.1 Material 0.015 to 0.250 In., Excl. Thick. Unless otherwise specified, the product shall be free from complete decarburization. It shall also be free from partial decarburization to the extent that the difference in hardness between the surface and the nondecarburized depth below the surface shall be not greater than 2 points on the Rockwell A scale.
- 5.1.2.3.2 Material 0.250 In. and Over Thick: The difference in hardness between the two prepared steps shall be not greater than 2 points on the Rockwell C scale.

5.2 Grain Size Predominantly 5 or finer with occasional grains as large as 3 permissible, ASTM E112, McQuaid-Ehn Test.

- 5.3 Properties After Heat Treatment Test specimens, austenitized by heating in a protective atmosphere to a temperature within the range of 1600 - 1650 F (871.1 - 898.9 C), held at the selected temperature within ± 10 F (± 5.6 C) for 1 hr, quenched in oil, stress relieved at 400 F ± 10 (204.4 C ± 5.6) for 1 hr, cooled in air, tempered for 4 hr at not lower than 1000 F (538 C), and cooled in air, shall conform to the following requirements:

5.3.1 Tensile Properties:

Tensile Strength, psi	224,000 min
Yield Strength at 0.2% Offset or at 0.0172 in. in 2 in. Extension Under Load (E = 29,500,000), psi	195,000 min
Elongation, % in 2 in. or 4D	7 min

- 5.3.1.1 For widths 9 in. and over, tensile test specimens shall be taken with the axis perpendicular to the direction of rolling. For widths less than 9 in., tensile test specimens shall be taken with the axis parallel to the direction of rolling.

- 5.3.2 Hardness: Not lower than Rockwell C 47 or equivalent.

6. **QUALITY:** Steel shall be premium quality and shall conform to the requirements of the latest issue of AMS 2300; it shall be multiple melted using vacuum consumable electrode process in the remelt cycle, unless otherwise permitted. The product shall be uniform in quality and condition, clean, sound, and free from foreign materials and from internal and external imperfections detrimental to fabrication or to performance of parts.
7. **TOLERANCES:** Unless otherwise specified, tolerances shall conform to all applicable requirements of the latest issue of AMS 2252; for strip, tolerances for cold finished shall apply.
8. **REPORTS:**
- 8.1 Unless otherwise specified, the vendor of the product shall furnish with each shipment three copies of a report of the results of tests for chemical composition, grain size, and AMS 2300 frequency-severity rating of each heat in the shipment and the results of tests on each thickness from each heat to determine conformance to the tensile property and hardness requirements after heat treatment. A heat shall be the consumable electrode remelted ingots produced from steel originally melted in a single furnace charge. When permitted by purchaser, a heat may be the consumable remelted product of individual melts of similar composition produced from the same lots of controlled raw material and having the same average composition as agreed upon by purchaser and vendor. This report shall include the purchase order number, heat number, material specification number and its revision letter, thickness size, and quantity from each heat.
- 8.2 Unless otherwise specified, the vendor of finished or semi-finished parts shall furnish with each shipment three copies of a report showing the purchase order number, material specification number and its revision letter, contractor or other direct supplier of material, part number, and quantity. When material for making parts is produced or purchased by the parts vendor, that vendor shall inspect each lot of material to determine conformance to the requirements of this specification, and shall include in the report a statement that the material conforms, or shall include copies of laboratory reports showing the results of tests to determine conformance.
9. **IDENTIFICATION:** Unless otherwise specified, each sheet, strip, and plate shall be marked as in 9.1 unless purchaser permits a method from 9.2.
- 9.1 Each sheet, strip, and plate shall be marked on one face, in the respective location indicated below, with AMS 6438A, heat number, manufacturer's identification, and nominal thickness in inches. The characters shall be of such size as to be clearly legible, shall be applied using a suitable marking fluid, and shall be capable of being removed in hot alkaline cleaning solution without rubbing. The markings shall have no deleterious effect on the material or its performance and shall be sufficiently stable to withstand normal handling. The specification number, manufacturer's identification, and nominal thickness shall be continuously line marked; the heat number may be included in the line marking or may be marked at one location on each piece.
- 9.1.1 **Flat Strip 6 In. and Under in Width:** Shall be marked in one or more lengthwise rows of characters recurring at intervals not greater than 3 feet.
- 9.1.2 **Flat Sheet, Flat Strip Over 6 In. in Width, and Plate:** Shall be marked in lengthwise rows of characters recurring at intervals not greater than 3 ft, the rows being spaced not more than 6 in. apart and alternately staggered.
- 9.1.3 **Coiled Sheet and Coiled Strip:** Shall be marked near the outside end of the coil. The inside end of the coil also shall be marked or shall have a tag or label attached and marked with the information of 9.1 above.

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- 9.2 When purchaser permits, each sheet, strip, and plate may be marked near one end, coils being marked near the outside end, with AMS 6438A, heat number, manufacturer's identification, and nominal thickness in inches, using any suitable marking fluid. As an alternate method, individual pieces and bundles shall have attached a metal or plastic tag embossed with the above information or shall be boxed and the box marked with the same information.
- 10 PROTECTIVE TREATMENT: Unless otherwise specified, the product shall be oiled prior to shipping.
- 11 REJECTIONS: Material not conforming to this specification or to authorized modifications will be subject to rejection.

