FINAL REPORT

CONTRACT NO NAS 7-691

ELECTROFORMED INJECTOR FABRICATION TECHNIQUES

CAMIN LABORATORIES INC.

BROOKLYN, NEW YORK

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PREPARED FOR NASA JET PROPULSION LABORATORY

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PREPARED BY: S. Hammer

S. HAMMER
PROJECT ENGINEER

APPROVED BY: S. Fialkoff

S. FIALKOFF
VICE PRESIDENT
PROGRAM MANAGER

Z. Cacha

Z. CACHA
CHIEF ELECTROCHEMIST

CAMIN LABORATORIES
104 SOUTH FOURTH ST.
BROOKLYN, N.Y.
11211

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FOREWORD

This final report presents the technical accomplishments achieved in the course of fulfilling contract NAS 7-691, Amendment No. 3, "Electroformed Injector Fabrication Techniques." The effort described in this report was technically managed by the Jet Propulsion Laboratory for the National Aeronautics and Space Administration. The work reported herein was performed during the period from 1 December 1969 to 28 February 1971.

The NASA Program Manager is Mr. Frank E. Compitello, NASA Headquarters, Washington, D.C. The NASA Technical Manager is Mr. Gary Heidenreich, Jet Propulsion Laboratory, Pasadena, California.

The Camin Laboratories Program Manager was Mr. Samuel Fialkoff and the Project Engineer was Dr. Sanford Hammer. Mr. Zdenek Cacha directed the electrochemical aspects of the investigation. The efforts of Dr. Vito D. Agosta in the design of the various electroformed assemblies are gratefully acknowledged. The contributions of Mr. Robert W. Riebling of the Jet Propulsion Laboratory, who initiated this research and development effort, are also acknowledged.

ABSTRACT

A program was conducted to continue the investigation and development of the electroforming technique as a fully competitive and advantageous method of fabricating complex rocket motor injectors for high energy space storable liquid propellants. A previous effort (Ref. 1) had developed the techniques for fabrication of most of the basic elements, or building blocks of contemporary space storable injectors. These included: impinging jet injector elements (.015 inch to .030 inch diameter), high L/D orifices containing turbulence generating entries, individual micro-orifices in the .002 inch diameter range, complex feeder passages with variable cross sectional area, and impinging sheet injector elements. The results of the previous program were used to modify the design of a JPL OF_2/B_2H_6 1000 lbf thrust injector which was subsequently fabricated and delivered to JPL during the program reported herein.

The present program also included the evaluation of utilizing the electroforming process for impinging jet doublet elements with orifice diameters in the nominal range of .003 inches and fabrication of injector baffles containing internal

cooling passages. In addition, the feasibility of electroforming identical segments of a full injector face from a single master plate that represents only a portion of the entire injector was investigated. The use of electroforming as a mechanism for joining the segments was also evaluated.

Another original objective of the present program was the fabrication, completely by electroforming, of a 1000 lbf micro-orifice injector containing several thousand injection orifices having diameters in the 0.003 - 0.006 inch range, and internally-cooled baffles. The intent was to demonstrate the feasibility of applying the electroforming technology evolving from this program to a space-storable micro-orifice injector not dependent upon stacked platelet technology. Such an electroformed micro-orifice injector was designed by JPL, and the drawings furnished to Camin Laboratories. Camin, in turn, prepared the final production drawings and planned the process sequence. However, before electroforming had begun, tests of platelet micro-orifice injectors conducted at JPL indicated that extremely small injection orifices were prone to internal plugging by the decomposition products of diborane (B_2H_6), one of the propellants.

Midway through the program, therefore, JPL directed that fabrication of the micro-orifice injector not proceed. By mutual agreement, modification was made to the work statement to include in its stead a demonstration of the feasibility of chemical and/or thermal barrier materials as an integral part of electroformed nickel injectors or thrust chambers.

The present program successfully demonstrated the feasibility of applying electroforming to the fabrication of complex injectors and indicated areas where additional research would be worthwhile; primarily in utilization of barrier materials with electroformed components.

INTRODUCTION

The overall objective of the work was the development of electroforming as a fully-competitive technique for the fabrication of complex rocket engine injectors for high-energy, space-storable liquid propellants. This work was necessary because existing fabrication techniques have proven to be costly, time-consuming, and generally unsatisfactory with respect to the reproducibility of critical dimensions and hydraulic characteristics, and the integrity of brazed or welded joints. Previous tasks of this effort have demonstrated the feasibility of electroforming as a method for simply and economically fabricating advanced space-storable propellant injection elements, some of which cannot be adequately fabricated by any other means. During the course of the original investigation, the following results were established, (Ref. 1):

1. Electroformed impinging jet elements with orifice diameters in the .020 - .030 inch range can be fabricated with reliable reproducibility of alignment, diameter and hydraulic characteristics.

2. The surface finish of the electroformed orifice was smoother than that obtained by drilling or electric discharge machining.

3. Separate components can be assembled by using electroforming in place of welding.

4. High L/D orifices (100:1) can be electroformed with contoured or threaded entries. Hydraulic reproducibility was ± 2% and variations in geometry were indiscernible.

5. Variable area manifolds which supply a number of orifices with constant cross flow velocity can be electroformed with reproducible flow characteristics.

6. Orifices with diameters in the .002 inch to .005 inch range can be electroformed. Aside from the stacking of etched platelets, electroforming is the only feasible method for fabricating reproducible micro-orifices with the necessary surface finish and depth requirements. However, there are several areas that can be further developed in order to improve the

quality of the electroformed micro-orifice. Improved inspection and sorting procedures to reduce the dimensional variation of the glass tubes will ensure a more uniform orifice diameter. Improved cleaning procedures employing combinations of ultrasonic agitation, chemical etching and thermal cycling will aid in positive removal of orifice pin materials. Where a complete micro-orifice injector is to be fabricated, containing several thousand orifices, alternate methods of mandrel fabrication and subsequent electroforming operations should be developed. These would include preparing a mandrel that represents the smallest repeating segment of the injector and electroforming a sufficient number of these segments to synthesize a complete injector.

7. Impinging sheet injection elements and orifice feed tubes can be electroformed as an integral unit devoid of welds and brazes. Hydraulic

reproducibility of similar units can be maintained at better than 3% maximum deviation. Electroforming techniques can be utilized to produce impinging sheet elements with more complex deflector surface geometry than is presently possible using conventional machining processes.

8. A contemporary 1000 lbf. thrust OF_2/B_2H_6 injector, originally designed for production by conventional methods, can be modified for compatibility with the electroforming process. The only modification necessary was changing the cross section of radial feed passages from circular to rectangular. The location, number, diameter, length and orientation of the orifices were not altered. The completed injector would be of one-piece construction devoid of any welds, brazes or joints.

The purpose of the present work was to advance and extend the existing electroforming technology. This was accomplished by studying the applicability of electroforming to additional kinds of injection elements and accessories, providing workable solutions to the problems uncovered on earlier tasks, and investigating composite material electroforms. The results of this work provide the rocket community with a much-needed alternative injector fabrication technique.

The present program was divided into two tasks:

TASK IV - This phase involved the design, development of fabrication techniques, and testing of individual components of a baffled micro-orifice injector and the refinement and continued study of previously developed fabrication procedures. This included:

A - Impinging jet doublet elements with orifice diameters in the nominal range of .005", were designed, fabricated and tested to ascertain the accuracy of orifice alignment, reproducibility of dimensions, surface finishes and the hydraulic characteristics attainable by using the electroforming process.

B - The development of fabrication procedures for the electroforming of injector baffles containing internal cooling passages.

C - The investigation of the feasibility of electroforming repeating segments of a full injector face from a single master plate that represents only a portion of the entire injector. The use of electroforming to join the segments was also investigated.

D - The continuation of fundamental studies in the areas of mandrel fabrication, cleaning procedures, deposition with ultrasonic agitation and those problem areas that arose as the work progressed.

<u>TASK V</u> -

A - To demonstrate the feasibility of, and generate preliminary design criteria for, the inclusion of chemical and/or thermal barrier materials as an integral part of an electroformed nickel injector body or thrust chamber.

The injector face materials included:

1 - Pyrolytic Graphite

2 - Vitreous Carbon

3 - Boron Carbide.

The thrust chamber materials included:

1 - Zirconium Carbide - Pyrolytic Graphite

2 - Zirconium Diboride

3 - Vitreous Carbon.

These materials were selected for investigation because of their demonstrated or potential compatibility with the combustion products of most space-storable propellants.

CONCLUSIONS AND RECOMMENDATIONS

During the course of the present investigation the following conclusions were reached:

1. Electroformed impinging jet elements with orifice diameters in the .006 inch diameter range can be fabricated with reliable reproducibility of alignment, diameter and hydraulic characteristics.

2. Baffle configurations for liquid rocket injectors can be electroformed with internal cooling passages.

3. A complete injector can be electroformed by combining several injector face sectors made from the same mandrel, which is itself only a sector of the full injector. The individual segments can be joined together using electroforming techniques.

4. Blistering of electroformed components during subsequent brazing operations to attach fittings, etc. is attributable to lack of cathode agitation during initial phases of deposition. It is recommended that all future electroformed components employ cathode agitation throughout

the fabrication cycle.

5. Electroformed nickel can be deposited on boron carbide, zirconium diboride, vitreous carbon and pyrolytic graphite. There is evidence of diffusion of the nickel into the first two substrates but not for the latter two carbonaceous materials. No conclusions have been reached with regard to deposition of nickel on the zirconium carbide-pyrolytic graphite composite substrate.

