R-8061

FABRICATION TECHNIQUES
FOR
SHROUDED TITANIUM IMPELLER

FINAL REPORT

ROCKETDYNE
A DIVISION OF NORTH AMERICAN ROCKWELL CORPORATION

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FINAL REPORT

Contract NAS8-20761

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FOREWORD

Rocketdyne, a Division of North American Rockwell Corporation has prepared this final report which documents the work performed in fulfillment of the program "Fabrication Techniques for Shrouded Titanium Impeller" during the period from 29 June 1967 to 30 September 1969. This program is sponsored by the National Aeronautics and Space Administration under Contract NAS8-20761. This work was performed by technical personnel from Turbomachinery and Advanced Systems Departments of Rocketdyne Division and Los Angeles Division of North American Rockwell Corporation. Mr. C. Miller MSFC, NASA was Technical Project Manager for this program.

ABSTRACT

This report describes the development of diffusion bonding technique for fabrication of shrouded titanium centrifugal impellers. Trial samples were used to develop the optimum procedure and two shrouded, titanium impellers were successfully diffusion-bonded and finish-machined. Both of the impellers were also successfully spin-tested to demonstrate the feasibility of the diffusion bonding process for attaching shrouds on centrifugal impellers.

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INTRODUCTION AND SUMMARY

Current oxygen/hydrogen engine development programs have emphasized the need for developing high speed centrifugal impellers for high pressure liquid hydrogen pumps. High speed, easily machined, open impellers are currently used and sensitivity of hydrodynamic performance and axial thrust to impeller blade clearance can be a problem. Shrouded impellers do not have this problem and thus have high hydrodynamic performance and stability in addition to good thermal characteristics for minimum chilldown. However, the shape, depth and curvature of the passages limit the machining of the impeller to those configurations where it is possible to reach with a cutting tool. For this reason machined shrouded impellers are limited to utilizing discharge angles higher than those used by open impellers.

Therefore, under the sponsorship of Marshal Space Flight Center, NASA, a study was made to develop impeller fabrication techniques for bonding a shroud onto the impeller after the proper blade passage shape has been machined. To obtain the highest operating speeds, a high strength-to-density ratio, forged titanium alloy 5Al - 2.5 Sn was used.

During the study, titanium impeller shroud design, fabrication and bonding techniques were investigated to determine the most promising technique that will produce satisfactory joints in complex shapes. The diffusion bonding technique was selected. Two sample impellers were fabricated and bonded to develop procedures and verify the feasibility of the bonding approach.

A shrouded impeller was designed. The head (46,100 ft), flow (9754 gpm), and speed (29,800 rpm) are the same as those for the Mark 29 fuel impeller for J-2S engine. The blade discharge angle was set at 37° (Mark 29 is 60°) and in order to develop the head the impeller OD is 12 in. (Mark 29 is 11 1/2 in.). Components for two impellers were fabricated, tooling was constructed, the impellers were diffusion bonded, finish machined, and balanced and spun in a spin pit to 31,500 rpm for 2 minutes. The program demonstrated the complete feasibility of the diffusion bonding technique for fabricating high speed, shrouded impellers. Figure (a) is a photograph of a completed diffusion-bonded, shrouded titanium impeller.

Figure (a). Diffusion Bonded Shrouded Titanium Centrifugal Impeller

TASK I - DESIGN STUDY AND EVALUATION

PRELIMINARY IMPELLER DESIGN

A preliminary impeller design was established as a basis for the investigation and selection of the fabrication method. The major design parameters of the impeller are shown in Table 1 compared to the existing Mark 29 design. The new impeller diameter was increased to maintain the same head rise as the existing Mark 29 fuel impeller at the same rpm. The number of vanes was increased because the hydrodynamic loading is reduced as the blade discharge angle is decreased.

Stress analysis was conducted on the following five configurations of the new design:

(1) Constant vane thickness (0.230 inches) and constant shroud thickness (0.125 inches).

(2) Thickened vanes (to 0.300 inch) and constant shroud thickness.

(3) Tapered vanes (to 0.160 inch) and constant shroud thickness.

(4) Tapered vanes and reduced shroud thickness (0.090 inch).

(5) Tapered vanes and tapered shroud thickness (to 0.110 inch).

Comparison of the results indicated that the vane stresses of configuration (5) were comparable to those in the existing Mark 29 impeller and superior to the other configurations.

FABRICATION INVESTIGATION AND TECHNIQUE SELECTION

Very little diffusion bonding or electron beam welding experience exists for fabricating complex impeller shapes. Table 2 lists and summarizes the areas investigated during Task I. Based on this investigation, it appears that with sufficient development either process could be employed to fabricate satisfactory impellers. From the current investigation it

TABLE I

PRELIMINARY DESIGN PARAMETERS
OF
IMPELLER COMPARED TO MARK 29 DESIGN

		Existing Mark 29	New Design
Headrise (pump overall)	- ft	46,100	46,100
Flowrate	- gpm	9754	9754
Speed	- rpm	29,800	29,800
Tip Diameter	- inches	11.5	12.0
Blade Discharge Angle	- degrees	60	37
Number of Vanes	-full	6	7
	- long splitter	6	7
	- short splitter	12	
Blade Inlet Angles			
	- hub , **degrees**	21	21
	- Mean , **degrees**	16	16
	- tip , **degrees**	13	13
Vane Thickness	- inches	0.25 constant	*
Vane Discharge Configuration		Axial	45°Skew

*** See previous page**

TABLE 2

Comparison of Shrouded Impeller Fabrication Methods

Area of Investigation	Diffusion Bonding	Electron Beam Welding
Design		
Layout		
Back Shroud	Profile simple to define	Profile simple to define
Vanes	Complexity of vane layout dependent on core design. (See Fig. 1) a) Solid core will require compromise of blade angles to facilitate practical blade insertion b) Core split along streamlines permits hydrodynamically prescribed angles with conventional layout method, but may limit number of vanes	Permits required hydrodynamically prescribed angles with conventional layout method
Front Shroud	Profile simple to define	Shroud joints at sections between vanes difficult to define for assembly with conventional blade layout methods. (See Fig. 1).
Cores	Defined by same coordinates as blade and shrouds (with allowance for Chem-milling)	Not required
Detail Drawings	Approximately the same number required for each method	

TABLE 2 (Continued)

	Diffusion Bonding	Electron Beam Welding
Hydrodynamic Limitations		
Discharge Angle	Same for Each Method	
Vanes	(Refer to vane under Design)	
Full	Number of full vanes may be limited by core design and number of partial vanes used	Number of full vanes may be limited by machining consideration (dependent on height at inlet)
Partials	Number of partial vanes may be limited by core design requirements and number of full vanes used	Length of partial vanes may be limited by machining consideration (dependent on height to spacing ratio)
Discharge Blade Height	Appears to have better tolerance control for impellers with very small discharge blade height	Front shroud fit up limits may make tolerance control on small discharge blade height difficult
Blade Height to Spacing Ratio	Not limited by machining considerations (with cores split along streamline)	Limited by machining considerations

TABLE 2 (Continued)

	Diffusion Bonding	Electron Beam Welding
Structural		
Joint Efficiency	100 percent if formed satisfactorily	100 percent if welded satisfactorily
Fillets	Formed during bonding to core shape	Machined integral with vane at outer shroud
Tip speed limitations	Same for each method assuming satisfactory joints and same number and shape of vanes.	
Fabrication		
Tooling Required		
Core Cavity	Required (reverse of vane cavity)	Not required
Vane Cavity	Required	Required - (requires additional tooling to define outer shroud joint)
Front Shroud	Simple tooling required	Complex tooling required to define shroud joint segments
Back shroud	Simple tooling required	None required
Weld or bond tooling	Simple tooling required	Tooling required to permit weld tracking in vacuum chamber

TABLE 2 (Continued)

	Diffusion Bonding	Electron Beam Welding
Pre-Weld or Pre-Bond Assembly		
Vane Fabrication	Refer to vanes under Design and Hydrodynamics	
		Vane spacing to height ratio limited by cutter L/D $\approx$ 10, and outer shroud fillet size.
Front Shroud Fabrication	Simple turning	Front shroud consists of many sections which must be fitted accurately along a three dimensional split line.
Core Fabrication	Steel core will define hydrodynamic passage shape. Complexity depends on number of full and partial vanes for a split core.	None required
Finish Machining	Same for each Method	
<u>Quality Assurance</u>		
Penetrant inspection	Practical (depending on passage size)	Not desirable
X-ray inspection	Not practical	Practical (depending on passage size)
Spin test	Same for each Method	

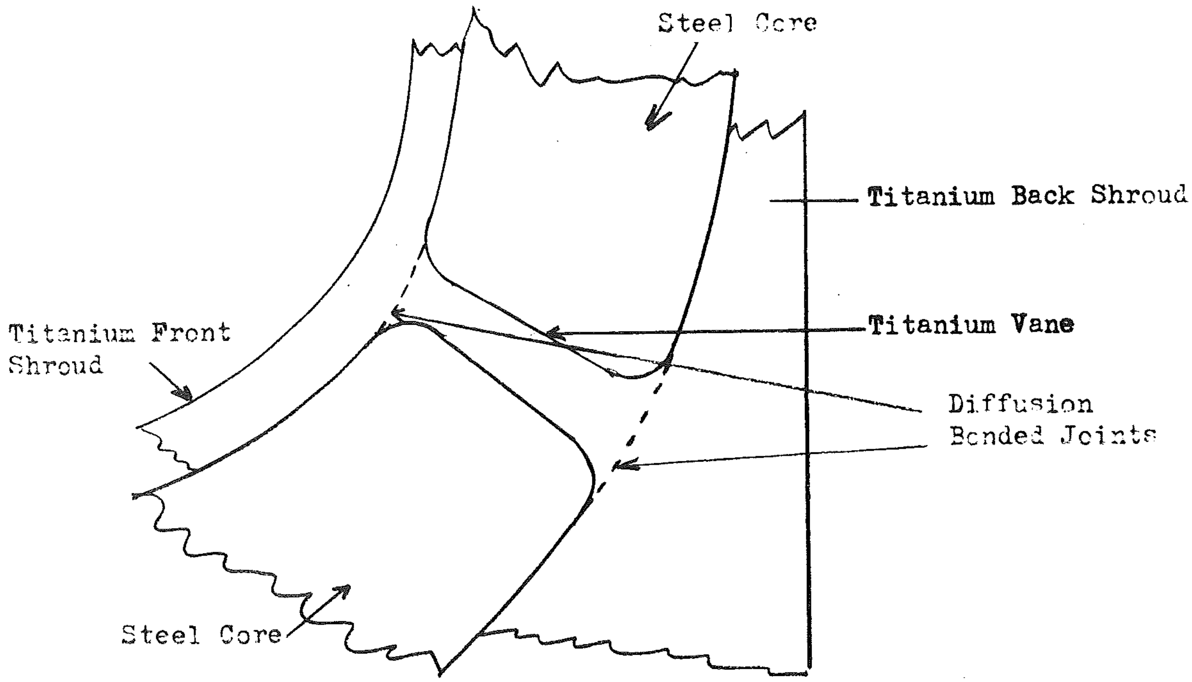
was concluded that satisfactory development of the diffusion bonding process would result in a lower per-part cost on a production basis. It was also concluded that the probability of producing a satisfactory part on the first attempt with diffusion bonding is somewhat lower than with electron beam welding. Table 3 lists the problem areas, and advantages associated with diffusion bonding and electron beam welding of the impeller. Fig. 1 illustrates the impeller joints requiring bonding or welding. Based on the ultimately lower per-part production cost, and the somewhat simpler design and pre-bond fabrication requirements, diffusion bonding was selected as the method to develop for manufacture of the shrouded titanium impeller.

TABLE 3

ADVANTAGES AND PROBLEM AREAS OF DIFFERENT FABRICATION METHODS

	Diffusion Bonding	Electron Beam Welding
Problem Areas	1) Application of uniform pressure on shrouds and vanes during bonding 2) Core design requirements may limit number of vanes practical	1) Layout of front shroud weld joints 2) Fabrication and fitup of front shroud sections 3) Accurate tracking of front shroud weld joints 4) Cutter L/D limitations
Advantages	1) Lower pre-part cost on a semi-production basis 2) May be more practical for very small discharge blade heights	1) Probability of fabricating satis-factory part on first trail higher 2) Repair of unsatisfactory joints possible

DIFFUSION BONDED IMPELLER JOINT



ELECTRON BEAM WELDED IMPELLER JOINT

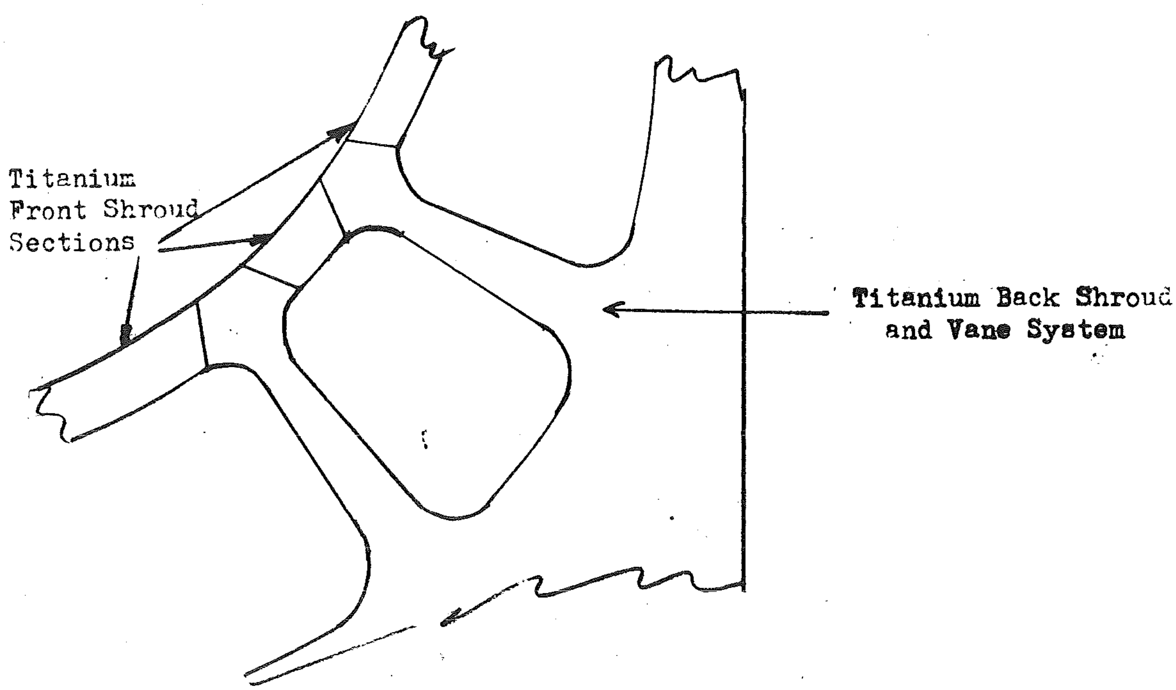


Figure 1. IMPELLER JOINTS

DETAIL DESIGN AND TECHNIQUE DEVELOPMENT

Impeller Design

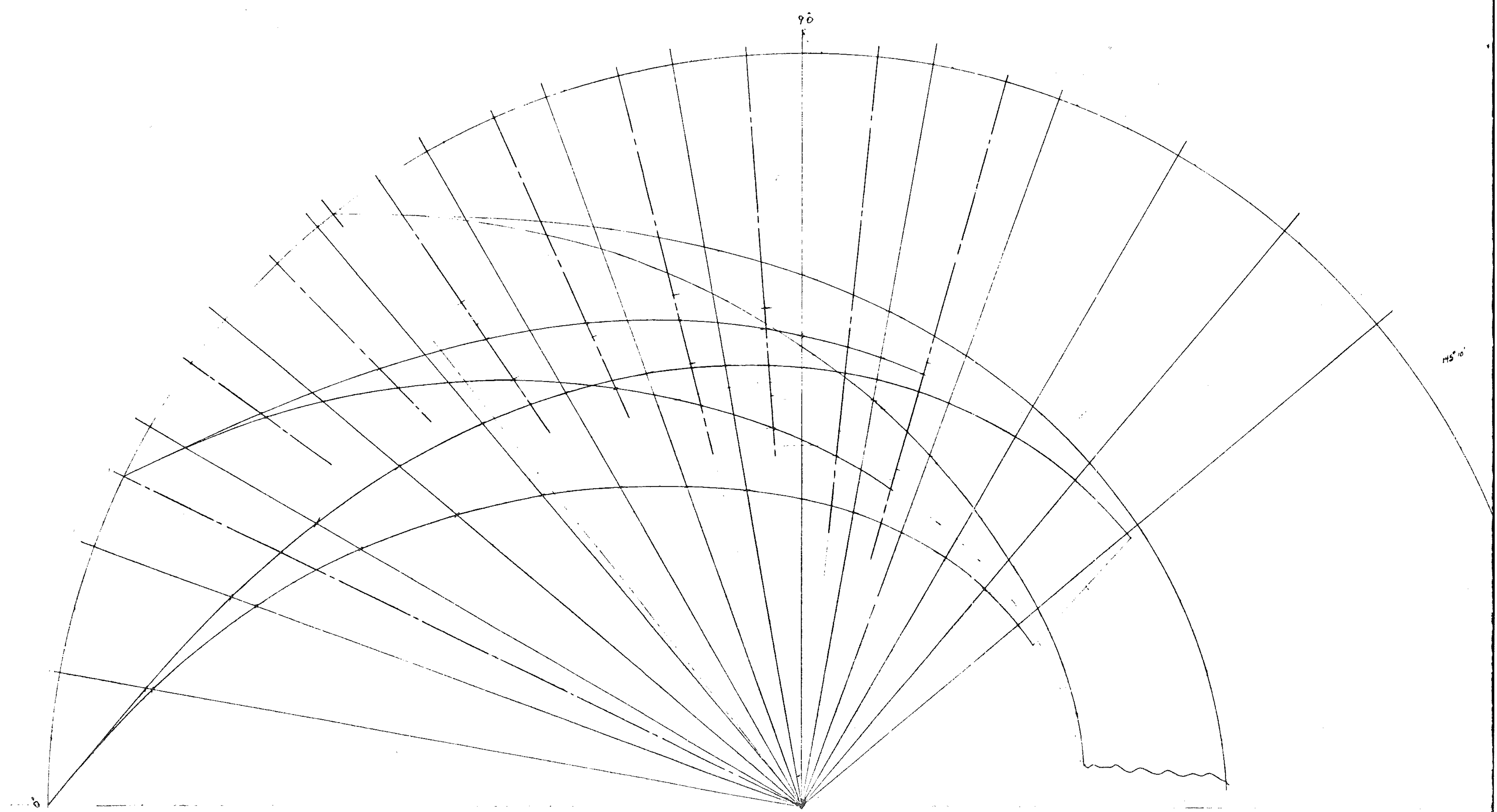
Upon completion of the preliminary design and technique selection, a detail design investigation of the impeller for the diffusion bonding process was initiated to formalize the final design.

Design Considerations

During the diffusion bonding process the steel cores must retain their shape and position if the completed part is to maintain design dimensions. Investigation indicates that circumferential core split lines within the impeller passage will permit core misalignment and/or deformation during the bonding process and thus may produce undesirable flow obstructions. An alternate possibility is to use a solid core; however, this limits the blade angle configuration that can be employed. Another solution is to limit the number of partial vanes and split the remaining partial vaned cores along a streamline, terminating at the inlet and outlet of the impeller. This permits freedom of blade angle configuration and provides full length cores which can be locked at the inlet and discharge of the impeller. The latter approach was investigated to establish the mininum number of blades that would be needed to satisfy structural requirements, hydrodynamic requirements, and minimum practical core thickness at impeller inlet. It was determined from a layout of the impeller eye area that either a 6 full plus 6 partial vane impeller or a 7 full plus 7 partial vane impeller would be acceptable from a core fabrication standpoint.

Stress Analysis

Layouts were made of two impellers each having 7 full and 7 partial vanes, with the difference being in the vane skew angle at the impeller discharge. One impeller had the vanes normal to the shrouds (Fig. 2) and the other had a skew angle of 45 degrees with the shrouds at the discharge (Fig. 3).



90°
0°
115°10'

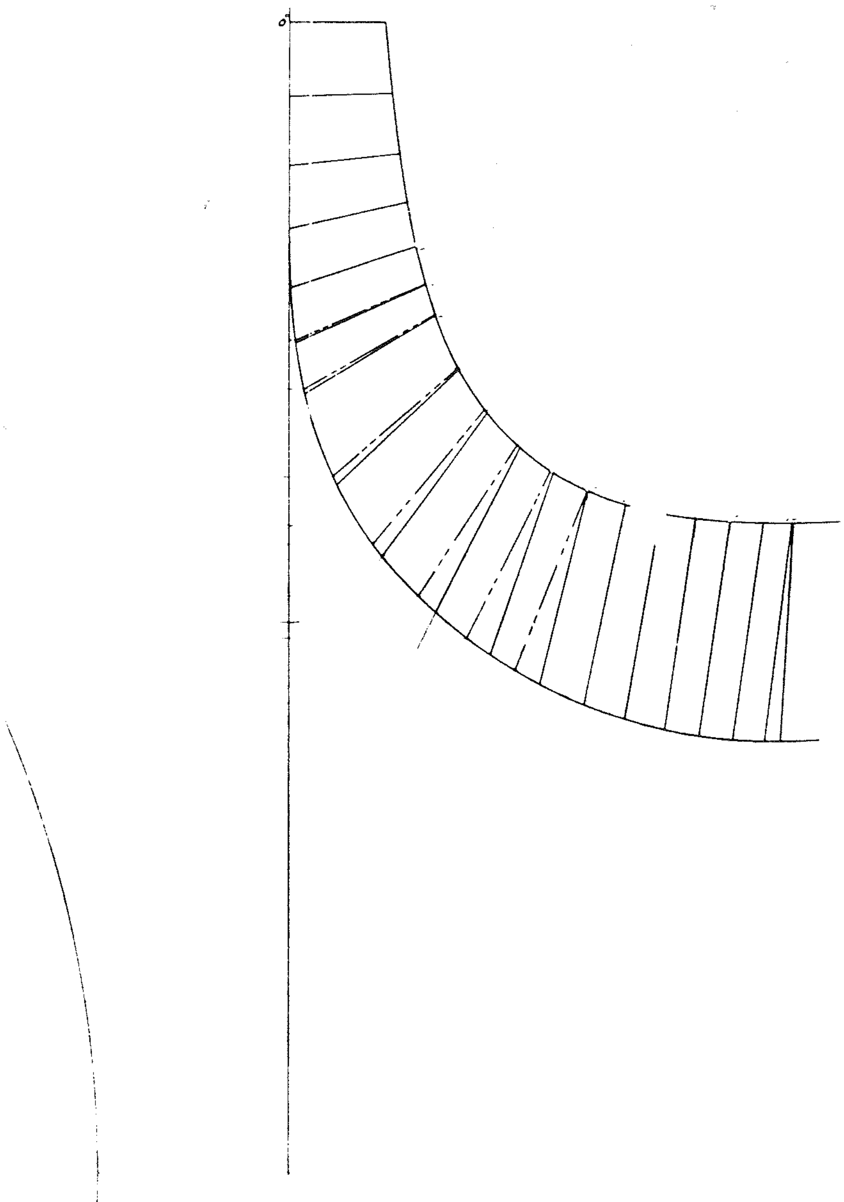


Figure 2. Impeller Layout
7 Full + 7 Partial Vanes - No Skew

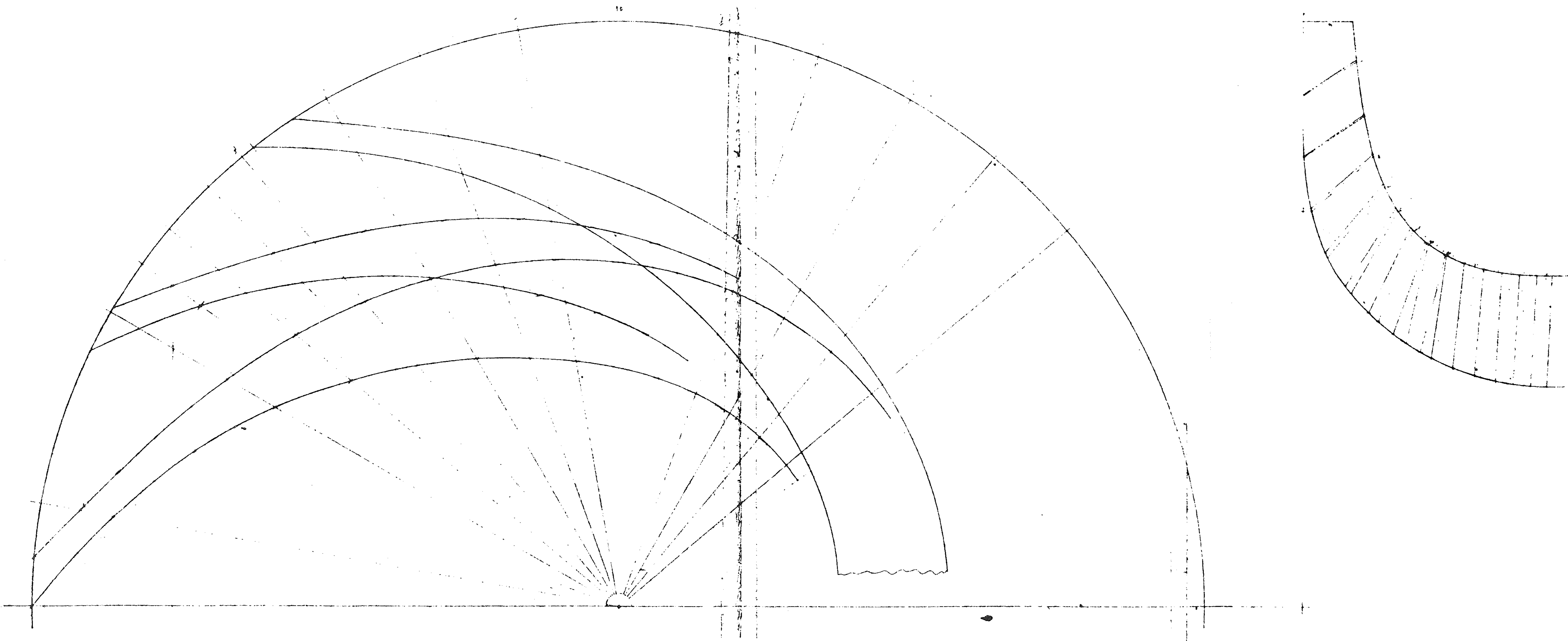


Figure 3. Impeller Layout
7 Full + 7 Partial Vanes - 45° Skew

A stress analysis was conducted on the following two configurations of the 7+7 vane impellers:

7+7 Vane with Axial Discharge:

(1) Tapered vanes (to 0.160 inch) and tapered shrouds (to 0.110 inch).

(2) Tapered vanes (local taper from 0.320 to 0.220 inch at 3.60 to 4.15 inch mean vane radius) constant shroud thickness.

(3) Tapered vanes (to 0.220) and constrant shroud thickness.

7+7 with Skewed Discharge:

(1) Tapered vanes (to 0.160 inch) and tapered shrouds (to 0.110 inch).

The following conclusions were made from a comparison of the vane configurations analyzed:

(1) It is desirable to taper the vane with the vane thickness decreasing from the backplate to the shroud. A vane of constant thickness if more highly stressed at the backplate than at the shroud since the centrifugal weight of both the vane and the shroud is imposing load at the backplate. Tapering the vane decreases the stress at the backplate by reducing the vane centrifugal weight and results in equilizing the stresses at the backplate and shroud junctions of the vane.

(2) Lower vane stresses result from reducing the centrifugal weight of the shroud by decreasing the shroud thickness. The shroud thickness must be sufficient to support the moment at the vane-shroud junction and to support the pressure differential across the shroud. Since the pressure differential across the shroud increases with decreasing shroud radius, an optimum shroud is thicker at the I.D. than at the O.D.

(3) A vane which is skewed to 45 degrees at the discharge is lower stressed than a similar vane which is axial at the discharge. The skewed vane offers a more nearly radial vane element between the backplate and shroud which is more effective in supporting the centrifugual weight of the shroud.

(4) Thicknening the vane locally along the vane wrap length has little effect on the stresses in the remainder of the vane. Local thickening may result from designing the vane only as thick as required along its length. This is desirable from a backplate burst speed consideration.

Based on stress considerations the 7+7 vane impeller with 45 degrees skewed and tapered vane configuration was recommended for the final design. Preliminary analysis of the impeller backplate indicates the backplate is structurally adequate for operation at 31,000 rpm with -200 degrees F material properties for all of the vane configurations considered.

Hydrodynamics

A hydrodynamic analysis was conducted on the 7+7 vane impeller with 45 degree skewed vanes (Fig. 3) to determine the pressure differences across the vane, relative flow velocities, and head rise. The inlet blade angles and the impeller shroud profiles are identical to those of the Mark 29 fuel pump. Figure 4 shows the predicted Δp across the vane vs distance in the meridional plane near the front shroud, meanline, and rear shroud. Figures 5 and 6 show the blade relative velocities vs distance in the meridional plane near the front shroud meanline and rear shroud. The impeller head will be 1 ot 2 percent lower than the Mark 29 impeller. Due to the lower impeller head coefficient, the impeller discharge velocity is lower at a given head rise than with the Mark 29 impeller. This results in less required diffusion, which should make up for the slight reduction in impeller head rise.

Impeller Selection

Based on core design considerations, and both hydrodynamic and stress analysis, the 7 full plus 7 partial vane impeller with 45 degree skewed vanes (Fig. 3) was selected as the final configuration for fabrication. A detailed assembly drawing was made and is shown in Figure 7. The front shroud, back shroud vanes and cores are fabricated as matched assemblies to minimize required tolerances and thus reduce the amount