APPENDIX II

	AEROSPACE MATERIAL SPECIFICATION	AMS 6546A																																				
Society of Automotive Engineers, Inc. 485 LEXINGTON AVENUE, NEW YORK, N.Y. 10017		Superseding AMS 6516 Issued 2-15-65 Revised 5-1-68																																				
STEEL SHEET, STRIP, AND PLATE 0.48Cr - 8.0Ni - 4.0Co - 0.48Mo - 0.09V (0.24 - 0.30C) Premium Quality, Consumable Electrode Melted, Annealed																																						
1. ACKNOWLEDGMENT: A vendor shall mention this specification number and its revision letter in all quotations and when acknowledging purchase orders. 2. APPLICATION: Primarily for heat treated parts, such as pressure vessels, requiring through hardening to high strength levels, and where such parts may require welding. 3. COMPOSITION: <table style="margin-left: auto; margin-right: auto; border-collapse: collapse;"> <thead> <tr> <th style="width: 40%;"></th> <th style="width: 10%; text-align: center;">min</th> <th style="width: 10%; text-align: center;">max</th> </tr> </thead> <tbody> <tr><td>Carbon</td><td style="text-align: center;">0.24</td><td style="text-align: center;">0.30</td></tr> <tr><td>Manganese</td><td style="text-align: center;">0.10</td><td style="text-align: center;">0.35</td></tr> <tr><td>Silicon</td><td style="text-align: center;">--</td><td style="text-align: center;">0.10</td></tr> <tr><td>Phosphorus</td><td style="text-align: center;">--</td><td style="text-align: center;">0.010</td></tr> <tr><td>Sulfur</td><td style="text-align: center;">--</td><td style="text-align: center;">0.010</td></tr> <tr><td>Chromium</td><td style="text-align: center;">0.35</td><td style="text-align: center;">0.60</td></tr> <tr><td>Nickel</td><td style="text-align: center;">7.00</td><td style="text-align: center;">9.00</td></tr> <tr><td>Cobalt</td><td style="text-align: center;">3.50</td><td style="text-align: center;">4.50</td></tr> <tr><td>Molybdenum</td><td style="text-align: center;">0.35</td><td style="text-align: center;">0.60</td></tr> <tr><td>Vanadium</td><td style="text-align: center;">0.06</td><td style="text-align: center;">0.12</td></tr> <tr><td>Copper</td><td style="text-align: center;">--</td><td style="text-align: center;">0.35</td></tr> </tbody> </table> 3.1 Check Analysis: Composition variations shall meet the requirements of the latest issue of AMS 2259, paragraph titled "Low Alloy Steels"; check analysis limits for cobalt shall be 0.05 under min or over maximum. 4. CONDITION: Unless otherwise ordered, the product shall be supplied in the following condition: 4.1 Sheet and Strip: Cold finished, bright or atmosphere annealed, and pickled if necessary; or hot rolled, annealed, and pickled, having hardness not higher than Rockwell C 36 or equivalent. 4.2 Plate: Hot rolled, annealed, and pickled, having hardness not higher than Rockwell C 36 or equivalent. 4.3 When normalized and tempered material is specified, hardness shall be not higher than Rockwell C 30 or equivalent. 5. TECHNICAL REQUIREMENTS: When ASTM methods are specified for determining conformance to the following requirements, tests shall be conducted in accordance with the issue of the ASTM method listed in the latest issue of AMS 2350. 5.1 Grain Size: Predominantly 5 or finer with occasional grains as large as 3 permissible, determined, unless otherwise specified, in accordance with ASTM E112, McQuaid-Ehn test. 5.2 Decarburization: 5.2.1 Material Under 0.045 In. in Thickness: The method of test and the allowance shall be as agreed upon by purchaser and vendor.				min	max	Carbon	0.24	0.30	Manganese	0.10	0.35	Silicon	--	0.10	Phosphorus	--	0.010	Sulfur	--	0.010	Chromium	0.35	0.60	Nickel	7.00	9.00	Cobalt	3.50	4.50	Molybdenum	0.35	0.60	Vanadium	0.06	0.12	Copper	--	0.35
	min	max																																				
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Molybdenum	0.35	0.60																																				
Vanadium	0.06	0.12																																				
Copper	--	0.35																																				

SAE Technical Board rules provide that: "All technical reports, including standards approved by the Board, are advisory only. Their use by anyone engaged in industry or trade is entirely voluntary. There is no agreement to adhere to any SAE standard or specification, and no commitment to conform to or be guided by any technical report. In formulating and approving technical reports, the Board and its committees will not investigate or consider patents which may, apply to the subject matter. Prospective users of the report are responsible for protecting themselves against liability for infringement of patents."

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5.2.2 Material 0.045 In. and Over in Thickness:

5.2.2.1 Specimens: Shall be the full thickness of the material except that specimens from plate over 0.250 in. thick shall be slices approximately 0.250 in. thick cut parallel to and preserving one original surface of the plate. Recommended specimen size is 1 x 4 inches.

5.2.2.2 Procedure: Specimens shall be hardened by austenitizing and quenching; preferably, they shall not be tempered but, if tempered, the tempering temperature shall be not higher than 300 F (149 C). During heat treatment, specimens shall be protected by suitable atmosphere or medium or by suitable plating to prevent carburization or further decarburization. Protective plating, if used, shall be removed from specimens of material 0.045 to 0.250 in., excl, in thickness and a portion of the specimen shall be step-ground to a depth of 0.050 in. or half thickness, whichever is less. Specimens from material 0.250 in. and over in thickness shall be ground to remove from the original surface of the plate the amount of metal shown below and a portion of the specimen shall be further ground to a depth of at least 1/3 the original thickness of the specimen. At least three Rockwell hardness readings shall be taken on each prepared step and each group of readings averaged.

Nominal Original Thickness Inches	Surface Depth Removal Inch
0.250 to 0.375, incl	0.020
Over 0.375 to 0.500, incl	0.025
Over 0.500 to 0.750, incl	0.030
Over 0.750 to 1.000, incl	0.035
Over 1.000 to 2.000, incl	0.040

5.2.2.3 Allowance:

5.2.2.3.1 Material 0.045 to 0.250 In., Excl, Thick: Unless otherwise specified, the product shall be free from complete decarburization. It shall also be free from partial decarburization to the extent that the difference in hardness between the surface and the nondecarburized depth below the surface shall be not greater than 2 points on the Rockwell A scale.

5.2.2.3.2 Material 0.250 In. and Over Thick: The difference in hardness between the two prepared steps shall be not greater than 2 points on the Rockwell C scale.

5.3 Micro-Inclusion Rating: Unless otherwise specified, the inclusion rating, determined in accordance with ASTM E45, Method D, using not less than 9 specimens per heat or lot selected parallel to the direction of rolling and representing the worst area of inclusions in the inspection sample, shall be as specified below. The method of selection of specimens shall be such that suitable rating of the heat or lot of steel being qualified is assured. Two-thirds of all specimens shall not exceed the following limits, except that the length of any inclusion shall be not greater than 0.015 inch.

Type	Inclusion Rating			
	A	B	C	D
Thin	1.5	1.5	1.5	2.0
Heavy	1.0	1.0	1.0	1.5

5.4 Properties After Heat Treatment: Material heat treated as in 5.4.1, except that annealing (5.4.1.1) is optional, shall conform to the requirements of 5.4.2 and 5.4.3.

