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FINAL REPORT

ADVANCED THRUST CHAMBER DESIGNS

By

F. J. DIETRICH

A. E. LEACH

Prepared For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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16. Abstract

A regeneratively cooled thrust chamber has been designed and fabricated, consisting of an inner TD nickel liner which was spin formed, welded, and machined and an outer shell of electroformed nickel. Coolant channels were produced in the outer surface of the inner liner by the electric discharge machining process before electroforming the shell. Accessory manifolds and piping were attached by welding. Manufacturing processes employed are described.

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NASA, Lewis Research Center
Cleveland, Ohio
Chemical and Nuclear Rocket
Procurement Section

Rudolph A. Duscha, Project Manager

FOREWORD

The work reported herein was performed for NASA/LeRC under contract NAS 3-7968 titled "Advanced Thrust Chamber Designs". Mr. R.A. Duscha was the NASA/LeRC project manager.

The authors wish to acknowledge important contributions to this report by several individuals. These include the treatment of welding by J. Biffl, spin-forming, electric discharge machining, and conventional machining by J.P. Morris, and electroforming by G.A. Malone.

Mr. A. E. Leach, a co-author of this report, was Program Manager of the subject program during the fabrication operations covered by this report. Mr. C.H. Brown was Program Manager during the design phase and early fabrication operations.

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ABSTRACT

A regeneratively cooled thrust chamber has been designed and fabricated, consisting of an inner TD nickel liner which was spin formed, welded, and machined and an outer shell of electroformed nickel. Coolant channels were produced in the outer surface of the inner liner by the electric discharge machining process before electroforming the shell. Accessory manifolds and piping were attached by welding. Manufacturing processes employed are described.

I. SUMMARY

Design evaluations led to the selection of a chamber consisting of an inner liner containing coolant flow channels, enclosed with an electroformed outer shell. A spinning procedure for forming the forward and aft sections of the chamber liner was developed using stainless steel blanks and a series of spinning mandrels for staging the spin form operation. The procedure so developed was successfully adapted to shear-spin forming the TD Nickel liner mandated by design evaluation.

Joint efficiencies of 85% of parent metal strength were achieved in the TD Nickel welds. Previously developed techniques were applied successfully to the joining of the forward and aft section liner components into a structurally sound inner liner.

Electrical discharge machining of the fluid flow channels was successfully accomplished on the TD Nickel liner after proving of the process and tools using a slave stainless steel liner.

Laboratory studies in the electroforming of pure nickel resulted in a process offering the capability of electroforming nickel having high strength properties particularly suitable for the chamber structure under study and methods for achieving adherent bonds to TD Nickel. Samples simulating chamber channel and land configuration were subjected to 1050 pounds of hydraulic pressure without an incident of failure.

A thrust chamber was completed employing the processes developed. During the hydraulic pressure phase of preliminary testing, a bulge developed in the aft section of the TD Nickel inner liner at 550 pounds pressure which subsequently was found to be caused by a separation of the inner liner channel lands and the electrodeposited outer nickel shell.

A temporary repair of the area and a retest which resulted in a second bulge at 550 pounds pressure led to the conclusion that the interface bond between the TD Nickel liner and the electroformed outer shell was inadequate to withstand internal pressures required of the chamber. It was evident that the process transition from laboratory study to application was not accomplished with complete success. The program was concluded at this point because basic fabrication methods had been successfully demonstrated and further repair attempts were not considered justifiable.

II. INTRODUCTION

A conventional regeneratively cooled rocket thrust chamber is usually constructed from a number of tubes that have been formed to the chamber shape and joined together by brazing or welding. The tubes have also been shaped such that the cross sectional area is tailored to the thermal and pressure requirements at any particular axial station in the engine. Though this method of construction results in an efficient heat exchanger there are many shortcomings relative to fabricating such a design. These usually concern intricate die forming of the tubes, fitup of the tubes, brazing or welding to form continuous bonds, leakage, local fluid flow disturbances, and little or no flexibility in incorporating new design innovations upon completion of fabrication.

The work reported herein concerns a new design configuration, fabrication techniques, and materials of construction that show promise of reducing fabrication costs and time, reducing heat flux to the coolant, and increasing thrust chamber life.

This program was sponsored by the National Aeronautics and Space Administration under Contract NAS 3-7968. In the initial, or design, phase of the program, various design configurations consisting of tubular and milled channel flow passages were analyzed and compared. An extensive material study was conducted comparing the advantages and disadvantages of refractory metals, super alloys, and dispersion hardened alloys. Alternate fabrication methods for inner liner, coolant passages and outer structural shell were evaluated. These included high energy rate forming (HERF), spinning and conventional forming. Chemical milling, electrochemical milling, electric discharge machining and conventional milling were compared for producing the flow passages. Electroforming, diffusion bonding, explosive welding, conventional welding, and brazing were evaluated for the outer structural shell. The effects of particular fabrication methods upon the design were evaluated to insure that the objectives of the program were not compromised.

The designs and analyses performed were specifically for an 8000 lb thrust hydrogen-fluorine engine, operating at a chamber pressure of 400 psia, with an oxidizer-to-fuel mixture ratio of 12, and having a nozzle expansion area ratio of 60. The chamber characteristic length is a minimum of 25 inches.

Detailed design studies and analyses led to the selection of TD Nickel for the inner liner material. The inner liner contains the coolant flow channels which are produced by electrical discharge machining. The outer shell is produced by electroforming nickel, which is attached to the lands of the inner liner.

Bell Aerospace report "Investigation of Advanced Thrust Chamber Designs", NASA CR-72320, dated February 1968, records in detail the studies and analyses which preceded the fabrication effort herein reported. Figure 1 shows a cross-section of the selected design. Figure 2 is a photograph of the completed thrust chamber.

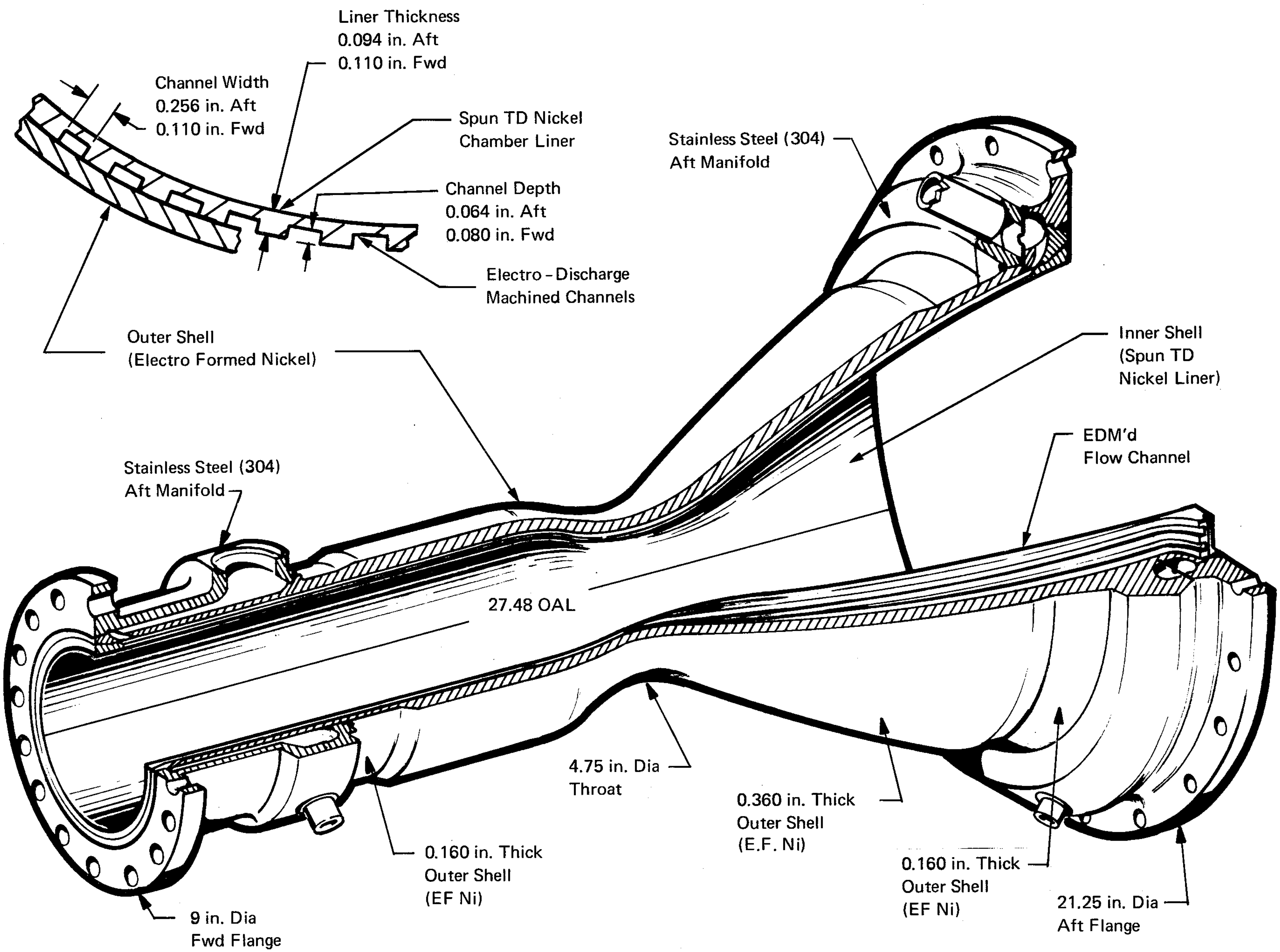

Figure 1. Advanced Regeneratively Cooled Thrust Chamber

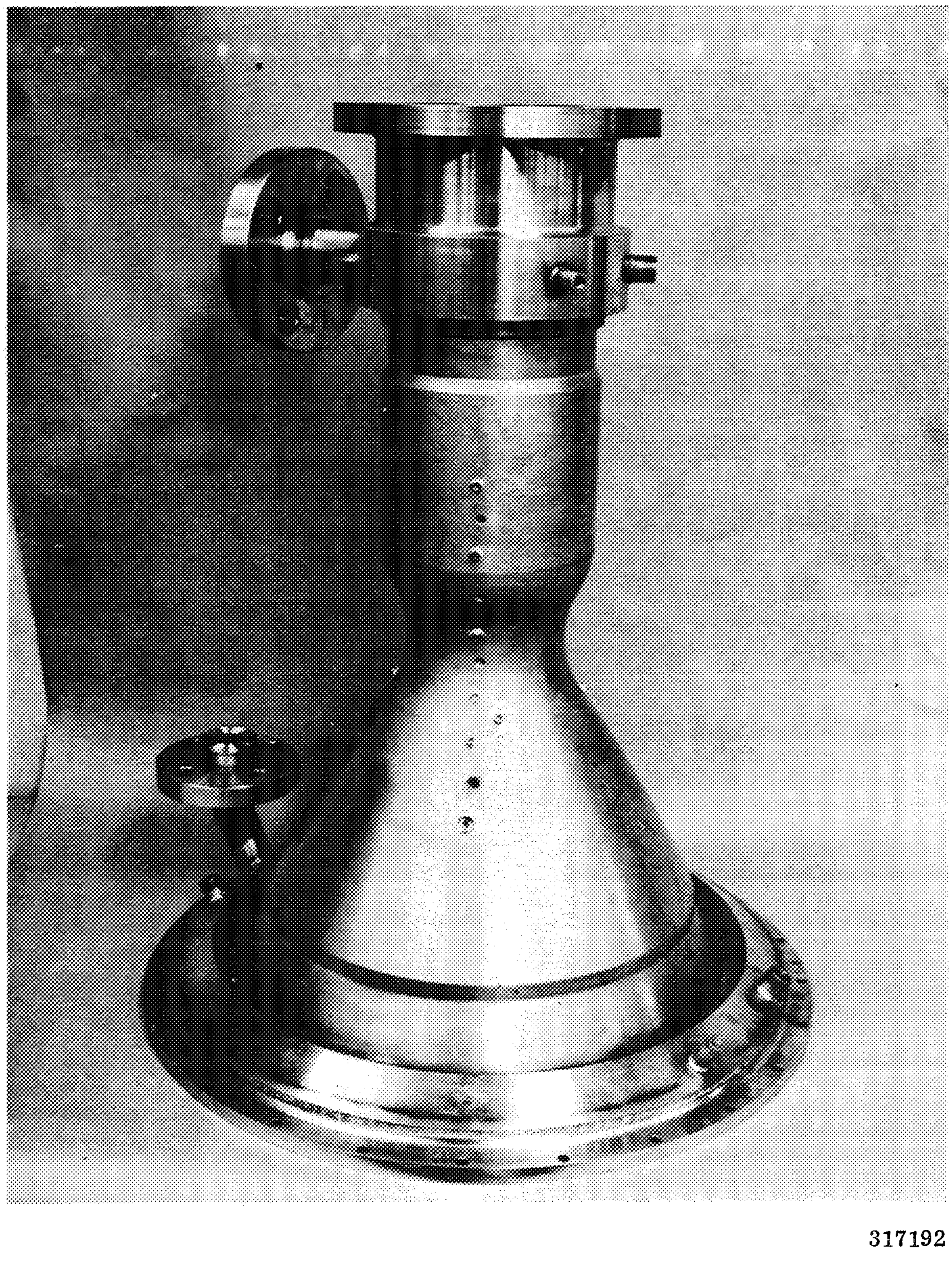

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Figure 2. Completed Regeneratively Cooled Thrust Chamber

III. MANUFACTURING OPERATIONS

The major operations requiring manufacturing consideration during the buildup of the regeneratively cooled thrust chamber were spin forming the forward and aft sections of the chamber inner liner, welding the forward and aft sections into a single unit liner, machining fluid flow channels into the outer wall of the inner liner using the electrical discharge machining approach, and electroforming the outer shell. These operations and other operations incidental to the fabrication of the thrust chamber are described in subsequent sections of this report.

A. FABRICATION SEQUENCE

The fabrication sequence outlined below was followed in the fabrication of the chamber: Operations

1. Spin forward and aft sections of the chamber liner
2. Trim sections to weld joint geometry
3. Weld sections to form chamber liner
4. Machine internal contour of liner
5. Electroform flange ends
6. Machine outside contour of liner
7. Electrical discharge machine fluid flow channels
8. Electroform shell
9. Final machine outside contour and diameter
10. Drill and tap instrumentation holes
11. Fabricate connection flanges and manifolds
12. Weld connection flanges and manifolds
13. Proof, leak, flow, and thermal shock tests.
14. Clean, package, and deliver to NASA.

It was originally planned to spin the TD Nickel liner to the final internal contour size, and machine the outside contour to obtain the required wall thickness over the entire length of the liner. It was later decided to spin the inside contour undersize and final machine to print dimensions in order to minimize effort devoted to spin forming development.

B. MATERIALS

Stainless steel was chosen for tool tryout and other preliminary process development work to avoid excessive expenditures for TD Nickel plate because of the similarity in the forming characteristics of stainless steel and TD Nickel. Therefore, stainless steel was used to develop the spin forming tools and mandrels for properly staging the spin forming operation. Further, a full scale stainless steel replica of the TD Nickel chamber was fabricated so that down-stream development work such as welding, electrical discharge machining, electroforming and fixturing could be accomplished without incurring high material costs such as would result if TD Nickel were used for this development effort.

The TD nickel plate used in this program was produced by the duPont Company. Three plates 1/4 inch thick by 24 inches wide by 96 inches long were produced. The dimensions of 24 inches x 96 inches are standard production size of this plate. The thickness of 1/4 inch exceeds duPont's standard for thickness. Only one of the three plates produced was considered to be free of discontinuities as determined by the ultrasonic inspection technique.

The three plates were cut into six plates 24 inches wide by 48 inches long. Discontinuities as determined by ultrasonic inspection were outlined on these plates. Figure 3 shows the location and extent of the discontinuities. Disks having a 24 inch diameter were cut from the TD Nickel plate. Each 24 inch x 48 inch plate yielded two disks.

C. INNER LINER FABRICATION

It was initially planned to stage spin forming of the aft section through four spinning operations followed with a flange forming operation. Spinning of the forward section of the chamber was planned to be accomplished in eight stages. In the case of the forward section, the first four spinning operations were to be accomplished on the mandrels used for spin forming the aft section. In accordance with this planning, eight spin form mandrels were made.

Upon completion of this tooling effort, stainless steel blanks were made having dimensions of 24 inches in diameter and 1/4-inch thick. One blank was spun through the first four stages and then put into a flanging tool to spin the flange. Spin forming as described was accomplished without difficulty.

The second blank was spin formed through the first four stages as in the case of the aft section. Spinning was continued through the originally planned fifth through eighth stage. Again, spin forming was accomplished without difficulty.

The stainless steel sections were evaluated and found to be dimensionally acceptable. This successful effort indicated the tooling and staging had been developed sufficiently to justify spinning attempts with TD Nickel blanks.

After preliminary attempts with TD Nickel blanks known to have flaws, two aft sections were spin formed complete through the flanging operation with material known to be good as determined by ultrasonic inspection. Cracking problems were encountered after the fourth spin form stage when attempting to spin form the forward section. Interstage deformation from the fourth to eighth mandrel was too severe and modifications were required in the spin forming plan. Eight additional mandrels were made to reduce the interstage deformations between the original fourth and eighth mandrels, resulting in sixteen spin forming stages as illustrated in Figure 4.

With the benefit of interstage hardness tests, mechanical property checks, dye penetrant inspection, interstage annealing, and torch heating during spinning using both sound material and material known to have discontinuities, two forward chamber sections were successfully spin formed. These sections were subsequently welded to the aft sections previously formed, thereby providing two completed TD Nickel chamber liners for this program.

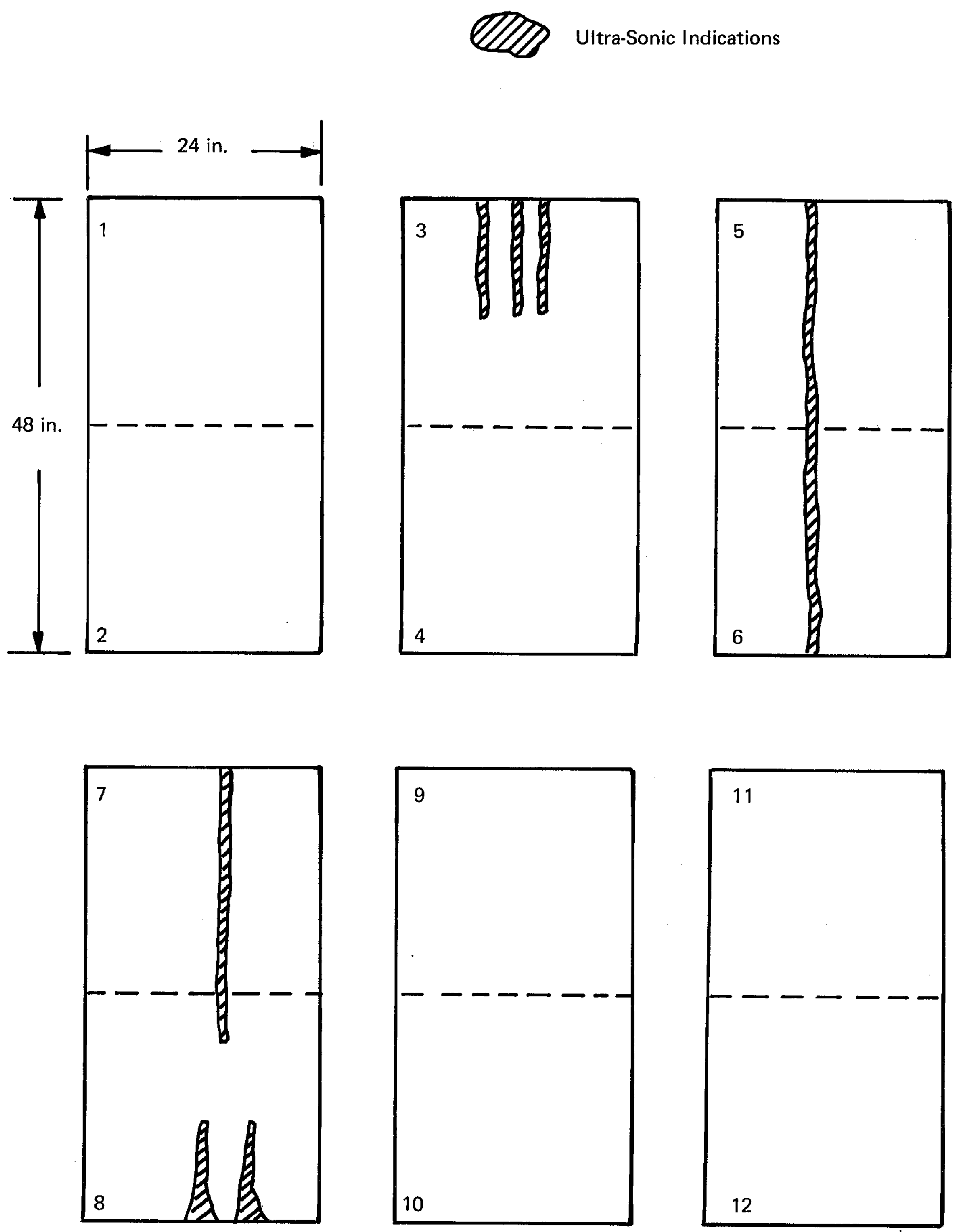
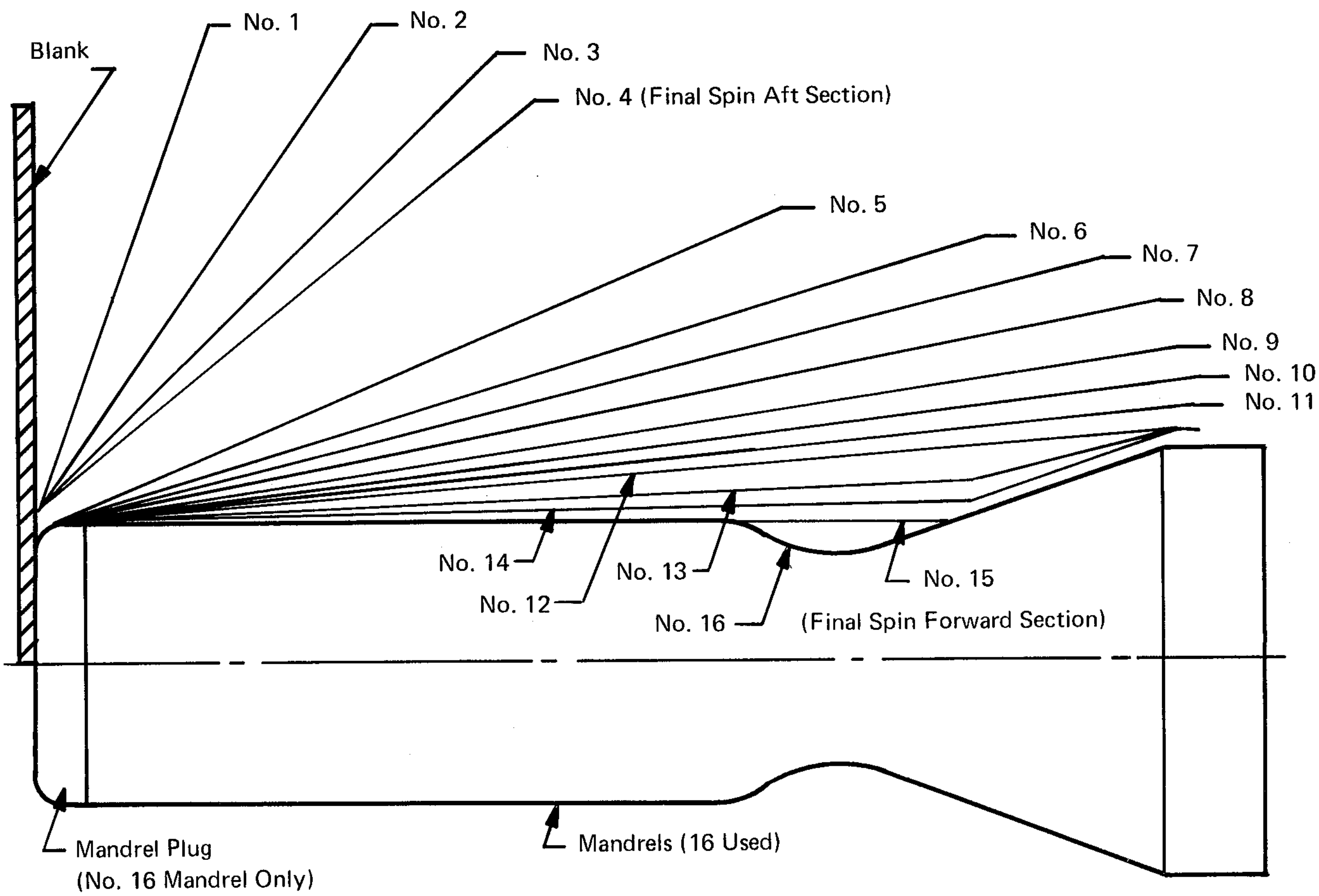
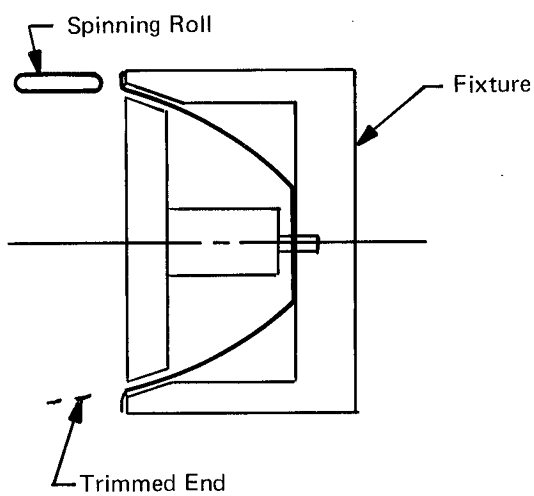


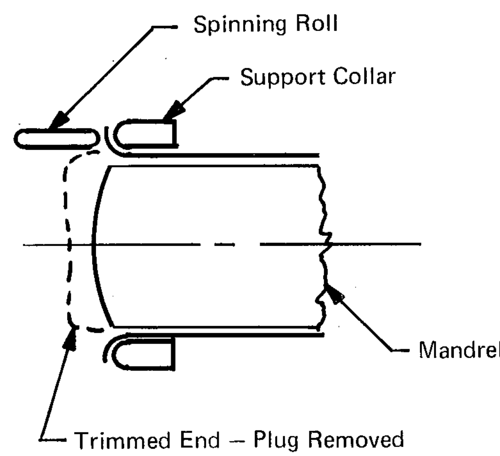
Figure 3. Locations of Discontinuities in TD Nickel Sheets



Mandrel Forms – Forward and Aft Sections



Flanging Aft Section



Flanging Forward Section

Figure 4. Spinning Sequence for Chamber Liner Sections

This successful effort indicates that TD Nickel plate can be readily spun without difficulty where total reduction is less than approximately 50%. Where total reduction is greater than 50%, as in the case of the forward section, the number of preform dies and interstage anneals must be carefully developed.

Inspection of TD Nickel plate is best accomplished by ultrasonic and dye penetrant inspection means. X-ray examination failed to locate areas of weakness during the preparatory and in-process stages of the spinning effort.

All interstage annealing was accomplished in a hydrogen atmosphere. The spun sections were held at 2000°F for a minimum of one hour and then cooled in the furnace to at least 300°F before removal. Annealing was accomplished after the 2nd, 4th, 5th, 7th, 9th, 11th, 14th, and 15th spin form stage.

Hot spinning during the final stages of reduction was accomplished by heating the mandrels to approximately 800°F. The form to be reduced was then placed on the hot mandrel and it, in turn, was torch heated to approximately 650°F. In each case, temperatures were determined with a contact pyrometer. Spin form stages 8 through 16 were accomplished hot. Propane torches were used for heating and "Molykote" was used for lubrication.

Interstage inspection using the dye penetrant procedures occasionally revealed cracks and other surface defects typical of spinning operations. When these indications were encountered, the preform surfaces were conditioned for subsequent spinning by grinding with a disk grinder to remove the indications. Although local indications required removal of 0.025 to 0.035 inch of material, normal conditioning of the overall surface required removal of only 0.003 to 0.005 inch of material from the preform surfaces.

Figures 5, 6 and 7 illustrate successful and unsuccessful attempts at spin forming. Defects in the aft sections shown are the results of spin forming blanks with known areas of delamination. The fracture in the forward section shown in Figure 5 is the result of excessive reduction during a single spin forming stage.

Basic methods for TIG welding of TD Nickel (which would prevent thoria agglomeration) had been developed prior to the inception of this program. Specimens of TD Nickel were welded by the automatic TIG process and subjected to tensile tests. The tests were conducted at 70°F, 1200°F, and 2000°F. Test results showed that weld joint efficiencies were in excess of 85% of the parent metal strength at all test temperatures. Since 85% efficiency exceeds design requirements, the joint geometry, weld parameters, and filler wire choice (Hastalloy "X") was established as a result of the tests conducted.

The forward and aft chamber sections, including the stainless steel sections, were fixtured as shown in Figure 8 and 9 for machining the weld joint geometry. The sections were mounted in a weld fixture and into an automatic TIG welding machine as shown in Figure 10. The setup shown in Figure 10 features automatic rotation of the chamber and automatic wire feed. Figure 11 shows the welded chamber. X-rays taken of the welds made on the three chambers showed no inclusions and negligible porosity.