DIFFUSION BONDED IMPELLER ON MARK 29

VANE △P PROFILE

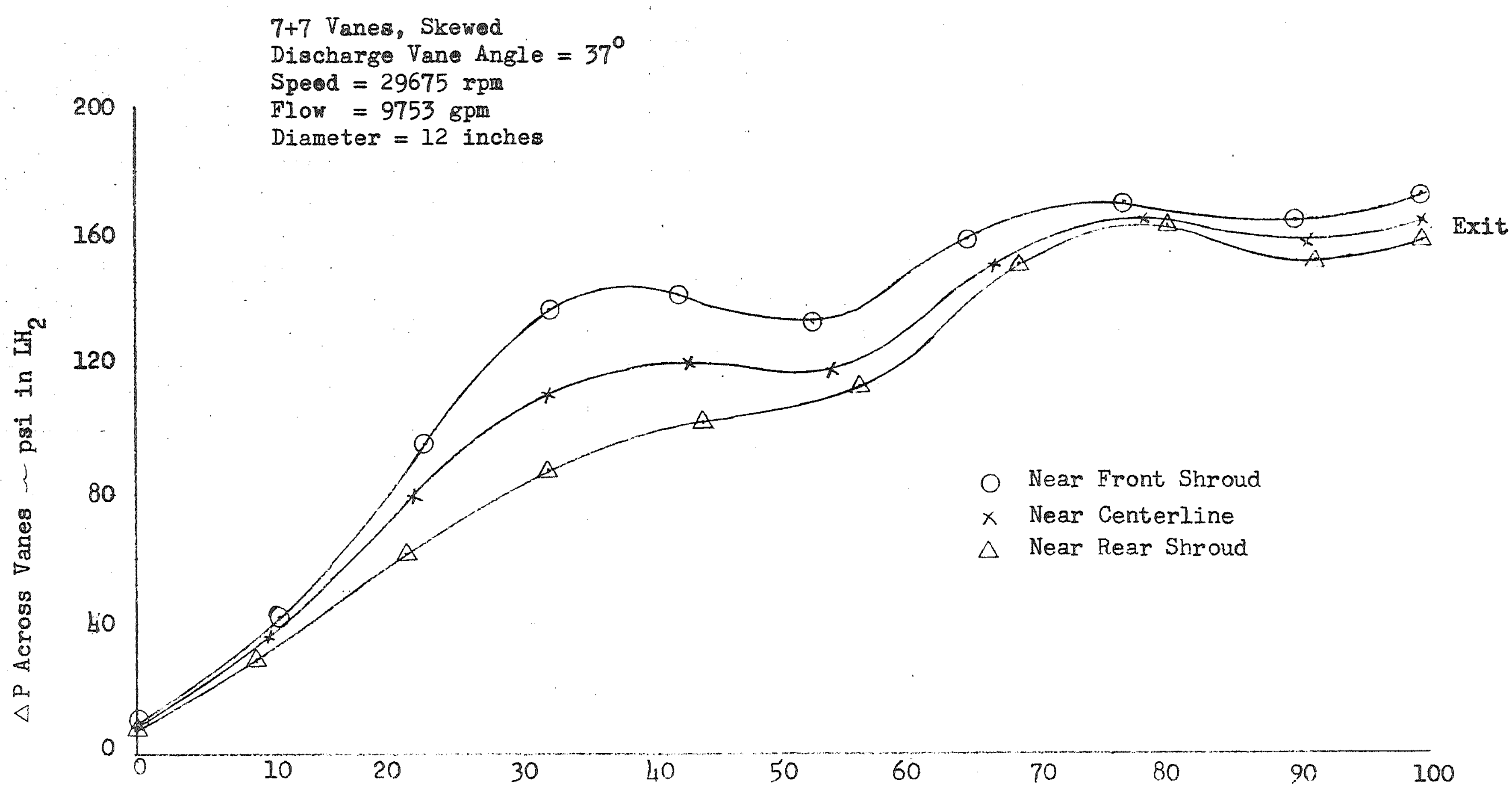


Figure 4. Diffusion Bonded Impeller - Vane Loading (Δ p) Profile

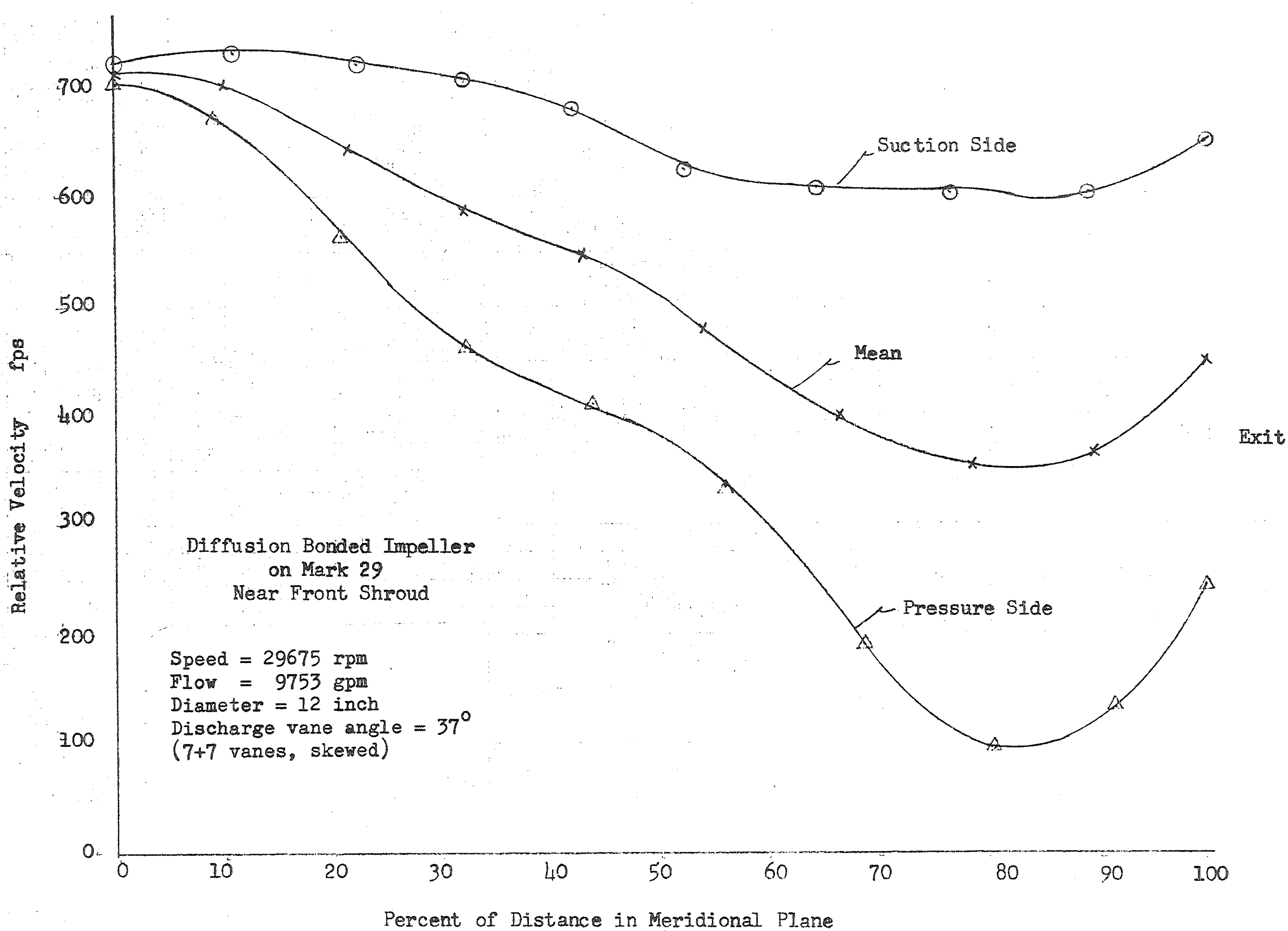
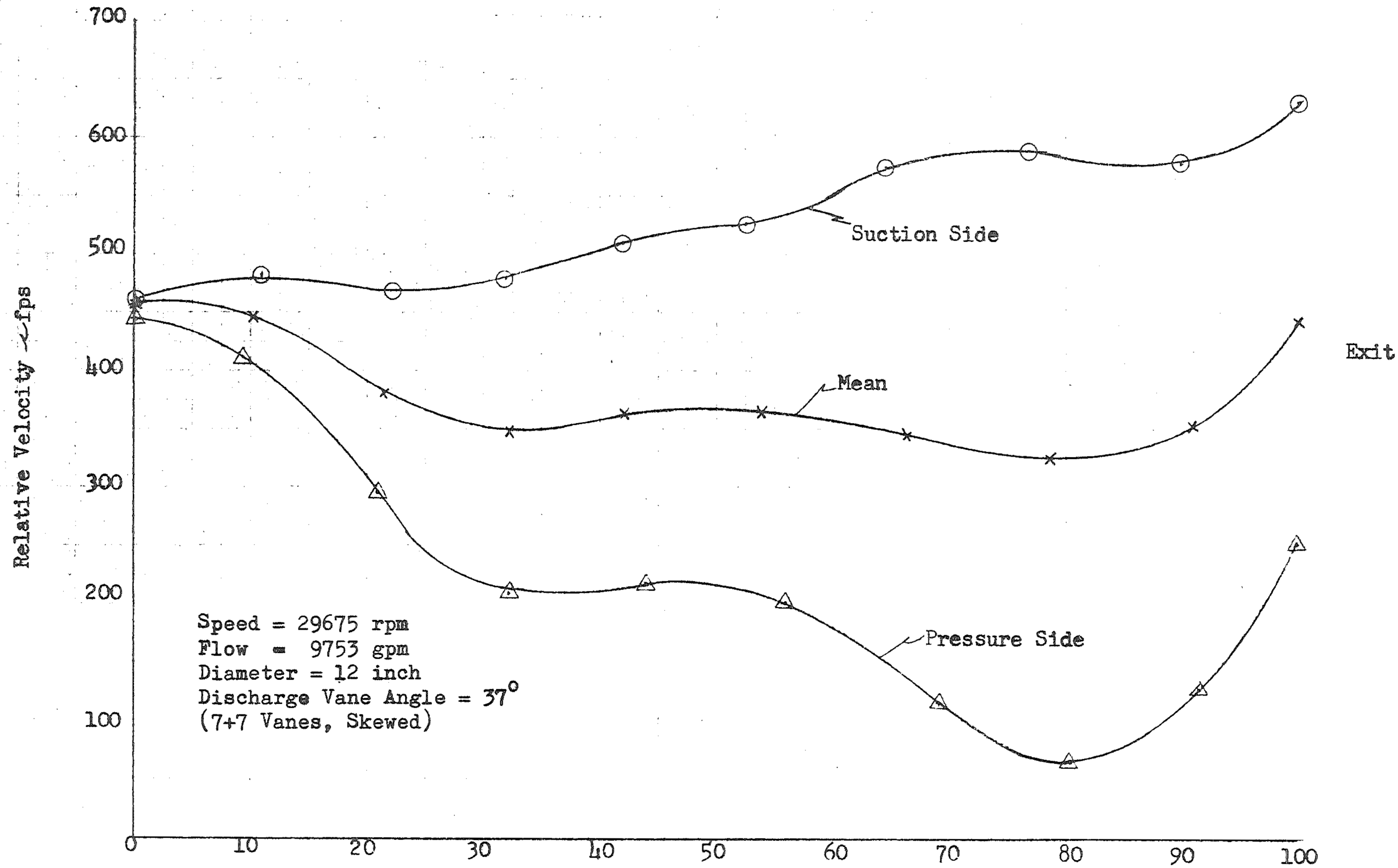
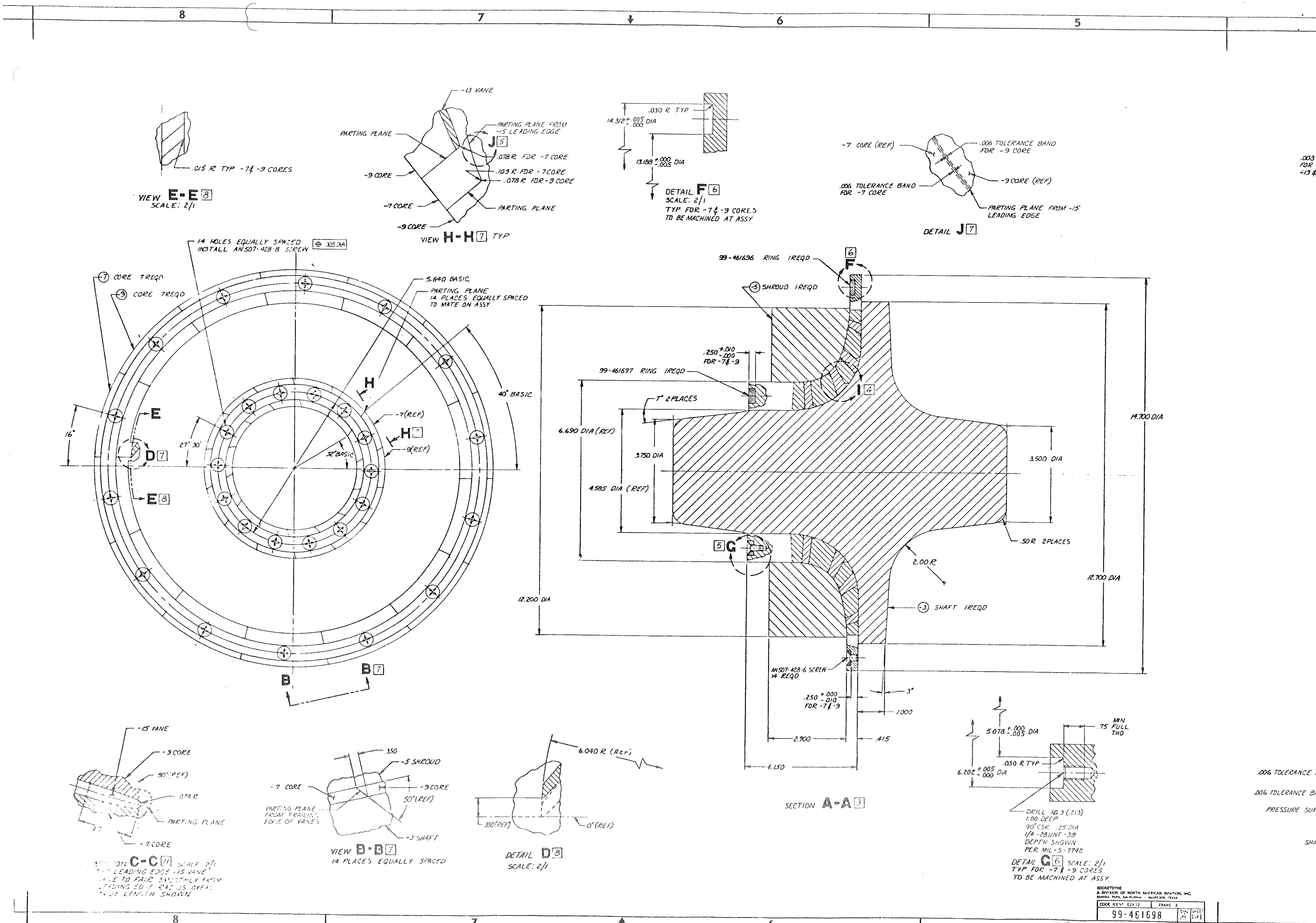


Figure 5. Diffusion Bonded Impeller Vane - Relative Velocity Near Front Shroud



Percent of Distance in Meridional Plane

Figure 6. Diffusion Bonded Impeller Vane Relative Velocity Near Rear Shroud



VIEW E-E 8
SCALE: 2/1
.015 R TYP -7 & -9 CORES
VIEW H-H 7 TYP
-13 VANE
PARTING PLANE
PARTING PLANE FROM -15 LEADING EDGE
.078 R FOR -7 CORE
.109 R FOR -7 CORE
.078 R FOR -9 CORE
-9 CORE
-7 CORE
DETAIL F 6
SCALE: 2/1
TYP FOR -7 & -9 CORES
TO BE MACHINED AT ASSY
.030 R TYP
14.312 +.005 -.000 DIA
13.188 +.000 -.005 DIA
DETAIL J 7
-7 CORE (REF)
.006 TOLERANCE BAND FOR -9 CORE
.006 TOLERANCE BAND FOR -7 CORE
-9 CORE (REF)
PARTING PLANE FROM -15 LEADING EDGE
14 HOLES EQUALLY SPACED
INSTALL AN507-428-8 SCREW
-7 CORE 7 REQD
-9 CORE 7 REQD
5.640 BASIC
PARTING PLANE
14 PLACES EQUALLY SPACED
TO MATE ON ASSY
40° BASIC
32° BASIC
27° 30'
16°
-7 (REF)
-9 (REF)
99-461696 RING 1 REQD
-5 SHROUD 1 REQD
99-461697 RING 1 REQD
.250 +.010 -.000 FOR -7 & -9
1° 2 PLACES
6.690 DIA (REF)
3.750 DIA
4.585 DIA (REF)
12.200 DIA
14.700 DIA
3.500 DIA
12.700 DIA
.50 R 2 PLACES
2.00 R
-3 SHAFT 1 REQD
AN507-428-6 SCREW 14 REQD
.250 +.000 -.010 FOR -7 & -9
3°
1.000
2.900
.415
4.150
SECTION A-A 3
5.078 +.000 -.005 DIA
6.202 +.005 -.000 DIA
.030 R TYP
MIN .75 FULL THD
DRILL NO. 3 (.213)
1.00 DEEP
90° CSK .25 DIA
1/4-28UNF-3B
DEPTH SHOWN
PER MIL-S-7742
DETAIL G 6 SCALE: 2/1
TYP FOR -7 & -9 CORES
TO BE MACHINED AT ASSY.
-15 VANE
-9 CORE
80° (REF)
.074 R
PARTING PLANE
-7 CORE
SECTION C-C SCALE 2/1
LEADING EDGE -15 VANE
TO FAIR SMOOTHLY FROM LEADING EDGE RADIUS OVER LENGTH SHOWN
.350
-5 SHROUD
-7 CORE
-9 CORE
50° (REF)
PARTING PLANE FROM TRAILING EDGE OF VANES
-3 SHAFT
VIEW B-B 7
14 PLACES EQUALLY SPACED
6.040 R (REF)
.350 (REF)
0° (REF)
DETAIL D 8
SCALE: 2/1
.006 TOLERANCE BA
.006 TOLERANCE BAN
PRESSURE SURFA
SHAFT
ROCKETDYNE
A DIVISION OF NORTH AMERICAN AVIATION, INC.
CODE IDENT 02602
FRAME 2
99-461698

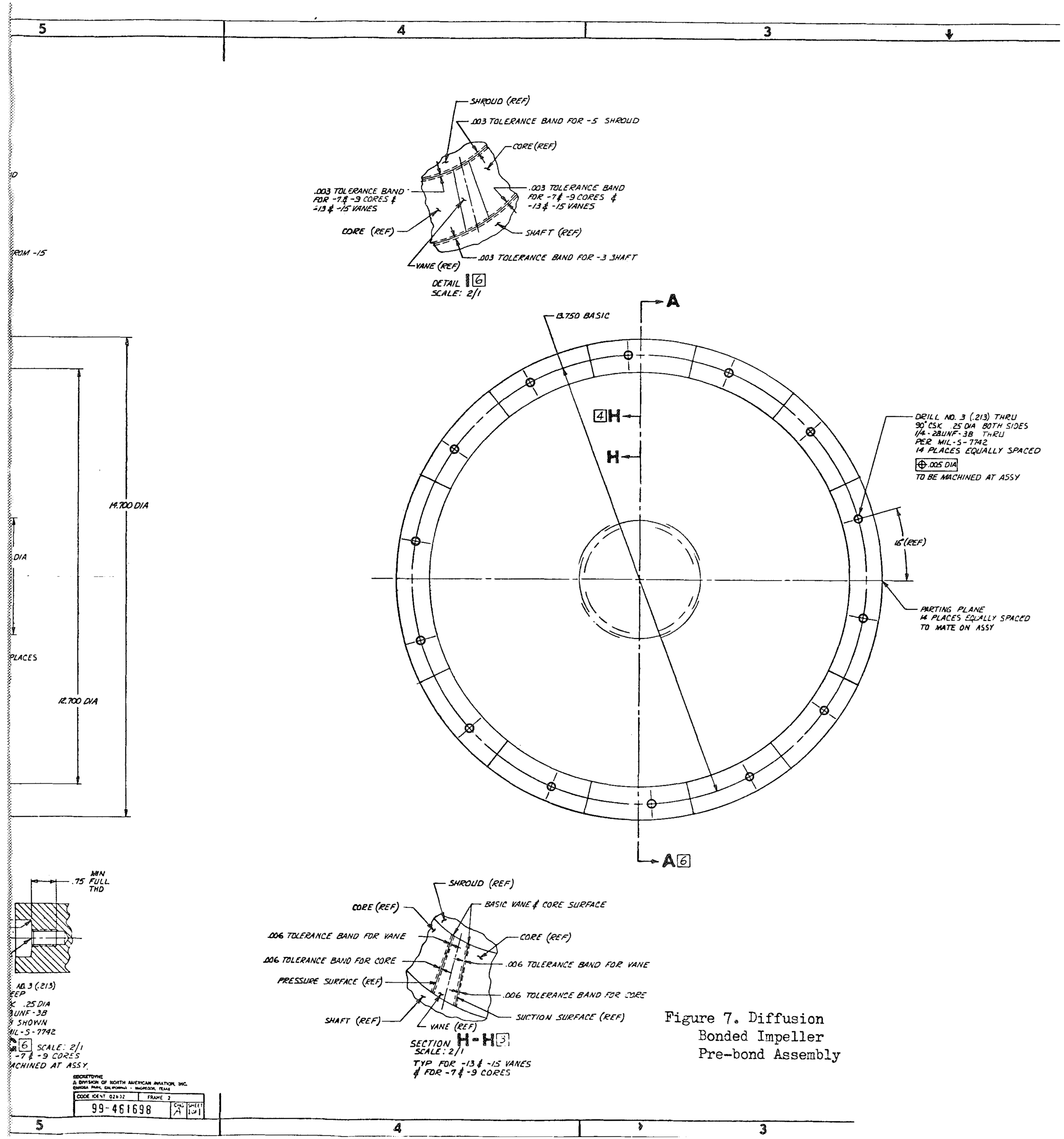


Figure 7. Diffusion Bonded Impeller Pre-bond Assembly

of titanium that must be moved during the bonding cycle. An allowance of 0.040 inch has been added to all passage surfaces to permit removal, by chemical-milling, of the interaction layer formed during the bonding process.

Diffusion Bonded Test Samples. A titanium alloy forging was procured to be used for trial diffusion bonding runs. Samples to be bonded were used to simulate and attempt to solve problem areas envisioned during fabrication of the actual impeller. For example, the inner and outer shroud contour, vane taper and filleting were simulated to determine conditions necessary to produce a satisfactory bond.

It was believed that the quickest approach toward achieving a diffusion bonded impeller was to attempt fabrication of simulated, simplified impeller using existing material, processing, and tool concepts. Modifications to the foregoing concepts were predicated upon the results obtained in these trials.

Due to the limited size and shape of the available forging, it was impractical to achieve the desired impeller eye opening of 1.25 inch. A compromise configuration shown in Figs. 8 and 9, provided for the following:

(1) Simulated inner shroud curved surface
(2) Simulated outer shroud curved surface
(3) Four impeller vanes spaced at 90 degrees
(4) Use of 3.5 inch I.D. 17-4 PH restrainer to hold total tool-part assemblage.
(5) Vertical and semi-horizontal bond joints
(6) Desired front and rear joint radii
(7) Simple geometry permits ready determination of volumes and various pre-bond and post bond measurements.
(8) Variations of internal tooling

The effects studied in bonding the above simulated impeller were:

(1) Die fill, flash and fillet formation

(2) Completeness of bonding
(3) Tooling behavior and dimensional changes
(4) Volume and configuration control
(5) Tool removal effectiveness
(6) Mechanical and metallurgical
(7) Effect of core splitting

Experimental Plan

The titanium and tooling details were fabricated for two impellers as shown in Fig. 8. and Fig. 9. The dimensions were taken and volumes calculated for all tool and titanium details. Sufficient volume of titanium was provided for complete die fill. One impeller was bonded using parameters outlined above. The as-bonded impeller was externally and dimensionally profiled with steel core remaining inside. The as-bonded impeller billet was X-rayed in several views to ascertain and locate possible non-fill voids or tool displacement anomolies.

The as-bonded billet was then cut into two halves along the major diameter to expose the dimensional profile including two of the impeller vanes. Dimensions were taken of the part and tool profiles. The two cut halves were acid leached to remove remaining core filler metal. X-rays of halves were taken and joint surfaces were visually examined for filleting and surface condition. Dye penetrant was applied to disclose possible bond line condition. The remaining impeller halves were then sectioned for removal of appropriate mechanical test specimens.

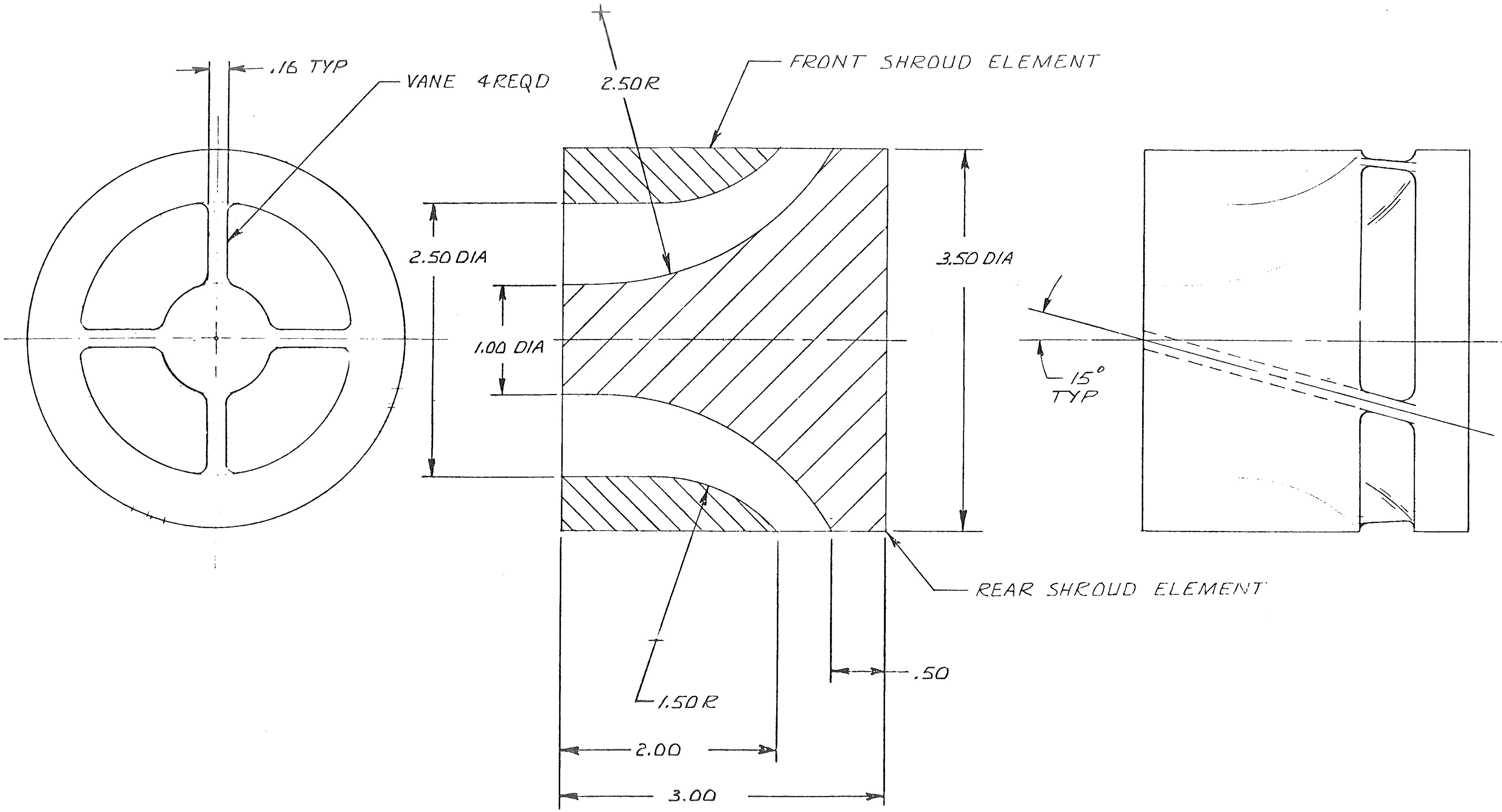


Figure 8. Trial Sample Configuration

NOTE: 1. VANE TO FRONT SHROUD FILLET R .08 R
2. VANE TO REAR SHROUD FILLET R .112 R
3. VANE HT TO HAVE EXCESS MATL TO FILL VANE TO SHROUD FILLETS

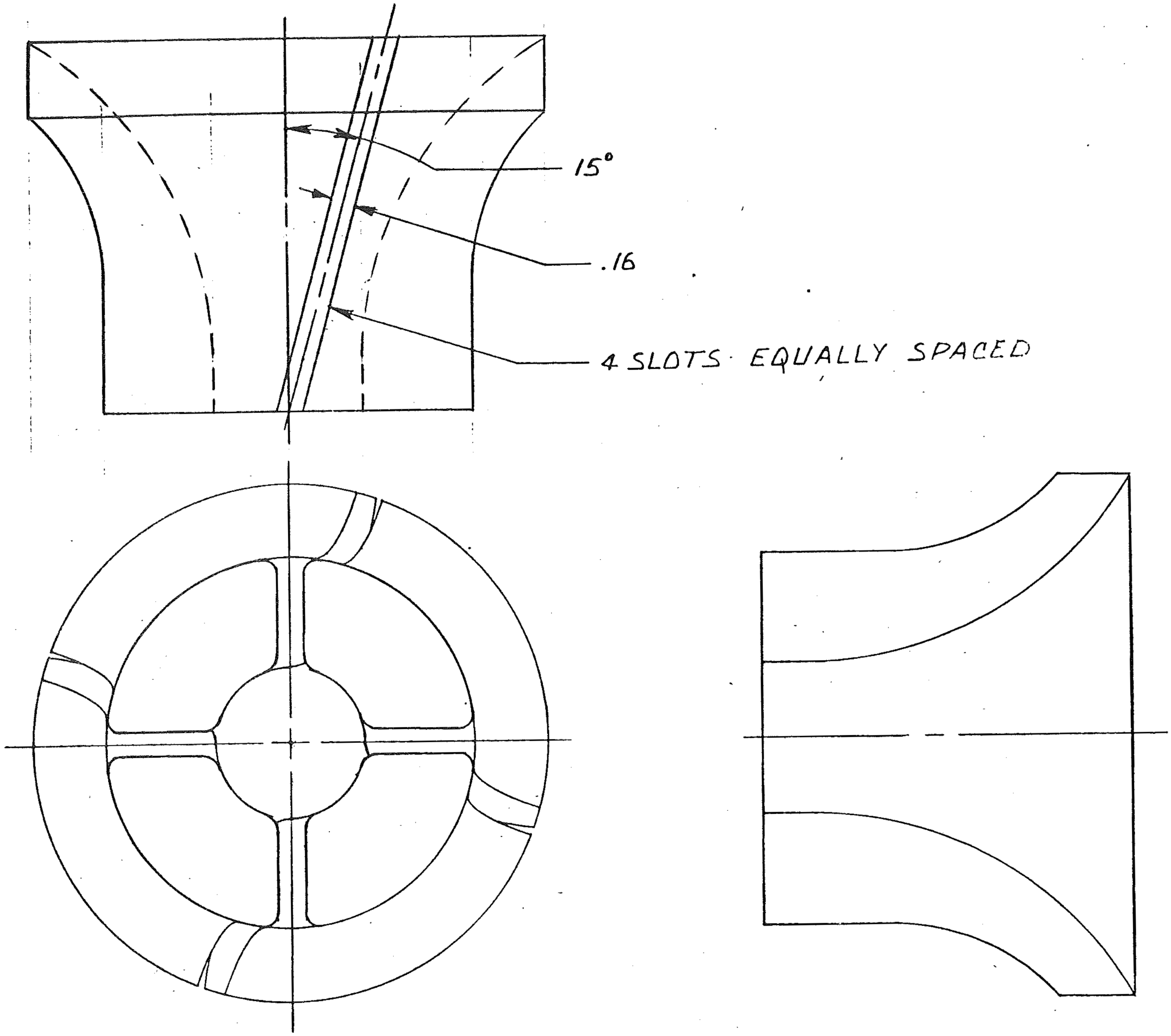


Figure 9. Steel Core for Trial Sample

Bonding

Three simulated impellers were fabricated and one impeller sample was bonded. Figures 10 thru 14 are a sequence of photographs showing the sample in various stages of assembly-type bonding. Figure 10 shows the simulated impeller front and back shrouds, and vanes. Figure 11 shows the impeller assembly with lower pressure plate, outer shroud, vanes and cores. The back shroud has been omitted to show the fillet that must be filled during the bonding process. Figure 12 shows the cores, upper and lower pressure plates and the outer restraining tooling. Figure 13b shows the impeller and tooling assembly prior to installation in the retort. Figure 14 shows the completed assembly in the retort ready for the bonding cycle.

First Trial Impeller Sample

The first sample was bonded for 16 hours at a temperature between 1700 to 1800 degrees F and at pressures that varied between 2000 to 4000 psi. Figures 15 and 16 show the sample after removal from the retort and restrainer tooling. A force of 280,000 pounds was required to remove the sample from the restrainer tooling, due to bonding of 4340 steel cores to the 17-4 PH outer restrainer. As can be seen from the photographs, this caused a slight separation of the tooling and rear shroud.

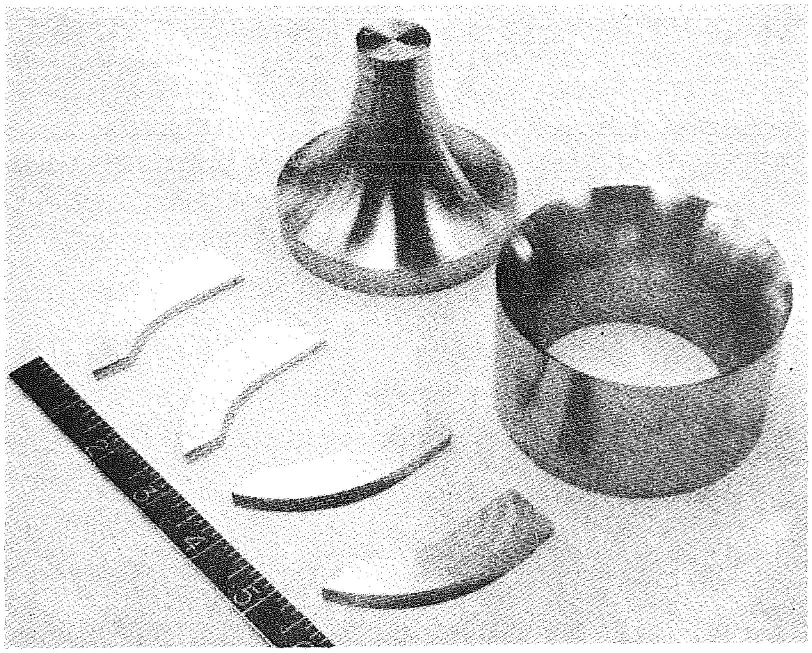


Figure 10a

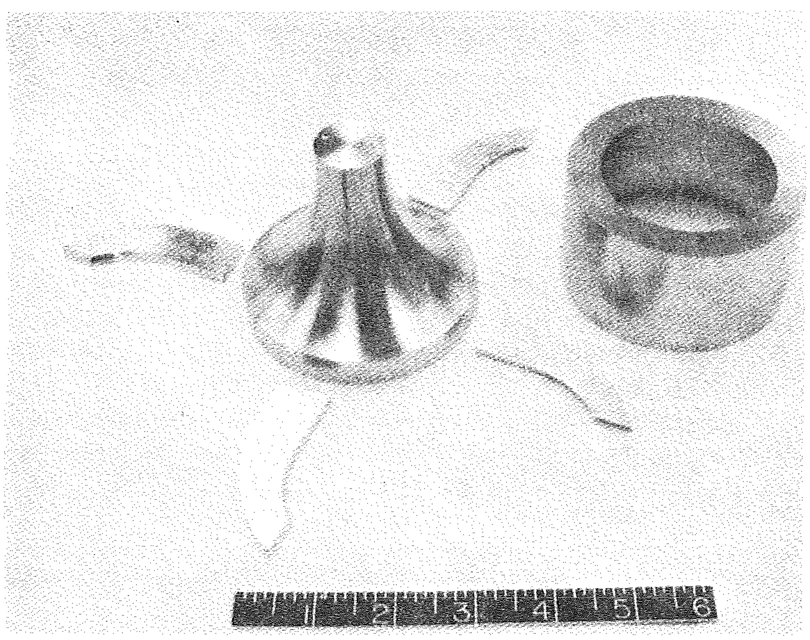


Figure 10b

Figure 10a and 10b. Simulated Impeller - Trial Sample

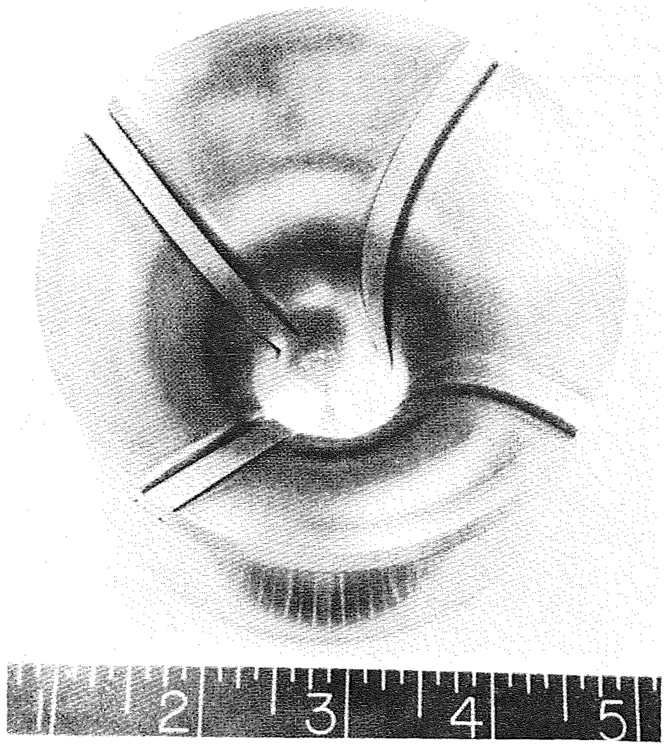


Figure 11a

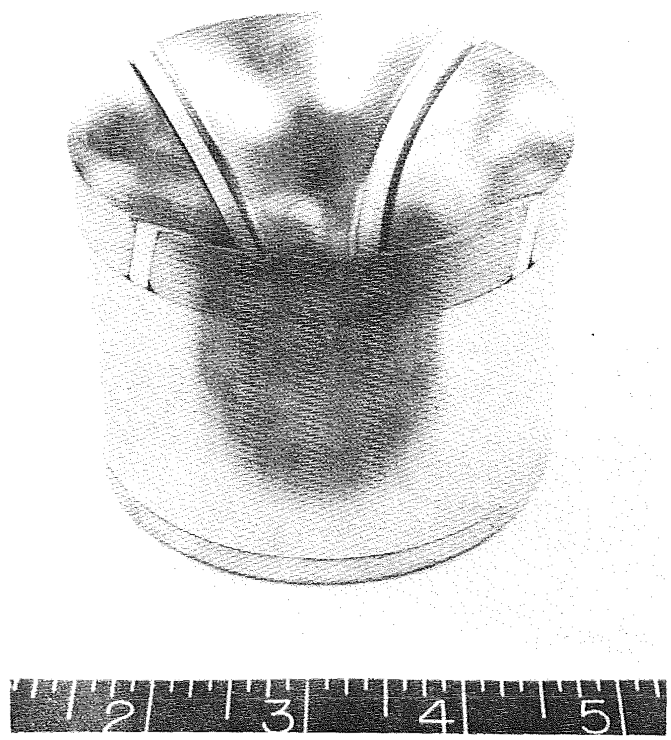


Figure 11b

Figure 11a and 11b. Simulated Impeller - Assembly with Cores and Lower Pressure Plate (Without Back Shroud)