5.4.1 Heat Treatment:

5.4.1.1 Annealing: Heat to 1140 F $\pm$ 25 (615.6 C $\pm$ 14), hold at heat for 8 - 24 hr, and cool in air to room temperature.

- 5.4.1.2 **Normalizing:** Heat to a temperature within the range of 1600 - 1700 F (871.1 - 926.7 C), hold at the selected temperature within ± 25 F (± 14 C) for 1 hr per inch of section thickness, and cool in air to room temperature.
- 5.4.1.3 **Hardening:** Heat to 1550 F ± 25 (843.3 C ± 14), hold at heat for 1 hr per inch of section thickness but at least 1 hr, and then from that temperature quench sections up to 4 in. in thickness into room-temperature oil or water.
- 5.4.1.4 **Tempering:** Heat to required temperature not higher than 1050 F (565 C), hold at heat for 2 hr per inch of thickness but at least 2 hr, and cool in air to room temperature.
- 5.4.2 **Tensile Properties:**
- | | |
|--|-------------|
| Tensile Strength, psi | 185,000 min |
| Yield Strength at 0.2% Offset or at 0.0159 in. in 2 in. Extension Under Load (E - 29,500,000), psi | 175,000 min |
| Elongation, % in 2 in. | |
| Nominal Thickness, in. | |
| 0.020 to 0.060, incl | 5 min |
| Over 0.060 to 0.100, incl | 8 min |
| Over 0.100 to 0.187, incl | 10 min |
| Over 0.187 | 13 min |
| Reduction of Area (round specimens), % | 50 min |
- 5.4.3 **Fracture Toughness:** When specified, shall be determined by a suitable method. Standards shall be as agreed upon by purchaser and vendor.
6. **QUALITY:** Steel shall be premium quality and shall conform to the requirements of the latest issue of AMS 2300. Unless otherwise permitted, material shall be multiple melted using consumable electrode practice in the remelt cycle; at least one of the melting cycles shall be under vacuum. The product shall be uniform in quality and condition, clean, sound, and free from foreign materials and from internal and external imperfections detrimental to fabrication or to performance of parts.
7. **TOLERANCES:** Unless otherwise specified, tolerances shall conform to all applicable requirements of the latest issue of AMS 2252.
8. **REPORTS:**
- 8.1 Unless otherwise specified, the vendor of the product shall furnish with each shipment three copies of a report of the results of tests for chemical composition, tensile properties, grain size, inclusion rating, and AMS 2300 frequency-severity rating of each heat in the shipment and the results of tests on each thickness from each heat to determine conformance to the tensile property requirements after heat treatment. A heat shall be the consumable electrode-remelted ingots produced from steel originally melted in a single furnace charge. When permitted by purchaser, a heat may be the consumable electrode remelted product of individual melts of similar composition produced from the same lots of controlled raw materials and having the same average composition as agreed upon by purchaser and vendor. This report shall include the purchase order number, heat number, material specification number and its revision letter, thickness, size, and quantity from each heat.
- 8.2 Unless otherwise specified, the vendor of finished or semi-finished parts shall furnish with each shipment three copies of a report showing the purchase order number, material specification number and its revision letter, contractor or other direct supplier of material, part number, and quantity. When material for making parts is produced or purchased by the parts vendor, that vendor shall inspect each lot of material to determine conformance to the requirements of this specification, and shall include in the report a statement that the material conforms, or shall include copies of laboratory reports showing the results of tests to determine conformance.

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9. IDENTIFICATION: Unless otherwise specified, each sheet, strip, and plate shall be marked as in 9.1. 1
Ø unless purchaser permits a method from 9.2.
- 9.1 Each sheet, strip, and plate shall be marked on one face, in the respective location indicated below, with AMS 6546A, heat number, manufacturer's identification, and nominal thickness in inches. The characters shall be of such size as to be clearly legible, shall be applied using a suitable marking fluid, and shall be capable of being removed in hot alkaline cleaning solution without rubbing. The markings shall have no deleterious effect on the material or its performance and shall be sufficiently stable to withstand normal handling. The specification number, manufacturer's identification, and nominal thickness shall be continuously line marked; the heat number may be included in the line marking or may be marked at one location on each piece.
- 9.1.1 Flat Strip 6 In. and Under in Width: Shall be marked in one or more lengthwise rows of characters recurring at intervals not greater than 3 feet.
- 9.1.2 Flat Sheet, Flat Strip Over 6 In. in Width, and Plate: Shall be marked in lengthwise rows of characters recurring at intervals not greater than 3 ft, the rows being spaced not more than 6 in. apart and alternately staggered.
- 9.1.3 Coiled Sheet and Strip: Shall be marked near the outside end of the coil. The inside end of the coil also shall be marked or shall have a tag or label attached and marked with the information of 9.1 above.
- 9.2 When purchaser permits, each sheet, strip, and plate may be marked near one end, coils being marked near the outside end, with the purchase order number, AMS 6546A, heat number, and nominal thickness in inches, using any suitable marking fluid. As an alternate method, individual pieces and bundles shall have attached a metal or plastic tag embossed with the above information or shall be boxed and the box marked with the same information.
10. PROTECTIVE TREATMENT: Unless otherwise specified, the product shall be oiled after descaling.
11. REJECTIONS: Material not conforming to this specification or to authorized modifications will be subject to rejection.

APPENDIX III

CODE IDENT
NO. 07703

THIOKOL CHEMICAL CORPORATION
Wasatch Division
Brigham City, Utah

STANDARD

WELDING, INERT GAS, TUNGSTEN ARC
(ROCKET MOTOR CASE AND CLOSURE ASSEMBLIES)

TW-STD-53A
10 January 1963
SUPERSEDES
TW-STD-53
19 October 1961
SCN 1/STD-53(163)
16 January 1962
SCN 2/STD-53R1(485)
10 January 1963

1. SCOPE

1.1 Scope. This standard covers tungsten arc inert gas welding used for welding solid-propellant rocket motor case and closure assemblies.

1.2 Classification

1.2.1 Class 1 Weldments. Class 1 weldments are those weldments subject to stresses in excess of 150,000 pounds per square inch (psi).

1.2.2 Class 2 Weldments. Class 2 weldments are those weldments subject to stresses up to and including 150,000 (psi).

2. APPLICABLE DOCUMENTS

2.1 Government Documents. The following Government documents, of the issues in effect on the date of this standard, form a part of this standard to the extent specified herein.

