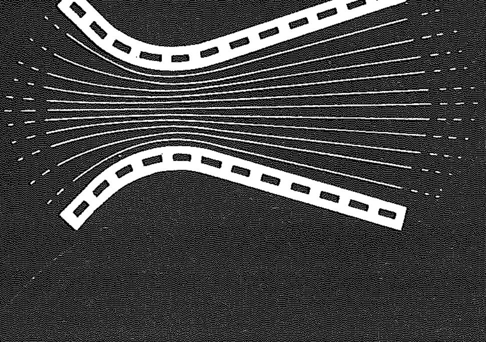
DEVELOPMENT OF ADVANCED FABRICATION TECHNIQUES FOR REGENERATIVELY COOLED THRUST CHAMBERS BY THE ELECTROFORMING PROCESS

prepared for
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
NASA Lewis Research Center
Contract NAS3-10304
John Kazaroff, Project Manager



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FINAL REPORT

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DATE: 1 October 1969

by

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ABSTRACT

A program was conducted to develop and evaluate advanced electrolytic deposition techniques (electroforming) for the construction of regeneratively cooled thrust chambers for large rocket engine requirements. A variety of material combinations and configurations were investigated. During the initial phase of the program processes were developed for the fabrication of regenerative type chambers containing Hastelloy X, Inconel 718, TD nickel, sprayed zirconia and sprayed zirconia-nichrome inner walls backed by electroformed nickel ribs and outer shells. In addition procedures were developed for fabricating inner walls from wire or ribbon that is wrapped on a mandrel and supported by the electroformed rib and outer jacket. All of the above configurations were demonstrated to be feasible. In addition the ability to reinforce the outer electroformed shell with intermediate wire windings was also demonstrated. The two most promising configurations; Hastelloy X and graded coating inner walls were selected for further evaluation.

Two spool pieces, for use with hydrogen-oxygen propellants at a chamber pressure of 500 psia and

30,000 lbf thrust, were designed and fabricated. One unit contained a Hastelloy X inner wall, while the second unit contained the graded zirconia-nichrome coating. Rocket firings were conducted at NASA Lewis Research Center with each of the spool pieces. Both units met all design requirements.

In order to further demonstrate the applicability of the process to rocket engine fabrication, contoured thrust chamber configurations with bifurcated ribs were designed and fabricated. No provisions were made for hot firing evaluation of these units. The graded coating chamber segments were completed and passed hydrostatic and helium leak tests. The Hastelloy X lined segment was not completed during the term of the contract. However, sufficient work was done to demonstrate the feasibility of the process.

The results of this program have definitively demonstrated the ability and advantages of electroforming regeneratively cooled thrust chambers containing high strength and/or high temperature service inner shells.

I. INTRODUCTION

The work reported herein constitutes the results of twenty-seven months' effort performed under Contract NAS 3-10304 for the NASA Lewis Research Center. Mr. John M. Kazaroff is the NASA Project Manager.

The objective of the program is to develop and evaluate advanced electrolytic deposition techniques (electroforming) for the construction of regeneratively cooled thrust chambers for large rocket engine requirements. Regeneratively cooled thrust chambers are usually fabricated from a large number of tapered, contoured tubes. This method requires the manufacture of thin walled tubing from the desired metal, tapering and contouring the tubes, positioning the tubes on a mandrel and ultimately furnace brazing the unit together. This fabrication method involves many tedious, expensive and time-consuming operations including hand repair of leaks in the braze. To the rocket designer, the method of fabrication often results in compromising the system performance due to the fact that the cross sectional area for coolant flow is often dictated by the nozzle contraction and expansion ratio and tube tapering limitations. Since a large amount of tooling is required (tube drawing, swaging or tapering, contouring and brazing mandrels) modifications to a thrust chamber contour are exceedingly expensive.

A second method of fabricating regeneratively cooled engines involves the machining of an inner liner with grooves or ribs on the outer diameter. An external shell in two or more sections is placed over the inner liner and welded or brazed in place. This method has all of the disadvantages attendant with high temperature joining processes.

The advent of high energy propellants operating at high chamber pressures results in combustion temperatures and heat fluxes of such a magnitude that pure regenerative cooling with metallic chambers is often unsatisfactory. The use of a ceramic or refractory liner to serve as a thermal and/or oxidation barrier for the inner wall is a common design feature. This, however, is not without its problems and drawbacks. Spraying a refractory coating on the I.D. is generally accomplished after the metallic thrust chamber has been virtually completed. I.D. spraying very often poses a problem in terms of access of the spray equipment to the throat regions. In addition, control of thickness and finish is difficult. Adhesion of the sprayed coating to the metallic substrate is often suspect.

A fabrication technique that has the ability to eliminate all of the disadvantages cited above is electroforming. The basic techniques and process specifications required to electroform entire nickel or entire copper rocket motor components containing integral cooling passage systems have been previously developed by Camin Laboratories, Inc., (Refs. 1,2,3). The fabrication procedure consists of electrolytically depositing a metal inner liner on a male mandrel. The deposit is machined, if necessary, to obtain the required wall thickness profile. The metal is then coated with a filler material to a thickness equal to the desired coolant passage height. Grooves are then cut in the filler material to expose the initial metal deposit. The work piece is returned to the electroforming bath to deposit the ribs and outer shell. The filler material is then removed creating the cooling passage. The resulting unit is of integral construction, devoid of any high temperature joining operations. The intermittent deposition does not result in laminations. Exhaustive tests have proven that when proper procedures are followed the interface bond strengths are as strong as the parent metals.

The ribs that connect the inner and outer shell determine the coolant passage configuration. These ribs in turn are formed as a function of the O.D. machining and groove cutting operation on the filler material. It is therefore possible to fabricate a thrust chamber containing both longitudinal and helical ribs. It is relatively simple to vary the rib height and hence the coolant passage height. It is standard procedure on high contraction ratio units to vary the number of ribs with axial location in order to achieve optimum coolant velocity profiles and coolant contact surface area.

Coolant passage configuration in an electroformed thrust chamber is quite independent of fabrication procedural limitations and can generally be dictated solely from heat transfer and stress considerations. Since the only major item of tooling is the mandrel upon which the inner wall is deposited, design modifications are relatively inexpensive to accommodate.

As a result of the above cited facts, the present program was initiated to further exploit the inherent advantages of electroforming. In particular, the program objectives are to develop composite (dissimilar materials) and reinforced electroformed thrust chambers in the material combinations oulined in Table I below.

TABLE I - MATERIAL COMBINATIONS

	ELECTROFORMED OUTER SHELL AND RIBS	ELECTROFORMED INNER LINER	DISSIMILAR METAL INNER LINER	COATINGS
1.	Nickel	-	Hastelloy X	-
2.	Nickel	-	Inconel 718	-
3.	Nickel	-	TD Nickel	-
4.	Nickel	Nickel	-	ZrO_2
5.	Nickel	Nickel	-	Gradated
6.	Nickel	Nickel Reinforced	-	-
7.	Nickel Reinforced	-	-	-

The first three combinations represent possible rocket motor configurations containing a high strength-high temperature service inner wall backed by an integral cooling passage electroformed rib and shell structure. The next two combinations represent complete nickel EF (electroformed) units containing an inner thermal or oxidation barrier. However, the coating is not to be applied to the finished unit in the conventional manner, but rather the coating is to be the basic form upon which the nickel is deposited. The sixth configuration is an attempt to increase the structural properties of an EF nickel chamber by including a high strength wire wrapping in the electroformed inner liner. The last combination, a wire wrap reinforcement of the electroformed outer shell, is applicable to any of the previous six configurations.

The overall program objective is to develop electroforming techniques suitable for fabricating regeneratively cooled rocket motor thrust chambers from the material configurations tabulated above. The development is to be accomplished by investigating the deposition of nickel on dissimilar metallic and non-metallic (coatings) substrates; fabrication and testing of ribbed structure samples; and design, fabrication and testing of small scale hardware simulating regeneratively cooled thrust chambers. The program is to include the following task areas:

Task I

A. Preliminary Laboratory Investigation
B. Test Sample Fabrication and Evaluation
C. Spool Piece Design

Task II

A. Fabrication, Test, and Delivery of Spool Pieces.

Task III

A. Design, Fabrication and Test of Chamber Segments.

The present report details the work performed under Tasks I, II and III during the period 1 July 1967 to 30 September 1969. Included is a discussion of the methods used to achieve a bond between the dissimilar metals and EF nickel; methods of mandrel removal from plasma spray coatings; tensile and photomicrographic testing of dissimilar material interfaces; methods of wire wrap reinforcement of inner and outer shells, the design, fabrication and testing of cylindrical ribbed specimens, (Part B), and the design, fabrication and evaluation of chamber segments and spool pieces.

II. DISSIMILAR METAL-ELECTROFORMED NICKEL ADHESION

The objective of this phase of the investigation is to develop process specifications for depositing adherent nickel on Inconel 718, Hastelloy X and TD Nickel. Quantitative examination of the interface bond strengths is also required. Results of this phase of the program would be applicable to the design and construction of thrust chambers containing inner liners of the latter materials supported by an adherent integral electroformed nickel cooling passage system.

The nickel bath used by Camin Laboratories, Inc., for production of thrust chambers has the following composition:

Nickel Sulfamate	45 oz/gal
Nickel Metal Content	10.2 oz/gal
Nickel Chloride	0.8 to 2.0 oz/gal
Boric Acid	4.0 - 5.0 oz/gal

The range of operating conditions for this bath formulation is as follows:

Temperature	100-140 degrees F

pH range	3.5 - 5.0 electrometric
Density (Baume)	29 to 31 degrees
Tank Voltage	6 to 9 volts

In order to obtain a strong bond between a deposited metal and any substrate, activation procedures must be developed. These generally consist of a series of mechanical, chemical and electrochemical cleaning cycles, which are dependent upon the chemical composition of the substrate and the nature of the deposited metal. Development of the procedures is generally a trial and error type process, that begins with procedures previously developed for similar type material combinations. Therefore, prior to fabricating specimens suitable for quantitative determination of interface bond strengths, a qualitative examination is made by using an arbor press. A cylindrical mandrel with a slight taper is fabricated from one of the dissimilar metals. The material is processed to obtain adhesion and a nickel shell is deposited around the mandrel. The press is then used in an attempt to extract the mandrel from the shell. If good adhesion has not been obtained, the mandrel is readily extracted from the shell. The taper on the mandrel aids in extraction and prevents a mechanical type bond due to an undercut on the mandrel surface. If adhesion has been obtained, the mandrel and shell cannot be separated.

The procedures found to be satisfactory for obtaining adherent nickel deposits on the candidate liner materials are given below:

A. Inconel 718

1. Abrasive clean mandrel
2. Water rinse
3. Treat the specimen anodically in Enthone 808, (Enthone Inc. New Haven, Conn.) 80 asf, 2 minutes, 180 degrees F.
4. Water rinse
5. Clean with Metex 629 (McDermid Co. Waterbury, Conn.) Use 1 lb./gal. of water at room temperature using lead anode.

    a. Specimen anodic 40 seconds - 4 volts
    b. Specimen cathodic 20 seconds - 4 volts
    c. Specimen anodic 40 seconds - 4 volts
    d. Specimen cathodic 20 seconds - 4 volts

6. Water rinse

7. Wood's Nickel Strike

Nickel chloride	30 oz/gal
HCL (30%)	10 oz/gal

   Treat specimen for three minutes at 50 asf at room temperature.

8. Insert specimen into the electroforming bath-making electrical contact prior to entry into bath.

B. Hastelloy X

1. Abrasive clean mandrel.
2. Water rinse
3. Treat the specimen anodically in Enthone 808 (Enthone Inc. New Haven, Conn.) at 80 asf for 2 minutes at 180 degrees F.
4. Water rinse
5. Dip in 10% HCL
6. Water rinse
7. Treat anodically in 50% sulfuric acid at 200 asf for 1 minute at room temperature. Use lead cathodes.
8. Water rinse
9. Wood's nickel strike at 50 asf for 3 minutes.

10. Insert into electroforming bath, making electrical contact prior to entry into bath.

C. TD Nickel

1. Abrasive clean mandrel
2. Water rinse
3. Treat the specimen anodically in Enthone 808 (Enthone Inc., New Haven, Conn.) at 80 asf for two minutes at 180 degrees F.
4. Water rinse
5. Acid pickle - 15 minutes
6. Water rinse
7. Clean with Metex 629 (McDermid Co. Waterbury, Conn.). Use 1 lb./gal. of water at room temperature, using lead anode.
    a. Specimen anodic - 40 seconds - 4 volts
    b. Specimen cathodic- 20 seconds - 4 volts
    c. Specimen anodic - 40 seconds - 4 volts
    d. Specimen cathodic- 20 seconds - 4 volts
8. Water rinse
9. Wood's nickel strike - 50 asf - 3 minutes
10. Insert into electroforming bath.

In order to quantitatively determine the bond strength between the dissimilar metals and electroformed nickel, a test specimen as shown in Figure 1 was designed. The dissimilar metal, which serves as a mandrel for nickel deposition, is machined from a rod. The entire part is masked except for the end face (.250"diameter) upon which nickel is to be electrodeformed. The electroformed nickel disk is then deposited with the aid of a lucite shield as shown in the insert of Figure 1. The results of the test program are shown in Table II below.

TABLE II

BOND STRENGTHS EF NICKEL-DISSIMILAR METALS

	ROOM TEMPERATURE	1000°F
INCONEL 718	95-110,000 psi	45,000 psi
HASTELLOY X	93-108,000 psi	53,000 psi
TD NICKEL	82-104,000 psi	29,000 psi

The lower values observed at room temperature were obtained with the tensile specimen as described above. In order to accommodate a heating unit for strength determinations at 1000°F the shank of the mandrel and hence interface area was reduced to .125" diameter. A series of room temperature test specimens were fabricated in this new configuration in order to determine if any size effect was present. The higher strengths shown at room temperature resulted. Two possibilities exist as to the cause of the variation. The first is the general observation that tensile strengths tend to increase as sample size decreases. The second concerns itself with the mode of failure at the interface. If the failure is not due to pure tension at the interface but rather is in part or whole due to excessive shear stress in the nickel disk then the larger diameter specimens would indicate lower adhesion strengths. Examination of the fractured specimens indicated that the bottom surface of the mandrel often retained some adherent nickel, but no correlation was found. However, it is apparent that the interface adhesion strength is at least equal to the minimum figures cited above.

Photomicrographs of the dissimilar metal - EF nickel interface were made. They are shown in figures 2,3,4.

III. SPRAYED COATINGS

The application of sprayed coatings to metallic thrust chambers to provide thermal or oxidation barriers poses many fabrication problems as discussed in the introduction of this report. However, if electroforming is to be used as the basic fabrication technique, several interesting advantages accrue in the area of sprayed coatings. It is suggested that the mandrel upon which electrodeposition is to occur first be sprayed with the required coating. Herein lie the primary advantages. Plasma or flame spraying is performed on the O.D. of a surface rather than the I.D., thus removing any spray equipment size limitations. Uniform or variable coating thicknesses can be achieved by grinding or similar processes. If inspection of the coating uncovers any flaws or suspect areas, the entire coating can be readily removed and replaced.

After a satisfactory sprayed coating is obtained a nickel integral cooling passage system can be electroformed on top of the coating. Depending on the exact coating selected, it is possible to obtain either or both a mechanical type bond (due to the roughness of the outer layers of coating) or an electrochemical type bond. Either of the above described bonds should result in better adhesion than that obtained by spraying on the inside of a chamber.

Two areas of investigation were required for the successful application of the above described concept. The first concerned itself with process specifications for electrodeposition on coatings. If the coating is conductive it is possible to deposit metal directly and obtain at least a mechanical type bond. However, zirconia was chosen as the primary coating to be utilized in this study. Zirconia is a poor electrical conductor, therefore requiring that procedures be developed for rendering the zirconia surface conductive. The second area of concern was methods of mandrel removal from the spray coating. When a nickel thrust chamber is electroformed directly on a mandrel a parting medium is utilized so that the mandrel can be readily extracted and reused. One goal of the present program is to develop methods to remove the mandrel from the spray coating so that it too can be readily extracted and reused, thereby keeping costs to a minimum.

A standard procedure for rendering the surface of a non-conductor conductive for the purpose of subsequent electrodeposition is to paint or spray the plating areas with a material such as silver paint. This, however, allows for little or no adhesion between the substrate and metallic deposit. Adhesion can be greatly improved by "firing" the silver into the non-conductive coating surface. This procedure was discarded since the impregnated silver might destroy the insulative qualities of the coating. It would be most desirable if the medium that is used to render the coating conductive had thermal properties (conductivity, coefficient of expansion) similar to electroformed nickel. This would of course keep thermal stresses to a minimum. As a result, attention was focused on the use of electroless nickel or plasma sprayed nickel as methods of rendering the zirconia coating conductive.

In the electroless nickel process the metal is deposited by chemical reduction without electric current. The resulting deposit is virtually pore free. One advantage of this process is that the deposited thickness is very evenly distributed over the entire surface of complex parts. Thus, the rough grainy surface of a plasma sprayed coating provides an excellent surface upon which to develop at least a mechanical type bond with the electroless nickel. Prior to immersion in the electroless nickel plating solution, the coating is first sensitized and activated by immersion in a stannous chloride solution (one minute) followed by immersion in a palladium chloride solution (30 seconds). The electroless nickel plating time is 20 minutes which results in a metal thickness of approximately .0002 inch based upon a nominal deposition rate of 0.0005 inch per hour. During the investigation it was found that a porosity free bond between the electroless nickel and zirconia required mechanical agitation of the solution coupled with rotary motion of the mandrel. After the electroless nickel has been applied, the surface is then prepared for electroforming. A photomicrograph of the electroformed nickel-electroless nickel-zirconia interface is shown in Figure 5. The copper served as the substrate or mandrel upon which the zirconia and nickel was deposited. The nickel-zirconia interface appears to be free of any porosity.

A second method of rendering the zirconia conductive in order to electroform upon it is to plasma spray a pure nickel coating. Accordingly a specimen containing a zirconia coating backed with approximately .002 inch sprayed nickel was prepared. Electroformed nickel was deposited on the sprayed nickel and photomicrographs were prepared, (Figures 6,7). Both figures indicate a porosity free bond between layers. The plasma sprayed nickel was in this instance actually a nickel-alloy containing aluminum oxide. It appears that either method (electroless deposition or plasma coating of nickel) is satisfactory for rendering the zirconia surface suitable for electrodeposition of an integral cooling passage system.

Consideration was given to selection of a graded coating system for the purpose of minimizing thermal stresses between the primary coating and electroformed nickel. Discussions with the NASA project engineer and past experiences at Camin Laboratories resulted in the selection of the following system:

.004" ZrO_2

.002" (10% Nichrome - 90% ZrO_2)

.002" (30% Nichrome - 70% ZrO_2)

.002" (70% Nichrome - 30% ZrO_2)

.002" (Nickel-plasma sprayed)

A coating system very similar to the above (nickel aluminide in place of nichrome) has previously been used by Camin Laboratories to provide a thermal and oxidation barrier to an electroformed water cooled thrust chamber using storable propellants at high chamber pressure. The coating was applied in the conventional manner by spraying on the I.D. of the completed unit. At that time, problems were encountered in ensuring the desired thickness of intermediate deposits and access of the spray equipment to the interior of the thrust chamber. The present technique of applying the spray coating to the O.D. of a mandrel will eliminate these problems.

Plasma spraying directly on a mandrel poses a problem in terms of mandrel extraction for subsequent reuse. One solution is to apply a parting medium to the mandrel surface prior to refractory coating. The parting medium thickness must be allowed for in the original design of the mandrel. It should be noted that thrust chamber mandrels that are to be used repetitively are normally fabricated from chromium plated stainless steel. One suggested parting medium is a silicone-aluminum paint which is sprayed on the mandrel. The "paint" is then cured in an oven after which the required refractory barrier is applied. Ref. 4 indicates that this technique has been successfully utilized to fabricate multiple free standing plasma sprayed shapes from a single mandrel. Inability to obtain delivery on certain parts required for this investigation, combined with the success of an alternate approach to the extraction problem, suspended all efforts to verify the ability of the silicone-aluminum paint to act as a parting medium.

The secondary approach was to electrodeposit non-adherent copper to the basic mandrel shape and plasma spray the refractory coating upon the copper. Ultimately, the chromium plated stainless steel mandrel would be extracted and the copper removed from the refractory by chemical attack. It was initially intended to use only a flash coating of copper (less than .001

inch) but this proved unsatisfactory, due to the necessity of grit blasting the copper surface prior to spray coating the zirconia. The thin layer of copper tended to ripple and tear. A copper layer in excess of .010 inch is required. This latter requirement was examined with respect to the fabrication of a thrust chamber.

If a .015 inch thick layer of copper is required the steel mandrel is designed and fabricated with a contour that is .030 inch diameter less than the finished I.D. Copper is deposited, and machined if necessary, to a uniform wall thickness of .015 inch.

Rather than electrodeposit copper for the purpose of showing the feasibility of the system, a copper tube was submitted for application of a zirconia coating (Figure 5). After electroforming a nickel shell around the zirconia, the copper was removed by dissolving it in nitric acid. Scrapings of the zirconia that had been in contact with the copper were subjected to a qualitative spectrographic analysis. The copper content was less than one part in ten thousand.

IV. WIRE WRAP REINFORCEMENT

It has been proposed to reinforce electroformed thrust chambers by utilizing a wire wrap inner and/or outer shell. For the inner liner it is suggested that a cylindrical shell be formed by wrapping a continuous wire around a mandrel. The wire material may be Nickel, Inconel 718, Hastelloy X or TD Nickel, since adhesion of electroformed nickel to these substrates has been developed. After the wire-wrap cylinder has been formed an adherent electroformed cooling passage system and outer shell is fabricated.

A three inch diameter by six inch long cylinder was fabricated from 1/2" wide by 0.015" thick Inconel 718 ribbon. The cylinder was fabricated by NASA Lewis Research Center by drawing the ribbon through a die which formed a step in the cross-section. The ribbon was wrapped on a mandrel, spot welding the steps every 180 degrees. The ribbon-wrap cylinder was then removed from the mandrel and fitted with end plugs. The cylinder was pressurized and, as expected, was found to leak in numerous places. This implies that if an inner liner is to be fabricated from a ribbon-wrap cylinder, an initial deposit of electroformed metal must be used to seal leaks from the cooling channels. Therefore, the cylinder was prepared for electroforming. An initial deposit of approximately 0.005" was applied at low current density. The unit was pressurized and found to be gas tight. Microscopic examination revealed a uniform deposit over the entire cylinder. The most encouraging aspect was the lack of any high current density edge buildup of the electroformed nickel. Figure 8 shows the metal ribbon, free standing wire-wrapped shell and the liner after deposition of nickel.

The outer shell reinforcement is obtained by electroforming a thin outer shell around the top of the cooling passage ribs. The rib build-up would be similar to that discussed in Section VI. The purpose of this thin shell is to seal off the coolant channels. At this point a wire wrapping is applied. The wrapping is not tight in the axial direction but rather there is a space between subsequent windings which is of the order of the wire width. If the wire thickness is greater than .020" the top surface of the wire is masked and nickel is deposited (with adhesion) in the areas between wire wraps. The process is interrupted when the nickel has grown over the top of the wire. A machining operation reduces the deposited nickel diameter equal to the wire wrap. At this point the maskant is removed and the remainder of the outer shell is deposited. If the wire thickness is less than .020" it is possible to eliminate the masking operation and simultaneously deposit metal in the space between windings and the top of the ribbon. This is possible because the deposited metal will fill in the region between windings before the metal that deposits on the top of the ribbon can accumulate and shield the space between windings. After the nickel has grown sufficiently above the top of the ribbon a machining operation turns the O.D. to a prescribed thickness. The procedure can now be repeated and a shell containing several windings can be achieved. Figure 9 is a photomicrograph of a double winding of nickel wire (.060" wide x .010" thick), in an electroformed nickel shell.

V. DESIGN OF RIBBED TEST SPECIMENS

The purpose of the preliminary laboratory investigation discussed in the previous sections of this report was to establish certain procedures for electroforming composite structures. Quantitative data as applied to adhesion strengths of dissimilar metal combinations was also obtained. The techniques and data were to be applied to the fabrication of either flat plate or cylindrical ribbed test specimens which contain an inner wall, rib-cooling passage configuration and outer shell. The material combinations enumerated in Table I of this report are to be utilized.

Accordingly, a design for the test specimens was prepared and submitted to the NASA project engineer on October 18, 1967. Approval was subsequently granted. The design analysis is presented as Appendix A of this report. The specimens containing solid inner walls (Inconel, Hastelloy X, TD Nickel) are 4.00 inch I.D. with a 0.030 inch thick inner wall. A total of 45 electroformed ribs (equally spaced) measuring .040 inch wide by .050 inch high join the inner liner to a .150 inch thick electroformed nickel jacket. The refractory coated electroformed nickel unit is 4.0 inch I.D. and contains .012 inches of coating, .040 inches of nickel liner, 60 ribs measuring .050 inches high by .050 inches wide and a .150 inch thick outer jacket. The wire wrapped inner liner will be fabricated from Inconel 718 wire. The liner thickness is .030 inches with a nominal I.D. of 3.0 inches. A total of 20 electroformed ribs, .060 inch wide by .050 inch high will join the liner to the .150 inch thick outer jacket.