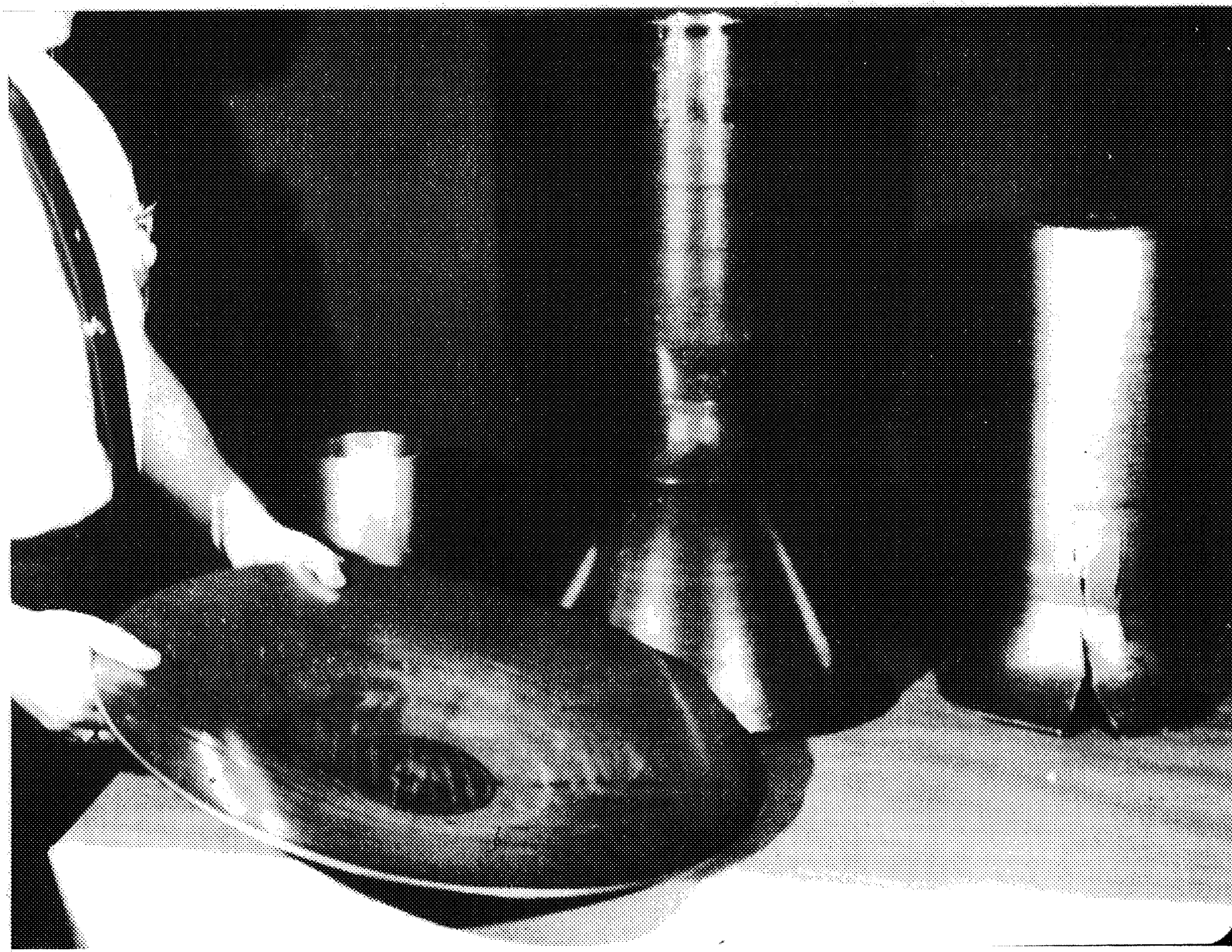

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Figure 5. Spin Formed Liner and Defective Preforms

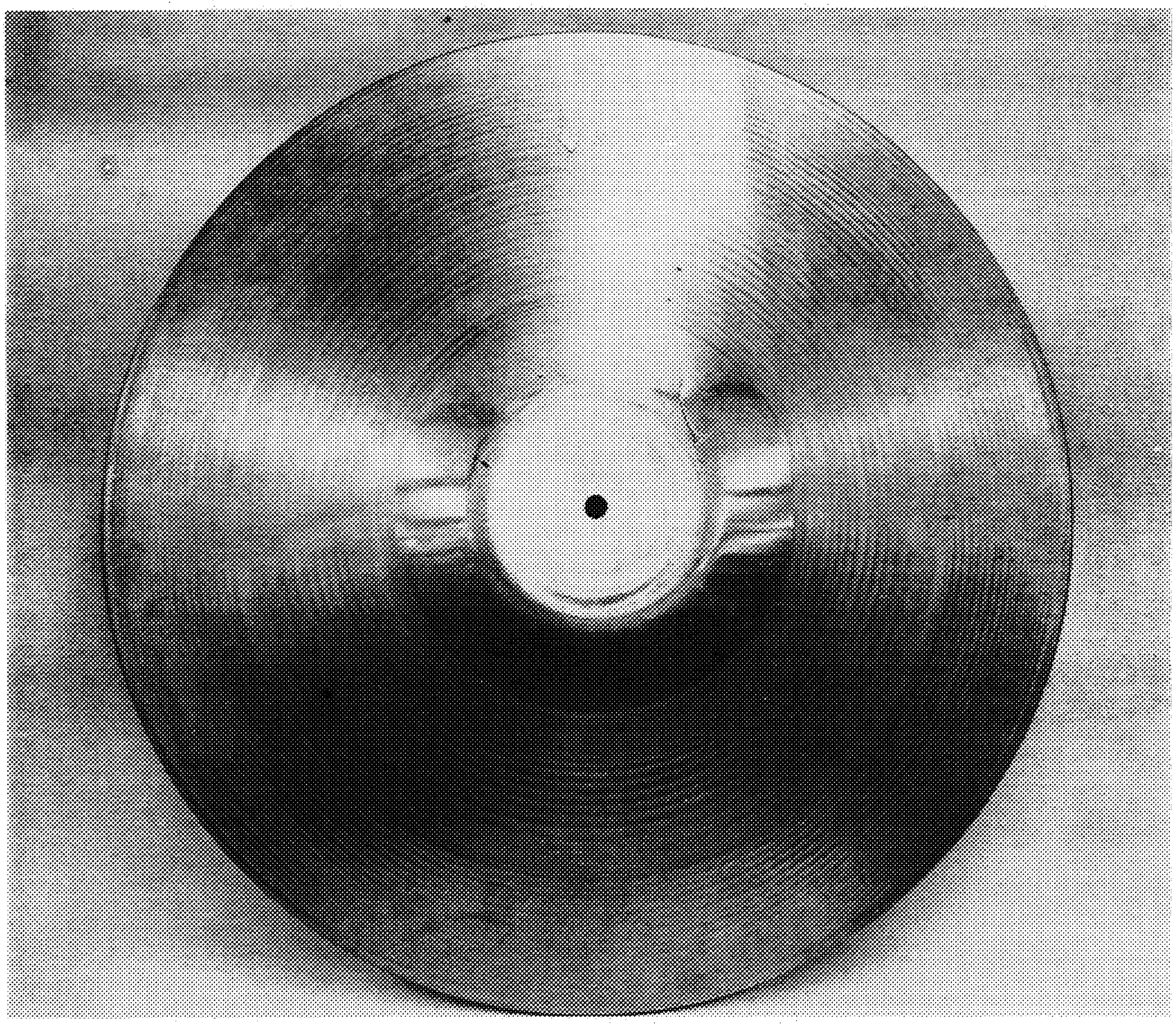

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Figure 6. Defective Aft Liner Section

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Figure 7. Successfully Spun Forward and Aft Liner Sections

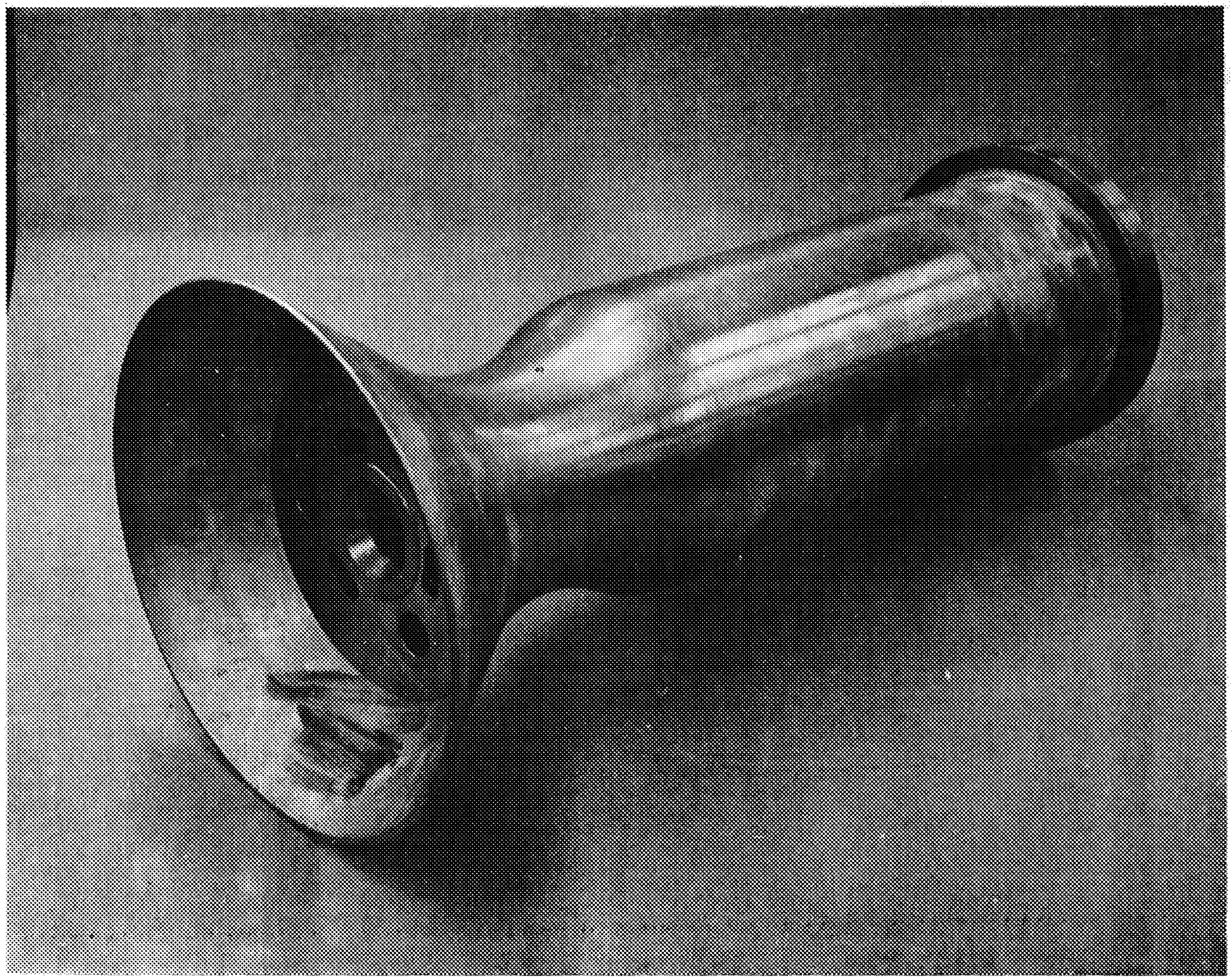

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Figure 8. Fixturing for Weld Joint Machining of Forward Section

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Figure 9. Fixturing for Weld Joint Machining of Aft Section

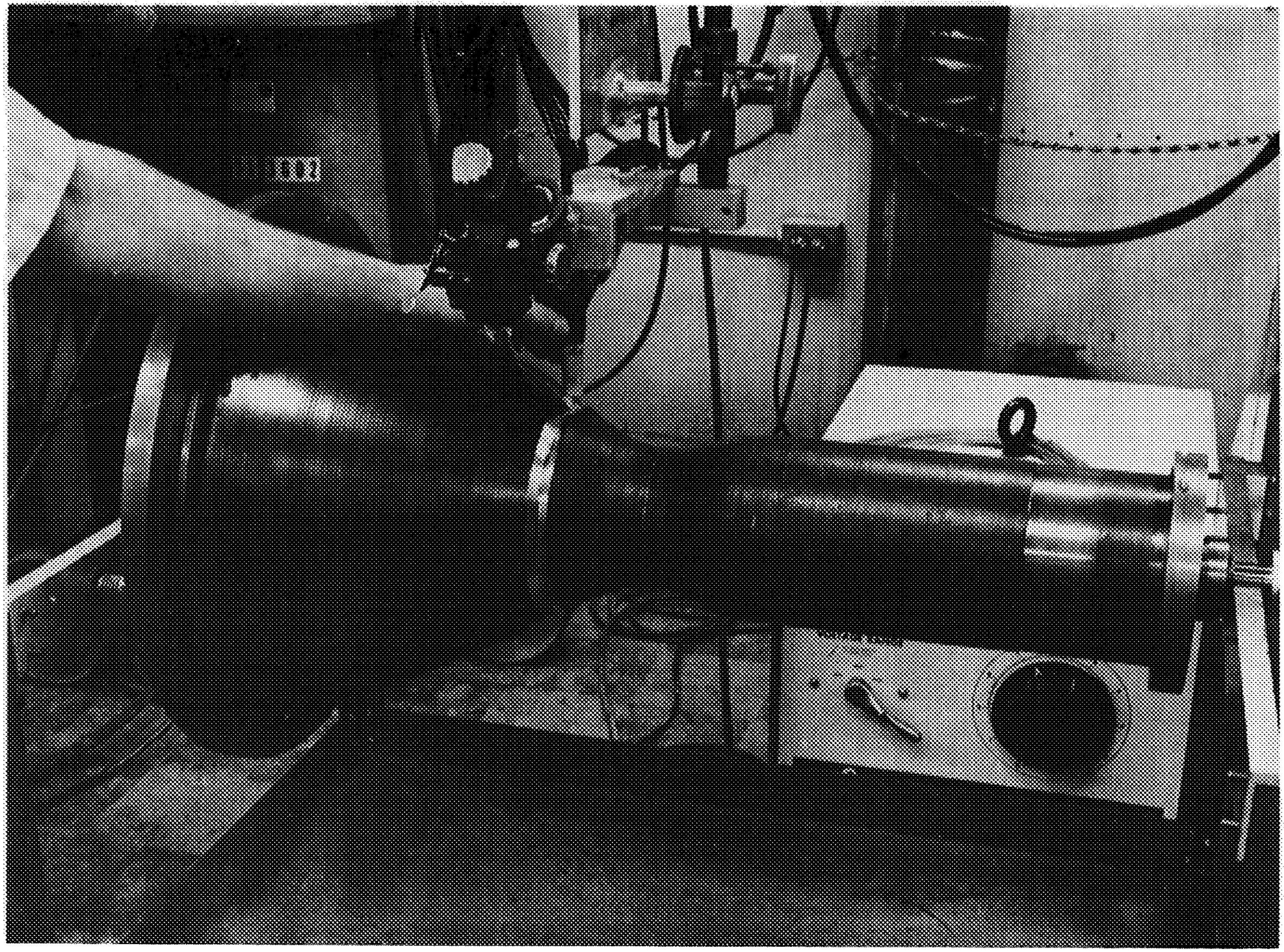

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Figure 10. Automatic TIG Welding of the Chamber Inner Liner

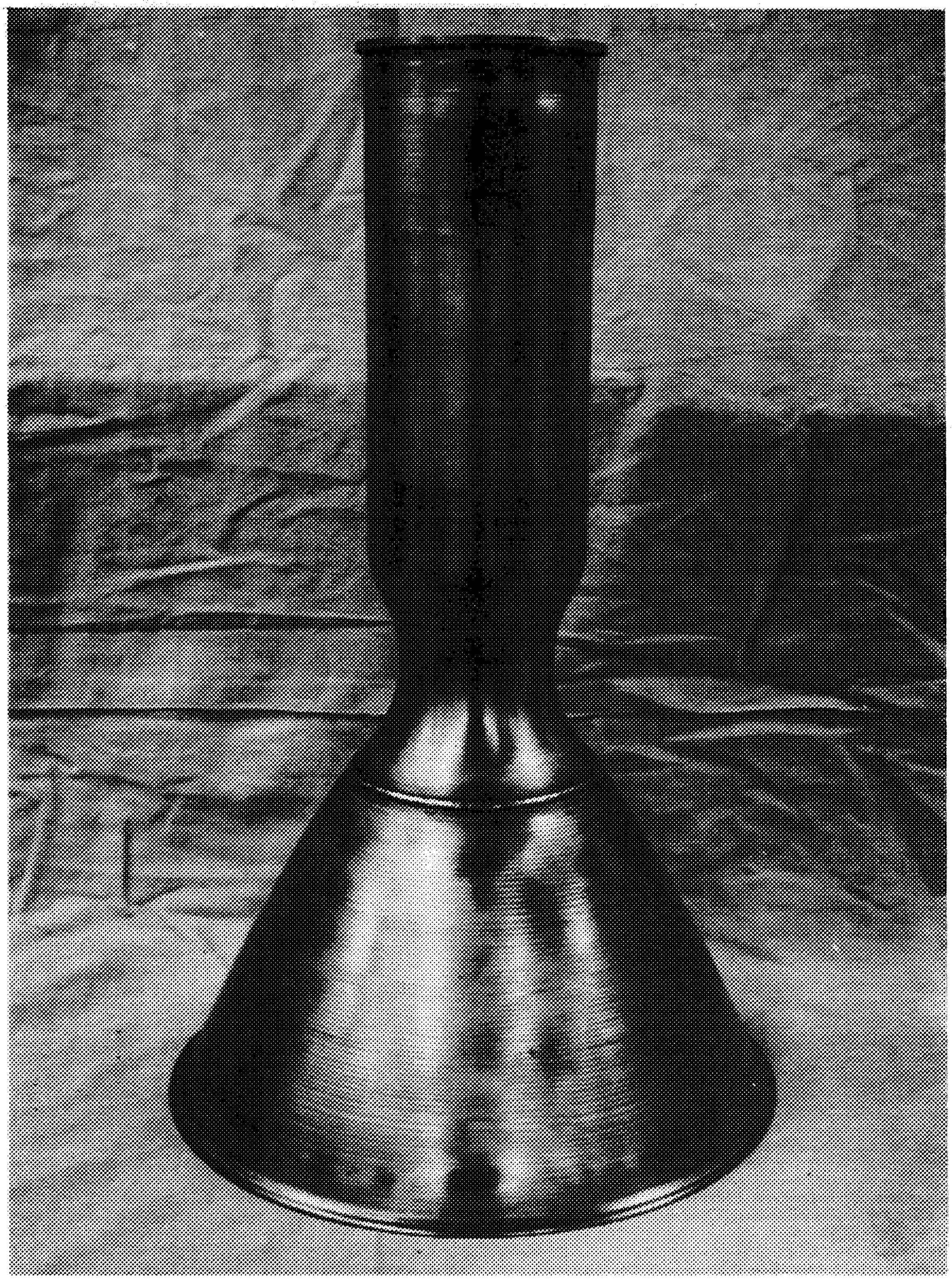

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Figure 11. Chamber Inner Liner After Welding

Consistent with a previous decision not to spin form to net internal dimensions and contour, machining of the internal contour was required. The TD Nickel chambers were set up in a machining fixture as shown in Figure 12. Dimensional checks made at this point indicated that both chambers were out of round to a degree which would not permit cleanup throughout the entire internal area of the chambers. As a consequence, it was determined to resize the chamber liners by respinning over the original spin form mandrels. The respinning/resizing operation is illustrated in Figure 12. Upon completion of resizing the chambers again were assembled in the machining fixture and the inside contours were machined to drawing requirements.

A dimensional inspection revealed that one of the TD Nickel chamber liners was 0.075 inches short of drawing requirement. This short length was determined to be acceptable as it would not adversely affect the performance of the engine. The second TD Nickel chamber liner was found to be 0.107 inch short in overall length. This short length was accompanied with an outward buckle at the weld joint and was considered unacceptable.

The shortness was fully recovered during the resizing operation. Recovery was accomplished by bringing the spin form machine roller into contact with the weld bead approximately perpendicular to the surface. The roller was traversed rearwards and forwards over the weld bead across the distance of approximately three inches. Working the bead in this manner recovered approximately 60% of the shortness in length. Remaining shortness was recovered during general resizing of the chamber.

Resizing to restore concentricity and to recover length was accomplished at 800°F. Temperature was achieved by first heating the spin mandrels with a propane torch and then assembling the chamber liners to the mandrel. After assembly of the chamber to the mandrel, the chambers were heated using a propane torch.

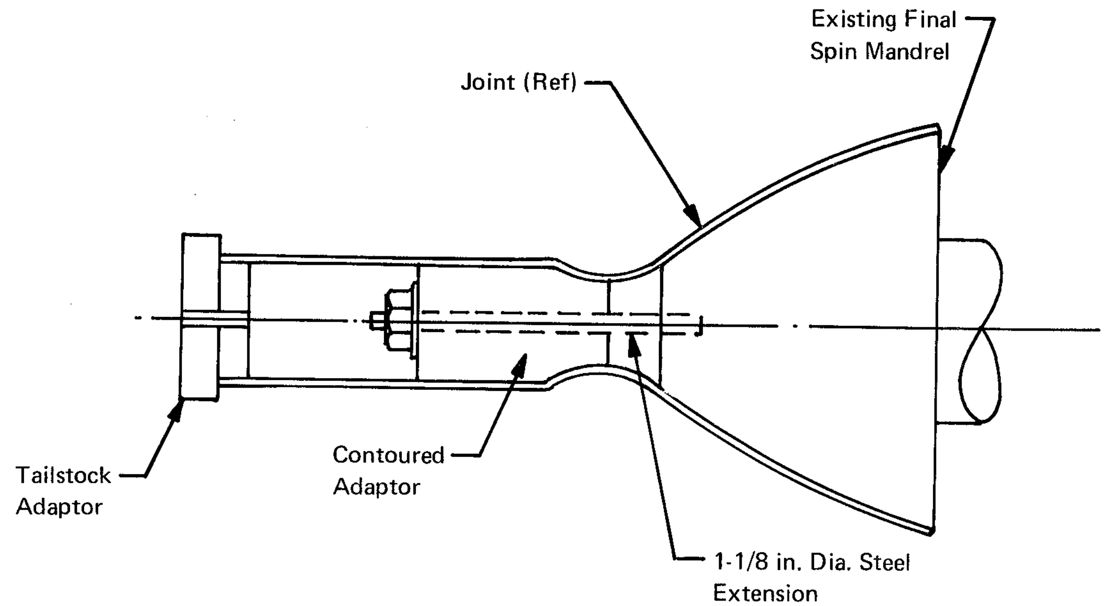
Upon completion of the internal machining, preparations were made for machining the outside contour. Plugs were placed in the ends of the chambers and they were set up in a lathe having a tracer template. Concentricity and wall thickness measurements were made using a dial indicator and Vidigage. Dimensional checks were satisfactory and machining was accomplished using a tracer template made to drawing configuration requirements. The outside surfaces of the chamber were machined to a 63 microinch finish or better.

D. ELECTROFORMING

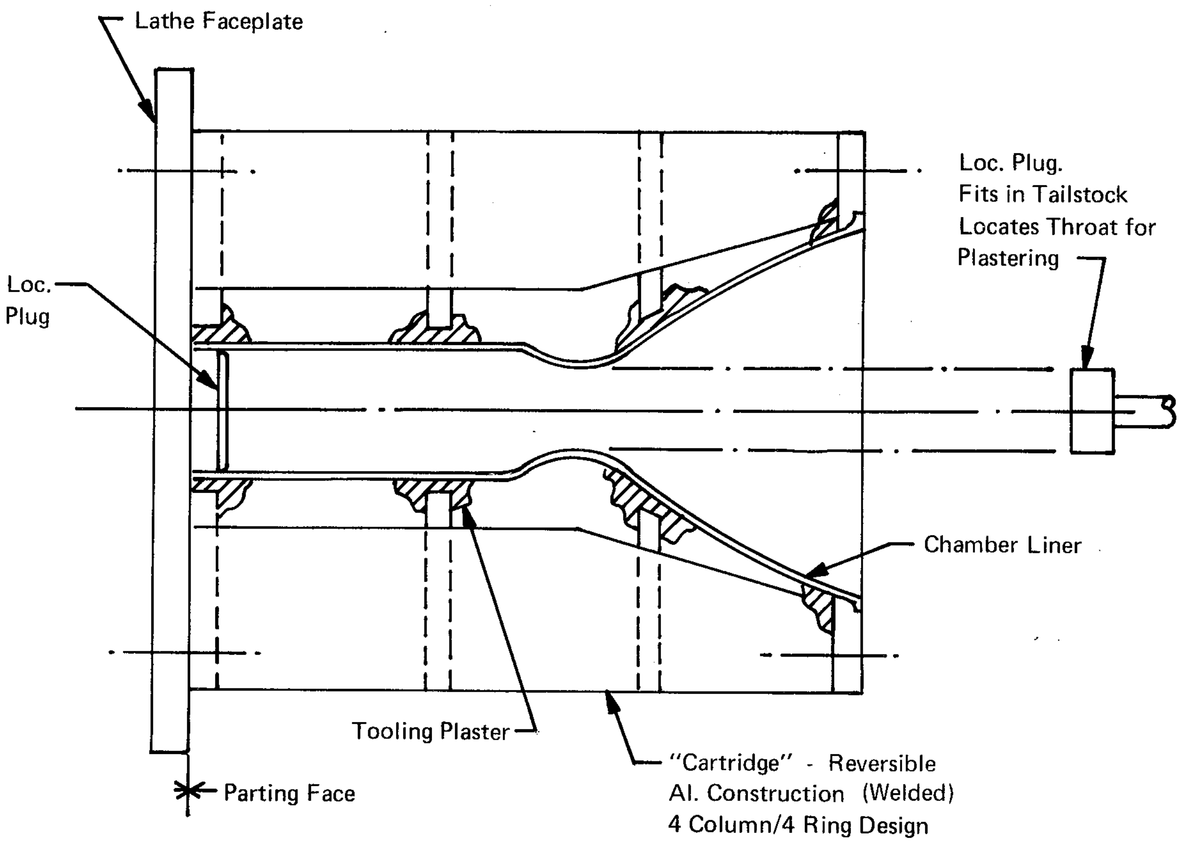
1. Development

Initial electroforming process development work was conducted with a five gallon sulfamate tank with means for supporting nickel anodes, temperature control, and variable direct current power inputs. Flushing of the process development samples was accomplished with tap water and bottled distilled water.

In the subscale facility described, standard concentrations of nickel sulfamate plating solution at various temperatures and current densities were explored. Nickel sulfamate was chosen as the plating solution because of its low residual stress in the electrodeposited form as determined by literature search and experience with the solution.



Tooling for Respinning after Welding



Inside Contour Machining

Figure 12. Liner Resizing and Inside Machining

Six inch by six inch nickel sheets 0.030 inch thick were electrodeposited on stainless steel backup sheets for metallurgical and physical property evaluation.

As a result of this subscale effort a plating bath concentration of 10 oz. of nickel (as metal) per gallon of plating solution was chosen, a plating temperature of 100 to 120°F was selected, and a current density of 50 amps per square foot was established.

The full-scale facility consisted of a 200 gallon tank for plating solution, thermostatic temperature control, a drag-out tank for tap water and distilled water rinsing, provisions for rotating the cathode (chamber), provisions for hanging stationary anodes, a filter pump bath cleaning system, and a 12 volt 500 ampere rectifier with a manual restart safety feature to preclude uncontrolled restart of a plating cycle in the event of a power failure.

Upon completion of the full scale facility, validity of the process developed under subscale conditions was confirmed. Electroformed nickel cylindrical specimens having a 12 inch diameter by 22 inch length and a thickness of 0.080 inch were produced. Test specimens were prepared which on the average exhibited the following mechanical properties.

Ultimate tensile strength - 70,000 psi
Yield strength - 42,000 psi
Elongation - 22%
Modulus of elasticity - 21,000,000 psi

Table I is a composite of data showing average values for all conditions of tests performed during the electroforming process development phase of this program.

The program plan called for an adherent bond between the electroformed nickel shell and TD Nickel liner. Therefore, it became necessary to explore surface preparation to assure achievement of this high strength bond. Exploratory effort centered around the standard nitric acid and sulfuric acid treatments commonly used in the surface preparation of nickel. Time of immersion and concentration of the acid solutions were varied and evaluated. The following surface treatment was chosen: Degrease in trichlorethylene at 160°F for two minutes, alkaline scrub, rinse, immerse in a 50% solution of nitric acid until the TD Nickel turns a light gray, scrub with tap water, anodic clean in a 50% solution of sulfuric acid at room temperature for two minutes at 100 amps per square foot, immerse immediately into the plating solution and begin plating.

The surface treatment described was acceptable as determined by preparation and test of a grooved specimen simulating the grooved chamber liner. The sample so prepared withstood 1,050 $lb/in.^2$ of hydrostatic pressure without failure.

Process interruption due to the need for dimensional checks, removal of nodular growth, and general process checks was anticipated. Therefore, there was a need for restarting the electroforming cycle with assurance of good adhesion of electrodeposited nickel upon the previously deposited nickel. Evaluation showed that the surface preparation treatment described above was satisfactory for restarting if used as noted with deletion of the nitric acid treatment.

TABLE I
TYPICAL MECHANICAL PROPERTIES OF ELECTROFORMED NICKEL

Electrotype Temperature (F)	Mech Property	Current Density ($Amps/ft^2$)			
		40	50	70	90
100	UTS (kpsi)		77	69	
	YS (kpsi)		50	45	
	Elong (%)		11	16	
110	UTS (kpsi)		105	69	63
	YS (kpsi)		70	41	37
	Elong (%)		11.5	16	17
120	UTS (kpsi)	85			87
	YS (kpsi)	58			56
	Elong (%)	11			9
Design Goals:					
	UTS (kpsi)	70			
	YS (kpsi)	40			
	Elong (%)	12 minimum			

A major problem related to outer shell electroforming was to develop a method for forming a bridge across the open coolant passages without changing passage geometry and at the same time electroforming the nickel shell on the TD Nickel liner. The most practical approach was to fill the grooves with a maskant material capable of conducting a current across its surface to bridge the grooves while electroforming the shell.

A suitable maskant material for filling the EDM channels had to be capable of withstanding electroforming temperatures of 100 to 120°F, have low shrinkage and expansion rates, and be capable of conducting a current or be compatible with an applied conductivizing agent, as well as being readily removable by melting or solvent action. The materials considered as maskants included low melting alloys such as cerrobond and cerrocast, polyethylene glycols, waxes, and waxes impregnated with metallic powders.

Low melting alloys were eliminated because of difficulties in uniformly filling the channels and, more important, because of possible foreign metal contamination of the electroforming solution during reverse plating.

Polyethylene glycols were eliminated because of handling problems such as providing accessory equipment for damming, etc. and because they are soluble in water.

Most waxes were eliminated because of brittleness and shrinkage characteristics when cast.

Wax combinations consisting of blends of waxes with conductive agents such as metallic powders were eliminated because the effectivity of the conductive powders was inhibited when individual grains of powder were encapsulated within the wax.

Upon completion of the above evaluations, a commercially available wax stop-off material, Unichrome 314, manufactured by M&T Chemicals Company, was chosen as the maskant for the grooves. Unichrome 314 was found to have favorable physical properties, a melting point of 180°F which is above all solution temperatures anticipated for use in the program, and can be removed with immersion and flushing with hot water.

Since a conductive filler material could not be found, it became necessary to investigate means for conductivizing or bridging the filled grooves. The importance of uniformly conductivizing the wax-filled grooves was recognized, since the conductivizing agent could degrade the electrodeposited nickel-to-TD Nickel bond by contaminating the surfaces of the groove lands.

Conductivizing agents investigated included silver/graphite composites, graphite dispersions, conductive paints, and reduced silver spray.

Silver graphite composites were eliminated because of poor conductivity.

Graphite dispersions, although effective, required extreme care in application to channels to prevent the coating of lands. Residual graphite on lands adversely affected bonding of the electrodeposited nickel onto the TD Nickel of the liner.

Conductive paints were eliminated because of difficulty in application and contamination of the electroforming solution during the reverse plating cycle.

The reduced silver spray approach was chosen as the conductivizing method. It proved to be the most effective conductivizer; overspray on land surfaces was readily removed during reverse plating, leaving lands clean and free of conductivizer, and was the most easily applied by spraying.

As a result of the channel filling and conductivizing development work described in the foregoing, the following filling and conductivizing procedure was adopted.

The TD Nickel liner, complete with EDM grooves, was cleaned using the surface preparation treatment previously described. The cleaned liner then was completely immersed into a reservoir of hot wax and withdrawn to allow the wax to harden upon cooling. This operation was repeated until a wax coating of suitable thickness was built up. All the wax above the channel lands then was scraped from the outer surface of the liner using a flexible spatula which could be easily contoured while scraping to suit the changing contour of the liner. When all excess wax was removed, only channel lands were exposed. With grooves filled flush with the channel lands, the chamber liner was scrubbed with a bristle brush using Shipley Scrub Cleaner and Alconox Cleaning Compound. Brushing and rinsing with cold tap water was done until a water break free surface was achieved. Next, the chamber was given the acid cleaning treatment previously described for surface preparation.

The chamber liner with filled grooves was immersed in the nickel sulfamate plating tank upon completion of the wax scraping and anodic acid cleaning operation. A one-mil thickness of electro-deposited nickel was plated onto the channel lands. After removal from the plating tank, rinsing, and drying, the entire outer surface area of the chamber liner was sprayed using the reduced silver approach previously described.

The chamber liner was immersed in a tank of spent nickel sulfamate electrolyte for subsequent reverse plating to remove silver conductivizing film from the channel lands. Silver is selectively removed from the lands due to the fact that the lands are metal and conductive whereas the wax in the channels is a non-conductor. With completion of this reverse plating procedure, the conductivized chamber liner was placed into the regular plating tank and electroforming was started.

2. Inner Liner Flanges

A procedure was needed for electroforming forward and aft inner liner flanges. This electroforming operation was completed before electric discharge machining of coolant channels and subsequent electroforming of the outer shell. The stainless steel slave liner was set up for electroforming as shown in Figure 13. The inner liner was mounted on a rotating spindle with both ends plugged and was immersed in the nickel sulfamate bath. A copper buss-bar supported the nickel anodes adjacent to the immersed liner. Another view of this setup with the liner withdrawn from the bath is shown in Figure 14. Figure 14 also shows the liner after a thin layer of nickel had been deposited at both the forward and aft flange areas.

Fixturing of the chamber liner was accomplished on two aluminum end plates and an intermediate plate concentrically mounted on a nickel plated copper shaft. The bulk of masking to prevent plating in undesired areas was done with a platers wax such as was used for filling the electroformed channels. Wax was then cut away where electroforming was desired, and exposed areas were thoroughly cleaned for surface treatment prior to plating.