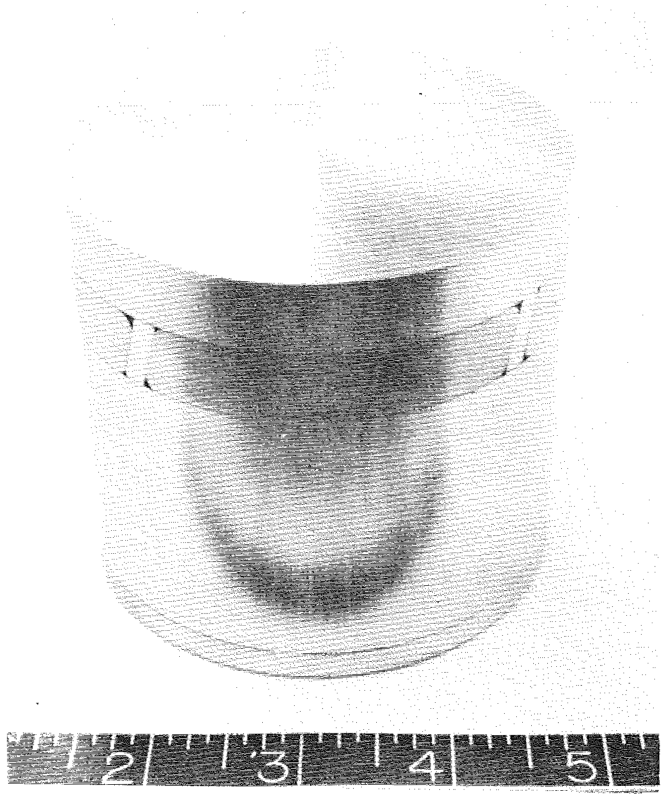


Fig. 12 a. Assembly with Back Shroud and Lower Pressure Plate, and Cores

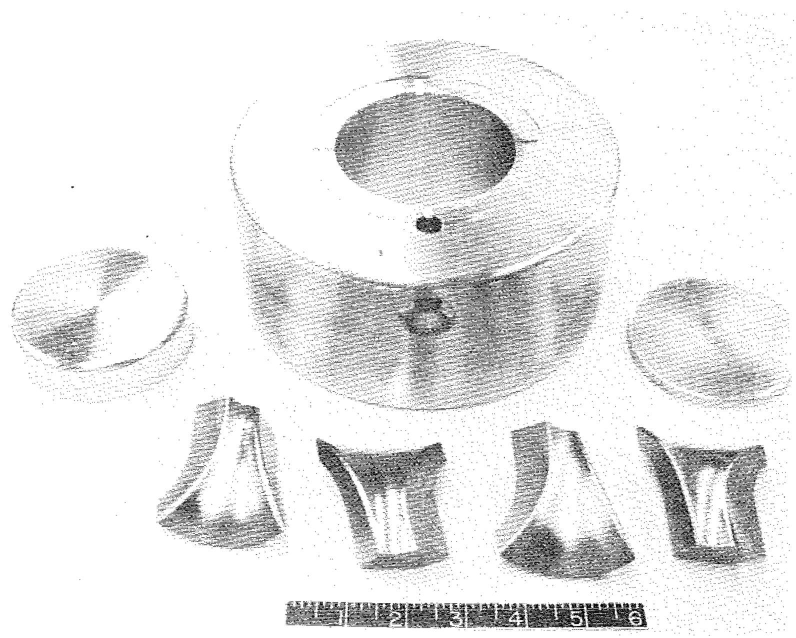


Fig. 12b. Cores, Pressure,Plates, and Outer Containment Tooling

Figure 12 . Simulated Impeller Assemblies

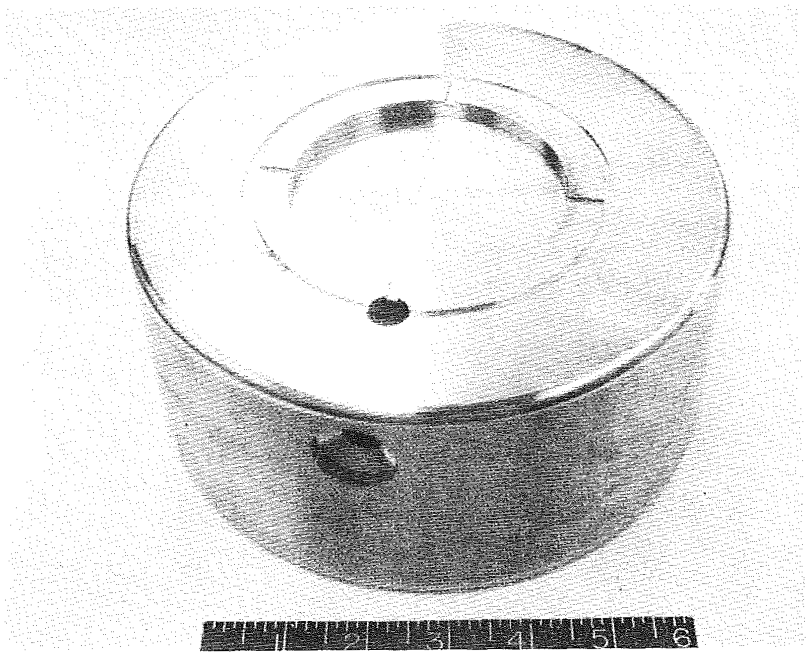


Figure 13a. Assembly Without Upper Pressure Plate

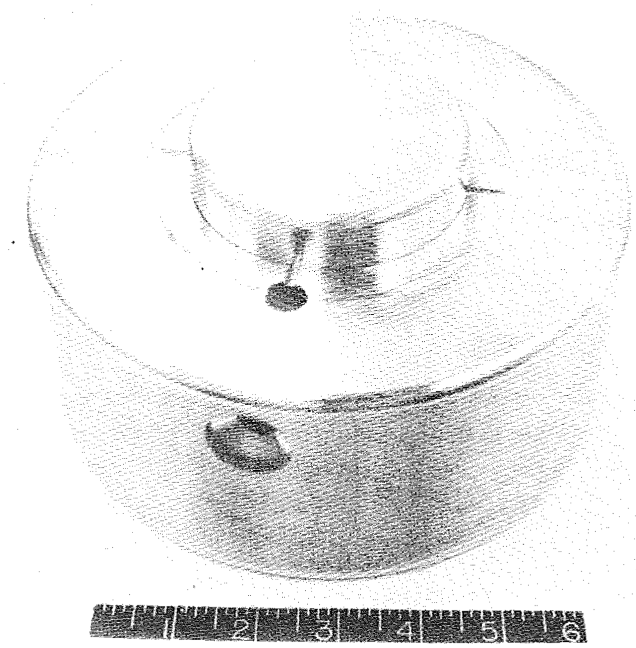


Figure 13b. Assembly With Upper Pressure Plate

Figure 13. Simulated Impeller Assembly

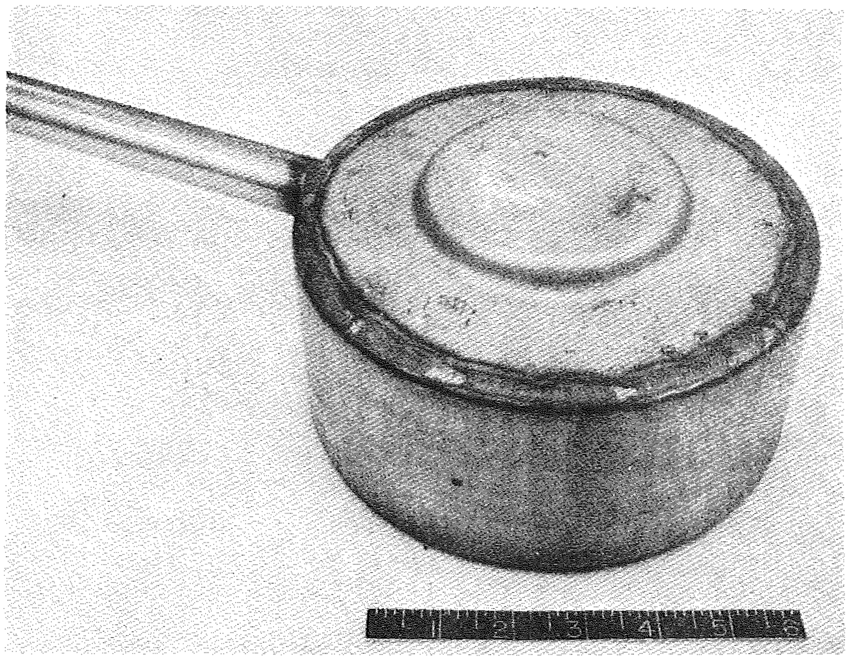


Figure 14. Complete Simulated Impeller Assembly
Ready for Bonding

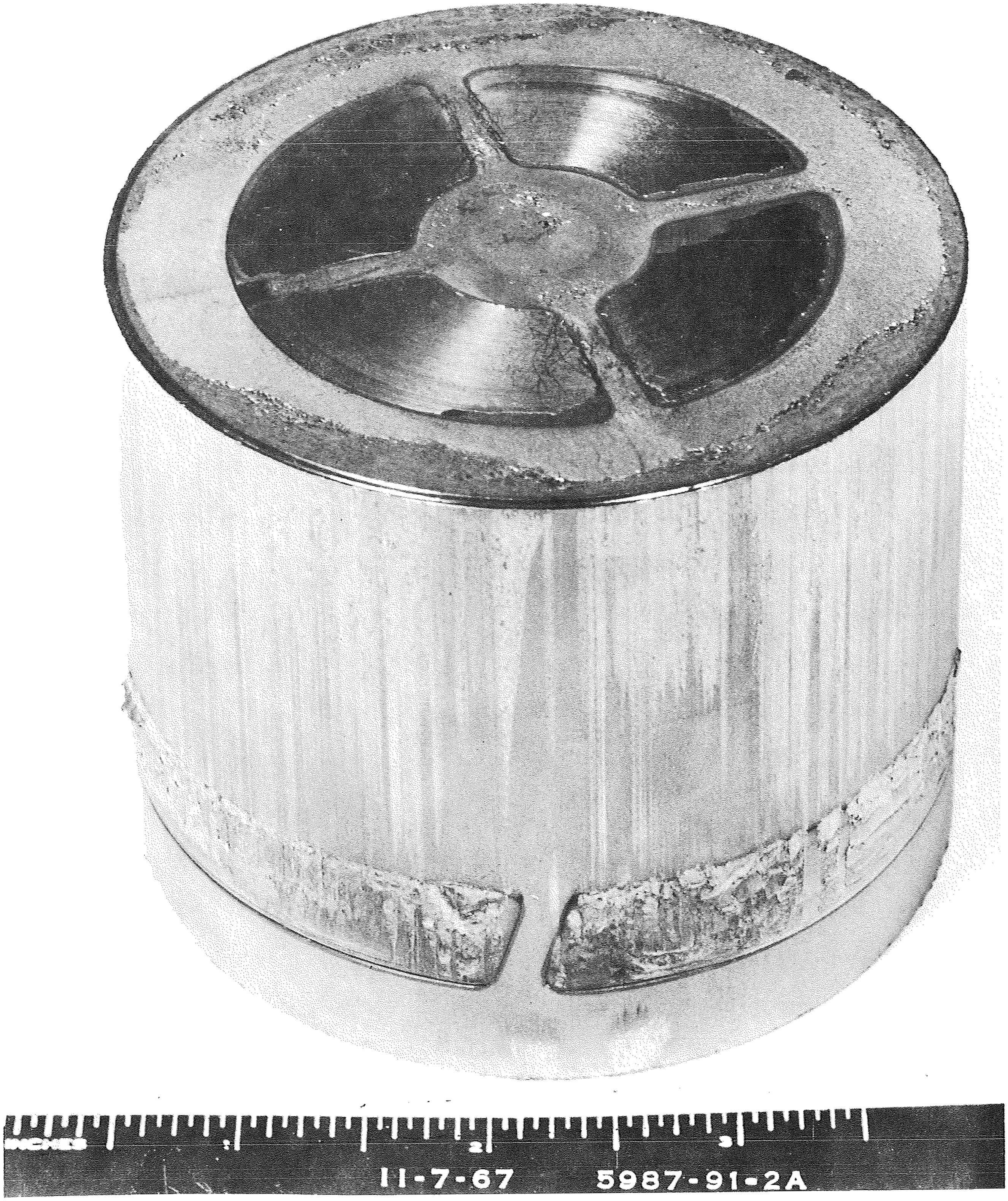


Figure 15. Test Sample After Removal From Restrainer Tooling

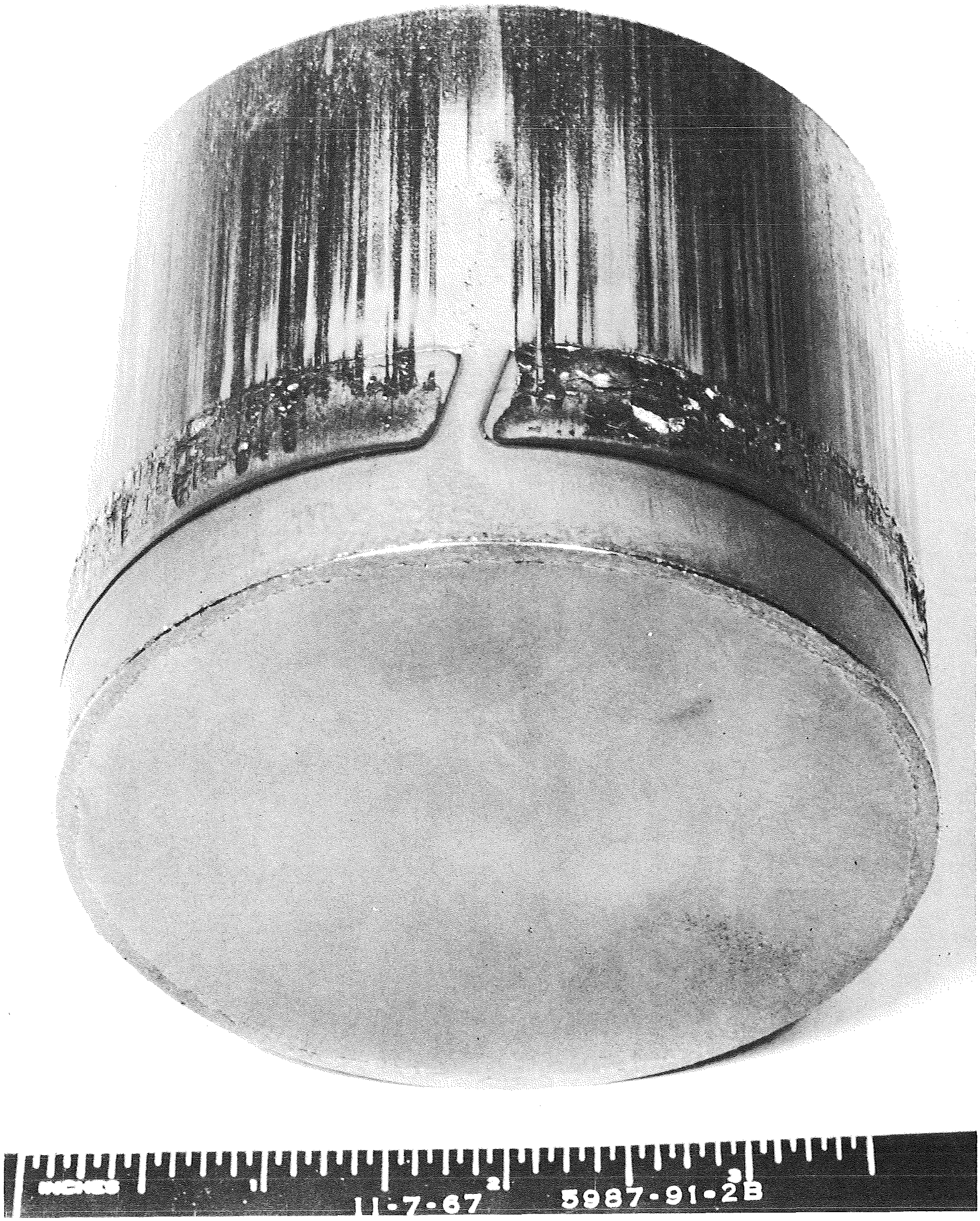


Figure 16. Test Sample After Removal From Restrainer Tooling

Detail inspection indicated the interaction layer between the cores and impeller to be less than 0.010 inch thick. It was also noted that complete forming of the fillets at the impeller discharge did not occur at all joints. Figures 17, 18, and 19 are different views of the impeller subsequent to a light machine cut for surface clean up. Figures 20(a) and 20(b) show the sample after leaching of the cores and initial chem-milling to remove the interaction layer. As can be seen from Fig. 20(a), a complete formation of the fillets did not occur on the vanes in the impeller passages. Investigation indicated that this was attributable to growth and yielding of the outer restrainer tooling and/or incorrect length of time and pressure at the bonding temperature. Examination of the fillet area at the impeller eye under a magnification of 250 (see Fig. 21) indicated that a slight notch of 0.004 inch existed after initial chem-milling. Lines existing on Figure 21 are scratches on the specimen. Additional chem-milling was performed on the part to remove a total of 0.020 inch of material and thus eliminate the notched area. Figure 22(a) and 22(b) show the inner and outer fillet at the impeller eye at a magnification of 40 after total material removal of 0.020 inch on each surface. Figure 23(a) and 23(b) show the grain structure of the titanium material before and after bonding at a magnification of 250X. As can be seen, grain growth occurred during the bonding process. Wrought titanium alloys, as received, have variations in properties. The diffusion bonding cycle produces a fully anealed structure with more uniform properties.

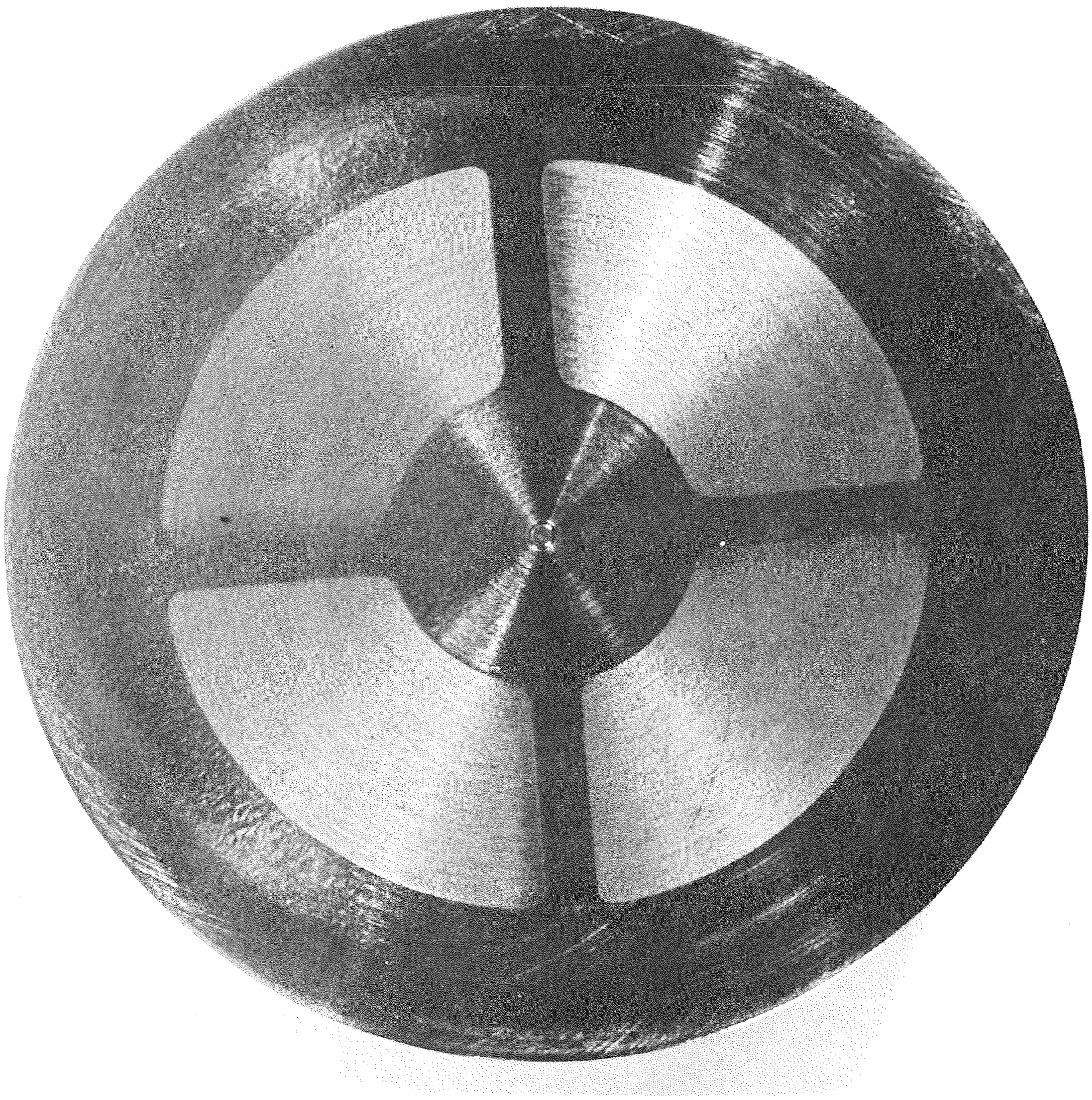


Figure 17. Test Sample After Clean Up Machining - Inlet Eye View

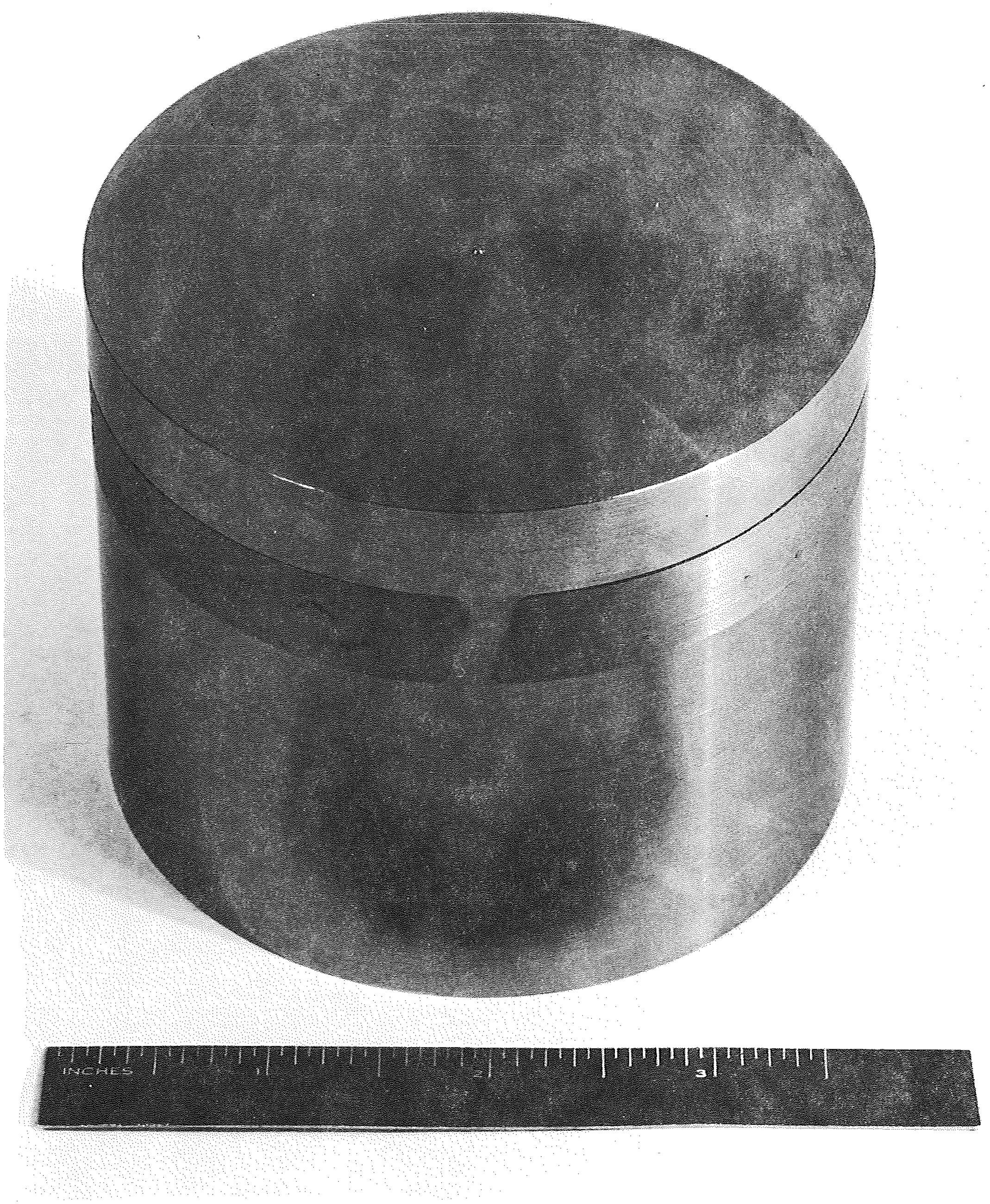


Figure 18. Test Sample After Clean Up Machining - Rear Shroud View

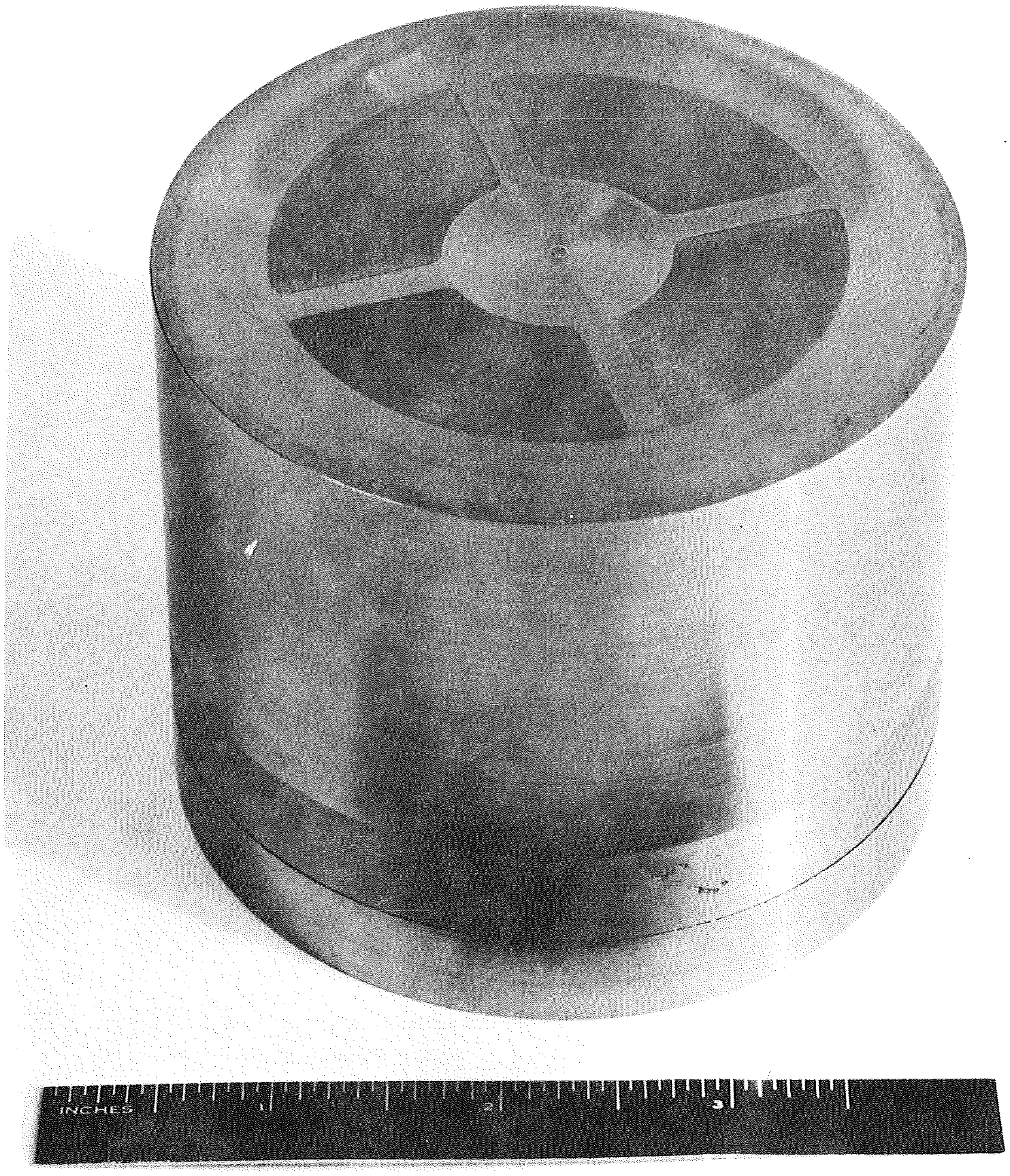


Figure 19. Test Sample After Clean Up Machining - Eye and Discharge View

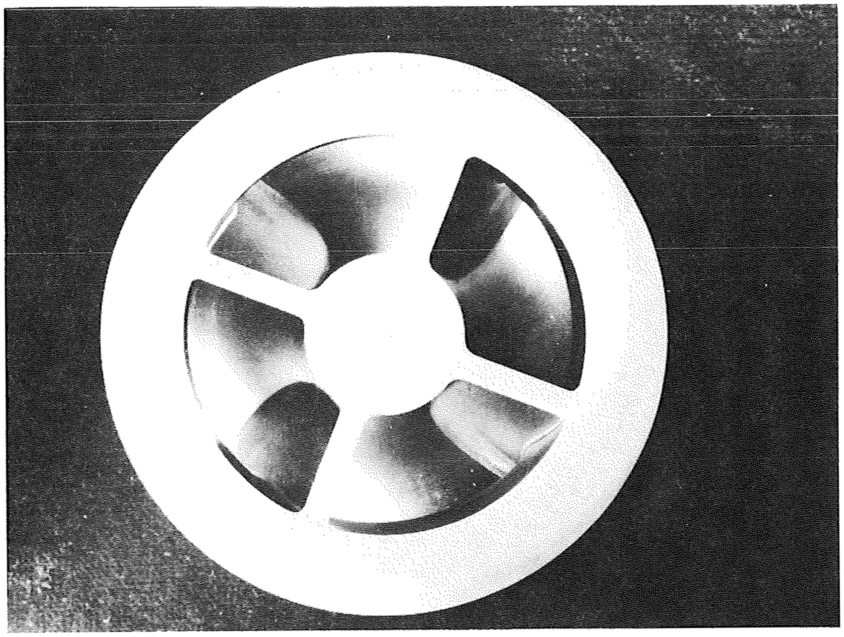


Figure 20 (a). Eye View

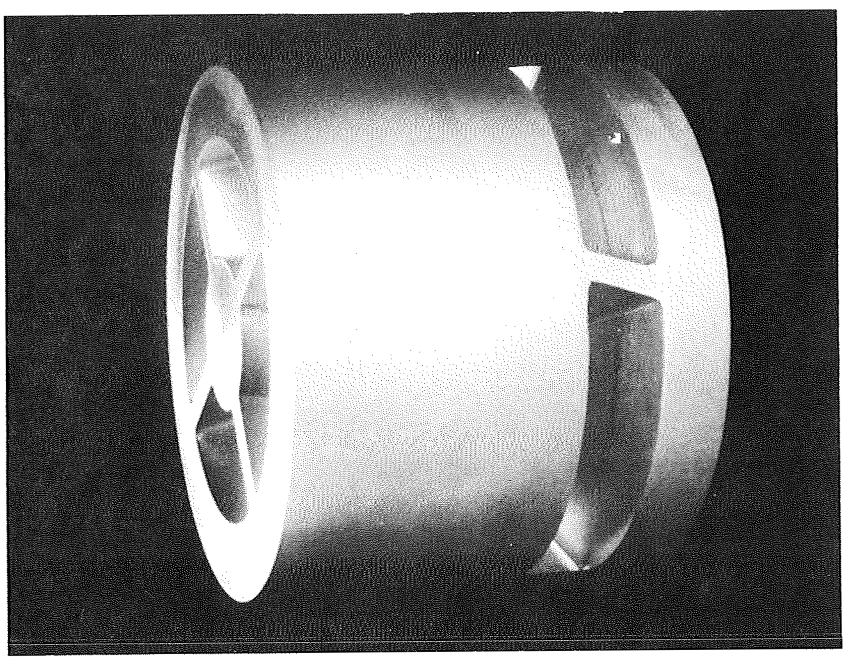


Figure 20(b). Side View

Figure 20. Test Sample After Core Removal

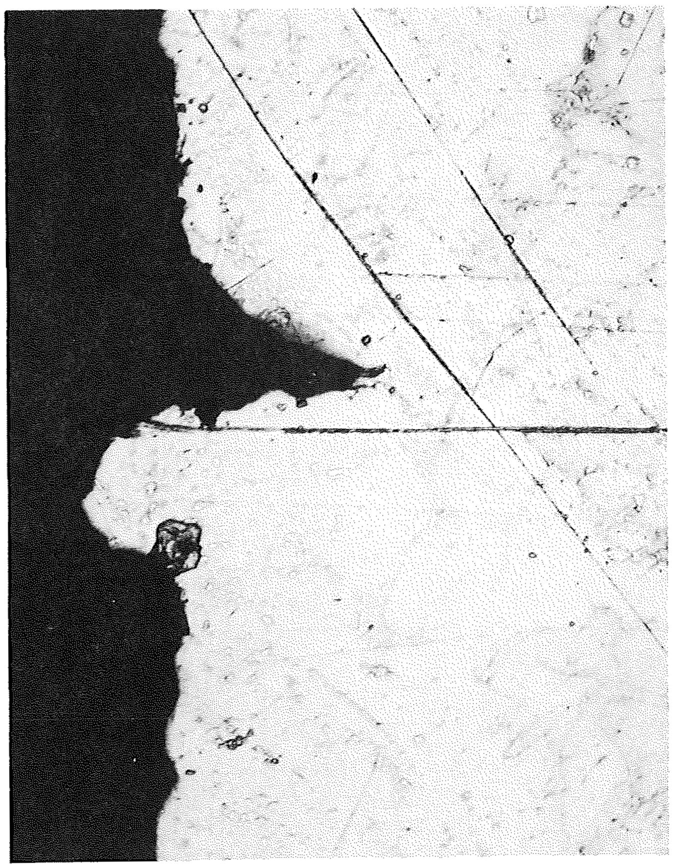


Figure 21. Typical notch at eye vane fillet on first trial sample. Magnification 250 x - Notch .004 inch deep.

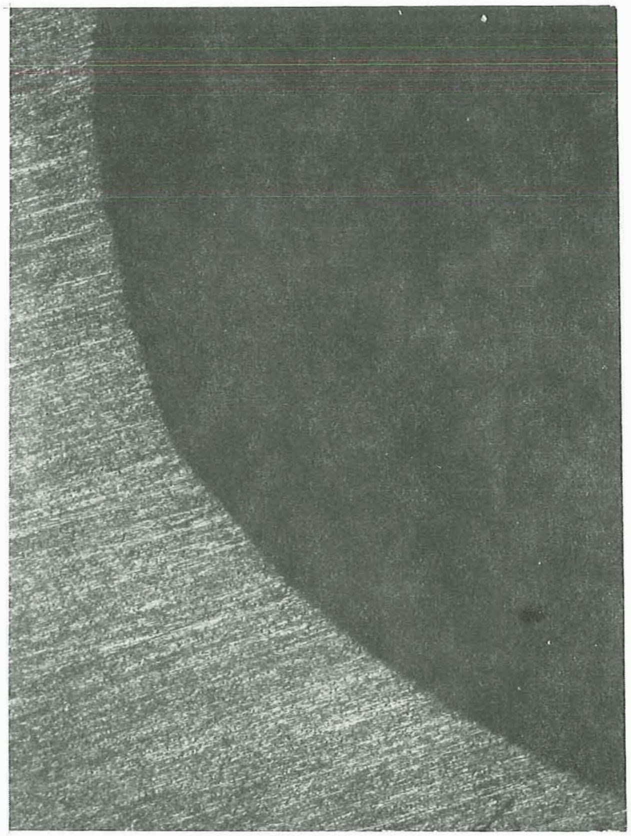


Figure 22(a)

Vane Fillet at Inner Shroud - 40X

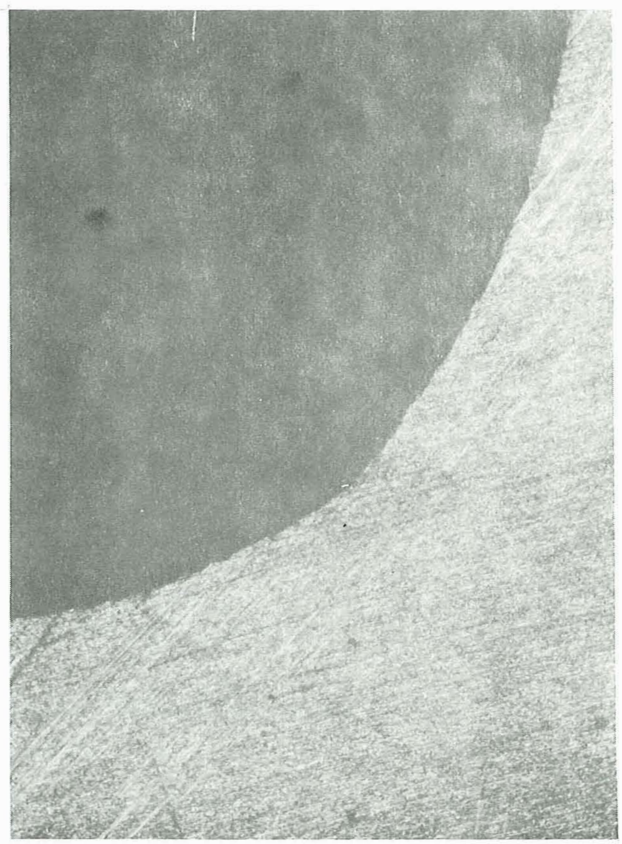


Figure 22 (b)

Vane Fillet at Outer Shroud - 40X

Figure 22. Photographs of Vane Fillets at Impeller Eye on First Trial Sample After Chem-milling of 0.020 Inch (Magnification 40X)

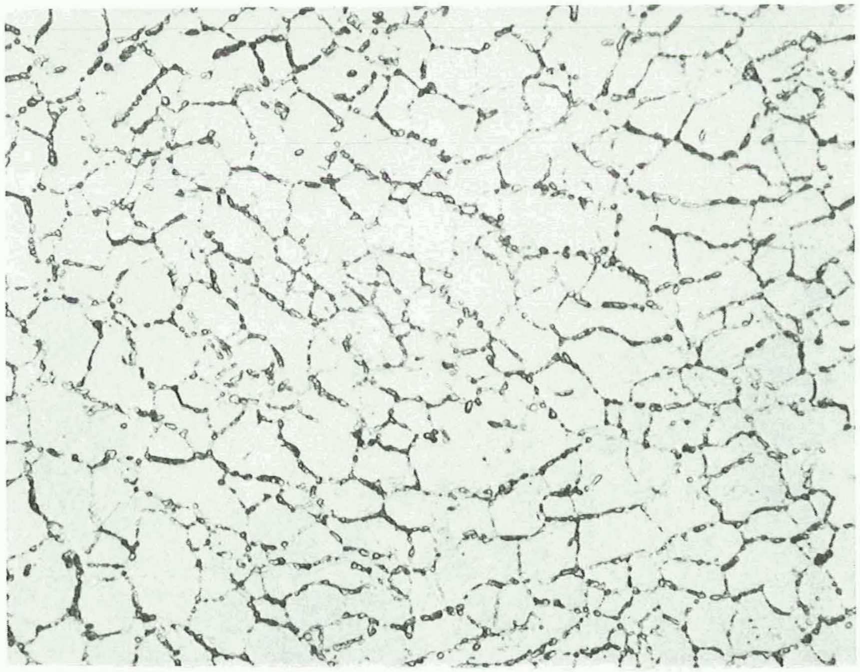


Fig. 23a. Before Bonding or as Received

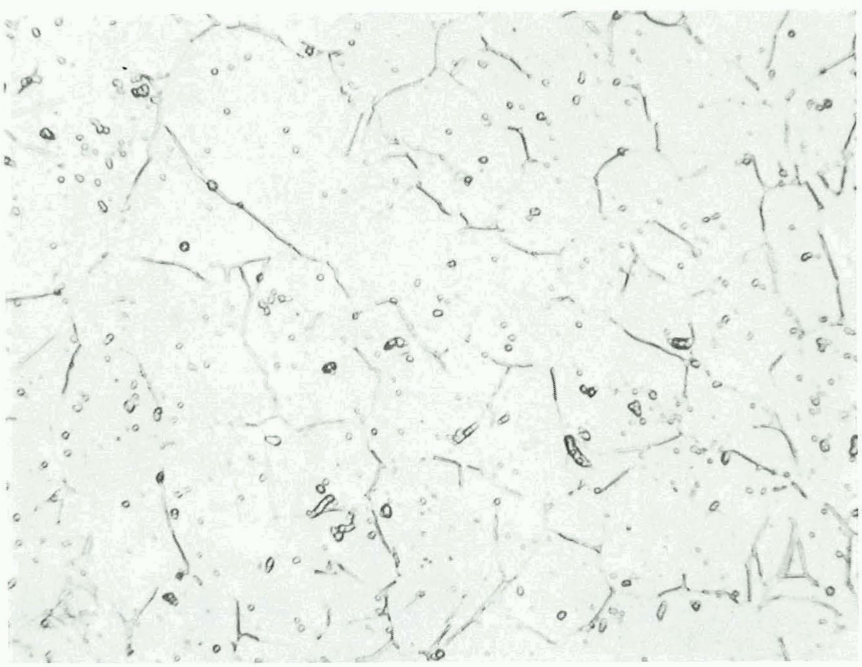


Fig. 23b After Bonding

Figure 23. Photographs of First Sample Grain Structure Before and After Bonding. Alloy T_i 5AL - 2.5 Sn Forging. Magnification 250X.