In order to test the concept of outer jacket reinforcement a 6.00 inch I.D. cylinder containing a double winding of 301 stainless steel ribbon (.250 inches wide by .020 inches thick) will be fabricated and subjected to hydrostatic burst test.

VI. FABRICATION OF RIBBED TEST SPECIMENS

Upon completion of the preliminary laboratory investigation wherein methods were developed for electroforming composite structures, cylindrical ribbed test specimens were designed and subsequently fabricated.

A. Dissimilar Metal Liners.

In order to fabricate a prototype thrust chamber containing an Inconel 718, Hastelloy X or TD Nickel liner with electroformed ribs and outer jacket it is first necessary to obtain the dissimilar metal liner. The liner must be 4.000 inches (±.005) internal diameter with a thickness of .030 inches (±.002). In addition, the liner must be mounted on a mandrel containing centers and must be concentric with the mandrel centers. For large quantity production it is conceivable that drawn tubing could be economically obtained. However, for the purposes of the present investigation the liners were fabricated from sheet stock that was rolled and welded.

The sheet stock (.040 inch thick) was rolled on an expandable mandrel and a longitudinal electron beam weld was made. The I.D. was bored and honed to remove any rough spots under the weld. The cylinder was replaced on the mandrel and the O.D. turned to achieve the required liner thickness. Figure 10 shows a finished Inconel 718 liner on its mandrel. At this point the unit is either spray or dip-coated with vinyl to a minimum thickness of .060 inches. After the vinyl has been cured it is turned to a uniform thickness of .060 inches. Forty-five equally spaced grooves are cut in the vinyl (.040 inch wide) exposing the liner material at the base of the groove. A band of vinyl is removed at both ends of the mandrel. Figure 11 depicts the unit after vinyl machining.

The part is processed in accordance with the procedures developed for obtaining adhesion of electroformed nickel to the liner material on the mandrel. The ribs are grown in the electroforming bath, uninterruptedly, until they have exceeded the height of the vinyl, Figure 12. The unit is turned to achieve a uniform rib height of .050". The vinyl was originally applied to a height of .060"so that the ribs could be machined back in order to remove the nodules that invariably form along the top of the ribs. After this last machining operation the vinyl is removed. Figure 13 shows the unit which now consists of the dissimilar metal liner with electroformed nickel end bands and longitudinal ribs forming a series of cooling passages. The top of the ribs are masked and wax is injected into cooling passages using a rolled piece of sheet metal and several clamps as a mold cover. The sheet metal cover is removed and a conductive medium is applied to the top of the wax. The maskant is removed from the top of the ribs and the unit is processed for nickel to nickel adhesion and returned to the electroforming bath for deposition of the outer shell. After sufficient metal has been accumulated the O.D. is turned to size, and .062 inch diameter feed holes are drilled into each cooling passage. Using the end of the mandrel as a reference the unit is trimmed to length (at the outside of the end bands, Fig. 11) and removed from the mandrel. Either individual feed tubes are welded into each feed hole or a pre-machined ring is welded in place to manifold all of the cooling passages. Figure 14 shows a completed unit.

The above procedures were used to fabricate 3 units containing Inconel 718 liners and 3 units containing Hastelloy X liners. However, the same procedures could not be used for obtaining reliable TD nickel liners. The initial attempts at electron beam welding the cylinders resulted in extensive thoria migration. The joining procedures outlined in NASA report #CR72320 were attempted. This involves TIG fusion welding using either nichrome 5 or Hastelloy X filler wire. The end results were porous crack sensitive welds with reduced mechanical properties, Fig. 15. Although there was a possibility that additional effort would result in reliable welded cylinders, this was not within the scope of the present investigation. As a result, it was decided to fabricate the TD nickel cylindrical ribbed specimens by rolling the sheet and clamping it to a mandrel. A longitudinal "weld" was created by electroforming a nickel rib directly over the seam. The TD nickel sheet (.045 inch thick) was rolled and clamped to a

4 inch diameter mandrel. In place of a longitudinal weld, an electroformed rib is positioned over the seam. This is accomplished by coating the TD nickel with filler material and positioning one groove (which subsequently becomes a rib) directly over the seam. The method of fabrication is that outlined previously for the Hastelloy X and Inconel 718 units. The configuration is that given in Appendix A except that the inner wall thickness is .045 inches. The Hastelloy X and Inconel 718 units contained inner wall thicknesses of .030 inches. This was achieved by machining the liners after the longitudinal EB weld was made. Since welding of the TD units proved to be impractical and the inner wall thickness can be accounted for in the stress calculations, no attempt was made to obtain a .030 inch thick TD nickel sheet. The .045 inch thick sheet which was obtained in anticipation of machining after welding was utilized. Three units were fabricated containing .040 inch wide by .050 inch high electroformed ribs. The cooling passage width is .244 inches and the outer shell thickness is .150 inches.

B. Sprayed Coating Liners.

Part of this development effort was to fabricate prototype chambers containing sprayed refractory liners and electroformed nickel rib-cooling passage systems and outer jackets. Two plasma spray coatings would be utilized. The first set of units would contain only a zirconia coating while the second set of units would contain the graded coating system outlined in Section III of this report.

A series of mandrels were fabricated by plugging the ends of copper pipe and turning the O.D. of the copper to 4.000 inches between centers. The mandrels were submitted to the Linde Division of Union Carbide Corporation for application of the coatings.

Upon receipt of the coated mandrels, all of which contained an outermost layer of .002"of plasma sprayed nickel, an electroformed nickel liner was deposited on to the coating. The O.D. of the nickel was machined to achieve a uniform thickness of .040 inches. The procedures outlined in part A of this section were then implemented in order to fabricate the ribs and outer jacket, (Figures 11,12 and 13). The electroformed part was trimmed to length and the mandrel plugs and centers were removed. The copper was removed from the interior of the sprayed ceramic by immersing the unit in 50% nitric acid. The feed holes were drilled and manifolds welded in place. The first manifold was welded by the Heliarc method. This resulted in spalling and cracking of the coating, Figure 17a. Subsequent units were electron beam welded, with no apparent disturbance to the coating, Figure 17b. In general, the fabrication of the units proceeded smoothly, and the finished surface of ceramic was free of cracks and as smooth as expected.

C. Wire Wrap Reinforcement - Inner Wall.

The scope of this phase of the investigation was to fabricate cylindrical chambers containing a ribbon or wire wrapping as an inner liner. These liners would then be backed by an electroformed rib-cooling passage system and outer jacket. The liners were supplied by NASA and fabricated as outlined in section IV of this report. The free standing liners (3 inch nominal diameter) were mounted on mandrels with centers, Figure 8. The units were inspected and found to be out of round by as much as .010". Since concentricity and dimensional control are essential to subsequent electroforming and machining operations, any subsequent units that are fabricated should be wrapped directly on the mandrel that will serve as the electroforming and machining mandrel.

Since the units as wrapped are not gas tight, a .010" thick jacket of electroformed nickel was deposited. The rib-cooling passage system and outer jacket was fabricated as previously described. A completed unit is shown in Figure 18.

D. Outer Jacket Reinforcement.

In order to determine the merits of a wire wrapping in an electroformed nickel outer jacket, several cylindrical shells were fabricated. The first shell was 6.000 inch I.D. by 6.140 inch O.D., and contained no reinforcement, i.e., it was pure electroformed nickel. The second and third shells had the same overall dimensions as the first except they contained windings of 301 stainless steel ribbon (.250" wide by .020" thick) in the electroformed nickel. All three shells were to be subjected to hydrostatic burst tests to determine if the ribbon did indeed supply reinforcement.

The reinforced units were fabricated by depositing .010 inch of nickel on a 6.000 inch mandrel. The unit was placed between centers in a lathe and the spool of wire was mounted in the tool post holder. One end of the wire was rigidly attached to the O.D. of the mandrel at one end. The rotational speed of the mandrel and motion of the wire spool was adjusted to result in two windings per inch. This results in a space of .250 inches between adjacent windings. Electroformed nickel is then deposited between and on top of the windings. A machining operation reduces the nickel to .010 inch on top of the windings or a total thickness of .040 inch. A second winding is made by starting 180° out of phase with the first winding. Thus the upper wrap will be located above the space between adjacent windings of the first wrap. Electroformed nickel is again deposited, filling the spaces between windings and enveloping the top of the wire with .010" of metal. Thus a total thickness of .070 inches has been achieved. The unit is stripped from the mandrel and end caps are welded prior to hydrostatic test.

VII. RESULTS AND DISCUSSION OF RIBBED SPECIMEN TEST PROGRAM

The following cylindrical ribbed test specimens were fabricated and tested:

A. Hastelloy X liner, electroformed nickel ribs and outer jacket (3 units).

B. Inconel 718 liner, electroformed nickel ribs and outer jacket (3 units).

C. Wire Wrap liner, electroformed nickel ribs and outer jacket (3 units).

D. Sprayed Zirconia (.012" thick) backed by electroformed nickel liner (.040" thick) electroformed nickel ribs and outer jacket (2 units).

E. Graded plasma sprayed liner backed by electroformed nickel ribs and outer jacket (4 units).

F. Wire wrap reinforced shell (2 units) and pure electroformed nickel shell of equal thickness (1 unit).

G. TD Nickel liner, electroformed nickel ribs and outer jacket (3 units).

All units were subjected to 50 psi helium leak tests by pressurizing the cooling passages and immersing the unit in a drum of water. No bubbles or leaks were detected. Thus all of the inner liners were shown to be impervious to helium. Since efforts were made to locate the weld on Inconel and Hastelloy liners under a cooling passage, the helium leak test is also a test of the porosity of the weld. The success of the helium test also indicates the ability to seal the spaces between adjacent wraps of the inner wire wrap liner.

In addition to the longitudinal ribs which form the cooling passage, each cylindrical ribbed specimen contains a circumferential rib at both ends. This circumferential rib joins the inner liner to the outer jacket and serves as an end closure or termination for the cooling passages. The helium leak test described above attests to the tightness of the joint between the liner and electroformed nickel, since any lamination or porosity at the nickel-liner interface would permit the leakage of helium to the exterior of the unit.

One specimen of each of category A, B, C, and G was fabricated so that each cooling passage could be individually pressurized. Helium leak tests were conducted by pressurizing individual passages and then determining the presence of helium in adjacent passages with the aid of a mass spectrometer. This test was performed to determine if there was any porosity at the rib-liner or rib-outer jacket interface. The procedure also tests the porosity of the rib itself. No leaks were detected.

The units that did not contain individual feed passages were subjected to hydraulic testing. The tests were conducted by pressurizing the coolant passages to failure of the chambers.

A. Hastelloy X Liners.

The first unit failed at 600 psi coolant passage pressure. Examination of the failed cross section, Fig. 19, indicates that the failure is at the interface of the top of the nickel rib and the nickel outer jacket. The nickel-Hastelloy X interface remained intact. The tensile stress in the rib at 600 psi coolant passage pressure is only 3600 psi, which is well below the allowable stress for nickel-nickel adhesion. The inference is that adhesion between subsequent deposits of nickel was not obtained in all areas. Since nickel to nickel adhesion is fundamental to the Camin electroformed rocket motor system, and has been proven on previous all nickel thrust chambers as well as on the remaining specimens for this program, this failure can only be attributed to improper cleaning and activation cycles on this particular unit. The critical external pressure which would cause collapse of the .030 inch thick Hastelloy X liner can be estimated with the data given in Reference 6 as 325 psi. Thus the electroformed ribs and shell have provided some degree of reinforcement to the liner.

The second unit burst at 1525 psi coolant passage pressure, as predicted. This was the design loading for failure of the inner wall due to bending. The failure is characterized, Fig. 20, by deformation of the Hastelloy liner beyond the yield point and a tearing away of the liner from the rib. The tensile stress in the rib is 9500 psi due to the coolant passage pressure. However, once the liner starts to deform beyond the elastic limit, additional bending stresses are imposed on the liner-rib interface.

A photomicrograph of the Hastelloy X-rib interface was made, Fig. 21. The sample was cut from the first unit, at a point directly under the failure. The Hastelloy-nickel interface is free from porosity and substantiates the ability to attain reliable Hastelloy X-nickel joints.

B. Inconel 718 Liners.

One unit failed at 700 psi and the other at 850 psi coolant passage pressure. Both separations occurred at the nickel rib-Inconel 718 liner interface. The failure, Fig. 22, is characterized by a separation of the liner from a single rib, deformation of the liner and a subsequent tearing from adjacent ribs. The coolant passage pressure at failure is greater than the critical collapsing pressure for an unsupported liner but approximately one third of the maximum bending stress for an integral rib construction. The inference is that complete adhesion was not obtained throughout the Inconel 718-rib interface.

The cause of this problem is believed to be due to the evolution of gas that occurs during the Inconel activation cycle. It should be noted that this phenomenon is not present during Hastelloy X or nickel activation. Since the Inconel 718 is activated at the bottom of grooves which are cut in the filler material, evolved gases can attach to the sidewalls of the grooves and prevent the proper cleaning of the Inconel 718 surface. During all of the steps in the activation cycle (see Section II) mechanical agitation of the work piece is employed. Air agitation of solution is also used in order to prevent stagnation of electrolytes and acids. Apparently, for the case of Inconel 718-rib interfaces, these procedures are insufficient. A technique which offers promise of alleviating the present problem is ultrasonic agitation of solution. It is suggested that any future efforts include an investigation of this technique as an additional tool for improved electroforming.

During the preliminary laboratory investigation of nickel to Inconel 718 adhesion the gas evolution problem was not encountered. That is not to say that gases were not evolved but rather the open area of the plating surface (Figure 1) did not provide surfaces to entrap the gas bubbles. As a result, the fabrication of adhesion specimens proceeded without forewarning of the problems to be encountered during fabrication of the ribbed specimens. Therefore, it is suggested that any future efforts to develop procedures for obtaining adhesion of electroformed metals to dissimilar materials include a redesign of the adhesion specimen. The new design should require deposition to the base of a groove simulating thrust chamber configuration.

C. Wire Wrap Inner Liners.

The one unit that was tested leaked at 500 psi coolant passage pressure. The leak occurred at the very end of the chamber between the layers of wire wrapping. It will be recalled that the liner is fabricated from a stepped wire which results in an overlapping of adjacent turns during winding. When the unit is trimmed to length, the inside of the first winding is only supported at the location of the spot welds to the outside of the second winding. As a result it tends to pull away from the unit. Therefore, the unsupported section of the first winding on the part is cut away. The leak occurred at the termination of this winding. It is felt that the final machining operation possibly damaged the liner, giving rise to the leak.

Since the unit had not been damaged during the hydrostatic test, it was decided to attempt to repair it by electroforming. The entire unit was masked, except for the end face containing the leak. A .030" thick layer of electroformed nickel was deposited. A second hydrostatic test was performed, at which time the unit failed at 1100 psi. This is approximately 90% of the estimated failure loading. The failure is characterized by deformation of the liner beyond the elastic limit, Fig. 23. The inside winding deformed more than the outside overlapping winding. The nickel shell remained adherent to the outside winding except in the region of the rib, where the nickel rib to nickel shell adhesion is greater than the nickel shell to Inconel 718 wire adhesion.

It is felt that feasibility of fabricating wire wrapped liner thrust chambers containing electroformed ribs and shells has been established. However, several modifications to the fabrication procedures are required. The mandrel upon which the wire is wrapped should serve as the electroforming mandrel. Concentricity of the wire wrapping and the mandrel must be assured. The wire wrap liner should be fabricated to the finished length prior to any electroforming operation. Simultaneously with the deposition of the nickel shell that serves to seal the liner, end rings of electroformed nickel should be deposited to seal the end faces of the liner.

D. and E. Plasma Spray Coated Liners.

One unit containing the graded coating and another unit containing pure zirconia were hydraulically tested with identical results. As the units were pressurized, they were examined for evidence of cracking or spalling of the ceramic coating at 300, 600, 900 and 1200 psi. The coating remained completely intact and exhibited no signs of crazing. Both units were pressurized to 6500 psi - at which point a leak occurred at the weldment of the manifold to the outer jacket. At this pressure the bending stress in the .040 inch nickel liner is 55000 psi. The tensile stress in the ribs is 27,000 psi which is indicative of the fundamental integrity of nickel to nickel adhesion. The coatings remained intact and without evidence of cracks during the entire pressure cycle.

A third unit containing the graded coating was subjected to hydraulic testing. This unit was pressurized to 14,000 psi at which point a leak developed in the weldment. No sign of cracking or other deterioration of the coating was evident. No permanent deformation of the liner was found. The bending stress in the .040" thick nickel liner is 118,000 psi and the tensile stress in the ribs is 58000 psi.

It is obvious that the design of these units (see Appendix A) was overly conservative, since the failure pressure was estimated to be 1500 psi. In the design analysis the bending stresses were calculated for the nickel liner thickness and the coating was assumed to offer no support. Failure was assumed to be characterized by cracking of the coating. Since the bending stress previously calculated exceeds the yield point stress for electroformed nickel it is suggested that the nickel liner is reinforced by the coating and as a result the equivalent liner thickness is greater than that of the nickel itself. Using the total thickness of nickel and coating, (.052 inches) the bending stress for the third unit is calculated from Equation 4, Appendix A to be 70,000 psi. The failure bending stress used in the original design was taken as 60% of the flexural strength of the coating, (21,000 psi). If the flexural strength is determined in a manner similar to that employed for determination of modulus of rupture, then this quantity is inadequate for the present purposes. Manufacturers data indicates compressive strengths for zirconia as high as 250,000 psi. It seems feasible therefore that the coating can support bending stresses, without failure, in excess of those calculated.

Figure 24 is a photomicrograph of the graded coating as applied to the excess length of the original mandrel. Figure 25 is an enlargement of the graded coating - electroformed nickel rib interface. Figure 26 shows a view of a sectioned unit after hydraulic testing. The I.D. of the unit is still circular and no permanent deformation has been found. The coating is intact and without signs of cracking.

The results of the test program conducted on the refractory coated liners clearly indicate that the method of fabrication is feasible and results in adherent nickel-ceramic interfaces. The structure has been shown to be capable of supporting stresses far in excess of those anticipated.

F. Wire Wrap Reinforced Shell.

The all electroformed nickel shell which was to be used for comparison of the reinforced shell burst at an internal pressure of 2400 psi. This loading corresponds to a circumferential stress of 103,000 psi which is approximately equal to the ultimate strength of Camin electroformed nickel. The first reinforced nickel shell burst at an internal pressure of 3100 psi, a 30% increase. The second reinforced shell developed a leak at the weld at an internal pressure of 1450 psi. From the results of the tests, it can be concluded that the method of fabrication, which incorporates intermediate winding of high strength ribbon in electroformed shells, is feasible, and that an increase in the bursting strength of the shell is obtainable.

G. TD Nickel Liners

The cooling passages of two units were pressurized to 3000 psi without deformation or destruction of the units. At this pressure, Equation 4 of Appendix A yields an inner wall bending stress of 45000 psi which corresponds to the .2% yield strength of TD nickel sheet. Just beyond this pressure permanent deformation of the inner wall between coolant passages was observed and the tests were halted.

The excellent results obtained with the TD nickel ribbed specimens and the unique method of obtaining the liner (electroformed rib replacing a weld) indicate additional effort with this material is worthwhile.

VIII. DESIGN OF SPOOL PIECES

The investigation of advanced electroforming techniques for fabrication of regeneratively cooled thrust chambers includes the design and production of two spool pieces. After reviewing the results of the test program conducted on the cylindrical ribbed test specimens, it was decided to fabricate one unit containing a Hastelloy X liner and a second unit containing a graded sprayed refractory coating. It was felt that these configurations could be most reliably fabricated and would offer the possibility of application, if successful, to various areas of NASA endeavors.

The spool pieces are to be 12 inches long with a 10.77 inch internal diameter. The propellant combination is hydrogen and oxygen at a chamber pressure of 500 psia. The design analysis is presented as Appendix B of this report.

IX. FABRICATION AND EVALUATION OF SPOOL PIECES

Upon receipt of approval of the spool piece designs detailed in Appendix B of this report fabrication of one Hastelloy X lined unit and one graded coating unit was initiated. Both units are 10.77 inch I.D. by 12 inches long. The Hastelloy X inner wall is .018 inches thick and is attached to the .250 inch outer nickel shell by 180 equally spaced .040 inch wide by .060 inch high electroformed nickel ribs. The coated unit contains an inner wall of .008 inches of graded zirconia coating and .030 inches of electroformed nickel. This is attached to the .250 inch outer shell via 120 equally spaced .040 inch wide by .060 inch high electroformed nickel ribs. Assembly drawings of the two units are shown in Figures 27 and 28.

Coated Spool Piece

A steel mandrel was fabricated and .020 inches of copper was deposited. This was machined to a diameter of 10.770 inches. The copper plated mandrel was then coated by the Materials Systems Division of Union Carbide Corporation with .002 inches of zirconia, .0015 inches of 90% zirconia - 10% nichrome, .0015 inches of 70% zirconia - 30% nichrome and .002 inches of plasma sprayed nickel. Test panels were attached to the mandrel and simultaneously sprayed. These were photomicrographically examined for adhesion between layers and porosity and found to be satisfactory. Upon receipt of the unit by Camin Laboratories the unit appeared as in Figure 16. A single deposit of electroformed nickel was applied to a total thickness in excess of .100 inches. A turning operation achieved a uniform nickel thickness equal to the nickel inner wall and rib height or .090 inches. The cooling passage configuration was then milled into the electroformed nickel. This consists of 120 equally spaced, .244 inch wide by .060 inch deep slots. The longitudinal ribs that remain are therefore .040 inches wide. The slot length is 11.750 inches so that a .125 inch wide circumferential rib remains at both ends of the spool piece. At this point the unit would appear as in Figure 13. The cooling passages are filled with wax and sufficient nickel is electroformed and then machined to form a .250 inch thick outer jacket. Premachined stainless steel manifold/flanges were then electron beam welded at both ends of the spool piece after the wax was removed from the cooling passage. This is accomplished by placing the unit in an oven at 250° F to melt the wax and then flushing the cooling passages with methyl enthyl ketone. The steel mandrel is extracted and the copper which remains on the I.D. of the coating is dissolved in nitric acid.

The cooling passages were successfully hydrostatically tested to 750 psia and helium leak tested at 50 psi. The unit was then shipped to Lewis Research Center for hot-firing evaluation. Two ten second tests were conducted with Hydrogen and Oxygen as the propellants at an O/F ratio of 4.5. The first test was conducted at a chamber pressure of 300 psia and thrust level of 19,000 lbf. while the second test was at 500 psia and 30,000 lbf. thrust. The cooling water flow rate was 65 lbm/sec at a nominal pressure drop of 350 psi through the cooling passages. This data yields a friction factor for the coolant channels of .014. The design calculations (Appendix B) employed an assumed friction factor of .013. Measured heat fluxes were 3 and 4.8 BTU/sec, sq. in. for runs 1 and 2 respectively. Post firing examination of the spool piece showed no deleterious effects. The coating shows no signs of cracking or spalling.

Hastelloy-X Spool Piece

The liner for the Hastelloy X spool piece was fabricated by rolling Hastelloy X sheet on a mandrel and forming a cylinder with a longitudinal electron beam weld as in Figure 10. The shell was inspected and found to be within tolerances. The outer surface of the Hastelloy X was sandblasted in order to obtain a roughened surface for application of the sprayed vinyl which must subsequently be machined. Inspection of the unit after application of the filler material indicated that the liner was no longer adhering to the mandrel and that the .018 inch thick Hastelloy X shell had expanded in some areas and was out of round. This deformation was attributed to the sandblasting operation. A second liner was fabricated and the surface was roughened by hand for adhesion of the vinyl.

After the vinyl was applied the unit was inspected and found to be satisfactory. The filler was machined to an O.D. of 10.960 inches (slightly in excess of the rib height) and excess filler was removed from the liner beyond the cutoff points. A series of 180 equally spaced .040 inch wide grooves were cut in the vinyl exposing the Hastelloy X at the bottom of each groove, Figure 29. Nickel was then electroformed on all exposed Hastelloy X surfaces, thus forming the cooling passage ribs and circumferential bands at either end. A turning operation achieved the exact rib height dimension and the vinyl was removed, Figure 30. The cooling passages were filled with wax and the outer jacket was electroformed and machined, Figure 31. After the wax and mandrel was removed the flanges were electron beam welded to the spool piece and successfully subjected to hydrostatic and helium leak tests. The completed Hastelloy X spool piece is shown in Figure 32 and the coated spool piece is shown in Figure 33.

The completed Hastelloy X spool piece was shipped to Lewis Research Center and subjected to three hot firings with Hydrogen/Oxygen propellants. Test number one had a duration of 5 seconds at a chamber pressure of 300 psia, thrust level of 19,000 lbf and O/F ratio of 5.8. The cooling water flow rate was 60 lbm/sec with a temperature rise of 38° F. Tests number 2 and 3 were at 500 psia and 30,000 lbf thrust. Test number 2 lasted 5 seconds at an O/F ratio of 4.5 and a calculated average heat flux of 6.6 BTU/sec.-sq. in. Test number 3 lasted 10 seconds at an O/F ratio of 5.5 and a calculated heat flux of 8.8 BTU/sec.-sq.in.

Post firing examination showed a slight discoloration in the Hastelloy X liner. Subsequent structural and dimensional inspection indicated no adverse effects from the firing.