6. Electroforming operations can be used to build a regenerative cooling passage configuration and outer close-out shell as a free standing liner of the barrier materials discussed in Item 5.

7. This program has demonstrated that it is possible to fabricate complete, complex, flight-weight injectors for space-storable propellants solely by the electroforming process, without resorting to the often-troublesome joining processes of brazing, welding, or diffusion bonding. Such injectors are, further, fully competitive with those fabricated by conventional machining processes, with respect to

dimensional and hydraulic reproducibility. However, electroforming a complete injector is a very time-consuming process, and may not be cost-effective. It is therefore suggested that the injector designer consider electroforming for those parts of the injector -- orifices, baffles, complex internal feeder passages -- for which it is best suited, while using more conventional machining methods for such items as flanges, fitting attach points, and thick members -- for which electroforming is technically acceptable but very time-consuming.

DISCUSSION

The overall objective of this investigation was to develop the electroforming technique as a fully competitive method for the fabrication of complex rocket injectors for high energy space storable liquid propellants. This work was deemed necessary because existing fabrication techniques have proven to be costly, time-consuming, and generally unsatisfactory with respect to the reproducibility of critical dimensions and hydraulic characteristics, and the integrity of diffusion-bonded, brazed or welded joints. The Camin Laboratories method of producing such injectors involves electroforming the individual components of a complete injector which are bonded together by electroforming to form an integral unit devoid of welds or brazes.

In order to extend the state of the art of electroforming as applied to injector fabrication, beyond the level achieved earlier under Contract NAS 7-691, an amendment was written to include additional work areas. The research effort was divided into two tasks. Task IV involved research and development of processes to demonstrate the capability of the electroforming process to fabricate additional types of constituent elements of a complete injector. The general approach was to develop mandrel designs and configurations and electrochemical processing parameters to fabricate a series of flow devices which exemplify the various constituent elements. The individual devices were to be hydraulically tested in order to assess the reproducibility of hydraulic characteristics and dimensional control. The types of elements to be investigated included: impinging jet doublet elements with orifice diameters in the nominal range of .006 inches, and injector face baffles containing internal cooling passages. Task IV also included studying the feasibility of joining several pie-shaped sectors of a complete injector via the electroforming process. Each sector would be electroformed from the same mandrel. Successful application of this concept would considerably reduce the cost and complexity of tooling (mandrels) especially for those injectors containing large numbers of orifices. Task IV also encompassed a continuation of fundamental studies in the areas of mandrel fabrication, cleaning procedures and any other problem areas that might arise as the work progressed.

Task V consisted of demonstrating the feasibility of including chemical and/or thermal barrier materials as an integral part of an electroformed nickel injector body or thrust chamber. The materials considered include pyrolytic graphite, vitreous carbon, boron carbide, zirconium diboride and a zirconium carbide-pyrolytic graphite composite.

Task II of Contract NAS 7-691 consisted of demonstrating the practical application of the developed electroforming processes by fabricating one complete flight prototype spacecraft engine injector. The injector was designed for service with OF_2/B_2H_6 propellants at a nominal thrust level of 1000 lbf. The basic injector design was furnished by the NASA Technical Manager but Camin Laboratories, Inc. implemented minor changes in the design to make its fabrication completely compatible with the electroforming process. The initial phases of fabrication of the injector were reported previously, (Ref. 1). However, the major fabrication effort was expended during the course of the present program. Therefore, fabrication of the 1000 lbf thrust injector will be documented in this report.

TASK II

Subtask A. Redesign of a JPL 1000 lbf. thrust injector for compatibility with the electroforming process.

In order to demonstrate the capabilities of electroforming as applied to liquid propellant injector fabrication, a flight-prototype spacecraft injector was manufactured. A design for a 1000 lbf. thrust injector for use with OF_2/B_2H_6 propellants was supplied by the NASA Technical Manager. This design was representative of contemporary units being evaluated for future missions (Ref. 2), and was originally intended for fabrication by conventional machining and joining techniques. An assembly drawing of the unit is shown in Fig. 1. The unit consisted of four major sub-assemblies; the injector body, manifold plate, enzian plate and injector ring. There are 56 fuel orifice tubes and 56 oxidizer orifice tubes arranged on a total of 32 rays. There are actually only four typical rays which are repeated every 45 degrees. The fuel orifice is .0225 inch diameter and the oxidizer orifice is .0292 inch diameter. Both orifices contain threaded-contoured entries. In addition, there are 32 fuel barrier-cooling orifices (.0122 inch diameter). If fabricated by conventional methods, all of the subassemblies would have to be furnace brazed together.

The fuel inlet is on the centerline of the injector. From the main inlet the fuel flows radially through 32 equally spaced face-cooling rays (.016 inch diameter) to a manifold formed between the injector ring and body. The barrier-cooling orifices are fed from this manifold. In addition, a total of 16 radial feed passages also emanate from this manifold. Each feed passage supplies fuel to either two or four fuel orifices and is formed by drilling a stepped hole to achieve a variable cross sectional area.

The oxidizer inlet is off center and feeds a variable area manifold formed between the manifold and enzian plate. The enzian plate contains 16 holes, located so as to distribute the oxidizer throughout the entire manifold formed by the injector body and enzian plate. The oxidizer is fed to the orifices through a series of holes drilled into the back of the injector body.

Modifications of the original design were necessary in order to make the unit compatible with the electroforming process. However, certain fundamental design criteria were established. The location, number, diameter, length and orientation of the orifices would not be altered. The arrangement of inlets, mounting studs and overall diameter would be maintained for compatibility with mating hardware. The entire unit would be electroformed as an integral unit devoid of welds or brazes.

In general, the major changes were in the cross section of the radial feed passages. Whereas the conventionally fabricated injector contained circular cross section passages, the electroformed unit would contain rectangular passages of equal cross sectional area. The countersinking of the orifice exits would be eliminated in the electroformed version. These are included in the conventional unit to provide a surface perpendicular to the drill that will form the hole for the orifice tube, and are not necessary in the electroformed unit.

The unit was electroformed from the injector face surface to the propellant inlet surface in ten steps. Electrodeposition was interrupted at various points in the cycle to form internal manifolding and place filler materials. Subsequent deposition is adherant to the previous metal. The total length of the orifices is such that deposition along the axis of the orifice pin is practical. The contour-threaded entry was formed by tapping and chamfering the orifice inlets. The shape and orientation of the manifold formed by the injector body and injector plate are such that it is more readily formed after the injector is virtually completed. Therefore, the manifold was treated as non-existent until all other steps were completed, at which time it was machined into the body from the circumference of the unit. The manifold was then filled with wax and the equivalent of the injector ring was electroformed.

A typical section of the electroformed injector is shown in Fig. 2. The fuel passages that distribute propellant to the orifices from the circumferential manifold are shown as milled slots of varying cross sectional area.

After the milling operation was accomplished the orifice inlets were inspected, deburred as necessary, and the passages were filled with wax. Additional nickel was then deposited. The radial passages shown in section B were milled earlier, after approximately .200 inches of nickel had been deposited. The section through ray 4 shows the two film cooling orifices electroformed into the plate but not attached to any manifold. As explained previously, the circumferential manifold was formed later. In addition, a single oxidizer orifice was electroformed on ray 4.

Another section through the injector is shown in Fig. 3. The oxidizer manifold, below the enzian plate, and the variable area feed passages to the orifices are shown. At this stage, the electroformed version of the conventional injector body had been formed. Figures 2 and 3 together depict the electroformed version of the main fuel and oxidizer manifolding. In achieving the configuration shown in these figures, several intermediate machining operations were required. After deposition of at least .190 inches of nickel the 32 radial passages and central core shown in Section B of Fig. 2 were machined.

The passages were filled with wax and additional nickel deposited. At the .344 inch level (Section A, Fig. 2) the fuel orifice entries were tapped and chamfered. These orifices were then filled with wax and additional nickel deposited until a total of .405 inches was accumulated. At this point, (Fig. 3), the oxidizer orifices were tapped and chamfered. Since the nickel growth is nonuniform, facing operations were required to achieve uniform thickness. This required that the glass pins be chemically dissolved and new ones inserted after machining when additional orifice length was required. At the .405 inch level all orifices were complete and were filled with wax. Nickel was deposited until a sufficient amount was present to machine the fuel manifold system shown in Fig. 2. The orifice entries were inspected, deburred as necessary, and the passages were filled with wax. Nickel was again deposited until a total thickness of .605 inches was achieved. The oxidizer distribution system as shown in Fig. 3 was then machined. After filling these passages with wax, additional nickel was deposited and the oxidizer manifold ring (between the .605 inch thickness and .699 inch thickness) was machined.

The enzian plate and upper oxidizer manifold were formed by a series of similar deposition and machining operations. Figure 4 depicts the manner in which these components were electroformed into the injector. The enzian plate was formed by depositing and machining nickel to a thickness of .070 inches. A total of 16 holes (.344 inch diameter) were drilled into the lower oxidizer manifold. The cavities were filled with wax and an additional .300 inches of nickel were deposited. The surface of the part was milled to achieve the non-uniform total thickness shown in Fig. 4. The variable area upper oxidizer manifold was then machined, the resulting passage filled with wax and additional nickel electroformed. A machining operation formed the fuel and oxidizer inlets and the circumferential fuel manifold, Fig. 1. This latter manifold was filled with wax and the equivalent of the injector ring was electroformed. The wax that filled the interior cavities was removed thermally and the entire unit was flushed with methyl ethyl ketone and ultrasonically cleaned. Upon completion of the unit the injector was delivered to the Jet Propulsion Laboratory for attachment of studs and fittings and for cold flow testing and hot firings.