Figures 24 to 26 are photographs of the first sample impeller after final chem-milling. A total of 0.020 inch of material per surface was removed by chem-milling from the first test sample. Dye penetrant inspection of the bond joints after final chem-milling indicated that a localized crack about 1/32 inch deep existed at the edge of the impeller discharge vane fillets.

Second Trial Impeller Sample

A second trial impeller was fabricated which was identical to the first sample. The sample was bonded using new restrainer tooling designed to minimize radial growth during the bonding cycle. The new restrainer consists of an inner cylindrical stainless steel liner 1/4 inch thick, an intermediate ceramic cylinder 6 inches in thickness, and an outer retainer of 4340 steel about 3/4 inch thick. The ceramic and outer steel restrainer are split to prevent damage to the ceramic during assembly and disassembly. A castable massrock material was used for the ceramic restrainer. This material has low coefficients of thermal expansion and heat transfer.

Figures 27 through 32 are a series of photographs showing the sample in various stages of assembly and disassembly before and after the bonding cycle. The second sample was bonded at a temperature between 1600 and 1700 degrees F for a period of 16 hours with constant pressure of 2000 psi. It should be noted that the cracks in the ceramic restrainer shown in Fig. 32 are curing cracks and were present before bonding.

Inspection of the second trial sample indicated that complete formation of the fillets did not occur because the impeller assembly was not completely seated in the tooling prior to the heating cycle. A new retort and restrainer was fabricated and the impeller was repressed in an attempt to complete fillet formation. To insure proper seating during repressing the assembly was placed under an initial pressure of 5000 psia and heated at a pressure of 2000 psi to assure seating of all parts.

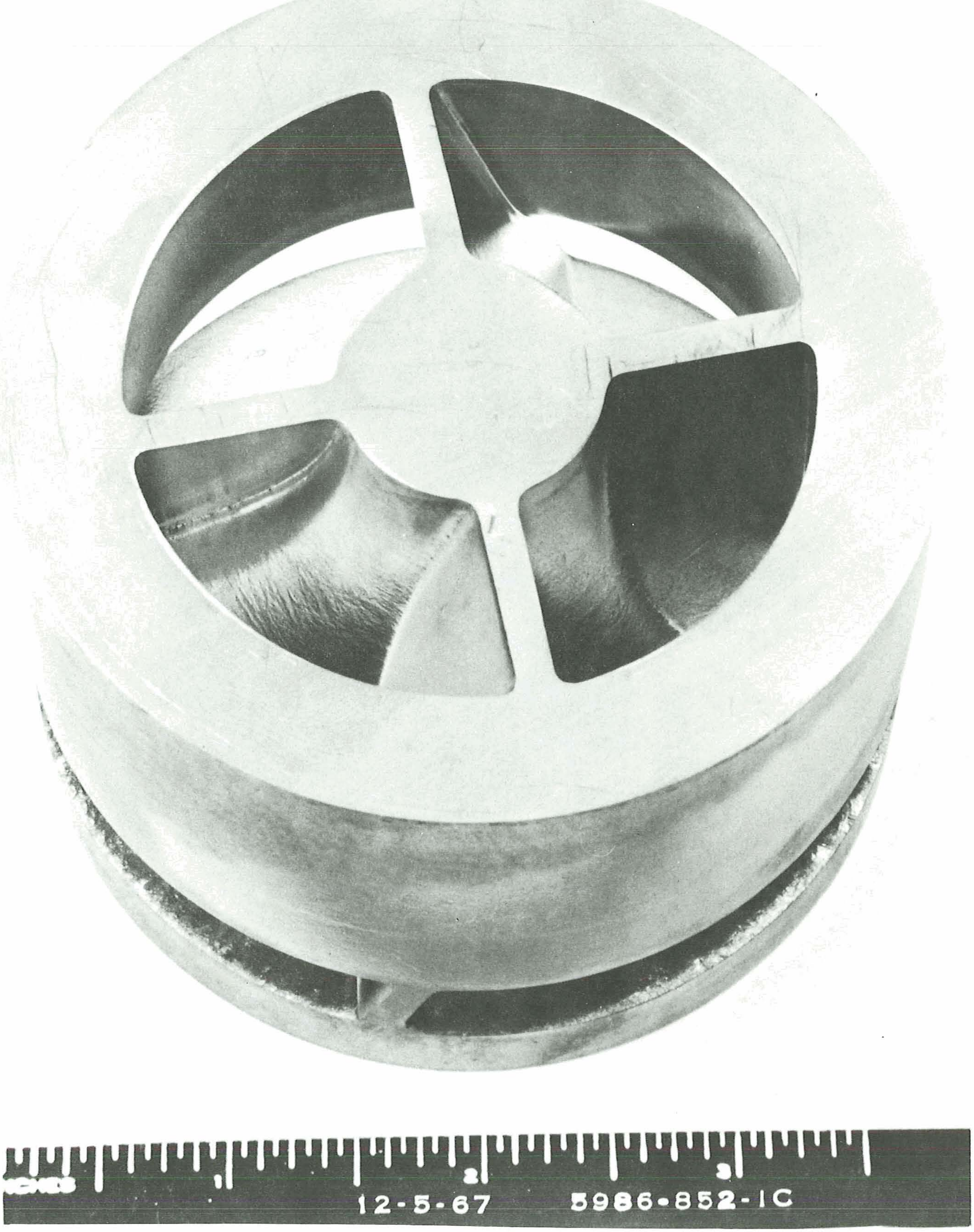


Figure 24. First Trial Sample After Final Chem-Milling - Eye Discharge View

Figure 25. First Trial Sample After Final Chem-Milling - Eye View

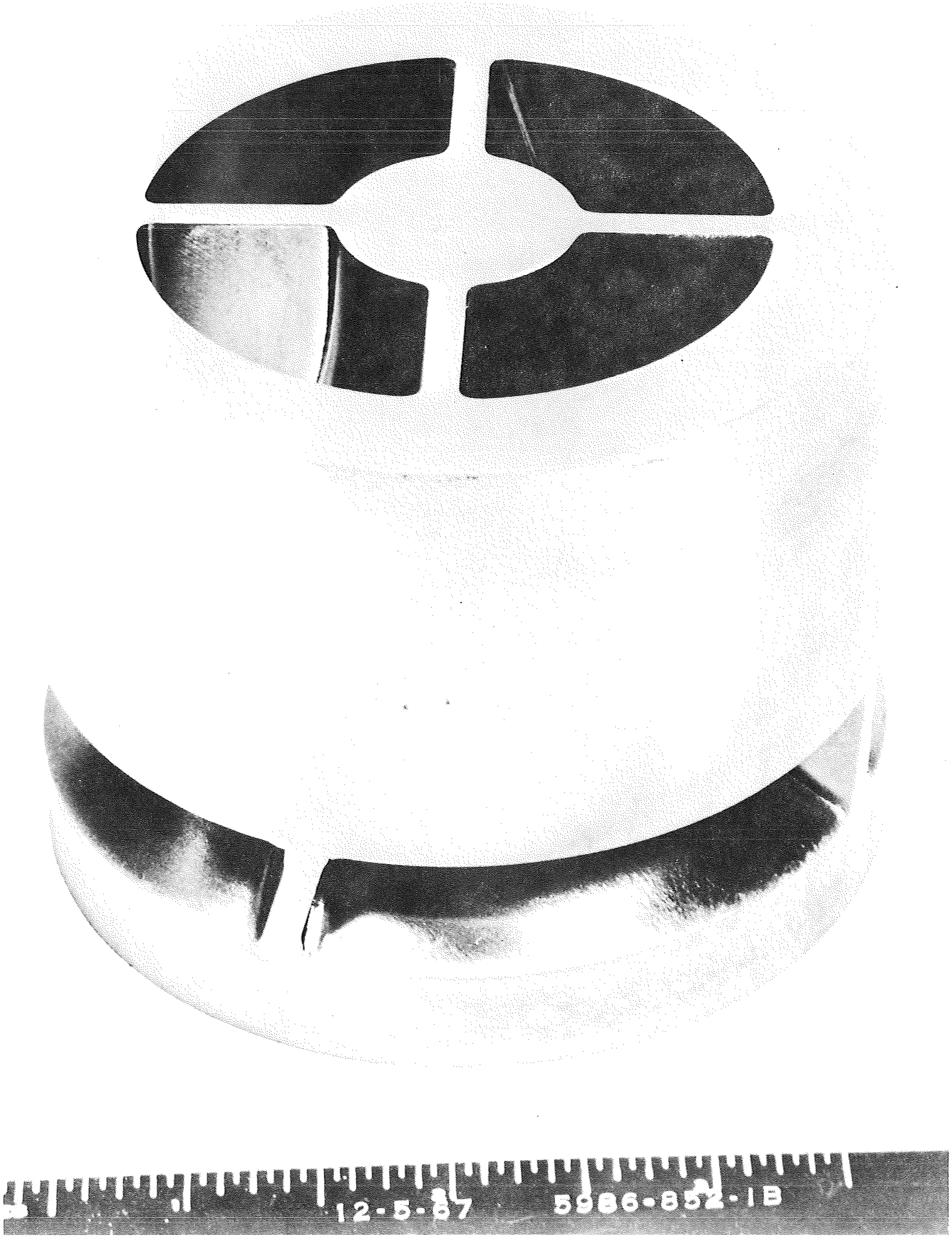


Figure 26. First Trial Sample After Chem-Milling - Discharge View

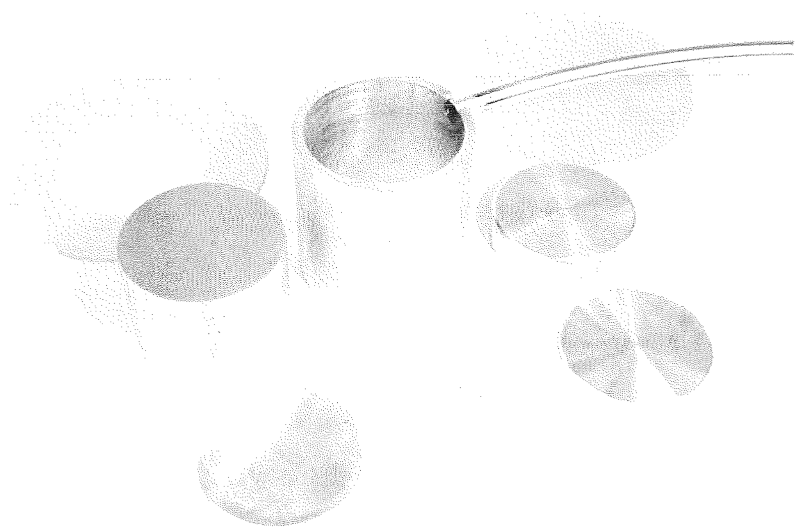


Fig. 27a. Impeller Assembly Outside of Retainer

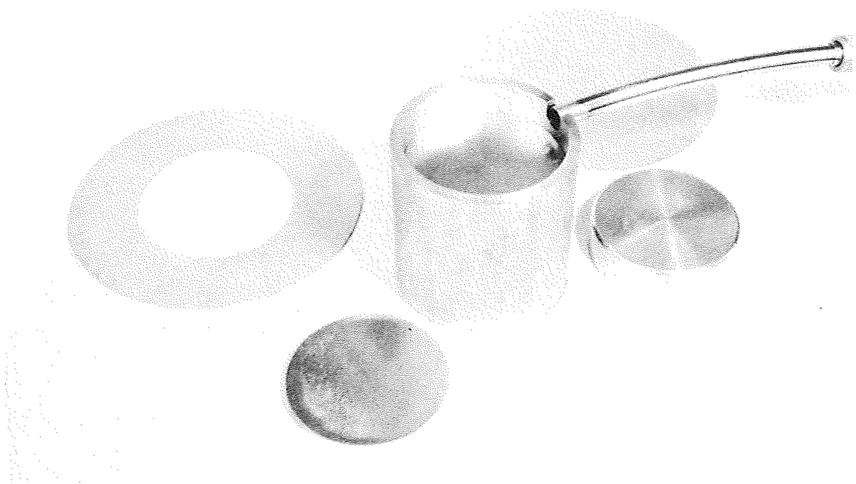


Fig. 27b. Impeller Assembly in Retainer

Figure 27. Third Trial Sample - Partial Assembly Prior to Bonding

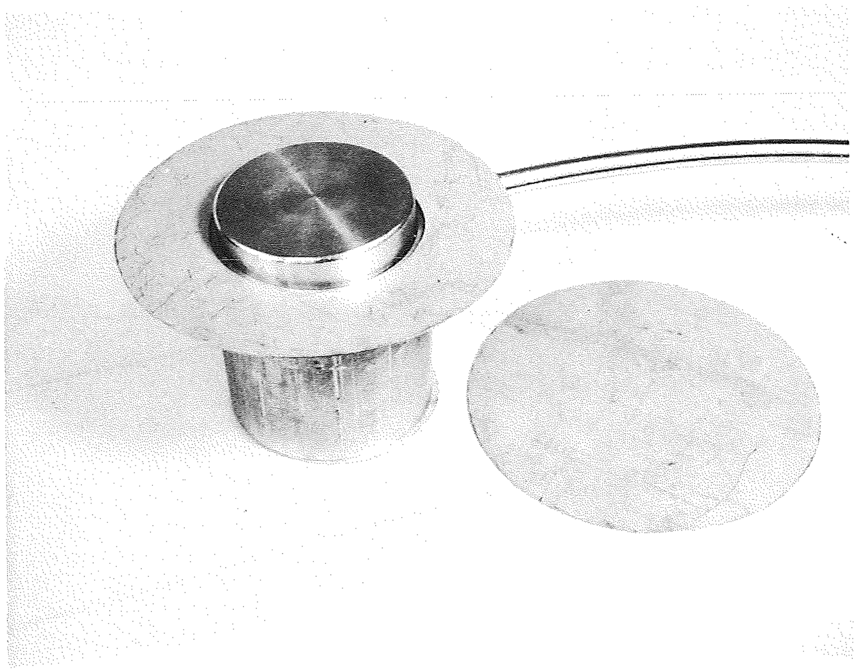


Fig. 28a. Assembly With Retort Cover Removed

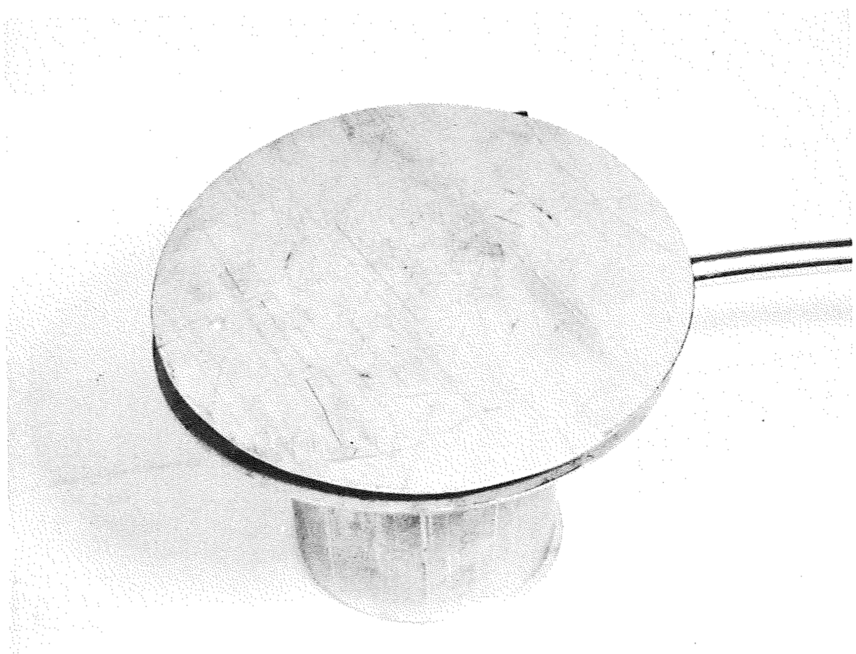


Fig. 28b. Assembly With Retort Cover in Place

Figure 28. Third Trial Sample - Prior to Welding Retort

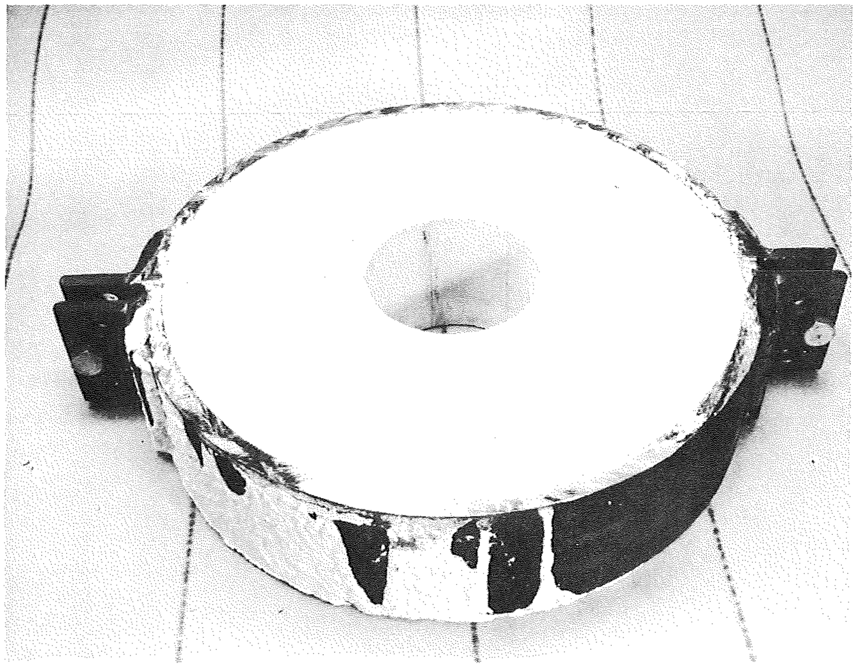


Fig 29a. Restrainer Without Steel Shims

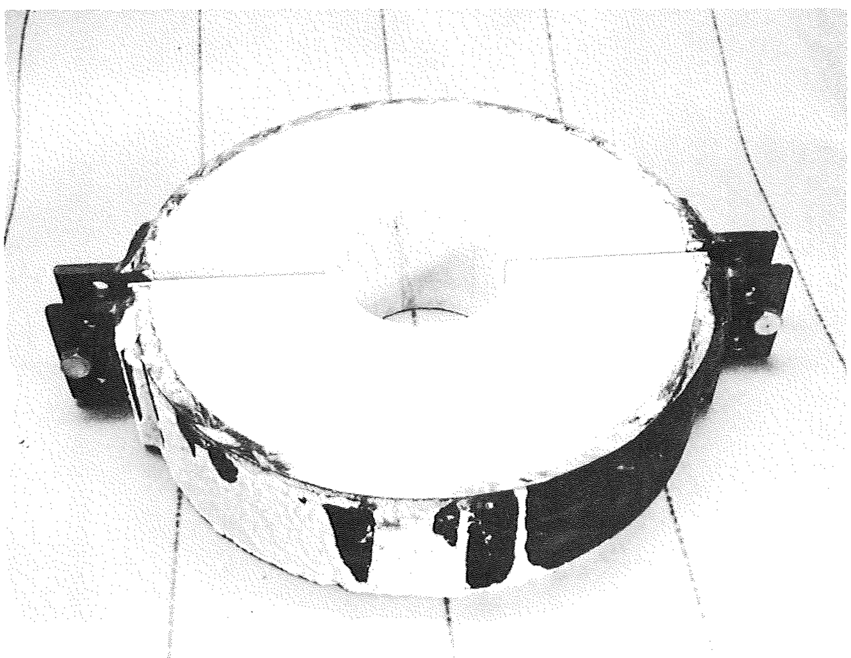


Fig. 29b. Restrainer With Steel Shims in Place

Figure 29. Third Trial Sample Restrainer Tooling

Fig. 30a. Retort Assembly Removed From Restrainer

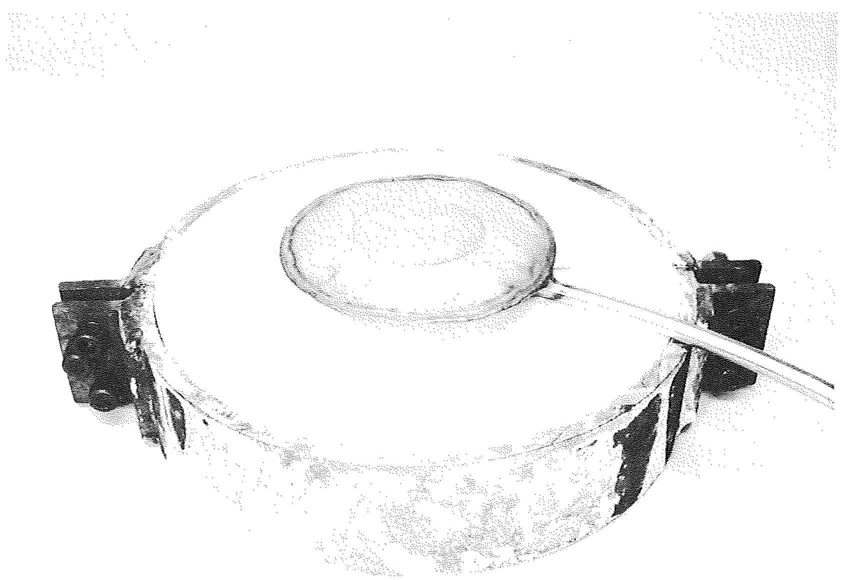


Fig. 30b. Retort Assembly in Restrainer

Figure 30. Third Trial Sample - Retort Assembly and Restrainer Tooling

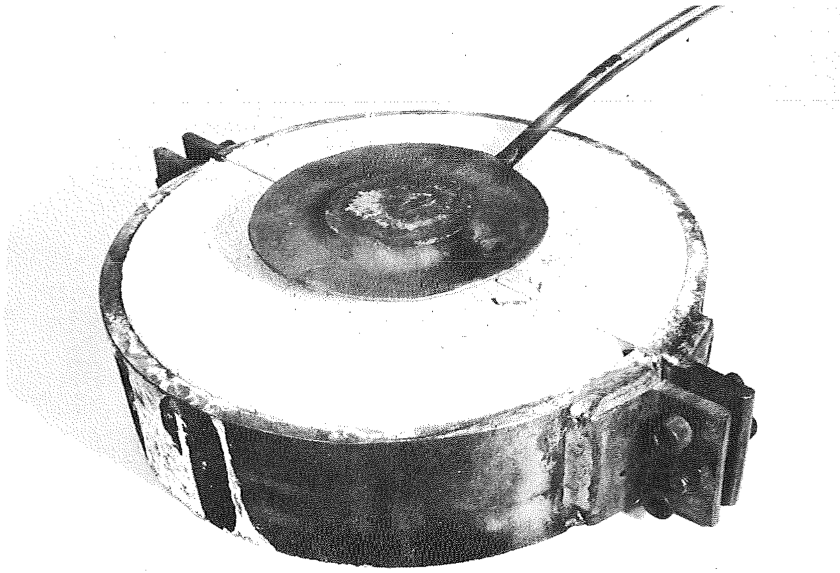


Fig. 31a. Retort Assembly in Restrainer

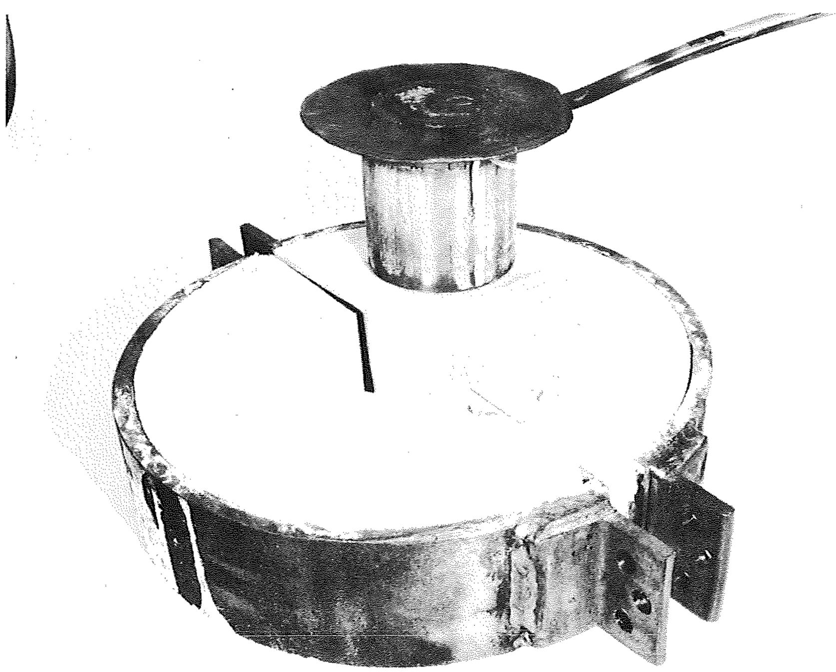


Fig. 31b. Retort Assembly Removed from Restrainer

Figure 31. Third Trial Sample After Bonding

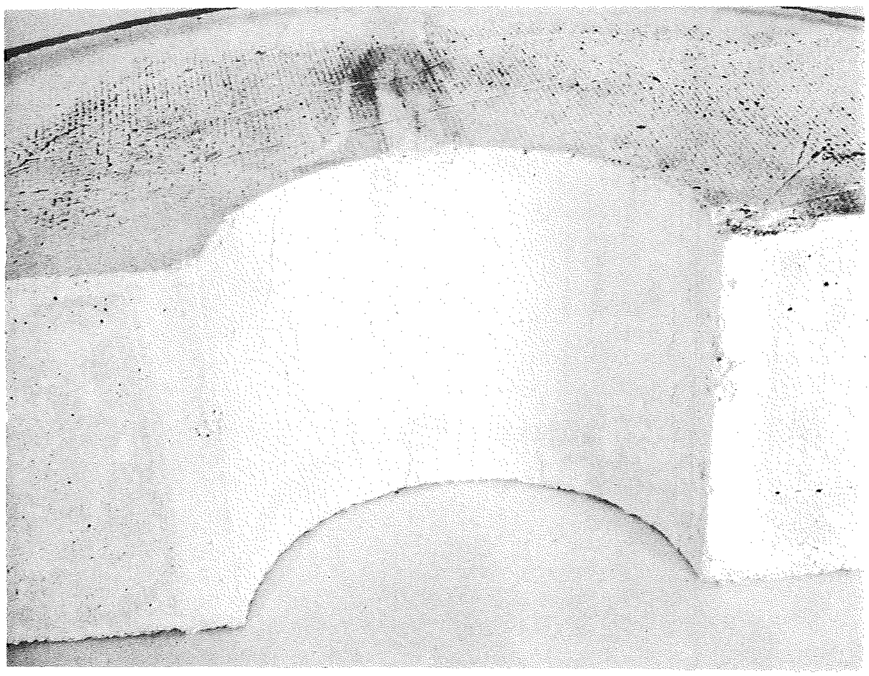


Figure 32. Close-Up View of Ceramic Restrainer - After the Bonding Cycle

The second simulated impeller sample after repressing is shown in Fig. 33 after complete removal of the cores, but prior to chem-milling. As can be seen, complete formation of the fillets did not occur in locations where the vanes intersected the shrouds at an acute angle.

Based on the two trial impellers bonded it was concluded that complete fillet formation did not occur because of friction between the core material and the titanium. The extent of filling a fillet formation appears to be largely a function of hardware geometry. A minimum of filleting occurred in areas where the vanes made acute angles with the shrouds; however, almost complete filleting occurred where the vanes formed obtuse angles with the shrouds.

Optimum Bonding Conditions

It has been found that some titanium alloys have an optimum temperature at which the material becomes most plastic and is thus more optimum for bonding. This temperature may also be significantly lower than the beta transition point, which must be avoided if material properties are to be maintained. As this information was not available on the particular alloy being used, it was decided to determine the best bonding temperature by performing tests on samples. Samples and tooling were fabricated and Figures 34 through 37 are a series of photographs showing one of these test specimens in various stages of assembly.

The first specimen was cycled under conditions identical to that of the first impeller test sample. These conditions were selected as a basis for comparison. Figure 38 shows the results of the test in the first specimen. It can be seen that the steel die deformed and complete filling of the large gap did not occur under the bonding conditions employed. The second specimen was pressed at approximately 1650°F with a pressure of 2000 psi for 16 hours. As shown in Figures 39 and 40, very little filleting occured. Figure 39 shows a small deformation of the steel core material. The third specimen was pressed