X. FABRICATION AND EVALUATION OF CHAMBER SEGMENTS

One phase of the present program was the demonstration that the processes used to fabricate spool pieces could be applied to the fabrication of contoured thrust chambers. A thrust chamber configuration was provided by the NASA project engineer, Figure 34. The Hastelloy segment was to contain a constant thickness liner of .040 inches while the coated liner inner wall would consist of .008 inches of coating and .060 inches of electroformed nickel. The cooling passage configuration would contain bifurcated ribs. Between stations 1 and 5 and between stations 10 and 15 there would be a .040 inch wide by .100 inch high rib every 3°. However, in the throat region between stations 5 and 8, every other rib would be eliminated. The outer jacket would be a shell of electroformed nickel, .200 inches thick. In order to obtain three segments from each chamber for subsequent testing an extra wide rib would be fabricated every 120 degrees. After fabrication of the full 360 degree segment the unit could then be sliced along each wide rib to obtain three segments.

The liner for the Hastelloy X segment was spun on a mandrel and is shown in Figure 35.

The coated segment mandrel was machined from aluminum and plated with copper. The O.D. of the copper was contour turned to achieve the required segment I.D. The plasma sprayed coating was then deposited on the mandrel followed by the electroformed nickel inner wall. The remaining procedures for both segments are identical. The inner wall surface was roughened and spray coated with vinyl. The vinyl was contour turned to achieve the necessary rib height profile. Contour milling the vinyl, then formed the grooves in the vinyl which were subsequently filled with electroformed nickel to create the integral rib system. Figure 36 shows the chamber segment after vinyl machining and prior to rib deposition. Figure 37 shows the cooling passage/rib configuration after the vinyl was removed. Prior to electroforming the outer jacket, the vinyl was replaced with wax. After sufficient nickel was deposited the part was contour turned to achieve the necessary O.D. profile. The mandrels were removed, the wax was melted, the cooling passages were flushed with methyl ethyl ketone and the manifolds were welded in place. A completed thrust chamber, prior to segmenting is shown in Figure 38.

The unit shown in Figure 37 contains a coated liner. This unit was hydrostatically tested to 700 psi and shipped to NASA Lewis Research Center for segmenting and further evaluation.

The Hastelloy X segment has not been completed. After the ribs were deposited and prior to electroforming the outer jacket, the top of the ribs are contour machined to remove any electroformed nickel nodule growth. During this latter operation the ribs lifted from the Hastelloy X liner over approximately 50% of the unit. The ribs could have been stripped from the liner and vinyl reapplied to repeat the rib growth cycle. However, a decision was made by NASA not to expend any further effort on this unit since the coated unit demonstrated the ability to electroform a complex contoured ribbed specimen. Furthermore, the success of the Hastelloy X spool piece demonstrated the feasibility of depositing electroformed nickel ribs on a Hastelloy X liner. In addition, funding was limited.

XI. RESULTS AND RECOMMENDATIONS

The intent of the present investigation is to develop advance electroforming techniques for the fabrication of regeneratively cooled thrust chambers. The several concepts that were investigated include:

A. The use of pre-machined liners of Hastelloy X, Inconel 718, and T.D. Nickel.

These liners are supported by electroformed nickel ribs and outer jackets. Techniques were developed for the adherent deposition of electroformed nickel. Preliminary tensile specimens indicated ultimate bond strengths as strong as the parent metals. Prototype thrust chambers were fabricated and subjected to helium leak and hydrostatic burst tests. The premature failure of the Inconel 718 units suggests the need for further investigation of the electrochemical activation cycle associated with Inconel 718. It is recommended that the use of ultrasonic agitation be investigated as a method of removing the gas bubbles formed at the Inconel surface during activation procedures.

The Hastelloy X lined units met design criteria. It was therefore recommended that one of the full scale spool pieces be fabricated with a Hastelloy X liner and electroformed nickel ribs and outer jacket.

The TD nickel inner wall units were fabricated by rolling and clamping TD nickel sheet on a mandrel and electroforming a nickel rib directly over the seam, thus eliminating the need to weld the inner liner. During hydrostatic testing of the prototype chambers, permanent deformation of the inner wall between adjacent cooling passage ribs was observed at a loading corresponding to an inner wall bending stress of 45,000 psi. This corresponds to the .2% yield strength of TD nickel.

The excellent results obtained with the TD nickel ribbed specimens and the unique method of obtaining the liner (electroformed rib replacing a weld) indicate additional effort with this material is worthwhile. In particular, fabrication of a thrust chamber or spool piece for hot firing evaluation is recommended.

B. The use of liners made by wrapping a continuous length of Inconel 718 wire on a mandrel.

These liners are enveloped with a .010 thick shell of electroformed nickel in order to seal the cooling passages from the chamber. Electroformed nickel ribs and outer jacket complete the unit. The prototype thrust chambers passed the helium leak test. During hydrostatic testing a leak developed at 500 psi in the end face. The leak was repaired by electroforming a .030" thick deposit of nickel on the end face. Subsequent hydrostatic tests met design estimates, resulting in buckling of the unit at 1100 psi coolant passage pressure. Recommendations for modifications to the method of fabrication of these parts are included in Sections VI and VII of this report.

C. The use of sprayed refractory coatings.

The basic concept that was developed to fruition involved the spraying of a refractory coating on a mandrel, electroforming a nickel integral rib cooling passage system into the refractory and subsequent removal of the mandrel for reuse. Pure zirconia and graded coatings of varying percentages of zirconia-nichrome were investigated.

The mandrel removal technique developed consists of fabricating a hardened steel mandrel slightly undersized and applying a non-adherent coating of electrodeposited copper. The plasma spray coating is applied to the copper and subsequently backed with the electroformed nickel structure. Upon completion, the copper, plasma spray coating, electroformed nickel structure is stripped from the steel mandrel and the copper is subsequently removed from the plasma coating by dissolving it in nitric acid.

Techniques were developed for ensuring the adherence of the electroformed nickel to the plasma spray coating in the instances when the sprayed coating is non-conductive. The non-conductive coating was rendered conductive with the use of either an electroless nickel or plasma sprayed nickel coating. Photomicrographs of the coating-electroformed nickel interface indicate that the joint is free of voids and consists of an interlacing of the electroformed metal and sprayed refractory.

Several prototype cylindrical-ribbed chambers were fabricated. Two units were pressurized to 6500 psi and a third unit to 14,000 psi. In all three cases, the tests were halted as a result of failure of the weldment of the manifold to the outer jacket. The coating remained intact and free of cracks.

It was originally estimated that the coatings would crack when the coolant passage pressure reached 1500 psi. This figure was arrived at by assuming the coating offered no support to the nickel liner and that it would crack when the bending stress in the nickel reached the flexural strength of the coating (21,000 psi). This is obviously extremely conservative. At 14,000 psi coolant passage pressure, the bending stress in the nickel liner (neglecting the presence of the coating) is 118,000 psi which is in excess of the yield strength of the electroformed nickel. However, cross sections of the test unit indicate no permanent deformation. If the coating thickness is included in the calculation of inner wall bending stress the latter figure becomes 70,000 psi. It is suggested therefore that the manner in which the electroformed nickel bonds to the coating results in a liner in which the plasma coating and electroformed nickel offer mutual support.

As a result of the excellent results and the many areas of application for this fabrication technique, it was recommended that a full scale spool piece be fabricated containing a graded coating liner and electroformed nickel integral cooling passage system. Additional laboratory scale investigations with other sprayed refractories are also recommended.

D. The use of high strength wire to reinforce an electroformed nickel shell.

Techniques were developed for encapsulating intermediate windings of wire in an electroformed shell. Photomicrographic investigation showed that the interface between windings and electroformed metal was free of voids. A reinforced shell burst at an internal pressure 30% greater than that of an equal thickness unreinforced shell. While this technique appears to offer promise no further investigations during the present program are contemplated. Future programs might investigate the effect of wire cross section, both from a point of view of electroforming implications and strength considerations. In addition, improved wrapping techniques, possibly including simultaneous winding and electroforming, should be examined.

E. Design, Fabrication and Evaluation of Spool Pieces

Using the procedures developed during Task I of this investigation, two full scale spool pieces were designed and fabricated for hot firing evaluation. The units were designed for use with hydrogen and oxygen at a chamber pressure of 500 psia and 30,000 lbf. thrust. One unit was fabricated with a Hastelloy X inner wall while the second unit contained a graded zirconia-nichrome-electroformed nickel inner wall. Both units contained the Camin integral rib-cooling passage configuration. Tests were conducted at NASA-Lewis Research Center at the design pressure and thrust level using water as the coolant. Examination of the chambers at the end of the test program showed no deleterious effects. The Hastelloy X was slightly discolored but is structurally and dimensionally sound. The coating showed no signs of cracking or spalling.

The excellent results obtained with the spool pieces under actual firing conditions definitively proves the merits of the fabrication process. It is recommended that the units delivered to NASA Lewis Research Center be evaluated further using hydrogen as the coolant.

F. Design, Fabrication and Evaluation of Chamber Segments.

The material configurations utilized for spool piece fabrication were also selected for fabrication of contoured thrust chamber segments. The primary purpose of this phase of the investigation was the demonstration of the ability of the process to fabricate typical contoured thrust chamber configurations. The basic configuration supplied by the NASA Program Manager contained bifurcated ribs.

Construction of a Hastelloy X lined unit was initiated and continued to a point where the electroformed nickel ribs were deposited. At that time, a machining operation on the top of the ribs indicated that adhesion of the nickel ribs to the Hastelloy X liner was obtained only over approximately 50% of the unit. In view of the success of the Hastelloy X lined cylindrical ribbed specimen and spool piece the problems associated with the chamber segment were attributed to human error during the activation cycle rather than a fundamental electrochemical problem. A decision was made by the NASA Program Manager not to strip the ribs and recycle the Hastelloy X liner.

The graded coating chamber segment was fabricated in accordance with the NASA furnished drawing. No problems were encountered during the manufacturing sequence. The contoured segments successfully passed hydrostatic pressure and helium leak tests and were shipped to NASA Lewis Research Center for further evaluation.

The general objectives of the contract, i.e., the development and evaluation of advanced electroforming techniques for fabrication of regeneratively cooled thrust chambers, were successfully accomplished. Hastelloy X and graded coating inner walls were successfully utilized as inner walls of spool pieces. It is recommended that additional material configurations be investigated and that full scale contoured thrust chambers with graded coating or Hastelloy X inner walls be fabricated for rocket firing evaluations.

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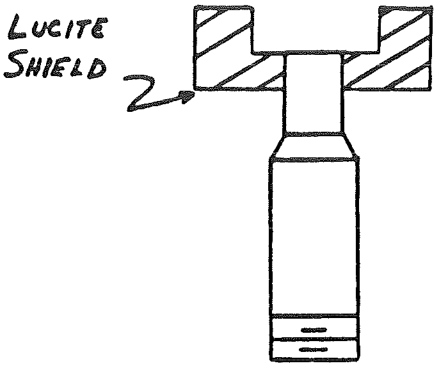
7. Timoshenko, S. and Goodier, E. "Theory of Elasticity," McGraw-Hill, New York, 1951.

FIGURES



MANDREL - LUCITE SHIELD
PRIOR TO DEPOSITION

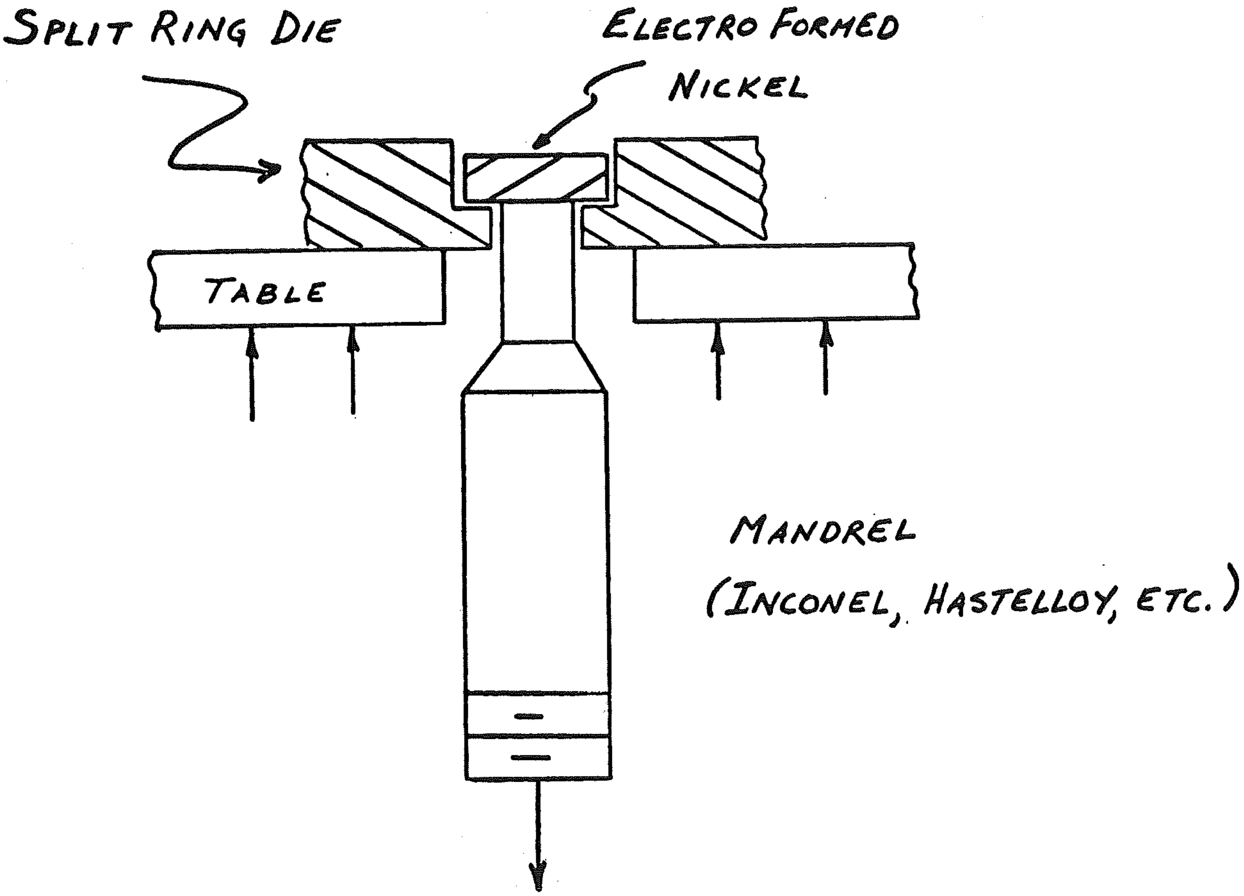
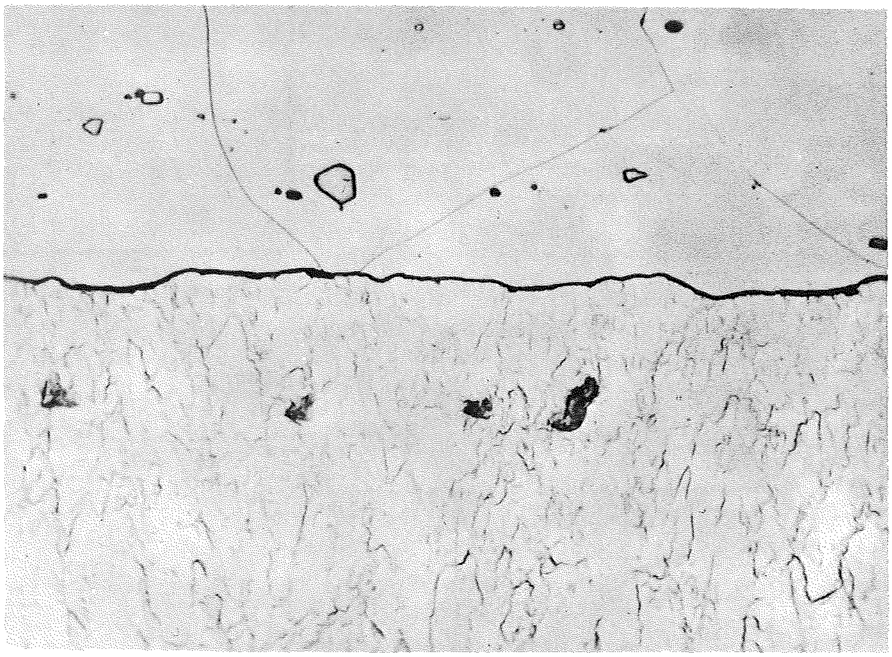
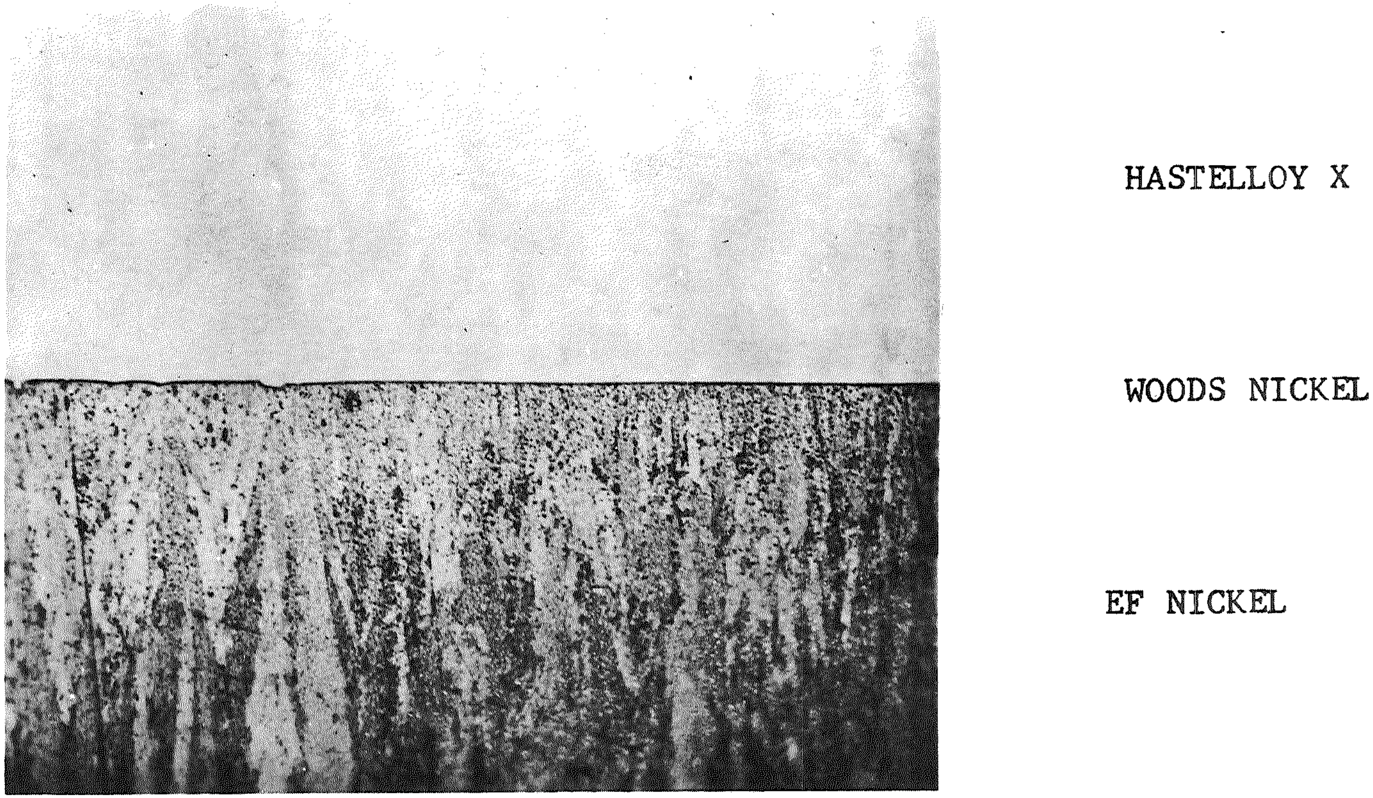