The electroformed injector described above is an integral unit equivalent to the multi-piece construction design supplied by the NASA Technical Manager. The modifications that were made in order to produce compatibility with the electroforming process did not alter the hydraulic characteristics of the injector. The unitized electroformed construction eliminated all of the problems commonly associated with welds, brazes and diffusion-bonded joints when they are used in spacecraft type injectors. The successful application of the techniques developed during the Task I component study demonstrated the capabilities of the electroforming process to synthesize complex, sophisticated, flight type spacecraft injectors.

It should be noted that in Task I it was demonstrated that each of the requisite "building-block" elements can be fabricated completely by electroforming, with conventional machining and joining techniques restricted to the creation of the mandrel. The redesign of the injector accomplished in this subtask, however, features modification of the electroform by several standard conventional operations (such as milling, drilling, tapping, machining, etc.) at various stages of its growth. These alternating steps of electroforming and machining represent the optimum symbiosis of both operations,and are more cost-effective and economical in time than straight electroforming. They represent the combined technique whereby production injectors could be manufactured in a manner which most effectively exploits the advantages of both processes.

Subtask B. Fabrication Details of electroformed 1000 lbf. thrust injector.

A nickel mandrel blank was designed and fabricated to produce the demonstration injector, Fig. 5. Holes were drilled in the master plate for positioning of glass pins that would ultimately form the orifices. The location and orientation of the holes were a transfer of the finished injector face. A typical element pair is shown in Fig. 5. The hole layout in the mandrel was inspected by inserting glass pins in the holes and checking angular orientation, alignment and location with the aid of a Comparitor. Five holes, of a total of 144, were found to be out of tolerance, either with respect to location or angular orientation. The tolerance requirements were .002 inch for decimals and 15 minutes for angles. The rejected holes were plugged, redrilled, and subsequently inspected and accepted. A major advantage of the electroforming process is exactly this ability to inspect the most critical dimensions, (orifice location and orientation) at the very beginning of the fabrication sequence.

After inspection the mandrel was vapor degreased, pumiced, and ultrasonically cleaned in trichlorethylene. The reference surface and chucking surface of the mandrel were masked with vinyl tape. Three plastic screws were inserted in the tapped holes on the mandrel surface. Nickel was allowed to deposit around the screws, forming a tapped hole in the electroform which was used to bolt the electroform to the mandrel during subsequent machining operations. The glass pins that formed the orifices were inserted in the mandrel holes. Since the impingement distance of the barrier cooling orifices permitted these holes to be drilled in the mandrel to a depth of only .030 inches, special fixturing was required to minimize the possibility of losing a glass pin during deposition. This consisted of mounting the mandrel on a lucite plate such that the mandrel face would always be directed upwards. In addition, circulation and agitation of solution only was employed without agitation of the workpiece during the initial stages of electrodeposition. The mandrel assembly is shown prior to deposition in Fig. 6. The mandrel was placed in the electroforming bath and deposition was initiated at 10 amps per square foot.

After a minimum thickness of .190 inches was obtained the unit was removed from the bath. The plastic screws were removed and replaced with steel screws prior to machining the workpiece according to Section B of Fig. 2. An electroform can be removed from the mandrel at this point and mounted on a holder for the remainder of the fabrication cycle. The mandrel can then be used to start another injector. The holder is simply a mandrel blank without the glass positioning holes. Fig. 7 shows the electroform with the radial fuel passages that connect the central fuel inlet with the circumferential fuel manifold. After machining, the glass pins were dissolved by immersing the work in a 25% solution of hydrofluoric acid for 20 minutes. The milled passages and the fuel barrier cooling orifices were filled with wax and the remaining holes were fitted with glass pins. The piece was then activated to obtain adhesion of subsequent nickel deposition. This consisted of treating the work anodically at room temperature for 30 minutes in a 25% sulfuric acid solution, at 20 amps/sq. ft. and an additional 5 minute treatment at 200 amps/sq. ft. After the electrocleaning operation, and without rinsing, the work was inserted in the electroforming bath with current on. The current density was again set at 10 amps/sq. ft. The above activation procedure was used each time the work was replaced in the electroforming bath.

The work was next removed from the bath and machined to a uniform thickness of .344 inches. The fuel orifice entrances were tapped and chamfered after all glass was dissolved. The tapped holes were filled with wax, the oxidizer orifice pins reinserted and additional nickel was deposited after proper activation. At a thickness of .405 inches, the remaining glass was dissolved and the oxidizer orifice entrances were tapped and chamfered. The work was returned to the bath for additional nickel deposition after these orifices were filled with wax.

After sufficient metal was deposited to achieve a uniform thickness of .546 inches, the fuel manifold shown in Fig. 2 was machined. In addition, eight radial oxidizer feed passages connecting the central oxidizer inlet with the orifices located on the innermost circle were machined.

After the milling operations the orifice entries were inspected, deburred if necessary, and all cavities were filled with wax. Nickel was again deposited to a clean-up thickness of .605 inches at which time the oxidizer distribution system was machined, Fig. 3. After filling these passages with wax, additional nickel was deposited and the oxidizer manifold ring (between the .605 inch thickness and .699 inch thickness) was machined. Figure 8 shows the actual unit at this stage of development. The apparently rough areas in the oxidizer feed passages is the filler material which had been placed there prior to machining the manifold ring. As a result the milling cutter passes over the top of the wax roughening its surface. An additional .070 inches of nickel was deposited in order to form an equivalent enzian plate by drilling a total of 16 holes (.344 inch diameter) into the lower oxidizer manifold, Fig. 4. The cavities were filled with wax and an additional .300 inches of nickel were deposited. The unit was machined to achieve the non-uniform thickness shown in Fig. 4. The variable area upper oxidizer manifold was milled, the resulting passage filled with wax and additional nickel was deposited to close out the back side. At this point, the oxidizer and fuel inlets, stud mounting holes and circumferential fuel manifold were machined. This latter manifold was filled with wax and an equivalent injector ring, Fig. 1, was electroformed. The injector contained two pressure taps and two thermocouple taps. These holes were formed through the entire injector by positioning glass pins in the mandrel, and depositing metal around these pins for the first .190 inches of thickness. The holes thus formed were filled with wax. After the injector was completed these holes were used as pilots to drill the through holes from the injector face through to the back of the unit. The injector was heated to 250°F to thermally remove the wax and then flushed with methyl ethyl ketone. This was followed by a thorough degreasing, back-flushing, and visual flow check to ensure that all orifices were clear. The completed injector, Fig. 9, which measures 4.500 inches in diameter by 1.300 inches thick was delivered to JPL for further cold flow and subsequent hot firing evaluation. During the course of the brazing operation, for attachment of studs, at the Jet Propulsion Laboratory, several small blisters were formed on the injector face. Subsequent studies at Camin Laboratories, Inc., determined the cause and procedures to eliminate this occurrence in future applications. This is discussed in detail in this report under Task IV, Subtask D.

TASK IV

Subtask A. Development and evaluation of the electroforming process for fabricating impinging jet micro-orifice doublet elements.

The primary element in an injector is the orifice which meters and controls the propellant flow. A vast majority of injectors are designed so as to obtain impingement of jets issuing from neighboring orifices. The accuracy and reproducibility of the jet alignment is a major factor in determining atomization, mixture ratio distribution and ultimately rocket engine performance. An injector that is conventionally fabricated by milling, drilling and brazing operations contains several steps in the manufacturing sequence that are undesirable. The drilling of a large number of relatively small diameter holes in a hard material frequently results in drill breakage, jet misalignment, orifice diameter variations, etc. When these occur, it is generally after a considerable amount of time and money have been invested in the part.

Where a multiplicity of injectors are involved, the problems are of greater significance, since reproducibility from injector to injector is required. The tool marks left by drills on the inside of the orifice are another undesirable characteristic that inhibits the ability to obtain uniformity between orifices. The limitations of drilling are sometimes overcome by forming the orifices from tubes that are brazed into an injector plate. However, the problems of leaks, distortion and high temperature joining operations make this process less than desirable. Recent interest by the Jet Propulsion Laboratory in micro-orifice injectors further compounds the manufacturing problems.

The electroforming method of creating injector orifices consists of fabricating a single master plate that is a transfer of the injector face. Holes in the master plate are fitted with precise O.D. and controlled surface finish non-conducting pins. Orifices are formed by depositing nickel on to the master plate to a required thickness, separating the electroform from the plate and then removing the pins from the electroform. The fabrication of the master plate is as difficult as fabricating a conventional injector plate. However, the master plate is a tool for the electroformer and can be used to generate a series of identical injectors. In addition, any problems or errors that occur do so at the very outset of the fabrication sequence and can be corrected by simply filling the incorrect hole in the master plate and redrilling it.

The choice of nickel as a master plate material, glass tubing as the pin for creating the orifice, and the composition of the electroforming bath have been previously documented (Ref. 3,4).