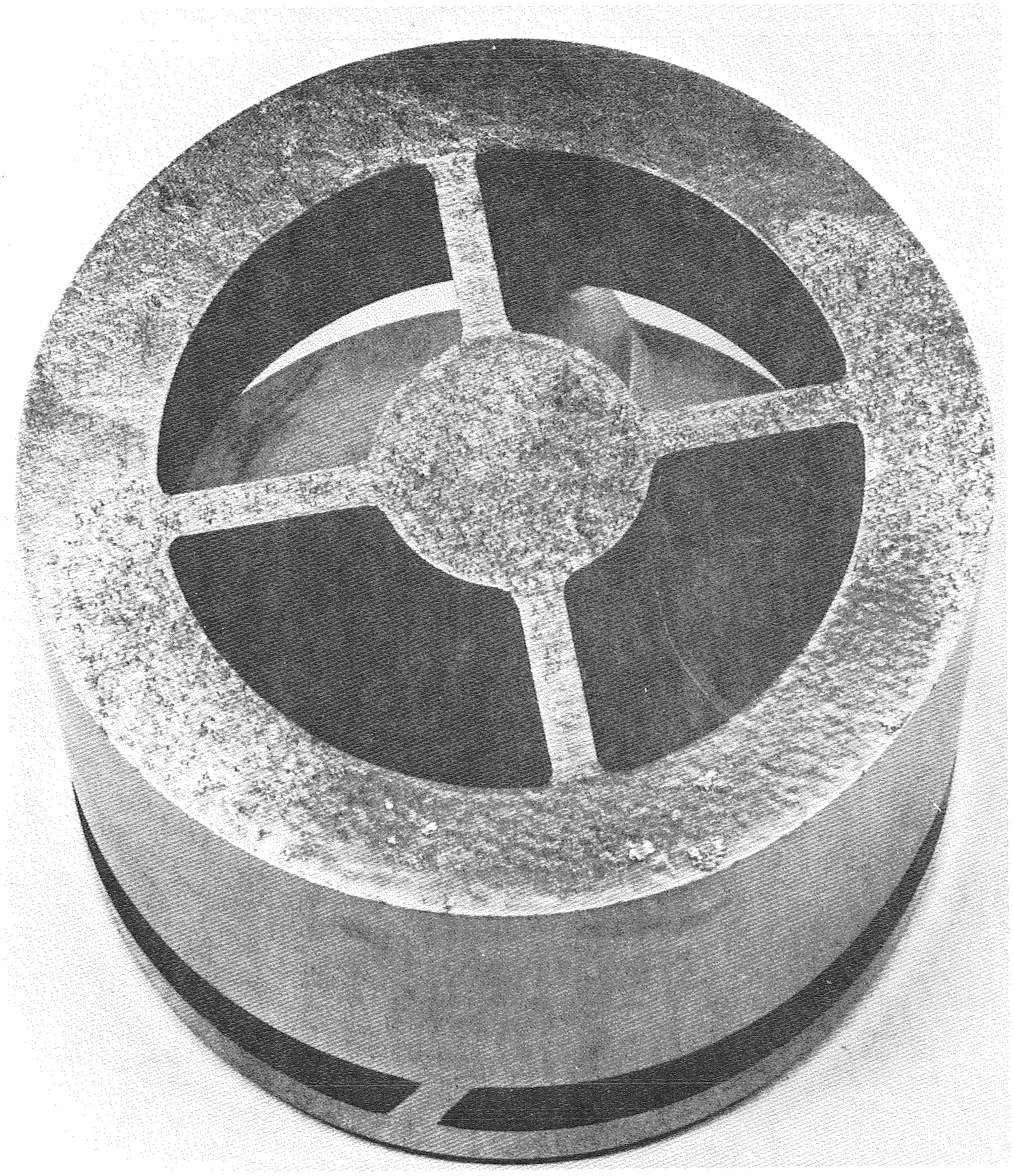


Figure 33. Second Simulated Impeller After Removal of H-11 Tool Steel Cores

Figure 34. Disassembled View of 7/8 Inch Specimen and Tooling

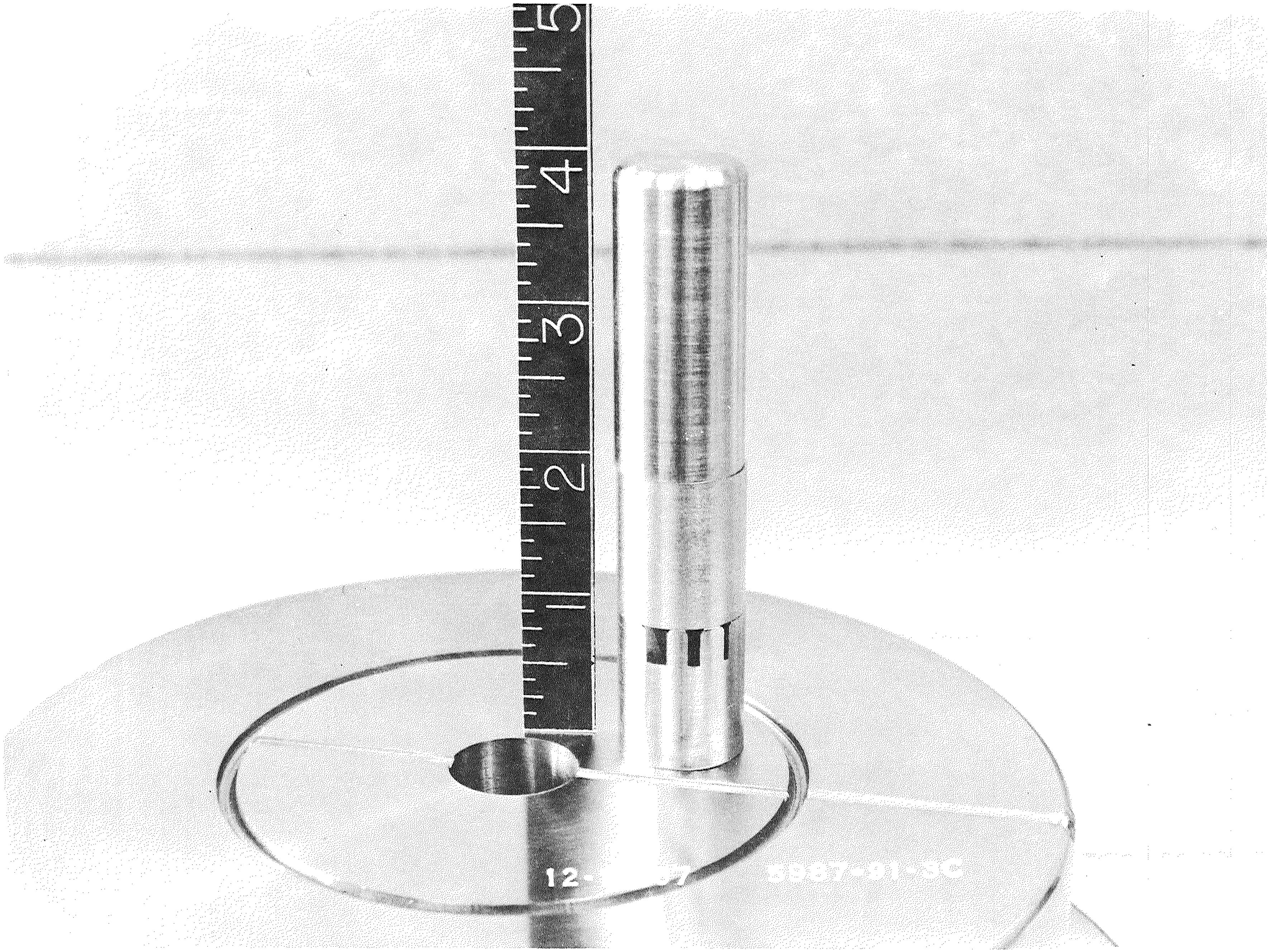
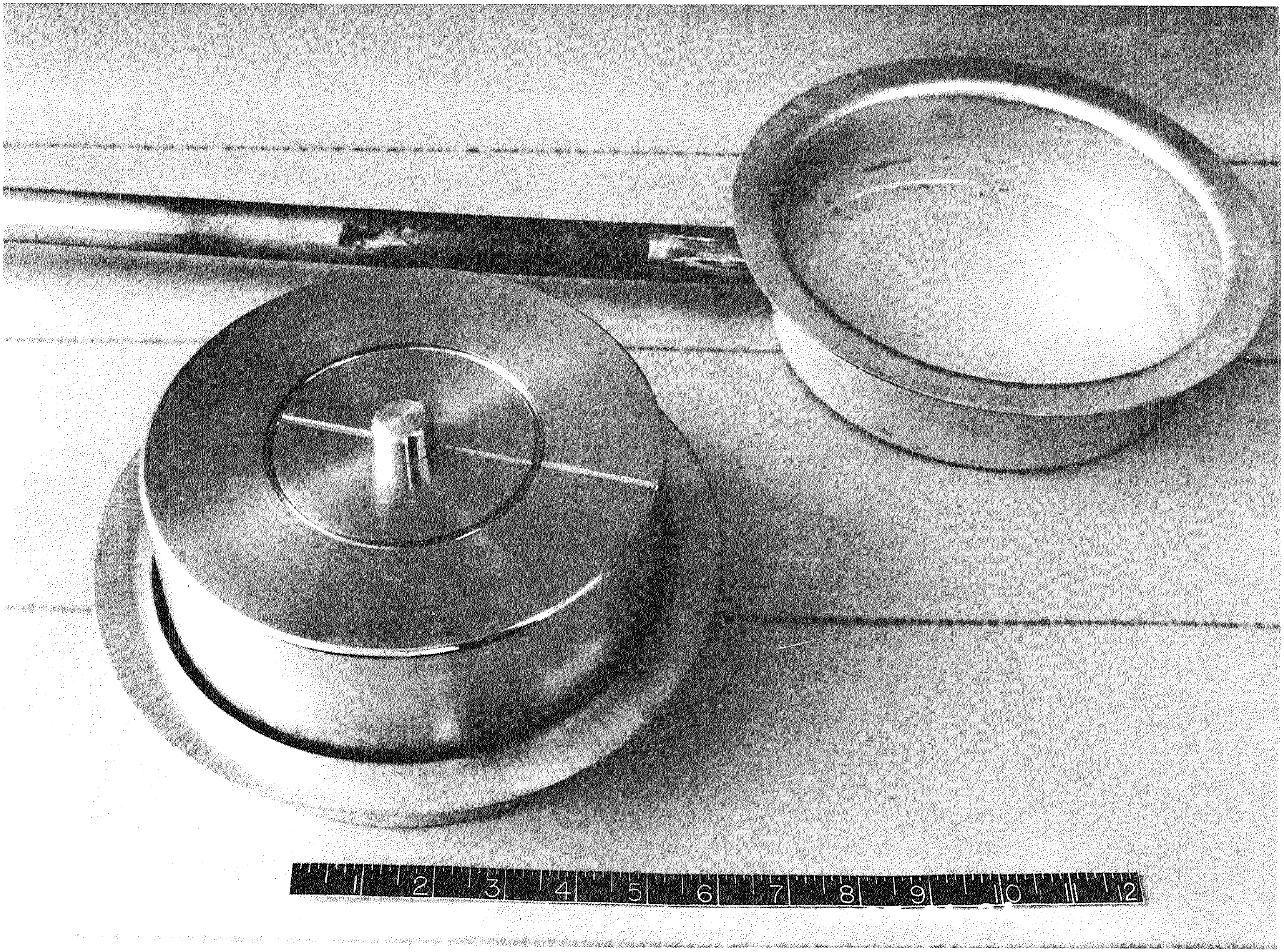
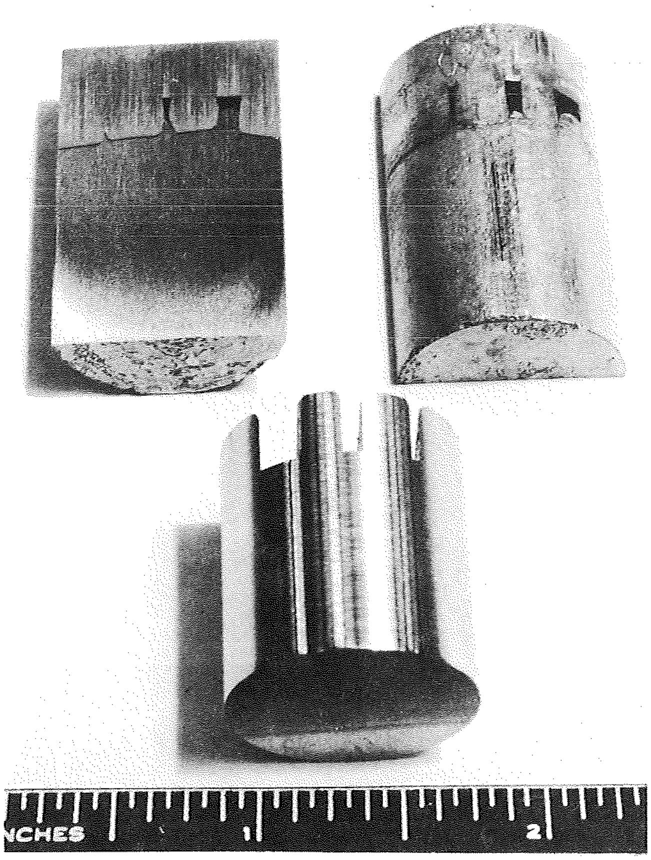


Figure 35. Close-Up View of Restrainer, Die, Plunger and 7/8 Inch Specimen

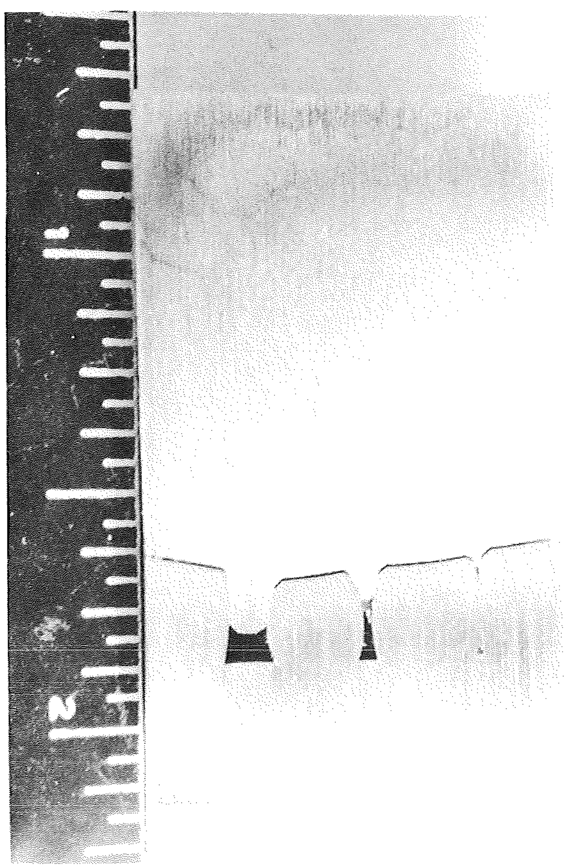


36. Assembled Views of 7/8 Iron Test Specimen and Tooling With Retort Cover Removed

Figure 37. Assembled View of 7/8 Inch Test Specimen and Tooling With Retort Cover in Place



38a. View Comparing Sectioned Part After Pressing and New Tooling



38b. Close-up View Showing Tooling and Titanium Deformation

Figure 38. Sectioned View of First 7/8 inch Test Specimen After Simulated Bonding Cycle

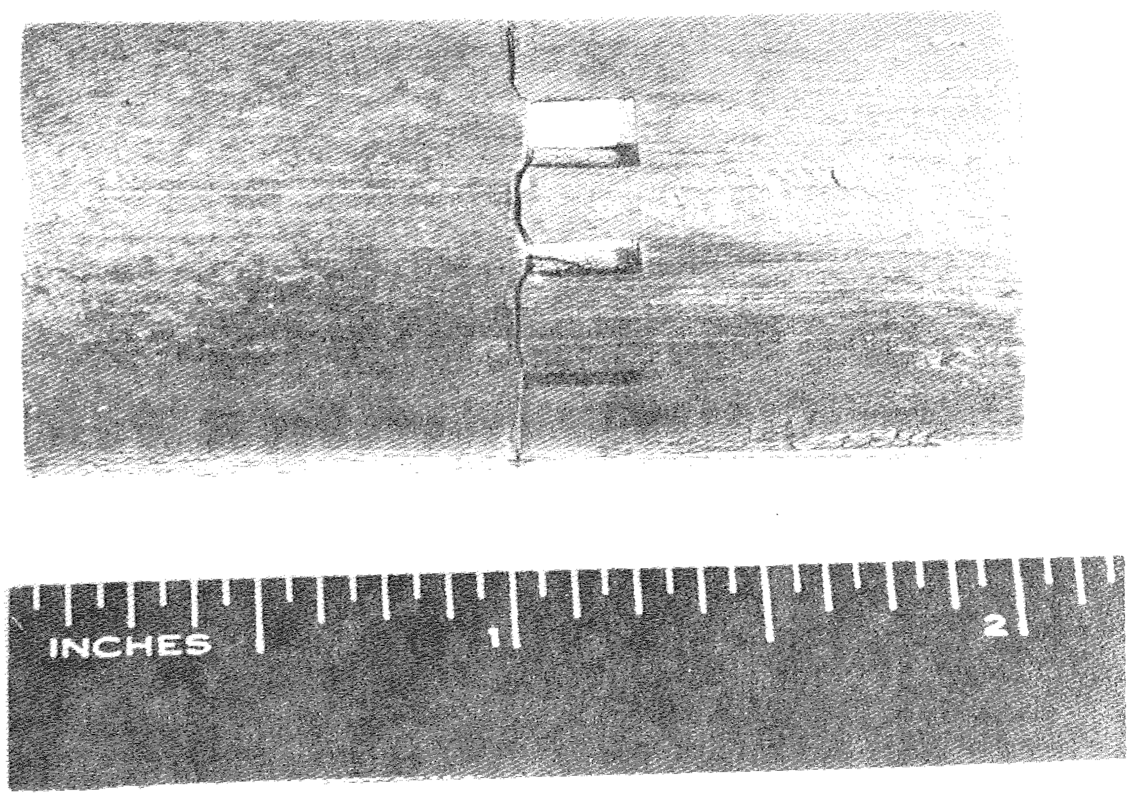


Figure 39. Assembled View of Second Test Specimen.

Figure 40. Disassembled View of Second Test Specimen.

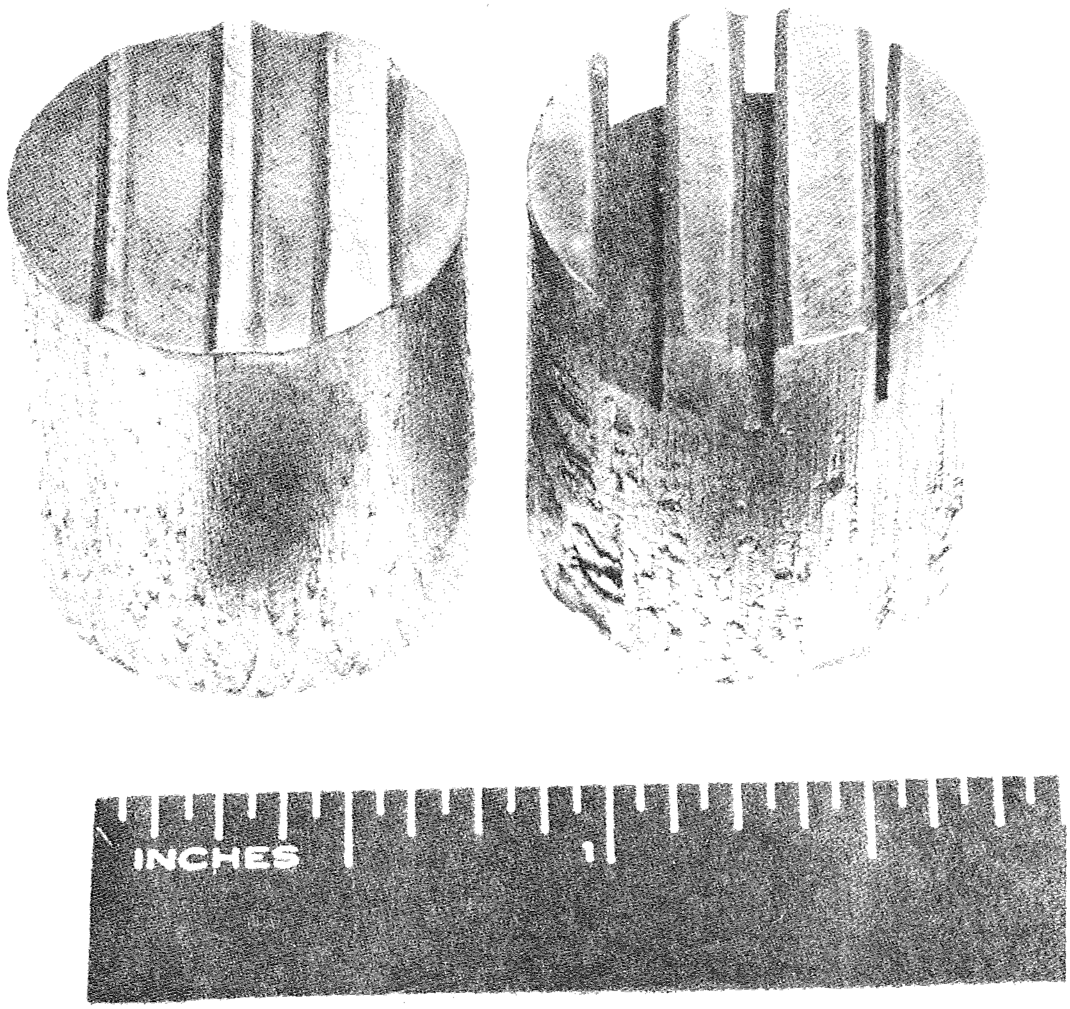


Figure 40. Disassembled View of Second Test Specimen.

at approximately 1850°F for 16 hours.

From these tests, Figure 41, it was concluded that using the highest temperature possible without exceeding the beta transition temperature and employing moderate pressures (2000 psi) appear to give the most satisfactory results when bonding titanium.

As a result of the tests to determine the optimum bonding conditions, the following bonding conditionswere selected for the final simulated impeller sample.

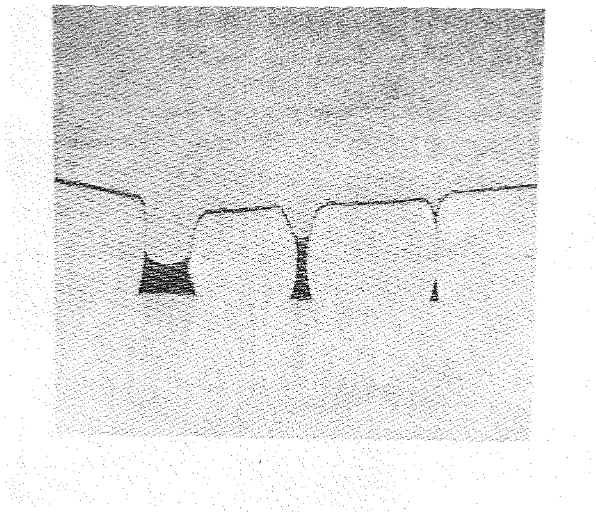
TABLE 4

BONDING PARAMETERS

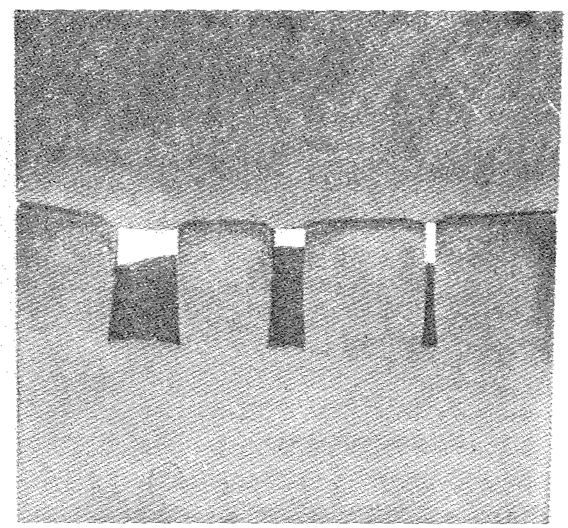
Temperature, deg. F	1850
Pressing time, hours	16
Pressure, psi (on end plate)	2000 psia

Figure 42 and 46 show the final simulated impeller sample in various stages of assembly prior to bonding. Two cores were split to simulate the effect of core shifting or deformation in passage geometry. The configuration of the split cores is shown in Figures 43 and 44. As shown in Fig. 45, titanium filler wires were placed in fillet voids where the vanes formed acute angles with the shrouds.

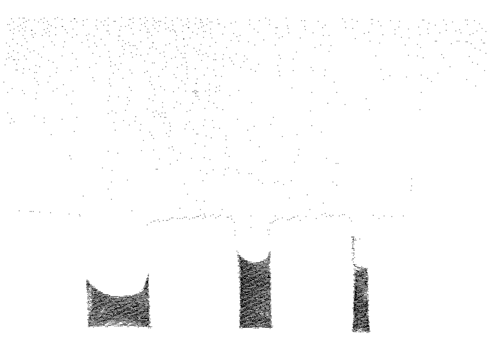
The ceramic restrainer employed for the previous ample was also used for the final sample. Figures 46 and 47 show the final sample inlet and discharge area after bonding and tooling removal, but prior to core removal. As can be observed, complete filleting occurred at both the inlet and discharge areas of the simulated impeller sample. Examination of Fig. 47 shows that shifting occurred on one of the split cores. Figures 48 through 50 show the final simulated impeller sample after core removal, but prior to chem-milling. Examination of these figures shows that complete fillet formation has occurred. Figure 50 shows lines in the fillet area where a wire was employed to fill the void during lay up. These lines disappeared after chem-milling .010 of an inch material from all surfaces and thus do not



(a) Bonding Material Titanium
Die Material 4340



(b) Bonding Material Titanium
Die Material 4340



(c) Bonding Material Titanium
Die Material H-11

Figure 41. Plasticity Test Specimens

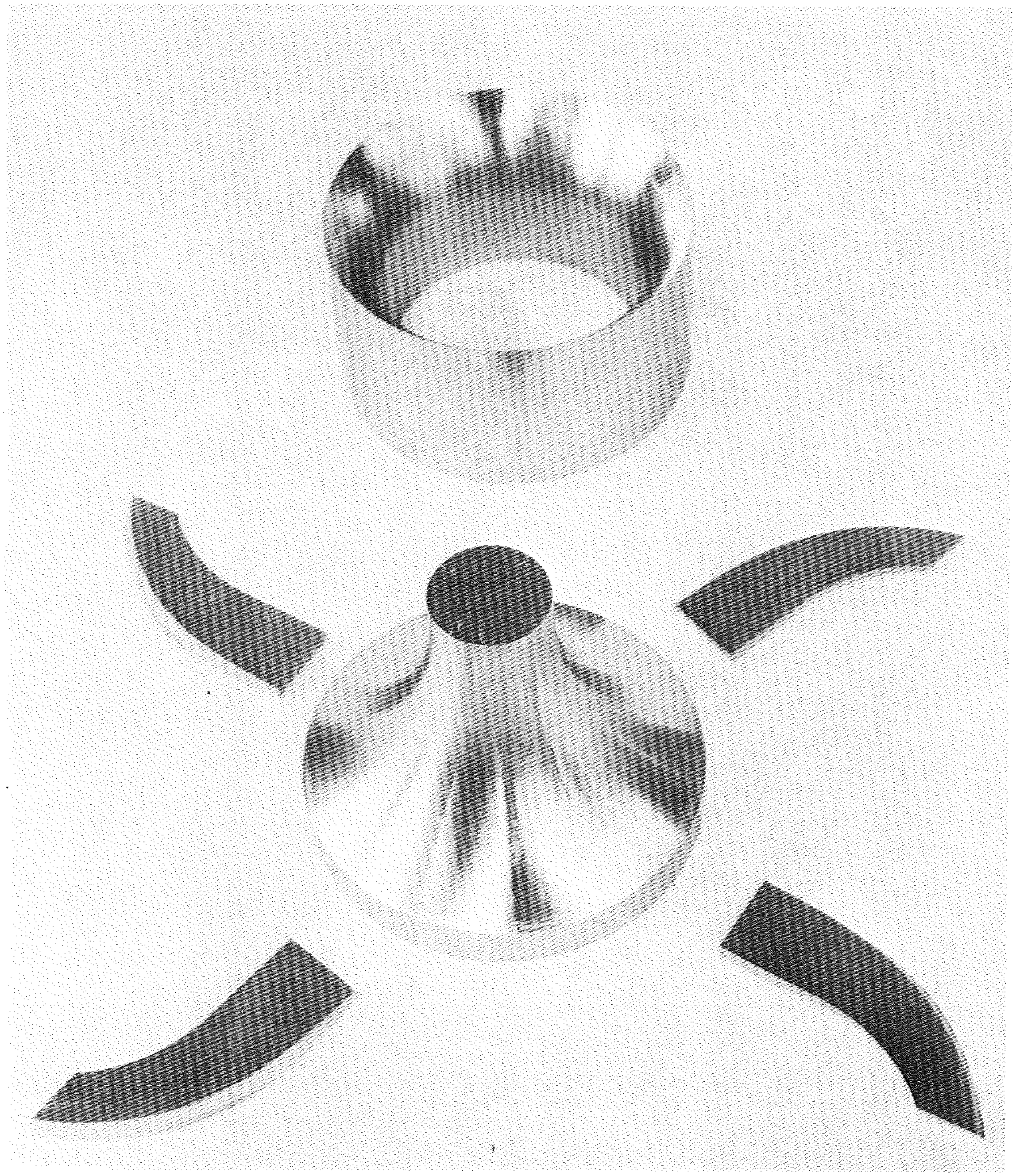


Figure 42. Final Simulated Impeller Sample Showing
Vanes and Shrouds

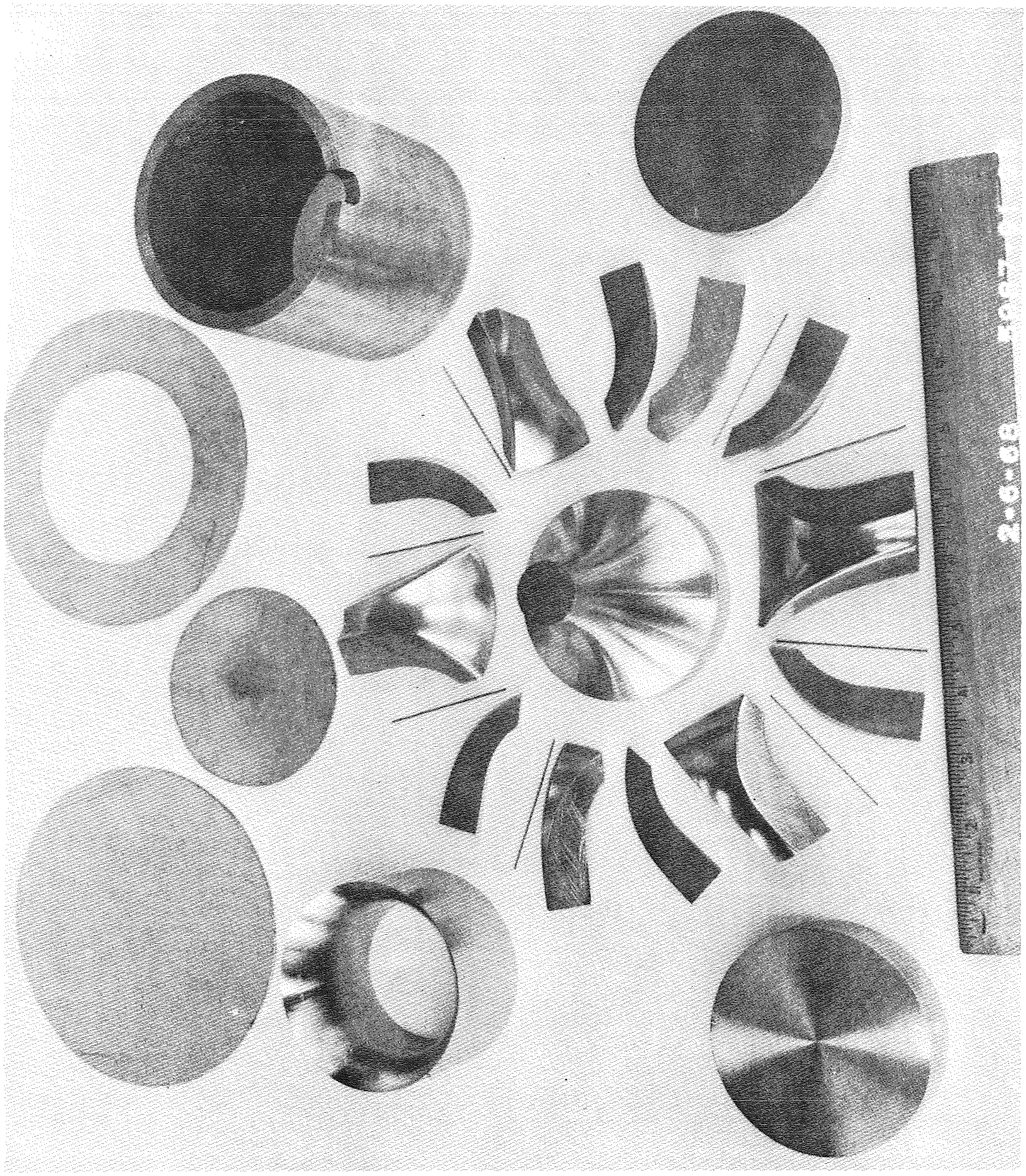


Figure 43. Final Simulated Impeller Sample Showing
Complete Bond Assembly Before Lay Up

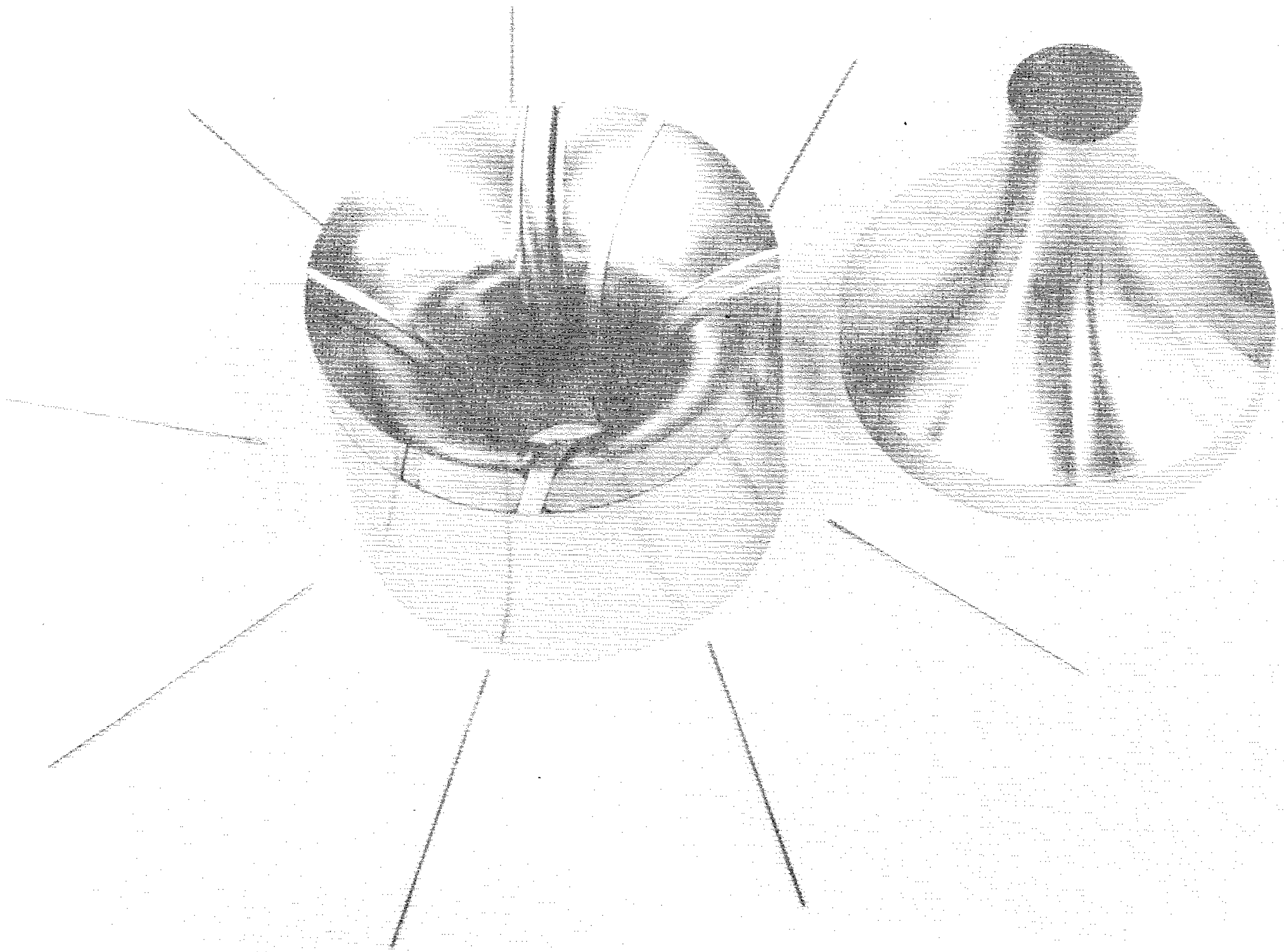


Figure 44. Final Simulated Impeller Sample Showing
Partial Lay Up of Pre-Bond Assembly

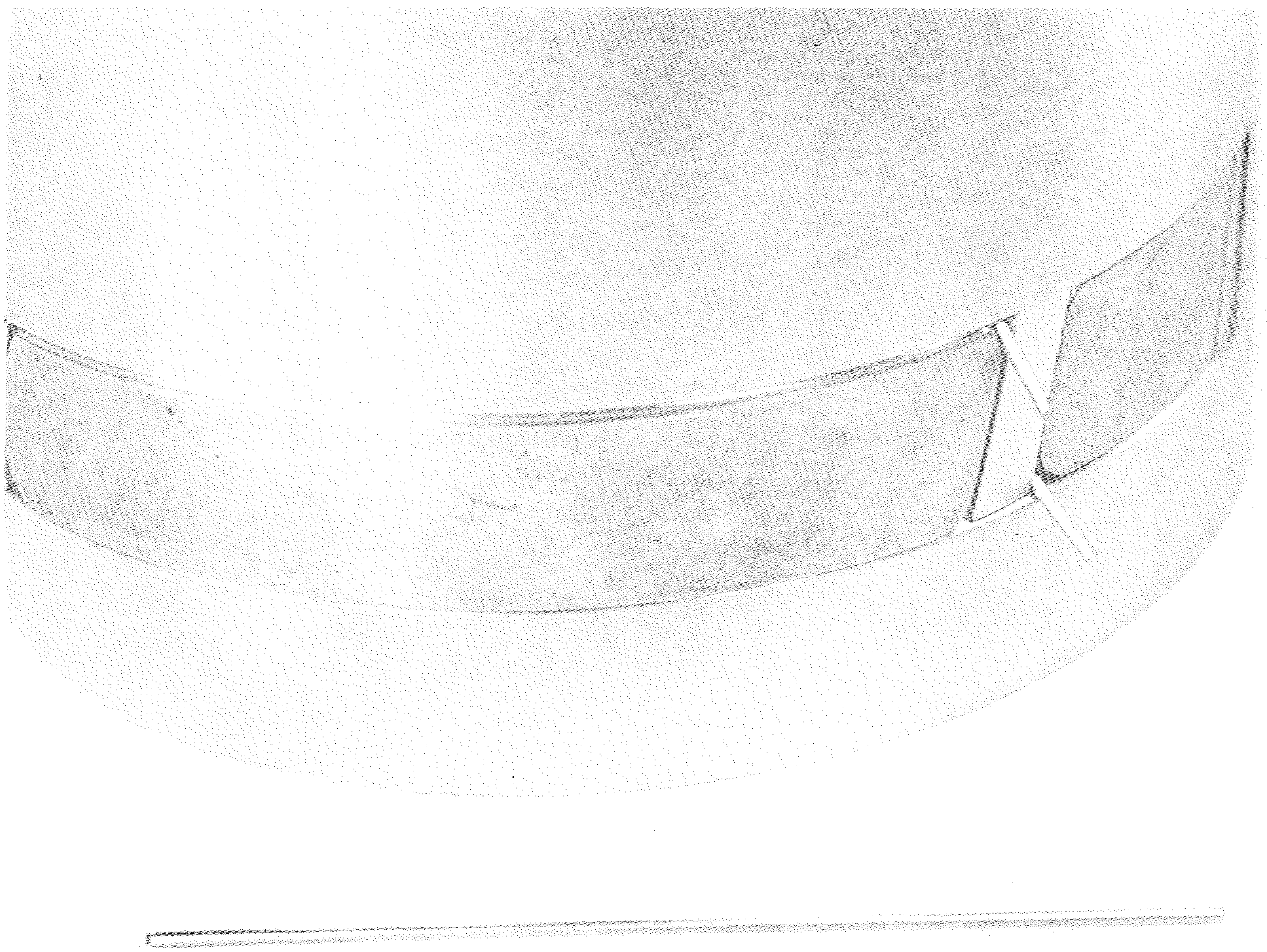


Figure 45. Final Simulated Impeller Sample Showing Titanium Wire Inserted in Fillet Voids Where Vanes Form Acute Angles with Shrouds

Figure 46a. Final Simulated Impeller Sample Showing Pre-Bond Assembly After Lay Up Prior to Welding of Retort

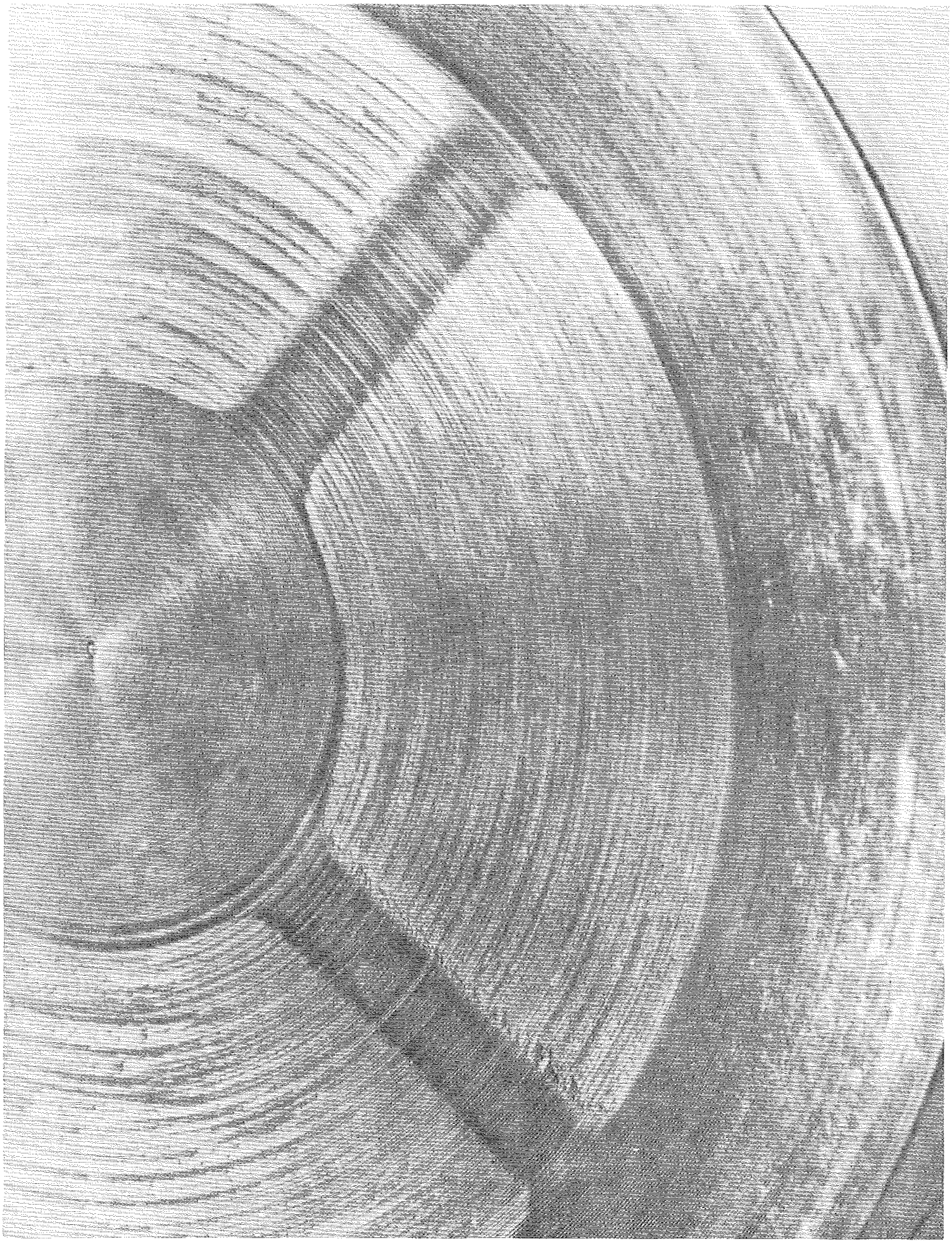


Figure 46b. Final Simulated Impeller Sample Showing Inlet Area After Bonding and Tooling Removal