FIG. 1 ADHESION STRENGTH SPECIMEN



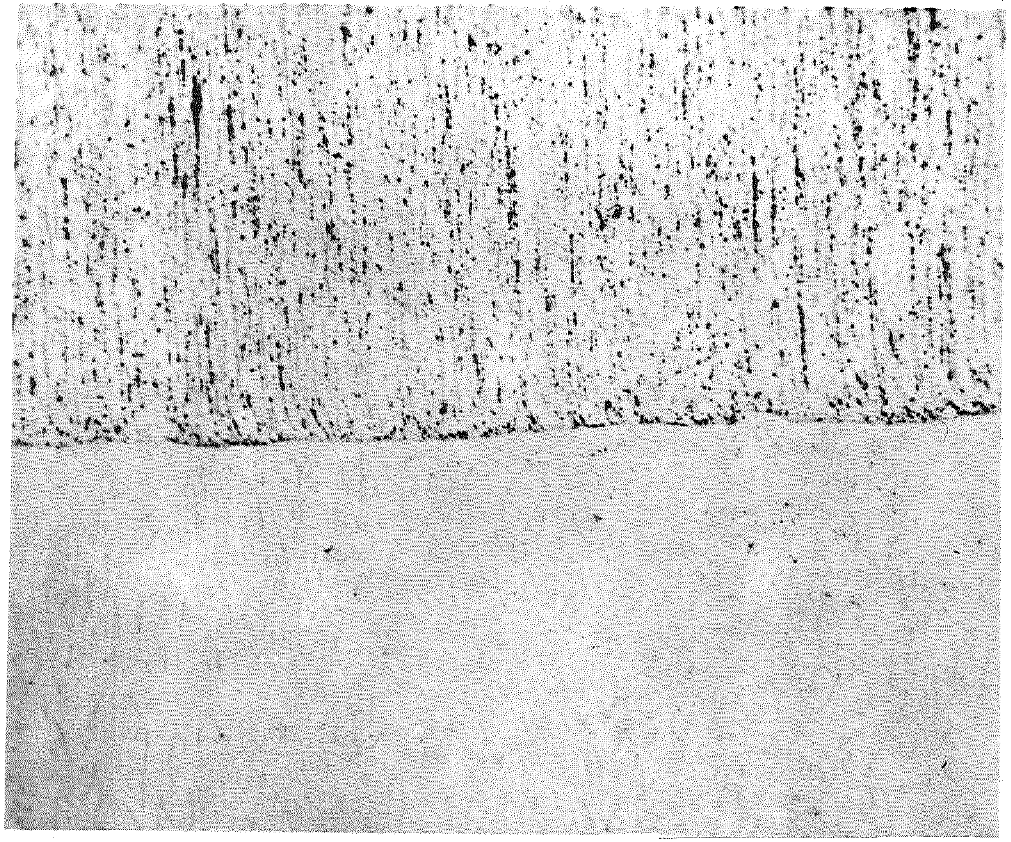
MAGNIFICATION; 500 X
ETCHANT : 50% NITRIC 50% ACETIC

FIGURE2. INCONEL 718- EF NICKEL INTERFACE



MAGNIFICATION : 500 X
ETCHANT : 50% NITRIC-50% ACETIC

FIGURE 3 HASTELLOY X - EF NICKEL INTERFACE

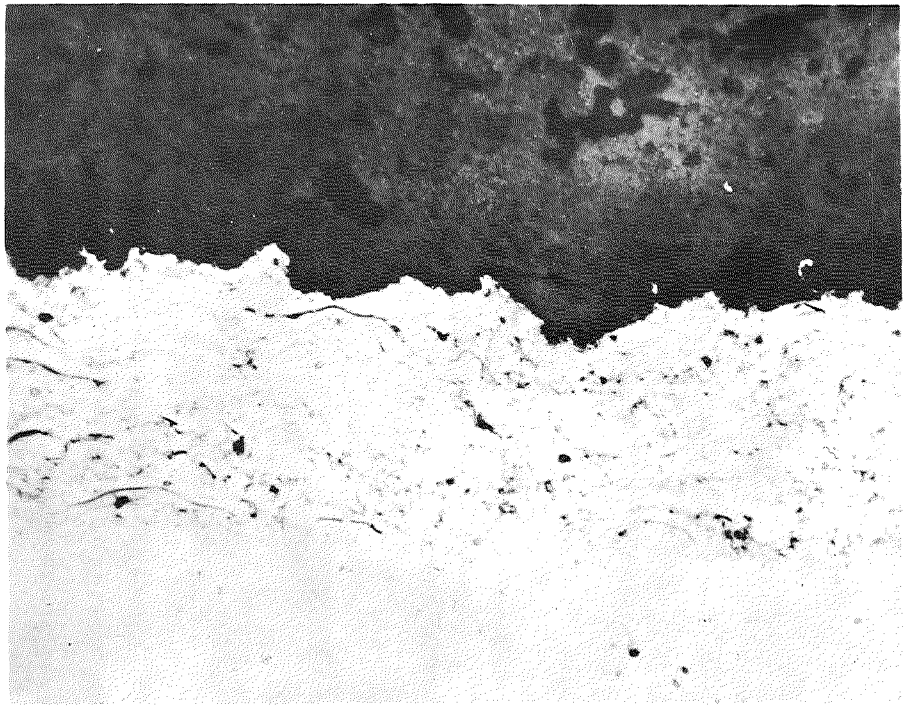


MAGNIFICATION : 500 X
ETCHANT : 50% NITRIC- 50% ACETIC

FIGURE 4. TD NICKEL - EF NICKEL INTERFACE

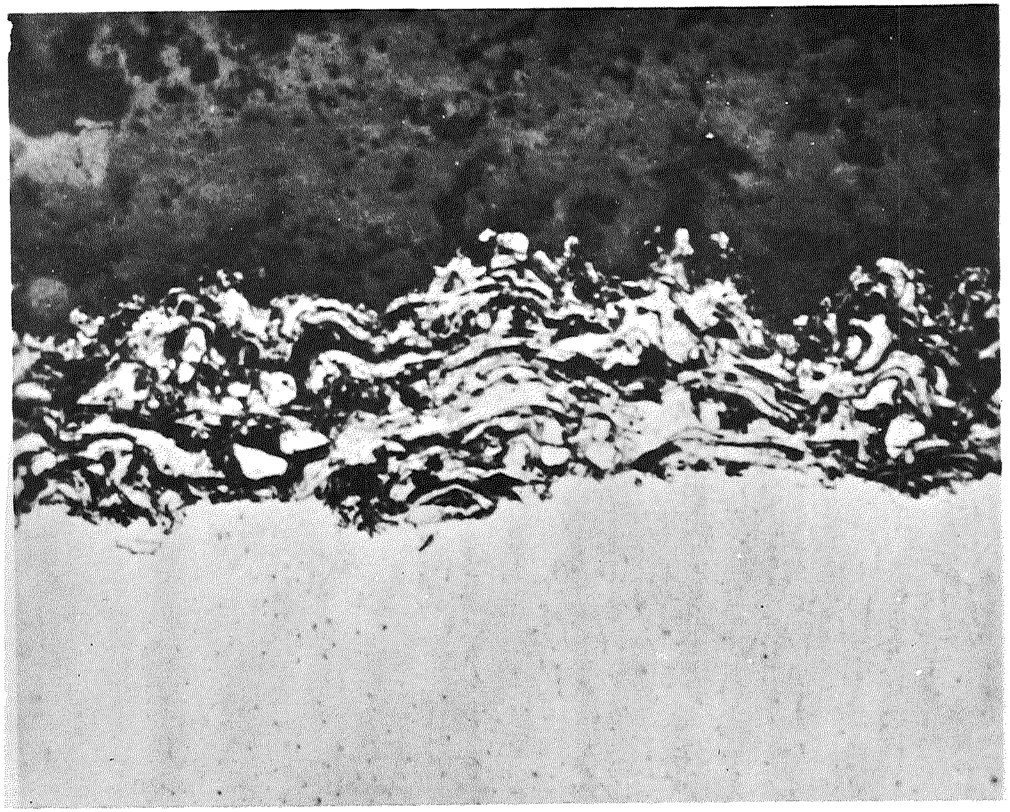
ETCHANT: NONE
MAGNIFICATION: 500 X

Figure 5 EF nickel- Electroless Nickel- Zirconia Interface



ETCHANT : NONE
MAGNIFICATION : 500 X

FIGURE 6. EF NICKEL - PLASMA NICKEL - ZIRCONIA INTERFACE



ETCHANT : 50% NITRIC, 50% ACETIC
MAGNIFICATION : 500 X

FIGURE 7. EF NICKEL- PLASMA NICKEL - ZIRCONIA INTERFACE

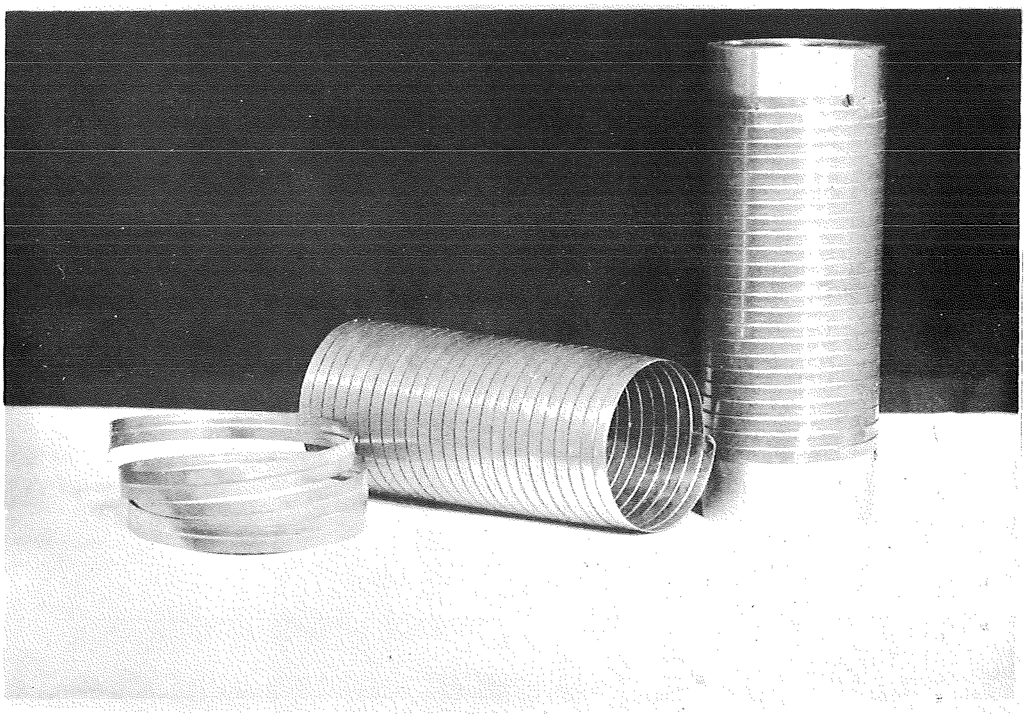


FIGURE 8 WIRE WRAPPED INNER SHELL

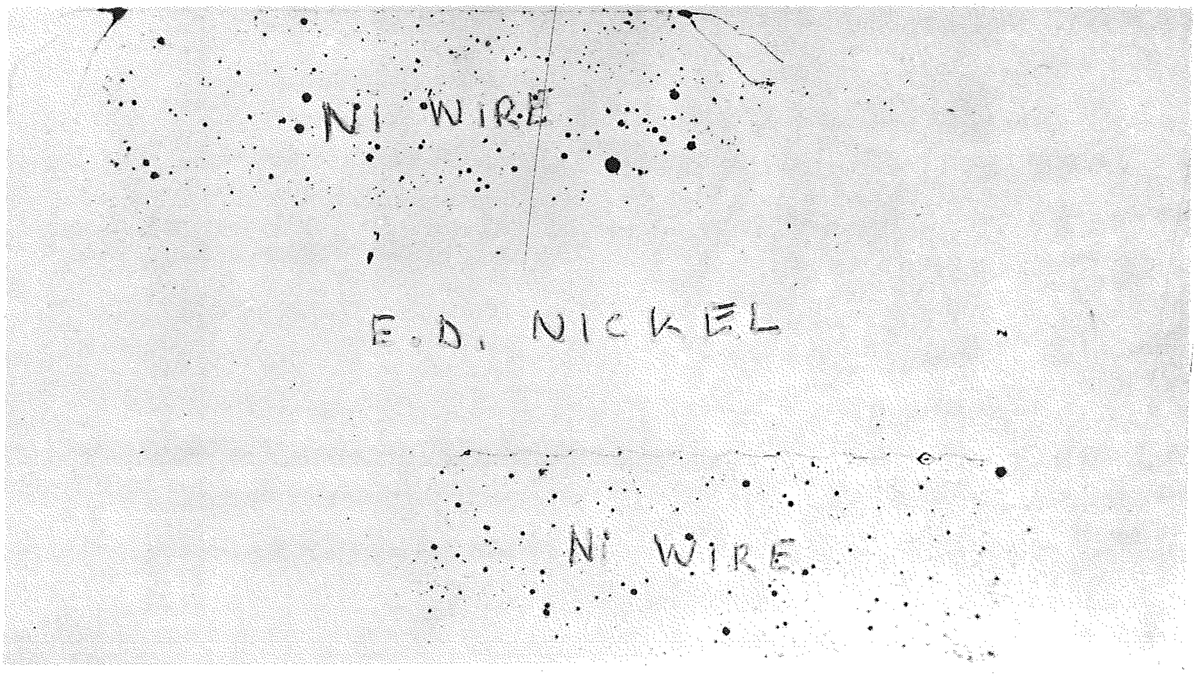


FIGURE 9 RIBBON WRAPPED REINFORCED ELECTROFORMED NICKEL

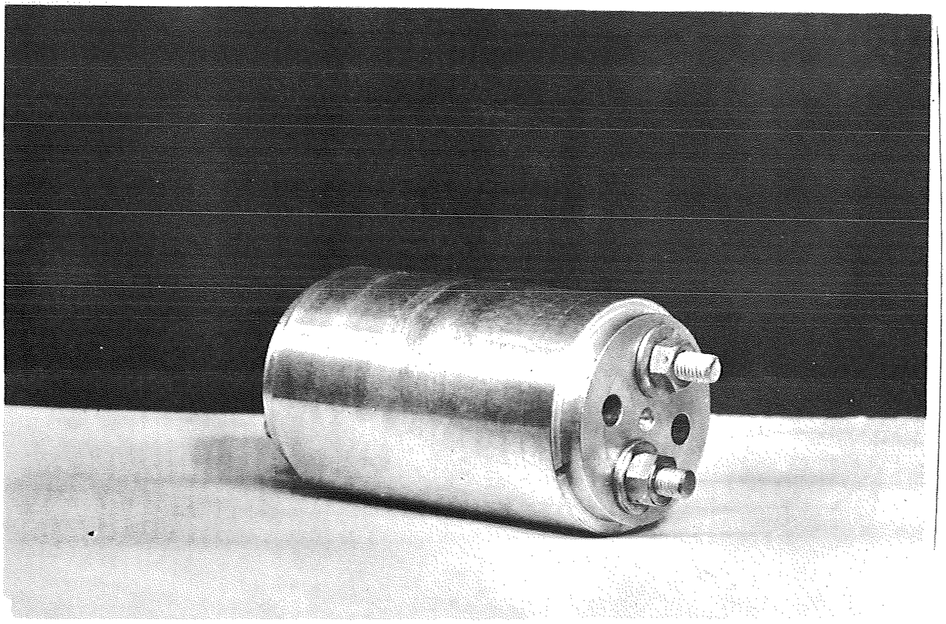


FIGURE 10 INCONEL LINER AND MANDREL

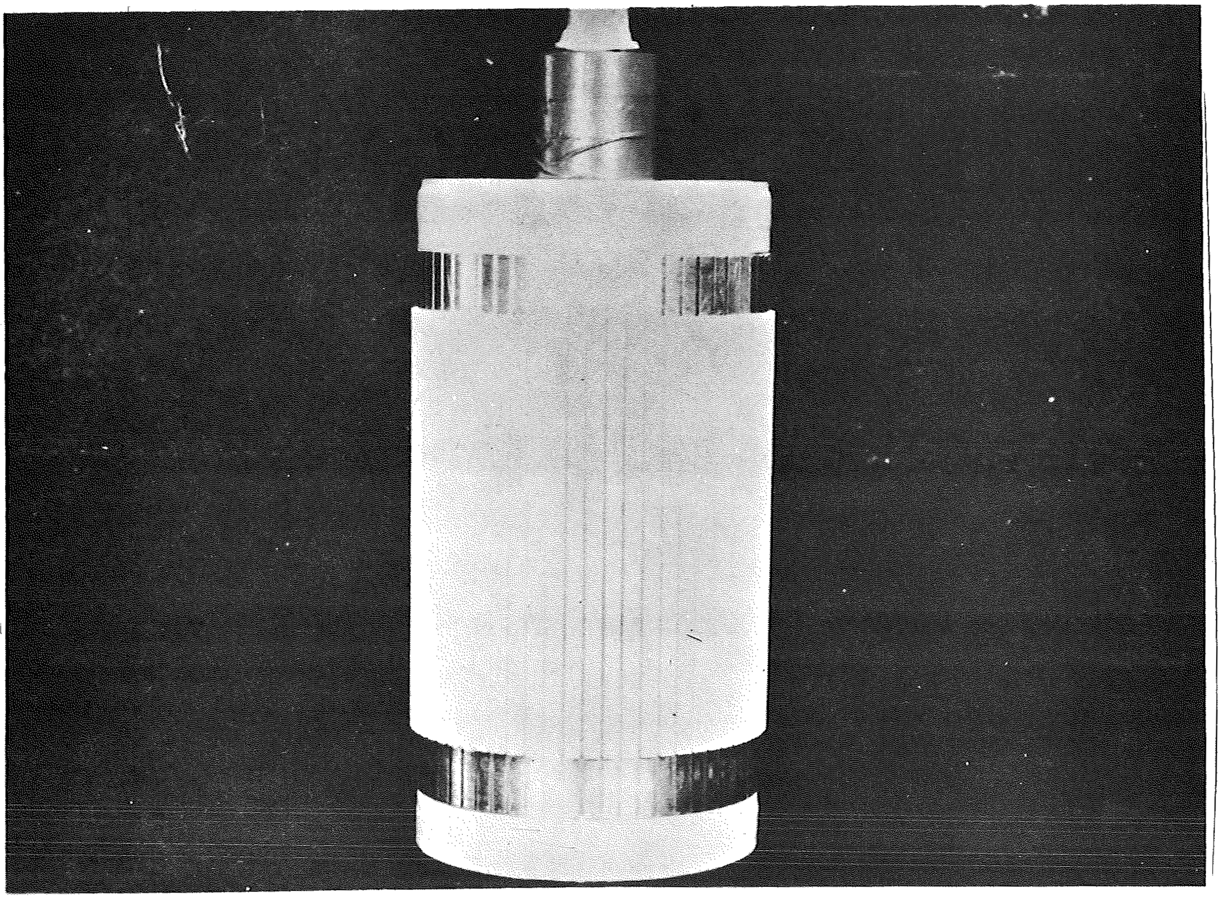


FIGURE 11 MANDREL AND LINER PRIOR TO RIB BUILDUP