SPECIFICATIONS

Military

MIL-T-5021	Tests; Aircraft and Missile Welding Operator's Qualification
MIL-I-6865	Inspection, Radiographic
MIL-I-6866	Inspection, Penetrant Method Of
MIL-I-6868 B	Inspection Process, Magnetic Particle

STANDARDS

Military

JAN-STD-19	Welding Symbols
MIL-STD-20	Welding Terms and Definitions

(Copies of Government documents can be obtained from the nearest military agency concerned or from a source recommended by that agency.)

2.2 Non-Government Documents. The following non-Government documents, of the issues in effect on the date of this standard, form a part of this standard to the extent specified herein.

THIOKOL CHEMICAL CORPORATION

Specifications

TUS-61-1	Steel, Alloy, High-Strength
TUS-61-15	Heat Treatment, TUS-61-1 Steel

Standards

TU-STD-18	Calibration and Certification of Measuring and Testing Equipment
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Publications

CC TW-STD-53	Classification of Characteristics for Welding, Inert Gas, Tungsten Arc (Rocket Motor Case and Closure Assemblies)
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(Copies of Thiokol documents can be obtained from Thiokol Chemical Corporation, Wasatch Division, Brigham City, Utah.)

3. DEFINITIONS

3.1 Welding Terms and Definitions. Welding terms and definitions used in this standard are in accordance with Standard MIL-STD-20.

3.2 Welding Symbols. Welding symbols used in the application of this standard are in accordance with Standard JAN-STD-19.

3.3 Welds. The weld shall be defined as that area of metal wherein coalescence is produced by heating the metal to a suitable temperature with or without the addition of filler wire.

3.4 Weld Repair. A weld repair is rework of a welded area by means of welding as defined in this standard, or by any means which can affect the temper of the material.

3.5 Thiokol. Thiokol is the Procurement Division of Thiokol Chemical Corporation, Wasatch Division, Brigham City, Utah.

3.6 Supplier. The supplier is the holder of the purchase order or contract issued by Thiokol.

3.7 Incomplete Penetration. Incomplete penetration is a lack of fusion in the root of the weld or gap left by failure of the weld metal to fill the root. Incomplete penetration appears on the radiograph as a dark continuous or intermittent line in the middle of the weld (see Fig. 1).

3.7.1 Cracks. A crack is a discontinuity produced by a fracture in the metal, and appears as a fine dark line, straight or wandering in direction (see Fig. 1A).

3.7.2 Undercut. An undercut is a groove or channel in the surface of the plate along the edge of the weld. It appears as a dark line, sometimes broad and diffuse, along the edge of the weld (see Fig. 2).

3.7.3 Sharp Weld Edge. A sharp weld edge occurs at the edge of the weld bead and may be caused by either the grinding operation or the welding operation or both such as the back-up plate. A sharp weld edge has a sharp edge which does not blend in with the parent material. It appears on the radiograph as a sharp indication, but may not have a density change on the film (see Fig. 2A).

3.7.4 Tungsten Swirl. A tungsten swirl occurs in the weld material and is caused by contamination from the tungsten arc used. A swirl appears on the radiograph as area of tungsten alloy with no definite boundaries (see Fig. 3).

3.7.5 Sharp-Tail Porosity. A sharp tail porosity is any cavity having a sharp tail-like indication (see Fig. 3A).

3.7.6 Porosity. Porosity is a cavity caused by entrapped gas (see Fig. 4).

3.7.7 Lack of Fusion. Lack of fusion is a defect due to lack of union between the weld metal and parent metal or both. Lack of fusion appears on the radiograph as a thin dark line with sharply defined edges. Depending upon the orientation of the defect with respect to the X-ray beam, the line may tend to be wavy and diffuse (see Fig. 4A).

3.7.8 Toe Porosity. (Limited to Class II Weldments) Toe porosity is a condition at the edge of the weld which is caused by oxide or gases being boiled out to the edge of the weld. Toe porosity appears as pitting and in most cases may be seen visually. It appears on the radiograph as small minute porosity (see Fig. 5).

3.7.9 Tungsten Inclusion. A tungsten inclusion is an inclusion of tungsten in the weld bead. It appears on the radiograph as a high density material with definite sharp boundaries and may have sharp edges (see Fig. 5A).

3.7.10 Measurement Criteria. Measurement criteria is a method of measurement for indications and the spacing between indications. All measurements shall be units of 0.005 increments.

Example: A measurement of 0.011 shall be counted as 0.015.

4. GENERAL REQUIREMENTS

4.1 Materials

4.1.1 Welding Wire. The welding wire shall be compatible with the parent metal and shall be capable of producing weldments that will meet the properties required for rocket motor cases and closure assemblies.

4.1.1.1 Welding Wire for D-6 Steel (TUS-61-1). Either of the following types of welding wires may be used:

a. Type A: Parent material wire, low carbon

Carbon	0.26	-	0.32
Manganese	0.60	-	0.90
Silicon	0.15	-	0.30
Phosphorous	0.015	-	Max. (0.010 aim)
Sulphur	0.015	-	Max. (0.010 aim)
Chromium	0.90	-	1.20
Nickel	0.40	-	0.70
Molybdenum	0.90	-	1.10
Vanadium	0.05	-	0.15

b. Type B: 2.50 Chromium 0.95 Molybdenum

Carbon	0.08	-	0.14
Manganese	0.40	-	0.70
Silicon	0.30	-	0.55
Phosphorous	0.02	-	Maximum
Sulphur	0.025	-	Maximum

4.1.1.2 Welding Electrodes. The welding electrodes shall be 2 percent Thoriated Tungsten

4.1.2 Inert Gases. Inert gases shall be of commercial quality, and shall be not less than 99.9 percent pure. Vapor content of the gases shall be controlled to ensure that the dew point is not above minus 70 degrees F (minus 56.5 degrees C).

4.1.2.1 Inert Gas Mixtures. A mixture of argon and helium gases may be used where greater torch sensitivity or greater arc stabilization is required. The following gases and gas mixtures shall not be applicable to this standard:

- a. Oxygen or hydrogen mixture with inert gas
- b. Carbon dioxide

4.2 Inspection. The supplier shall ensure that all inspection requirements have been met prior to submitting the welded item to Thiokol for inspection and acceptance. Visual, radiographic, wet magnetic particle inspection of the welds (see MIL-I-6868B) shall be performed prior to and after heat treatment. Penetrant inspection may be used in lieu of wet magnetic particle inspection only upon approval by Thiokol. The supplier may use his own facilities or the facilities of any commercial laboratory acceptable to Thiokol.