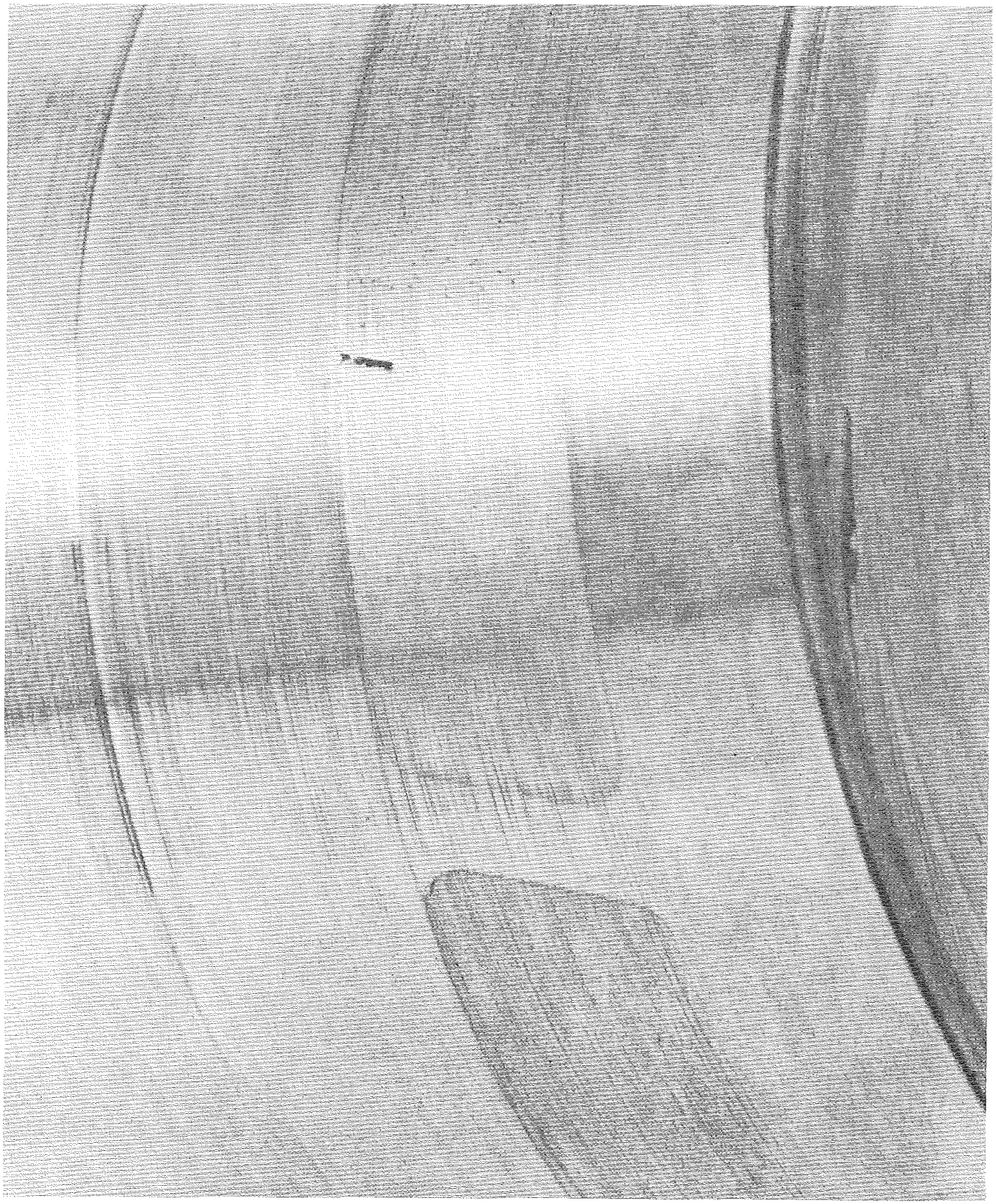


Figure 47. Final Simulated Impeller Sample Showing Discharge Area After Bonding and Tooling Removal

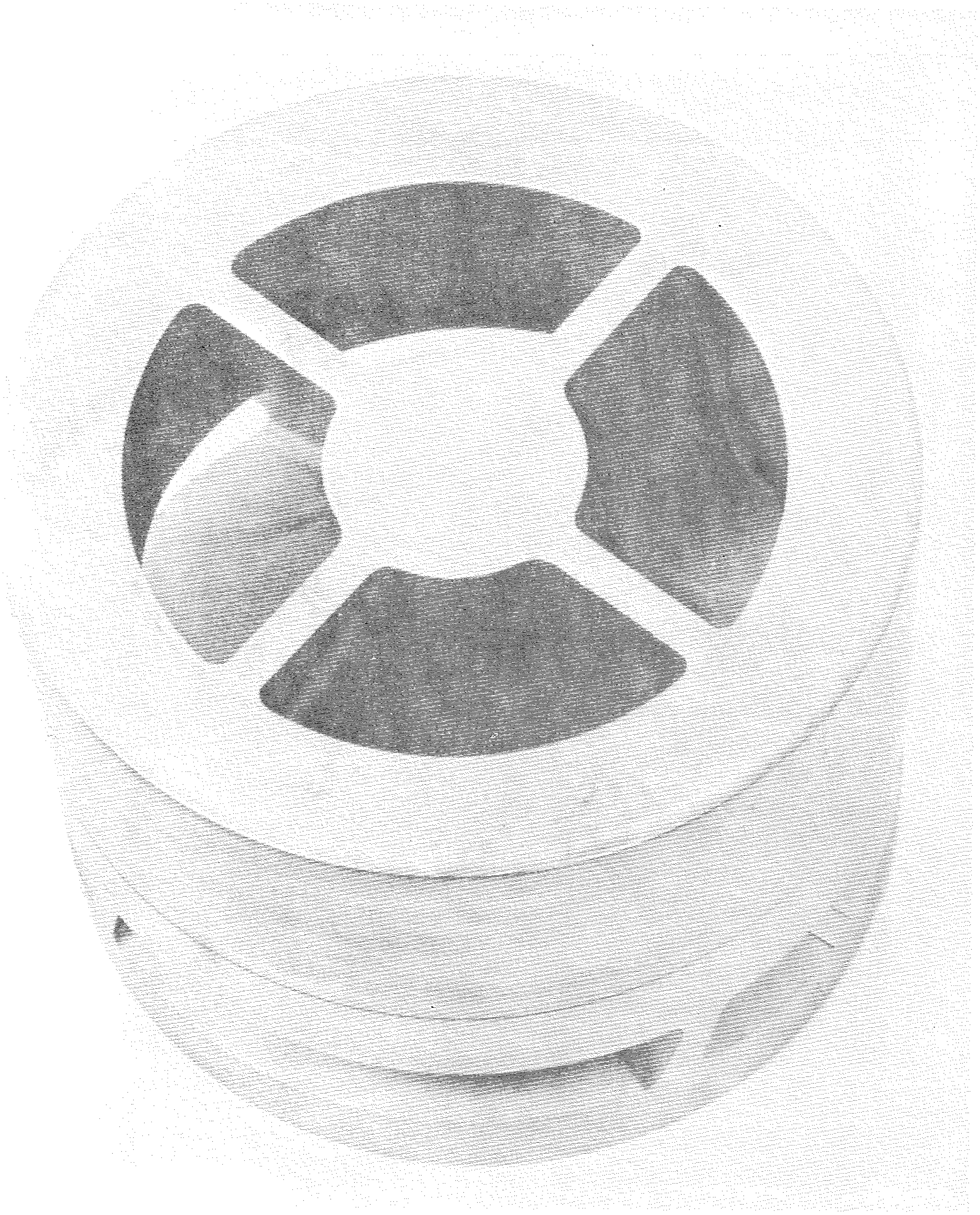


Figure 48. Final Simulated Impeller Sample Showing Inlet
Area After Removal of 4340 Steel Cores

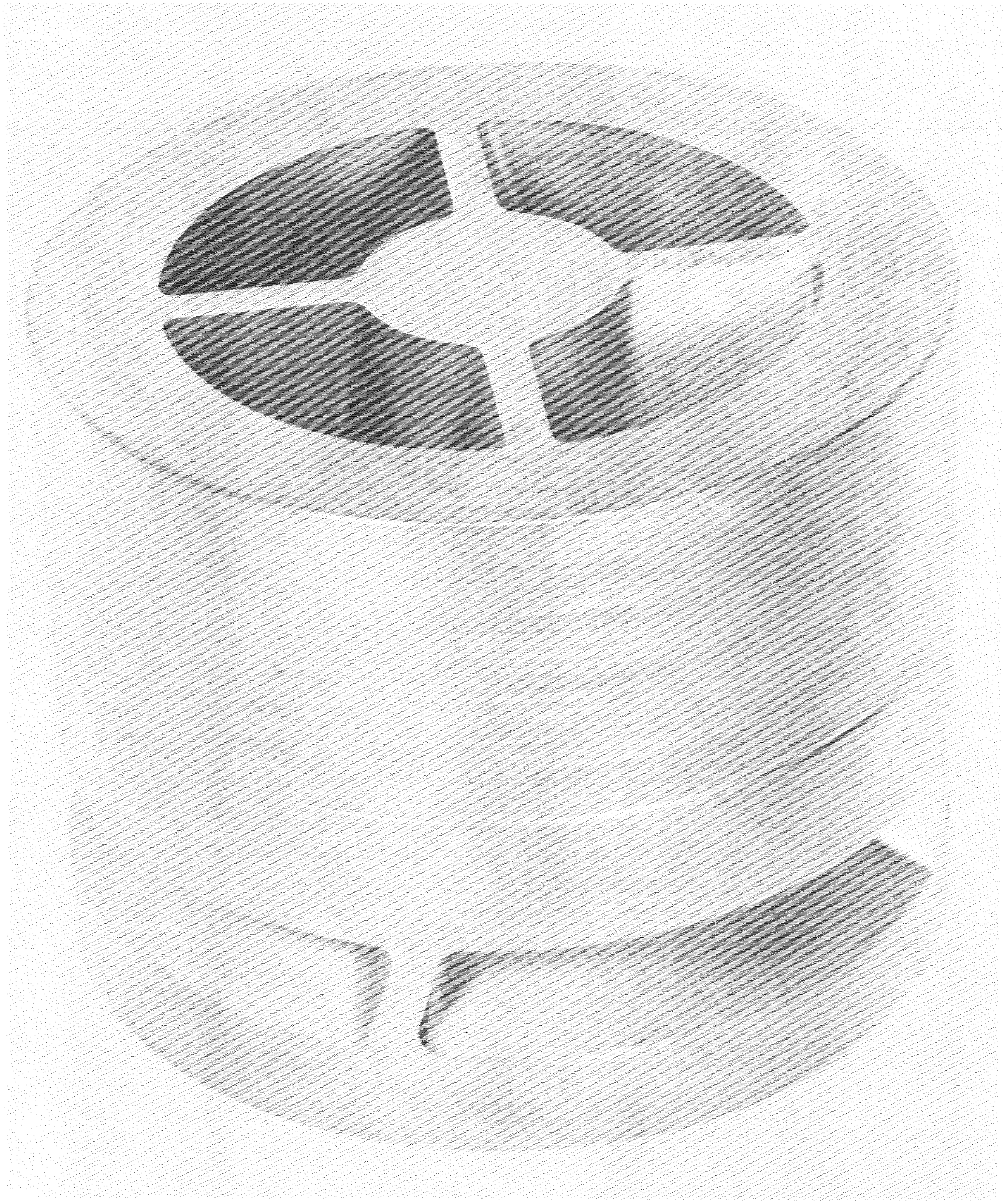


Figure 49. Final Simulated Impeller Sample Showing Inlet and Discharge Area After Core Removal

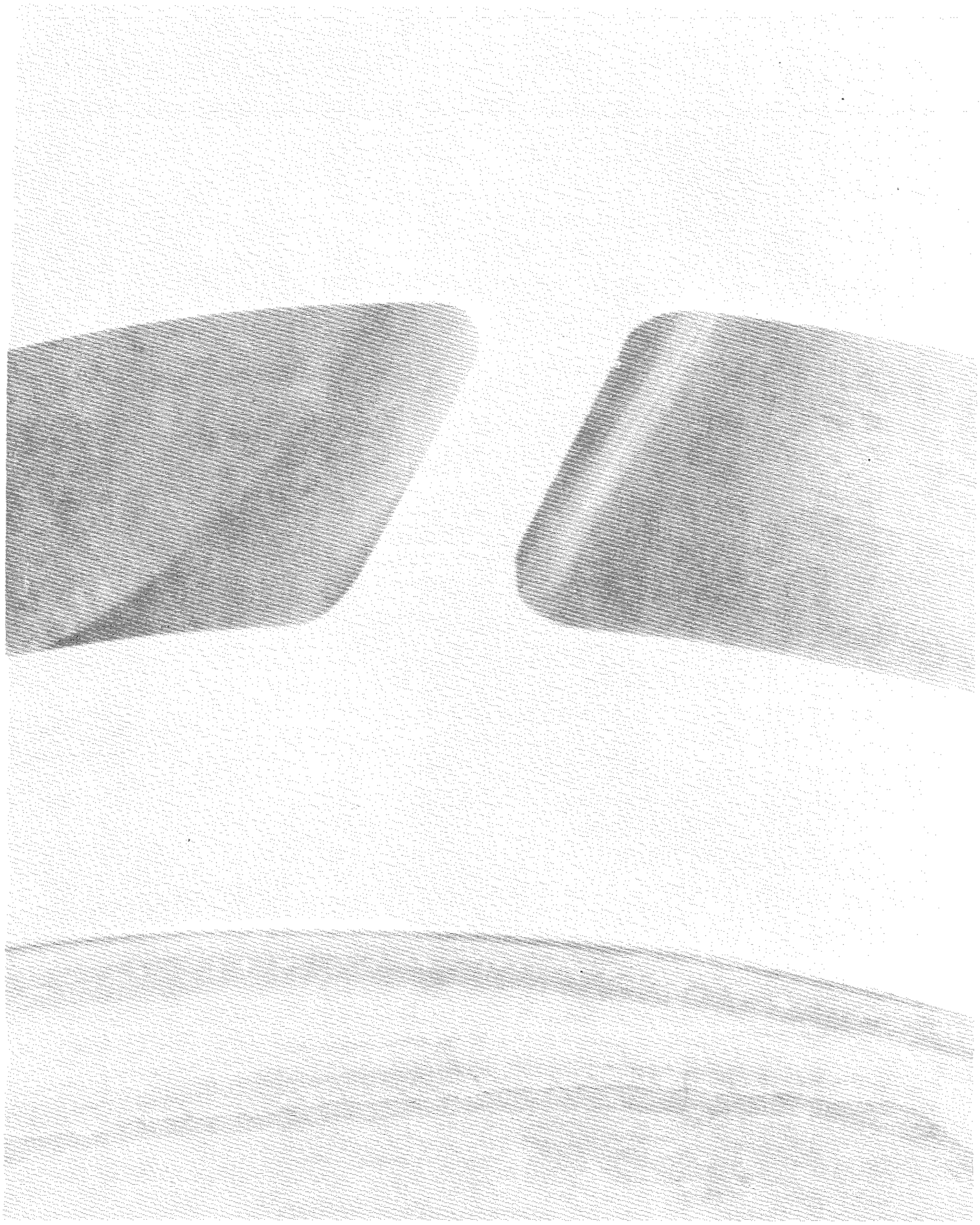


Figure 50. Final Simulated Impeller Sample Showing Close Up of Discharge Area After Core Removal

represent cracks of any significant depth. Figures 51 and 52 show the final simulated impeller after chem-milling .020 of an inch of material from all surfaces. In Fig. 53, 0.040 of an inch of material has been removed from all surfaces.

Photo-micrographs and tensile specimens were taken from the final simulated impeller because it was representative of the conditions under which the full scale impellers will be bonded. Figs. 54 and 54(b) show photo-micrographs of the bond area at magnifications of 50X and 250X, respectively. As may be observed, no indication of the bond joint is visible, although considerable grain growth has occured. Fig. 55 (a) shows a photo-michrograph of the non-bonded area at a magnification of 250X. In comparing Figs. 54(b) and 55 (a), no significant differences are noted between bonded and non-bonded areas. The photo-micrographs shown were taken of specimens from the impeller inlet.

Figure 55 (b) shows three tensile specimens taken from the impeller inlet. These specimens were stressed in tension to failure with the following results:

Spec. No.	Ultimate Load - lbs	Ultimate Strength - KSI	Elongation 1/2 in.-%
2	762	122.5	15
3	843	124.3	15
4	567	122.1	10

The values of ultimate strength and elongation are typical for titanium alloy at room temperature. As can be seen from Fig. 55 (b), failure occurred well below the fillet area.

Comparison of Simulated Impellers.

Figure 56 shows similar views of the three simulated impeller samples for comparison. The first and third samples bonded have 0.040 of an inch material removed by chem-milling from all surfaces, while the second sample bonded is shown with 0.020 of an inch of material removed.

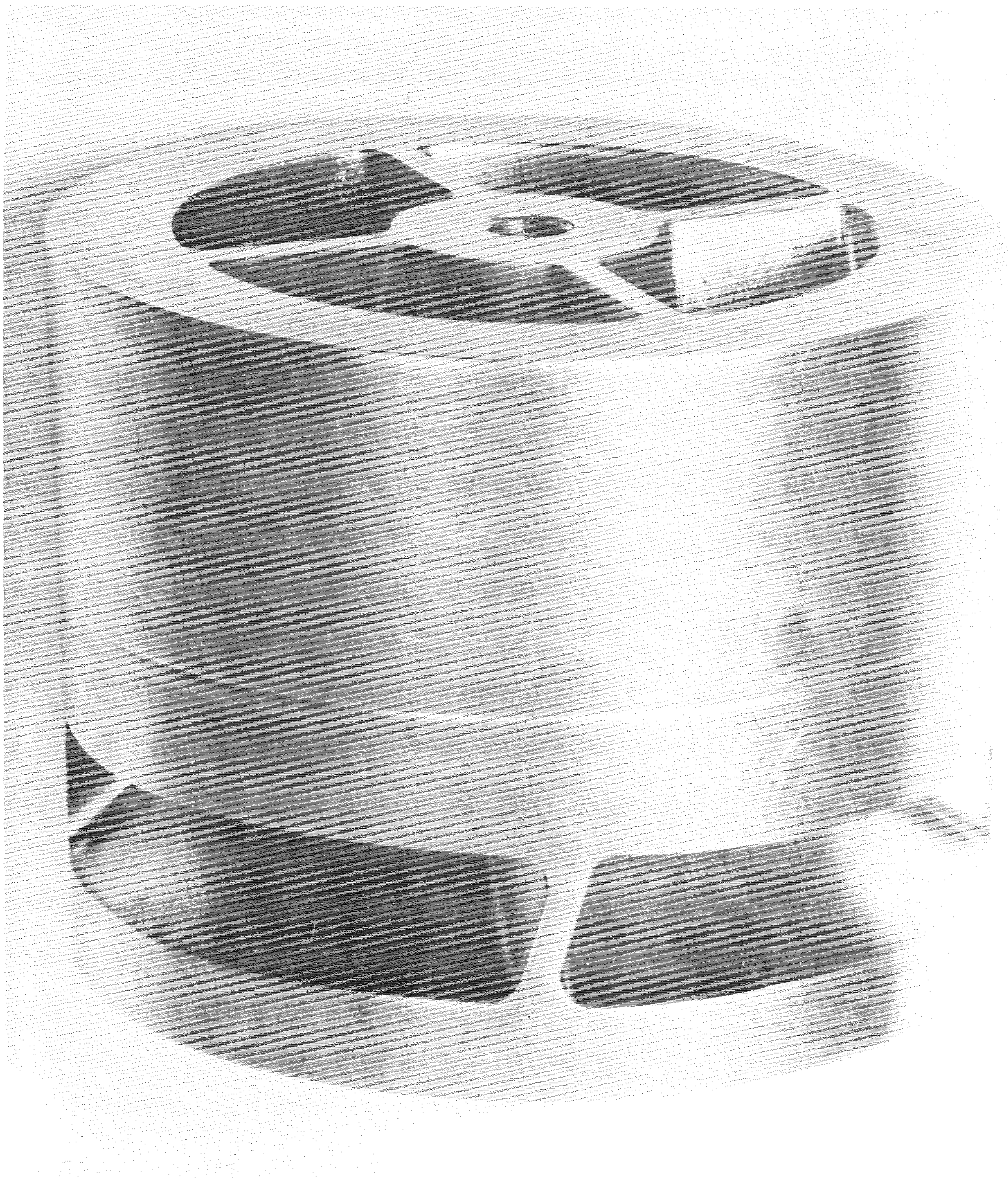


Figure 51. Final Simulated Impeller Showing Discharge Area After Removing 0.020 of an Inch of Material From All Surfaces by Chem-Milling.

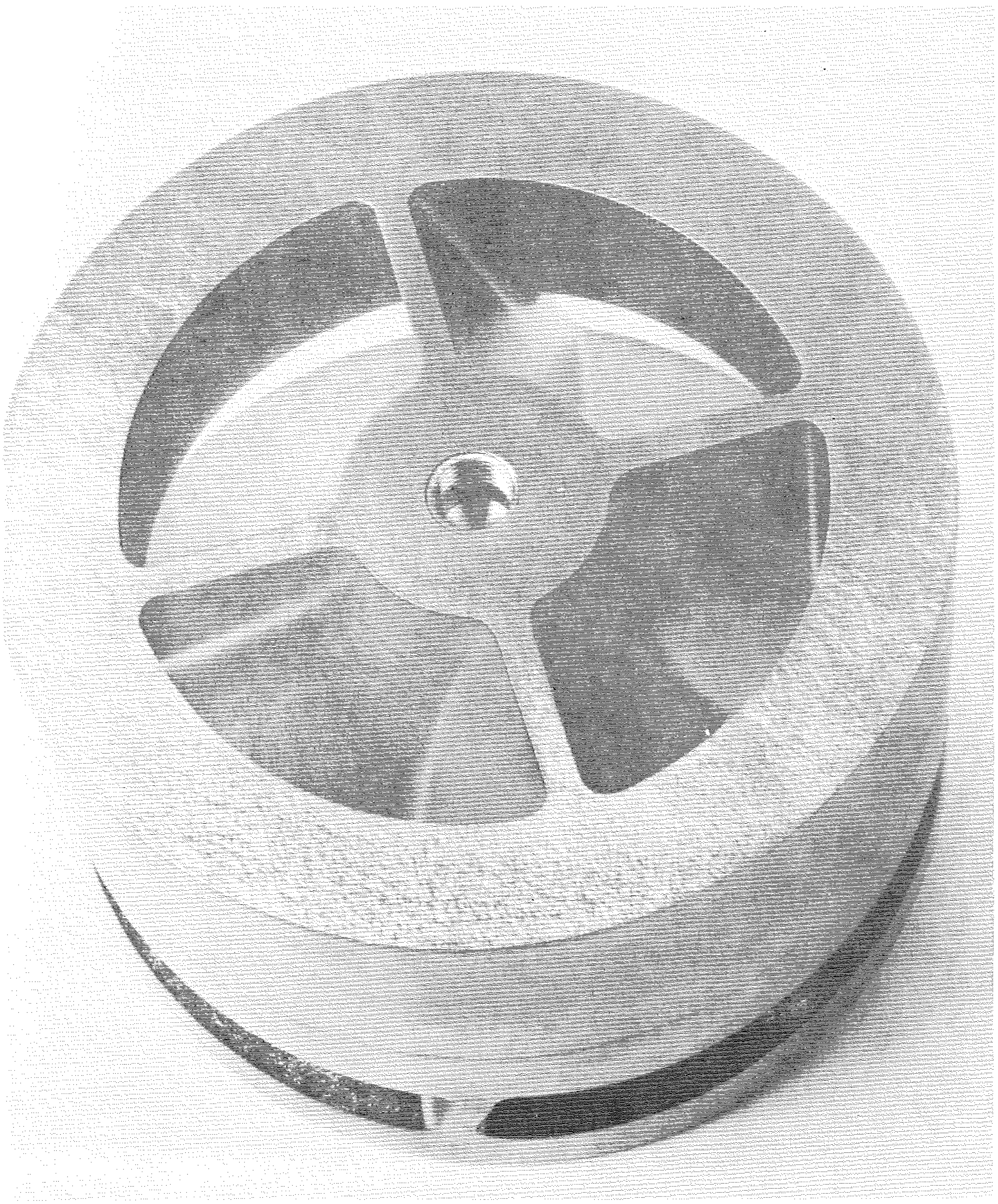


Figure 52. Final Simulated Impeller Showing Inlet Area After Chem-Milling 0.020 of an Inch Material From All Surfaces.

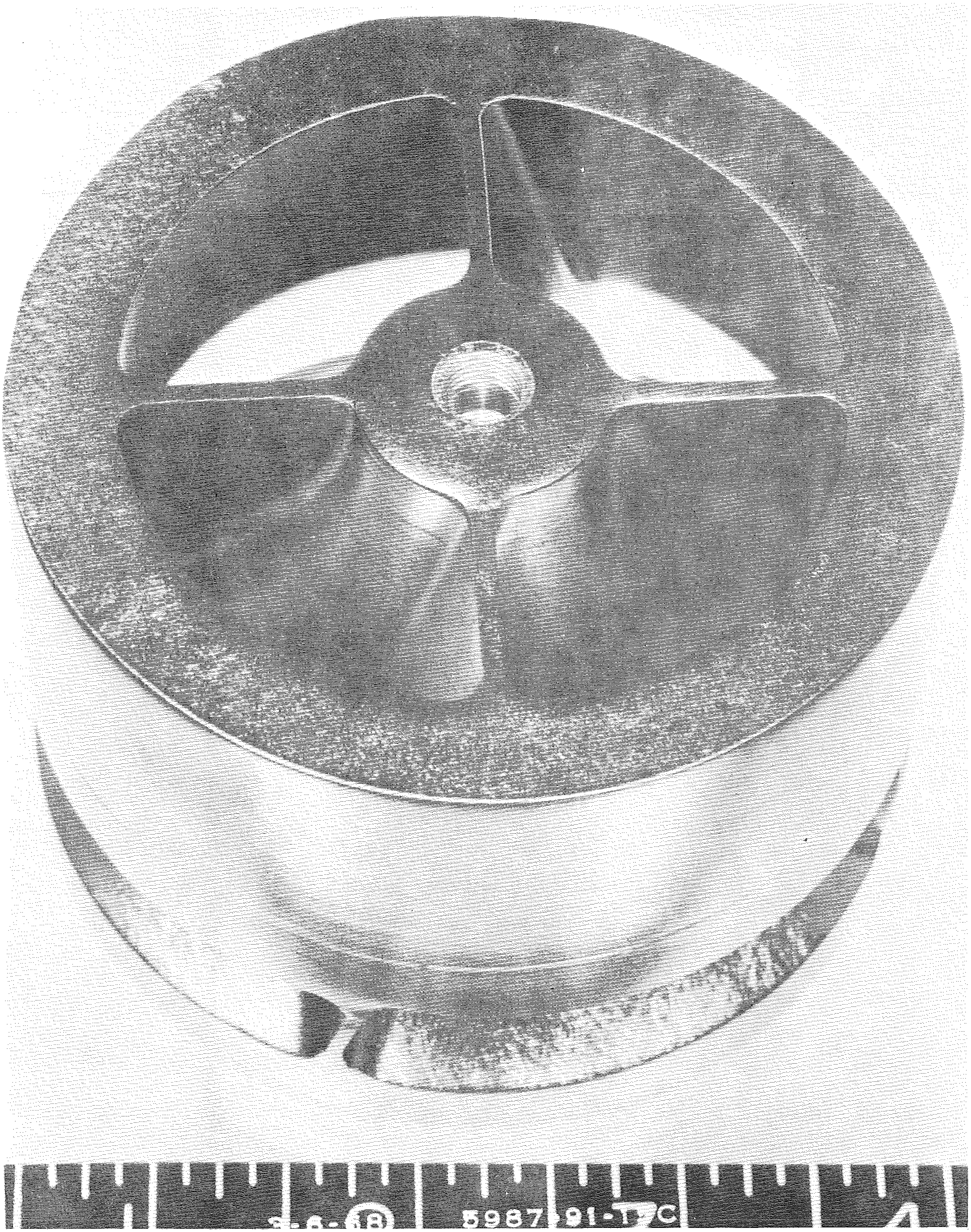


Figure 53. Final Simulated Impeller Showing Inlet Areas After Chem-Milling 0.040 of an Inch Material From All Surfaces.

Figure 54a. Photo-Micrograph of Bonded Area. 50X

Figure 54b. Photo-Micrograph of Bonded Area. 250X

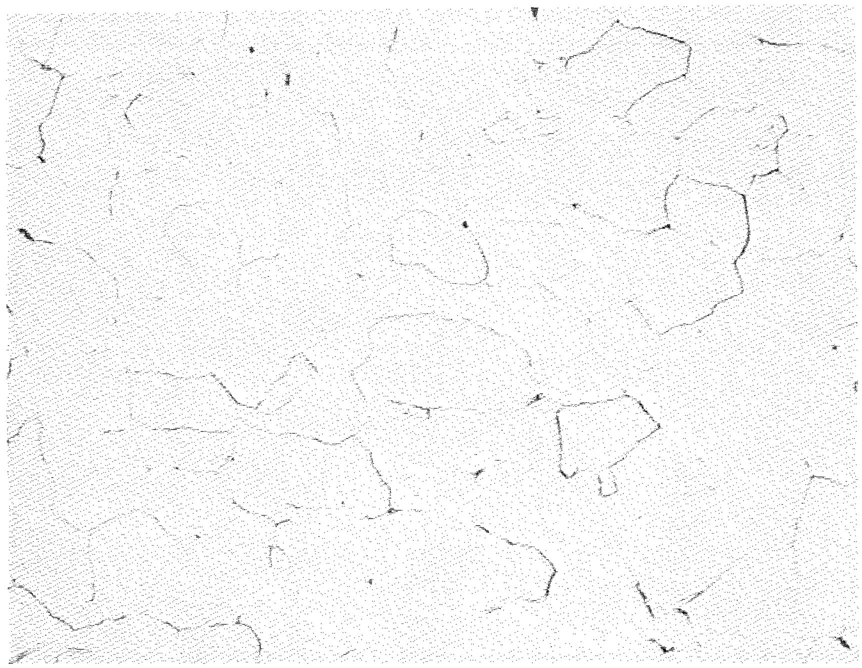


Figure 55a. Photo-Micrograph of Non-Bond Area. 250X

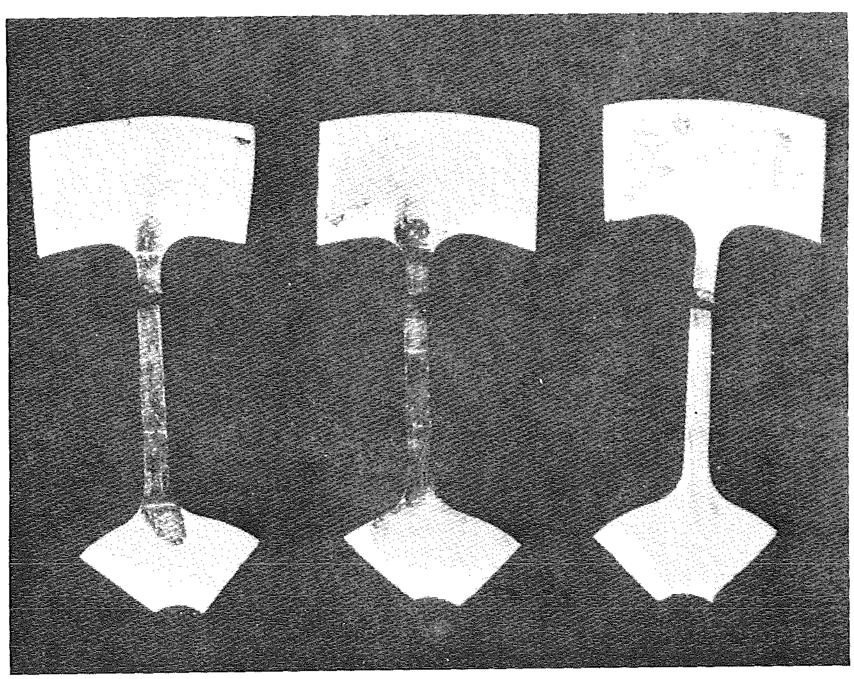


Figure 55b. Tensile Specimens Taken From Simulated Impeller Inlet Area

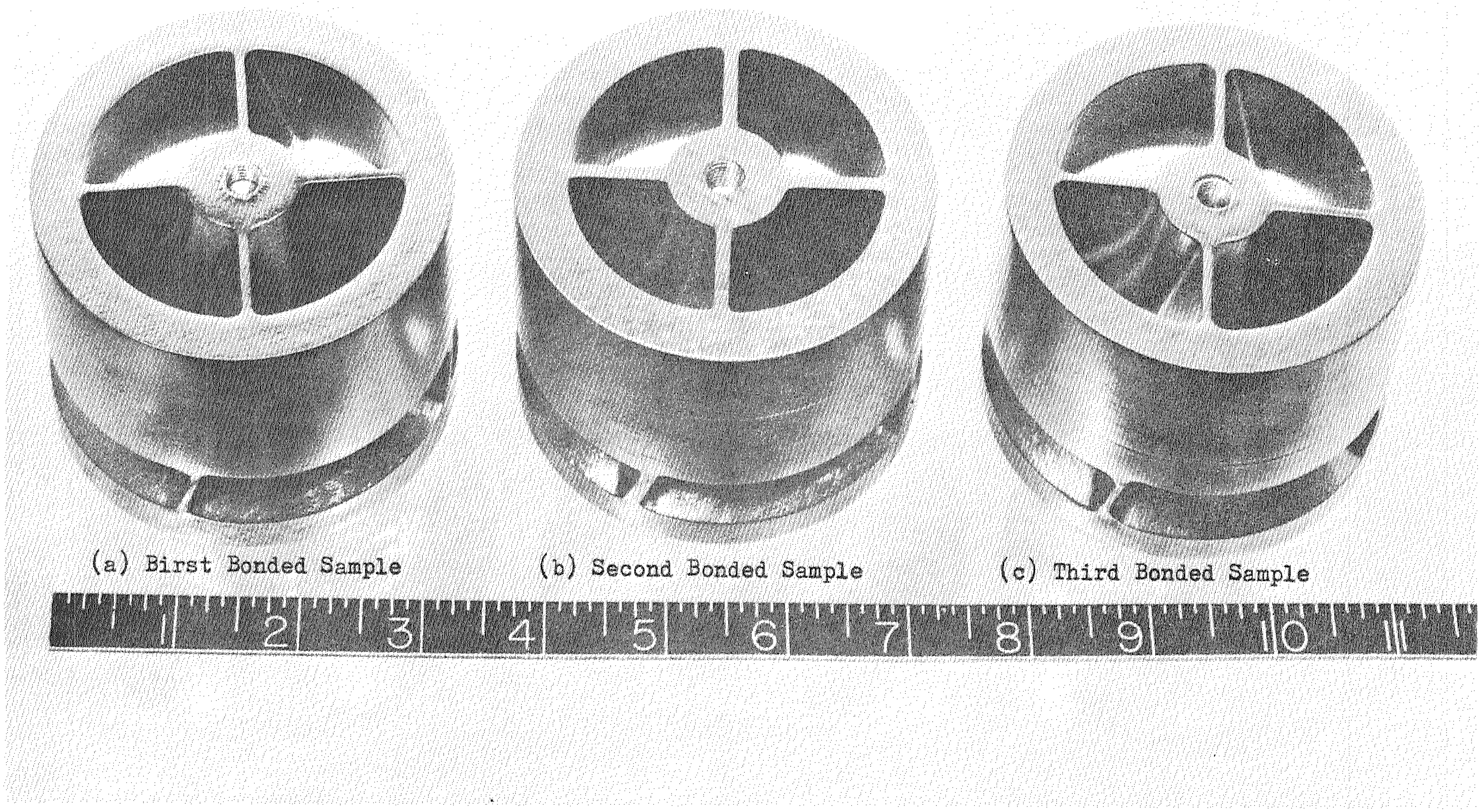


Figure 56. Simulated Impeller Samples Bonded.