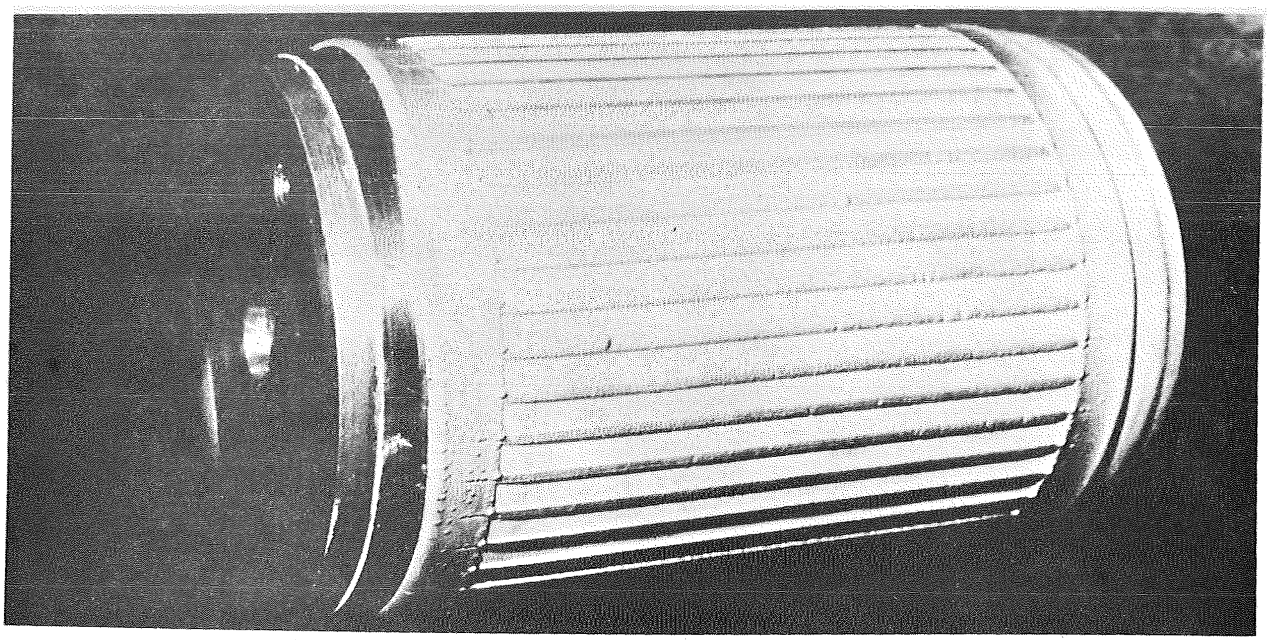


FIGURE 12 MANDREL AFTER RIB BUILDUP

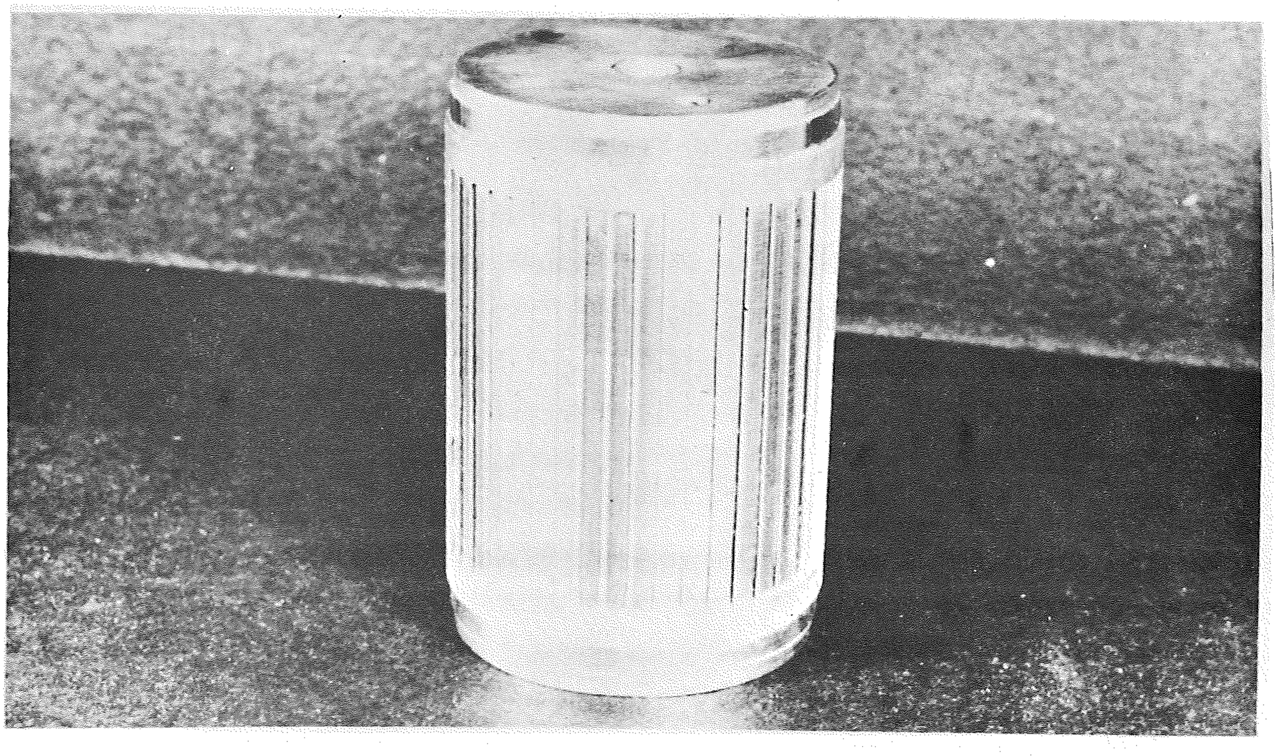


FIGURE 13 LINER WITH ELECTROFORMED NICKEL RIBS

FIGURE 14 COMPLETED CYLINDRICAL RIBBED TEST SPECIMEN

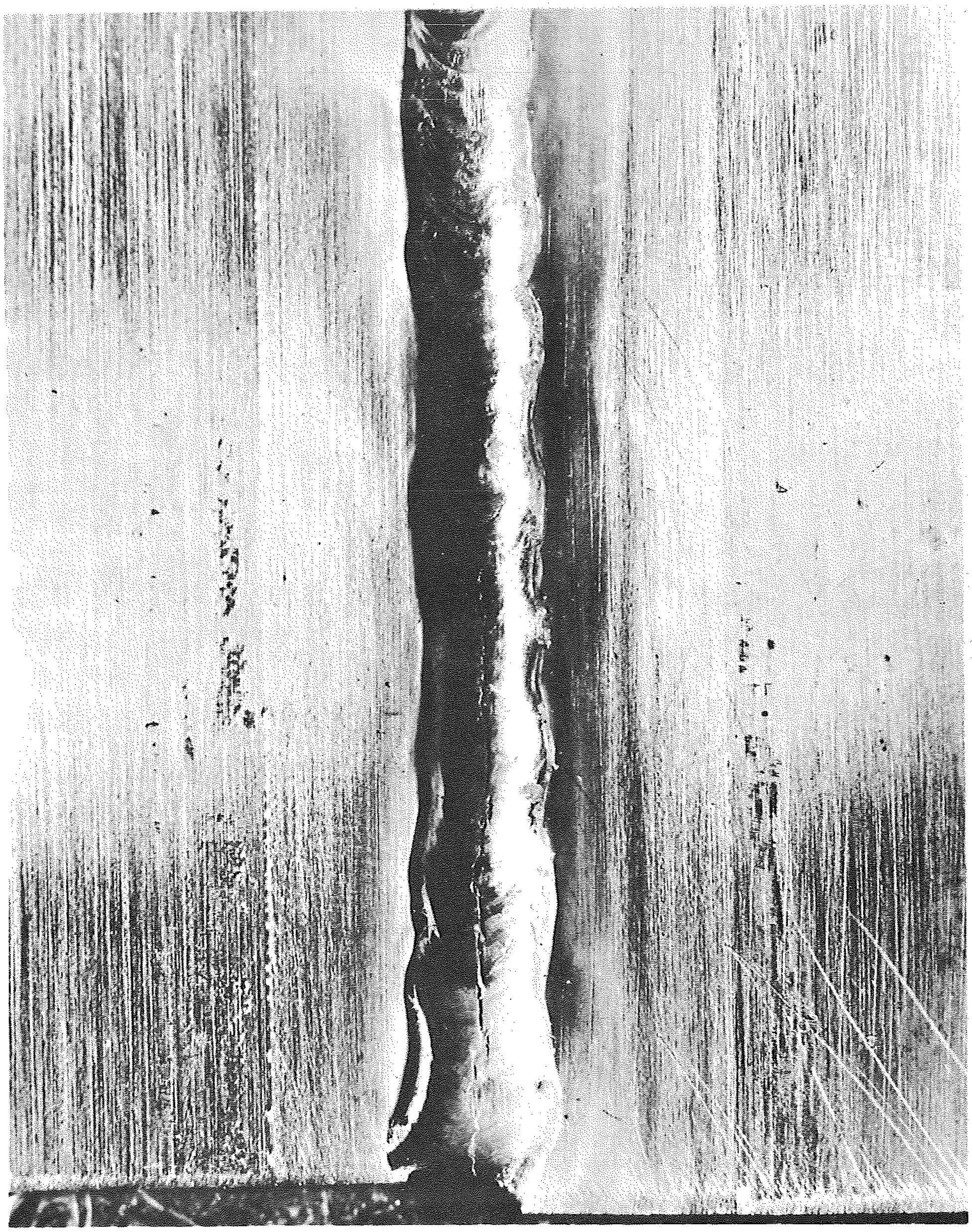


FIGURE 15 TD NICKEL WELD

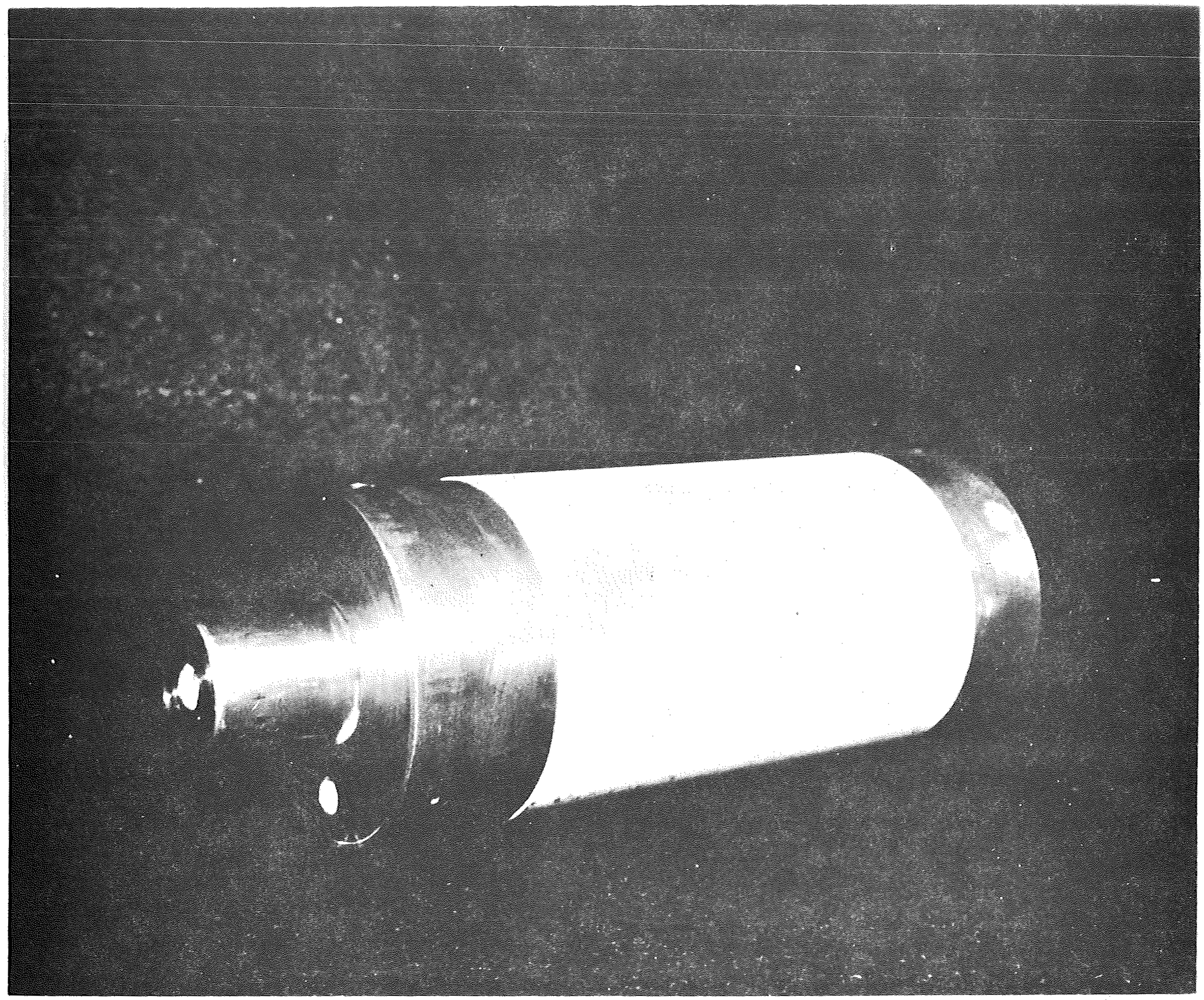
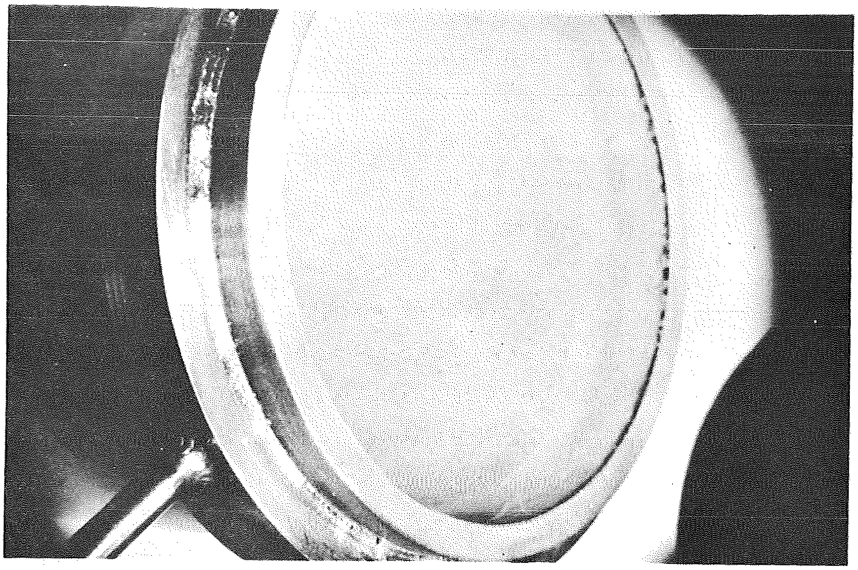
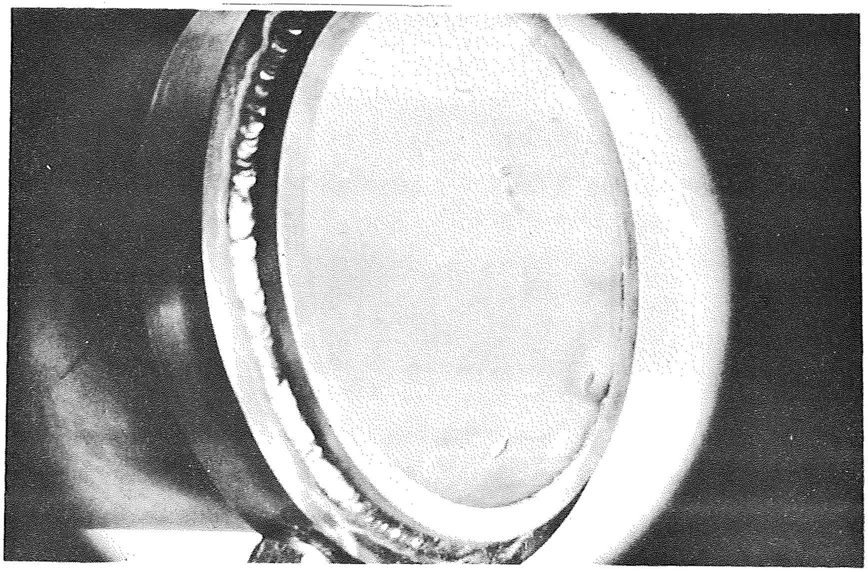


FIGURE 16 PLASMA COATED COPPER MANDREL



A) HELIARC WELD



B) ELECTRON BEAM WELD

FIGURE 17 CERAMIC LINED UNITS AFTER WELDING

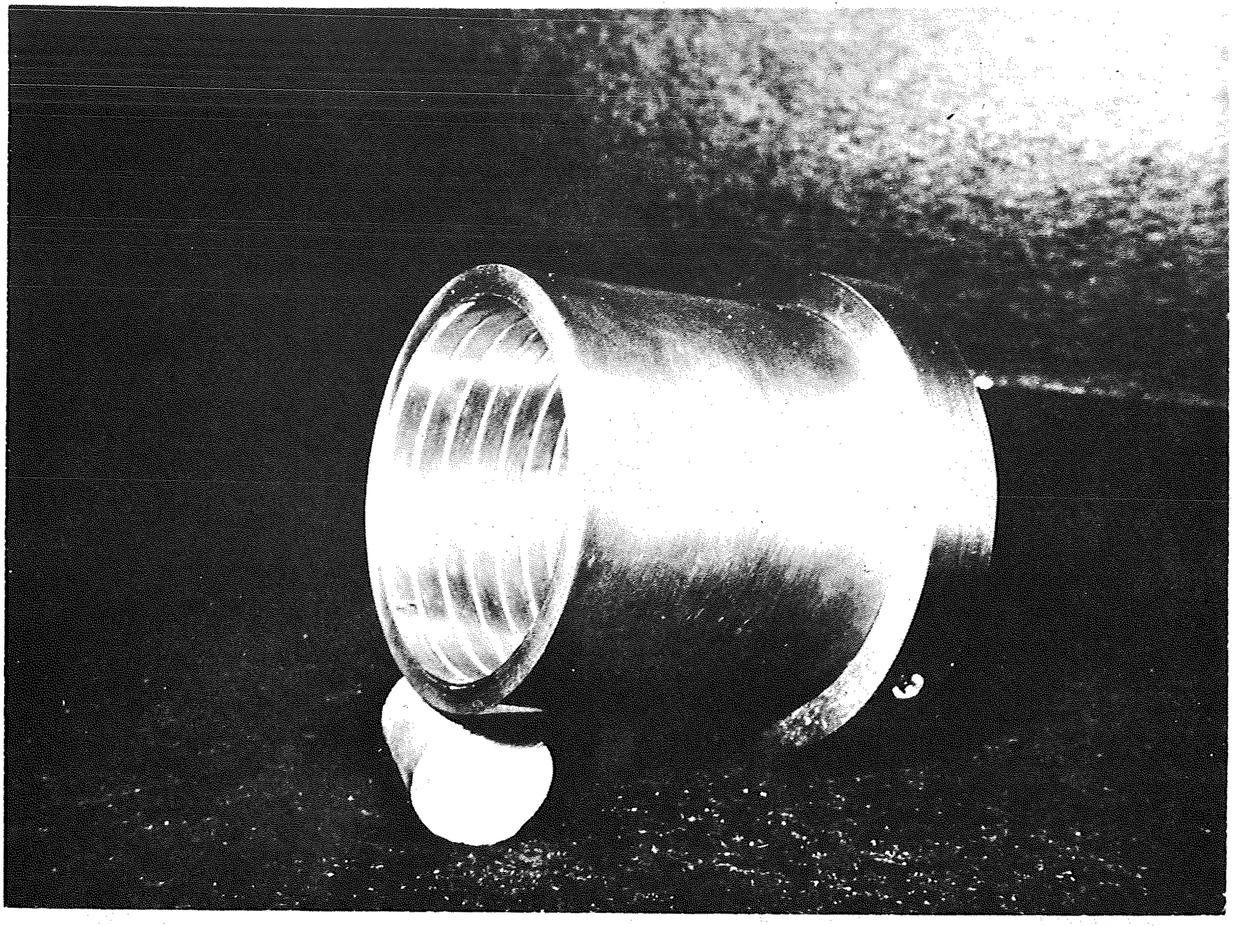


FIGURE 18 RIBBON WRAP INNER LINER TEST SPECIMEN

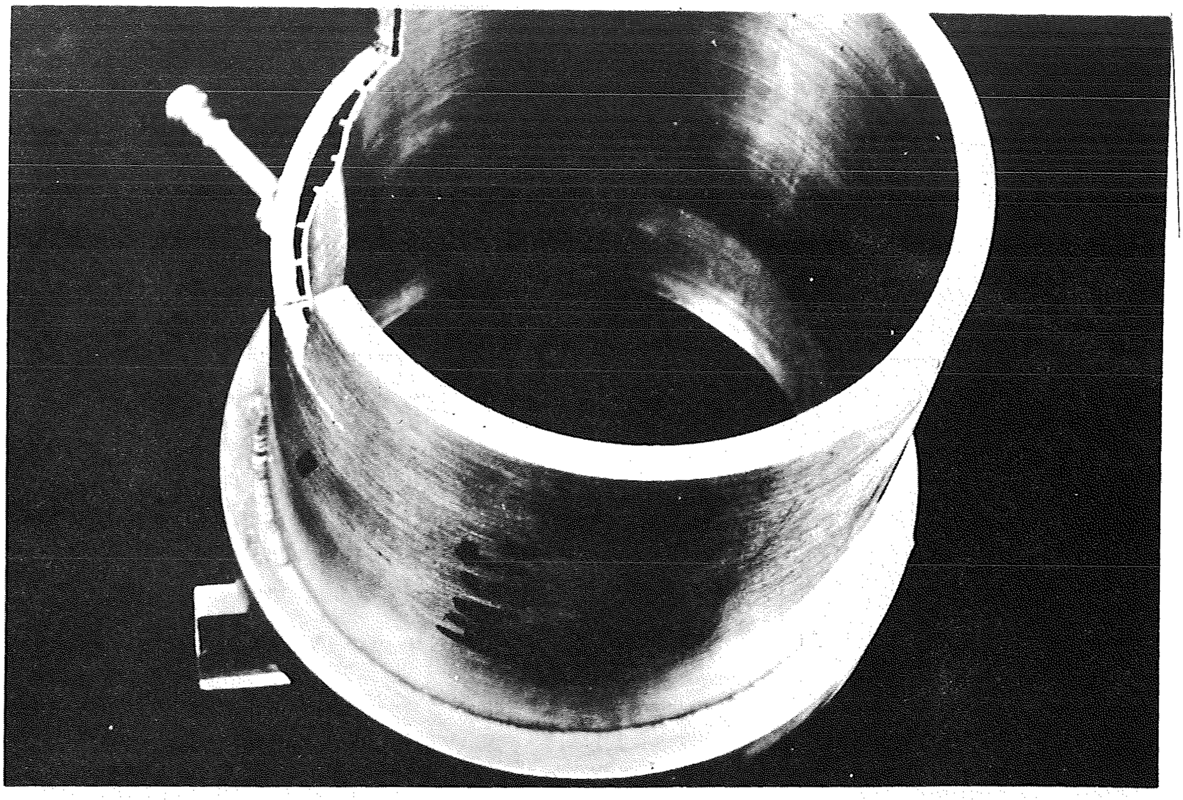


FIGURE 19 HASTELLOY X LINER #1

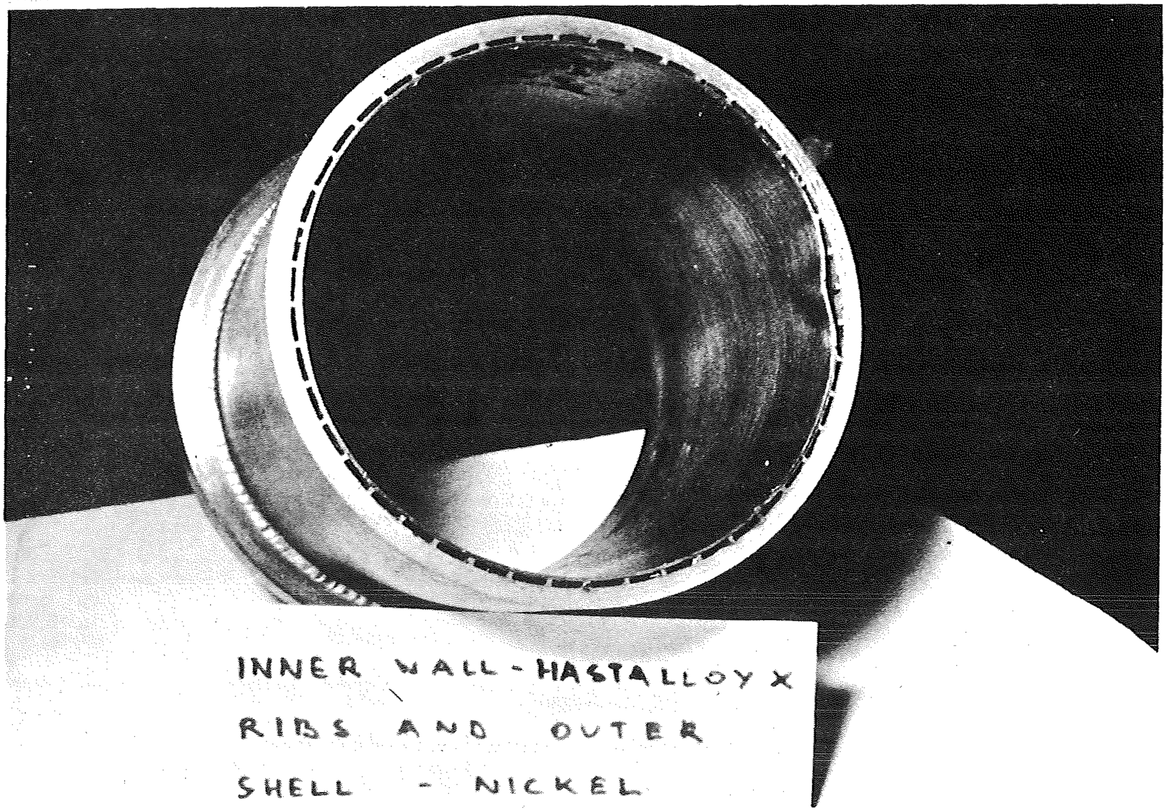
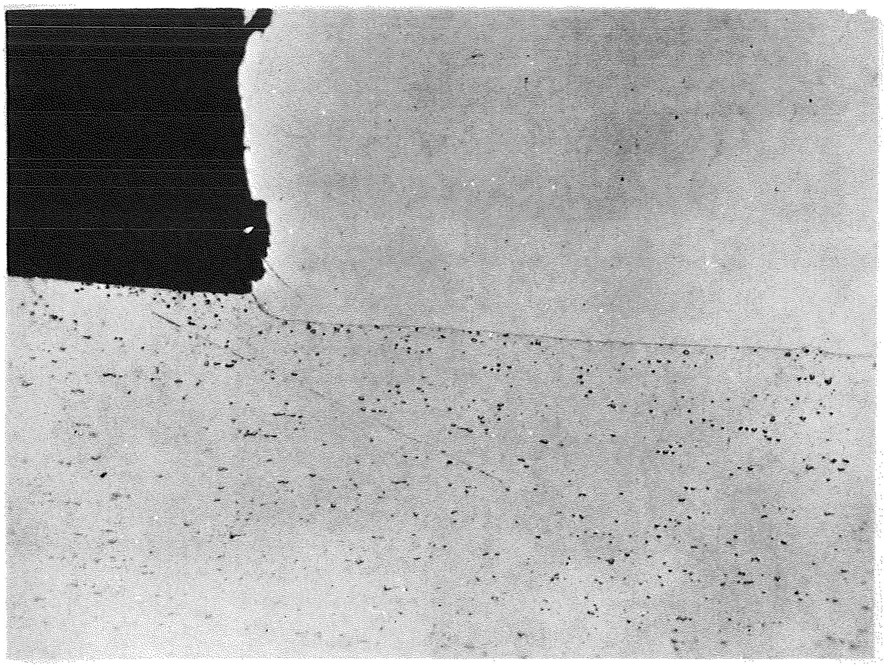
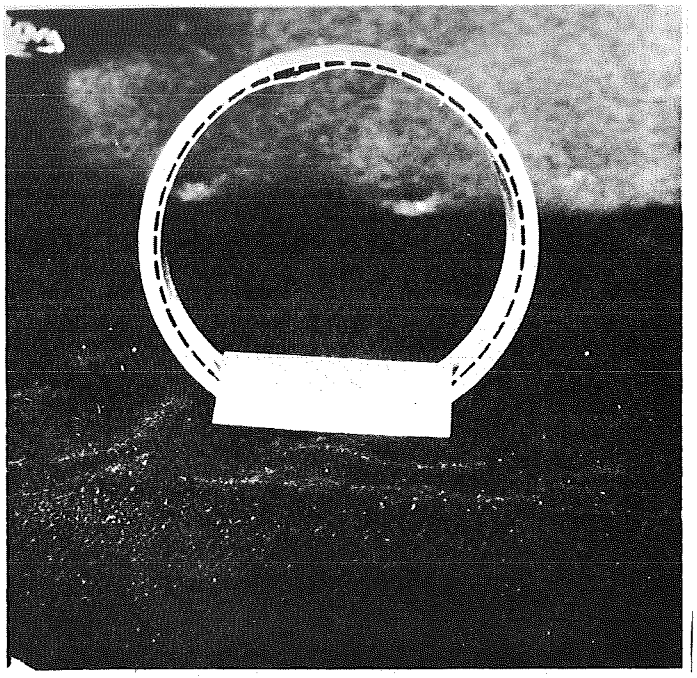


FIGURE 20 HASTELLOY X- LINER #2

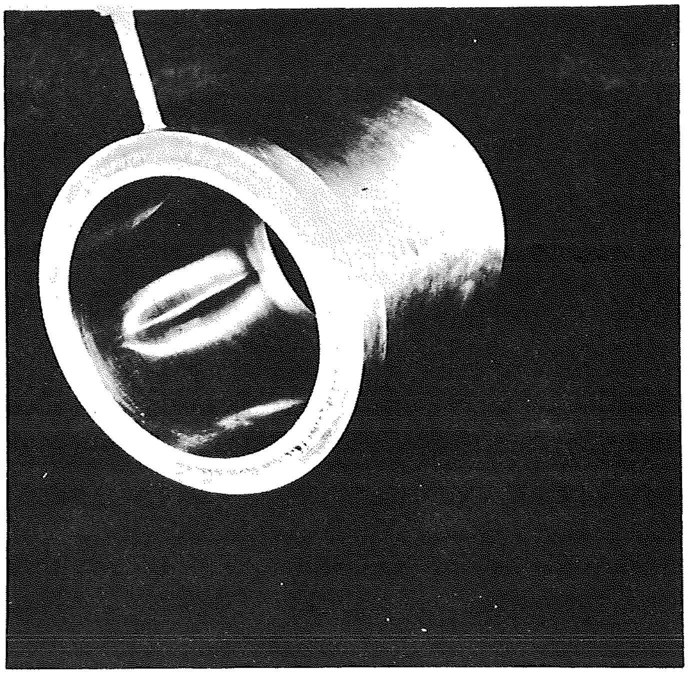


MAGNIFICATION : 175 X

FIGURE 21 HASTELLOY X- EF NICKEL RIB INTERFACE



(A)



(B)

FIGURE 22 INCONEL LINER FAILURE

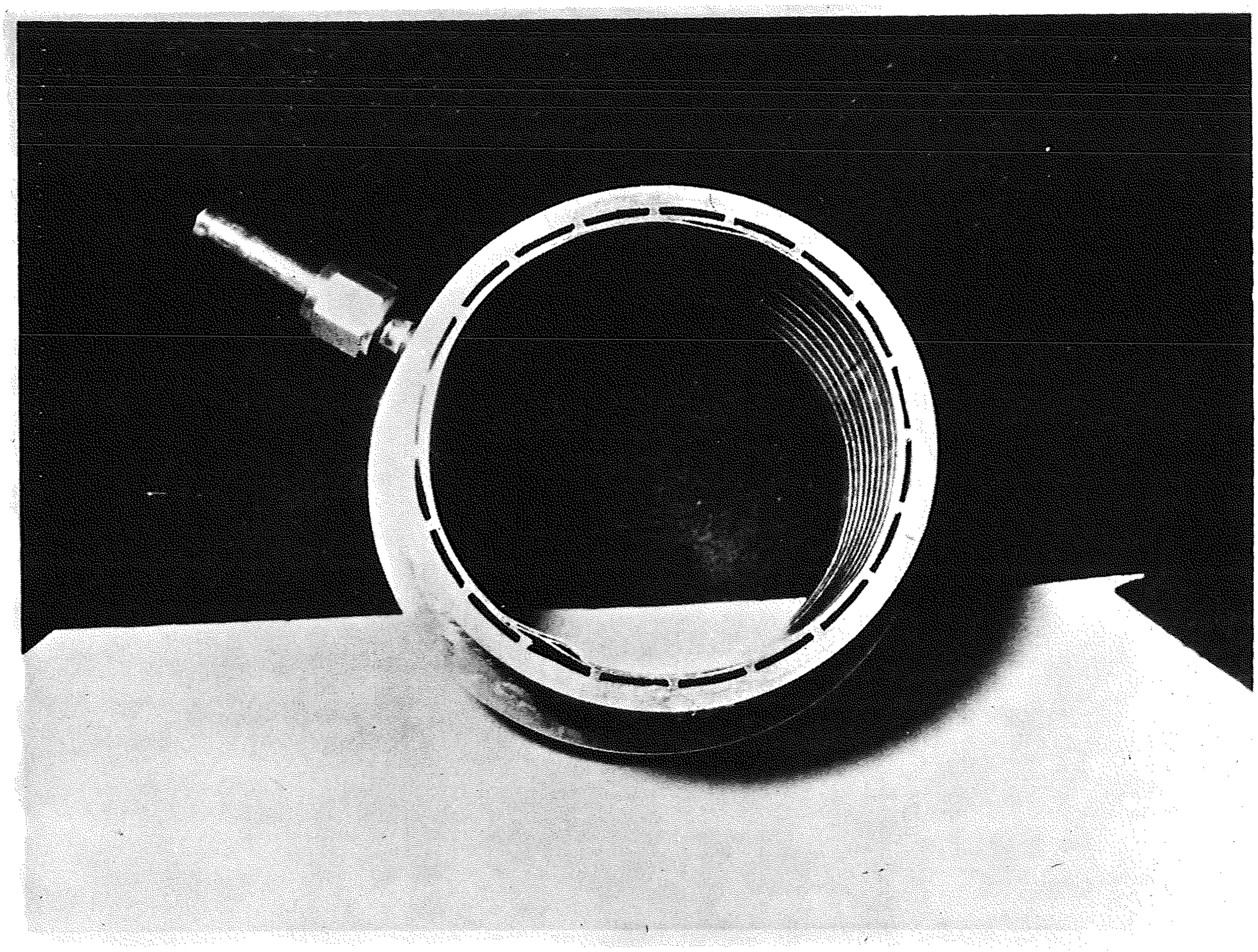
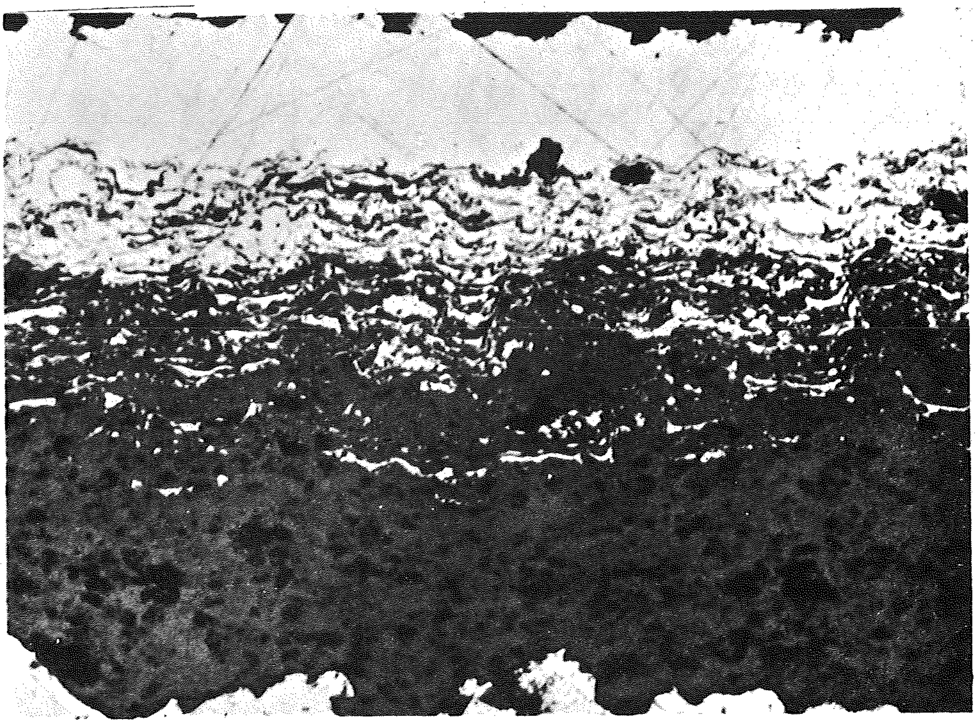