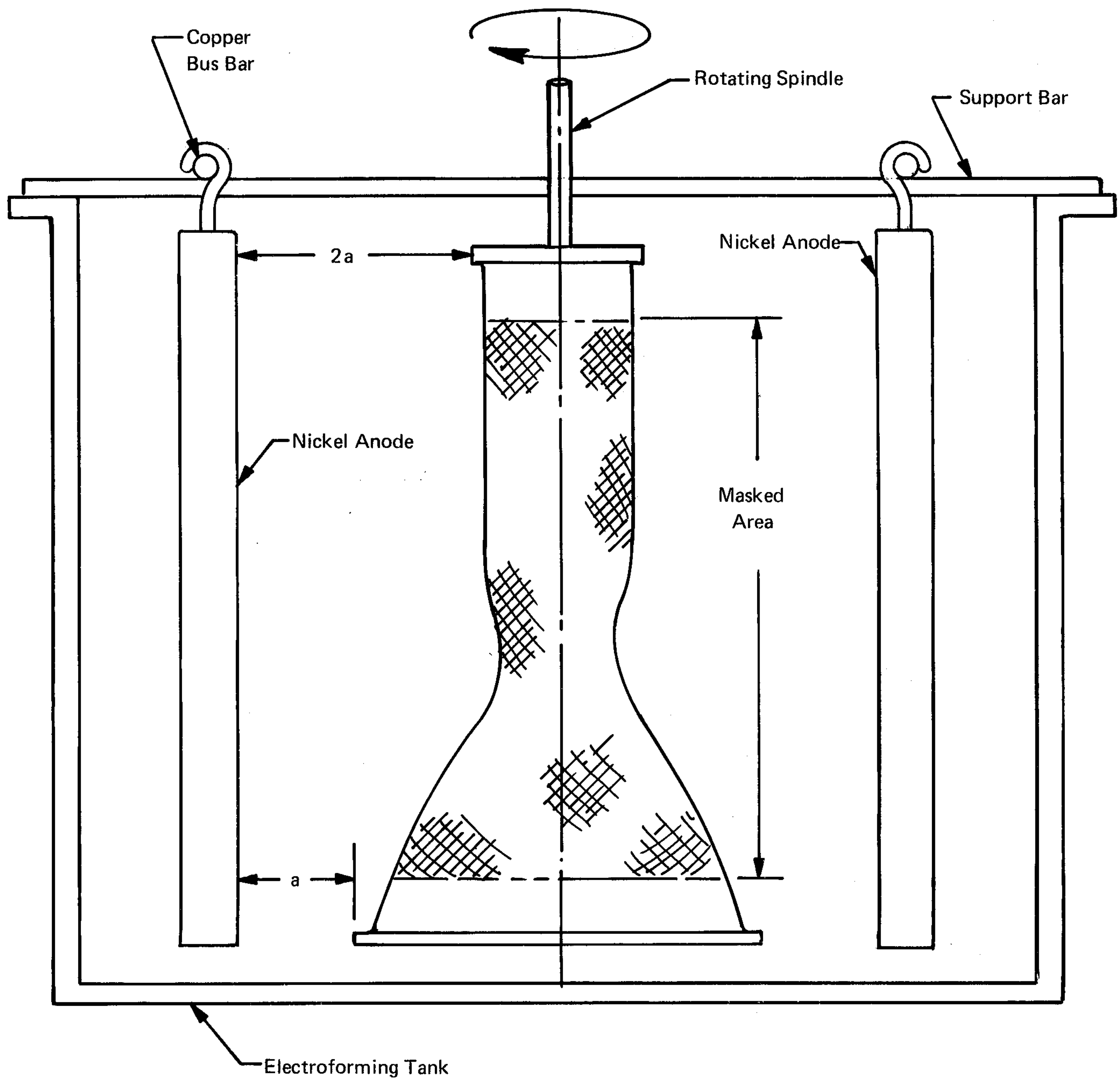


Figure 13. Electroforming of Liner Flanges

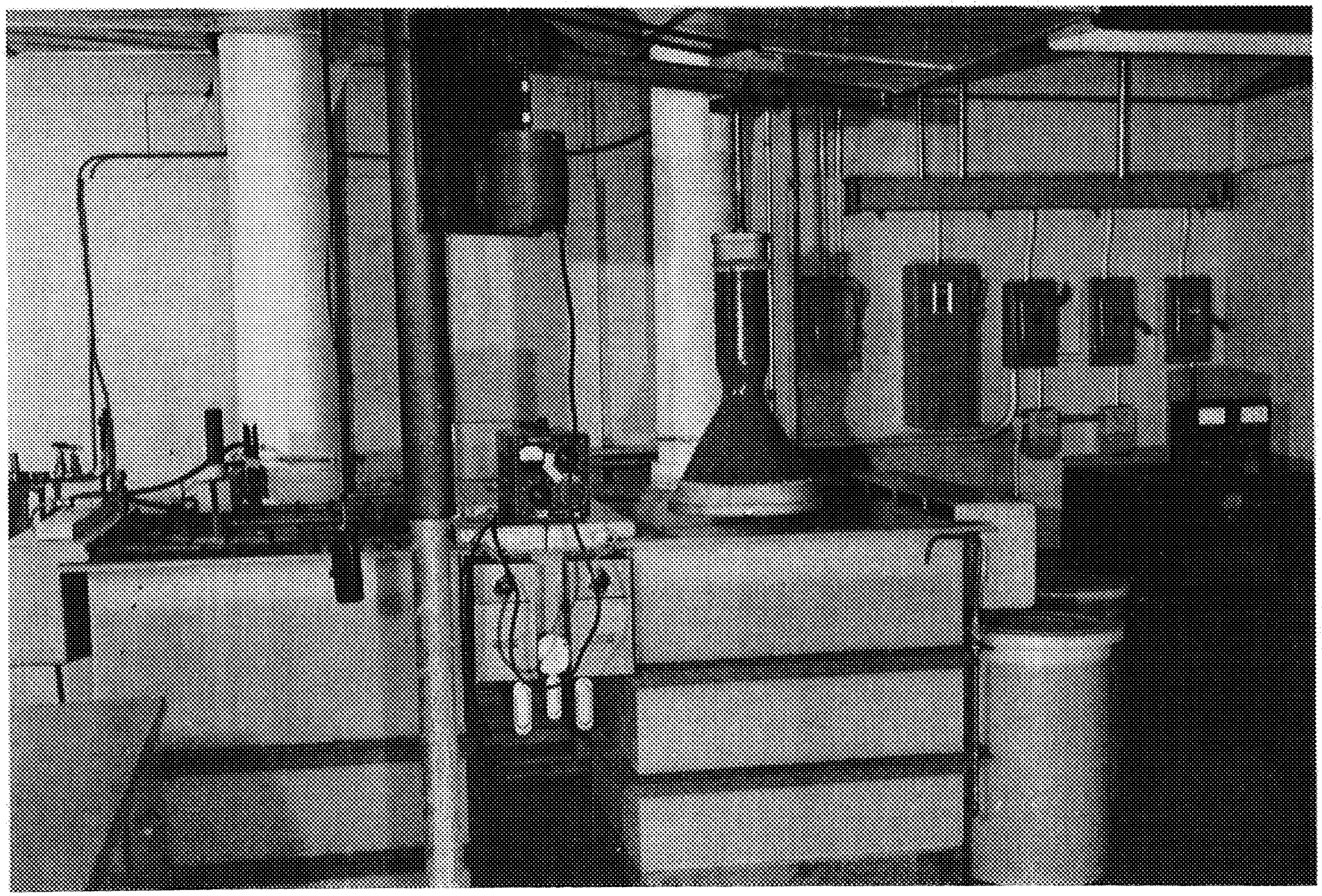


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Figure 14. Partially Electroformed Flanges on Rocket Thrust Chamber

Problems related to electroforming were pitting, nodular growth, in-process inspection, preferential deposition of nickel, machining and grinding to remove defective surfaces and nodules, and restarting for continued electroforming. Pitting was caused by insufficient solution agitation and by nodule growth which robs metal from adjacent areas during deposition. The pitting problem was resolved with additional air agitation, increasing the solution wetting agent concentration, and with the addition of two filter pump output hoses which were carefully aimed at the top and bottom flanges in order to provide a washing action against the direction of rotation of the thrust chamber. The hoses were positioned approximately seven inches from the flanges at an angle of approximately 30 degrees to the axis of rotation of the thrust chamber.

Nodular growth, caused by high current densities at the edges of the flanges, was not completely eliminated. The extent of nodular growth is illustrated in Figures 14 and 15. The rate of nodular growth was somewhat inhibited with procedures established for preferential deposition (use of plastic shields).

In-process inspection was considered necessary for process control and to inspect the quality of the plating while the electroforming was taking place. A technique employed utilized two lucite rods with highly polished ends. One rod was used to conduct light to the subject while the second was used for viewing only. It was necessary to station the rods less than one inch from the area to be viewed because the opaque quality of the plating bath hindered illumination and hence visual observation. Although not visual, another method of inspection of the upper flange consisted of feeling the flange area by hand with a very thin rubber glove worn to keep the part clean and yet permit sensitivity to touch. A third technique employed was to touch the lower flange area with a lucite rod in order to determine the formation of nodules. This technique indicated the presence of nodules but did not indicate their magnitude because nodule growth was in a near vertical direction.

Preferential deposition of nickel was needed because of the insufficient rate of deposition in the flange radii, too-rapid deposition at the flange edges in the area of high current density, and because of the nodule buildup. Preferential deposition was accomplished with the use of auxiliary anodes, shields, the addition of masking in flange areas to preclude buildup, and the addition of thief rings and bi-polar anodes. Arrangements employed for preferential deposition are illustrated in Figures 16, 17, and 18. Use of non-metallic shields and masking reduced or eliminated plating current in specific areas where retardation of plating was desired. Auxiliary anodes increased the plating rate where desired.

The electroforming process had to be interrupted on numerous occasions to allow removal of surface defects and nodules and to restore suitable surface and flange profiles for continued plating. This correction was accomplished locally by hand grinding with belt and disk grinders or by turning in a lathe when major correction was required. This restoration procedure led to the need for a restarting and replating process.

The surface treatment previously described was used for surface preparation prior to plating. However, the nitric acid treatment was deleted for restarting. The electrodeposit of nickel was reactivated with an anodic sulfuric acid treatment. This anodic deoxidation provided for good adhesion and allowed plating buildup to continue without evidence of lamination.

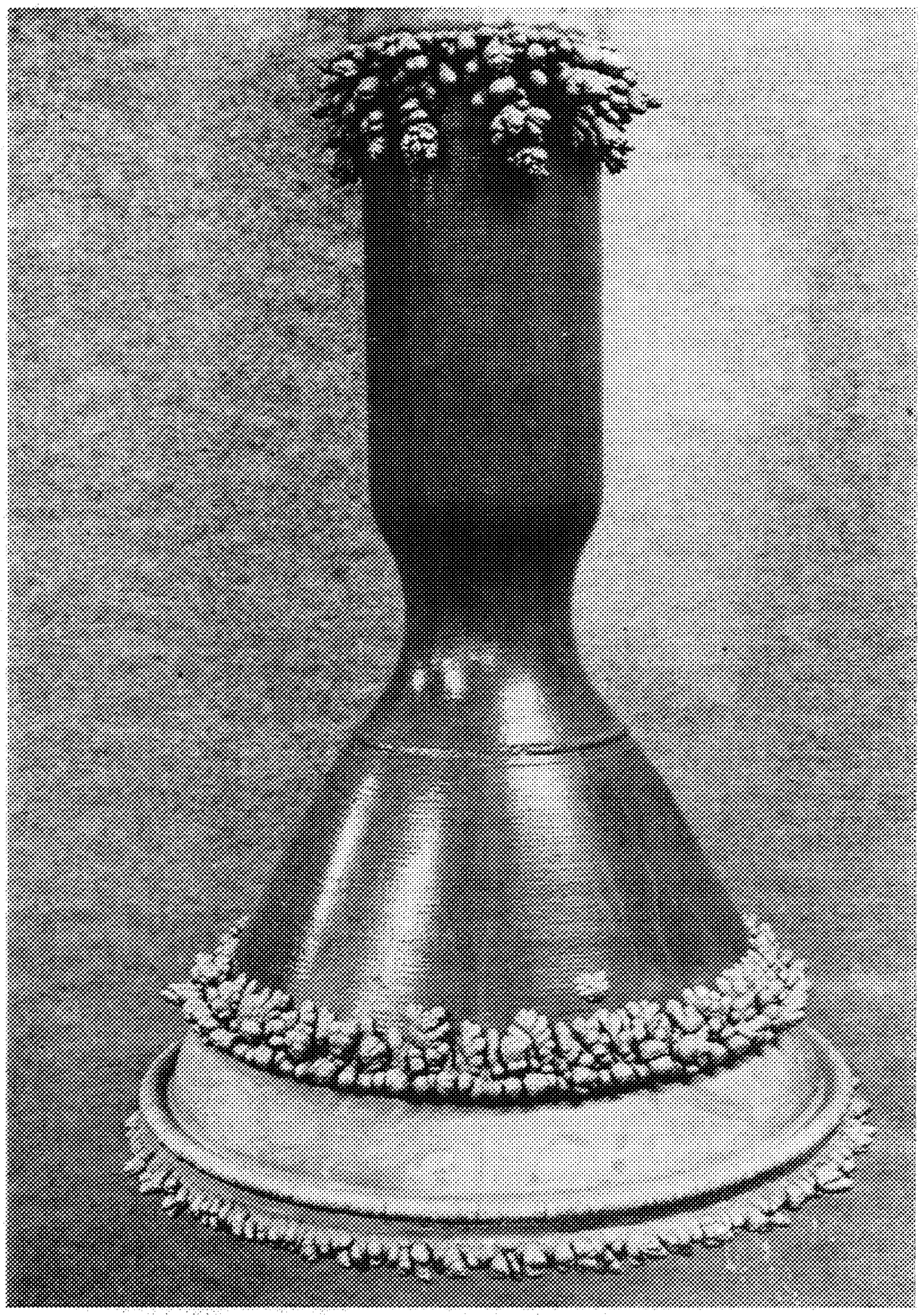

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Figure 15. Nodular Growth During Electroforming of Flanges

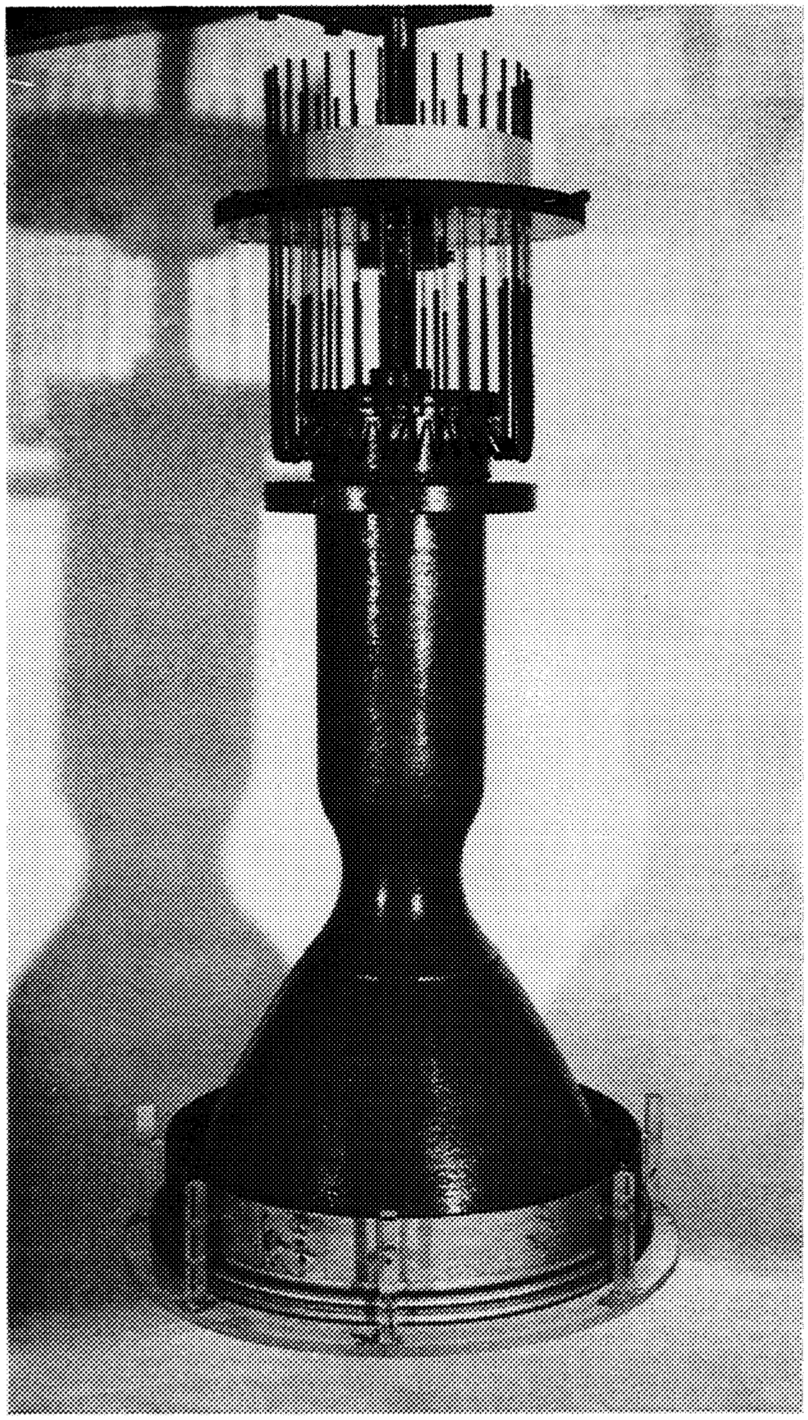

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Figure 16. Auxiliary Anodes and Shields for Preferential Electroform Deposition

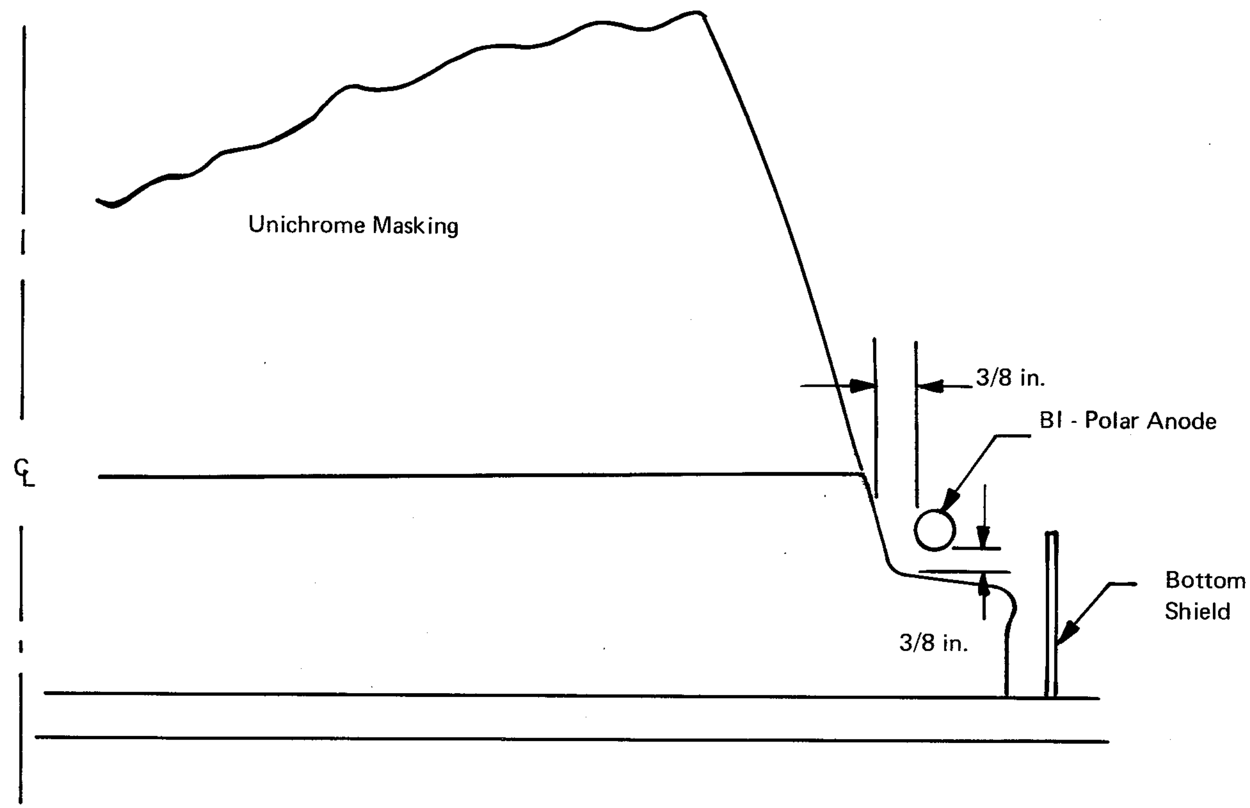

Figure 17. Bi-Polar Anode Setup for Preferential Electroform Deposition

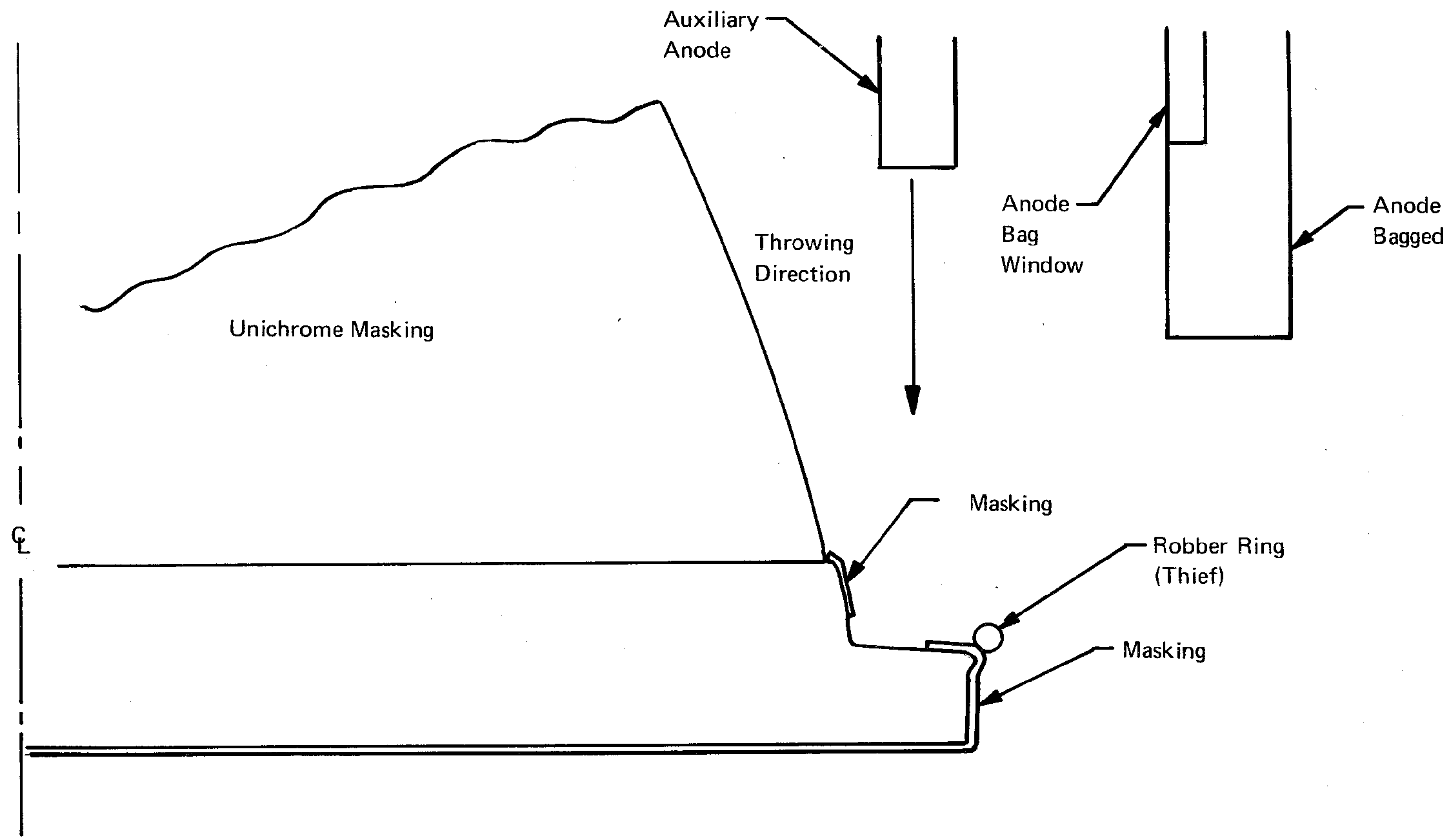

Figure 18. Masking and Thief Ring Setup for Preferential Electroform Deposition

With the ability to control the electroform buildup as developed and described above, the TD nickel chamber liner flanges were successfully electroformed.

The TD nickel chamber liners were set up in a lathe and flange profiles were machined to drawing configuration and dimensions when electroforming of the forward and aft flanges was complete. At this point the liners were ready for electrical discharge machining of the fluid flow channels.

3. Outer Shell

The setup for electroforming the outer shell differed only slightly from the flange electroforming setup shown in Figures 13 and 14. The primary difference was in the rotational mechanism which was reworked for handling the higher currents required for shell electroforming.

As previously stated, electroforming of the outer shell was accomplished after electrical discharge machining of fluid flow passages. Therefore, to remove all residual contamination from the nickel liner due to electrical discharge machining, the nickel liner was thoroughly cleaned by vapor degreasing, alkaline cleaning, and scrubbing. The liner was then installed in a holding fixture consisting of a base plate, mid plate, and top, supported by a center shaft. This holding fixture supported the liner during all subsequent operations and was the means of rotating the liner during electroforming of the shell. Figure 13 shows in principle the fixturing described.

The liner was then scrubbed with a commercial cleaner to a water break free surface. After flushing with acetone, the liner was air dried. At this time, initial dimensions of the liner were recorded for measurement of the electroformed shell buildup.

Unichrome 314 wax was melted in a container large enough to accommodate the entire liner assembly. The maskant was maintained at a temperature of 190 to 200°F. The liner assembly was suspended from an overhead hoist with the nozzle extension at the top. After preheating the liner to approximately 160°F with heat lamps it was lowered into the molten wax covering the liner and holding fixture. The assembly was kept in the molten wax until the temperature stabilized. At this time it was removed for the excess wax to drain and the first layer to harden. Successive dipping and immediate withdrawal allowed the wax in the grooves to build up above the top of the land. The waxed surface was allowed to cool to approximately 90 to 100°F. The surplus wax was removed with the flat edge of a spatula until the lands were free of wax and the channels were uniformly filled and faced off. When cooled to room temperature, the liner was scrubbed with a mixture of commercial cleaner (Shipley cleaner and Alcanox) to remove all traces of wax from the lands as indicated by a water break free surface. Figure 19 shows the liner at this stage of preparation for electroforming.

The chamber as shown in Figure 19 was anodically cleaned in the 50% solution of sulphuric acid. The liner then was immersed in a sulphamate nickel plating solution to build up a 1.5 to 2.0 mil nickel layer on the lands. This provided means for the nickel bridge over the channel to bond to nickel rather than TD Nickel. The liner was then removed from the plating solution in preparation for conductivizing the waxed channel surfaces.

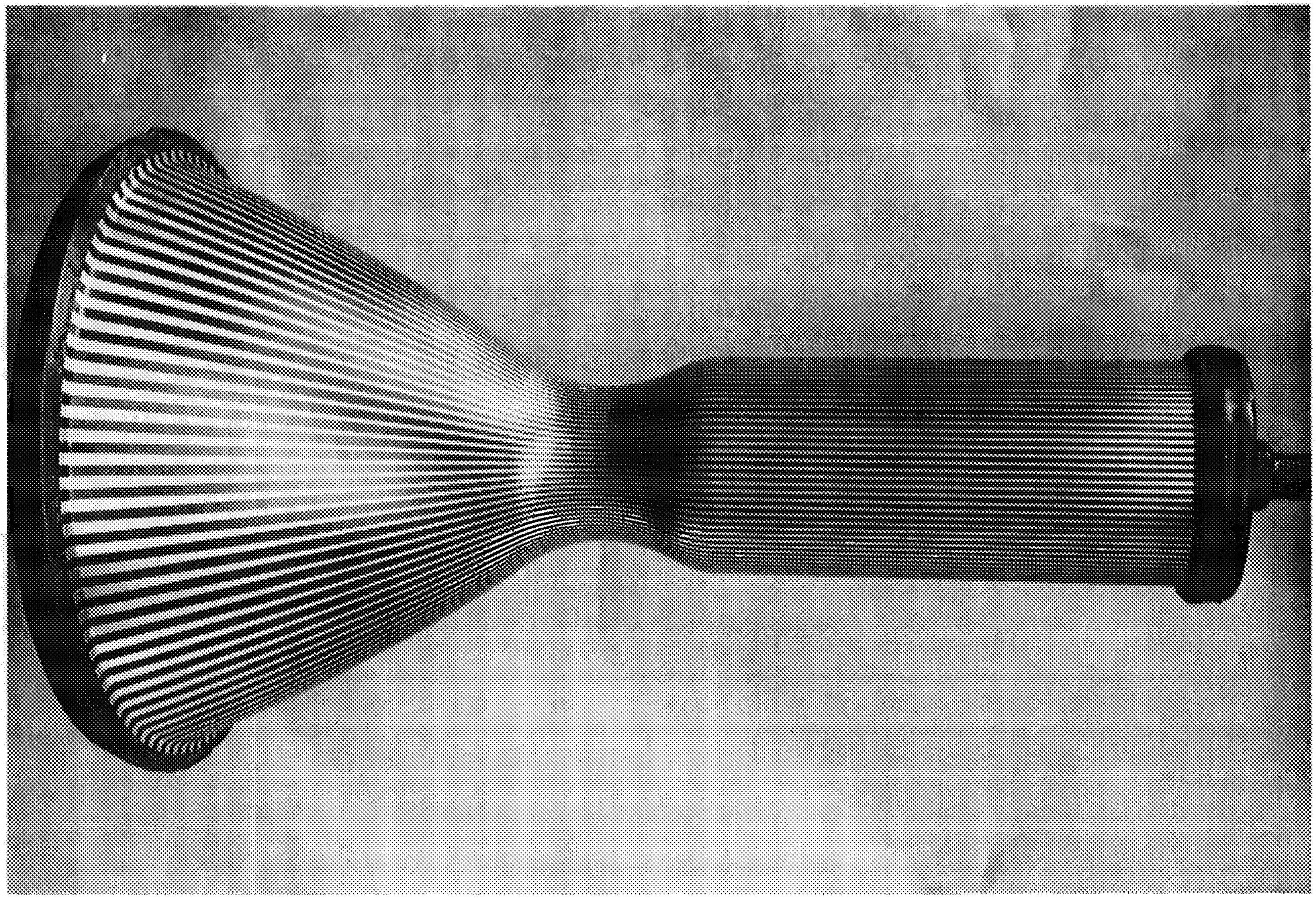

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Figure 19. TD Nickel Liner with Wax Filled Channels

Reduced silver spray was applied as the conductivizing coating. First the liner was flushed with a wetting agent and rinsed with distilled water. While still wet, it was thoroughly sprayed with sensitizing solution. After rinsing excess sensitizer with distilled water, the reduced silver (silver nitrate-formaldehyde) was applied by means of a two-nozzle spray gun. After drying, a second coat was applied to assure deposition in the land groove interface areas. After drying, the fixtured liner was mounted into the overhead rotating device with the nozzle extension at the bottom.

To remove the conductivizer covering the land surfaces, the unit was immersed in a separate drum containing spent sulfamate nickel solution. The liner then was reverse plated for 2.5 minutes at 30 amps per sq ft. This liberated the silver on the lands without disturbing the groove areas.