Three typical micro-orifice impinging jet elements were designed in order to serve as a vehicle for developing and evaluating the electroforming process as a method for fabricating these types of elements. The orifice diameters were selected as .0058 inches and .0078 inches which were sizes found on a contemplated Jet Propulsion Laboratory flight prototype unit. The orifice angle (angle between the jet direction and normal to the plate) varies from 15° to 45°. The impingement distance is .078 inches for units one and two and .110 inches for unit number three. These are again typical of the impingement distances on the envisioned flight prototype unit. Mandrels for the three units were designed and fabricated in acdordance with Figure 10. The mandrel was a two-piece unit with a cavity behind the main plate. The holes in the main plate were .015 inches. The glass orifice pins consisted of .0058 inch or .0078 inch O.D. tubes fitted into .015 inch O.D. glass bushings. The necessary pins were ordered, received and inspected. As with previous orders of glass pins, diameter tolerances were found to be ± .0002 inches. The orifice pins were mounted in bushings and the assembly was positioned in the hole in the mandrel plate from the backside. The .015 inch bushing was allowed to terminate within ± .005 inches of the front of the plate. The completed mandrel assemblies were inspected on a Jones and Lamson Comparitor to verify orifice alignment and impingement accuracy. All three units passed inspection. Electroforming operations were initiated by mechanically and chemically cleaning the mandrel and inserted pins.

Each mandrel was utilized to electroform three micro-orifice impinging elements. Each part was electroformed to a thickness of .120 inches and turned -- while still on the mandrel -- to a thickness of .100 inches. The plates were removed from the mandrel and the glass pins were dissolved in hydrofluoric acid with the aid of ultrasonic agitation. Visual examination at 75 magnification revealed that the orifices were clear. Mechanical inspection of impingement and orifice diameters was made and found to be equal to the dimensional control of the mandrel. The individual face plates were fitted with manifolds and submitted for hydraulic calibration. The nominal data is shown below.

PART NO.	ORIFICE SIZES	ΔP(PSI)	WATER FLOW (cc/min)
1	(2) .0078	60	84
2	(2) .0058	60	43
3	(1) .0078 (1) .0058	60	62

The part numbers refer to Figure 10. Calibrations were conducted at pressure drops varying from 20 to 80 psi. For part number 1 the maximum flow rate deviation in the three units was less than 5%. For part number 2 the deviation between the lowest and highest units was 6%. For part number 3 no apparent variation in flow rate was noted. During the calibration, visual confirmation of impingement was noted for all elements. The above data indicates a mass flow rate discharge coefficient of 0.8. Several units were delivered to NASA - Jet Propulsion Laboratory for further evaluation.

It is of interest to note the use of ultrasonic agitation with simultaneous chemical etching in order to remove the glass pins from the electroform. This has apparently eliminated any residue from the completed orifices as witnessed by the results of the mechanical inspection and hydraulic calibration.

As a result of the present study, it is apparent that electroforming can be utilized to fabricate a multiplicity of reproducible impinging jet elements in the micro-orifice range from a single master.

<u>Subtask B</u>. Development of fabrication procedures for the electroforming of injector baffles containing internal cooling passages.

A research program was conducted to develop procedures for the electroforming of injector baffles containing internal cooling passages. The basic baffle configuration and design was provided by the NASA Technical Manager. Drawings supplied to Camin Laboratories indicated that the configuration of current interest to Jet Propulsion Laboratory programs was a series of radial baffles, fed from a central hub, each containing "stacked" cooling passages, i.e., each baffle ray contained several cooling circuits at various distances above the injector face. A typical radial segment is shown in Figure 11. Consideration was given to the manner in which the baffle would be electroformed. Electroforming in a direction outward from the injector face would theoretically allow forming of the entire baffle configuration (all six rays and the central hub) as an integral unit. However, there were several formidable problems with this concept. A total deposition thickness of .500 inches would be required with a series of intermediate machining operations to form the cooling passages. From a technical point of view this is feasible albeit economically disadvantageous. The major technical problem is the requirement of a controlled width of deposit, i.e., the thickness of the rays from face 1 to face 2 in Section B-B of Figure 11. If the width of the rays are not precisely controlled during deposition by the use of shields and maskants, extremely critical machining operations will be required after deposition is completed. In order to avoid these developmental problems it was decided to electroform individual segments of the baffle in a direction from face 1 to face 2. The individual segments could then be assembled by combinations of electroforming and electron beam welding. The mandrel for the baffle segment would be machined from nickel and consist of the portion of the baffle from face 1 to plane 3 in Section B-B of Figure 11. The cooling passage circuit is therefore machined into the baffle, filled with wax and the thickness from plane 3 to face 2 is adherantly electroformed to the "mandrel". This represents the most economical and practical technique for baffle fabrication. A drawing of the baffle mandrel is shown in Figure 12. The wax is injected into the passages with the aid of a mold cover that is assembled onto the mandrel. The mold cover and mandrel cause the injected wax to form the variable area cooling passages.

Three baffle segments mandrels were machined together with a mold cover. After wax is injected and the mold cover is removed, the wax form protrudes above the mandrel surface. This is similar to techniques previously employed to form variable area manifolds in injectors. It has been learned from experience that the nickel that is deposited up and around the protruding wax forms has a tendency to be more porous than the nickel deposited directly on a metallic mandrel surface. Accordingly the baffle segments were electroformed at a lower current density than usual, 10 ASF, and with greater agitation in order to avoid pitting.

Three baffles segments were fabricated, fitted with a manifold and hydraulically calibrated to determine reproducibility. At 80 psi pressure drop the nominal flow rate was 3950 cc/min. The deviation between the lowest and highest unit was 5%. A single unit was cut in order to view the cross section through both legs of the baffle, Figure 13. In both photos, the lower half of the unit is the mandrel or machined nickel. The upper portion represents the electroformed portion. In the upper photo the electroformed nickel is above the top of the passages. In the lower figure the electroformed nickel starts at a point .017 inches below the top of the cooling passage. The sample was also cut to expose the interior of passage that was deposited over the wax, i.e., the upper surfaces of the cooling passages in Figure 11. The nickel surface did not appear to contain any pits or porosity, rather the presence of small nodules were noted. This is due to surface porosity in the molded wax. The nodules appeared no larger than .002 to .003 inch in any direction and covered approximately 10% of the surface. We believe this type of surface characteristic is satisfactory for a baffle cooling passage and the procedures utilized can be applied to actual baffle fabrication. However, an alternate baffle fabrication procedure, which eliminates the need to grow up and over a protruding wax surface was investigated.

The technique consists of machining the entire cooling passage circuit into a plate of nickel. The machined grooves are filled with wax flush to the nickel surface and a covering plate is electroformed. This process involves more precise machining than the original fabrication method but less critical wax molding and electrodeposition processes. Two cooled baffle segments were fabricated by this alternate method and sectioned for comparison with the original method. As expected, the cooling passage surfaces are smoother and the cross section is more precise than that obtained with the original fabrication sequence, Figure 14.

Subtask C. Investigation of the feasibility of electroforming repeating segments of a full injector face from a single master plate that represents only a portion of the entire injector.

In order to electroform injectors, it is necessary to produce a master plate by conventional fabrication techniques. The master plate is a transfer of the finished injector face and drilling of the orifice pin positioning holes is as difficult as when a conventionally fabricated injector face plate is produced. However, the master plate is a tool for the electroformer and can be utilized to generate a multiplicity of injectors. Where a micro-orifice injector containing thousands of .003 to .008 inch diameter holes is required, it would be advantageous, even to the electroforming process, to eliminate the need for drilling the master plate or at least reduce the amount of holes to be drilled.

Towards this end, the present program includes the investigation of the feasibility of electroforming repeating segments of a full injector face and then joining these segments to form the complete injector. In this manner, the master plate will represent only a portion of the entire injector. The number of holes to be drilled in the master is similarly reduced.

For the purpose of this investigation a master plate representing a 90 degree segment of a showerhead injector with .030 inch orifices was machined. Four segments, each .060 inch thick, were electroformed from the same master. The four segments were fixtured so that additional electroforming could be utilized to increase the orifice length (plate thickness) to .100 inches and simultaneously join the four segments. Leak checks were conducted to determine if the electroformed joint was leak tight. The crack between segments on the face of the injector was examined to determine if it is necessary to eliminate it by additional electroforming. The use of electron beam welding was also considered as a method of joining the electroformed segments in the event electroforming itself proved to be unsatisfactory.

A simple injector was designed to evaluate the basic concept, Fig. 15. The unit contains 32 showerhead type .030 inch orifices arranged on 16 equally spaced rays. The orifice length is .080 inches. Alternate rays are fed either from a central core manifold or a circumferential manifold.

A single 90 degree segment nickel mandrel containing eight holes for glass pins was machined for the purpose of electroforming four injector face segments. This mandrel was assembled with a 270 degree lucite shield and mandrel holder. The lucite surface protruded .040 inches above the nickel master surface, so that the edges of the electroformed nickel injector segment were formed precisely and required no further machining after the deposited nickel was machined flush to the lucite surface.

A second technique was also explored. This consisted of utilizing a full 360 degree nickel master with holes for glass pins only in a 90 degree sector. A full circle of nickel was electroformed, from which the 90 degree sector containing the orifices was cut.

The top photo in Figure 16 shows the lucite shield -- nickel mandrel with deposited metal prior to machining.

A turning operation, flush to the lucite surface, results in a .040 inch thick, 90 degree sector nickel plate containing eight showerhead injector elements. The middle photo shows several electroformed segments together with the mandrel. The lower and left-hand segment in the middle photo were electroformed on the lucite-nickel mandrel and require no further edge trimming. The right-hand segment was cut from a deposit formed over a full 360 degree metallic mandrel and requires additional edge trimming. No major problems were encountered with either type of mandrel and four segments were electroformed from each type of mandrel.