It can be observed from Fig. 19 that the fillets in the final sample are considerably larger than in the first sample. The radius of the fillet is increased during the chem-milling process.

Full-Scale Impeller Fabrication

Based on the successful results of the final simulated impeller sample, drawings of the full size impeller pre-bond assembly were released for fabrication. Design of the ceramic restrainer tooling for the full size impeller assembly was also made and is shown in Fig. 57.

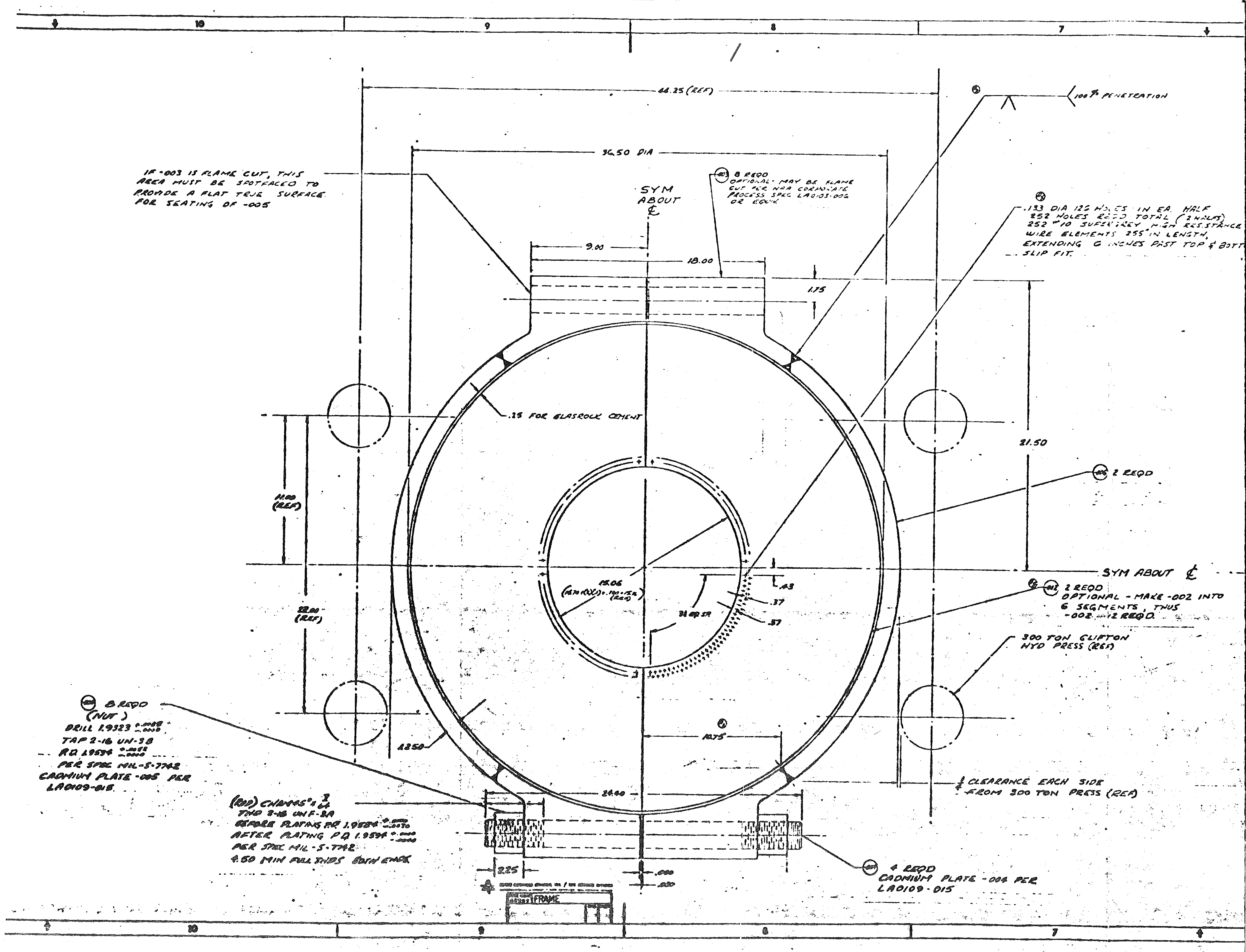
TASK II - FABRICATION OF TWO DIFFUSION BONDED IMPELLERS

Fabrication of Components

Fabrication of the titanium impeller components was accomplished using conventional machining methods and the impeller components are shown in the accompanying photographs. Figure 58 shows a full set of impeller vanes (seven full vanes and seven partial vanes). Fig. 59 shows the finish machined impeller hub and vane shroud. Fig. 60 shows the cores which are used to position and support the vane elements during bonding and Fig. 61 is a view of a complete set of impeller components ready for the bond sequence.

The ceramic restrainer (Fig. 57) was fabricated from fushed silica ceramic. Holes were cast in the die for accommodating nichrome heater wires. A heavy steel split clamping ring was fabricated for restraining the ceramic die as a bolted assembly.

A thermal trial of the die was made using a dummy load of steel instrumented with thermocouples in the die cavity to simulate the impeller and retort assembly. The steel load was brought to a temperature of 1700°F.. An initial power level of 13 KW was employed with a final controlling level of 3.5-5 KW required to maintain temperature. The maximum temperature difference throughout the dummy load after stabilizing at 1700°F was $\pm$ 10°F.



44.25 (REF)
36.50 DIA
100% PENETRATION
IF -003 IS FLAME CUT, THIS AREA MUST BE SPOTFACED TO PROVIDE A FLAT TRUE SURFACE FOR SEATING OF -005
8 REQD OPTIONAL - MAY BE FLAME CUT PER NAA CORPORATE PROCESS SPEC LA0103-006 OR EQUIV.
SYM ABOUT ℄
.133 DIA 126 HOLES IN EA. HALF 252 HOLES REQD TOTAL (2 HALVES) 252 #10 SUPER KEY HIGH RESISTANCE WIRE ELEMENTS 255 IN LENGTH, EXTENDING 6 INCHES PAST TOP & BOTT. SLIP FIT.
9.00
18.00
1.75
.25 FOR ELASROCK CEMENT
21.50
2 REQD
SYM ABOUT ℄
2 REQD OPTIONAL - MAKE -002 INTO 6 SEGMENTS, THUS -002 - 12 REQD.
.43
.37
.37
300 TON CLIFTON HYD PRESS (REF)
(REF)
(REF)
8 REQD (NUT) DRILL 1.9323 TAP 2-16 UN-3B P.D. 1.9594 PER SPEC MIL-S-7742 CADMIUM PLATE -005 PER LA0109-015
10.75
1.250
24.00
¼ CLEARANCE EACH SIDE FROM 300 TON PRESS (REF)
(REQ) CHAMFER TO ¼ THD 2-16 UNF-3A BEFORE PLATING P.D. 1.9594 AFTER PLATING P.D. 1.9594 PER SPEC MIL-S-7742 4.50 MIN FULL THDS BOTH ENDS
2.25
.000
.030
4 REQD CADMIUM PLATE -004 PER LA0109-015
FRAME
10
9
8
7

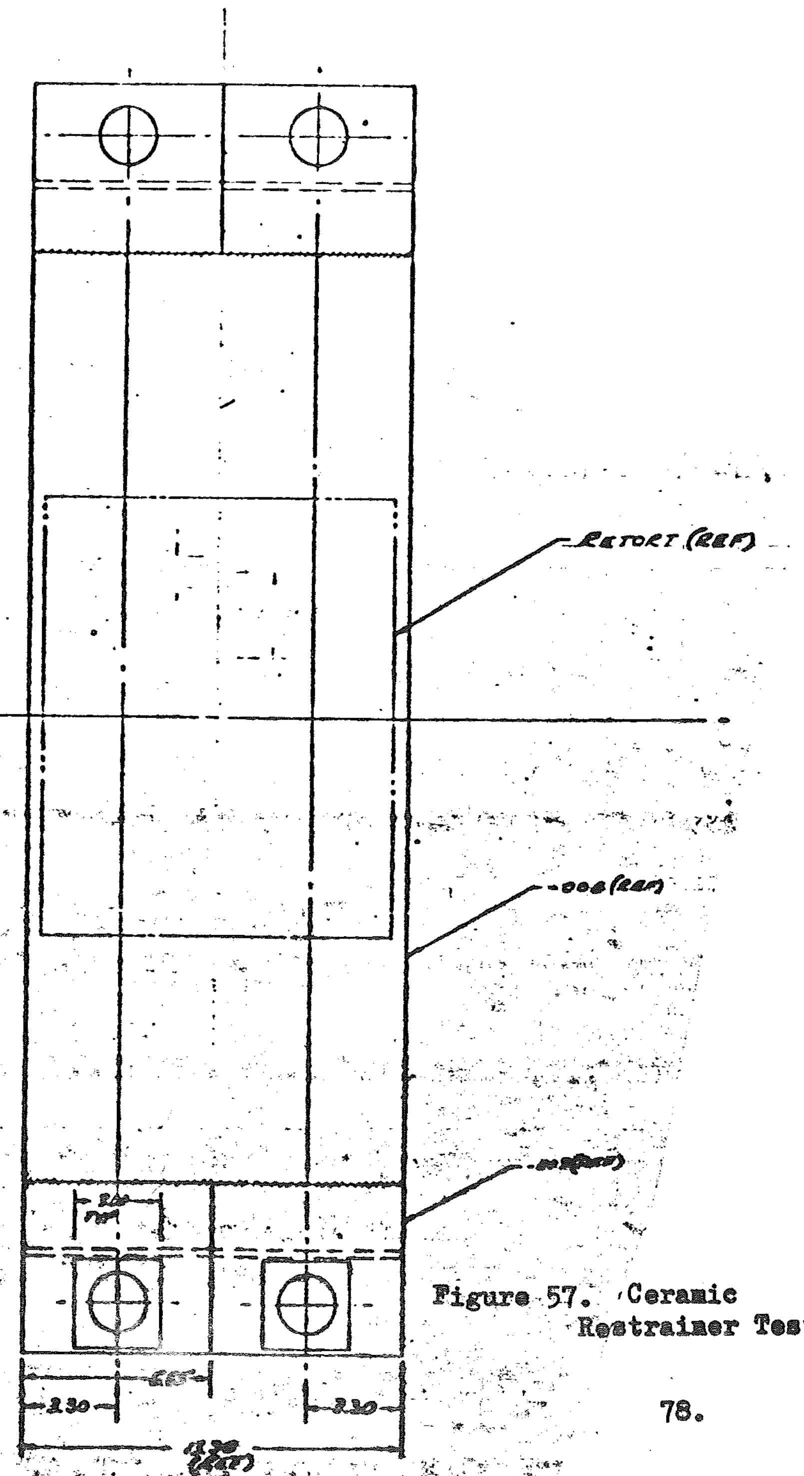


Figure 57. Ceramic Restrainer Testing

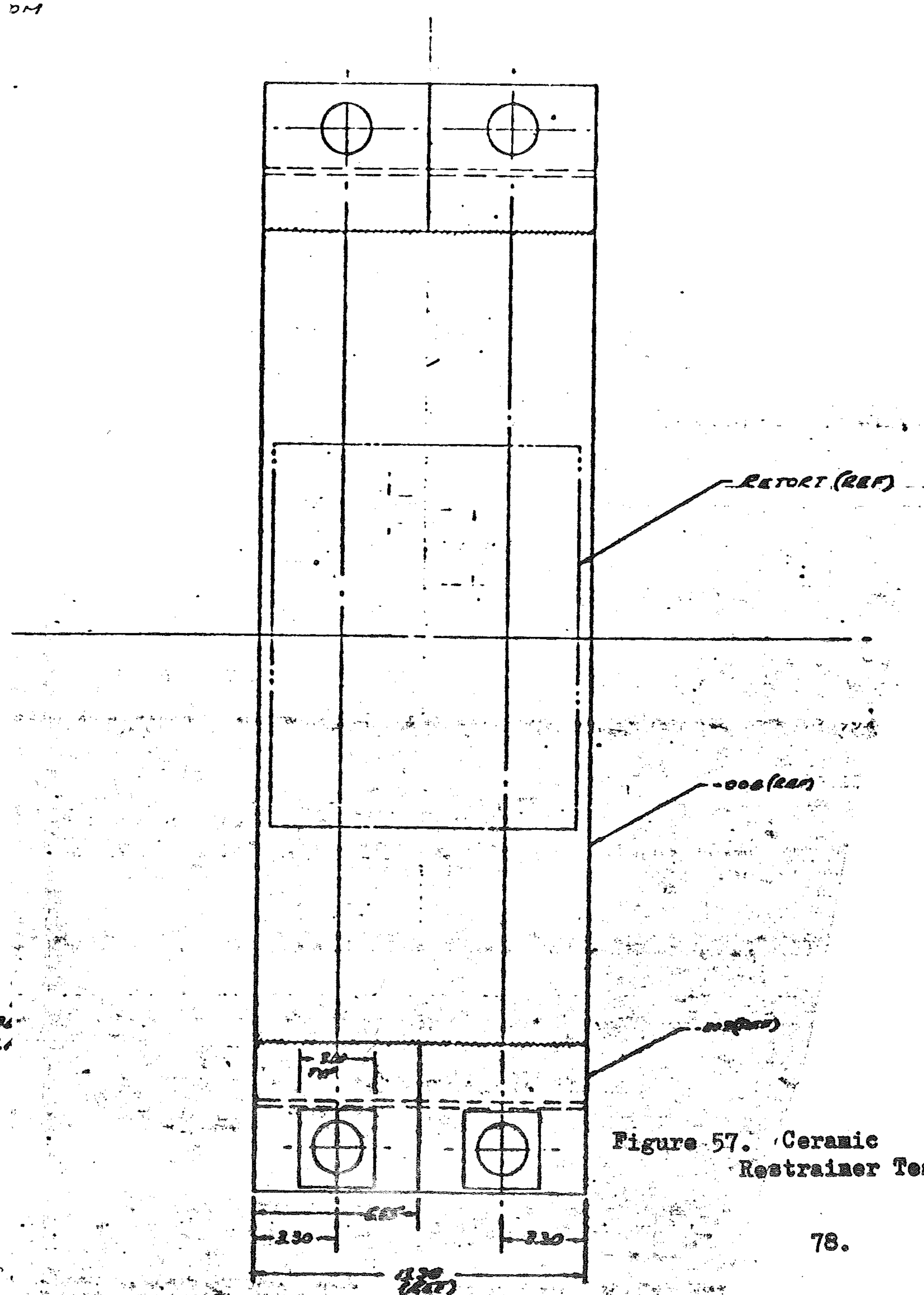


Figure 57. Ceramic Restrainer Testing

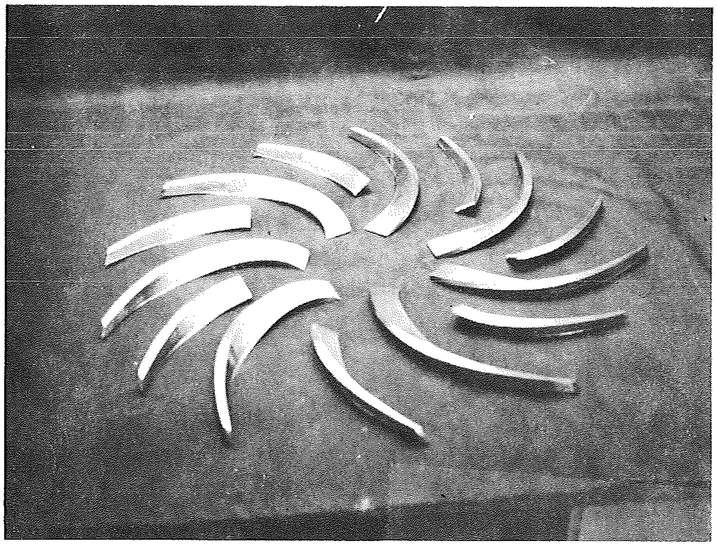
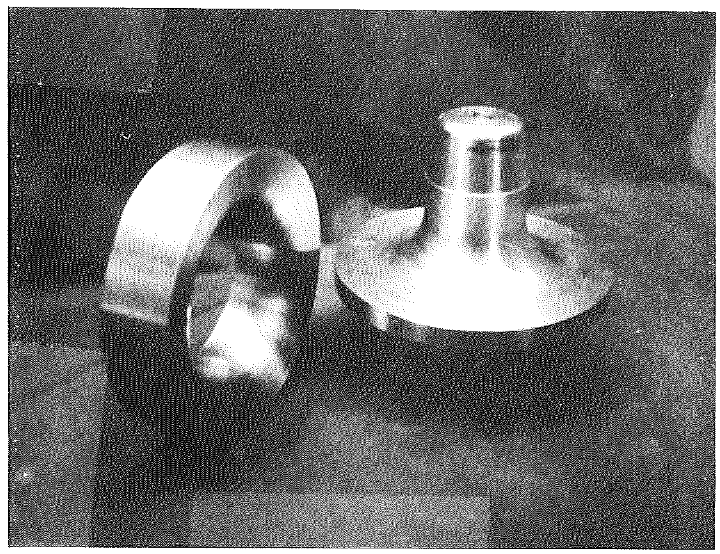


Figure 58. Full Set of Vanes (Partial and Full)

Figure 59. Impeller Hub and Shroud



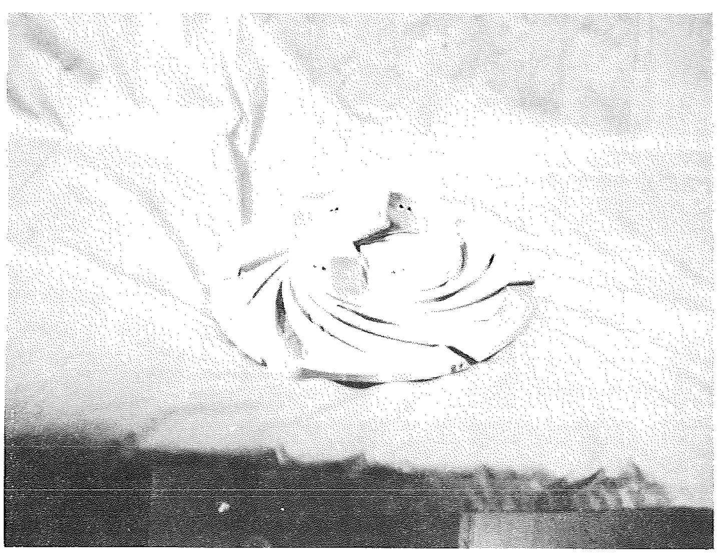


Figure 60. Impeller Cores

Figure 61. Impeller Components Ready for Bonding

Layup and Bonding

The layup of the impellers in preparation for bonding is shown in the accompanying photographs. Figure 62 shows the partially assembled steel cores which are used to position and support the impeller vanes during the bonding process. Fig. 63 illustrates the assembly of the full length impeller vanes into the core assembly. Two vanes are shown installed and a third vane ready for installation. Fig. 64 is a view from the back side of the impeller showing all of the full length vanes installed in the core assembly. Fig. 65 shows the installation of the partial vanes and Fig. 66 is a back view of the complete core assembly with all of the vanes in place.

Figure 67 shows the prebond layup of the complete impeller assembly, which includes the front impeller shroud; the core assembly, which includes the impeller vanes; and the impeller backplate and shaft. Fig. 68 is anoghter view of the prebond layup of the complete impeller assembly showing the core locks (the two rings with the screw heads showing) which hold the vanes and cores together to form the core assembly. The fit between the vanes and steel cores of both impellers was such that gaps up to 0.030 inch were present. To compensate for this, shims of titanium sheet were used to fill the gaps during assembly.

The arrangement of the various components for bonding of the impellers is shown in the sketch of Fig. 69. Tooling components surrounding the impeller assembly, as shown in Fig. 70, consisted of a base, sleeve and load cap. The load plate was cast and machined from Esco alloy 58 which has superior high temperature strength. This material was selected to prevent yielding under load which could create interference with the steel sleeve. The retort was fabricated from type 321 stainless steel because of its proven reliability as a high temperature diffusion bonding vacuum retort system.

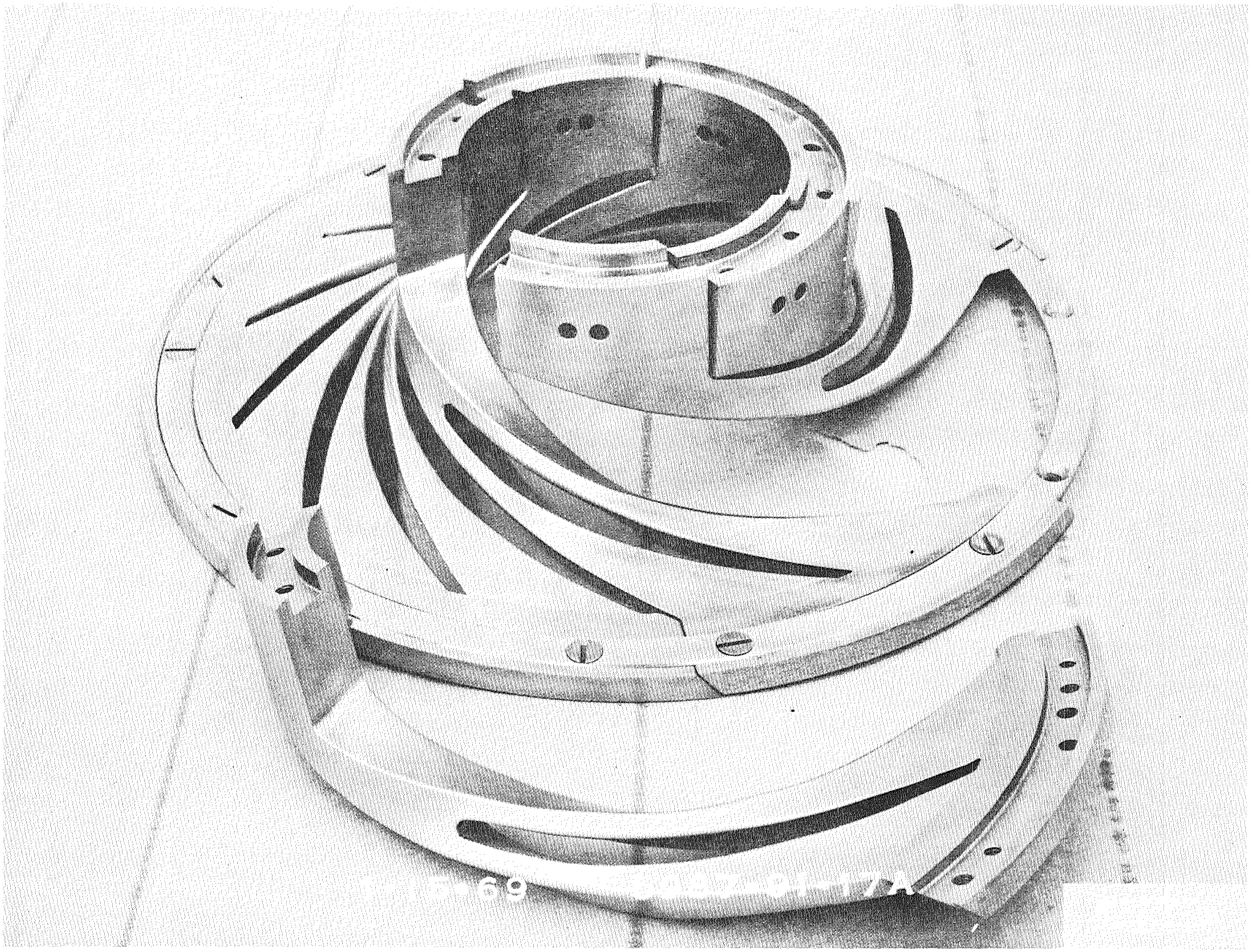


Figure 62. Partially Assembled Steel Cores

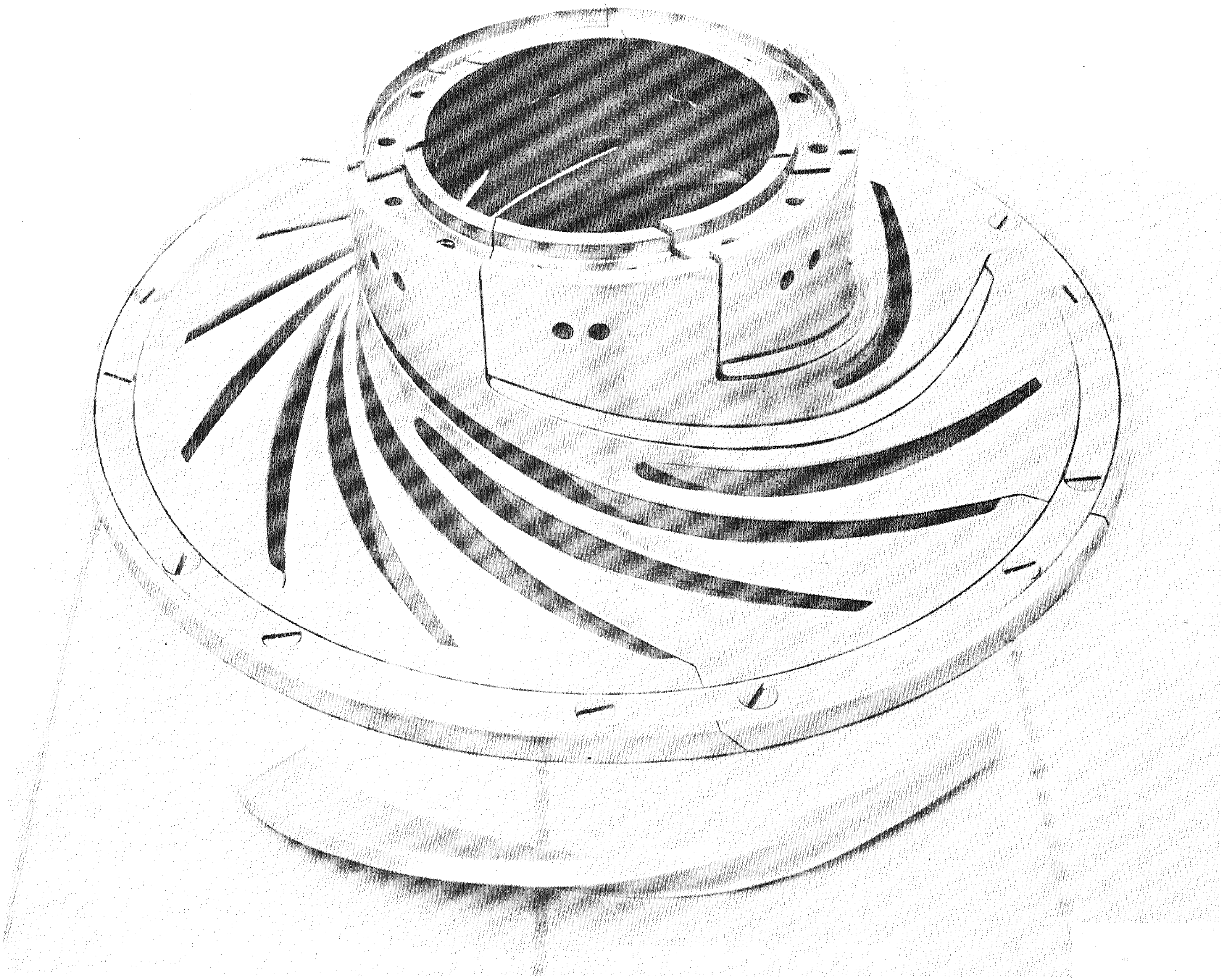


Figure 63. Assembly of Full Length Vanes Into Core Assembly

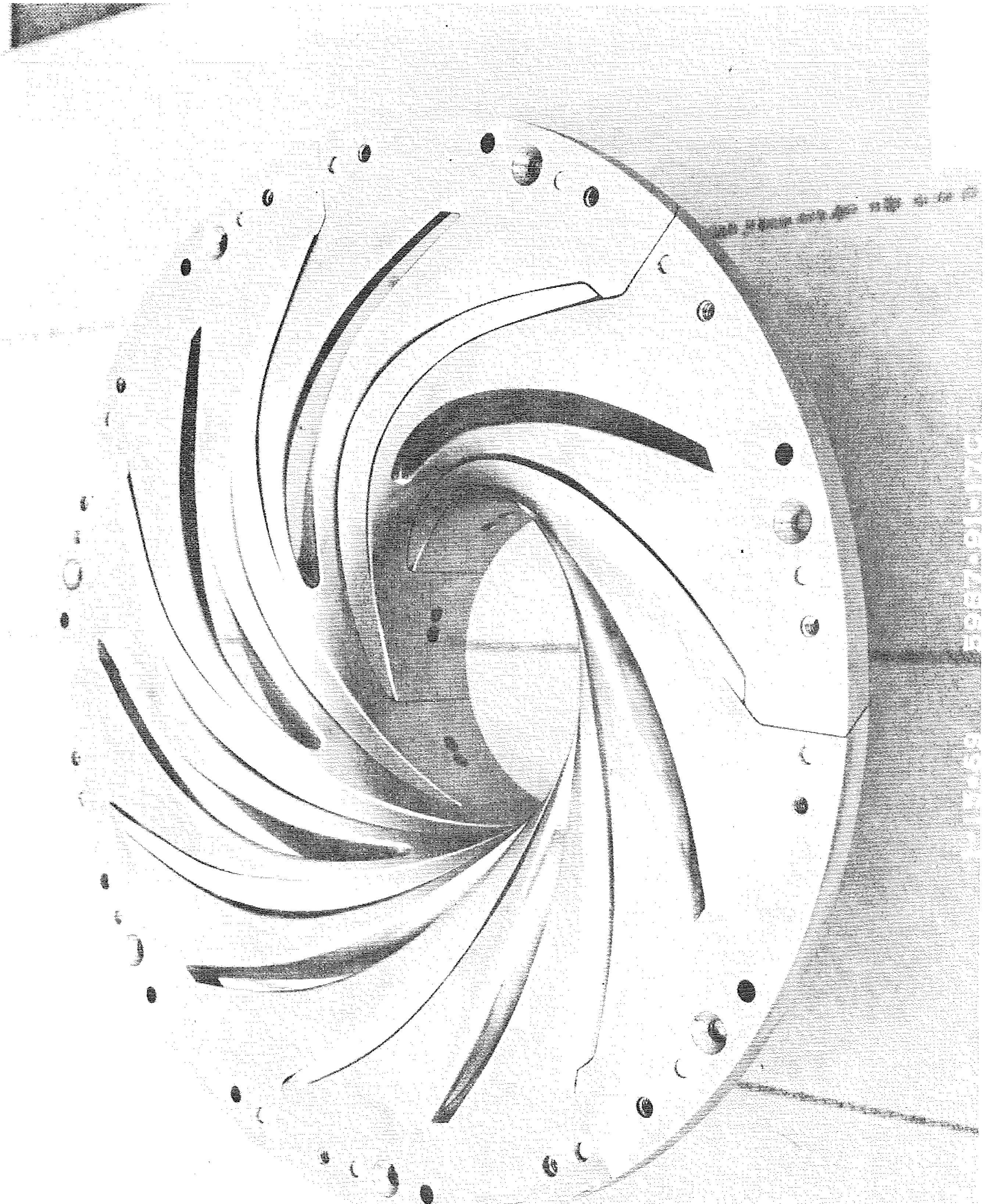


Figure 64. Full Length Vanes installed in Core Assembly.

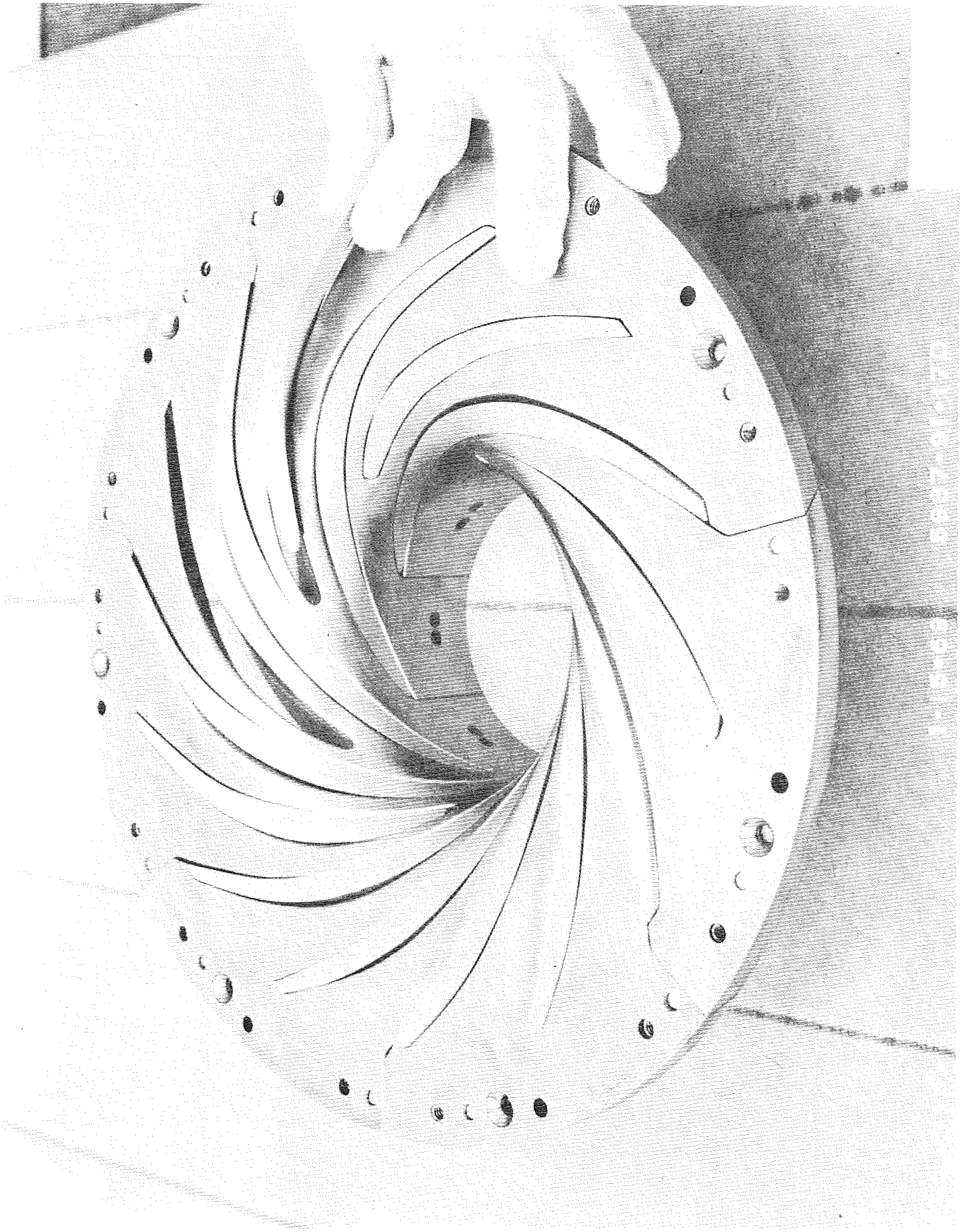


Figure 65. Installation of Partial Vanes Into Core Assembly.