The liner then was rinsed with water to remove loose material and was examined for adhesion of the silver at the land groove interface. The liner was then again reverse plated but at 50 amps per sq ft in a 50% solution of sulphuric acid for 2.5 minutes. After rinsing with cold flowing water and a reexamination, the unit was again immersed in a 50% sulphuric acid solution for 30 seconds. Excess acid was allowed to drain from the liner and, the unit was immediately immersed in a 200 gallon sulphamate nickel bath and forward plated at low current density to minimize burning of the thin silver conductivizing film (5 amps per sq ft for 24 hours at 90°F).

The assembly was rotated and two pumps were used to facilitate hydrogen degassing during plating. A high flow pump was directed at the throat area and a lower flow pump at the top flange of the barrel section. Approximately 4 mils of nickel were deposited. Bridging and bonding at the interface of the electrodeposited nickel and the channel lands and the wax filled and sensitized channels was good. However, detailed examination at 10 X revealed some discontinuities on some of the grooves. The discontinuities were reconductivized with reduced silver spray. After reverse plating in a sulphamate nickel tank and immersion in a 50% solution of sulphuric acid to remove silver from all sound metallic coated areas, plating was resumed at 5 amps per sq ft for 16 hours at 90°F. Approximately 7 mils of nickel had been deposited at this point of the liner preparation for outer shell electroforming.

The chamber was thermally soaked in a water bath at 140 to 150°F for 30 minutes to permit plating at higher temperatures and to offset problems due to the expansion of wax in the fluid flow channels. This allowed the maskant to expand and relieve itself through the open ports at both ends of the liner.

The next step in preparing the liner for continuous electroforming of the outer shell was to build up the 7 mil shell thickness to a 40 mil thickness. The chamber was removed from the electroplating tank and thoroughly rinsed and dried after 40 mils of electrodeposited shell thickness was achieved. The chamber was then set up in a milling machine and 33 instrumentation holes of 0.020 inch diameter were drilled into the liner at locations specified by the chamber drawing. The hole pattern consisted of 3 rows of 11 holes, 120° apart, as shown in Figures 41, 42, and 43. Instrumentation holes are located in both TD Nickel lands and directly in coolant channels. Glass pins were inserted into the drilled holes to provide a straight hole during the ensuing buildup of the shell to final thickness.

The chamber liner then was prepared for an electroforming restart and electroforming to final buildup was started. The average electroforming rate was 0.002 inch of build-up per hour based on a current density of 70 amperes per square foot of chamber surface. This rate was considered necessary to provide adequate deposit ductility in the outside shell – especially in regions subject to subsequent welding.

During the early stages of electroform buildup a surface roughness problem was encountered. It was determined that the problem was the result of insufficient agitation of the plating electrolyte at the surface of the chamber. This was the result of the chamber being plated in the vertical position with the bell shape at the bottom. Air agitation from perforated air lines at the bottom of the tank was blocked by the large diameter of the bell, thereby precluding agitation at the smaller diameters above the bell.

Spray nozzles were added to furnish additional agitation with electrolyte over the entire surface of the chamber. Figure 20 shows the manner in which air agitation was supplemented with electrolyte spray agitation.

The surface roughness problem, illustrated in Figure 21, generated the need for a surface conditioning procedure. Surface conditioning consisted of grinding the chamber surface with disk and belt grinders to restore a smooth surface of sufficiently accurate configuration suitable for additional nickel buildup. In order to do this the glass inserts had to be removed from the instrumentation holes and the chamber had to be mounted in a fixture on centers so that it could be rotated while grinding. After grinding, new glass inserts were installed in the instrumentation holes.

Another surface irregularity problem appeared during the early stages of electroforming. These irregularities followed the rise and fall of channel lands and grooves from the forward to aft end of the chamber. These irregularities were the result of the difference in conductivity of the land and channel surfaces after the conductivizing operation. This condition was corrected by surface conditioning with the disk and belt grinder to restore a smooth chamber surface. As the electrodeposited nickel became thicker (resulting in uniform current density) this problem disappeared.

In order to meet chamber thickness requirements to accommodate thermocouples, preferential deposition of the nickel became necessary in certain areas of the chamber. Preferential deposition was accomplished by repositioning the chamber with respect to the nickel anodes to bring the anodes into closer proximity to the chamber where a greater thickness buildup was required. This resulted in a current density gradient over the surface of the chamber with the highest current density in the areas requiring the greatest thickness buildup. Shielding further directed deposition of nickel to achieve the varying thickness of the outer shell. As the shell approached final thickness, wax coatings were applied to the surface areas that had achieved final thickness in order to reduce the final machining operation. The electroforming procedure was interrupted on numerous occasions because of the recurring incidences of surface roughness and irregularities and because of the changes in plating procedure to achieve preferential deposition in areas requiring greater thickness buildup. On each occasion electroforming was resumed with normal reactivation of the nickel following anodic pickling in sulphuric acid.

Figure 21 shows the chamber after complete electroforming. It is evident in the photograph where preferential deposition of the nickel had to be achieved. Surface roughness and the tendency toward nodular buildup also is in evidence. Upon completion of electroforming the chamber was dimensionally checked to assure that sufficient electroform buildup had been obtained over the entire surface of the chamber to allow for final machining to blueprint configuration.

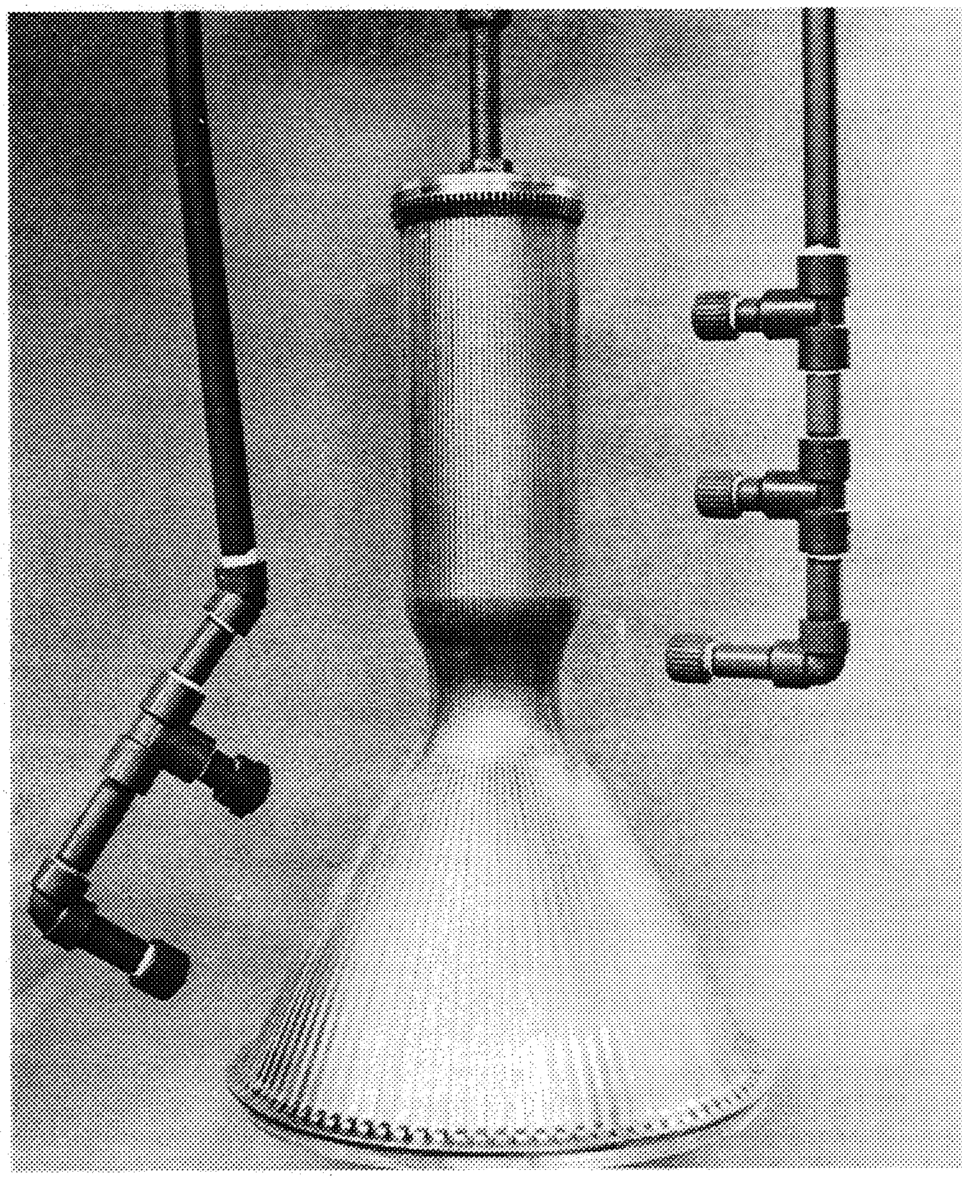

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Figure 20. Electrolyte Spray Agitation for Electroforming

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Figure 21. Thrust Chamber at Completion of Electroforming

E. ELECTRICAL DISCHARGE MACHINING

Electrical discharge machining of the fluid flow channels was accomplished after completion of inner liner fabrication and before electroforming of the outer shell.

One of the potential problem areas requiring exploration related to electrode materials. These included brass, nickel, copper, coarse-grain graphite, and ATJ fine-grain graphite. All of the materials noted exhibited favorable wear ratios and cutting rates during preliminary test work. The final choice for electrode material to be used in this program was the ATJ fine-grain graphite. The ATJ graphite was chosen because it was easily machinable, provided a fine surface finish, and was easily redressed.

Evaluation of electrode configuration was conducted concurrently with the electrode material exploratory work. It was determined that the electrode would be of three-piece construction so that rough cutting could be accomplished with the three pieces individually and final cuts could be made with the electrode elements joined into a single unit electrode. Figures 22 and 23 show the electrodes as a three piece electrode and as a single electrode. The single electrode was made by bonding the two end members to the long center section using a silver filled conductive epoxy resin.

A master model was needed for accurate fabrication of electrode blanks since the fluid flow channels had a changing contour generally conforming to the profile of the chamber and having varying width and depth from the forward to the aft flanges. Accordingly, a master electrode model was made for three-dimensional machining of the electrode blanks.

The chamber required 90 fluid flow passages electrically discharge machined to close tolerances on width and depth. This required that a large number of electrodes would be used with a need for recontouring and dressing as electrical discharge machining progressed. Therefore, a contour cutting and dressing fixture was necessary for purposes of economy and dimensional control.

An electrode contour cutting and dressing router fixture was made as shown in Figures 24 and 25. The fixture consists of rails providing two dimensional travel, a mounting plate for accurately locating the electrode, a hinged plate which is also a master template, and a router head containing a cutter and a bearing for following the master template during the dressing operation. The router cutter was driven with an air motor and had a rotational speed of 14,000 rpm. Use of graphite electrodes and the router fixture as described provided a very efficient means for restoring accurate electrode configuration, thereby prolonging the life of the electrodes.

A critical element in electrical discharge machining is the dielectric used. Dielectrics normally used in the process have a hydrocarbon base which tends to have a heavy residual waste after machining. Since the fluid flow channels had substantial depth the residual waste could build up and stagnate the cutting process. This problem was recognized in advance and electrical discharge machining tests were made on sample sheets of nickel to determine the cutting characteristics of alternate dielectrics. The dielectrics evaluated included:

1. Certex 1102 Mobile
2. Mentor 28
3. Distilled water
4. Tap water
5. Acetone
6. Methylene chloride
7. Bayol 35

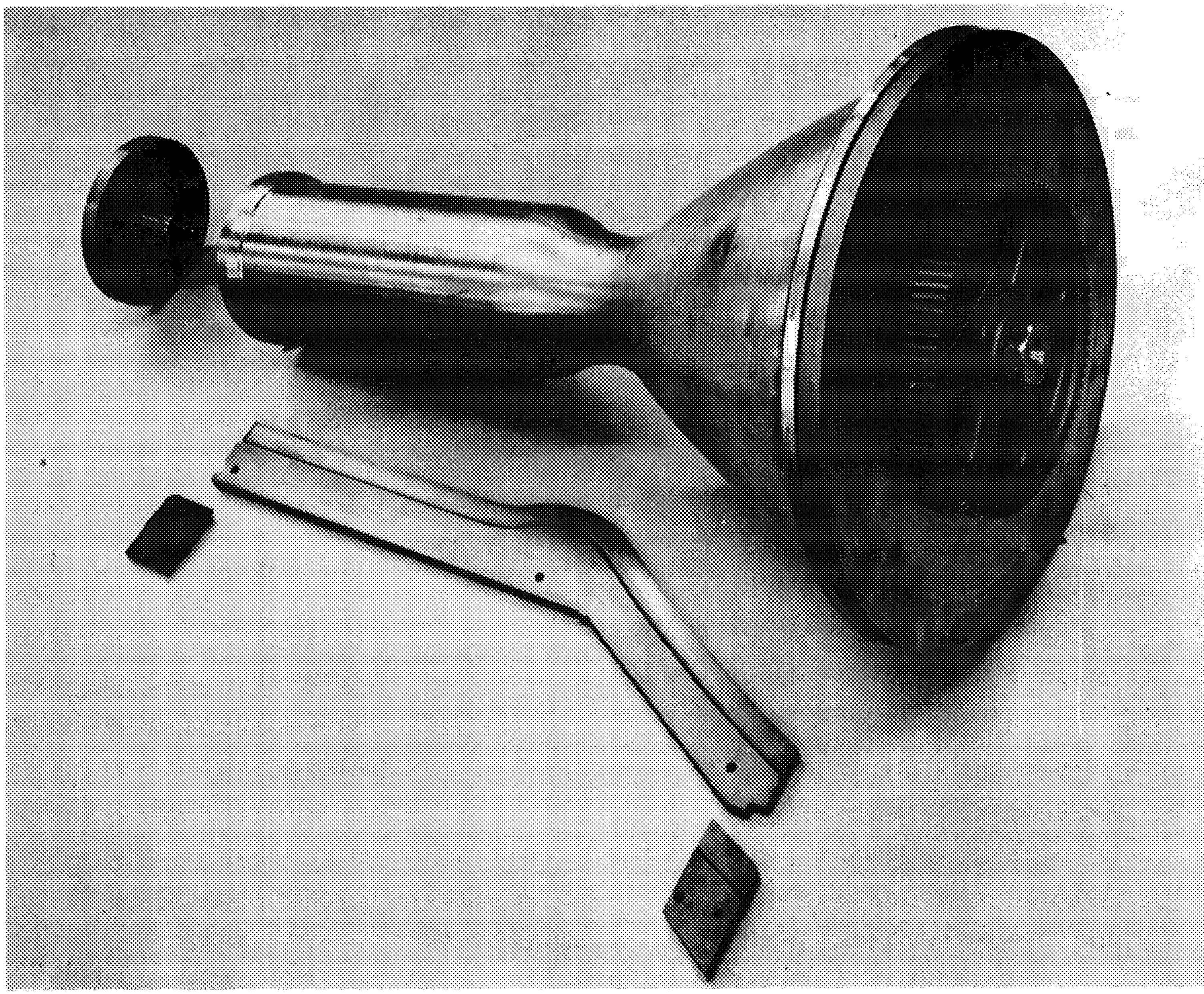

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Figure 22. Three Piece Electrode for Electric Discharge Machine

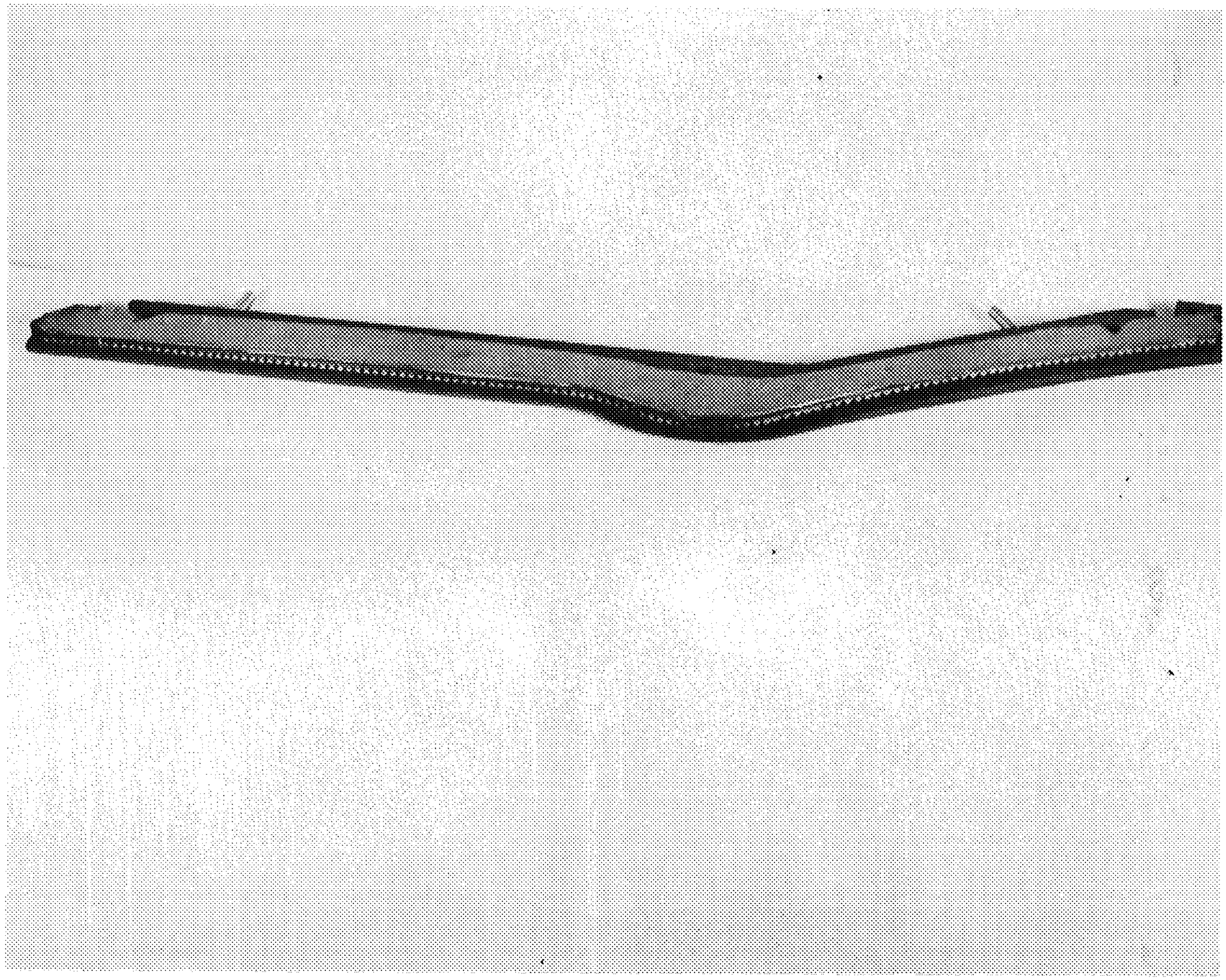

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Figure 23. One Piece Electrode for Full-Length Channel Cutting

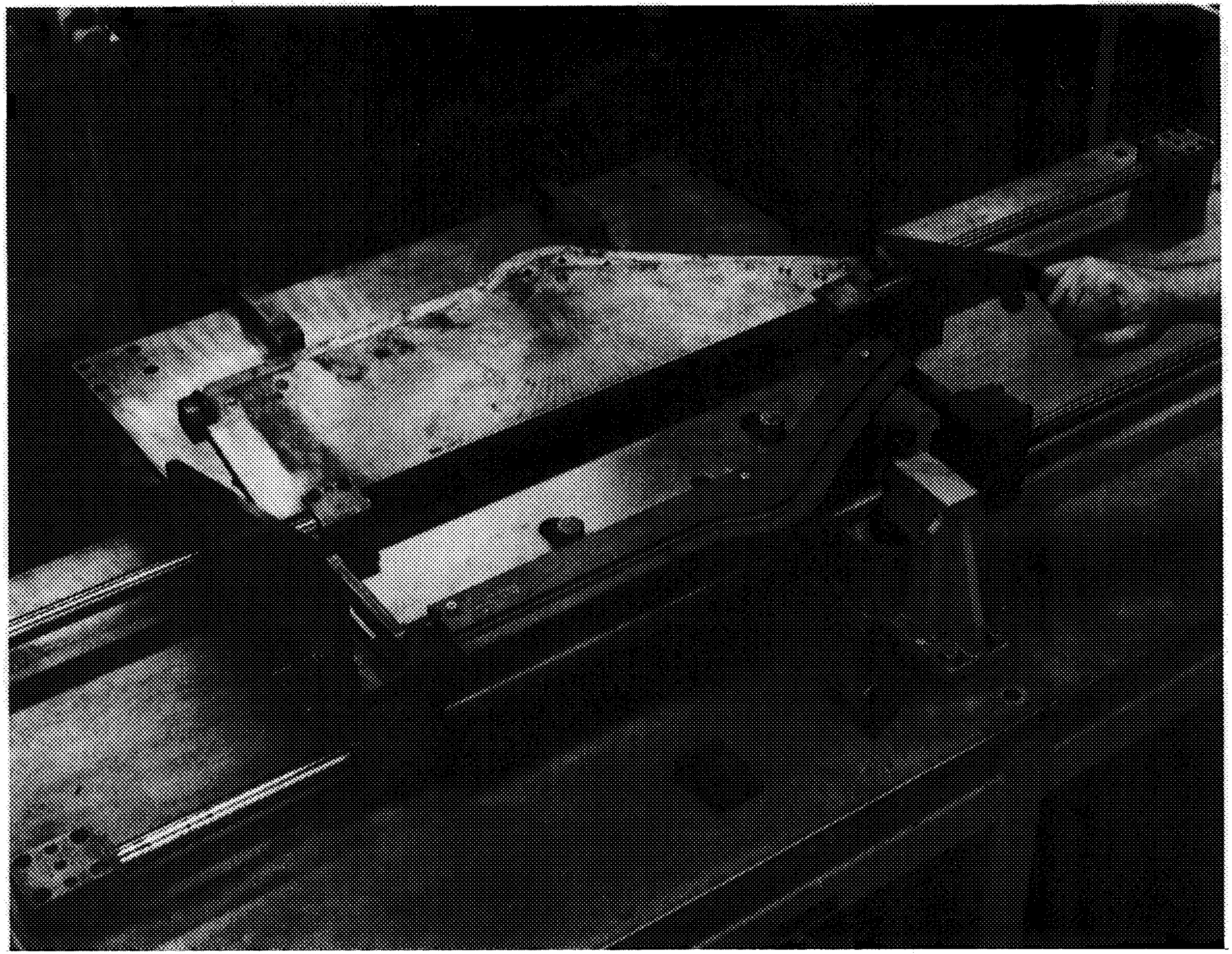

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Figure 24. Electrode Dresser Showing Router

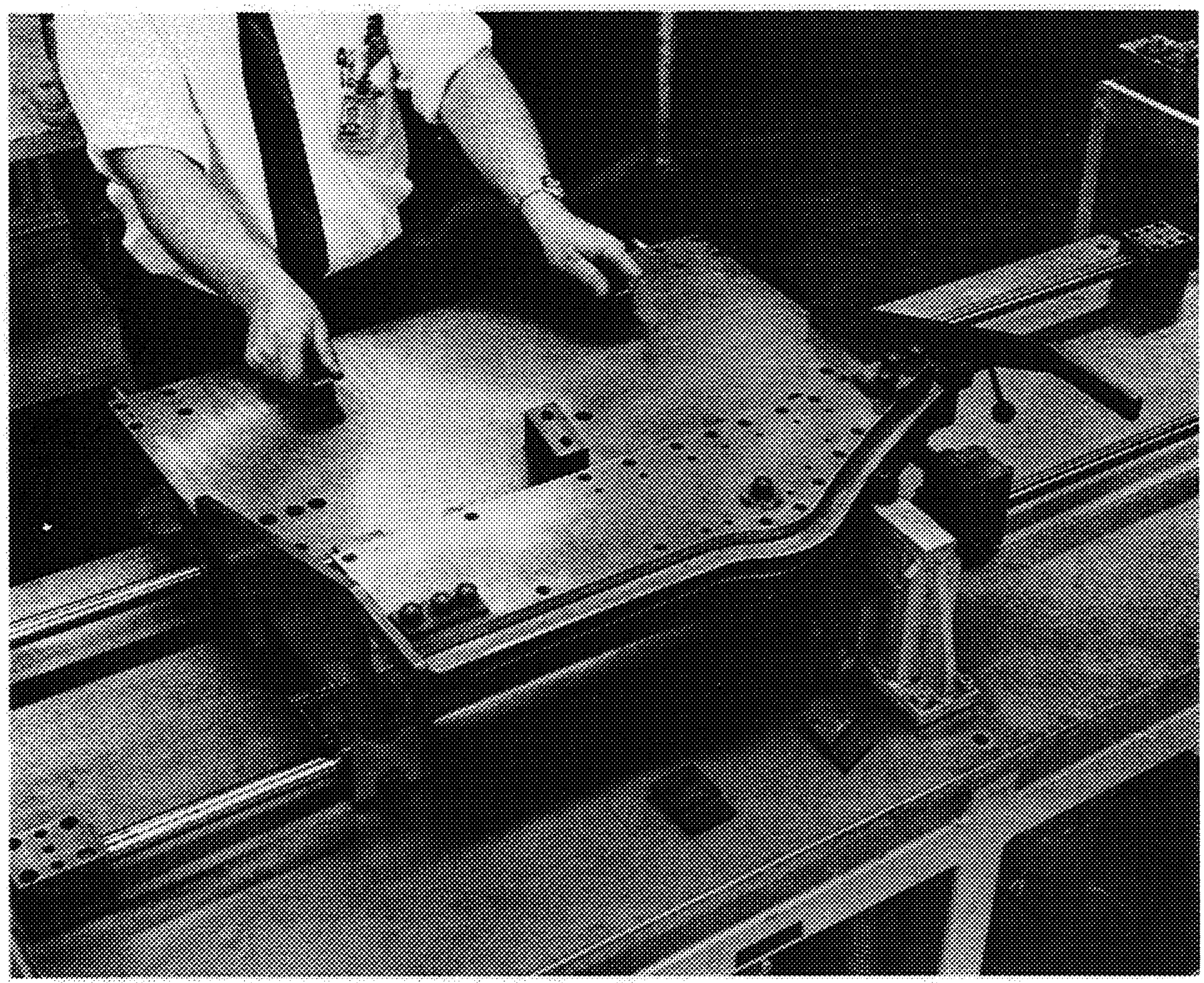

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Figure 25. Electrode Dressing

This evaluation showed that Mentor 28 gave the best combination of cutting rate, surface finish, and consistency for electric discharge machining of TD Nickel. Mentor 28 is a dielectric coolant, transformer type oil with an API gravity at 60° of 39.6. The flash temperature COC is 275°F with a pour point of 25°F. The viscosity at 100°F is 41 and the dielectric strength is 275 VPM at 0.010 gap.

Upon completion of electrode evaluation and fabrication and dielectrics evaluation, full length channel cuts were made on the stainless steel slave chamber to further refine the electrical discharge machining process. A flushing problem became apparent during these trial cuts. It was found that the dielectric fluid became trapped in the closed end groove being cut into the chamber liner and created an arcing condition between the electrode and the metal liner. This arcing caused a sludge to build up in the grooves and prevented or greatly retarded the EDM cutting process.

A ram cycle timer and a vibrator were installed on the electrical discharge machine to rectify this problem. The ram cycle timer provides for cycled withdrawal of the electrode from the groove to allow flushing of the groove with electrolyte to remove the sludge. Addition of the vibrator on the electrode caused a pumping action to occur in the groove which in turn forced the dielectric fluid to circulate out of the groove during the cutting cycle. Experiments conducted with these machine accessories improved performance. However, as the process development work continued, it became apparent that this stagnation problem was not completely eliminated.

The flushing problem was ultimately resolved with the addition of 0.042 inch diameter holes on one side of the electrode spaced at one quarter inch intervals over its entire length. The top of the electrode was manifolded so that dielectric oil could be forced into the manifold and through each of the 0.042 inch diameter holes throughout the length of the electrode. In this manner force flow flushing was achieved which, in conjunction with the ram cycle timer and the vibrator, effectively flushed the fluid flow channels as channel generation progressed. Although the entire chamber and electrode are submerged in dielectric, the spark generation along the face of the electrode soon contaminates the oil in the spark gap. This contaminated oil causes erratic behavior of the servo mechanism because the swarf particles in suspension change the dielectric strength in the gap. With the forced flow flushing on one side of the electrode, filtered dielectric is forced under the electrode into the spark gap whenever the ram retracts. In the subsequent forward movement of the ram, the contaminated dielectric is forced out the opposite side, creating a condition of stable voltage across the gap and therefore a uniform smooth forward cutting movement of the ram. Figure 26 illustrates an electrode prepared for force flow flushing.

It was not known at the beginning of the electrical discharge machining process development effort whether or not temperature variations resulting from the process would adversely affect the geometry or the metallurgical characteristics of the chamber liner. To better understand the power/temperature relationship of the electrical discharge machining process as applied to the chamber liner, and to determine and evaluate the value of a dielectric heat sink under the channel being cut, a simple test procedure was initiated. It consisted of forming a section of TD Nickel into a ring 1-3/4 inches long, 6 inches in diameter, and having a wall thickness of 0.200 inch. An 0.040 inch diameter hole was drilled into the edge of this ring to a depth of 0.125 inch. An iron-constantan thermocouple was inserted into the hole and the leads were connected to a multibalance recorder. A graphite electrode shaped to cut a channel approximately 0.200 inch wide by 1 inch long was installed into an electrical discharge machine. The test consisted of EDMing a channel into the TD Nickel ring and recording the temperature as the cut approached the thermocouple.

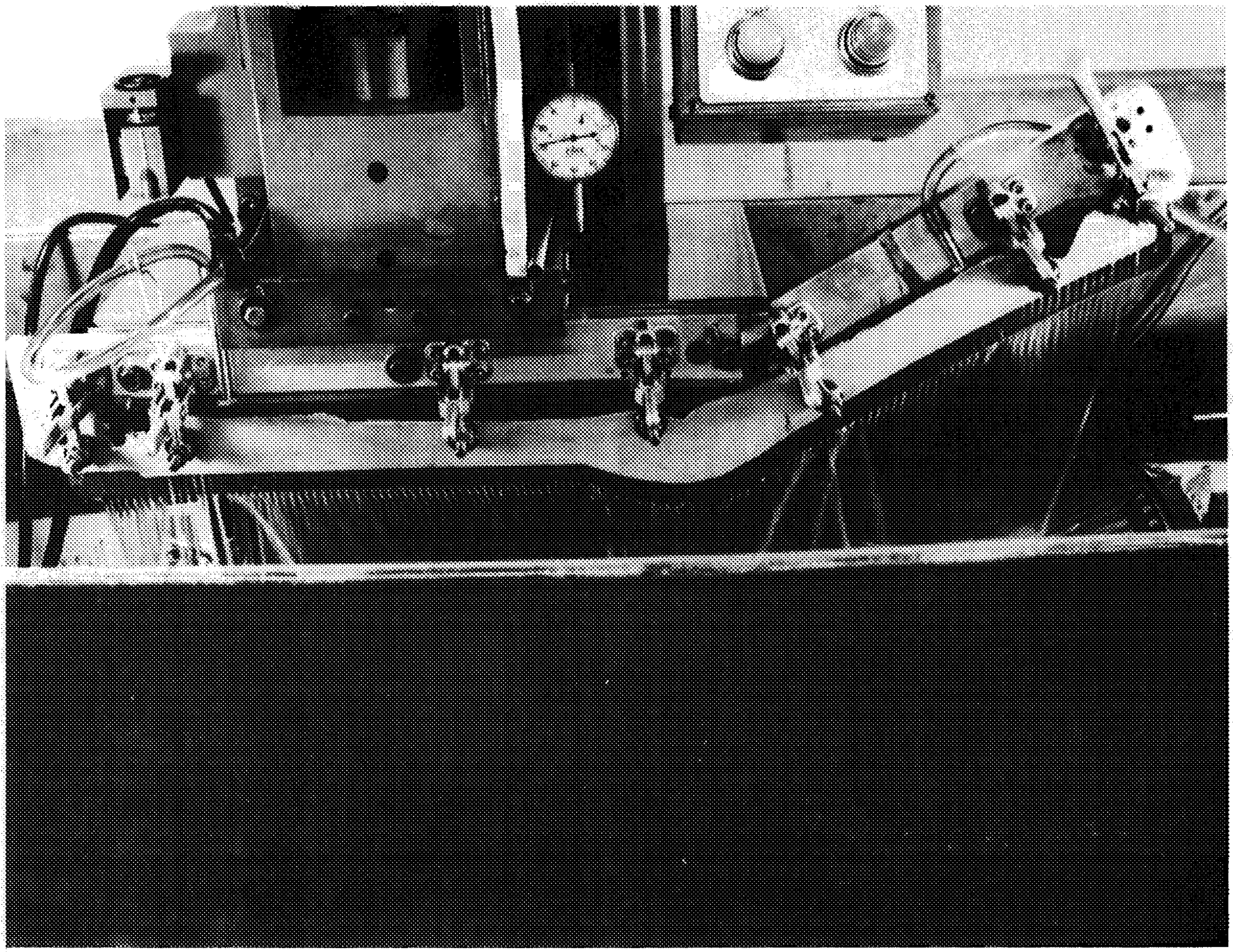

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Figure 26. Electrode with Force Flow Flushing

The test was conducted with the ring completely immersed in a tank of dielectric fluid, thereby providing a dielectric heat sink inside and outside of the ring. The test was also conducted with plexiglass bolted to each side of the ring to simulate an air-tight container. In this manner the dielectric heat sink was limited to the outside of the ring only. Significant variations in temperature rise were noted when the TD Nickel ring was not surrounded by the dielectric heat sink.