In each case, the four segments which were .040 inches thick, were mounted on a full circular holder. Glass pins were inserted in the orifices formed in the injector face segments to increase the orifice length during subsequent metal deposition. The units were activated and placed in the electroforming bath in order to join the segments and deposit sufficient metal for machining of the manifolds. After a facing operation, which resulted in a total nickel thickness of .120 inches, a series of radial and circumferential manifolds, .040 deep were machined. This results in an orifice length of .080 inches and a nickel thickness of .040 inches between the point at which the four segments are joined and the bottom of the manifolds. The manifolds were filled with wax and a backplate of approximately .080 inches was deposited. The lower photo in Figure 16 shows the completed injector. After thorough cleaning and degreasing, the units were hydrostatically inspected. The internal manifolding is such that half of the orifices are fed through a central inlet fitting and the other half are fed through a fitting mounted near the circumference of the injector. Each inlet was separately supplied with water at 200 psi., one at a time. The outflow was examined and it was found that only those orifices connected via the internal manifold to the connection being fed, were discharging fluid. Thus there was no internal leakage between the "fuel" and "oxidizer" orifices, and the method of joining the original face plate segments by electroforming sealed the "crack" between the original segments such that there was no hydraulic leakage.

The success of the segment joining by electroforming operations resulted in abandoning any thoughts of using electron beam welding as an alternative joining method.

The success of the previous investigation strongly recommends the use of the segmented mandrel concept as a means of bringing further economies to the electroforming process as applied to injector fabrication.

Subtask D. Continuation of fundamental studies.

In any research and development effort, especially one associated with the development of fabrication techniques, there is always a need for continuous refinement and reappraisal of methods and techniques. During the course of the present effort, it was deemed necessary to examine three such areas. The first is concerned with the effect of orifice spacing on the deposition of nickel; the second with cleaning procedures for the removal of glass pins and the last with the causes and elimination of blister formation on injector faces during brazing operations.

The interest in micro-orifice injectors together with our present efforts to develop methods for electroforming micro-orifice impinging jet elements indicated the need to examine the problems of electroforming face plates containing many elements in close proximity to one another. Accordingly, an injector plate containing twenty-five (25) .0058 inch diameter orifices arranged in five rows and five columns with a separation of .025 inches was designed. After fabrication of the mandrel and insertion of glass pins in a manner similar to that described in Task IV, Subtask A of this report, electroforming operations were initiated. In order to promote dense deposition in the regions between the protruding glass pins both mechanical agitation of the solution and rotation of the mandrel were employed. When the work was inspected after approximately .040 inches were deposited several glass pins were found to have been dislodged. The deposit was stripped and the mandrel was refitted with glass pins. During the initial stages of deposition, the mandrel was held stationary and only mechanical agitation of solution was used. After sufficient metal was deposited, and the pins were "locked" in place, mandrel agitation was employed.

Metal was deposited to a thickness in excess of .100 inches. The regions between glass pins, being shielded, of course grew at a slower rate than the exterior portions of the mandrel. It is possible however to achieve .100 inches in the regions of the orifices by plating to thicknesses of .130 on the extremities of the mandrel. It is also possible to design shields for the external regions of the mandrel in order to inhibit metal growth in those regions.

Microscopic examination of the metal in the region between the pins indicated that it had basically the same grain structure as metal deposited on the outer extremities of the mandrel.

During previous studies of electroforming techniques as applied to injector fabrication, the methods employed to remove glass pins from the deposited metal were never completely satisfactory. The glass is chemically removed by immersing the entire work piece in a hydrofluoric acid solution. The glass pins are actually tubes so that the hydrofluoric acid can attack the glass on as large a surface area as possible. Previous studies showed that if the work remained in the hydrofluoric acid for a period of time long enough to completely remove the glass, some etching of the nickel occurred together with a bell-mouthing of the orifice inlets and exits. On the other hand, if the work was removed prior to onset of the etching, small amounts of residue were found on the inside of the orifices.

This problem has been attacked in a simple and straightforward manner by employing ultrasonic agitation during immersion in the hydrofluoric acid. All orifice specimens fabricated during this effort employed this technique and no evidence of glass residue was found. However, some bellmouthing was still evident and this area requires further investigation.

The injector fabricated and shipped to the Jet Propulsion Laboratory, described in this report under Task II was prepared for brazing of mounting bolts and other appurtenances by Jet Propulsion Laboratory personnel. During the furnace brazing operation at 1800°F, small blisters formed on the injector face, Figure 17. Blisters were not found on the circumference or back face of the injector.

Investigations were conducted to determine the reason for the formation of these small blisters. The blisters were believed to be the result of thermal expansion of trapped inclusions of gas evolved during the electroforming process. During most electroforming operations cathode agitation is employed to inhibit bubble formation on the work-piece. However, the first electroforming operation performed on this injector involved deposition of nickel on a mandrel which contained 144 protruding glass pins. The use of cathodic agitation during the initial electroforming process posed the probability of dislodging a glass pin from the mandrel. Therefore, approximately .030 - .040 inches of nickel were deposited before cathode agitation was employed. During the remainder of the electroforming operations the work-piece was continuously agitated.

Several small injector plates were prepared, using cathodic agitation from inception to conclusion. Similar specimens were fabricated without any agitation during the entire deposition process, (still plating). These units, together with several that were fabricated at the beginning of the project with continuous cathode agitation were heated to 900°F and inspected for blisters and then heated to 1800°F and inspected. None of the units showed any signs of blistering at 900°F. Only those units which were still plated showed evidence of blistering at 1800°F. We therefore conclude that the blister formation during the brazing operation is attributable to the lack of cathode agitation during the initial nickel deposit. Future electroformed injectors must therefore be fabricated with continuous agitation of the work-piece starting with the very first nickel deposit.

TASK V

Subtask A. To demonstrate the feasibility of, and generate preliminary design criteria for, the inclusion of chemical and/or thermal barrier materials as an integral part of electroformed rocket motor components.

The basic goal of this task was to increase the utility of the electroforming process as applied to rocket motor components by developing processes to incorporate free-standing chemical and/or thermal barrier materials into electroformed structures. The refractory type materials considered were:

1 - Pyrolytic graphite

2 - Boron carbide

3 - Vitreous carbon

4 - Zirconium diboride

5 - Zirconium Carbide - Pyrolytic Graphite.

A laboratory scale program was conducted in order to investigate the following areas:

1 - Deposition of metal on the candidate barrier materials. If the barrier material is a non-conductor of electricity then it is impossible to electrodeposit any metal directly to the substrate. In this case it is necessary to render the surface conductive by firing silver or nickel into the surface or applying electroless nickel to the surface of the barrier material. Electroformed nickel can then be deposited into the interface.

2 - Electrochemical processes for obtaining adhesion between the substrate and electroformed nickel. Proper cleaning and activation procedures were to be developed in order to obtain the maximum adhesion strength between the electroformed nickel and the substrate. Various procedures were qualitatively evaluated by filing or grinding the interface of a sample, wire brush burnishing, etc. After a promising system was developed, quantitative specimens were produced. These consisted of rods of the barrier materials with an electroformed nickel disk deposited on one end. The adhesion strength was determined by applying an axial load through the nickel disks mounted in a tensile test machine.

After the laboratory scale program was completed, thrust chamber configurations were electroformed.

Various cleaning and activation procedures were evaluated for depositing adherant electroformed nickel on the various substrates. Each of the candidate procedures were qualitatively evaluated by depositing small quantities of nickel on the end of a cylindrical rod of the substrate and then filing or wire brushing the nickel/barrier surface interface. The following electrochemical procedures were selected for further quantitative evaluation.

Boron Carbide

1 - Roughen the substrate surface with sand paper

2 - Rinse in methyl ethyl ketone

3 - Hand pumice

4 - Alkaline clean

5 - Treat anodic in 30% sulfuric acid at 300 amps per square foot for two minutes.

6 - Woods Nickel strike

Anodic - 30 sec

Cathodic - 30 sec

Anodic - 5 sec

Cathodic -30 sec

Anodic - 5 sec

Cathodic - 2 minutes

7 - Deposit electroformed nickel from nickel sulfamate bath.

Specimens made with the above procedure exhibited adhesion strengths of 10,000 psi. Examination of the electroformed nickel interface after testing revealed the presence of a boron carbide layer indicating that adhesion was obtained. Since the boron carbide is basically a passive type material a decision was made to modify the above electrochemical procedures to include a positive activation of the surface. Additional specimens were fabricated by replacing the anodic treatment in sulfuric acid (step 5) with a painting of the substrate surface with Dupont silver paint (Number 6260). The part was heated to 600°F, held for ten minutes and then heated to 1500°F and held for five minutes. After cooling in air, steps 6 and 7 above were implemented. Test pieces made with this procedure exhibited adhesion strengths between 15,000 and 18,000 psi, an increase in excess of 50%. The separation plane again indicated the presence of boron carbide on the nickel.

It is appropriate at this point to discuss the configuration of the test specimens. The above procedures and others developed for vitreous carbon were utilized initially to deposit a .125 inch thick by .250 inch diameter nickel button on both ends of a .125 inch diameter by 1.0 inch long cylinder of the substrate. During machining of the plated nickel, several substrates fractured. Those specimens which were completed were tested by applying an axial tensile load through both nickel buttons. However, the substrates fractured as soon as load was applied, due solely to the fact that the loads were not purely axial and the substrates were therefore subjected to bending loads. Our previous experience with the candidate substrates indicated that they were of course very brittle and relatively weak in loading configuration other than purely axial.