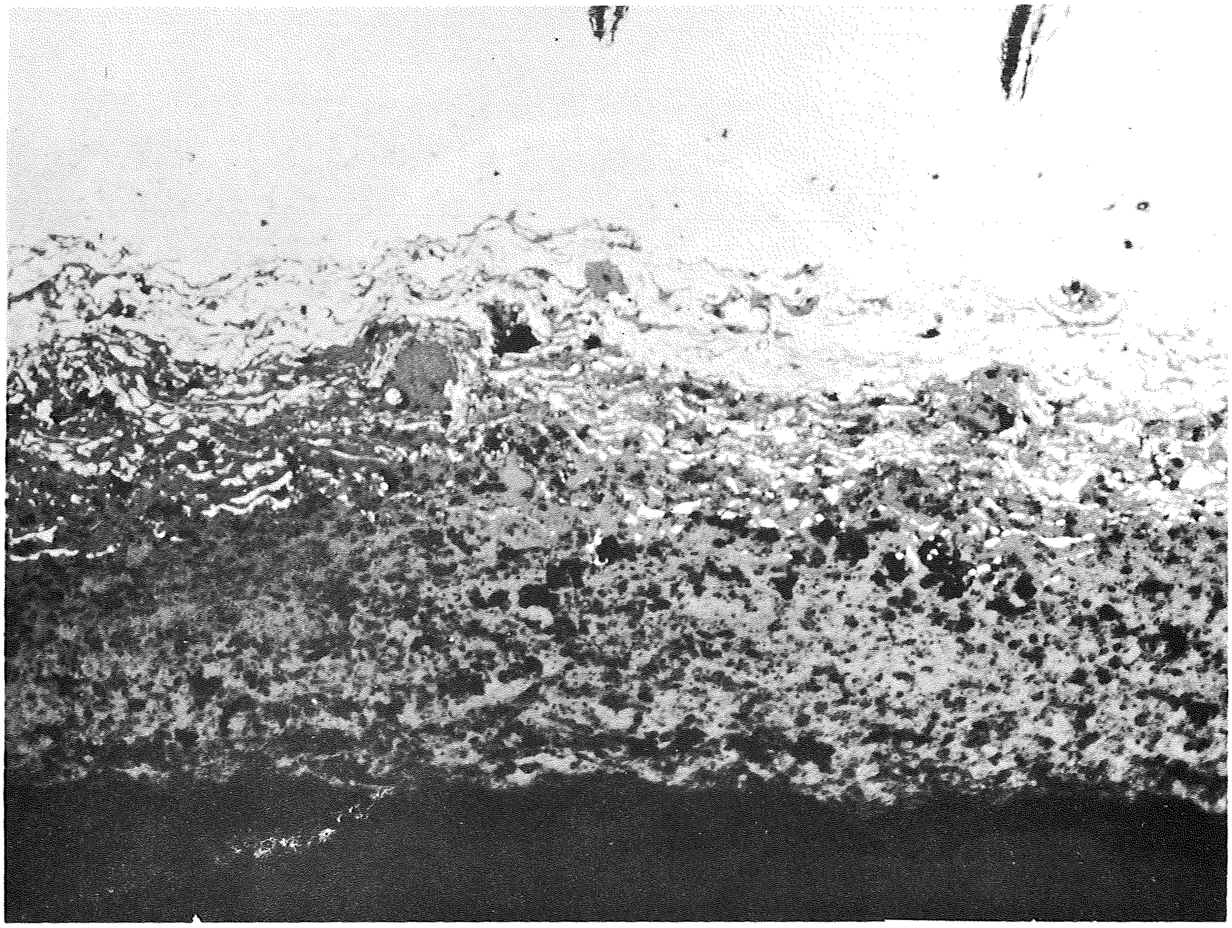
FIGURE 23 WIRE WRAPPED LINER FAILURE



.012 "

MAGNIFICATION : 200 X

FIGURE 24. GRADED COATING SAMPLE PHOTOMICROGRAPH



MAGNIFICATION : 30 X

FIGURE 25 GRADED COATING - NICKEL RIB INTERFACE

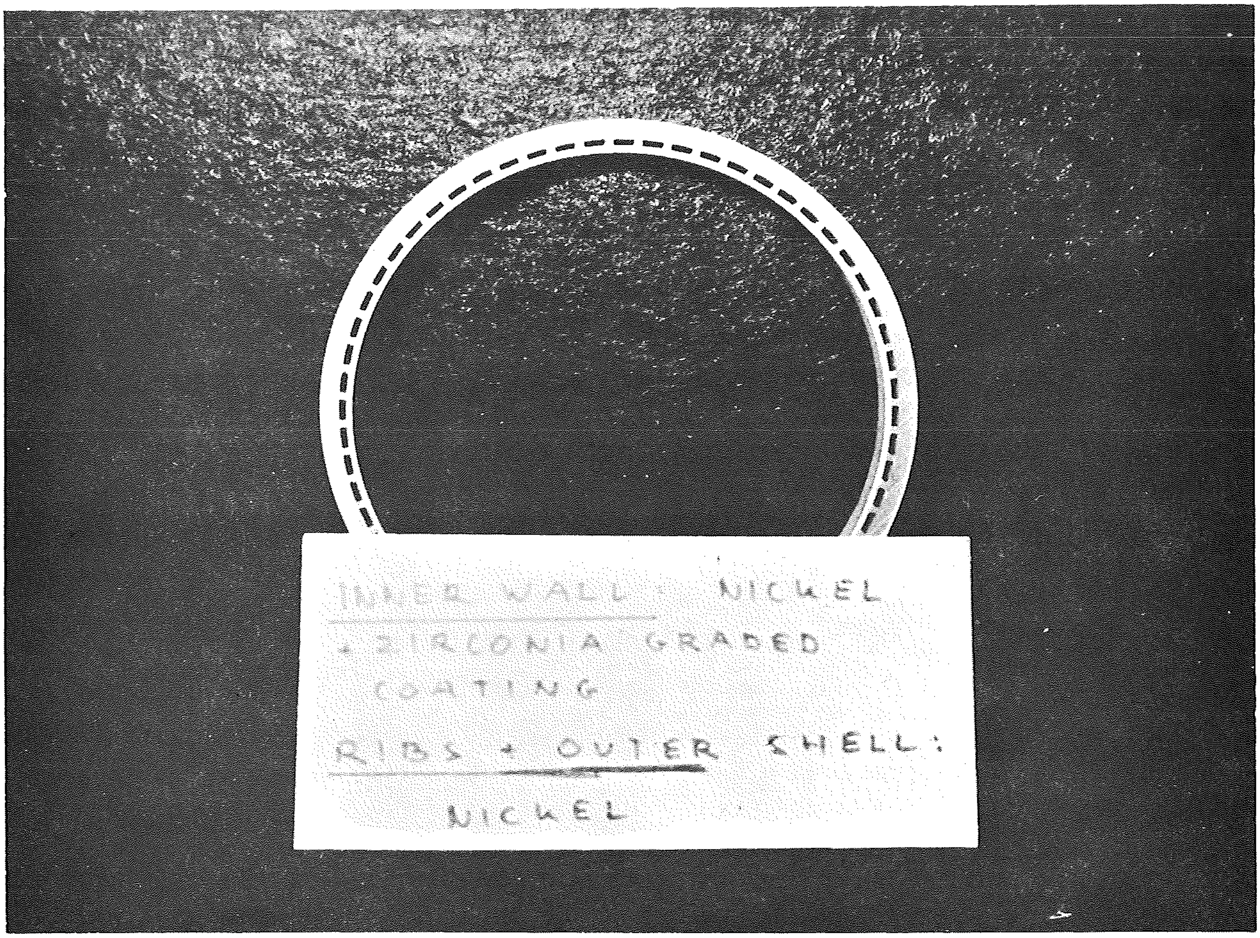
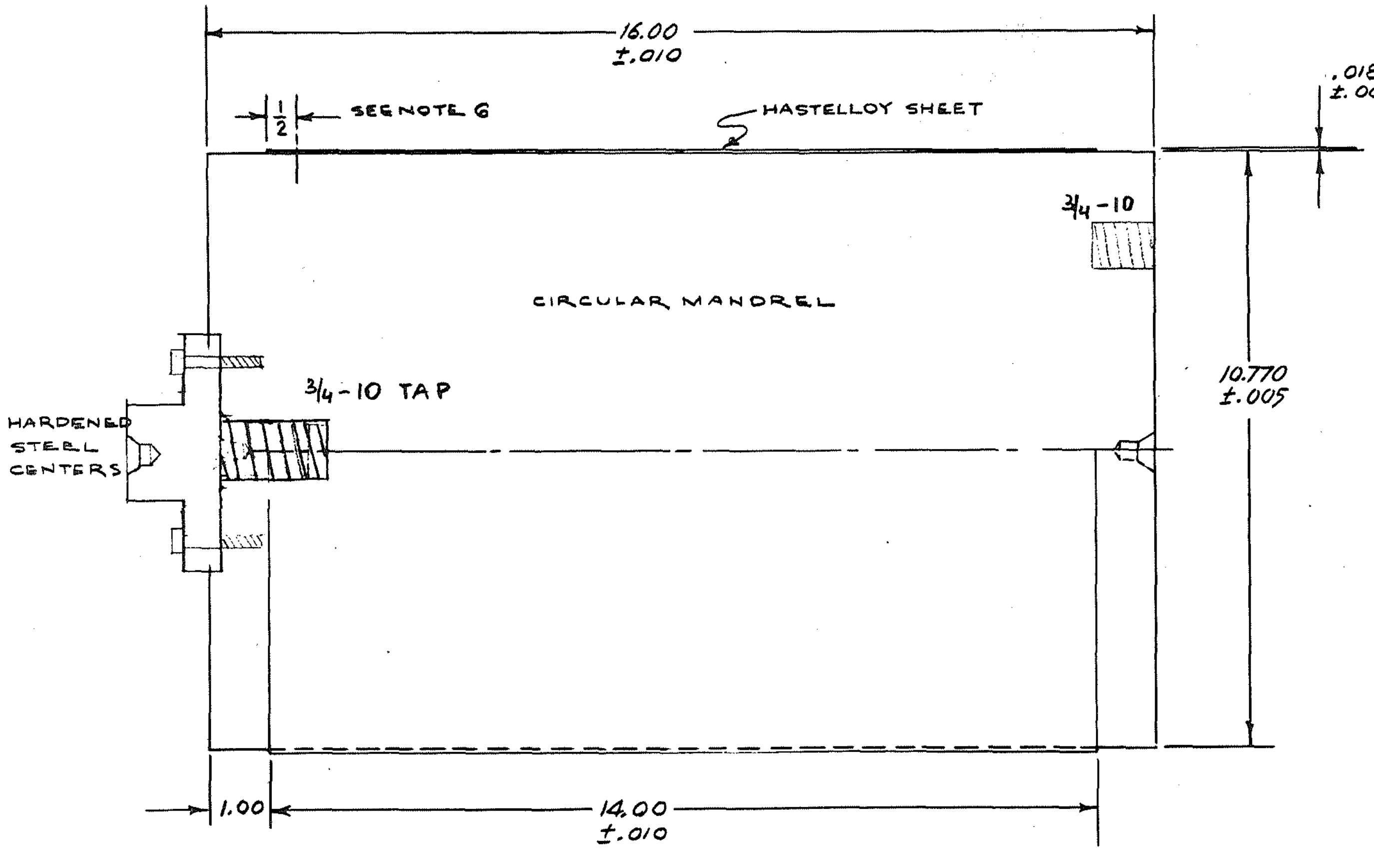


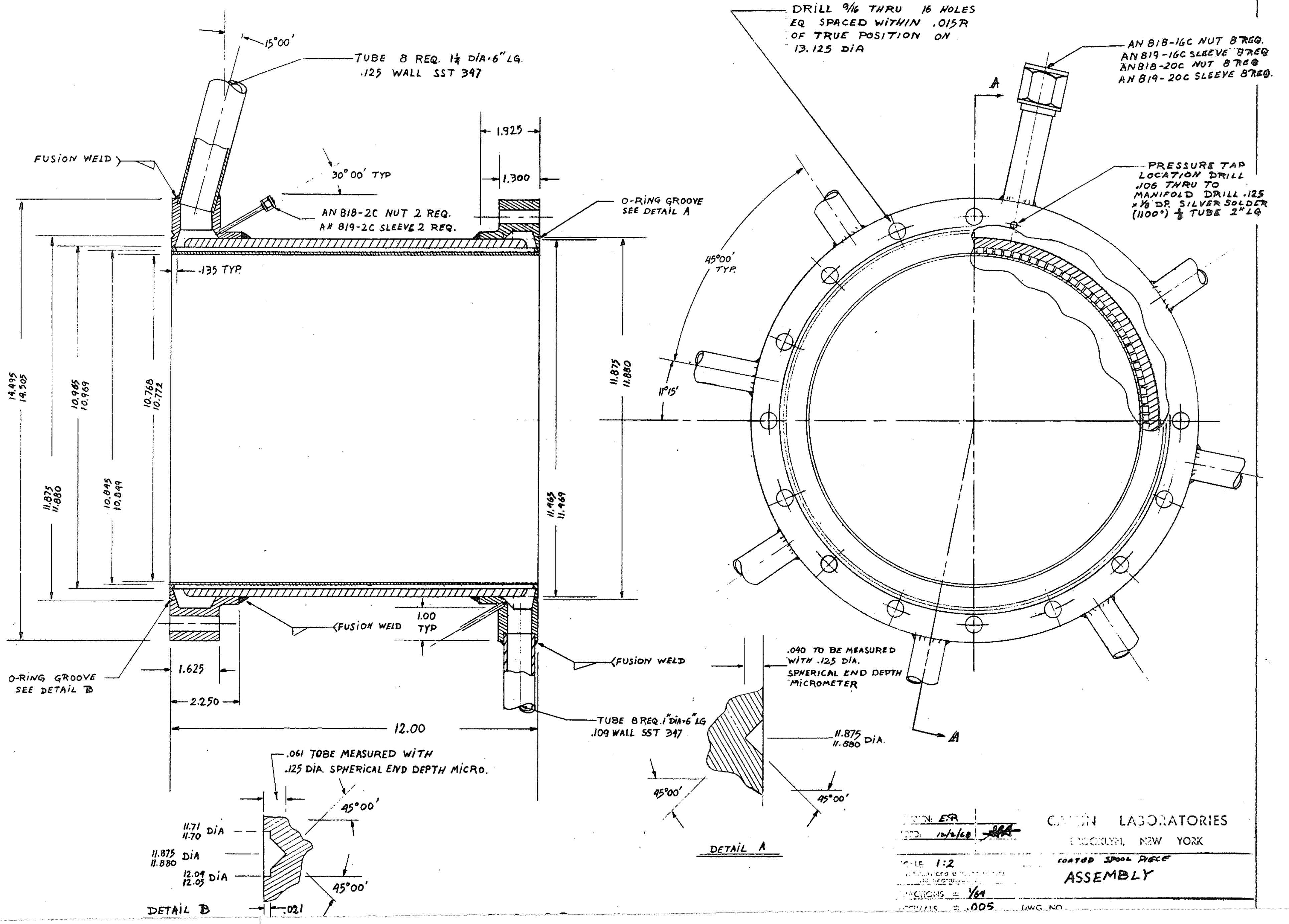
FIGURE 26 SECTIONED GRADED COATING LINER



NOTE:
1. HASTELLOY TIGHT TO MANDREL.
2. IF NECESSARY, TAPER TO BE WITHIN DIAMETRAL TOLERANCES.
3. NO UNDERCUTS ON MANDREL SURFACE.
4. MANDREL HOLLOW IF POSSIBLE.
5. HASTELLOY TO BE CONCENTRIC WITH MANDREL.
6. IF NECESSARY, PIN WITHIN 1/2" OF END OF SHEET.
7. HASTELLOY SHEET ULTIMATELY TO BE REMOVED FROM MANDREL.

SCALE: ~ 1/2	CAMIN LABORATORIES, INC.
TOLERANCES: AS SHOWN	CHAMBER MANDREL (HASTELLOY LINER)
	DWG. NR. EFM LK 050

FIG. 27



DRN: ESR
CHKD: 12/2/68

LABORATORIES
BROOKLYN, NEW YORK

SCALE: 1:2

FRACTIONS ± 1/64
DECIMALS ± .005

COATED SPOOL PIECE
ASSEMBLY

DWG. NO.

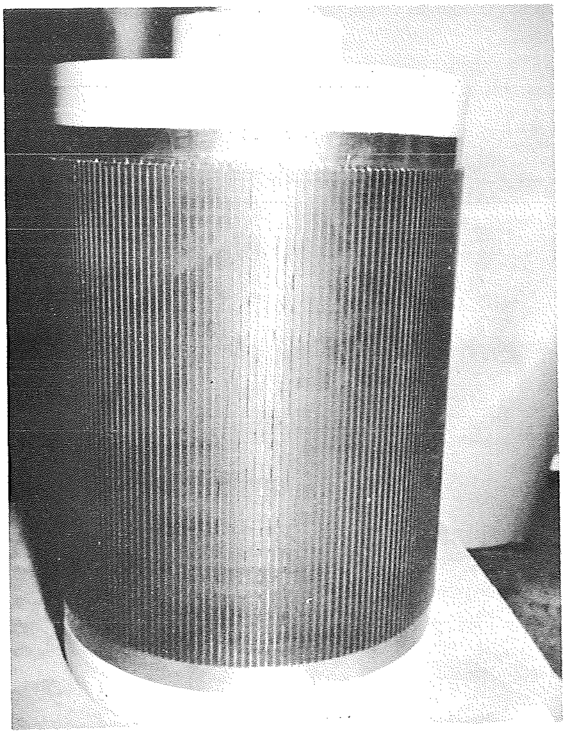


FIG. 29 HASTELLOY SPOOL-GROOVED VINYL

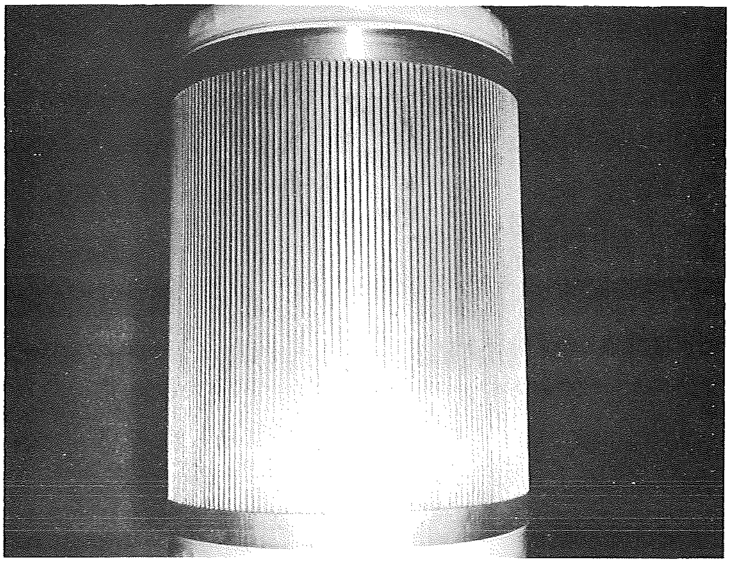


FIG. 30 HASTELLOY SPOOL-EF NICKEL RIBS

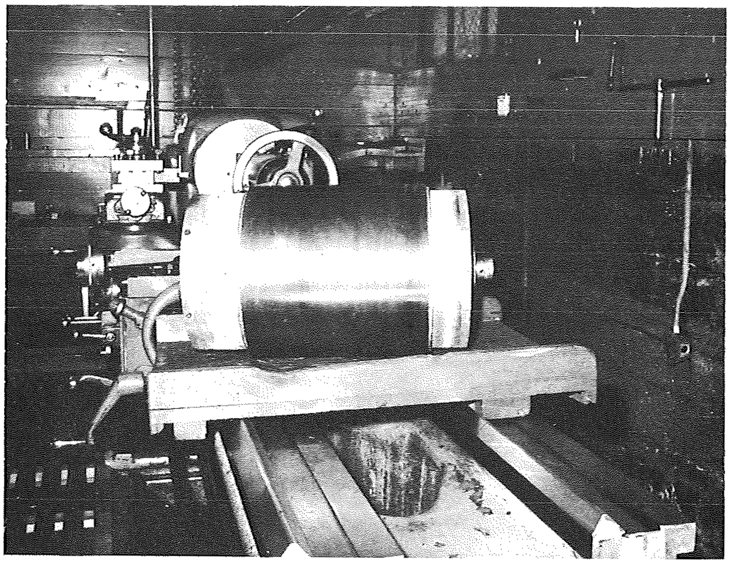


FIG. 31 SPOOL PIECE OUTER JACKET

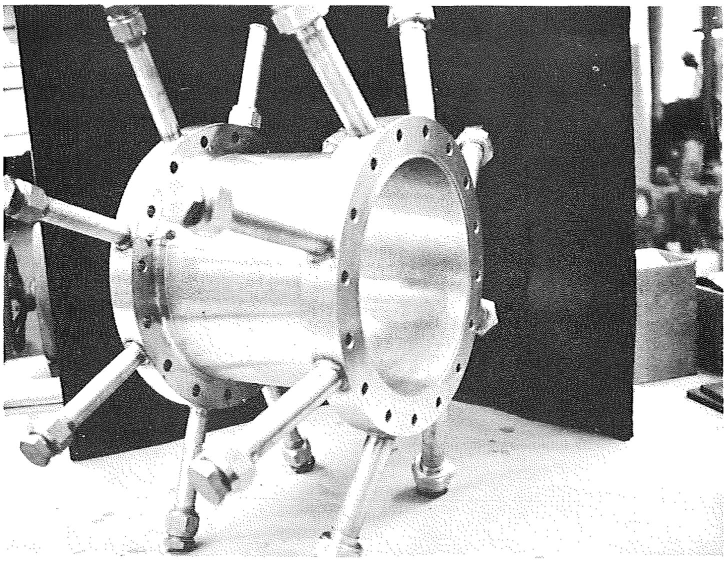


FIG. 32 HASTELLOY SPOOL PIECE

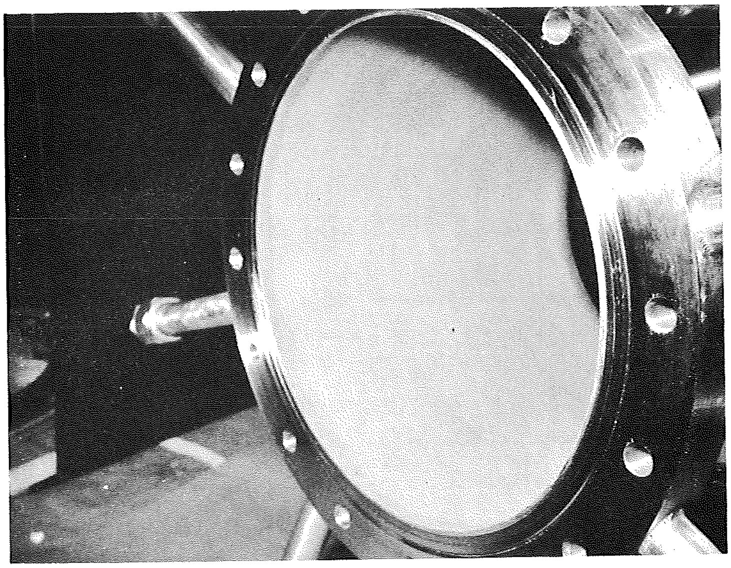
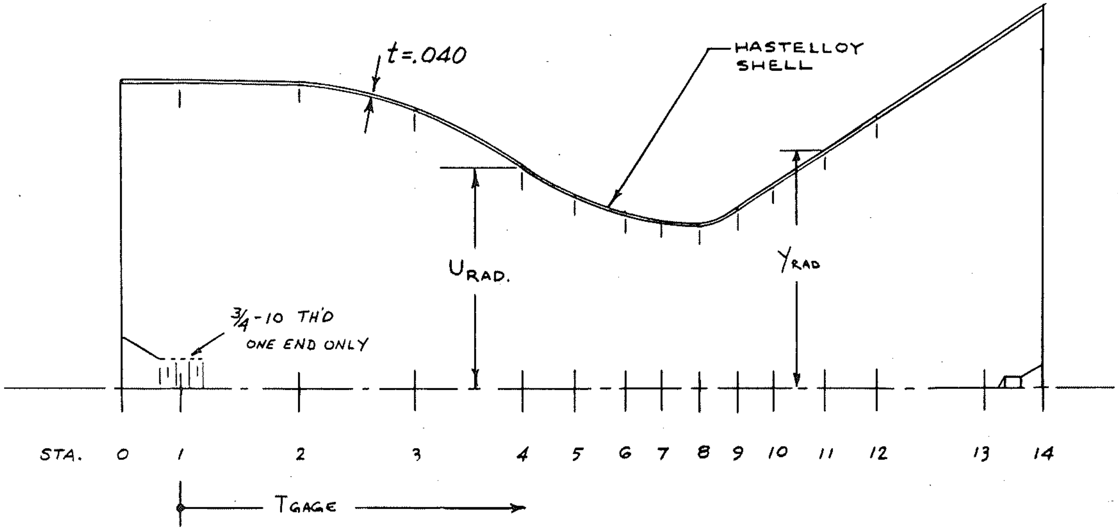


FIG. 33 COATED SPOOL PIECE



STA	T_{GAGE}	$U_{RAD.}$
0	-1.000	5.100
1	0	5.100
1A	1.000	5.094
2	1.997	5.070
2A	3.000	4.937
3	3.993	4.655
3A	4.870	4.251
4	5.750	3.709
4A	6.100	3.487
5	6.619	3.220
5A	7.000	3.064
6	7.494	2.907
7	8.097	2.765
7A	8.400	2.720
8	8.744	2.710
8A	9.000	2.797
9	9.391	3.000
10	9.994	3.385
11	10.869	3.960
12	11.738	4.530
12A	12.650	5.103
13	13.555	5.667
14	14.555	6.292

NOTES

1. 1" MIN HARDENED CENTERS
2. MANDREL SPLIT AT STA. 8 AND BOLTED TOGETHER
3. O.D. OF SHELL TO BE CONCENTRIC WITH CENTERS
4. TOLERANCES NON ACCUMULATIVE
5. OUT OF ROUNDNESS LESS THAN .005., I.E., DIAL INDICATOR READINGS OF Y_{RAD} TO INDICATE LESS THAN .005 VARIATION IN Y_{RAD} AT EACH T_{GAGE}.