An experiment was conducted with the stainless steel chamber liner to evaluate the feasibility of outside diameter contouring using the electrical discharge machining approach rather than conventional machining. Electrodes cut to the outside diameter contour were positioned against the rotating chamber and metal was removed until the chamber contour matched the electrode. This was necessary to provide a print configuration area for electrode wear analysis. It suggests the possibility that future outside diameter and contour machining can be done on an electrical discharge machine in the same fixtures used for cutting the cooling channels. Although the results of this effort described were favorable, further exploratory work was discontinued. In consideration of the overall program objectives and milestone schedules, it was concluded that outside diameter and contour machining would be more feasibly and economically accomplished using conventional machining methods.

The major items of equipment used in electrical discharge machining the chamber liners included an Elox electrical discharge machine equipped with the cycle timer and vibrator attachment previously described and an enlarged tank sufficient in size to contain the chamber and the necessary fixturing.

To control accurate spacing of the fluid flow channels the indexing fixture shown in Figures 22 and 27 was made. This indexing fixture when assembled to the chamber liner was mounted into the holding fixture in the tank of the Elox machine as shown in Figures 28 and 29. The other major item of equipment related to electrical discharge machining was the electrode shaping tool previously described.

With the benefit of the process development work and the equipment described in the foregoing, and with the experience gained with the stainless steel slave liner, the procedure developed for electrical discharge machining and dimensional control of a TD Nickel liner was as described in the following text.

The chamber contour, overall material thickness throughout the chamber length, depth of channel, and thickness of material remaining below the channel are especially critical. Therefore, several methods of verifying chamber contour and material thickness were developed and employed on the slave and final chambers to assure achieving print dimensions. The initial chamber measurements were made in the tracer lathe and checks with the tracer template, a dial indicator in place of a cutting tool, and Vidigage measurements were made. These checks were made primarily to establish coordination between the inside chamber contour and the outside chamber contour with respect to the chamber axis. Further, these checks assured sufficient material to permit full clean-up during the outside contour and diameter machining operation. Verification measurement procedures were developed which ultimately resulted in remachining of the outside contour of the chambers to remove localized surplus material.

One method employed to verify outside surface contour was to support the chambers in a horizontal position with the center line of the chambers exactly parallel to the face of a surface

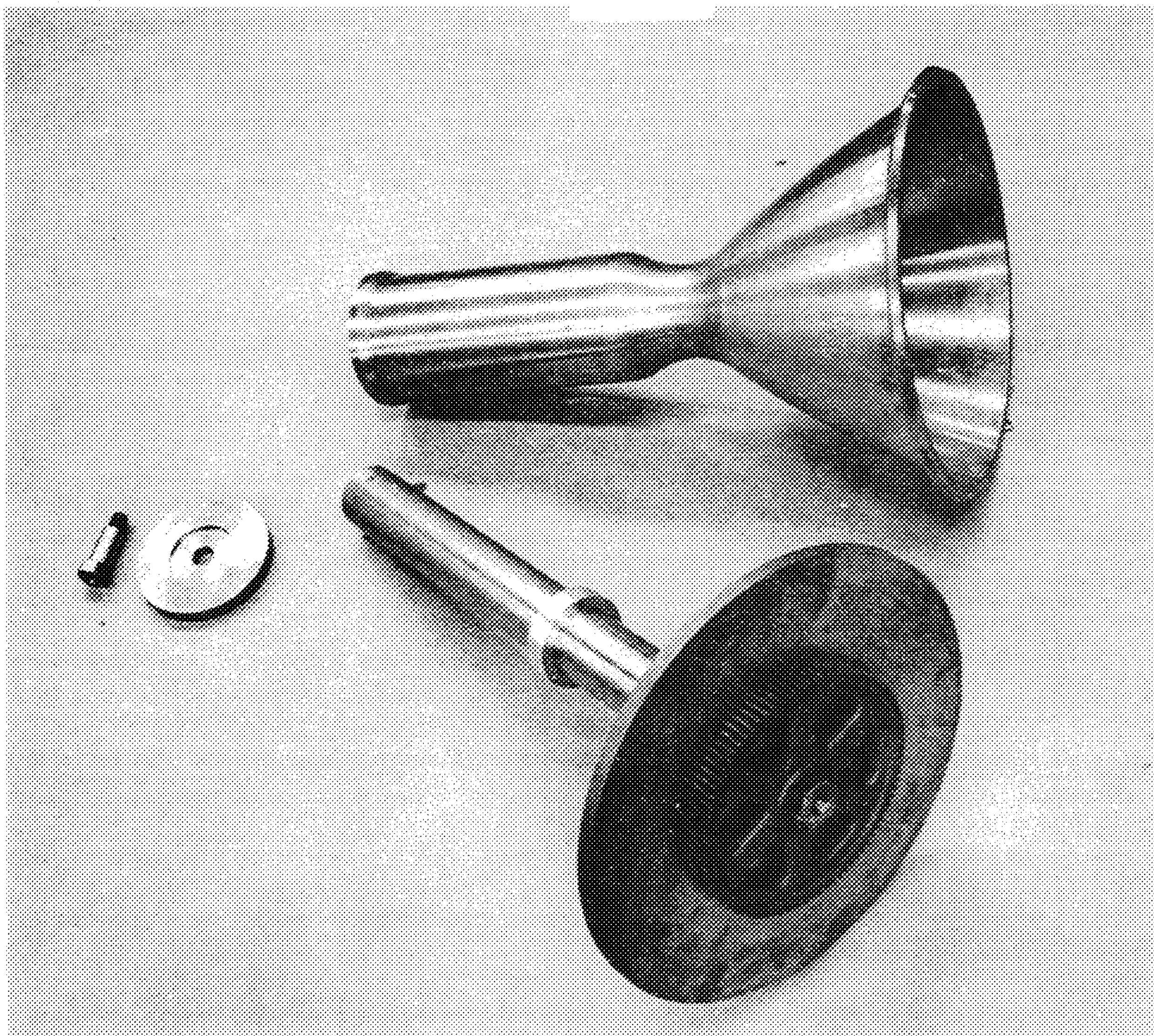

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Figure 27. Chamber Liner and Indexing Fixture

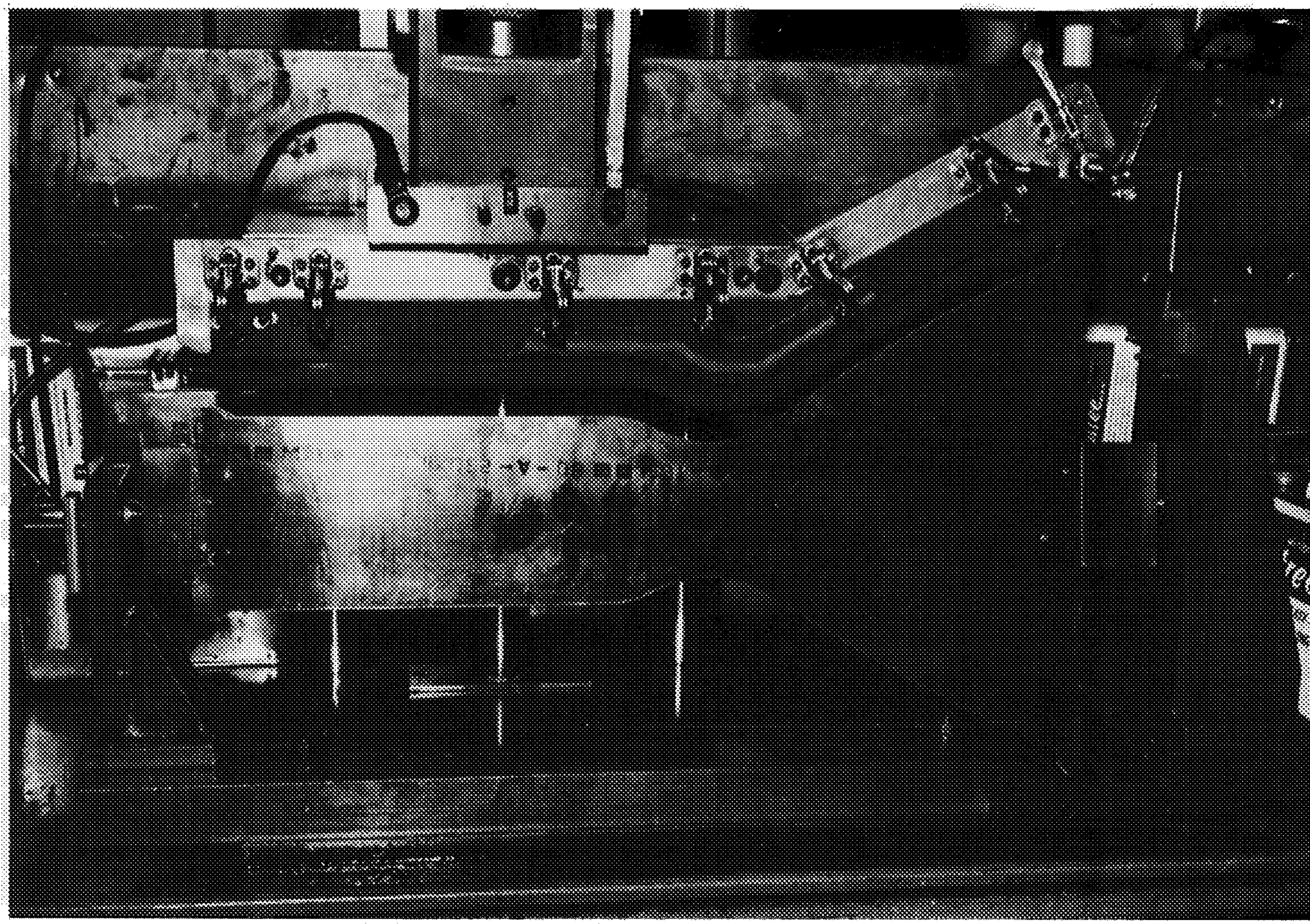

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Figure 28. Holding Fixture and Electrode Alignment

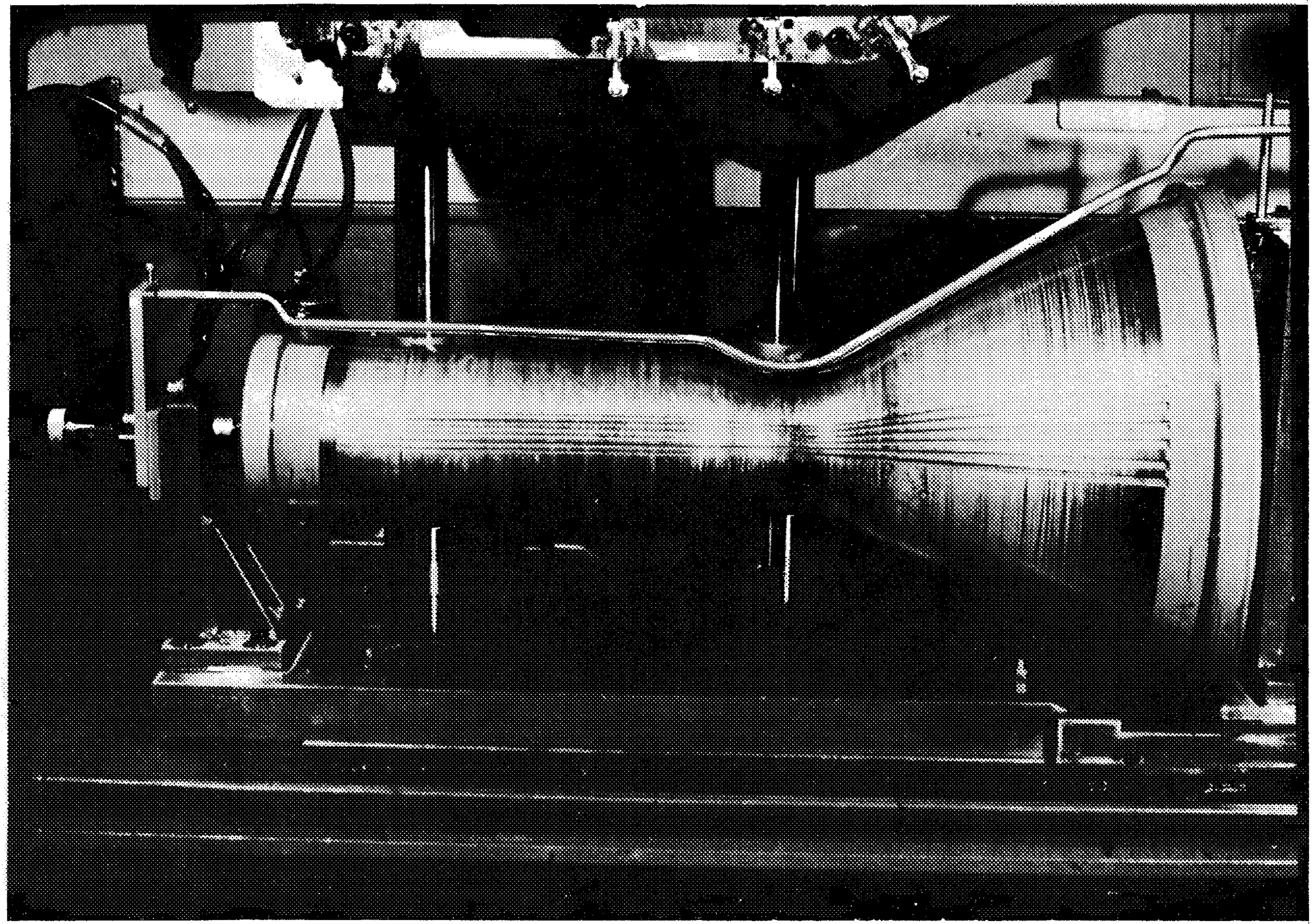

Figure 29. Liner Setup for Electrical Discharge Machining

plate. Center line to outside diameter readings were taken at 32 stations along the length of the chambers. Eight sets of readings 45 degrees apart were taken to verify contour.

To verify coordination of outside and inside contour, loosely fitting inside and outside contour templates were made and positioned appropriately inside and outside the chambers. The templates were pinned to a plate at each end of the chamber to establish a fixed relationship. Plastic material was cast between the template and chamber along the inside and outside contour to make a casting of the chamber wall. When the plastic cured, the templates were removed from the chamber and repinned to the end plates. The space between the inside and outside cast surfaces of the templates established the relationship between the inside and outside contours and also the chamber thickness along its entire length. These casts were made at four radial positions 90 degrees apart.

Material thickness was also measured with a dial indicator mounted on a specially made deep throated C-frame. Material thickness measurements at half inch intervals along the length of the chambers were made in four radial positions 90 degrees apart. These measurements in turn were verified with standard deep throated micrometers. However, these micrometer readings could be made for a distance of only ten inches in from each end of the chambers. The configuration of the micrometers would not permit taking readings deeper into the chamber.

The chamber measurement procedures described in the foregoing were used in combination throughout this program from liner fabrication through fluid flow channel generation. In this manner, a constant check on contour and chamber liner thickness was made during electrical discharge machining operations and electroforming operations. Figure 30 shows the casting and template technique for establishing liner contour and material thickness used in this program.

The procedure followed for electrical discharge machining of the fluid flow channels was to assemble the chamber liner to the indexing fixture as shown in Figure 22. When the fixture and chamber were assembled, the assembly was placed on centers and rotated. Dial indicator readings of eccentricity in rotation were measured and adjustments in assembly were made until concentricity of the outside fore and aft diameters of the chamber was achieved.

Before setting up the fixtured liner in the Elox electrical discharge machine, a preliminary alignment of the electrode and the Elox holding fixture was made as shown in Figure 28. The set-up in Figure 28 permitted close axial and radial alignment of the electrode and the holding fixture. The template represents the liner profile after fore and aft flange build up with electrodeposited nickel.

The fixtured liner was then assembled into the holding fixture and final axial and radial alignment adjustments were made. Reference points on the electrode holder in the throat area and on the throat of the liner were matched to achieve axial alignment of electrode and liner. Radial alignment was achieved with reference points at both ends of the electrode holder and the chamber holding fixture. Alignment in each case was assisted with the use of optical equipment and engaging the chamber liner with the electrode at a very low power setting. The low power setting provided superficial electrical discharge machining and thereby provided an imprint of the electrode on the chamber liner to serve as a positive alignment reference.

The fluid flow channels were generated by first machining the channels in the built up areas of the fore and aft flanges. These channels were cut until the depth blended in with the outside

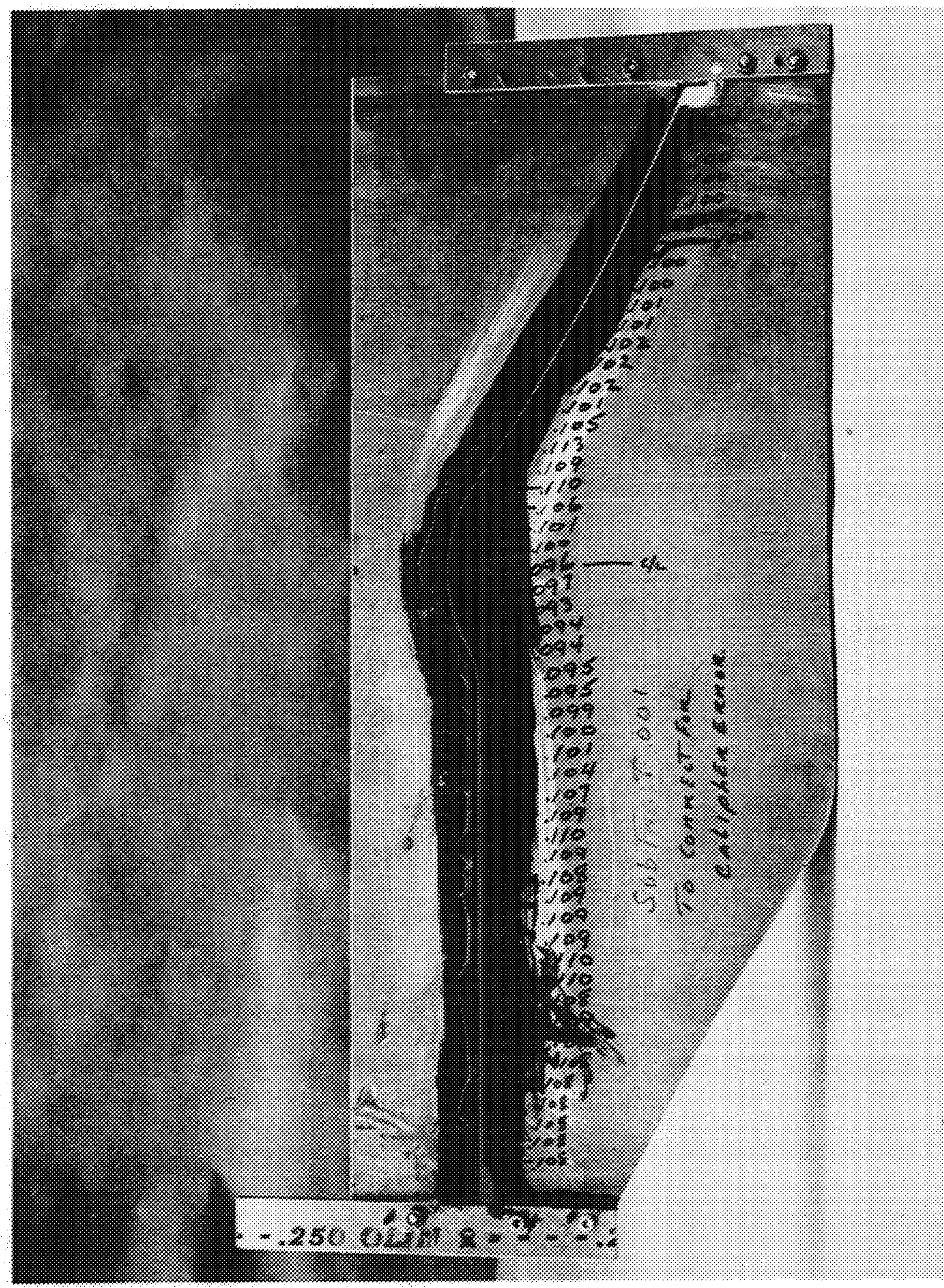

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Figure 30. Cast Check Template for TD Nickel Liner

contour of the chamber liner. The set-up for this cutting operation is illustrated in Figure 31. In order to avoid stress relieving, which might encourage an out of round condition to develop in the liner, the chamber was indexed 90 degrees after the first cut was made. Following this procedure the chamber was indexed 90 degrees approximately after each cut was made and until all the flange channel sections were set to the depth conforming to the outside contour of the chamber liner.

The flange cuts were made before any of the center section cuts were attempted (Figure 31) because of the extreme tool wear experienced in making these cuts. Therefore, excessive tool replacement cost was avoided.

In the development of the channel through the flanges a burn rate of approximately 0.0005 per minute was used to reduce the electrode degradation. Electrode wear was approximately 30% of channel development. Identical cutting rates were accomplished with the full length electrode for the roughing cut and were reduced approximately 50% for the finishing portion of the cut.

When all flange channel sections were cut, a full length electrode was mounted into the tool holder and electrical discharge machining was continued with full length cuts. The practice of indexing the chamber 90 degrees after each cut was continued with the full length cuts until all the channels were within 0.010 inch of final depth. At this point power settings were reduced and fine finishing cuts were made to drive all fluid flow channels to print depth dimension.

The chamber was marked with over thirty stations longitudinally and each station was measured individually as the channel depth was generated. This maintained a control of the progress as compared to the electrode errosion rate which varied over the electrode length because of the difference of width and depth at the various lengthwise stations.

In the process of advancing the depth of the channels in the No. 3 chamber, close to the finished depth a burnthrough was experienced. Detailed investigation indicated a combination of factors contributed to the cause. The material was to the minimum thickness as a result of some mismatch of station lines at the throat, a probable mismatch of the centerline of the throat on the electrode and the centerline on the chamber and a possible defect in the material. Also, no dielectric was admitted to the inside of the No. 3 chamber. With no coolant on the inside, temperature rose as EDM progressed. This caused a movement of the chamber toward the electrode due to thermal expansion.

The cutting operations were interrupted frequently so that chamber measurements could be maintained. The template casting technique was applied to the finish-machined channels to assure that deviations from print configuration did not occur.

During all cutting operations on the No. 4 chamber a frequent change of electrodes was made to avoid excessive electrode wear and to maintain contour integrity of the fluid flow channels. The frequent electrode changes coupled with the practice of incrementally increasing all channel depths to avoid stress relief and possible chamber distortion resulted in the successful electrical discharge machining of the fluid flow channels in the TD Nickel thrust chamber. All channels were cut to the nominal print dimension within the print tolerance of ±0.005 inch. The addition of a row of 0.042 inch diameter holes, spaced at one quarter intervals along the edge of the electrode, created a sheet of pressurized dielectric oil on one side of the electrode for complete channel flushing (Figure 35).

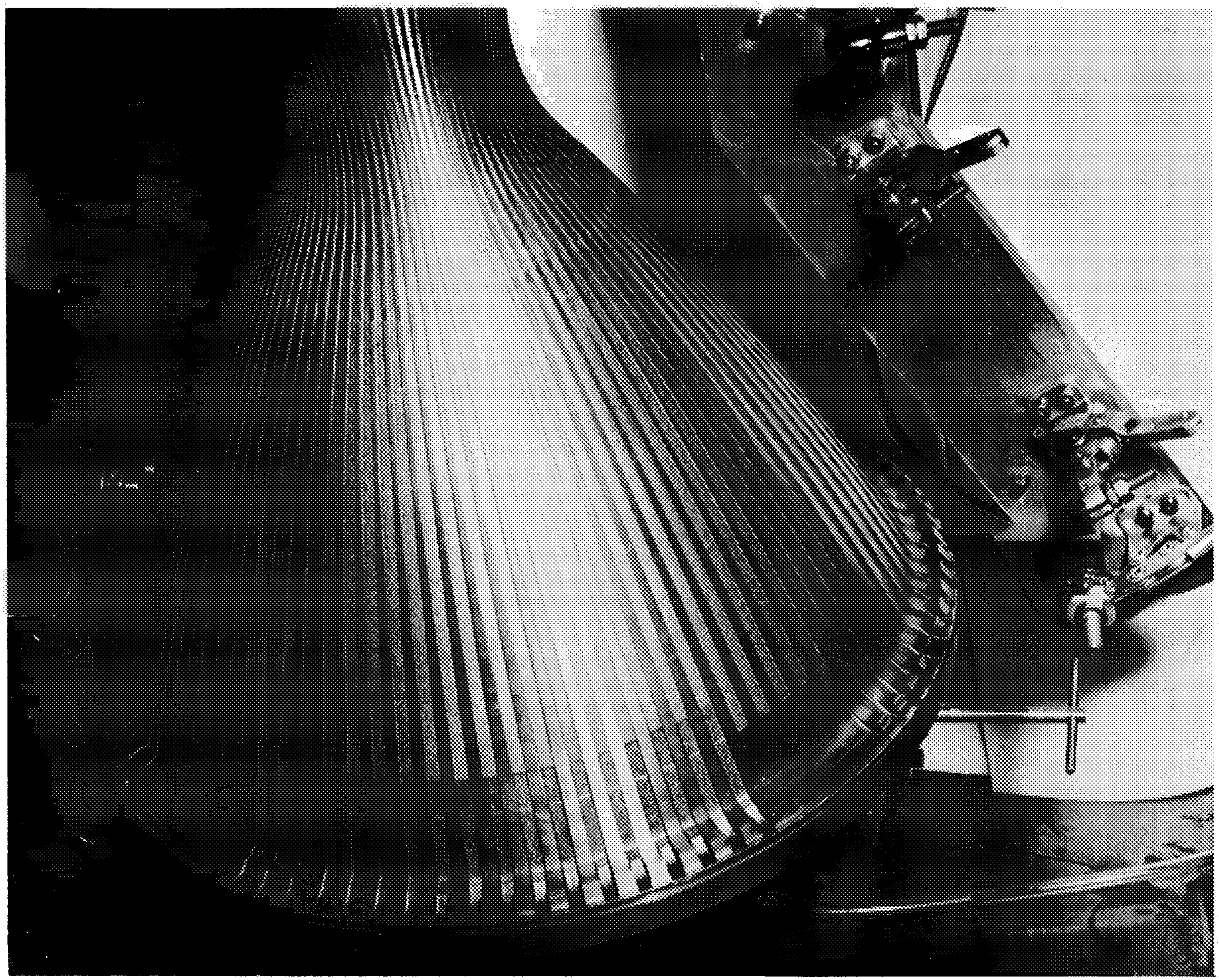

Figure 31. Blending Flange Channel Sections to Contour

301988

Various facets of the electrical discharge machining procedure are illustrated in Figures 32 through 35. Upon successful completion of the electrical discharge machining, shown in Figure 36, and final chamber measurements, the chamber was prepared for electroforming of the outer shell. Electroforming was accomplished as previously described in this report.

F. FINAL MACHINING AND WELDING

The chamber was removed from the plating tanks and set up in a fixture on centers in a horizontal position after completion of the electroforming operation which formed the outer shell. The chamber was rotated and examined; no flaws were found.

With use of a coarse disk grinder, excessive nodular buildup was removed to avoid tool breakage and tearing during machining. The flared portion of the chamber shown in Figure 37 shows the surface finish upon completion of the grinding operation. The chamber was stripped of its fixturing and micrometer measurements were made to check material thickness. Micrometer measurements indicated sufficient electroform build-up in all areas to assure clean-up during the final outside contouring and diameter machining operation. The chamber was then immersed in hot water to remove all the wax masking material from the fluid flow passages. Alternate immersion and flushing with hot water removed all of the wax.

The chamber was plugged at each end and set up in a tracer lathe. The tracer template was coordinated axially with the chamber. Primary reference points in this set up were the center of the chamber throat with reference points on the template and additional reference points representing the fore and aft flanges on the chamber. Concentricity of the chamber was set up within plus or minus 0.001 inch as shown by dial indicator readings on the forward and aft flanges of the chamber.

Machinability parameters suitable for pure nickel were used to machine the electroformed material to establish the outside configuration of the chamber to blue print dimensions. Figures 37 through 40 illustrate the various stages of this final machining operation. The chamber was prepared for instrumentation hole drilling after completion of the final contouring machining operation.

The chamber was again set up on centers as shown in Figure 41. To simplify instrumentation hole location, and to correct for any misalignment of hole entry point due to glass rod tipping during the outer shell electroforming operation, the instrumentation hole pattern was laid out on the outside surface of the chamber as is evident in Figure 41. The glass rods were removed from the outer shell using mechanical and chemical means. Mechanical means involved chipping and removing glass particles from the holes with use of an undersize drill and reamer. To insure complete glass removal, a 12% solution of hydrofluoric acid was used to dissolve the remaining glass in the holes. The acid was known to not attack nickel electrodeposits.

The chamber with the centering fixture was then set up on a tilting head vertical milling machine. Axial alignment of the chamber and centering fixture in the milling machine was accomplished with optical equipment and reference points on the centering fixture.

The instrumentation holes were drilled, counterbored and tapped for 1/8-inch pipe fittings per print callout. Some slight discrepancies were found in hole entry points as indicated by the hole pattern layout and the hole established by the glass rods. All discrepancies were well within one hole diameter and in all cases drilling was accomplished using the hole pattern layout as reference. This choice in reference proved to be correct since on completion of the drilling and tapping operation the small diameter and large diameter of the instrumentation holes were concentric.