4.2.1 Visual and Nondestructive Inspection. The exposed surfaces of welded joints shall be visually and nondestructively inspected for smoothness of surface of the weld bead, weld contour, and evidence of excessive irregularities, unsoundness, craters, lack of fusion, cracks, concavity, discontinuities, surface oxidation and other evidences of unacceptable welds as defined in this standard.

4.2.1.1 Complete Joint Penetration. The entire weld joint shall consist of a homogeneous cast structure with all surfaces completely fused. Complete joint penetration will be ensured by a visual check immediately after welding to ensure that weld drop-thru is present continuously on the ID (inside diameter) of the weld joint.

4.2.1.2 Recording of Weld Current. For Class I weldments permanent continuous recording shall be made of the welding current (amps) for each weld pass required to complete the joint. These records shall be forwarded to Thiokol for additional quality assurance data.

4.2.2 Radiographic Inspection. All welds shall be radiographically inspected after heat treatment in accordance with Specification MIL-I-6865 to determine discontinuities or defects exceeding the permissible limits of this standard for Class 1 and Class 2 weldments as applicable (see 5.1).

4.2.2.1 Reports. Radiographic inspection reports shall be maintained as specified in Specification MIL-I-6865.

4.2.3 Penetrant Inspection. If approved by Thiokol, penetrant inspection of all welded areas may be made using either the Type I or Type II Method in Specification MIL-I-6866 in lieu of magnetic particle inspection.

4.2.4 Magnetic Particle Inspection. Magnetic particle inspection of all welds, assemblies, or component parts shall be made in

accordance with the wet process method specified in Specification MIL-I-6868 B to determine acceptance as defined by this standard.

4.2.5 Calibration. Calibration of supplier measuring and testing equipment shall be in accordance with Standard TU-STD-18.

4.3 Qualification. Welders and welding machines shall be qualified (see 4.3.1 and 4.3.2) prior to being permitted to perform work on weldments for Thiokol.

4.3.1 Welder Qualification. Each welder shall demonstrate his skill or proficiency by passing the applicable qualification tests required in Specification MIL-T-5021 for the process, position, joint types, and alloys to be welded.

4.3.2 Welding Machine Qualification. Qualification tests of welding machines shall be performed to determine the adequacy and consistency of operation of the machines. The machines shall be qualified to meet the weld requirements for the highest classification for which they are intended to be used. Qualification shall be based on the demonstrated ability (a minimum of two consecutive sets of test specimens as required in 4.3.1) of the machine. When operated by a qualified welder, to consistently produce weldments which shall meet the requirements specified herein.

4.3.3 Requalification. Requalification of welders shall be as specified in Specification MIL-T-5021.

4.3.4 Destructive Tests. If destructive test requirements for production items are specified in the applicable documents, the tests shall be performed as directed by Thiokol. Selection of welded items from which test specimens will be removed for destructive testing shall be accomplished by an authorized representative of Thiokol.

4.4 Supplier Responsibilities. Suppliers who have not furnished Thiokol with the type of welding required as specified herein shall, before beginning production, furnish welded test specimens required by the applicable documents.

4.5 Workmanship. Welds shall be of complete penetration unless otherwise specified on the engineering drawing. Welds shall be clean and free from scale, dirt, foreign particle inclusion, porosity, undercutting, concavity, and discontinuities within the limits established in this standard. All work shall meet the requirements and intent of the purchase document.

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4.6 Classification of Characteristics. Classification of Characteristics CC TW-STD-53 forms a part of this standard and is incorporated herein by reference.

5. DETAIL REQUIREMENTS

5.1 Defects and Acceptability Limits. Classification of defects and limits of acceptability shall be as specified in Table I for Class 1 weldments and as specified in Table II for Class 2 weldments.

5.2 Rework. Weldments which require repairing shall be repaired in a manner which will not alter the quality of the weldments as defined in Tables I and II.

5.2.1 Limitation of Rework. There shall be no more than two rework operations applied to any affected area of a welded joint after heat treatment. When a weld repair is required on a heat-treated component, the repair must be followed by reheat treatment of the entire component in accordance with Specification TUS-61-15.

5.2.2 Requirements After Rework. Reworked material shall meet all of the applicable test requirements of this standard and shall be inspected as specified in 4.2.2 and 4.2.4.

6. NOTES

6.1 Ordering Data. Procurement documents should specify title, number, and date of this standard.

Table I (cont.)

Classification	Limits of Acceptability	Example
Section 3 Minute Porosities	a. All porosity whose largest dimension does not exceed 0.010 inch is classified as minute porosity. Spacing and relationship with other indications is not a criteria within the limits of this standard.	
Section 4 Cluster Porosity	a. Ten or more indications of any size per 1 linear inch of weld shall be defined as cluster porosity. b. Groups of clusters shall be defined as follows: (1) A cluster shall have a maximum of 30 minute scattered porosities with no other indications present in 1 linear inch of weld. (2) A cluster shall have a maximum of 10 minute scattered porosities when combined with other indications of 0.015 thru 0.035 inch. The total number of indications shall not exceed 25. The area limit as specified in 4 c shall control the amount of other indications as specified herein. c. The acceptable limits shall be based on the total square inches of indications of 0.015 thru 0.035 inch not to exceed a total of 0.0026 sq inch in area. This max. area shall limit the acceptable number of indications (0.015 thru 0.035 inch) in one cluster.	DO NOT CONSIDER. *TOTAL AREA OF 0.015 TO 0.035 INDICATIONS NOT IN EXCESS OF 0.0026 SQ. IN.

Table I
(Class I Girth Weld Requirements)

Classification	Limits of Acceptability	Example
Section 1 Individual Porosities	a. The largest dimension of a single indication shall not exceed 0.040. b. There shall be no more than three indications of 0.035 to 0.040 per single girth weld. c. Indications of 0.035 to 0.040 shall have a minimum spacing of 2.500 inches.	
Section 2 Adjacent Porosity	a. This is for indications whose largest dimension is 0.015 thru 0.030. b. The spacing between any two indications shall be equal to, or greater than, one times the largest dimension of the smaller indication. c. If the spacing is less than b (above) the multiple defects shall be considered as one indication and the largest overall dimension shall not exceed 0.040 with spacing limitations as specified in 1 c. of this table.	