FIG. 34

DRAWN 10-25-68 MM
CHKD. 11/1/68

CAMIN LABORATORIES
BROOKLYN, NEW YORK

SCALE 1"=2"

NOZZLE SEGMENT
HASTELLOY LINER

FRACTIONS ±
DECIMALS ± .003
ANGULAR ±

DWG. NO. EFM-LK 600

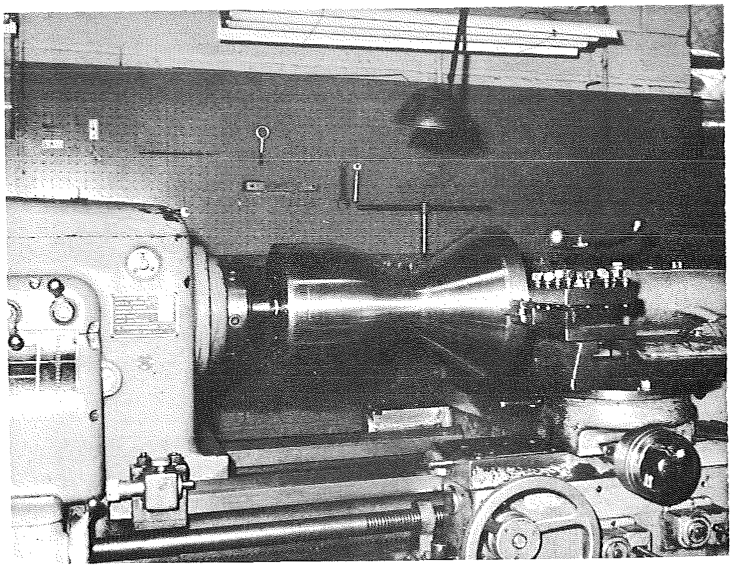


FIG. 35 HASTELLOY CHAMBER SEGMENT MANDREL

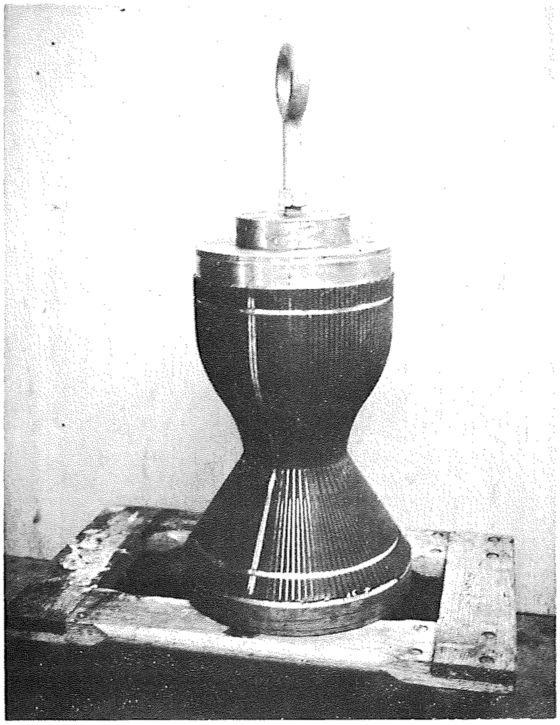


FIG. 36 CHAMBER SEGMENT PRIOR TO RIB GROWTH

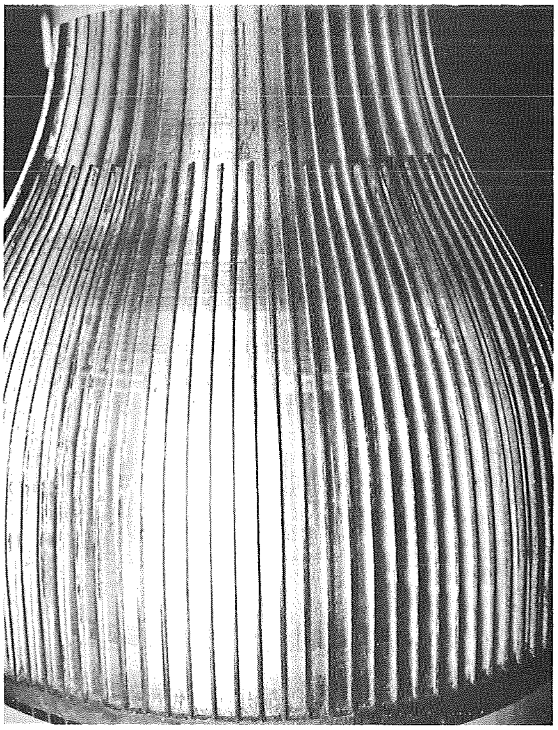


FIG. 37 CHAMBER SEGMENT~EF NICKEL RIBS

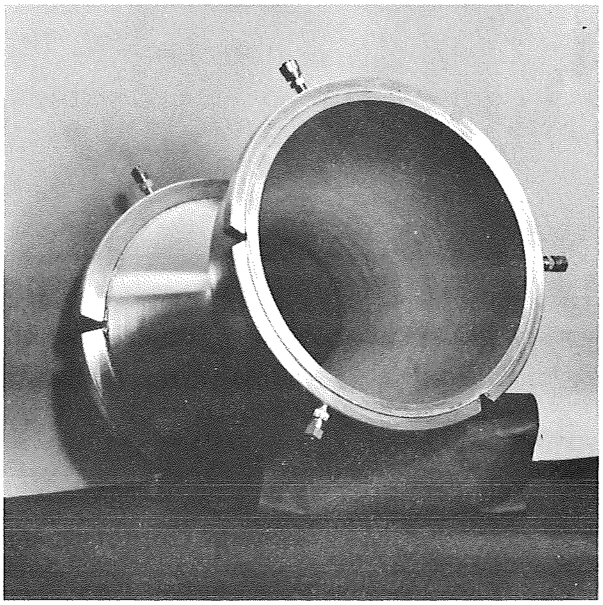


FIG 38 COMPLETED COATED SEGMENT

APPENDIX A: DESIGN ANALYSIS OF RIBBED TEST SPECIMENS

The mechanical stresses imposed on the cylindrical ribbed specimens are discussed below. The nomenclature is noted on the following page.

The tensile stress in the inner wall under the action of a hydrostatic loading in the cooling passage is given by (Ref. 5).

$$\sigma_{t_i} = \frac{Eu^2}{3(1-\nu^2)} \left(\frac{t^2}{h^2}\right) \qquad (1)$$

where

E = Young's Modulus

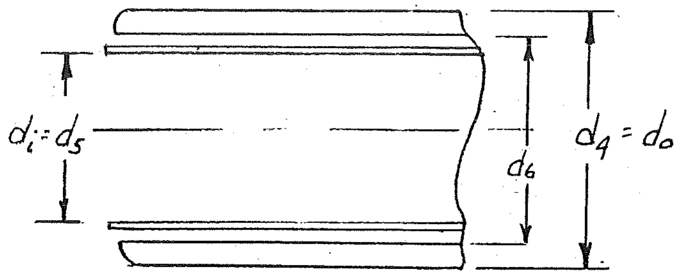
t = inner wall thickness

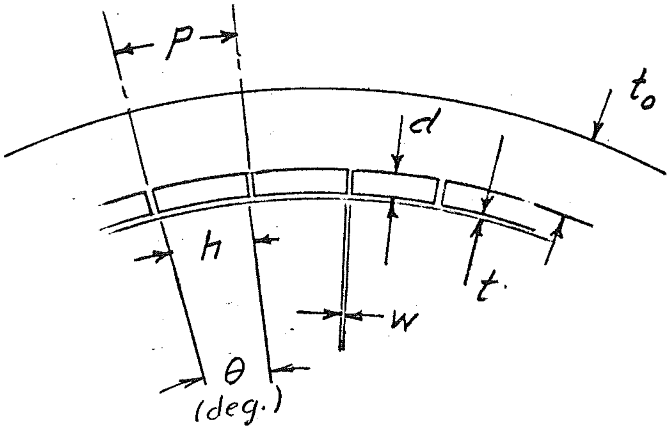
h = cooling passage width

ν = Poissons ratio

The parameter u satisfies the relationship

$$\frac{E^2t^8}{(1-\nu^2)q^2h^8} = -\frac{81}{16u^7\tanh u} - \frac{27}{16u^6\sinh^2 u} + \frac{27}{4u^8} + \frac{9}{8u^6} \qquad (2)$$





p = RIB SPACING

h = DISTANCE BETWEEN RIBS

w = RIB WIDTH

d = RIB HEIGHT

t_i = INNER WALL THICKNESS

N = NUMBER OF RIBS

t_o = OUTER WALL THICKNESS

NOMENCLATURE USED IN STRUCTURAL ANALYSIS where q = maximum pressure differential across the inner wall.

The maximum shear stress in the inner wall occurs at the rib-wall joint and is given by (Ref. 3),

$$\sigma_{s_i} = \frac{qh}{2t} \tag{3}$$

The maximum bending stress is obtained from,

$$\sigma_{b_i} = \frac{q}{2} \left(\frac{h^2}{t^2}\right) \tag{4}$$

In the case where the chamber pressure, P_c is greater than the coolant passage pressure, P_w, the ribs receive a compressive loading. The resultant compressive stress is

$$\sigma_{cr} = \frac{q}{w} (h+w) \tag{5}$$

where w = rib width.

If, on the other hand, the coolant passage pressure exceeds the chamber pressure, the stress on the ribs becomes tensile and is determined by

$$\sigma_{t_r} = \frac{q}{w} h \tag{6}$$

The circumferential stress in the inner and outer walls of the unit is,

$$\sigma_\phi = \frac{q\bar{r}}{t_i + t_o} \tag{7}$$

where $\bar{r}$ = mean radius of section under consideration

t_o = outer wall thickness

t_i = inner wall thickness

A. Dissimilar Metal Liners.

Considering first the design of the dissimilar metal liners it would be ideal to design these units to fail due to tensile stresses at the rib-shell interface. This would result in further quantitative data concerning the strength of the bond between the electroformed rib and the metal liner. However, it will be shown by the subsequent calculations, that the geometry required to achieve this type failure is not indicative of thrust chamber geometry nor practical to fabricate.

If we assume the following geometry:

d_i = inside diameter = 4 inches

t_i = inner wall thickness = .030 inches

N = number of ribs = 45

w = rib width = .040 inches

d = rib height = .050 inches

t_o = outer shell thickness = .150 inches

q = cooling passage pressure = 1500 psi

h = cooling passage width = .244 inches

the following stresses are calculated:

σ_{s_i} = inner wall shear stress = 6100 psi

σ_{b_i} = inner wall bending stress = 49,500 psi

σ_{t_r} = rib tensile stress = 9150 psi

σ_{ϕ} = circumferential stress = 17,600 psi

Examination of the tensile stress in a rib (Equation 6) shows that to achieve a stress of 90,000 psi at a coolant passage pressure as high as 3000 psi, the ratio of coolant passage width to rib width must be 30. For rib widths as small as .020" the coolant passage width must be .6 inches. However, at these conditions the inner wall thickness would be in excess of .100 inches in order to prevent the inner wall from failing due to bending. Examination of the previous equations (in particular Equations 4 and 6) indicates that for realistic thrust chamber configurations, the critical stress is that due to bending of the inner wall.

The above configuration was therefore chosen for the cylindrical ribbed test specimen. The inner wall thickness, rib width and cooling passage width are indicative of realistic thrust chamber designs.

B. Sprayed Refractory Coating.

Manufacturers' data indicates that the flexural strength of zirconia is 21,000 psi. Owing to the brittle character of the oxide and the uniqueness of the fabrication techniques, the allowable stress was limited to 60% of the bending strength or 12,600 psi. A non-failure criterion is assumed such that the electroformed nickel (bonded to the coating) will not allow the bending stress imposed on the coating to exceed the above value when the pressure differential across the inner wall approaches a value, $q = 1500$ psi.

Solving equation 4 for h/t_i,

$$\frac{h}{t_i} = \left[\frac{2\sigma_{bi}}{q}\right]^{\frac{1}{2}} = 4.10$$

The rib spacing is defined by

$$\theta = \frac{360P}{\pi(d_i+2t_i)} \tag{8}$$

Assuming a value, $d_i = 4.0$ in., $t_i = .040$ in. and $w = .050$ in., h is found to be .164 in. and $\theta = 6$ degrees.

Therefore, the configuration will contain 60 ribs measuring .050 wide by .050 high.

The total nickel thickness, T, is computed by limiting the circumferential stress,

$$\sigma_\phi = q \left[\frac{d_i + t + T}{2(t + T)} \right]$$

where t = coating thickness (.012 in.)

Solving the previous equation for T and imposing σ_ϕ = 12600 psi, T = .254 in. If the inner wall (nickel) thickness is .040 in. and the rib height is .050 in., then the outer jacket thickness is t_o = .160 in. for a pressure differential of 1500 psi.

C. Wire Wrap Liner.

In view of the lack of analytical procedures for this configur~~ation,~~ a simplified design process is used. It is assumed that the inner wall is Inconel 600 throughout for which the allowable bending stress is

$$\sigma_b = .6\ \sigma_{y.p.} = 72{,}000 \text{ psi}$$

Solving equation 4 for h at a differential pressure of 1500 psi and an inner wall thickness of .040 (.030 wire wrap and .010 nickel) yields a cooling passage width equal to .392 inches assuming a 3.0 inch inside diameter and a rib width of .060 in., the rib spacing, equation 8 is

$$\theta = 16.8°$$

Assuming 20 ribs, ($\theta = 18°$) and a rib width of .060 in. the cooling passage width is recalculated to be .425 in. Equation 4 for the bending stress yields a maximum allowable differential pressure of 1280 psi. At this pressure the following stresses are determined

σ_{b_i} = bending stress in inner wall = 72,000 psi

σ_{s_i} = shear stress in inner wall = 6800 psi

σ_{t_r} = tensile stress in rib = 9000 psi

σ_{ϕ} = circumferential stress = 8300 psi

D. Outer Wall Reinforcement.

As explained previously, the wire wrapped reinforced shells were fabricated with a total thickness equal to that of a pure electroformed nickel shell. The bursting pressure of the units is to be compared to determine if any reinforcement is obtained. For the electroformed nickel shell, 6 inch inside diameter by

.070 inches thick the burst pressure is calculated from equation 7 to be 2300 psi for a maximum stress of 100,000 psi. No attempt was made to analyze the reinforced configuration.

APPENDIX B. SPOOL PIECE DESIGNS

Hastelloy X-EF Nickel Chamber Design

DATA: EF Nickel-Hastelloy X Bond Strengths$^{(1)}$

at room temperature - σ_{u_t} = 93000 psi

at 1000°F - σ_{u_t} = 53000 psi

EF Nickel tensile strengths - Figure B1

Hastelloy X tensile strengths - Figure B2

INITIAL GEOMETRY:

Chamber diameter, $d_i = 10.77$ in. $= d_5$

Rib height, $d \doteq .060$ in. (as per coolant requirement)

Rib width, $w \doteq .040$ in. N = 180 ribs @ 2.00°

Chamber wall thickness, $t_i = .018$ in., $t_o = .250$ in.

LOADING CRITERIA:

Coolant Pressure, $P_L = 500$ psi

Chamber Pressure, $P_C = 0$ $\quad q = 500$ psid

1. Post-Firing (Hot)
   Chamber Pressure, $P_C = 500$ psi
   Coolant Pressure, $P_L = 400$ $\quad q = 100$ psid

2. Hydrostatic Test, $P_L = 750$ psi
   Chamber Pressure, $P_C = 0$ $\quad q = 750$ psid
   (Cold)

The geometry notation used in this analysis is defined in Figure B3.

OPERATING TEMPERATURES:

Gas side wall temperature,

$$920 \leq T_{w_g} \leq 1020°F$$

Coolant side wall temperature

$$400 \leq T_{w_L} \leq 500°F$$

See thermal analysis.

The most critical loading of the unit occurs immediately upon termination of a firing. At this time, the pressure differential across the inner wall reaches a maximum value for a "Hot" motor.

The rib spacing, P is determined from the geometric relationship,

$$\theta = \frac{360P}{\pi(d_5+2t_i)} = 2.00° \text{ (180 ribs)}$$

For $d_5 = d_i = 10.77$ in., and $t_i = .018$, we obtain $P = .189$.

The distance between ribs is consequently,

$$L=P-W=.149 \text{ in.}$$

We now determine,

$$\frac{L}{t_i} = 8.29 \quad (\frac{L}{t_i})^2 = 68.5 \text{ and } (\frac{t_i}{L})^2 = 1.47\text{x}10^{-2}$$

The critical mechanical stress developed in the chamber wall under the hydrostatic loading is bending adjacent to the rib. Fortunately, the maximum tension occurs on the cooled side of the wall. The value of the inner wall bending stress is,

$$\sigma_{b_{w_L}} = \frac{q\ (P-w)^2}{2t_i^2} = \frac{q}{2}\ (\frac{L}{t_i})^2$$

For the loading, q = 500 psid,

$$\sigma_{b_{w_L}} = 17100 \text{ psi}$$

The maximum tension occurs on the cooled side of the inner wall i.e. at 500°F. At this temperature, $\sigma_{y_t} = 45400$ psi (see Figure 2). The maximum tensile stress on the hot side of the inner wall is evaluated as two-thirds of this value, (Ref. 5)

$$\sigma_{t_{w_g}} = .667(17100) = 11400 \text{ psi}$$

The tensile stress in the ribs when the coolant passages are pressurized and the chamber is not is given by

$$\sigma_{t_r} = q\ \frac{(P-w)}{w} = 1860 \text{ psi}$$

for the given loading.

The circumferential stress in the outer nickel wall may be considered constant since the wall is thin compared with its radius and has the value (7)

$$\sigma_{\phi_o} = \frac{\alpha E(\overline{T}_i - \overline{T}_o)}{1 - \nu}\ [\ \frac{t_i}{t_i + t_o}\ ]$$

where $\alpha \doteq 7.4\text{x}10^{-6}$ per °F

$\overline{T}_i \doteq 710°\text{F}$

$\overline{T}_o \doteq 100°\text{F}$

$\nu \doteq 0.3$ $E = 30\text{x}10^6\text{psi}$

Thus

$$\sigma_{\phi_o} = 13000 \text{ psi}$$

The average circumferential stress in the inner wall is (7)

$$\sigma_{\phi_i} \doteq - \frac{\alpha E(\overline{T}_i - \overline{T}_o)}{1 - \nu} \left[\frac{t_o}{t_i + t_o}\right]$$

Substituting values $\alpha = 8.0\text{x}10^{-6}$, $E = 25\text{x}10^6$, $\overline{T}_i = 710°\text{F}$
$\overline{T}_o = 100°\text{F}$

$$\sigma_{\phi_i} = - 191000 \text{ psi (compressive)}$$

If we consider theshear strain in the ribs to be negligible we may estimate the largest shear stress value as (7)

$$\sigma_{s_r} = \frac{P\alpha E(\overline{T}_i - \overline{T}_o)}{5w\ (1-\nu)} \left[\frac{t_o t_i}{(t_o + t_i)^2}\right]$$

For $P=.189$, $w=.040$ and the above values for the remaining variables,

$$\sigma_{s_r} = 11400 \text{ psi}$$

During firing, the ribs are loaded compressively as a consequence of the imposed temperature difference between the inner and outer walls. This compressive stress is given by (5)

$$\sigma_r = \frac{E\alpha\ (\overline{T}_i - \overline{T}_o)}{(1-\nu) r_o \frac{W}{P}} \left[\frac{t_i + t_o}{t_i t_o}\right]$$

Substitution of values provides

$$\sigma_r = 2680 \text{ psi}$$

The chamber hoop strength requirement is given by,

$$\sigma_\phi \doteq q\bar{r} \frac{1}{t_i+t_o}$$

where $\bar{r} = \frac{r_o+r_i}{2}$ and $r_o = r_i+t_i+d+t_o$

Substituting these identities yields

$$\sigma_\phi = \frac{q}{2} \left[\frac{(d_i+d) + (t_o+t_i)}{(t_o+t_i)}\right]$$

Here q is the total differential pressure across the chamber walls.

For $d_i = 10.77$ in., $d = .070$ and $q = 500$ psi,

$$\sigma_\phi = 13000 \text{ psi}$$

During hydrostatic test, the unit experiences a cooling passage pressure, $P_L = 750$ psi. Thus $q = 750$ psi.

The ribs undergo a tensile load corresponding to

$$\sigma_{t_r} = q \frac{(P-w)}{w}$$

For the above geometry and $q = 750$ psi,

$$\sigma_{t_r} = 2800 \text{ psi}$$

The shear stress in the inner wall reaches a maximum at the rib-inner wall junction. This is computed from

$$\sigma_{s_i} = \frac{q}{2} \left(\frac{L}{t_i}\right)$$

Consequently, for $q = 750$ psi

$$\sigma_{s_i} = 3110 \text{ psi}$$

The critical mechanical stress developed in the unit under the coolant hydrostatic loading is bending adjacent to the rib. The maximum tension occurs on the coolant side of the wall. Using the maximum bending moment equation given in Reference 5,

$$M_q = .0839\ (P-w)^2$$

and the equation for plate bending stress,

$$\sigma = \frac{6M}{t_i^{\,2}}$$

we obtain,

$$\sigma_{b_i} = q\frac{(P-w)^2}{2t_i^{\,2}} = \frac{q}{2}\left(\frac{L}{t_i}\right)^2$$

Substituting gives

$$\sigma_{b_i} = 32200 \text{ psi}$$

The most critical region in the unit is the gas side of the inner wall as exemplified by the large value of the inner wall thermal stress. Since this value exceeds the yield point stress it is necessary to examine the plastic behavior. This thermal stress occurs in the form of isotropic compression, and is given by (3),

$$\sigma = \frac{\alpha E}{1-\nu}\left\{\frac{t_o}{Kt_i+t_o}\left[\overline{T}_o + \overline{T}_i\left(\frac{Kt_i}{t_o}\right)\right] - T_s\right\}$$

Where T_s = gas side wall temperature

$K = \left|\frac{\sigma_{y_t}}{\sigma_e}\right|$ when $\left|\frac{\sigma_{y_t}}{\sigma_e}\right| < 1$

$$\text{and} \quad K = 1 \quad \text{when} \quad \left|\frac{\sigma_{y_t}}{\sigma_e}\right| \geq 1$$

Where σ_{y_t} is the 0.2% offset yield strength of the inner wall material and σ_e is the average inner wall thermal stress derived on an elastic basis:

$$\sigma_e = \frac{\alpha E}{1-\nu} (\overline{T}_o - \overline{T}_i) \frac{t_o}{t_i+t_o}$$

The stress strain relationship in an elastic system is given by (7)

$$\varepsilon_\phi = \frac{1}{E} [\sigma_\phi - \nu (\sigma_z + \sigma_r)] \quad .$$

At the surface of the isotropically stressed inner wall,

$$\sigma_r = 0 \ ; \ \sigma_\phi = \sigma_z$$

Thus

$$\varepsilon_\phi = \frac{1-\nu}{E} \sigma_\phi$$

Substitution of the stress equation (σ) gives the total thermal strain at the surface,

$$\varepsilon_\phi = \frac{\alpha E}{E} \{\frac{t_o}{Kt_i+t_o}[\overline{T}_o+\overline{T}_i (\frac{Kt_i}{t_o})] - T_s\}$$

Based upon the elastic-plastic stress-strain relationship above, the plastic strain component is given by

$$\varepsilon_P = \varepsilon_\phi - \frac{\sigma_{y_t}}{E}$$

$$= \frac{1}{E}\{\alpha E [\frac{t_o}{Kt_i+t_o}(\overline{T}_o+\overline{T}_i \frac{Kt_i}{t_o}) - T_s] - \sigma_{y_t}\}$$

For the previously used values,

$E = 25\text{x}10^6$,

$\alpha = 8\ \text{x}10^{-6}$,

$t_o = .250 \quad t_i = .018$,

$\overline{T}_o = 560°R \quad \overline{T}_i = 1170°R \quad T_s = 1480°R$,

and $K = \frac{43000\,(\text{yield})}{191000} = .225$

We obtain,

$$\varepsilon_P = -.0088 \text{ in/in.}$$

Thermal Analysis - Hastelloy X Liner

Assume Heat Flux = 6 BTU/in^2/sec

Heat Transfer Area = π(I.D.)(Length) = π(10.77)(12) = 405 in^2

Total Heat to be Absorbed = (q/A) A = 6(405) = 2430 BTU/sec

Assume water as coolant and $T_{in} = 70°$ $T_{out} = 120$

$\dot{W}_{H_2O}$ = Water Flow Rate = $Q/\Delta T_{H_2O}$ = 48.6 lbm/sec = 348 qpm

N = number collant passages = 180

d = coolant passage height = .060

ℓ = coolant passage width = .149

Flow Area for Coolant = (N)(d)(ℓ) = 1.6 in^2

$$V = \text{coolant velocity} = \frac{W_{H_2O}}{\zeta A} = \frac{48.6}{62.5(\frac{1.6}{144})} = 70 \text{ ft/sec}$$

$$dH = \text{Hydraulic Diameter} = \frac{4A_{passage}}{\text{Wetted perimeter}} = \frac{4(\ell)(d)}{2[\ell+d]} = .085 \text{ in.} = .007 \text{ ft.}$$

The heat transfer to the coolant is assumed to be due to forced convection. A modified Colburn equation is used with all thermodynamic data evaluated at the film temperature.

$$\frac{hd_h}{k} = .023\, R_e^{\,.8}\, P_r^{\,1/3}$$

where R_e = Reynolds number = $\frac{d_h \rho V}{\mu}$

P_r = Prandtl number = $c_P\,\mu/k$

The heat transfer coefficient (h) is determined at several film temperatures

T_{film}(°F)	μ lbm/hr-ft	k BTU/hr-ft°F	P_r	R_e	h BTU/in^2-sec-°F
150	1.06	.378	2.95	103000	.0354
200	.7	.393	1.79	156000	.043
250	.46	.394	1.17	234000	.049

The liquid side wall temperature T_{w_L} is determined by a trial and error solution:

1. Assume a film temperature
2. Using the corresponding h, calculate $T_{w_L} = T_{H_2O} + \frac{q/A}{h}$
3. Calculate a film temperature $T_f = \frac{T_{w_L} + T_{H_2O}}{2}$
4. Continue above procedure until T_f assumed (Step 1) and T_f calculated (Step 3) are equal.