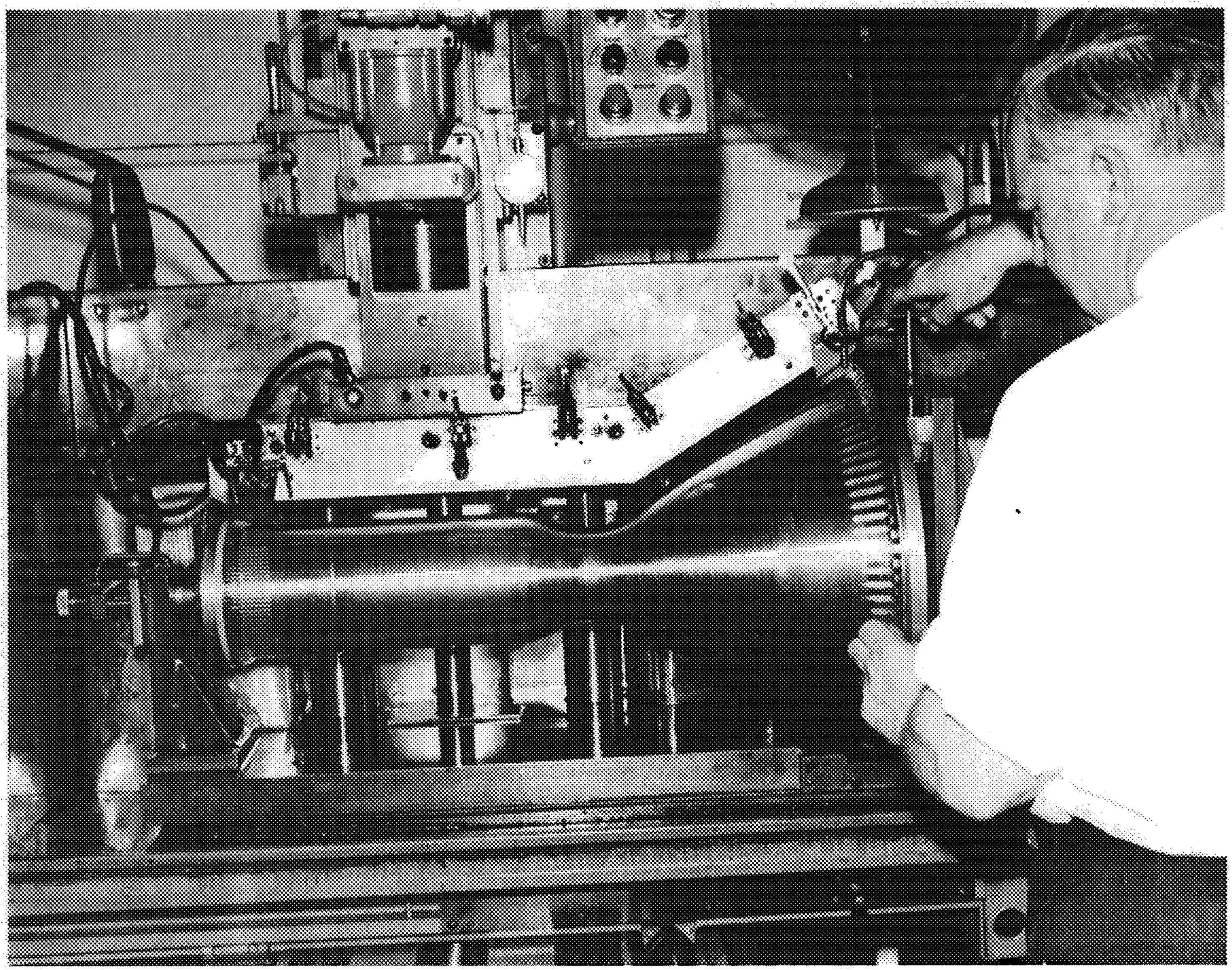

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Figure 32. Flange Cutting

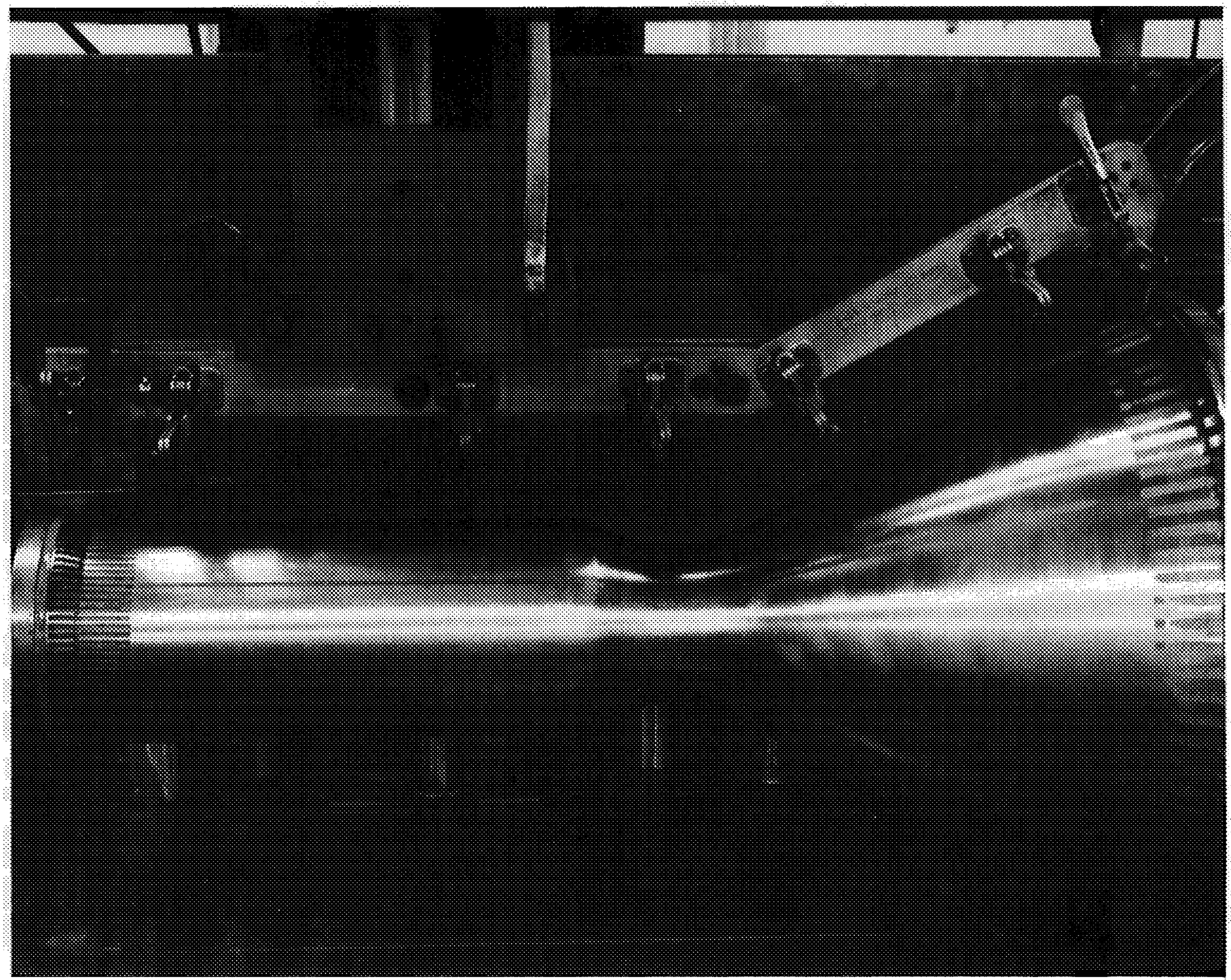

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Figure 33. Center Section Cutting

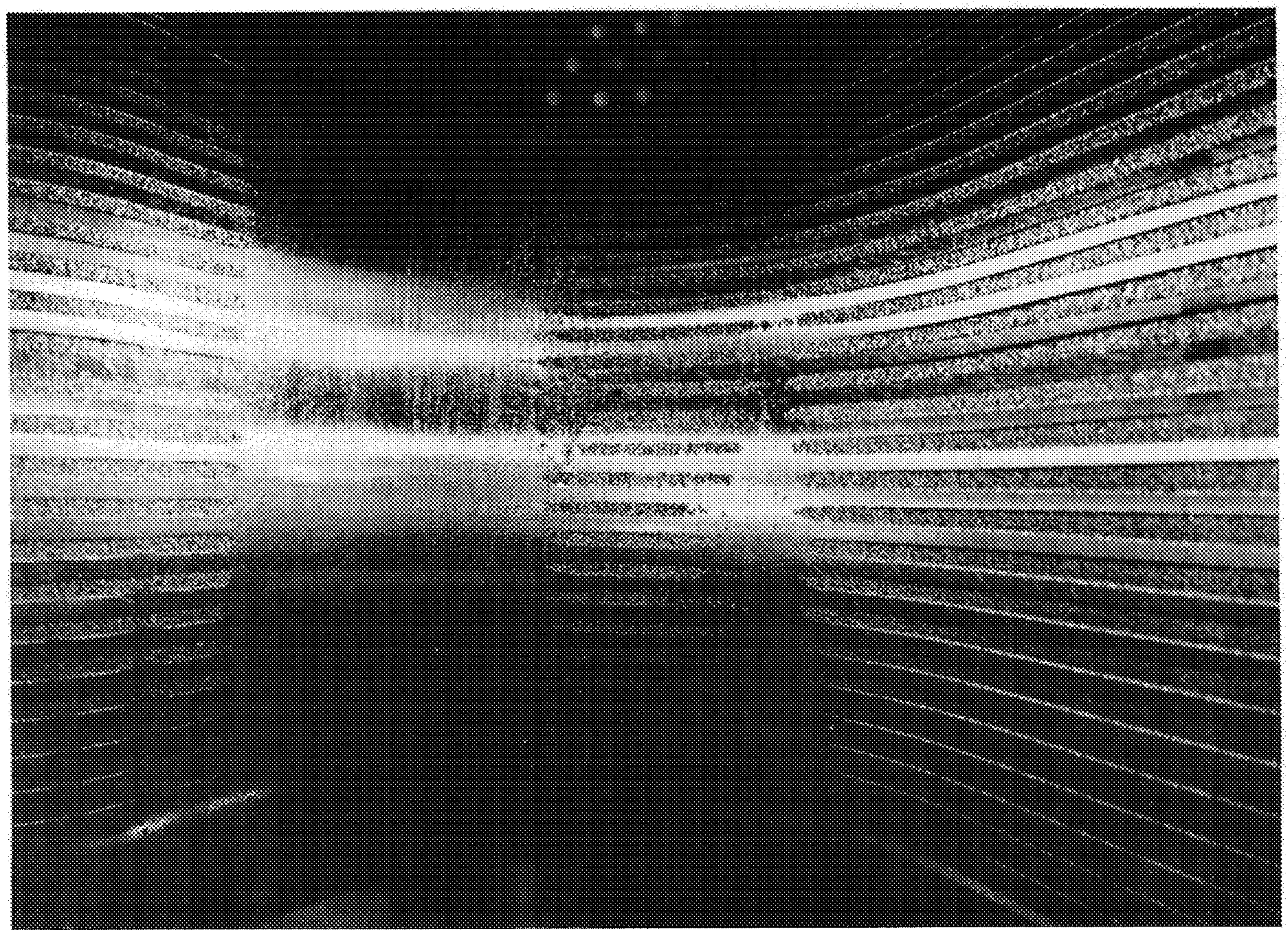

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Figure 34. Concentricity in Throat Section Shown by Depth of Cut

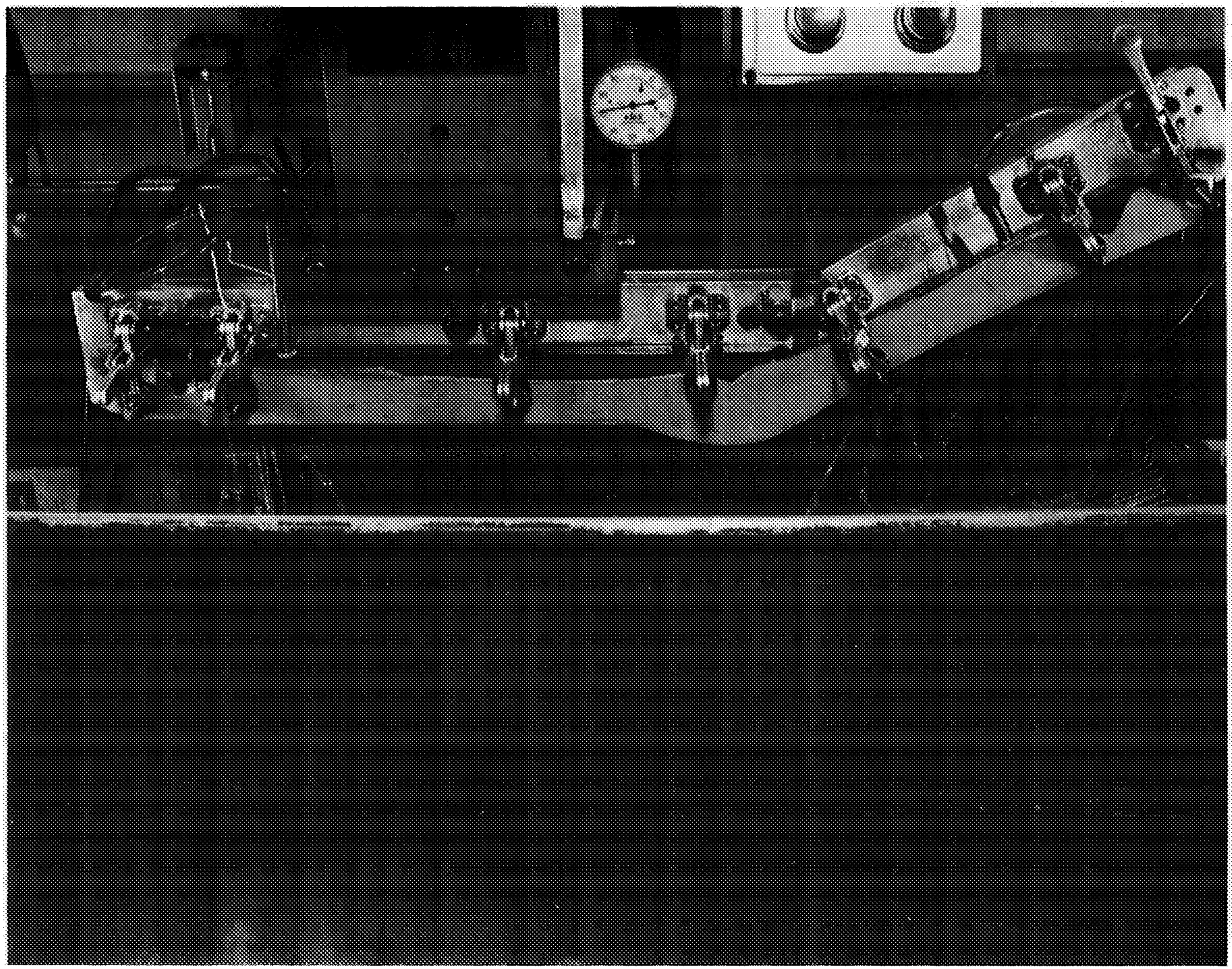

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Figure 35. Full Length Cutting with Force Flow Electrode

313031

Figure 36. TD Nickel Liner Complete with Channels

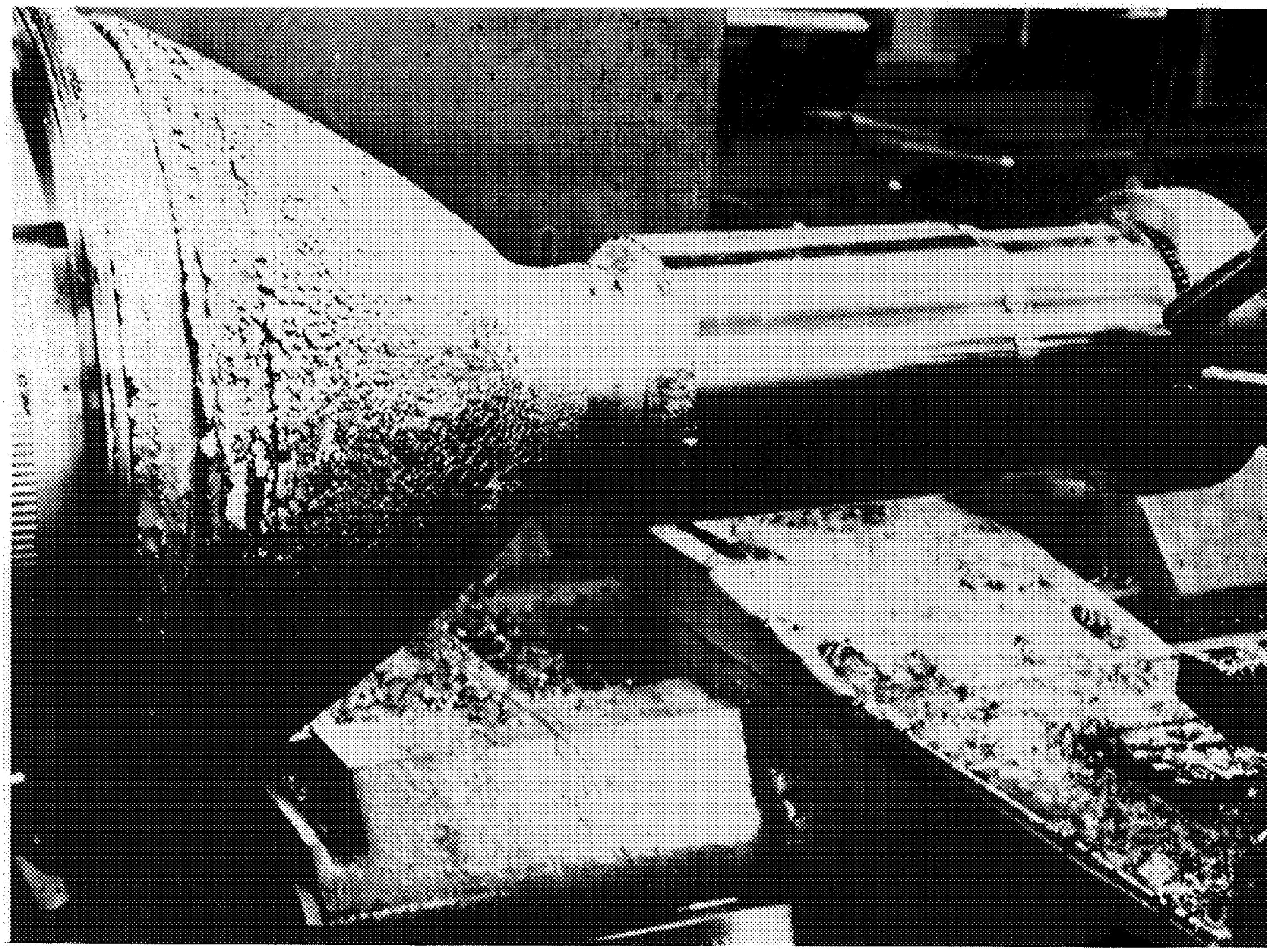

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Figure 37. Machining Forward Chamber Diameter

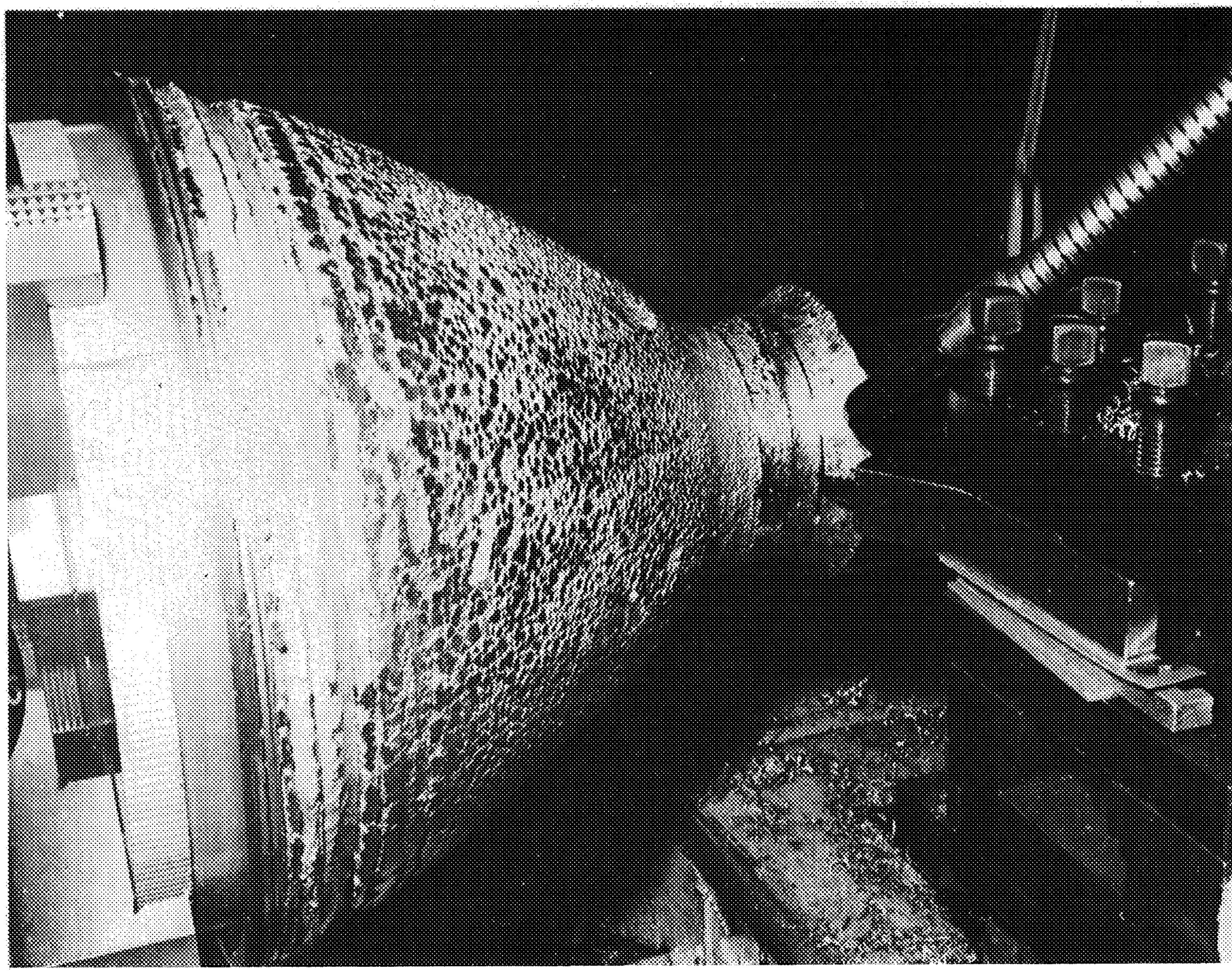

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Figure 38. Machining Throat and AFT Chamber Contour

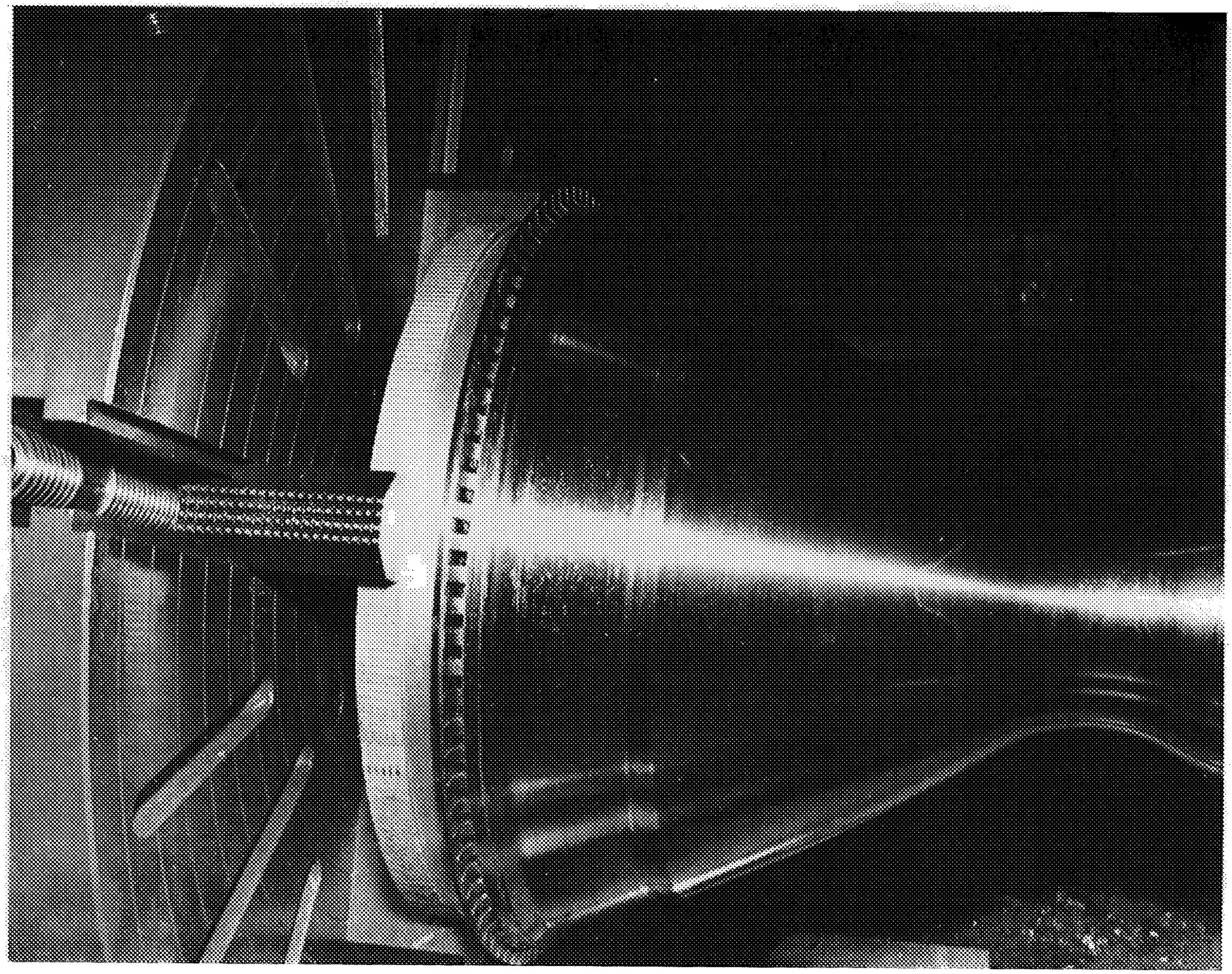

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Figure 39. Machined AFT Section with Flange Channels Exposed

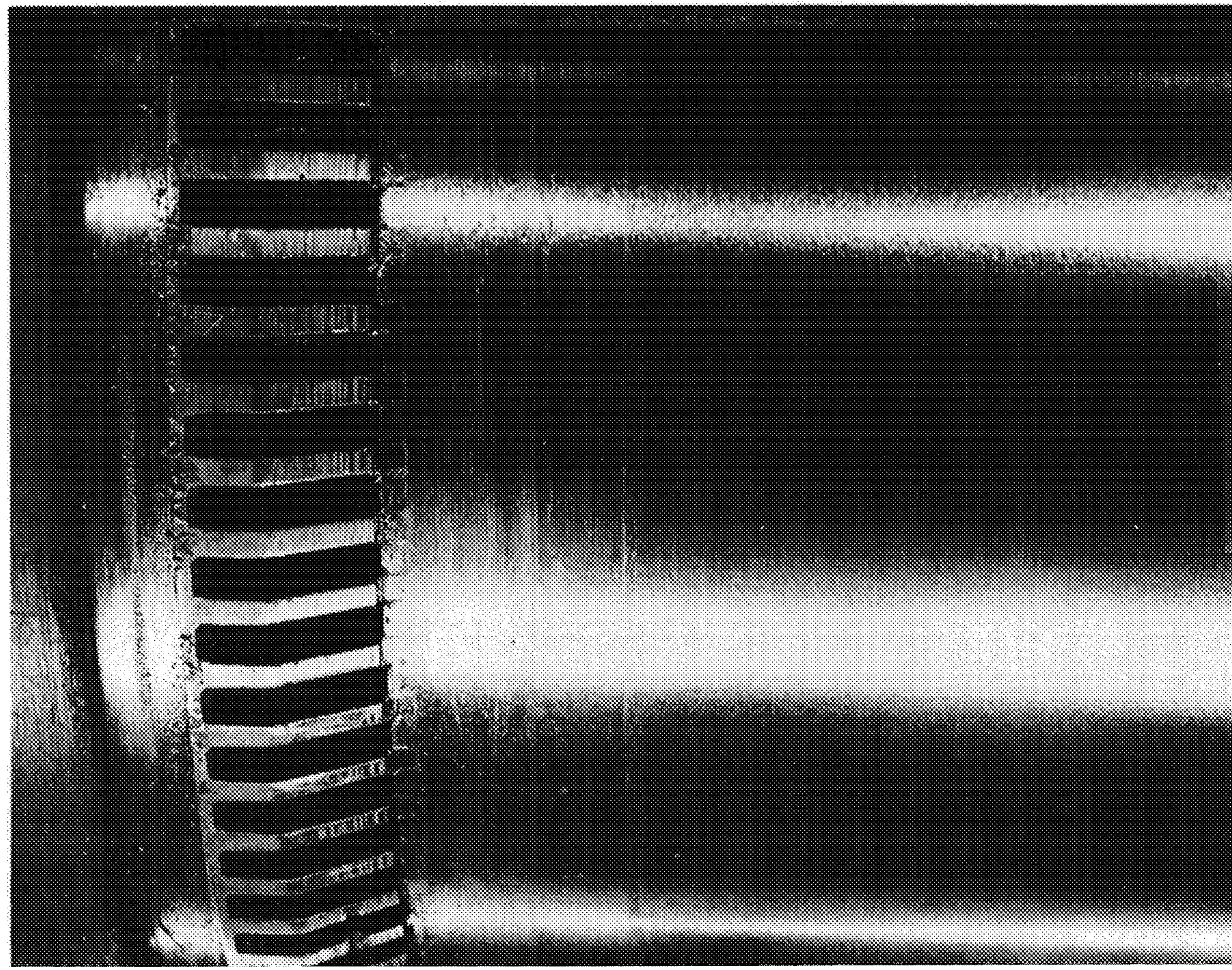

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Figure 40. Machined Forward Section with Flange Channels Exposed

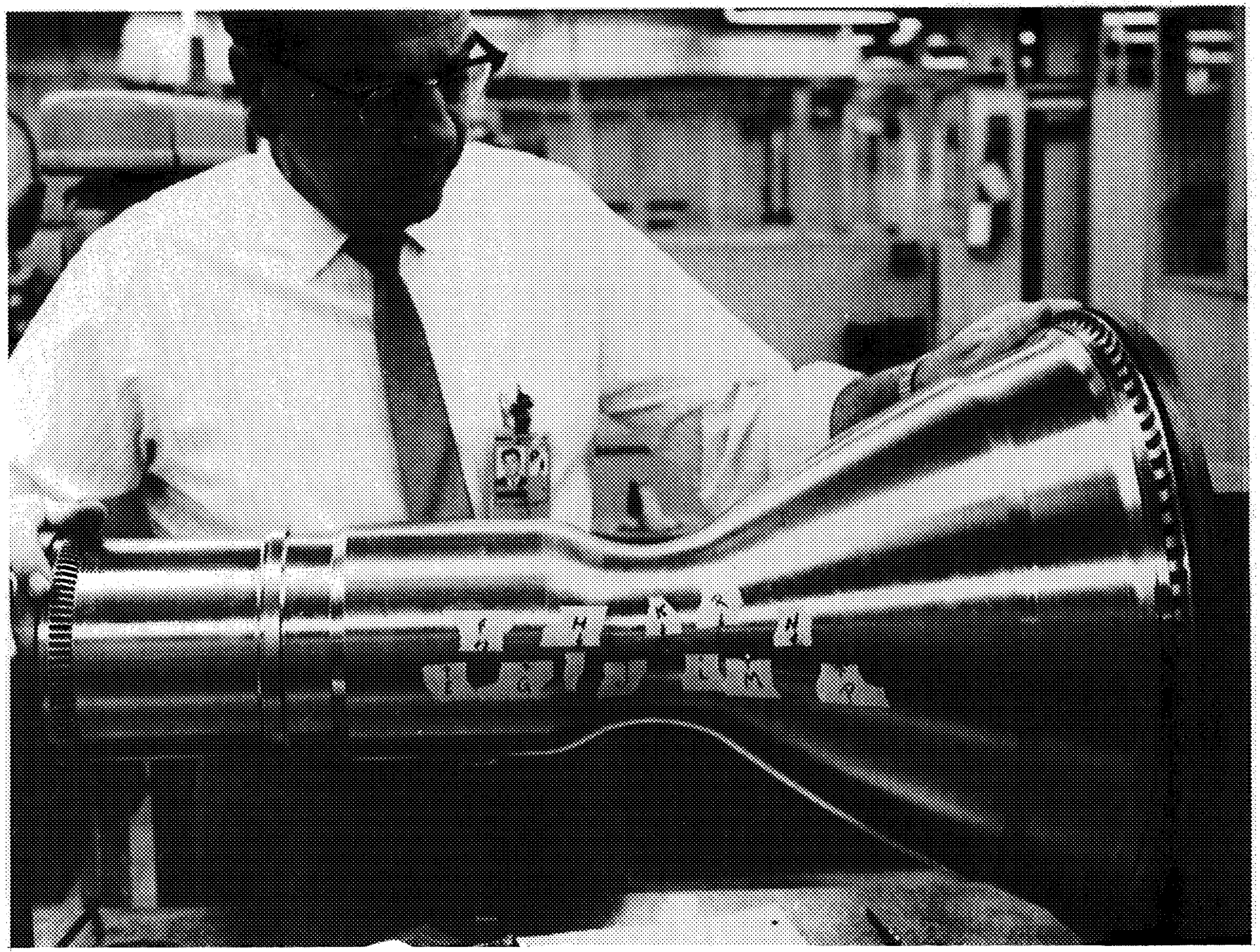

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Figure 41. Instrumentation Hole Layout

Alignment of the holes and depth control for drilling, counterboring and tapping was assisted with optical equipment, and micrometer and dial indicator attachments on the milling machine. Figure 42 shows the TD Nickel chamber upon completion of the instrumentation hole drilling and tapping operation. The weld sample in the figure was made to establish the manifold to shell weld procedure. It was later metallographically evaluated and confirmed a structurally sound weld without degradation of the inner shell to electroformed shell interface.