The above results and conclusions were discussed with the NASA Project Engineer and it was agreed that the nature of the bond between the barrier material and electroformed nickel would be tested by depositing a full cylindrical jacket around the barrier material cylinder. An axial compressive load would be applied to the barrier material in order to push it through the nickel jacket. By accurately machining the O.D. of the nickel jacket, the specimen could be held in a die while a punch applied a pure axial force to the substrate, Fig. 18.

Vitreous Carbon

1 - Steps 1 through 4 as per boron carbide procedures.

2 - Heat treat at 400°F for two hours, 1300°F for 10 minutes followed by air cooling.

3 - Soak in Woods Nickel bath without current for 10 minutes then treat as in step 6 of boron carbide procedure.

4 - Deposit electroformed nickel from nickel sulfamate bath.

The above procedures were utilized to deposit a .125 inch thick wall of electroformed nickel on a .125 inch diameter rod of vitreous carbon. The ultimate shear stress applied to the vitreous carbon samples was 4250 psi.

The separation plane was sharp and clean indicating that the electroformed nickel did not diffuse into the carbon surface.

A modified procedure for depositing on vitreous carbon was tried, utilizing the fired silver paint prior to the Woods Nickel strike. Test samples fabricated in this manner had failure shear stresses of 5200 psi. The separation plane was again clean and sharp with very little indication of carbon remaining on the interior nickel surface.

<u>Pyrolytic Graphite</u>

1 - Roughen the substrate surface with sand paper

2 - Rinse in methyl ethyl ketone

3 - Hand pumice

4 - Alkaline clean

5 - Etch in 30% hydrofluoric acid for five minutes

6 - Brush with metallic silver paint

7 - Heat to 800°F uniformly in eight minutes

8 - Heat to 1250°F in six minutes

9 - Cool in ambient

10 - Treat alternately anodic and cathodic in Woods Nickel

11 - Deposit electroformed nickel from nickel sulfamate bath.

Three pyrolytic graphite substrates (.400 inches long, .250 inches diameter) were processed in accordance with procedures described above. The units were tested and found to have ultimate shear strengths of 5200 psi ± 5%. The separation planes were relatively clean with little evidence of nickel diffusion into the pyrolytic graphite.

Pyrolytic Graphite-Zirconium Carbide

The above processes were also utilized on the Pyrolytic Graphite - Zirconium Carbide substrate. The samples of this material were supplied by JPL and were fabricated as part of a contractual effort by Marquardt Corporation under contract No. NAS 7-555. The material is extremely brittle and multilamina. During the heating cycle for firing in the silver paint the sample cracked and delaminated. The material was also compltely covered with a white powder upon removal from the oven. The change in color from black to white occurred on all exposed surfaces, including some that had not been silver painted. It appears that oxidation of the zirconium occurred. No further effort was expended on the PG-ZrC composite but an attempt to use an inert atmosphere during firing of the silver paint is indicated.

Zirconium Diboride

Four specimens of Zirconium Diboride (.400 inches long, .250 inches diameter) were jacketed with nickel. Two cylinders were prepared using the original Boron Carbide cycle (no silver) and two units were processed in accordance with the latest Boron Carbide cycle. The first two units exhibited ultimate shear stresses of 4750 psi and 5100 psi. The second set of samples exhibited ultimate shear stresses of 29,000 psi and 30,000 psi. The interior of the nickel again showed signs of Zirconium Diboride on the surface.

The last phase of the project was to demonstrate the ability to fabricate typical regeneratively cooled thrust chamber configurations using barrier material liners supplied by the Jet Propulsion Laboratory. These included a specimen of pyrolytic graphite, vitreous carbon, and the zirconium carbide - pyrolytic graphite composite. The first two samples were cylindrical with a flared conical end, while the last sample was a contoured prototype thrust chamber configuration.

The procedures discussed previously for depositing adherant nickel on pyrolytic graphite and vitreous carbon were employed to envelop the samples with electroformed metal. In the case of the pyrolytic graphite a net thickness of .150 inches was deposited. A series of equally spaced .060 inch wide by .100 inch deep grooves were milled to form a cooling passage. The cooling passage spacing was such that a .060 inch wide rib remained in the cylindrical section. The nickel thickness between the outside of the substrate and the bottom of the cooling passage is .050 inches. A similar rib-cooling passage geometry was used for the vitreous carbon except that the nickel layer between the carbon and cooling passage is only .030 inches.

Since no definitive procedures had been previously established for the deposition of adherant nickel on the zirconium carbide - pyrolytic graphite composite, the sample was cleaned and the surface was rendered conductive by applying a coating of silver paint. Due to the apparent delamination and oxidation problem, the silver was not fired into the surface. A sufficient amount of nickel was deposited to create the same geometry as that employed on the pyrolytic graphite. During the machining operations there was no relative motion between the nickel and the substrate indicating that the natural porosity of the substrate surface is sufficient to give at least a mechanical bond between the liner and electroformed nickel jacket.

All three liners with electroformed nickel rib/ cooling passage circuits are shown in Fig. 19.

Figure 20 shows the segment of the vitreous (glassy) carbon containing the regenerative cooling passages.

Due to cost and time limitations needed to determine feasibility and develop the basic electroforming parameters for electroforming composite materials, it was not possible to fabricate composites with nickel orifices or conduct thermal cycling tests on the specimens.

REFERENCES

1. Hammer, S. and Cacha, Z., "Electroformed Injector Fabrication Techniques", Interim Report on Contract No. NAS 7-691, November 26, 1969.

2. Riebling, R.W., "Application of Space Storable Injector and Chamber Design Criteria to Spacecraft Engine Development." AIAA Paper No. 69-508, AIAA Fifth Propulsion Joint Specialist Conference, U.S. Air Force Academy, June 1969.

3. Hammer, S. "Final Report on Contract No. NAS 9-6177" NASA CR 85641 Camin Laboratories, Inc., May 15, 1967.

4. Hammer, S. and Cacha, Z. "Development of Advanced Electroforming Techniques for Injectors and Composite Thrust Chamber Fabrication." AIAA Paper No. 69-583, Camin Laboratories, Inc., June 1969.

LIST OF FIGURES

*Photo supplied courtesy of Jet Propulsion Laboratory.