Table I (cont.)

Classification	Limits of Acceptability	Example												
	NOTE: See information below for individual area. <table><thead><tr><th>Indication Size</th><th>sq. Inch of Area</th></tr></thead><tbody><tr><td>0.015</td><td>= 0.00018</td></tr><tr><td>0.020</td><td>= 0.00032</td></tr><tr><td>0.025</td><td>= 0.00049</td></tr><tr><td>0.030</td><td>= 0.00071</td></tr><tr><td>0.035</td><td>= 0.00096</td></tr></tbody></table> d. Minimum spacing between any cluster shall be 16 inches, with a limit of 4 clusters per weld length. The total number of indications per 90-degree length of weld shall be controlled by Section 5 of this table.	Indication Size	sq. Inch of Area	0.015	= 0.00018	0.020	= 0.00032	0.025	= 0.00049	0.030	= 0.00071	0.035	= 0.00096	TOTAL INDICATIONS 9 OR UNDER TOTAL INDICATIONS 9 OR UNDER 
Indication Size	sq. Inch of Area													
0.015	= 0.00018													
0.020	= 0.00032													
0.025	= 0.00049													
0.030	= 0.00071													
0.035	= 0.00096													
Section 5 Total Indications	a. The maximum number of any size indications acceptable for any 90° quadrant of a girth weld is 75.													
Section 6 Metallic Inclusions	a. The largest dimension of acceptance for a tungsten inclusion is 0.035 inch. b. The spacing and distribution shall meet the requirements as specified in Sections 1, 2, 4, and 5 of this table. c. Metallic inclusions shall be included with, and not in addition to, the nonmetallic limits.													

Table I (cont.)

Classification	Limits of Acceptability	Example
Tungsten Swirls Section 7	a. The maximum length of an individual tungsten swirl shall not exceed 1.40 inch. b. The minimum spacing between tungsten swirls shall be 4.0 inch. c. When the sum of the lengths of two or more tungsten swirls and their spacing is less than 1.40 inch, they shall be considered as a single swirl. d. The maximum number of tungsten swirls per girth weld is 7. e. Any combination of indications specified in Sections 1, 2, 3, 4, and 6 with indications specified in Section 7 shall be cause for rejection.	
Other Indications Section 8	Any of the following items shall be cause for rejection: a. Cracks b. Crack-like indications c. Sharp tail indications d. Sharp weld edge e. Surface porosity in excess of 0.010 inch. f. Undercut g. Lack of penetration h. Lack of fusion	

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Table II
(Class II Blast Tube Weldments)
Allowable Discontinuities

Classification	Limits of Acceptability
Porosity and Nonmetallic Indications	a. Thirty percent of material thickness at the location of the indications. b. The minimum spacing between the indications shall be equal to, or larger than, the dimension of the smaller indication. c. Clusters of either random or scattered indications, or a combination of both, of various dimensions with a minimum of 5 indications within a 1/4 inch circle from 0.015 thru the maximum size as specified in "a" above is acceptable providing that the total summation of all indications shall not exceed 0.001 square inch area and the spacing between the indications within the 1/4 inch circle shall be one times the largest dimension of the smaller indication. The spacing between clusters shall have a minimum spacing of 0.500 inches. d. Fine porosity clusters (0.010-inch diameter and less) shall be acceptable, provided the accumulated area of the porosity per 0.250-inch diameter area of the surface does not exceed the area of the maximum acceptable diameter (see a above) and spaced not closer than 0.500 inch.
Surface Porosity	a. Maximum of 0.030-inch diameter. b. Three of maximum size or equivalent area per inch. c. Surface voids to be a minimum of 0.100 inch apart. d. Toe porosity in excess of 0.015 inch shall not be acceptable.

Table II (cont'd)

Classification	Limits of Acceptability
Tungsten Inclusions	a. Thirty percent of the material thickness at the location of the defect. b. The minimum spacing between the indications shall be equal to, or larger than, the dimension of the smaller indication. c. Sharp edges or jagged inclusions are not acceptable. d. The distance between a tungsten inclusion and a pore or nonmetallic inclusion to be considered as "acceptable" within the limitations of pores and nonmetallic inclusions.
Other Indications	Any of the following items will be cause for rejection: a. Cracks b. Crack-like indications c. Sharp tail indications d. Sharp weld edge e. Undercut f. Lack of penetration g. Lack of fusion

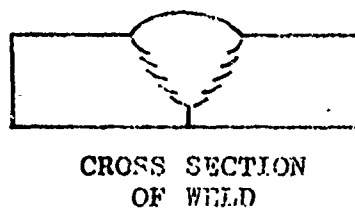
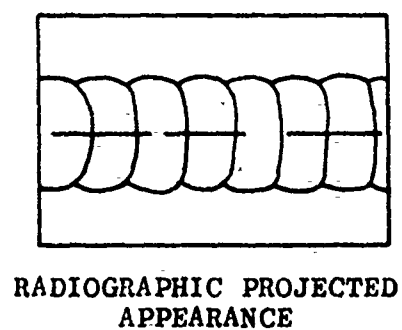


FIG. 1
INCOMPLETE PENETRATION

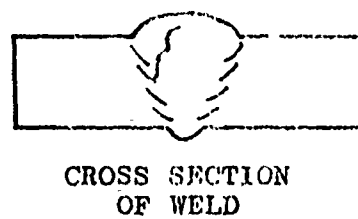
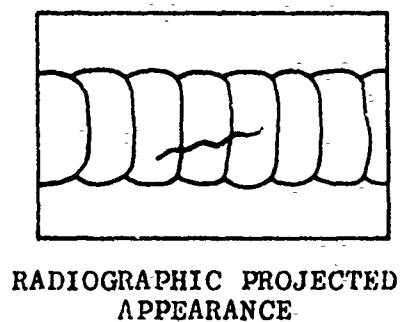
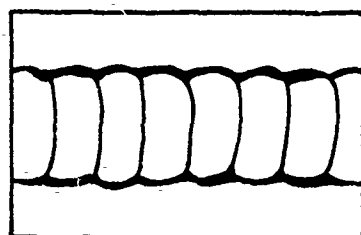