Finished channel instrumentation holes, for thermocouples measuring coolant temperature during hot firing tests, were plugged with 1/8-inch stainless steel pipe plugs in preparation for subsequent chamber hydraulic pressure test. These are evident in Figures 2 and 43. It was not necessary to plug the blind land instrumentation holes for those thermocouples measuring chamber inner wall temperatures.

The drilling and tapping operation indicated some wax remained in the fluid flow channels. The remaining wax was removed from the channels and inside walls of the chamber by submerging the chamber in a hot water bath at 190°F to 195°F. This immersion operation was followed by vapor degreasing the chamber and flowing trichlorethylene through each of the channels. The silver conductiviser used to bridge the channels during the electroforming operation was then removed by submerging the chamber in nitric acid for a maximum of three minutes. Prior to nitric acid immersion, a test specimen was processed to insure silver removal was effected without attack on the nickel and TD Nickel by the nitric acid. The chamber was now ready for the final welding operation.

Weld parameters, filler material and joint geometry were established using slave units. No cracking problems were experienced nor were any defects noted. 347 stainless steel was used for filler material in welding stainless steel to stainless steel. ER Ni-3 nickel alloy wire was used for welding electroformed nickel to stainless steel. All welding was manual, utilizing the gas tungsten arc process with argon as the torch and back-up gas.

The first step in weld build-up to final configuration consisted of welding the threaded bosses to the forward and aft manifold members. The coolant inlet and outlet members then were welded into subassemblies. After completion of these subassembly operations, the aft manifold ring was welded to the aft liner flange and to the chamber outer shell. The manifold to shell weld was made first in order to take advantage of the minimal restraint exerted by the tacked assembly. The flange to liner weld was made next. In both cases, two passes were required and a skip sequence was used with welds being four inches to five inches long, approximately 180 degrees apart, and the sequence continued until the circumference was completely welded. At this point a dye penetrant and helium sniffer detector test was made to verify no-leak welds. The coolant inlet assembly was then welded to the aft ring manifold. Figure 43 shows the weld build up of the final chamber assembly at this point.

To insure that all passages were open, a water flow check was made after the aft manifold was welded and before the front manifold was assembled. A water line was attached to the aft inlet and low pressure water flow was started so that a visual inspection could be made of the flow through each channel. The pressure was increased to a manifold pressure of approximately 200 psi. There were no differences in the flow characteristics of channels, showing that all channels were open. The water flow check is shown in Figures 44 and 45.

The forward manifold was welded to the forward flange and outer shell after completion of the flow test. The coolant outlet assembly was then welded to the forward manifold. This completed buildup of the TD Nickel chamber.

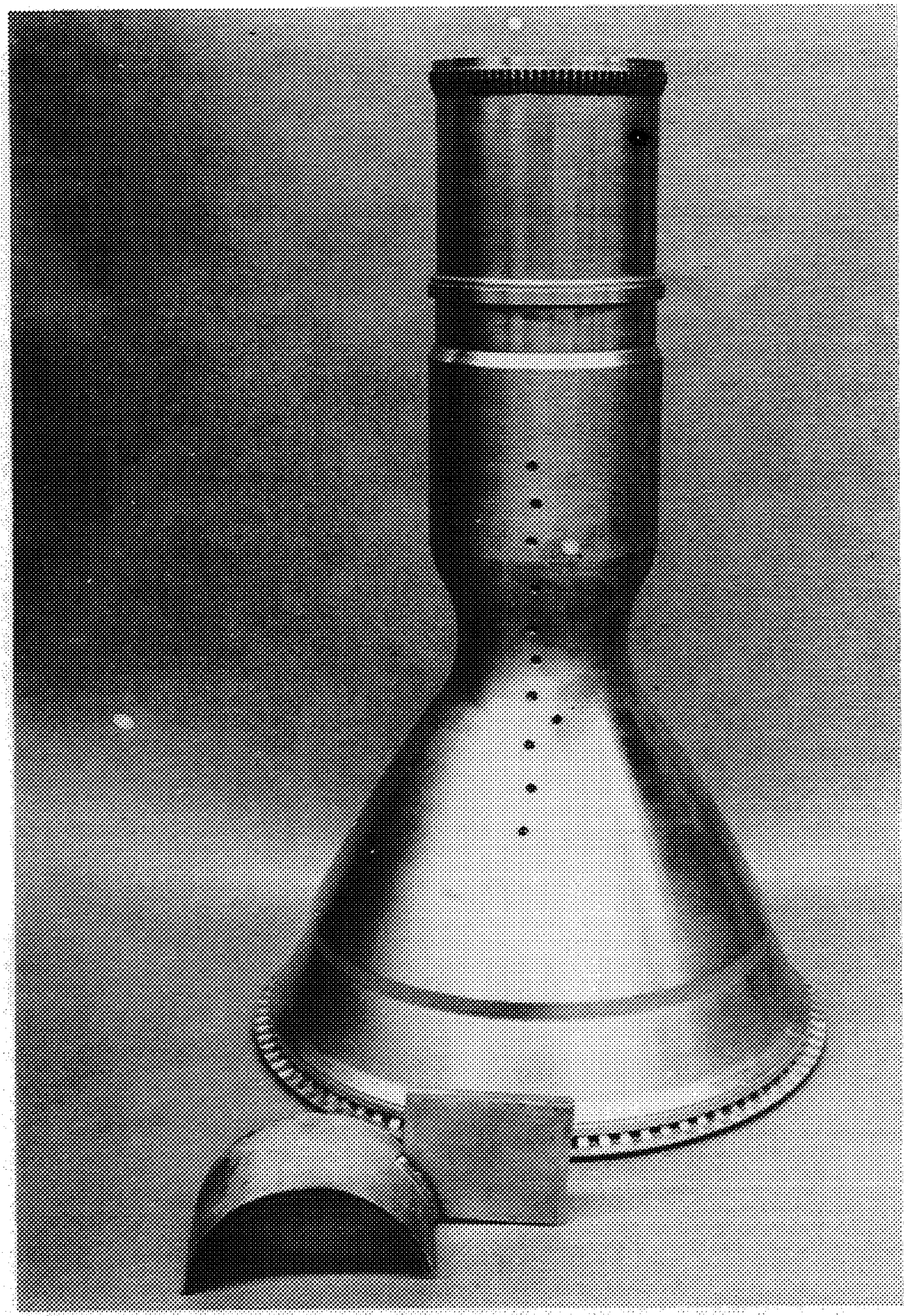

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Figure 42. Chamber Drilled and Tapped for Instrumentation

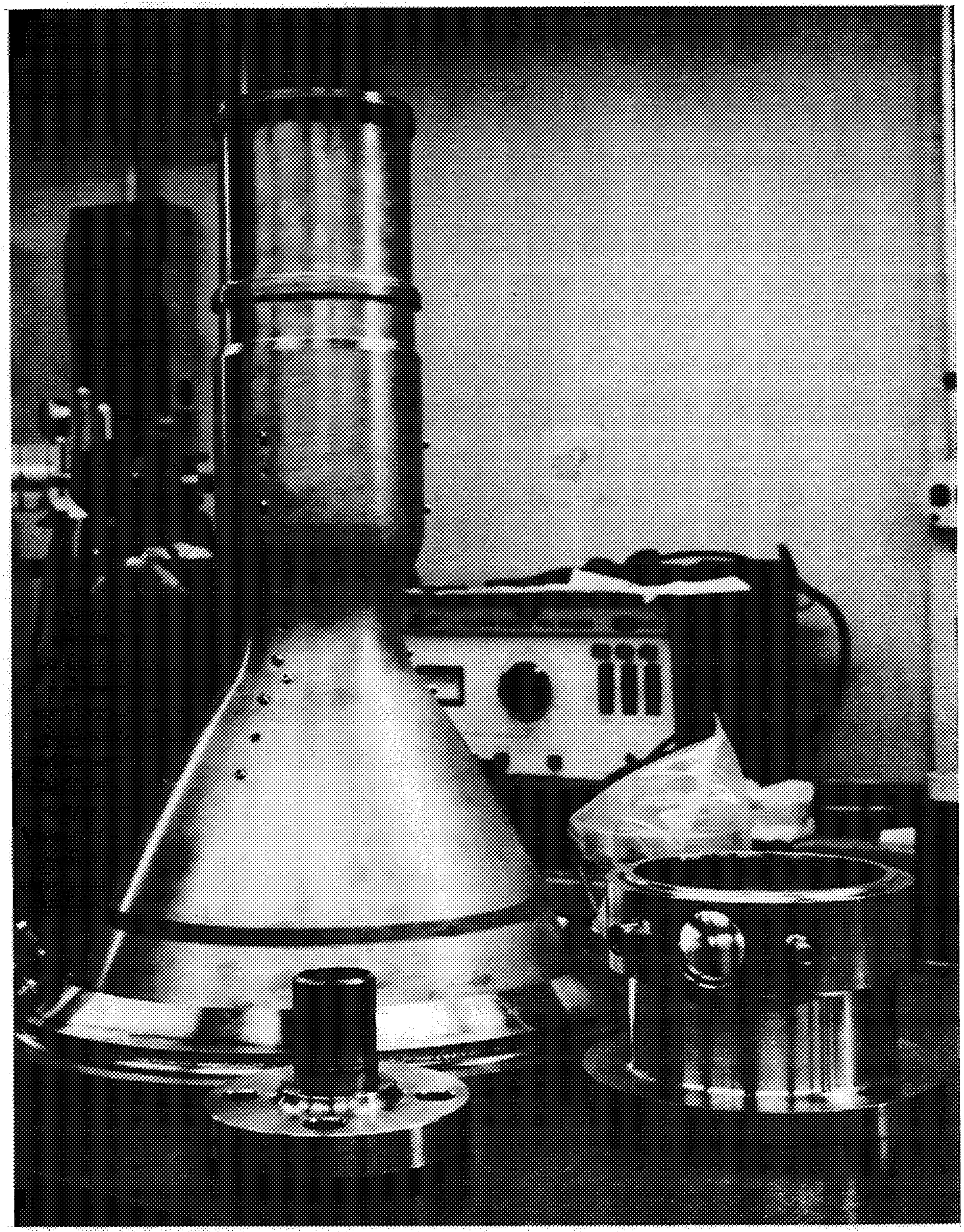

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Figure 43. Final Weld Buildup of Chamber

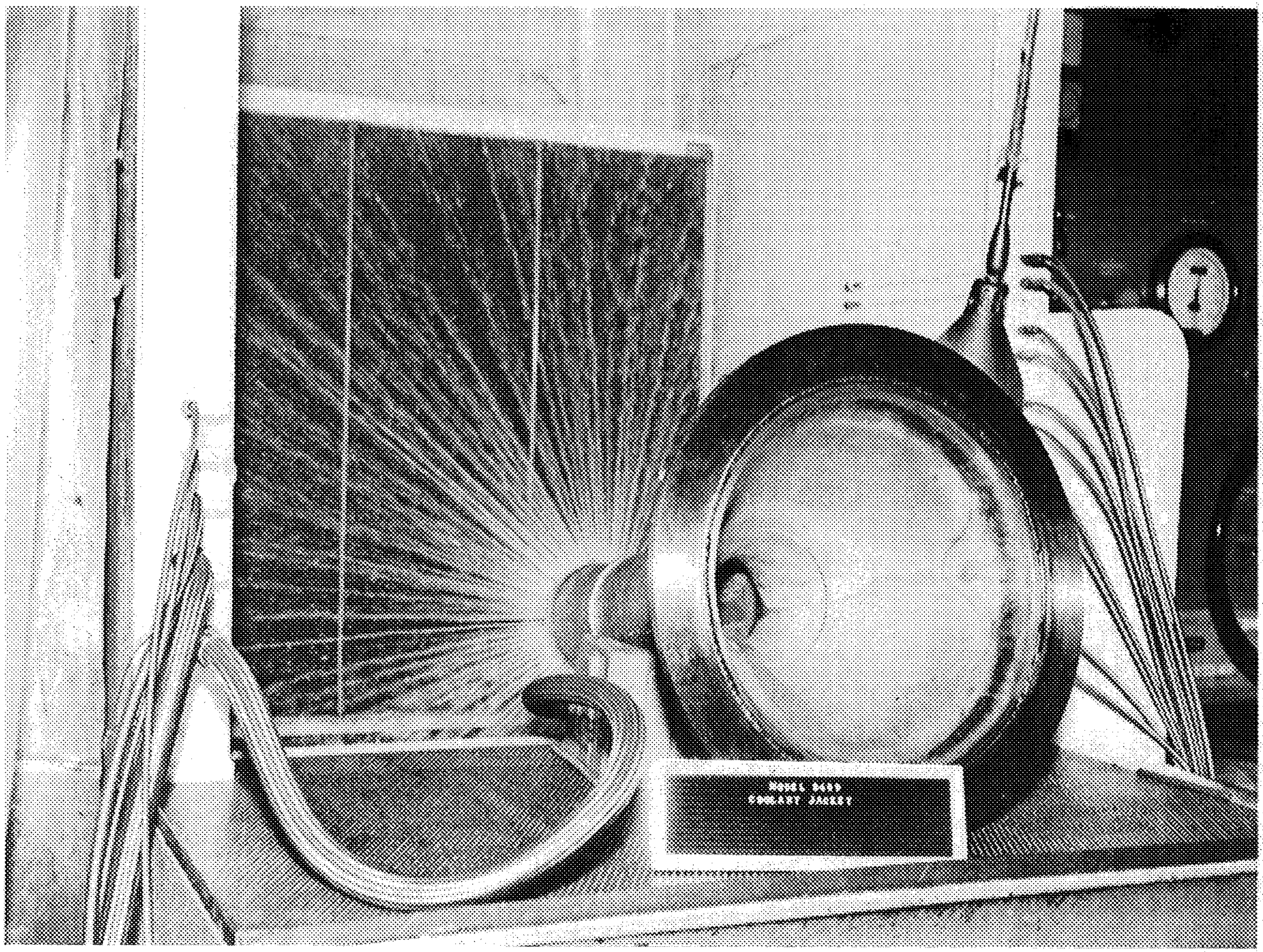

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Figure 44. Water Flow Check

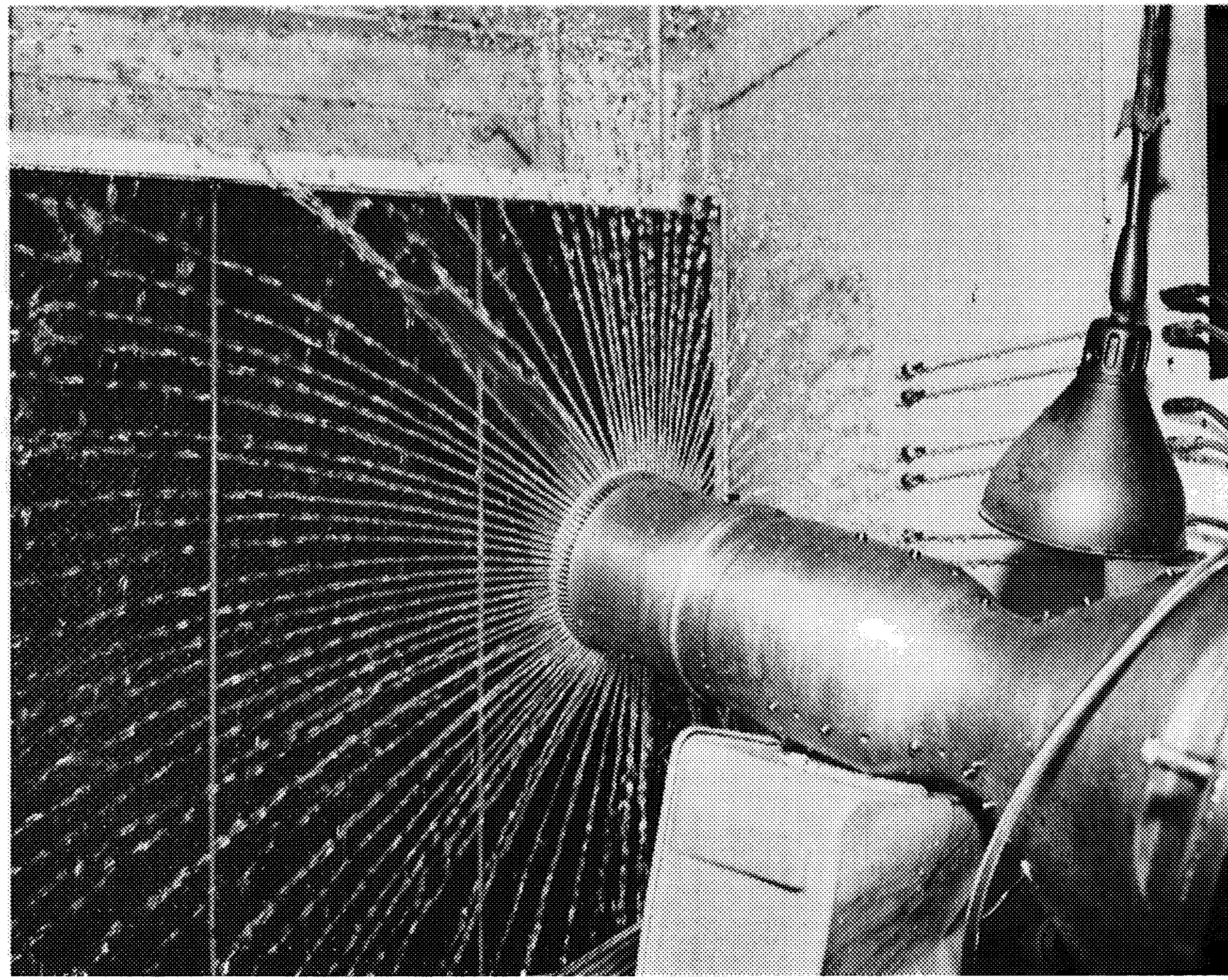

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Figure 45. Water Flow Characteristics Test

To meet all drawing requirements for chamber centerline parallelism and aft flange perpendicularity, a locating fixture was fabricated and used to hold the coolant inlet assembly for the tacking and welding operation. Alignment of all manifold members and inlet and outlet flanges was established and maintained using this fixture during the weld assembly operations.

The completed chamber assembly was then subjected to a dye penetrant and helium sniffer test to assure no-leak welding had been accomplished throughout the entire chamber buildup. Minor leaks were discovered which were successfully repaired by rewelding in small local areas.

The chamber was then set up in a standard engine lathe, and with the assistance of a dial indicator concentric rotation of the outer contour of the chamber with its longitudinal axis was achieved. The forward and aft liner flanges were faced perpendicular to the axis. Sufficient material was allowed on the flanges before assembly so that machining would clean up the entire flange faces.

The chamber assembly was then moved and set up in a jig-bore and all bolt holes were drilled and reamed to blueprint pattern and dimensions. The chamber then was thoroughly cleaned to remove all residual oil and machining contaminations.

At this point the chamber assembly was ready for final flow and pressure tests.

IV. TESTING

The first test was for leaks in the instrumentation holes. All holes were sealed with plastic tape and 1/4 inch stainless steel pipe plugs. The front outlet was sealed by a pressure plate bolted to the outlet flange. The inlet manifold was connected to a test instrumentation stand, and the unit was pressurized to 100 psi using nitrogen gas. This test was successfully completed with no leaks.

The chamber was next calibrated for flow test pressure drop. Water was used as the flow medium and inlet pressures were recorded for 10, 12.5, 14, and 15.5 lb/sec flow rates. Results are shown in Figure 46.

The third test was a hydraulic pressure test. The objective was to pressurize the coolant channels to 810 psi in 200 psi increments to verify the structural integrity of the cooling system.

During the hydraulic pressure test, pressures of 200 and 400 psi levels were reached without pressure loss or leakage. When pressurizing to 600 psi, a pressure loss was observed. Inspection of the chamber showed no leaks. Main attention was given to weld joints, instrumentation holes, and manifold blocks, since these were areas of potential trouble. The test was started again and at 550 psi, a metallic pinging sound was heard. The test was stopped.

A decision was made at this point to retest flow rates. When preparing for the flow rate test, a bulge was observed in the aft region of the liner. The bulge was approximately 1-1/2 inches wide, 5 inches long, and 1/4 inch high. The bulge started 4-1/2 inches forward of the aft flange. Figures 47 and 48 show the bulge in the inner liner.

An ultrasonic analysis of the bulge area indicated that the lands were intact and separation occurred between the top of lands and the shell. This was later confirmed when an area of the shell opposite the bulge was removed.

Alternative courses of action were reviewed. A decision was reached to remove the shell in the area of separation, analyze causes, reshape the liner, and pressure check the balance of the chamber to 810 psi by blocking off the affected channels.

In keeping with the above decision the periphery of the liner bulge was carefully identified and outlined and then was traced on transparent paper. The chamber then was placed in a horizontal position on a surface plate with the bulge at the three o'clock position. The longitudinal dimensions of the bulge were measured from the aft flange parallel to the center line of the chamber. These dimensions were then transferred to the outside shell of the chamber in the area of the bulge. Radial dimensions of the bulge were established with a height gage and also were transferred to the outside surface of the chamber.

In the manner described above the extreme edges of the liner bulge were accurately located on the outside of the chamber. The tracing of the bulge perimeter made on the transparent paper was then placed on the outside surface of the shell within the transferred lines. The traced outline of the bulge was then transferred to the outer shell with closely spaced punch marks made with a center punch and hammer.

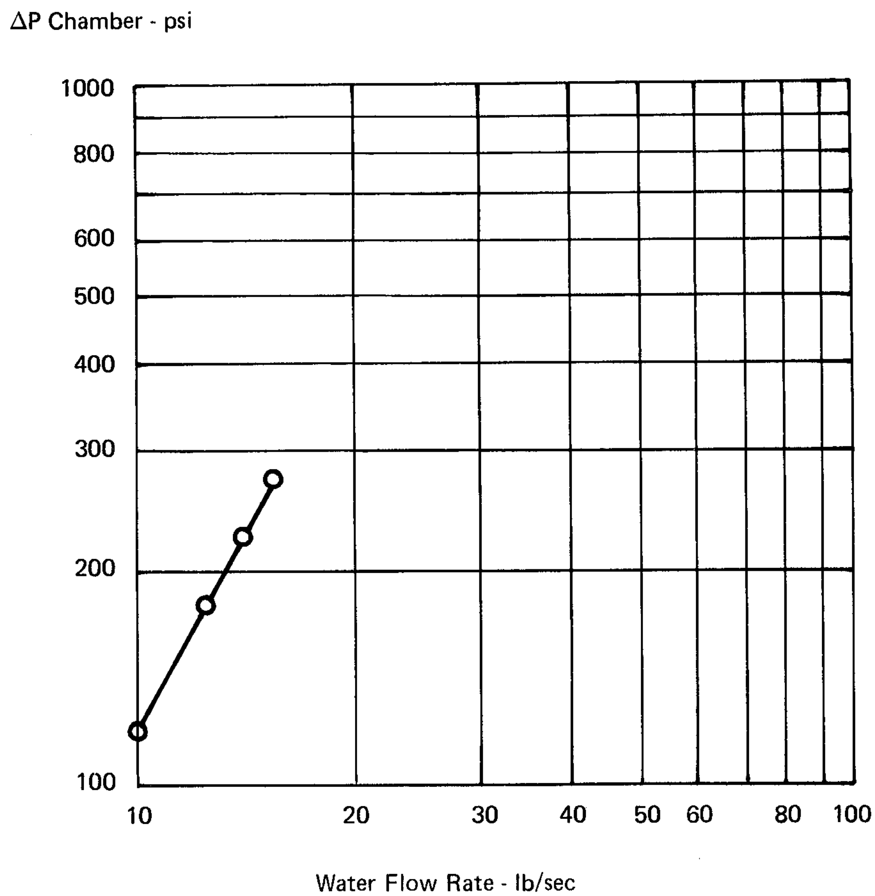

Figure 46. Thrust Chamber Flow Calibration

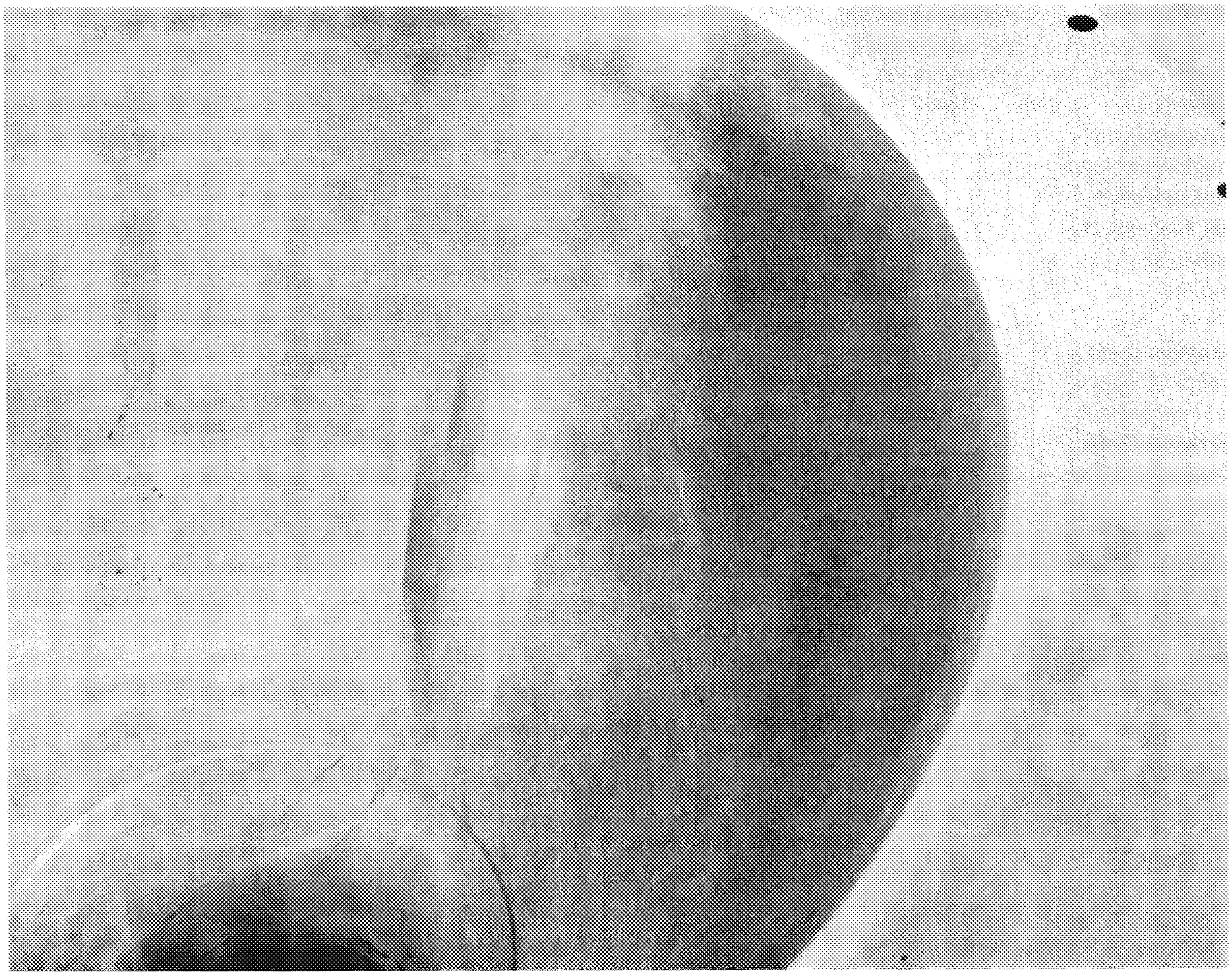

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Figure 47. Top View Inner Liner Bulge

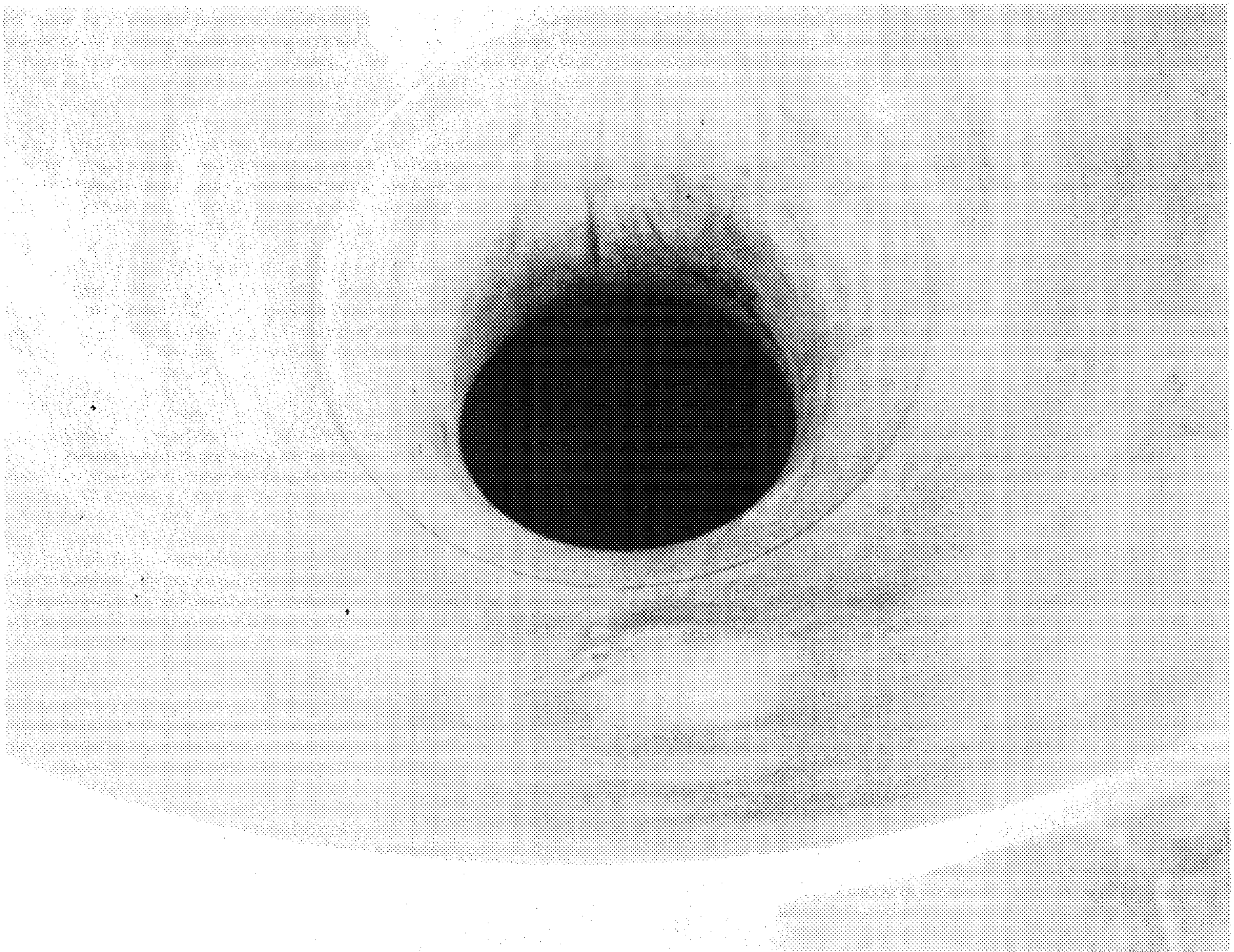

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Figure 48. End View Inner Liner Bulge

The chamber was then assembled in the same fixture used for drilling the instrumentation holes and was mounted in a vertical mill. The section of the shell in the bulge area was removed by cutting through the shell with an end mill around the perimeter of the bulge as identified with the punch marks. Figures 49 and 50 show the chamber with the shell section removed exposing the inner liner with the fluid flow channels intact. The section of the shell removed was approximately 1 inch wide and 4 inches long and is shown in Figure 51.