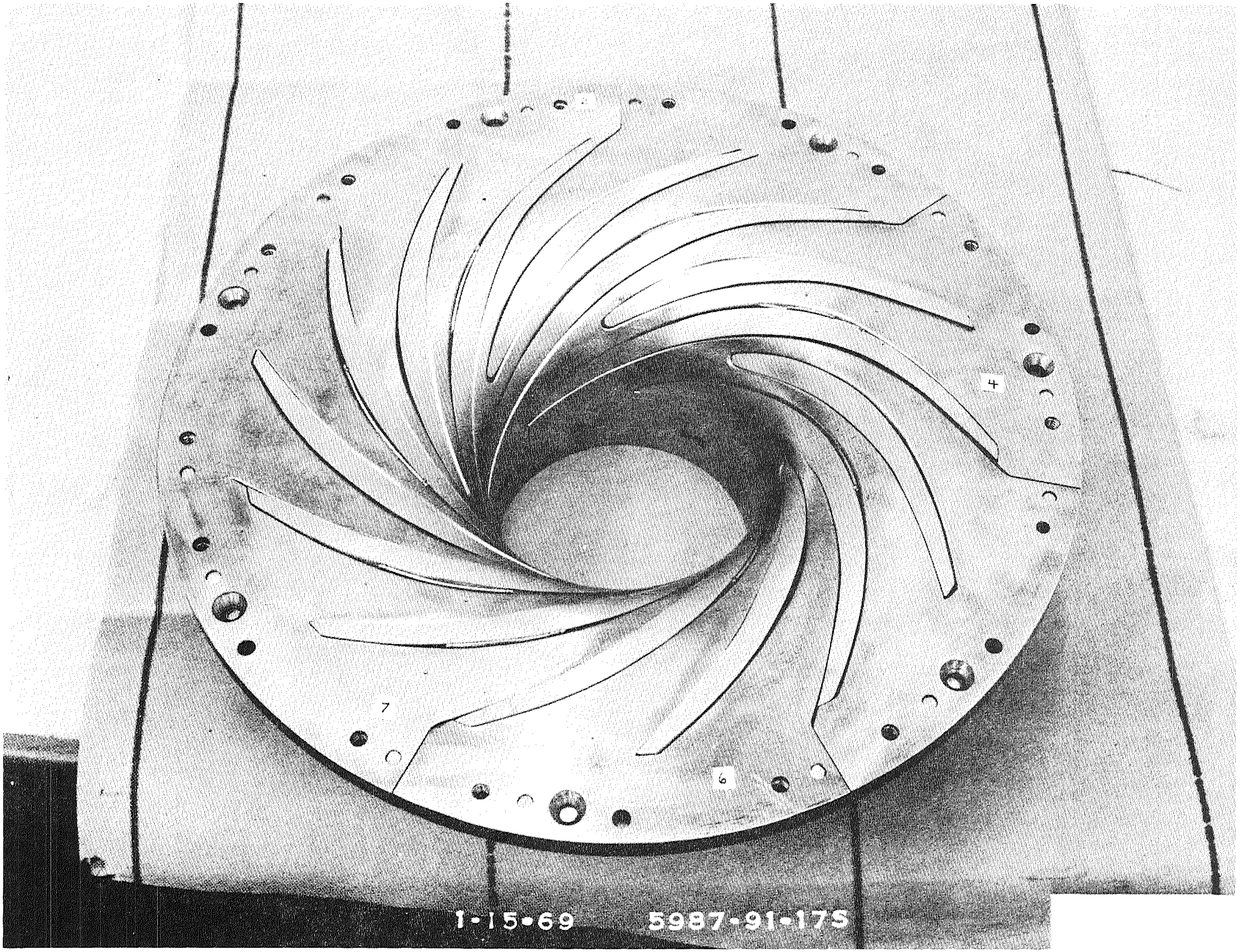


Figure 66. Back View of Core Assembly With All Vanes in Place

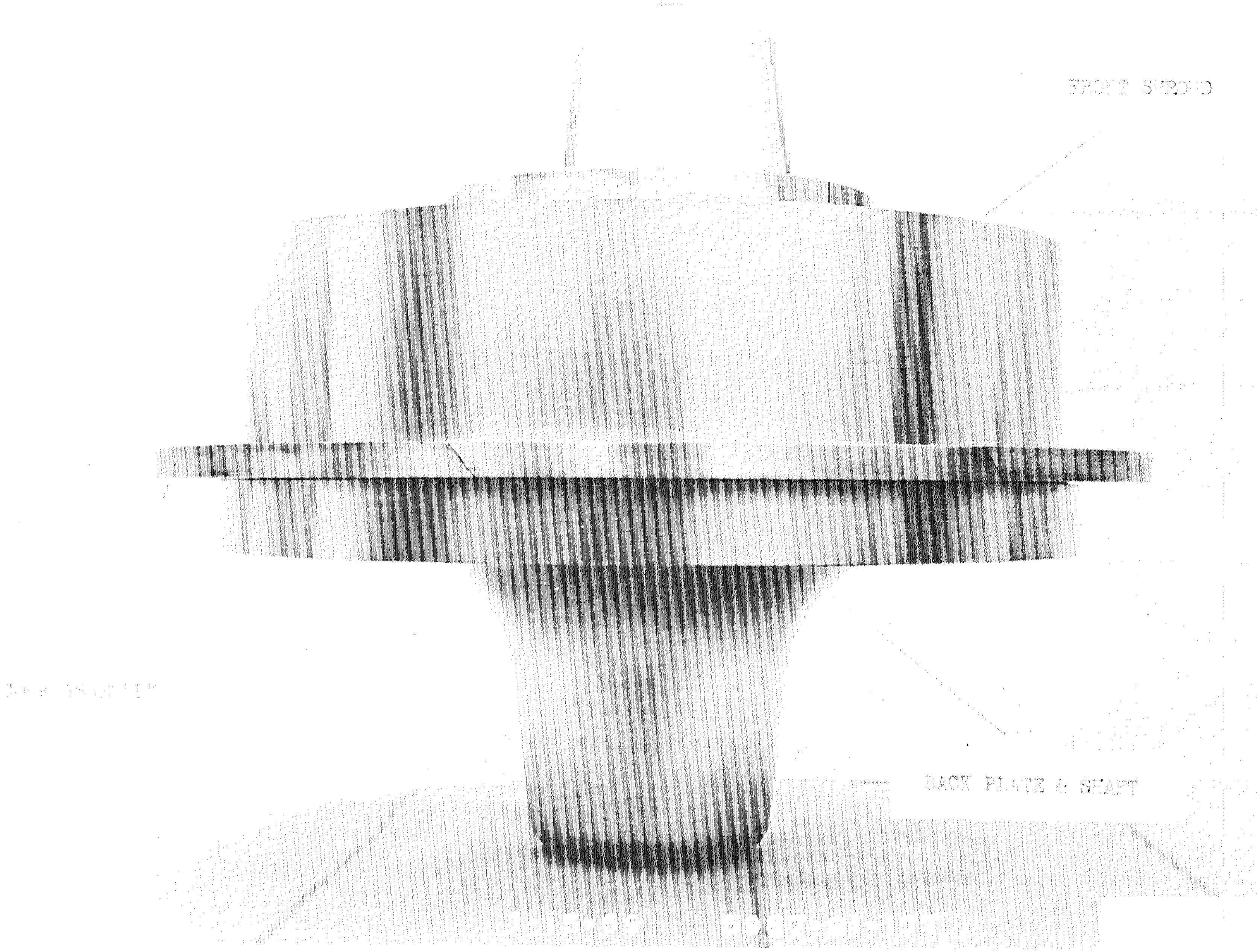


Figure 67. Prebond Layup of Complete Impeller Assembly.

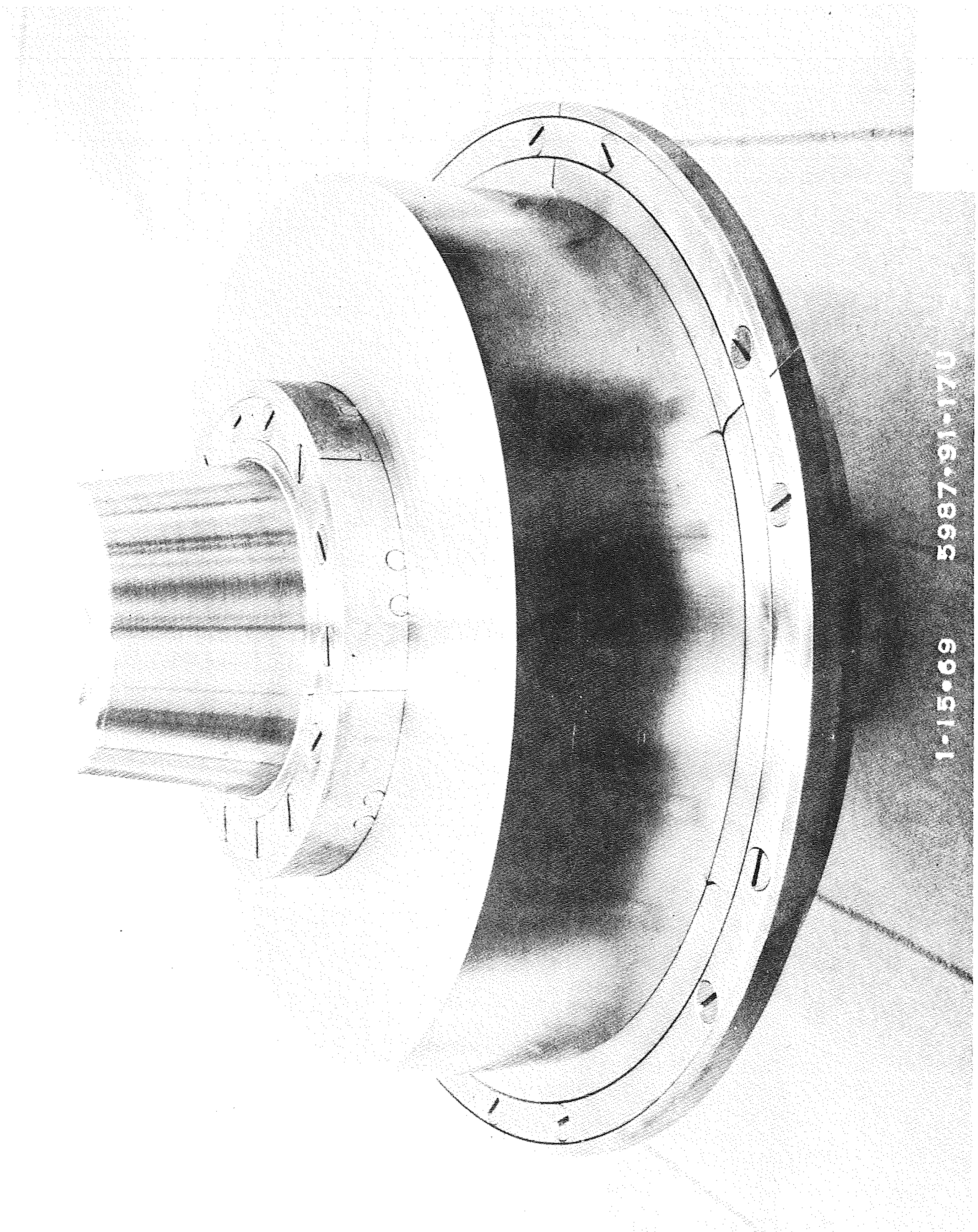


Figure 68. Prebond Layup

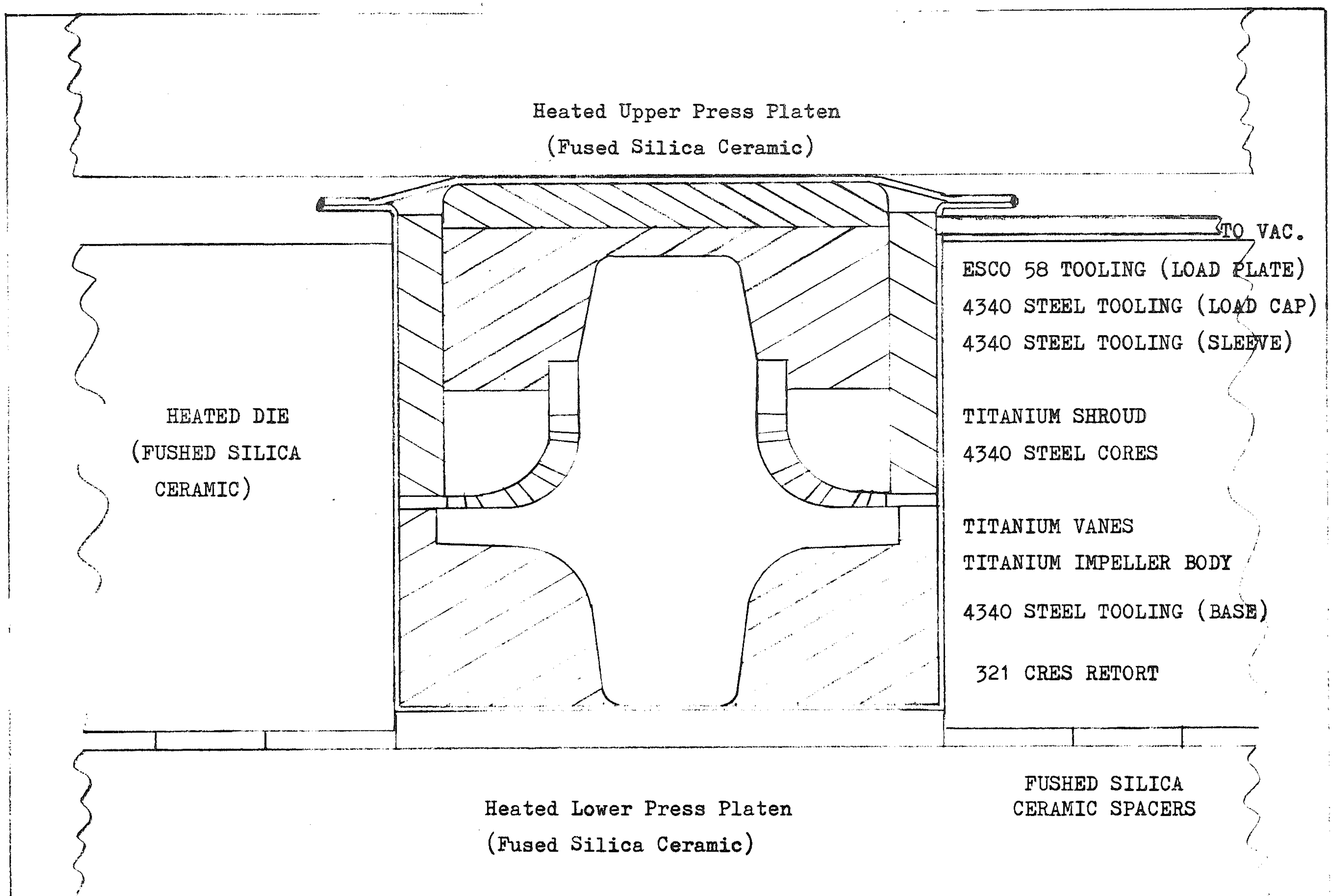


Figure 69. Arrangement of Components for Diffusion Bonding the Full Scale Shrouded Impeller

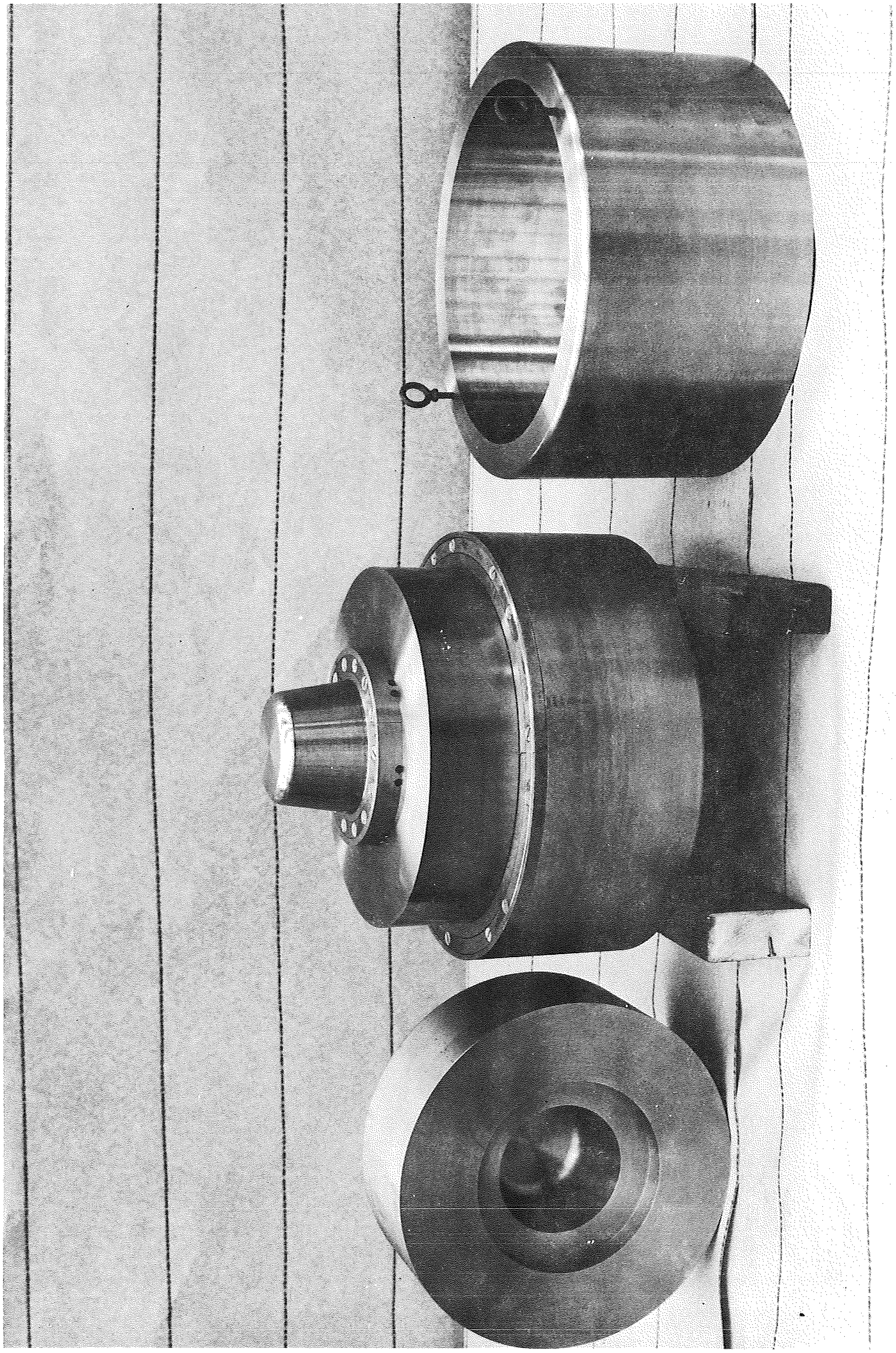


Figure 70. Tooling Components for Bonding Impeller

The impeller details and tooling were assembled in the retort (Fig. 71). The retort assembly was placed in the ceramic die and positioned in a hydraulic press, as shown in Fig. 72. The retort was evacuated with a 4-inch diameter high vacuum oil diffusion pump coupled to a mechanical roughing pump. Thermocouples were positioned at the top, bottom, and opposite sides (midway) of the retort and in extra holes provided in the ceramic die.

The upper and lower ceramic plates were also heated in order to minimize heatup time and to reduce heat losses from the retort assembly. The bonding parameters used are given in Table 4 but the bonding time was reduced to 8 hours. During bonding of the first impeller, a heating element in one quadrant of the heater circuit burned out due to spalling at the base of the ceramic die. However, sufficient heating surface area was available to continue the bond cycle without detrimental results although the bonding load was reduced to prevent further spalling of the die. No problems were experienced with the second impeller bond cycle. The same external tooling was used for both impellers and required only minor rework to true-up dimensions for the second run. The spalling in the ceramic die was repaired with fushed silica cement and the heater circuit was rewired for the second run.

Post-Bond Processing

Each of the bonded impellers was carefully inspected to insure uniformity in the shroud. The outer portion of the steel core locks were machined away so as to expose the discharge vanes, as shown in Fig. 73. This provided a means of partially inspecting the bonding and filleting of the vanes to the shroud and impeller body. The satisfactory appearance of the discharge vanes provided the basis for proceeding to remove the remainder of the steel cores by acid leaching.

Leaching of the steel cores from the bonded impellers was accomplished in a hot solution of nitric acid. The highest leaching rate was observed at temperatures of about 210-220°F. One of the as-leached impellers is shown in Fig. 74.

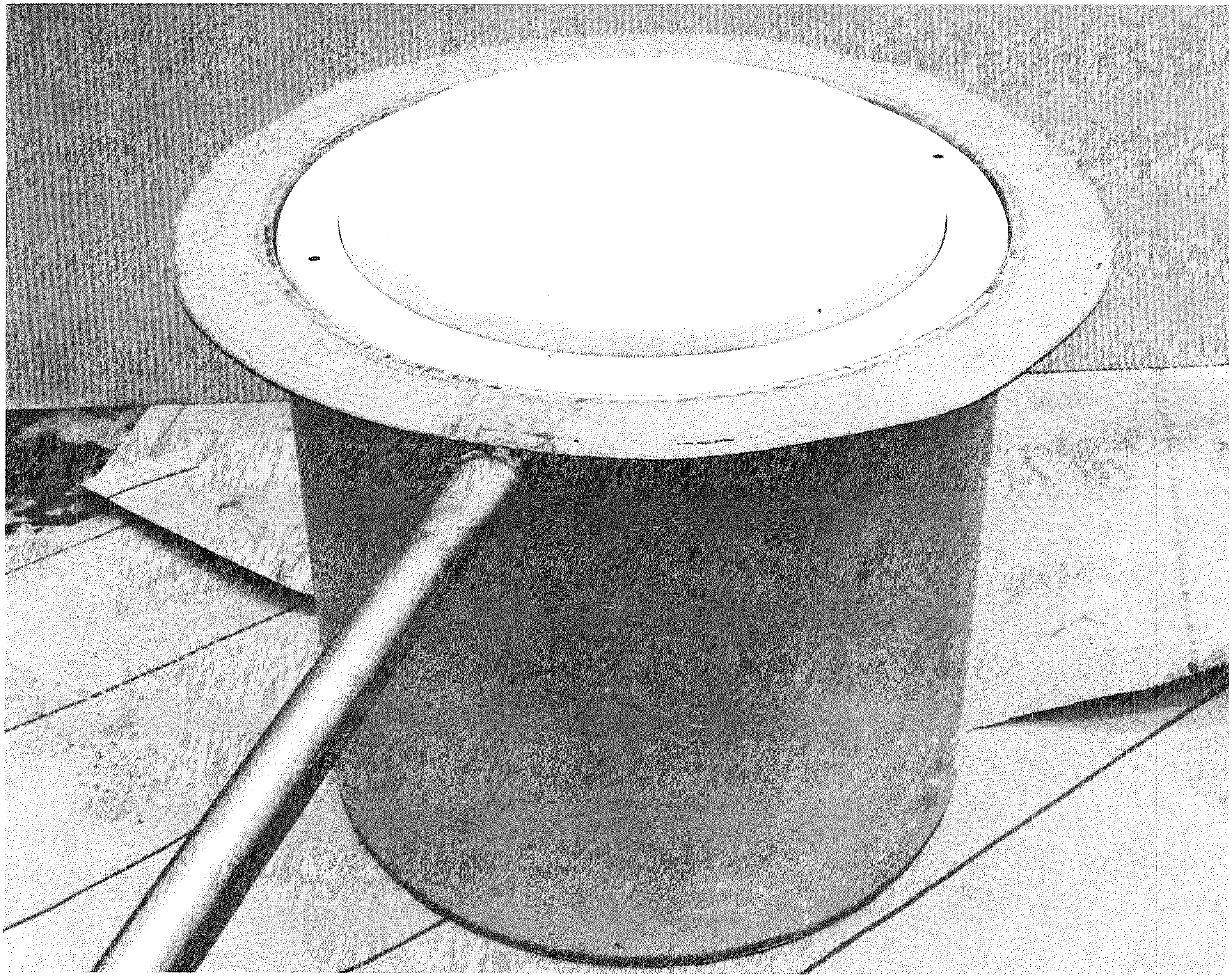


Figure 71. Impeller and Tooling Assembly in Retort

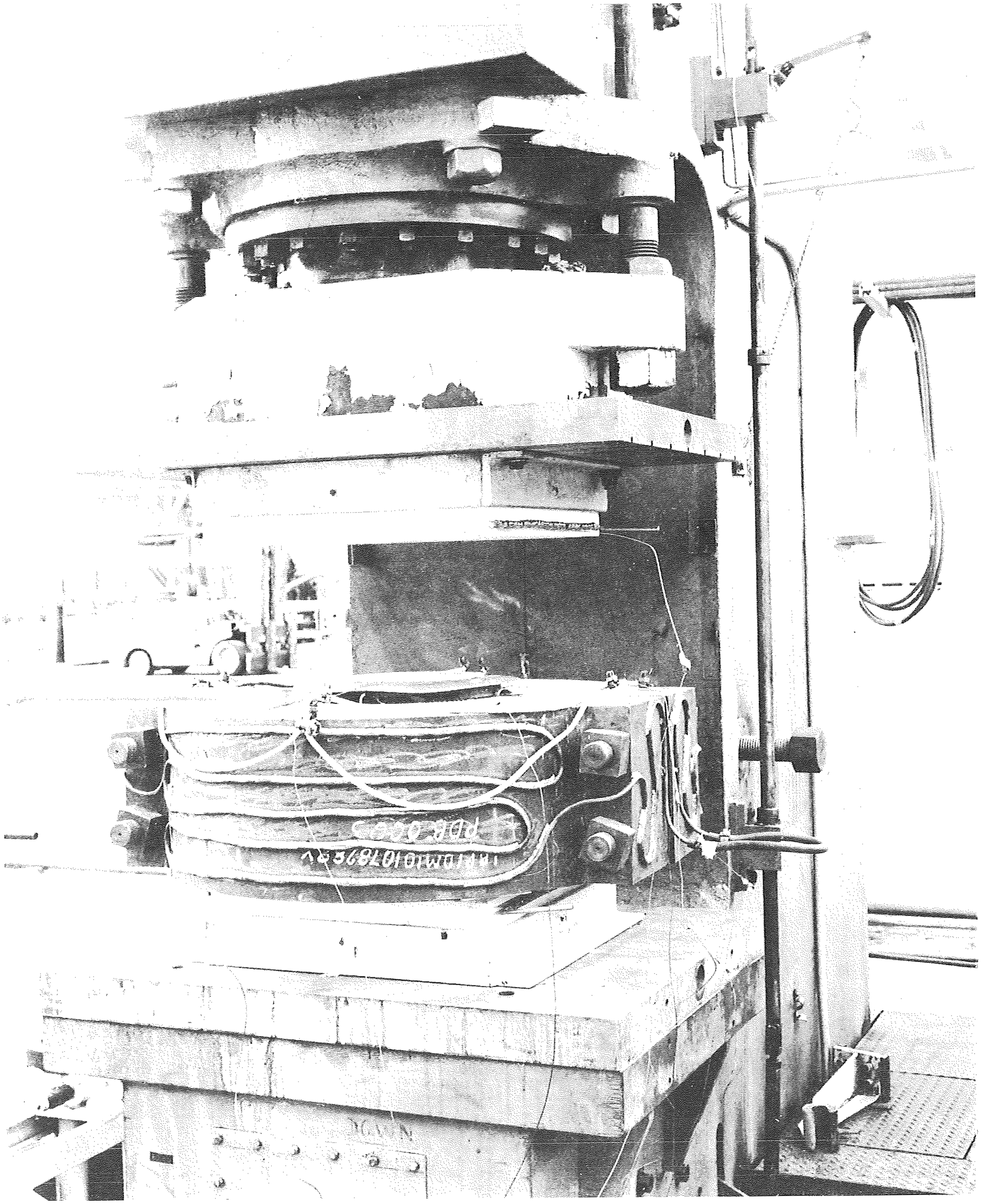


Figure 72. Retort Assembly in Ceramic Die
and Positioned in Hydraulic Press

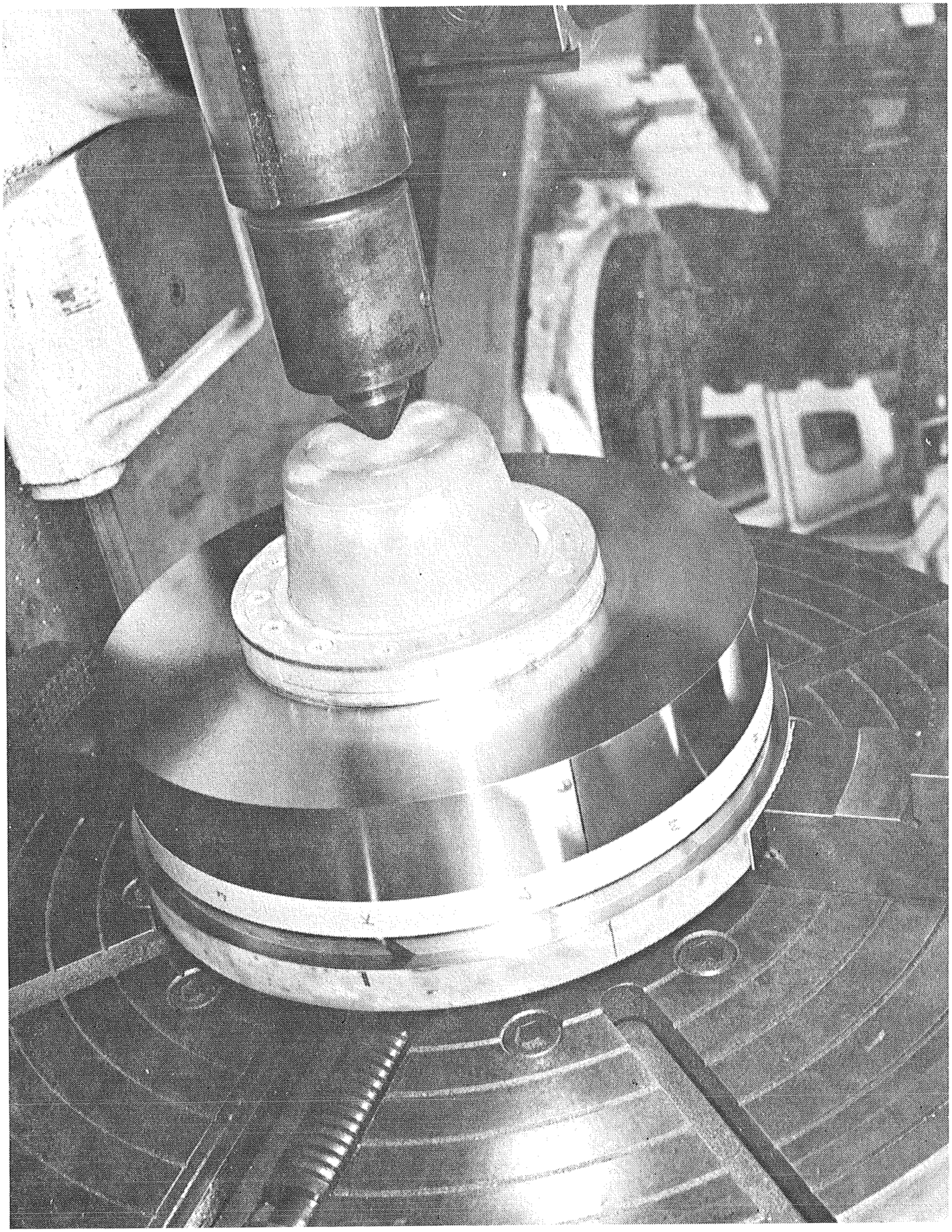


Figure 73. Machining Off the Steel Core Locks

Figure 74. Leaching of Steel Core from Bonded Impellers

Each of the two impellers was chemically milled to remove 0.040 inch from each surface. A rotating fixture with a variable speed drive was used to slowly turn each impeller in the chemical milling solution. The direction of rotation allowed solution to enter the inlet side of the impeller and to flow out the discharge side. Progress of the titanium removal was monitored by periodic measurements of inlet and outlet vane thickness and the distance between the shroud and impeller body at the inlet and outlet vanes. After chemical milling, the impellers were cleaned by pickling. A chemically milled impeller is shown in Fig. 75.

TASK III - IMPELLER SPIN TEST

Non-distructive static and dynamic spin tests were conducted on each of the two impellers to verify their structural integrity.

Following the chemical milling operation the impellers were visually and dye penetrant inspected. The units then finish machined. Following machining the impellers were balanced to within 2.0 gm -in by running material at two correction planes. Impellers were then installed in the spin fixture and rebalanced to 2.0 gm in., correcting on the fixture only.

After balancing the impellers were installed in a spin pit and successfully spun at 31,000 rpm for two minutes. These tests demonstrated the feasibility of this method of fabrication. A completed impeller is shown in Fig. 76.

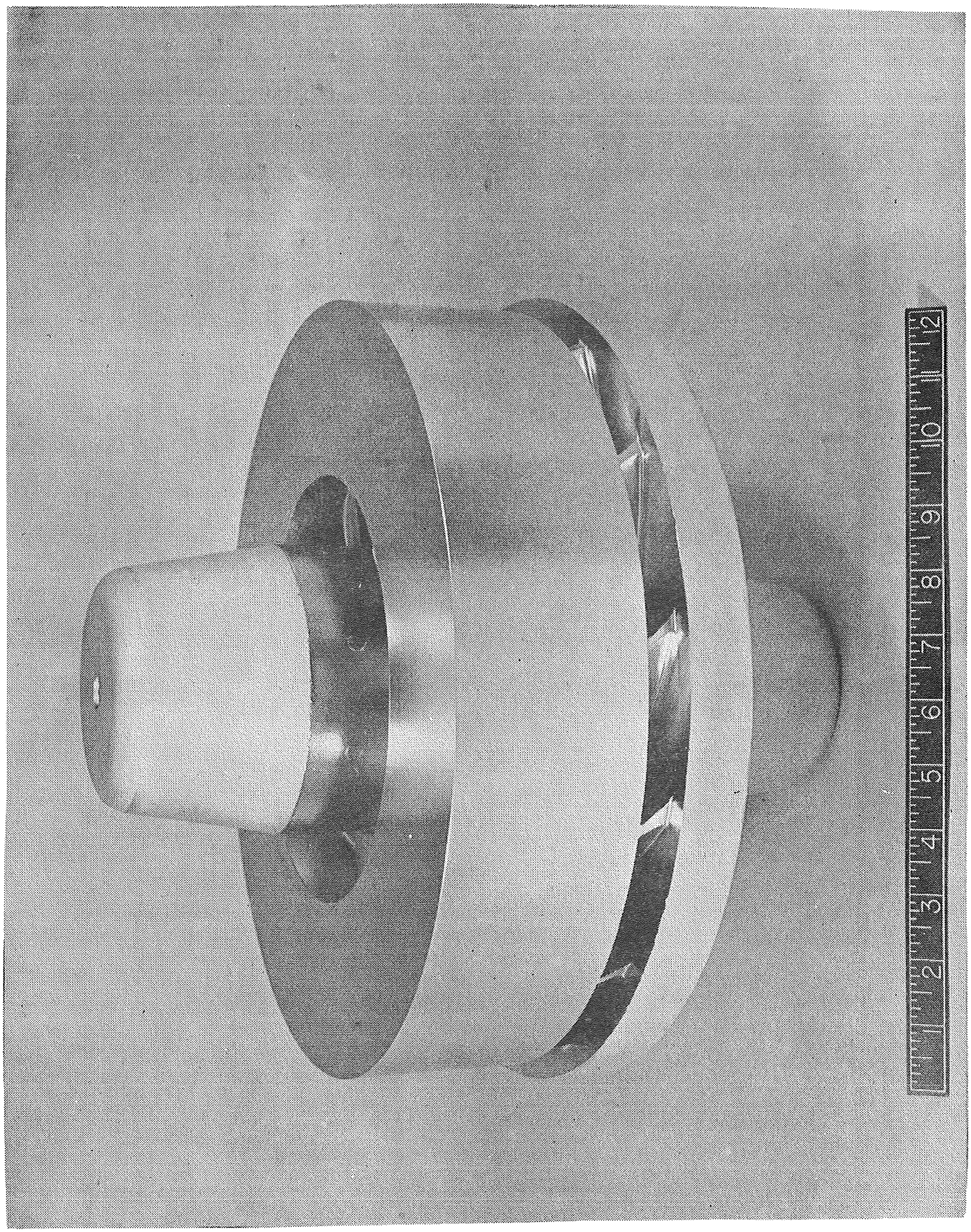


Figure 75. Impeller After Chemically Milled

Figure 76. Completed Diffusion Bonded Shrouded Titanium Impeller

CONCLUSION

The highly successful results obtained in this program have definitely established the feasibility of utilizing the diffusion bonding technique of fabricate high-tip speed, shrouded impellers with titanium and with blade angles optimized for hydrodynamic performance instead of by the machining process. This new technology may have applications in the high pressure liquid hydrogen pumps required by high performance engines in the space shuttle vehicle. Thus, it is important to continue the development of this new fabrication technique and to demonstrate the structural and hydrodynamic performance of the two titanium impellers already fabricated by the diffusion bonding process.

RECOMMENDATIONS

To take advantage of the significant technical accomplishments achieved during this program, it is recommended that additional effort be undertaken to: a) further evaluate the diffusion bonding process by testing the two impellers structurally and hydrodynamically, b) explore the economics of this method of impeller fabrication for low cost, and c) investigate other applications of the process where it might advantageously be utilized to decrease cost or increase reliability of performance.

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13. ABSTRACT

This report describes the development of diffusion bonding technique for fabrication of shrouded titanium centrifigual impellers. Trial samples were used to develop the optimum procedure and two shrouded titanium impellers were successfully diffusion-bonded and finish-machined. Both of the impellers were also successfully spin-tested to demonstrate the feasibility of the diffusion bonding process for attaching shrouds on centrifugal impellers.

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