FIG. 1A
CRACKS

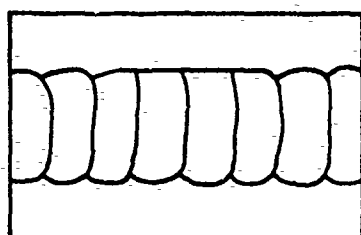


RADIOGRAPHIC
APPEARANCE



CROSS SECTION
OF WELD

FIG. 2
UNDERCUT



RADIOGRAPHIC
APPEARANCE



MAY APPEAR ON TOP
OR BOTTOM BEAD

FIG. 2A
SHARP WELD EDGE

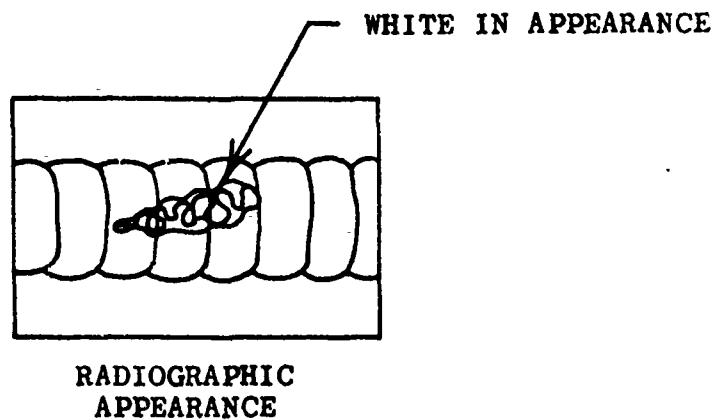


FIG. 3
TUNGSTEN SWIRLS

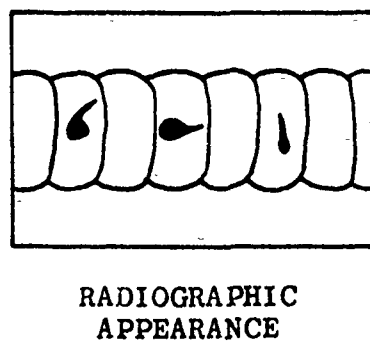


FIG. 3A
SHARP-TAIL POROSITY

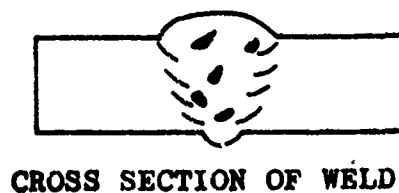
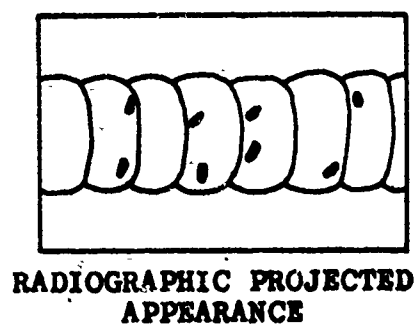


FIG. 4
POROSITY

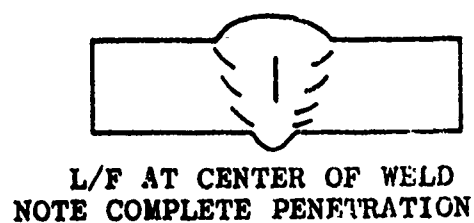
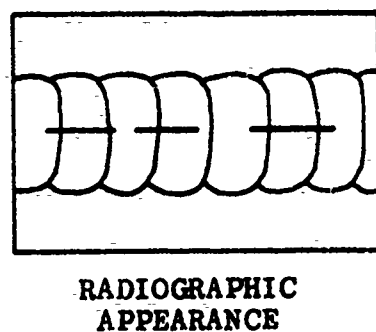
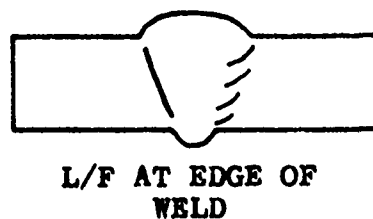
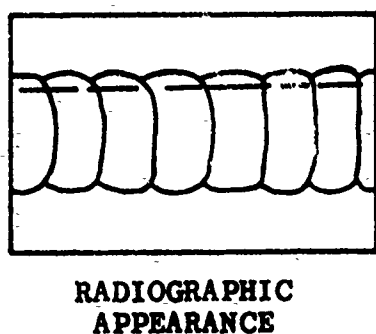
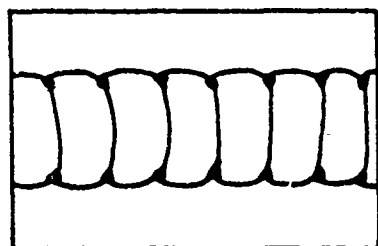


FIG. 4A
LACK OF FUSION

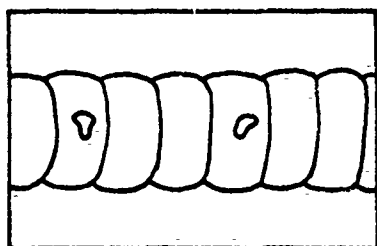


RADIOGRAPHIC
APPEARANCE



CROSS SECTION OF
WELD

FIG. 5
TOE POROSITY



RADIOGRAPHIC
APPEARANCE



CROSS SECTION OF
WELD

FIG. 5A
TUNGSTEN INCLUSION

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Prepared by:

Thiokol Chemical Corporation
Wasatch Division
Brigham City, Utah

CODE IDENT
NO. 07702

APPENDIX IV

STW7-832
3 July 1969

THIOKOL CHEMICAL CORPORATION
Wasatch Division
Brigham City, Utah

STANDARD

WELDING, INERT GAS, TUNGSTEN ARC,
STEEL, ALLOY, SELECTED CHEMISTRY
(HP9-4)

1. SCOPE

1.1 Scope. This standard covers tungsten arc insert gas welding of HP9-4 nickel steel (AMS-6546) for development purposes.

1.2 Classification

1.2.1 Class 1 Weldments. Class 1 weldments are those weldments subject to stresses in excess of 200,000 pounds per square inch (psi).

1.2.2 Class 2 Weldments. Class 2 weldments are those weldments subject to stresses up to and including 200,000 psi.

2. APPLICABLE DOCUMENTS

2.1 Government Documents. The following Government documents, of the issues in effect on the date of this standard, form a part of this standard to the extent specified herein.