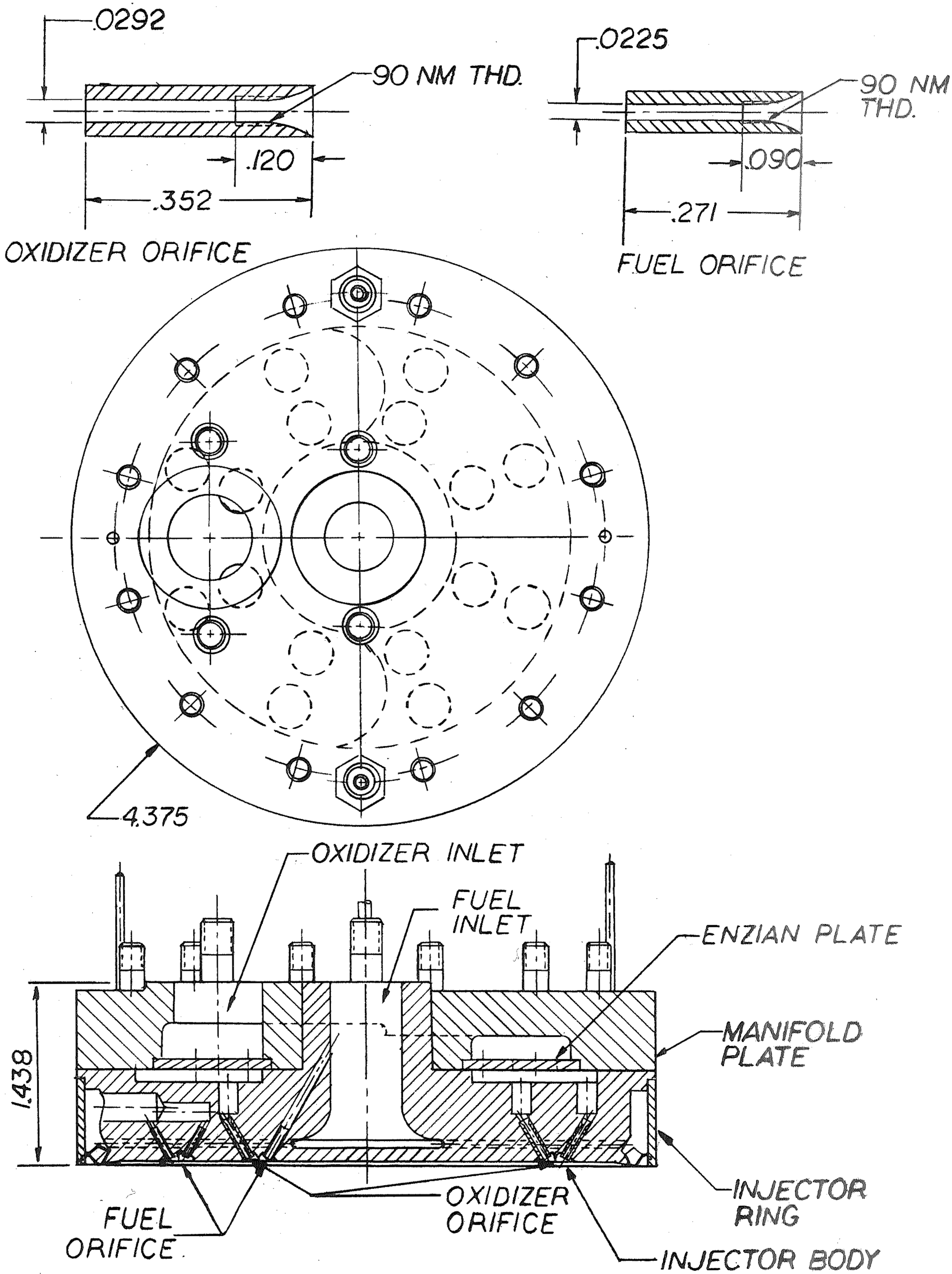


FIGURE 1 : INJECTOR ASSEMBLY

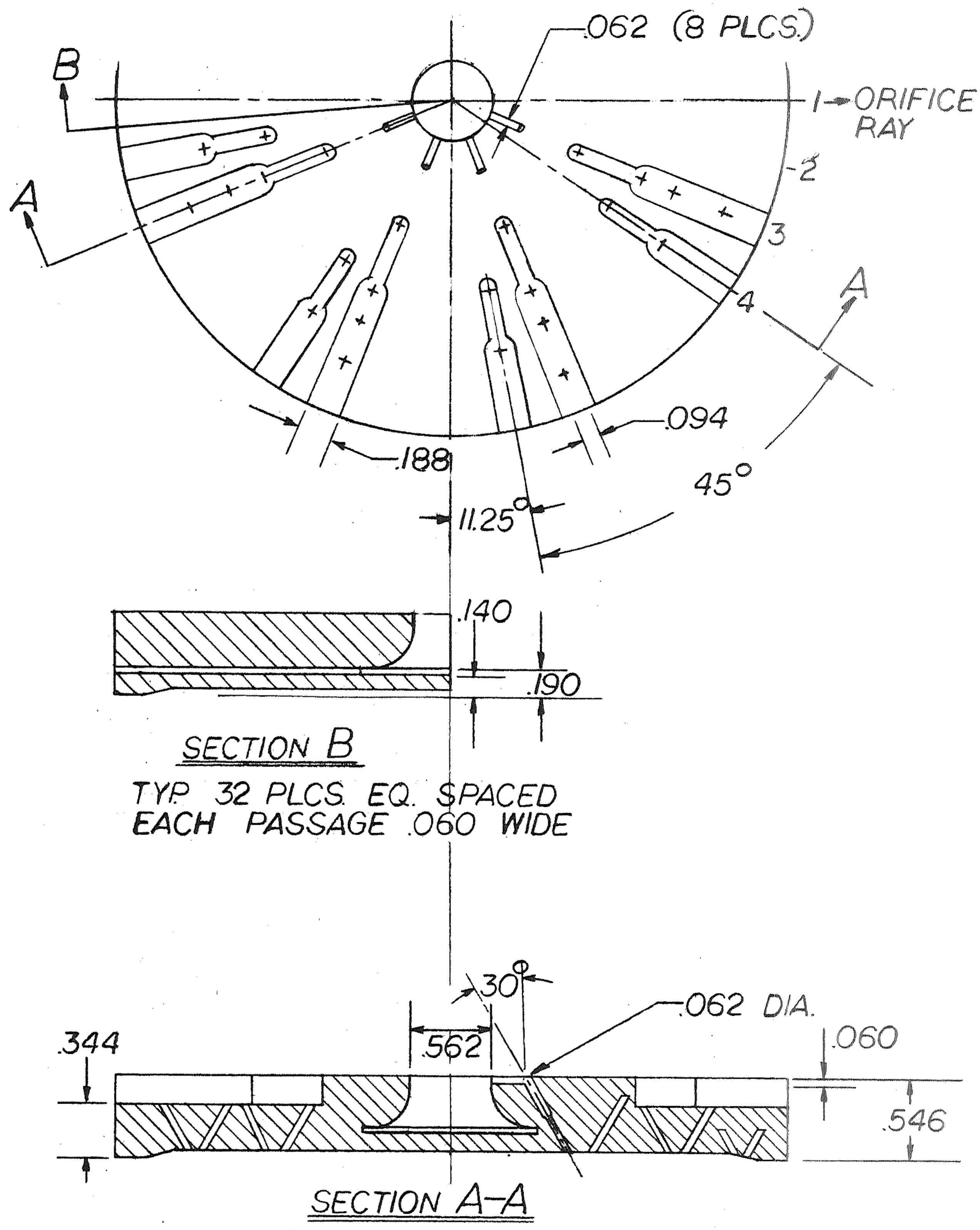


FIGURE 2 : ELECTROFORMED INJECTOR— FUEL MANIFOLD.

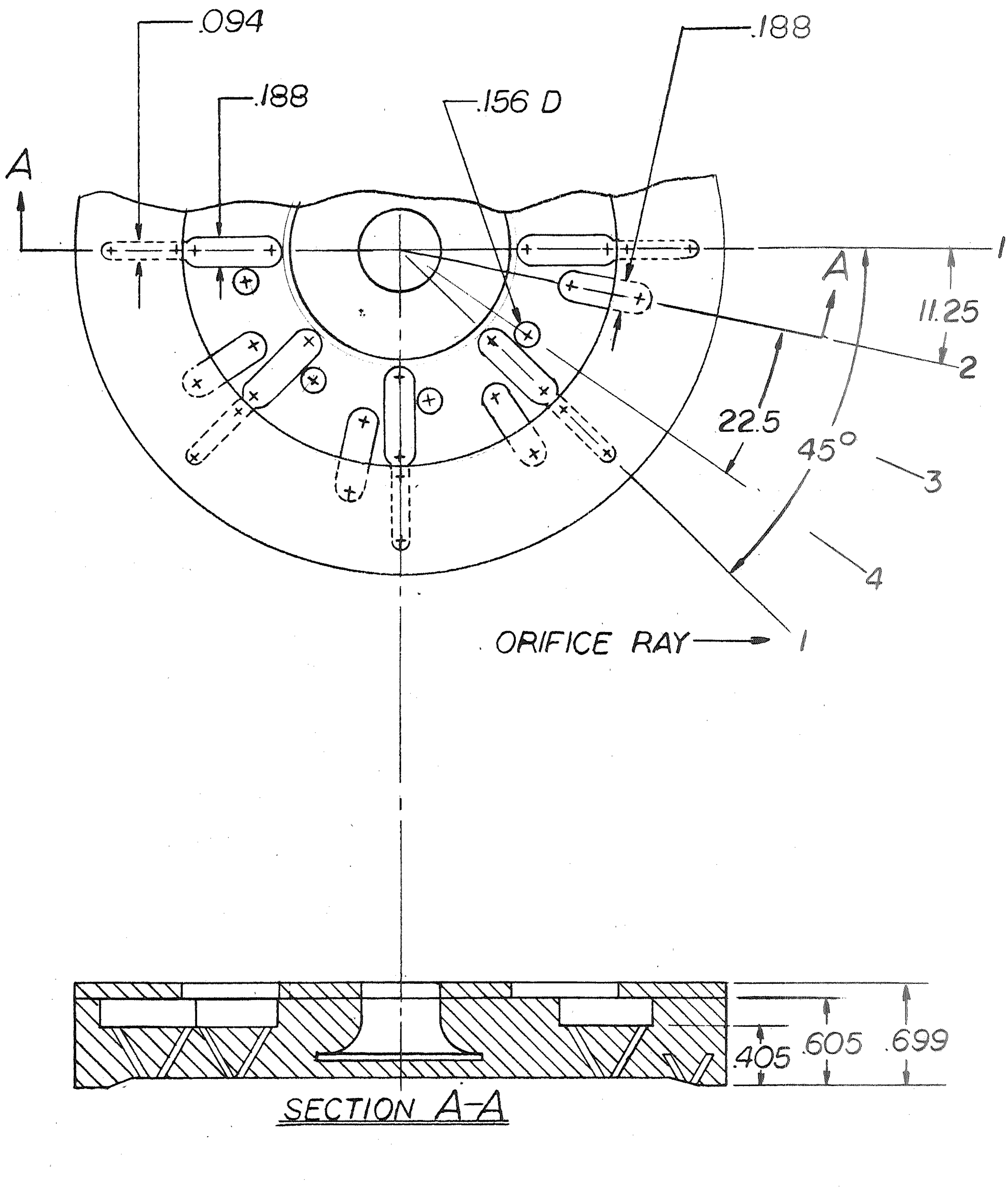


FIGURE 3 : ELECTROFORMED INJECTOR – OXIDIZER FEED PASSAGES.