The chamber was removed from the milling machine and fixture and the liner was returned to its original contour with the assistance of C-clamps and contour blocks especially made to match the contour in the bulge area.

The repaired cavity was filled with a cast-in-place fiberglass and epoxy resin plug. Barriers were positioned in the channels at the edge of the cavity to avoid resin flow into the channels, thereby preventing accidental removal of the plug.

With completion of the repair as described above the chamber was again submitted to hydraulic pressure test. At 550 psi, a second bulge occurred in the inner liner in an area approximately 170 degrees from the original bulge. Occurance of the second bulge led to a decision not to repair the liner.

No conclusive reasons for bond separation evolved from the investigation of material trepanned from the bulged region. There exist possible causes which are discussed below.

There are two distinct electroform bond types present in the chamber. The first type, electroformed nickel to TD Nickel, occurs once at the liner-shell interface. The second type, electroformed nickel to electroformed nickel, occurs frequently within the outside shell and represents plating restarts after periodic inspections during electroforming. The latter bond type represents no processing problem because electroformed nickel (and wrought nickel) can be activated for electroform bonding by acid cleaning with anodic or anodic-cathodic current.

Activation of wrought TD Nickel for electroform bonding is more complicated. When anodic acid cleaning is applied to a TD Nickel surface, nickel is dissolved and thorium oxide dispersion is released. Since thorium oxide is chemically inert to most acid cleaning solutions, it remains on the activated nickel surface and is visible as a pale blue film when present in large quantity. Mechanical scrubbing removes the bulk of this film including visual signs of its presence. However, the thorium oxide dispersion particles have an average diameter of 0.1 microns or less. Trace amounts of dispersion remaining on the TD Nickel liner lands could possibly contribute to a bond with less than full strength.

A second possible cause for the failure is stress mode. Successful laboratory samples made in the development stage were designed so that loading was essentially uniform tension across the bond. The thrust chamber was constructed so that a "peeling" force could be expected in the failure region; the electroformed bond might be less resistant to this type of load.

A third possible cause is residual stress resulting from the manifold welding. This residual stress could have been superimposed on the pressure test stress, making actual stresses much higher than expected.

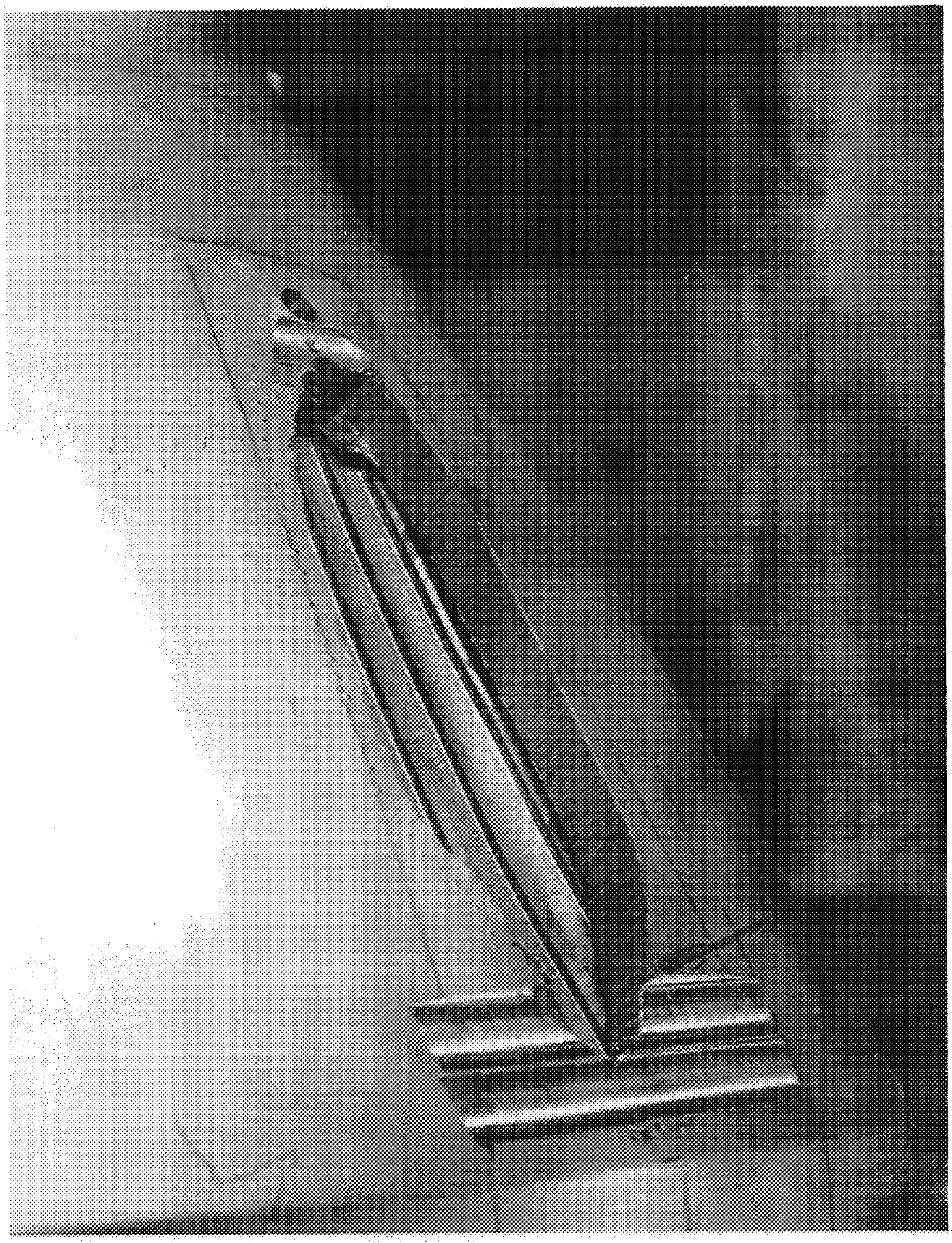

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Figure 49. Chamber Shell Removed from Liner Bulge

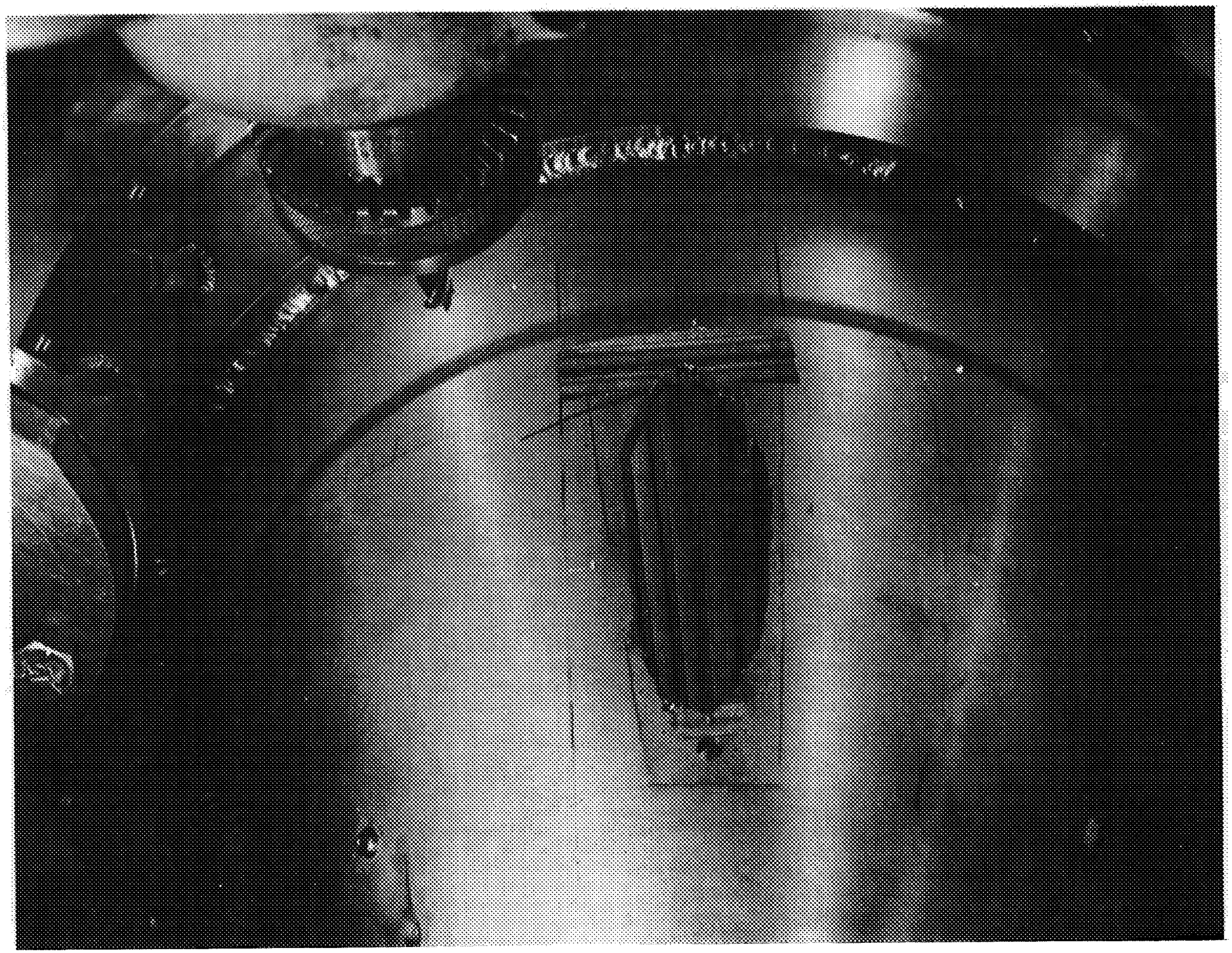

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Figure 50. Fluid Flow Channels in Bulged Area

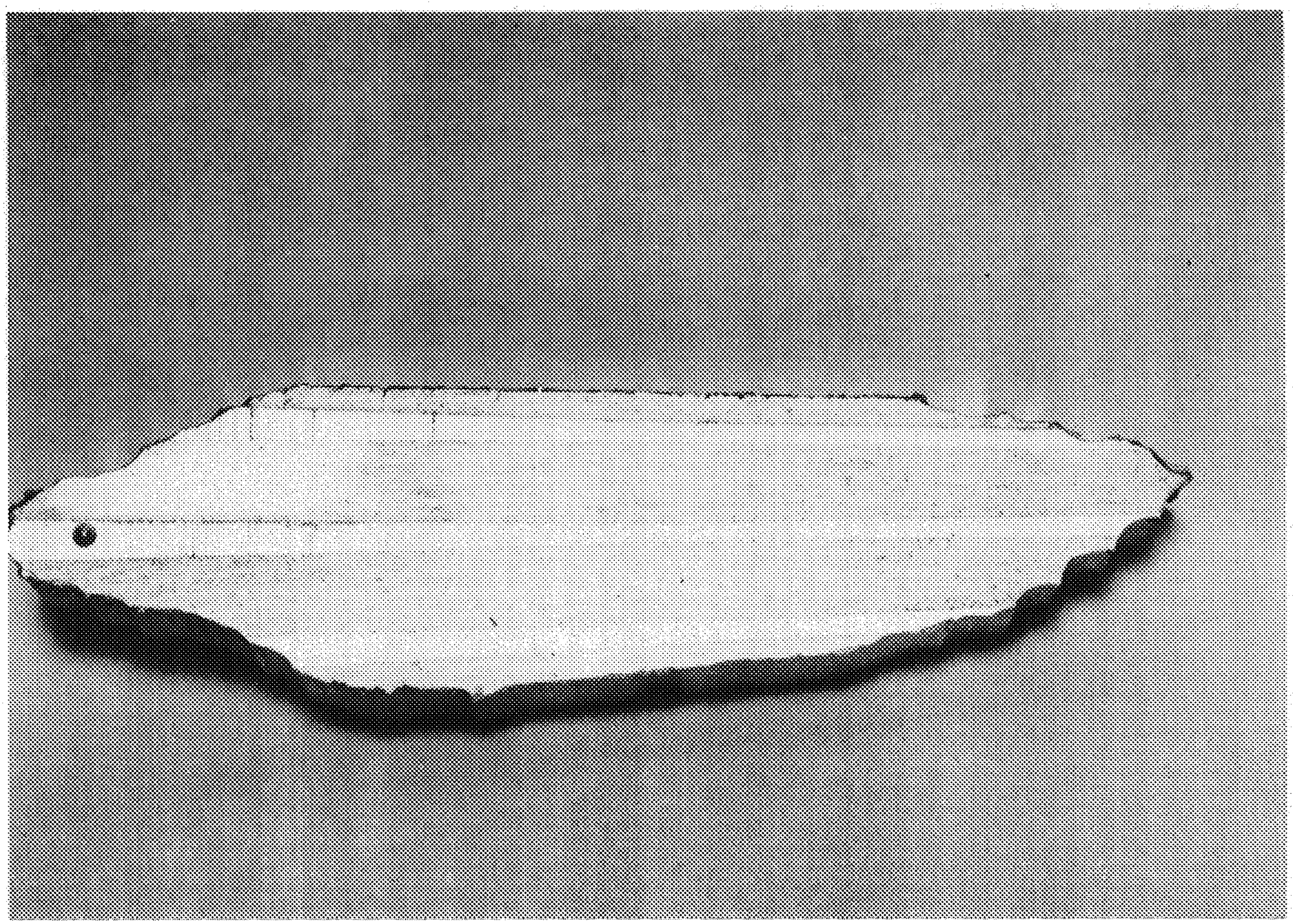

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Figure 51. Shell Section Removed Showing Shell to Channel Land Interfaces

V. CONCLUSIONS AND RECOMMENDATIONS

A review of the manufacturing technologies developed and employed in this program show that they are practical, reproducible, and controllable, with the exception of bond strength between electroformed nickel and substrate TD Nickel.

Spin forming of TD Nickel is readily achievable providing proper staging tools are developed. More staging tools are required than for other materials because of lower ductility. Interstage surface conditioning is necessary to retain satisfactory surface condition. Heating to approximately 800°F is an aid to spin forming. Machining characteristics of TD Nickel are very similar to those of pure nickel. Similar cutting feeds, speeds, and tools can be used.

There was no observable difference between TD Nickel and other nickel base alloys in electric discharge machining characteristics. Existing practices with regard to electrodes, electrode material, dielectrics, etc., can be used. However, in EDM'ing hardware of the type fabricated under this contract, it is extremely important to dimensionally coordinate all tools, fixtures, and parts. The electric discharge machining process is ideally suited to generating cavities of unusual geometries, but this advantage makes a more thorough tool coordination mandatory.

Welding of TD Nickel can be accomplished by the automatic TIG process. Hastelloy X was found to be the most suitable filler material in this program. The proper combination of weld speed, amperage, filler wire input, etc., must be determined so that the minimum amount of base metal is dissolved in the weld. This will prevent thoria agglomeration, the primary cause of weld embrittlement in this material.

Work under this contract indicates that reliable bond strengths cannot yet be obtained between electroformed nickel and TD Nickel. Preliminary electroforming development and testing indicated that bond strengths would meet design requirements in the thrust chamber; this was not the case, as shown by the pressure test failure which fractured the bond between the electroformed shell and the TD Nickel liner. More experimental work is required on the effects of cleaning and electroforming parameters on bond strength and the nature of the bond between electroformed nickel and TD Nickel.

In addition, nondestructive testing methods should be developed which will reliably determine the quality of electroformed bonds. Such NDT methods must be capable of indicating degree of bond quality.

APPENDIX A

THERMAL ANALYSIS OF MODEL 8489 THRUST CHAMBER OPERATING AT "OFF DESIGN" CONDITIONS

Additional heat transfer analyses were conducted to determine the effect of various "off design" operating conditions on thrust chamber thermal characteristics.

The operating conditions shown in Table II included, the design rated (Case 0), increased fuel (coolant) flow rate (Case No. 1 and 2), reduced mixture ratio (Case No. 3), and reduced mixture ratio with reduced chamber pressure (Case No. 4).

The same analysis programs as used for the original design described in Report NASA CR-72320 were used for this effort.

The thrust chamber wall was divided into a nodal network as shown in Figures 52 and 53.

Analysis results are presented in Tables III through VII. Coolant temperature and pressure as well as wall temperature results are tabulated for each of the fluid and metal nodes. It can be seen from inspection of the analysis results that the maximum gas side wall temperature is reduced by operating at any of the off-design conditions. As expected, reduced mixture ratio and reduced mixture ratio combined with reduced chamber pressure show greater influence on wall temperature than does increased coolant flow rate.

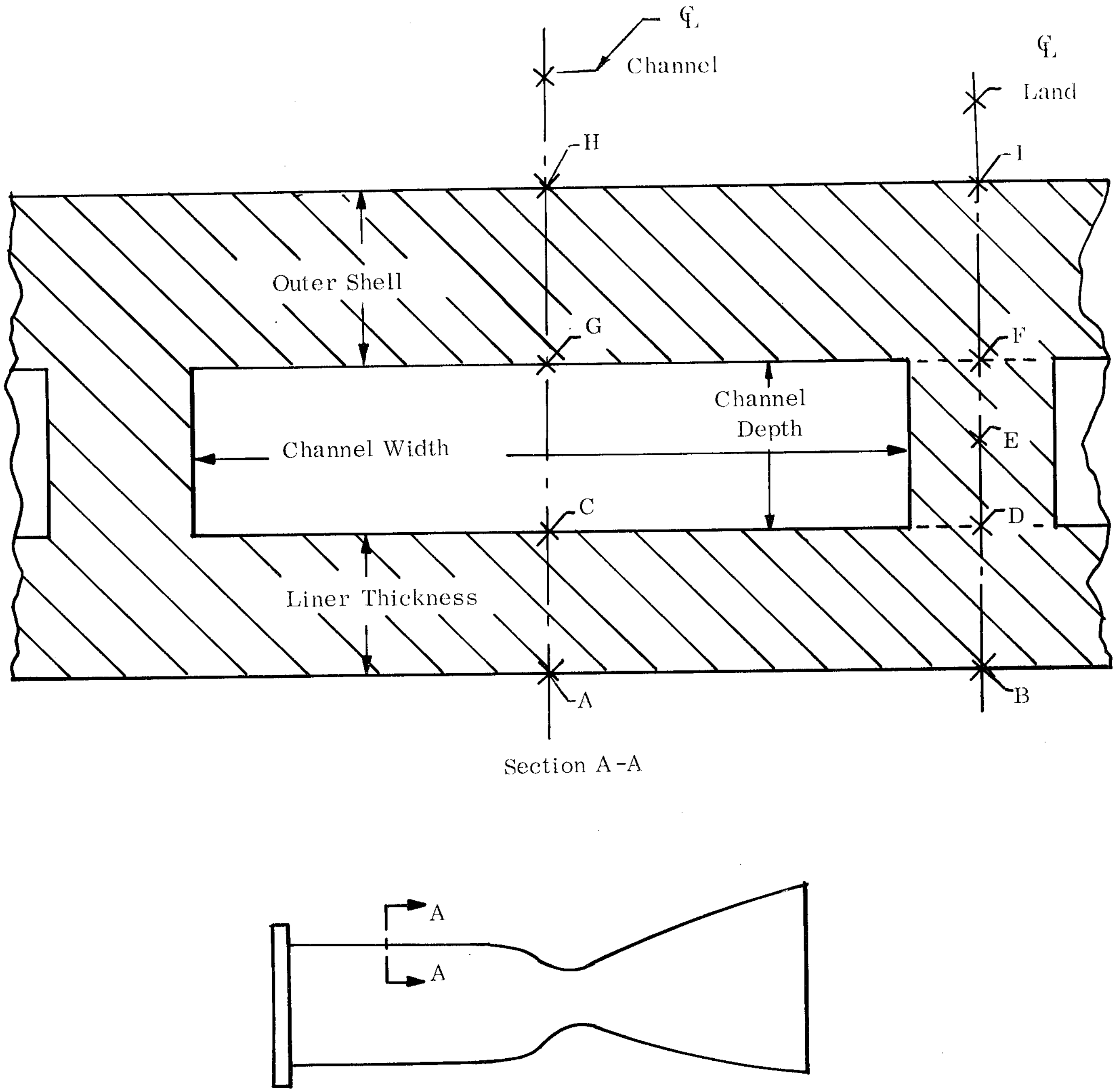

Figure 52. Alphabetical Nodal Distribution about Any Flow Channel

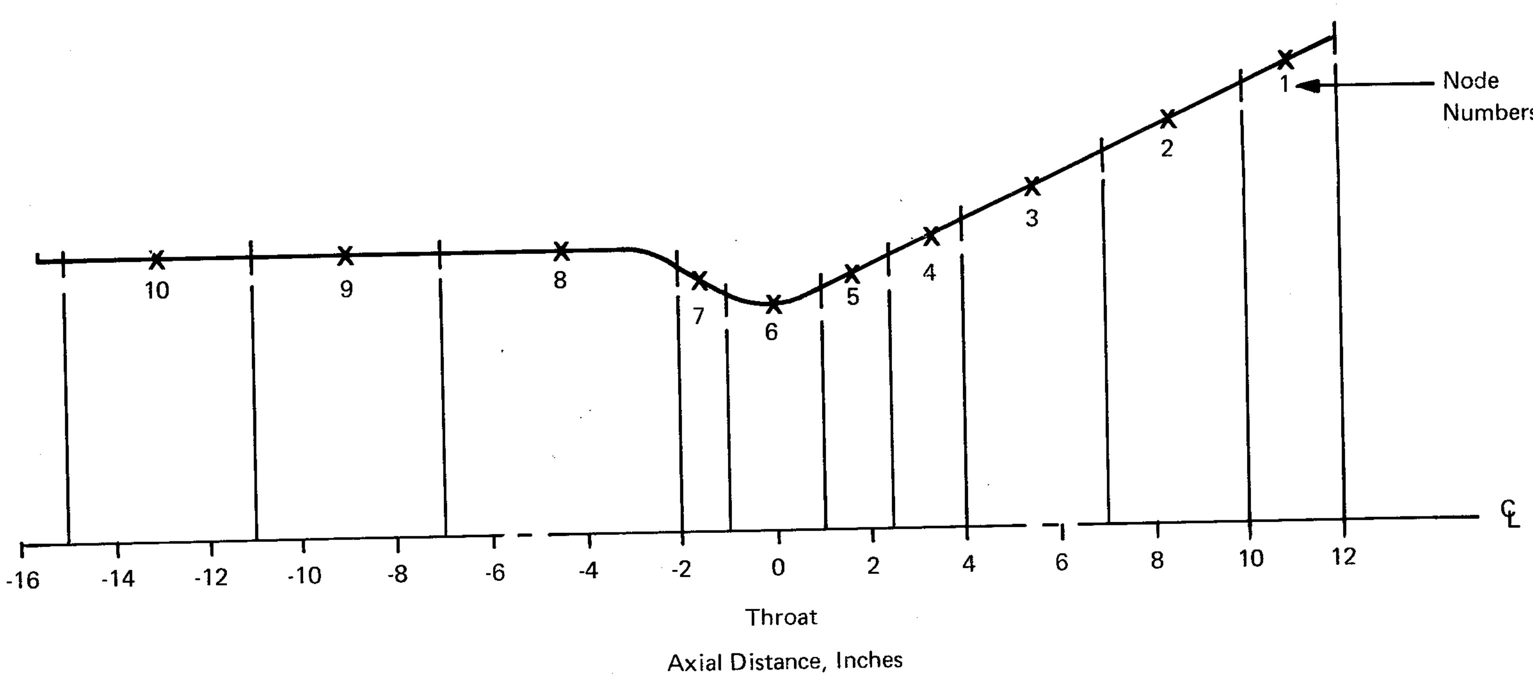

Figure 53. Axial Node Legend

TABLE II

OPERATING CONDITIONS

Case No.	Chamber Pressure (psia)	Mixture Ratio O/F	Fuel Flow Rate	Desired Coolant Exit Pressure (psia)
0	400	12	100%	550
1	400	12	125%	550
2	400	12	150%	550
3	400	8	100% = 2.05 lb/sec	550
4	300	8	100% = 1.54 lb/sec	400

TABLE III

CASE O TD NICKEL (WALLS MODIFIED 0.030 INCH CONSTANT THICKNESS WALL) THERMAL ANALYSIS SUMMARY 90 CHANNEL - NICKEL COVER

Pc = 400 psia
MR = 12
W Hydrogen = 1.442 lb/sec

Inlet Pressure = 830 psia
Inlet Temperature = 60°R

Fluid Node	Node Length (in)	Outlet Temp °F	Outlet Pressure Psia	Corresponding Wall Temperature °F								
				A	B	C	D	E	F	G	H	I
1	2.20	-376.8	829.1	144	226	105	188	151	126	-196	-173	97
2	3.30	-333.8	827.1	260	243	201	184	128	90	-201	-178	49
3	3.30	-271.2	821.6	725	344	597	219	90	14	-200	-182	- 55
4	1.65	-235.0	812.8	1092	772	837	489	232	118	-120	- 82	27
5	1.65	-191.4	774.5	1591	1459	1091	889	382	215	- 48	26	112
6	2.20	-125.6	685.1	1779	1811	1040	1096	519	313	6	115	196
7	1.10	- 76.1	740.8	1872	1927	1136	1236	730	495	55	174	311
8	5.00	113.8	688.9	2178	Max2068	1667	1494	761	531	154	265	323
9	4.00	266.8	638.5	2152	2107	1626	1556	877	666	299	409	467
10	4.00	413.3	570.6	2142	2147	1609	1615	980	779	430	543	599

Est. required inlet pressure = 810 psia to exit at 550 psia

ΔP = 260 psia

100% Hydrogen Flow Rate

TABLE IV

CASE 1 TD NICKEL (WALLS MODIFIED) THERMAL ANALYSIS SUMMARY

90 CHANNEL - NICKEL COVER

Pc = 400 psia
MR = 12
W Hydrogen = 1.8025 lb/sec

Inlet Pressure = 900 psia
Inlet Temperature = 60°R

Fluid Node	Node Length (in)	Outlet Temp °F	Outlet Pressure Psia	Corresponding Wall Temperature °F								
				A	B	C	D	E	F	G	H	I
1	2.20	-379.8	898.8	54	150	18	114	80	56	-245	-223	31
2	3.30	-347.2	896.7	160	168	105	113	61	27	-242	-220	-11
3	3.30	-297.2	890.0	549	242	426	129	12	-55	-244	-227	-116
4	1.65	-266.5	879.2	925	650	678	377	147	45	-172	-137	-37
5	1.65	-230.1	831.5	1478	1359	954	782	290	139	-107	- 36	44
6	2.20	-177.0	718.1	1656	1702	879	962	406	223	- 60	42	117
7	1.10	-135.1	790.8	1735	1819	955	1096	611	383	- 18	92	220
8	5.00	17.1	729.2	1975	1906	1400	1288	595	381	54	153	205
9	4.00	141.7	667.8	1997	1980	1423	1396	712	511	185	283	334
10	4.00	261.7	580.7	1992	Max 2025	1410	1463	806	618	299	396	446

Est. required inlet pressure = 884 psia to exit at 550 psia

ΔP = 334 psia

125% Hydrogen Flow Rate

TABLE V

CASE 2 TD NICKEL (WALLS MODIFIED) THERMAL ANALYSIS SUMMARY

90 CHANNEL - NICKEL COVER

Pc = 400 psia
MR = 12
W Hydrogen = 2.163 lb/sec

Inlet Pressure = 950 psia
Inlet Temperature = 60°R

Fluid Node	Node Length (in.)	Outlet Temp °F	Outlet Pressure Psia	Corresponding Wall Temperature °F A	B	C	D	E	F	G	H	I
1	2.20	-382.2	948.4	-5	96	-40	62	29	7	-279	-258	-16
2	3.30	-354.7	946.1	93	117	41	65	15	-16	-270	-250	-52
3	3.30	-314.5	938.2	418	170	309	64	-43	-103	-272	-258	-158
4	1.65	-288.2	925.3	777	537	535	292	80	-12	-210	-178	-87
5	1.65	-256.8	867.3	1368	1253	823	692	228	86	-147	-80	- 3
6	2.20	-212.5	723.1	1579	1634	778	875	332	162	-105	- 8	62
7	1.10	-175.4	817.0	1627	1728	813	982	514	307	- 72	34	154
8	5.00	- 49.4	743.3	1832	1789	1207	1139	477	287	- 15	78	126
9	4.00	52.9	669.2	1862	1864	1241	1244	589	393	96	187	234
10	4.00	148.9	553.8	1866	Max 1912	1242	1317	672	487	195	284	330

ΔP = 396 psia

150% Hydrogen Flow Rate

TABLE VI

CASE 3 TD NICKEL (WALLS MODIFIED) THERMAL ANALYSIS SUMMARY

90 CHANNEL - NICKEL COVER

Pc = 400 psia
MR = 8
W Hydrogen = 2.05 lb/sec

Inlet Pressure = 870 psia
Inlet Temperature = 60°R

Fluid Node	Node Length (in.)	Outlet Temp °F	Outlet Pressure Psia	Corresponding Wall Temperature °F A	B	C	D	E	F	G	H	I
1	2.20	-387.4	868.6	-152	-97	-172	-116	-135	-149	-328	-315	-163
2	3.30	-367.1	867.1	- 46	-39	- 79	- 73	-105	-127	-305	-290	-151
3	3.30	-338.2	861.2	152	4	88	- 65	-137	-180	-303	-292	-219
4	1.65	-318.8	851.3	322	187	199	58	- 68	-128	-259	-237	-176
5	1.65	-294.3	807.1	686	582	383	277	34	-54	-209	-163	-112
6	2.20	-249.9	689.5	1371	1380	702	713	252	106	-134	- 46	17
7	1.10	-217.0	760.6	1402	1444	719	772	380	216	-110	- 16	87
8	5.00	-103.7	698.9	1568	1482	1020	892	344	193	- 66	15	56
9	4.00	- 12.4	639.3	1561	1533	1005	964	430	279	29	107	147
10	4.00	76.7	552.9	1591	Max 1602	1037	1053	525	369	120	198	237

ΔP = 317 psia

100% Hydrogen Flow Rate

TABLE VII

CASE 4 TD NICKEL (WALLS MODIFIED) THERMAL ANALYSIS SUMMARY

90 CHANNEL - NICKEL COVER

Pc = 300 psia
MR = 8
W Hydrogen = 1.54 lb/sec

Inlet Pressure = 650 psia
Inlet Temperature = 60°R

Fluid Node	Node Length (in.)	Outlet Temp °F	Outlet Pressure Psia	Corresponding Wall Temperature °F								
				A	B	C	D	E	F	G	H	I
1	2.20	-388.7	649.3	-164	-135	-180	-150	-164	-175	-324	-312	-187
2	3.30	-371.2	648.0	- 65	- 77	- 91	-103	-129	-147	-298	-285	-167
3	3.30	-339.8	643.3	116	- 26	67	- 81	-142	-180	-293	-283	-216
4	1.65	-318.4	635.7	266	135	174	33	- 72	-125	-244	-224	-169
5	1.65	-291.4	601.1	574	456	352	230	29	- 48	-188	-147	-100
6	2.20	-243.1	504.4	1194	1144	687	625	249	119	-101	- 20	38
7	1.10	-207.3	560.3	1228	1204	706	679	351	210	- 82	2	96
8	5.00	- 84.8	508.0	1424	1285	984	801	340	205	- 35	41	79
9	4.00	13.3	455.3	1441	1361	997	882	435	300	67	140	177
10	4.00	105.0	373.3	1466 Max	1427	1022	966	527	389	161	233	269

Est. Inlet Pressure for 400 Outlet Pressure is 665 psia i.e. 100% Hydrogen Flow Rate

ΔP = 265 psia

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