SPECIFICATIONS

Military

MIL-T-5021	Tests; Aircraft Welding Operators' Certification
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MIL-I-6866	Inspection, Penetrant Method of
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STANDARDS

Military

JAN-STD-19	Welding Symbols
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MIL-STD-20	Welding Terms and Definitions
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MIL-STD-453	Radiographic Inspection
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(Copies of Government documents can be obtained from the nearest military agency concerned or from a source recommended by that agency.)

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2.2 Non-Government Documents. The following non-Government documents, of the issue in effect on the date of invitation for bids, form a part of this standard to the extent specified herein.

SOCIETY OF AUTOMOTIVE ENGINEERS INC. (SAE)

Aerospace Material Specifications (AMS)

AMS 6546

Steel Sheet, Strip, and Plate ...

(Application for copies should be addressed to the Society of Automotive Engineers, Inc., 485 Lexington Avenue, New York, N.Y. 10017.)

3. DEFINITIONS

3.1 Welding Terms and Definitions. Welding terms and definitions used in this standard are in accordance with Standard MIL-STD-20.

3.2 Welding Symbols. Welding symbols used in the application of this standard are in accordance with Standard JAN-STD-19.

3.3 Thiokol. Thiokol is Thiokol Chemical Corporation, Wasatch Division, Brigham City, Utah.

3.4 Supplier. The supplier is the holder of the purchase order or contract issued by Thiokol.

4. GENERAL REQUIREMENTS

4.1 Materials

4.1.1 Welding Wire. The welding wire shall be compatible with the parent metal and shall be capable of producing weldments that will meet an ultimate tensile strength of 200,000 psi minimum.

4.1.2 Inert Gases. Inert gases shall be of commercial quality, and shall be not less than 99.99 percent pure. Vapor content of the gases shall be controlled to ensure that the dew point is not above minus 70 degrees F (minus 56.5 degrees C).

4.1.2.1 Inert Gas Mixtures. A mixture of argon and helium gases may be used where greater torch sensitivity or greater arc stabilization is required. The following listed gases and gas mixtures shall not be applicable to this standard:

- a. Oxygen or hydrogen mixture with inert gas
- b. Carbon dioxide

4.2 Inspection. The supplier shall insure that all inspection requirements have been met prior to submitting the welded item to Thiokol for inspection and acceptance. Penetrant inspection or magnetic particle inspection in conjunction with radiographic and visual inspection shall be sufficient to determine compliance with this standard. The supplier may use his own facilities or the facilities of any commercial laboratory acceptable to Thiokol.

4.2.1 Visual and Nondestructive Inspection. Upon completion of each weld bead, all welds shall be visually inspected to ensure the absence of undercutting, cracks concavity, discontinuities, and other evidences of unacceptable welds.

4.2.2 Radiographic Inspection. Upon completion of each weld and after heat treatment, unless otherwise specified in the procurement document or indicated on Thiokol engineering drawings, all welds shall be radiographically inspected (see 6.1) in accordance with the procedures established in MIL-STD-453 to determine discontinuities or defects exceeding the permissible limits of this standard for Class 1 and Class 2 weldments as applicable (see 5.1).

4.2.3 Penetrant Inspection. When specified on engineering drawings, penetrant inspection of all welded areas shall be made using either Type I or Type II Method of Specification MIL-I-6866 to determine acceptance as defined by this standard (see 5.2.2).

4.3 Qualification and Certification

4.3.1 Machine Qualification. Welding machines shall be capable of making satisfactory welds when operated by a certified welder or welding operator. If the representative of Thiokol has reason to doubt the capability of any welding apparatus to function satisfactorily, he shall require welders certification tests as described in Specification MIL-T-5021 applicable to the type of work for which the equipment is intended. The tests shall be made by a welder certified for the material and the type of welding. If under these conditions the applicable requirements cannot be met, the equipment shall not be used until the necessary repairs, adjustments, or replacements have been made.

4.3.2 Welding Operator Certification. All welding operators shall pass the certification tests specified in Specification MIL-T-5021 for the alloy to be welded. Welded test specimens presented for welding operator certification shall be subject to test and evaluation for determination of welding operator proficiency.

4.3.3 Destructive Tests. Destructive tests of welded items, if required by applicable documents, shall be performed as directed by Thiokol.

4.4 Supplier Responsibilities. Suppliers who have not furnished Thiokol with the type of welding required as specified herein shall, before beginning production, furnish welded test specimens required as specified in the applicable documents.

4.5 Workmanship. Welds shall be of complete penetration unless otherwise specified on the engineering drawing. Welds shall be free from scale, dirt, foreign particle inclusion, porosity, undercutting, concavity, and discontinuities within the limits established in this standard. All work shall meet the requirements and intent of the purchase document.

5. DETAIL REQUIREMENTS

5.1 Defects and Acceptability Limits. Classification of defects and limits of acceptability shall be as specified in Table I for Class 1 weldments and as specified in Table II for Class 2 Weldments.

5.2 Rework. Weldments which require repairing shall be repaired in a manner which will not deviate from the limits of acceptability as specified in Tables I and II. Rework procedure shall be agreed upon by Thiokol and the supplier prior to accomplishment of the rework.

5.2.1 Limitation of Rework. There shall be no more than two rework operations applied to any affected area of any welded joint.

5.2.2 Requirements After Rework. Reworked material shall meet all of the applicable test requirements of this standard, and shall be inspected for conformance to the requirements of 4.2.2 and 4.2.3.

6. NOTES

6.1 This section is not applicable to this standard.

Table I
(Class 1 Weldments)
Allowable Discontinuities

Classification	Limits of Acceptability
Porosity and nonmetallic inclusions	a. Twenty percent maximum of the average parent material thickness (not weld build-up area) b. Voids of 0.010-inch and above in diameter to be a minimum of 0.250 inch apart c. Below 0.010-inch diameter, voids to be a minimum of 0.125 inch apart d. Maximum of one 0.030-inch inclusion per linear inch e. No hook-tail porosity acceptable
Surface porosity	No surface porosity over 0.010-inch acceptable
Tungsten inclusions	a. Twenty percent maximum of the average parent material thickness (not weld build-up area). b. Maximum of one per linear inch weld c. Inclusion to be a minimum of 0.500 inch apart from any other inclusion