At inlet: $T_{H_2O} = 70$ Assume $T_f = 150$ (h=.0354)

$$T_{w_L} = 70 + \frac{6}{.0354} = 240$$

$$T_f = \frac{70+240}{2} = 155$$

At outlet: $T_{H_2O} = 120$ Assume $T_f = 200$ (h=.043)

$$T_{w_L} = 120 + \frac{6}{.043} = 260$$

$$T_f = \frac{120+260}{2} = 190$$

The difference between the calculated and assumed film temperatures (5-10 °F) is negligible for this type calculation and repeated iterations are not deemed necessary.

The gas side wall temperature is determined by considering conduction through the .018" Hastelloy liner

$$\Delta T_{wall} = \frac{q/A}{k/t_i} = \frac{6}{.00018/_{.018}} = 600\ °F$$

For a liquid side wall temperature of 250°F $T_{w_g} \simeq 850°F$

Pressure drop (water)

$$\Delta P = \frac{4fL}{d_h} \left[\frac{\zeta V^2}{2gc} \right]$$

For $100{,}000 < R_e < 150{,}000$ $f \simeq .005$ (Pg. 156 McAdams "Heat Transmission")

As a result of consultations with Mr. Paul Sirocky of NASA Lewis Research Center, the friction factor used in the previous design analysis (f = .03) was investigated. This latter value was based on recent test data obtained with Camin water cooled spool pieces at NASA-Lewis. The data reduction which resulted in an f = .03 included the pressure drops in the inlet and outlet manifolding. Subtracting the pressure drops in the manifolds yields an f = .013. Communication with Mr. G. Repas of NASA Lewis Research Center (8/9/68), yielded additional flow/pressure drop data from other Camin hardware. The reduction of this data also indicates a value of f in the above equation equal to .013.

For f = .013 $$\Delta P = \frac{4(.013)(12)}{.085}\left[\frac{62.5(70)^2}{2(32.2)(144)}\right] = 243 \text{ psi}$$

INLET	OUTLET
$P = 375$	$P = 130$
$T_{sat} = 435$	$T_{sat} = 347$
$T_{H_2O} = 70$	$T_{H_2O} = 120$
$T_{w-L} = 240$	$T_{w-L} = 260$
$T_{wg} = 850$	$T_{w-g} = 850$

Thus the liquid side wall temperature is always below saturation.

If a value for f = .005 is used the resultant pressure drop is 95 psi and the exit saturation temperature is increased to 410°F.

The temperature under a rib can be determined using the method outlined in Barrere "Rocket Propulsion" Pg. 450. The thinness of the rib and inner wall results in temperatures under a rib that are approximately equal to those under the coolant passage.

Graded Zirconia - EF Nickel Chamber Design

DATA: EF Nickel tensile strengths - Figure B1

Coating/bond strengths - Test data from Camin-fabricated specimens indicates strengths on the order of four times that originally assumed. On this basis, a nominal joint strength for the coating/nickel wall,

$$\sigma_{b_i} = 50000 \text{ psi}$$

appears to be valid.

ESTIMATED GEOMETRY:

Diameter, d_i = 10.77 in. = d_5

Rib height, $d \doteq 0.060$ in. (per coolant requirement)

Rib width, $w \doteq 0.040$ in. N = 120 ribs @ 3.00°

Chamber wall thicknesses,

t_i coating - .008 in.
EF Nickel- .030 in.

t_o EF Nickel- .250 in.

LOADING CRITERIA:

1.
coolant pressure, P_L = 500 psi
chamber pressure, P_c = 0
q = 500 psid

post-firing (Hot)
chamber pressure, P_c = 500 psi
coolant pressure, P_L = 400 psi
q = 100 psid

2. Hydrostatic test, P_L = 750 psi

   Chamber pressure, P_c = 0
   (Cold)

   $q = 750$ psid

OPERATING TEMPERATURES (Average values)

Gas side wall temperature, (during 1. above)

$$\bar{T}_{wg} = 4280°F$$

Coolant side wall temperature,

$$\bar{T}_{wL} = 140°F$$

Interface (Nickel-coating) temperature

$$\bar{T}_{w_{int.}} = 200°F$$

Outer wall temperature

$$\bar{T}_o \doteq 70°F$$

1. Upon termination of firing, with coolant flow, the pressure differential across the wall is a maximum and, since the inner wall is still "hot," the maximum stresses are obtained. Consequently, this condition will be investigated first.

   The rib spacing, P is determined from the geometric relationship,

$$\theta = \frac{360P}{\pi(d_5+2t_i)} = 3.00°\text{(120 ribs)}$$

   For d_5 = 10.77 in., t_i = .038 in. we obtain

$$P = .284 \text{ in.}$$

   The distance between ribs (cooling passage width) is thus, for w = .040 in.,

$$L = P-w = .244 \text{ in.}$$

We now determine, for $t_i = 0.038$ in.

$$\frac{L}{t_i} = 6.42 \quad \left(\frac{L}{t_i}\right)^2 = 41.2 \quad \text{and} \quad \left(\frac{t_i}{L}\right)^2 = 2.43 \times 10^{-2}$$

The critical mechanical stress developed in the chamber wall under the hydrostatic loading is bending adjacent to the rib. The maximum tension induced in the inner wall fibers fortunately occurs on the cooled side of the inner wall. The magnitude of the bending stress in the inner wall is

$$\sigma_{b_{w_L}} = q\frac{(P-w)^2}{2t_i^2} = \frac{q}{2}\left(\frac{L}{t_i}\right)^2$$

For the applied loading, $q = 500$ psid,

$$\sigma_{b_{w_L}} = 10300 \text{ psi}$$

The maximum tensile stress on the hot side of the inner wall is evaluated as two-thirds of the above value,

$$\sigma_{t_{w_g}} = 0.67(10300) = 6900 \text{ psi}$$

The tensile stress in the ribs when the coolant passages are pressurized and the chamber is not is given by

$$\sigma_{t_r} = q\frac{(P-w)}{w} = 3050 \text{ psi}$$

for the given loading.

The circumferential stress in the outer (Nickel) wall has the value.

$$\sigma_{\phi_o} = \frac{\alpha E(\overline{T}_i - \overline{T}_o)}{1-\nu} \left[\frac{t_i}{t_i + t_o}\right]$$

where $\alpha \doteq 7.4 \times 10^{-6}$ per°F

$\overline{T}_i = (200+140) \div 2 = 170°F$

$\overline{T}_o = 70°F$

$\nu = 0.3$ $\qquad$ $E = 30 \times 10^6$ psi

This stress is considered to be constant through the outer wall since the wall is thin compared with its radius.

For the above values,

$$\sigma_{\phi_o} = 4200 \text{ psi}$$

The average circumferential stress in the inner (Nickel) wall is

$$\sigma_{\phi_i} = -\frac{\alpha E(\overline{T}_i - \overline{T}_o)}{1-\nu} \left[\frac{t_o}{t_i + t_o}\right]$$

Substituting the above values,

$$\sigma_{\phi_i} = -27{,}500 \text{ psi (compressive)}$$

If we consider the shear strain in the ribs to be negligible we may estimate the largest shear stress value as

$$\sigma_{s_r} = \frac{P\alpha E(\overline{T}_i - \overline{T}_o)}{5w(1-\nu)} \left[\frac{t_o t_i}{(t_o+t_i)^2}\right]$$

For $P = .284$, $w = .040$ and the values cited above for the remaining variables,

$$\sigma_{s_r} = 5200 \text{ psi}$$

During firing, the ribs are loaded in compression as a result of the imposed temperature difference between the inner (hot) and outer (cold) walls. This compressive stress is given by

$$\sigma_r = \frac{E\alpha(\overline{T}_i - \overline{T}_o)}{(1-\nu) r_o \frac{w}{P}} \left[\frac{t_i+t_o}{t_i t_o}\right]$$

Substituting values, we obtain,

$$\sigma_r = 1300 \text{ psi}$$

The chamber hoop strength requirement is given by

$$\sigma_\phi \doteq q\overline{r}\,\frac{1}{t_i+t_o}$$

where $\overline{r} = \frac{r_o+r_i}{2}$ and $r_o = r_i+t_i+d+t_o$

Substituting these identities yields

$$\sigma_\phi = \frac{q}{2}\left[\frac{(d_i+d)+(t_o+t_i)}{(t_o+t_i)}\right]$$

Here q is the total differential pressure across the chamber walls.

For $d_i = 10.77$ in., $d = .060$ in. and $q = 500$ psi,

$$\sigma_\phi = 9700 \text{ psi}$$

2. During hydrostatic test, the coolant passages are pressurized to $P_L = 750$ psi. Since $P_c = 0$, $q = 750$ psid.

The ribs undergo a tensile loading corresponding to

$$\sigma_{t_r} = q\,\frac{(P-w)}{w}$$

For the above geometry and the hydrostatic loading,

$$\sigma_{t_r} = 4570 \text{ psi}$$

The shear stress in the inner (Nickel) wall is a maximum at the rib-inner wall junction. This is determined from the relation,

$$\sigma_{s_i} = \frac{q}{2}\left(\frac{L}{t_i}\right)$$

For the hydrostatic loading, $q = 750$ psid

$$\sigma_{s_i} = 3050 \text{ psi}$$

The critical mechanical stress developed in the unit under hydrostatic loading is bending adjacent to the rib. The maximum tension (as indicated previously) occurs on the coolant side of the wall. Using the maximum bending moment equation for thin shells,

$$M_q = .0839\ (P-w)^2$$

and the equation for plate bending stress,

$$\sigma = \frac{Mc}{I} = \frac{6M}{t_i^{\,2}}$$

we obtain $$\sigma_{b_i} = q \frac{(P-w)^2}{2t_i^2} = \frac{q}{2} \left(\frac{L}{t_i}\right)^2$$

substitution yields,

$$\sigma_{b_i} = 17250 \text{ psi}$$

Thermal Analysis - Graded Coating

In the analysis that follows the thermal conductivity of the graded coating will be taken as 3.1 (10^{-6}) BTU/in.sec.°F.

The presence of a sprayed refractory coating will considerably decrease the heat flux to the coolant . Based upon a heat flux of 6 BTU/sq in/sec to the uncoated Hastelloy-X liner, a Hastelloy gas side wall temperature of 850°F and a flame temperature of 5500°F the gas side heat transfer coefficient is found to be .0013 BTU/sq in/sec.°F.

An estimate of the overall heat transfer coefficient can be made with the following assumptions:

hg = gas side heat transfer coefficient = .0013

Δx_c = coating thickness = .008 in.

k_c = coating conductivity = 3.1×10^{-6}

Δx_N = nickel liner thickness = .030 in.

k_N = nickel conductivity = 75×10^{-5} BTU/in-sec °F

h_L = liquid side heat transfer coefficient = .04 BTU/in^{2}sec°F.

$$\frac{1}{U} = \frac{1}{hg} + \frac{\Delta x_c}{k_c} + \frac{\Delta x_N}{k_N} + \frac{1}{h_L} = 3415$$

For a flame temperature $T_g = 5500$ and a bulk liquid temperature $T_L = 100$

$$q/A = U\ (T_g - T_L) = \frac{5400}{3415} = 1.58\ \mathrm{BTU/in^2/sec}$$

with the above heat flux, the following temperature drops are found

$\Delta T_{gas} = 1220$

$\Delta T_{coating} = 4080$

$\Delta T_{nickel} = 60$

Therefore

$T_{coating\text{-}gas\ side} = 4280°F$

$T_{coating\text{-}nickel\ interface} = 200°F$

$T_{nickel\text{-}liquid\ side} = 140°F$

Assume the following thrust chamber configuration

I.D. = 10.77 inches

Length = 12 inches

Heat transfer area = 405 in^2

Total heat to be absorbed = q/A (A) = 1.58(405) = 640 BTU/sec

Coolant water flow rate = 40 lbm/sec = 286 gpm

$\Delta T_{H_2O} = Q/w_{H_2O} = 640/40 = 16\ °$

N = Number cooling passages = 120

d = Coolant passage height = .060

ℓ = Coolant passage width = .244

Flow area for coolant = $N \times d \times \ell$ = 1.76 in^2

V = coolant velocity = $\frac{\dot{w}_{h_2 0}}{\varsigma A}$ = 52 ft/sec

d_h = Hydraulic diameter = $\frac{4\ \text{Area}}{\text{Wet.Peri.}} = \frac{4(\ell x d)}{2(\ell + d)}$ = .096 in = 008 ft.

The heat transfer to the coolant is assumed to be due to forced convection. A modified Colburn equation is used with all thermodynamic data evaluated at the film temperature.

$$\frac{hd_h}{k} = .023\ R_e^{\ .8}\ P_r^{\ 1/3}$$

using an average film temperature of 110°F

$$h_L = .0225\ \text{BTU/in}^2\ \text{sec}\ °\text{F}$$

Since the bulk water temperature rise is low (16°) the axial variations of temperature will be neglected. The temperature drop through the liquid film is

$$\Delta T = {}^{1.58/}.0225 = 70°\text{F}$$

i.e. for a bulk liquid temperature of 70°F the liquid side wall temperature will be 140°F. This is the value previously determined using a bulk temperature of 100°F and a liquid side heat transfer coefficient = .04.

Using the last values of h (.0225) and $T_L \simeq 75°$ changes $\frac{1}{U}$ to 3435 and q/A remains unchanged. The temperature profile also remains unchanged.

Since the wall temperature is below the normal boiling point, no danger of boiling exists.

The pressure drop is estimated from

$$\Delta P = \frac{4fL}{d_h} \left[\frac{\zeta V^2}{2g_c}\right] \text{ with } f = .013$$

$$= \frac{4(.013)(12)}{.096''} \left[\frac{62.5(52)^2}{2(32.2)(144)}\right] \simeq 120 \text{ psi}$$

The graded coating consists of

.002"	Zirconia
.0015"	90% Zirconia - 10% Nichrome
.0015"	70% Zirconia - 30% Nichrome
.0015"	30% Zirconia - 70% Nichrome
.0015	Nickel

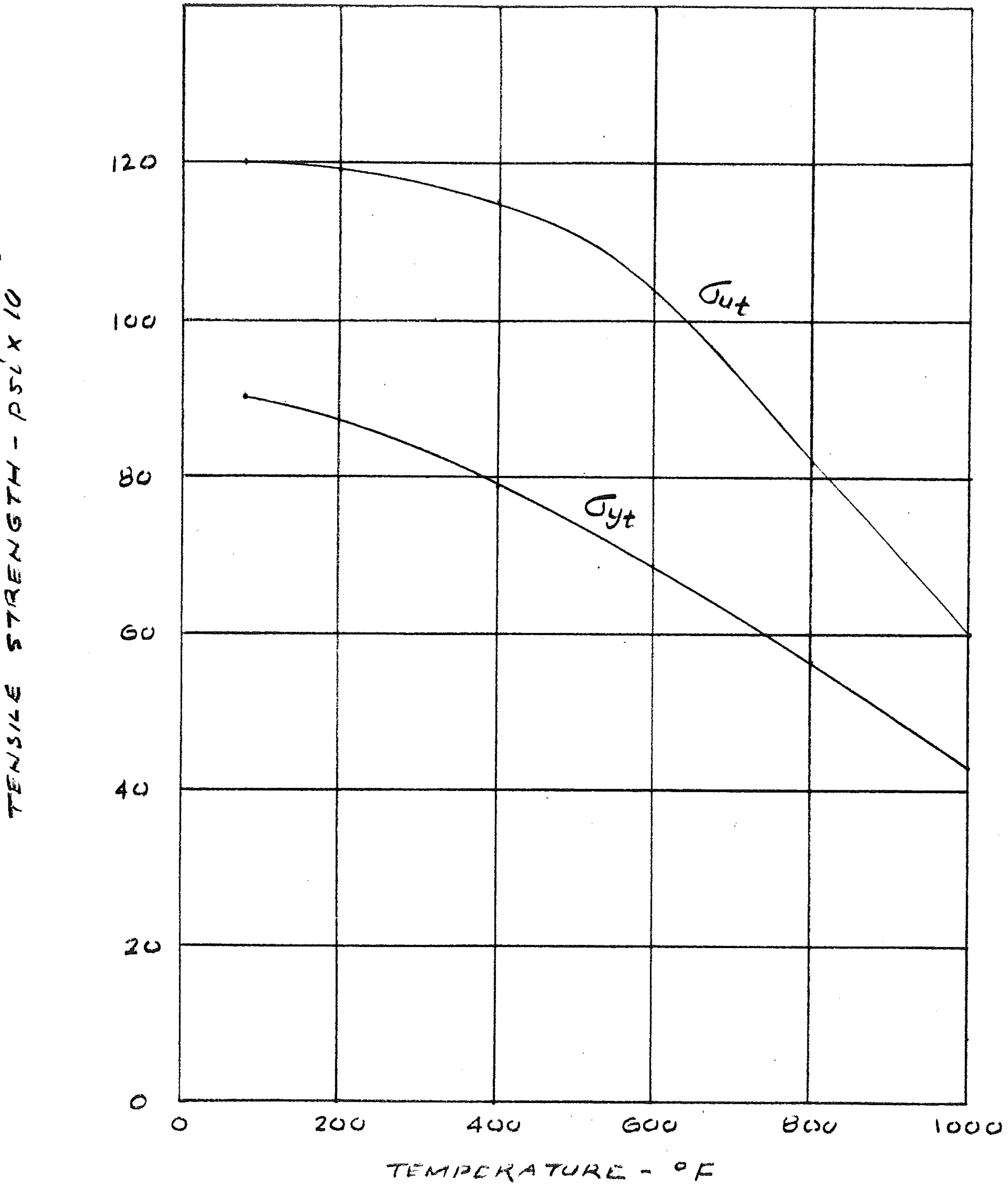


FIGURE B1 - ELECTROFORMED NICKEL TENSILE STRENGTH

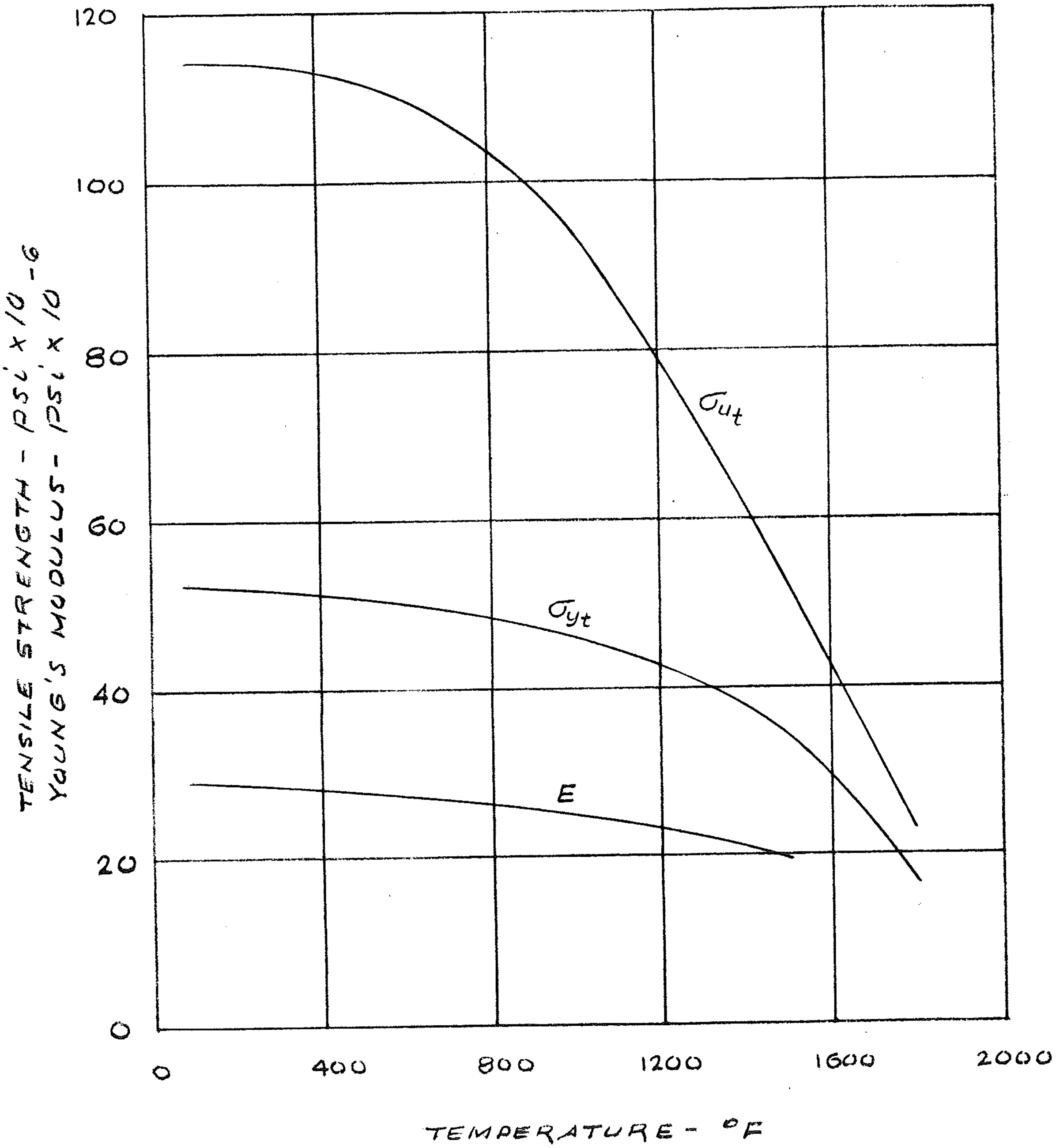
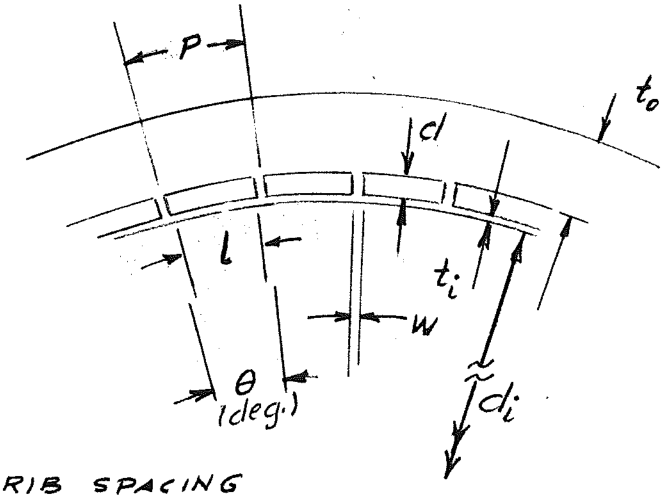


FIGURE B2 - HASTELLOY X TENSILE STRENGTH



$p =$ RIB SPACING

$l =$ DISTANCE BETWEEN RIBS

$w =$ RIB WIDTH

$d =$ RIB HEIGHT

$t_i =$ INNER WALL THICKNESS

$N =$ NUMBER OF RIBS

$t_o =$ OUTER WALL THICKNESS

$d_i =$ CHAMBER INSIDE DIAMETER

FIGURE B3 - GEOMETRY NOTATION USED IN STRUCTURAL ANALYSIS

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