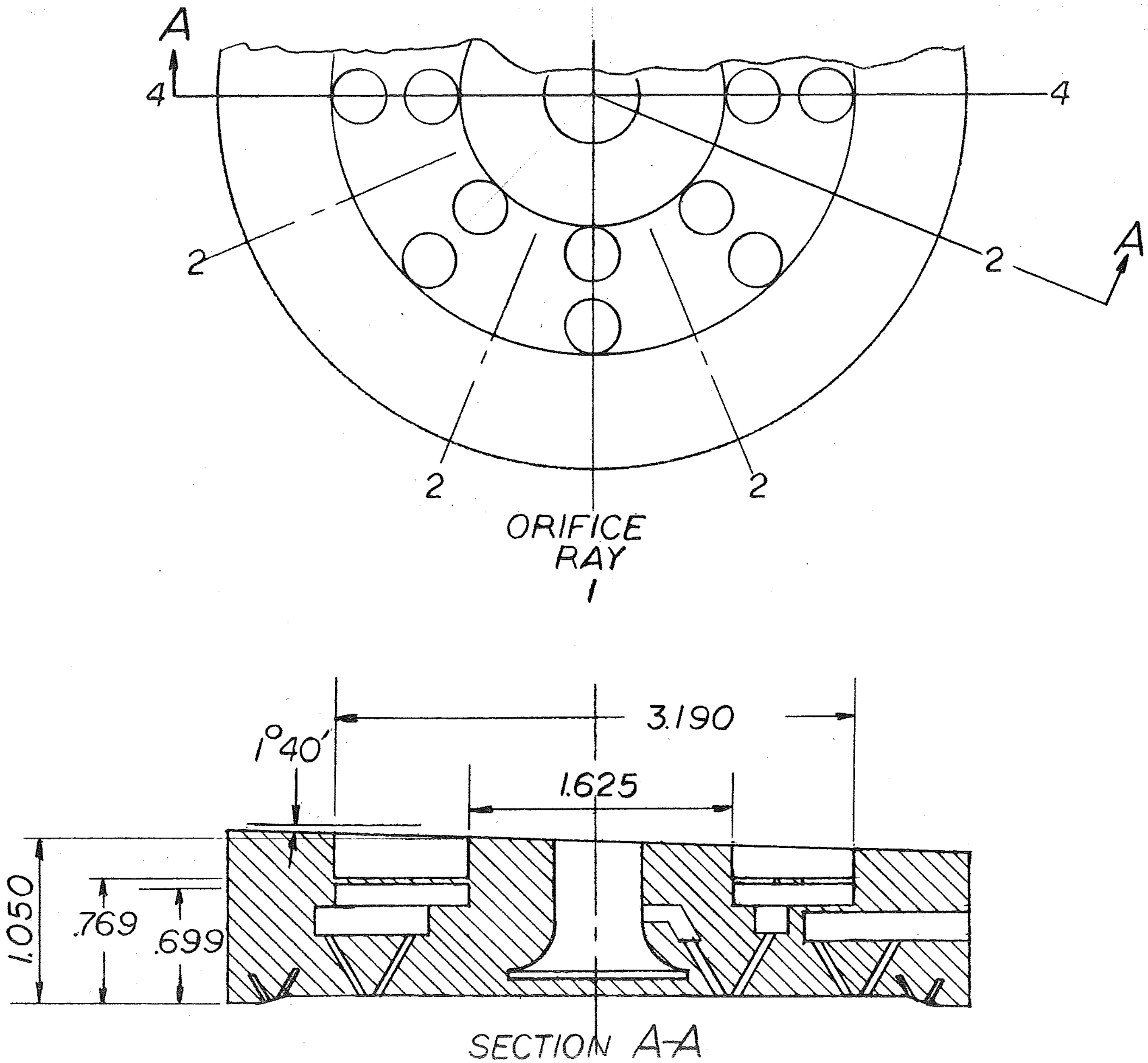


FIGURE 4 ELECTROFORMED INJECTOR ENZIAN PLATE AND OXIDIZER MANIFOLD

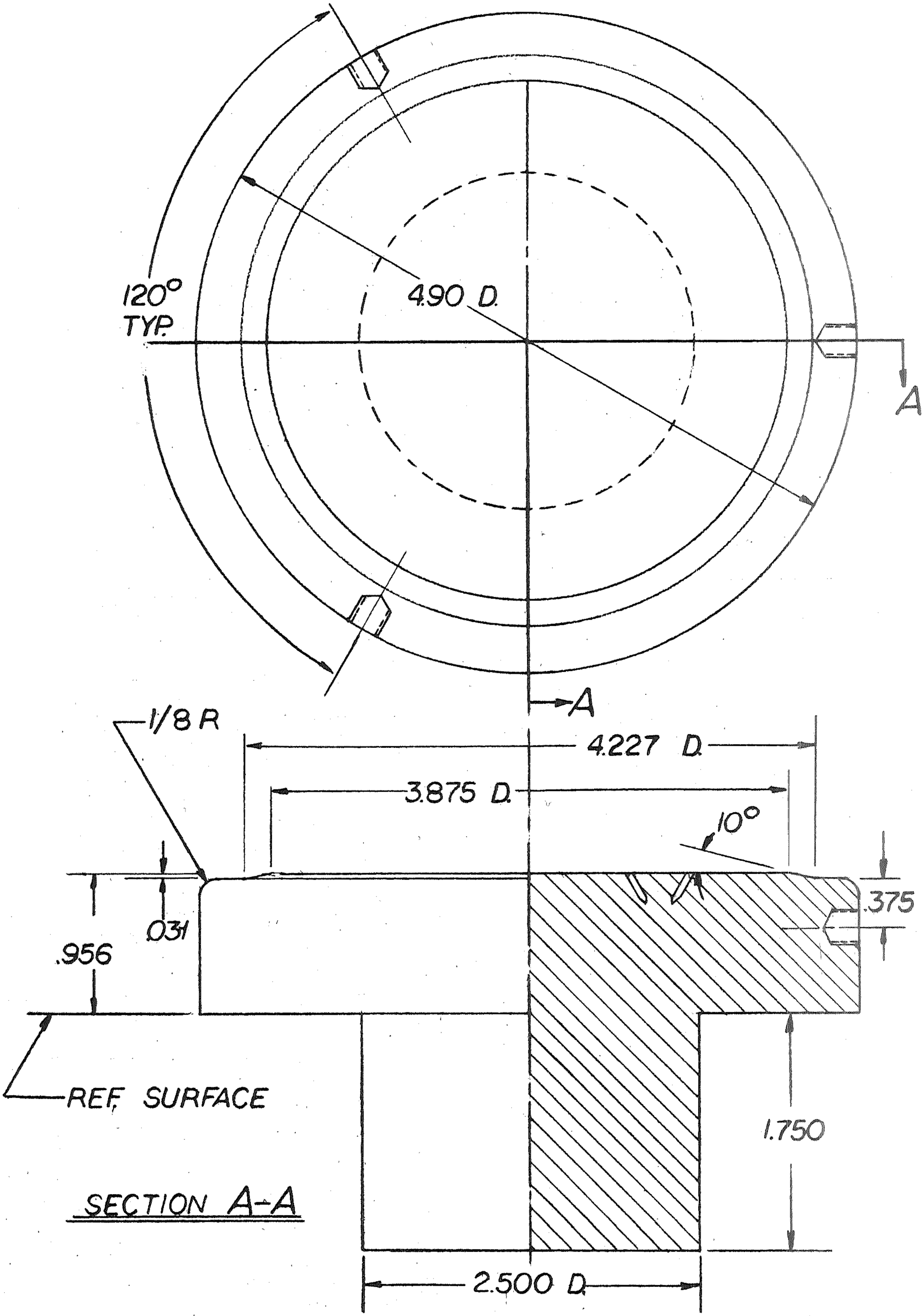
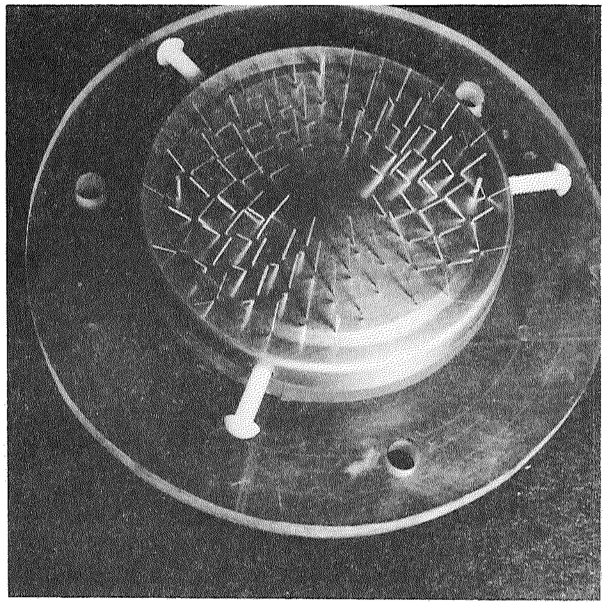
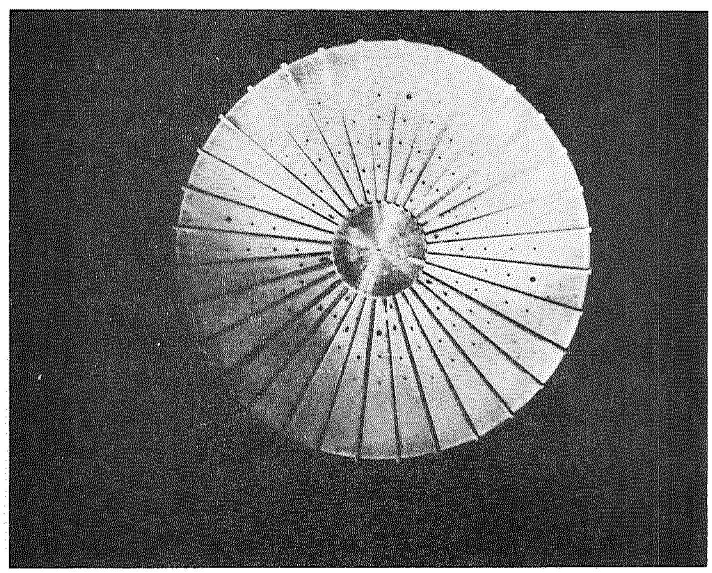


FIGURE 5 : ELECTROFORMED MANDREL DESIGN.



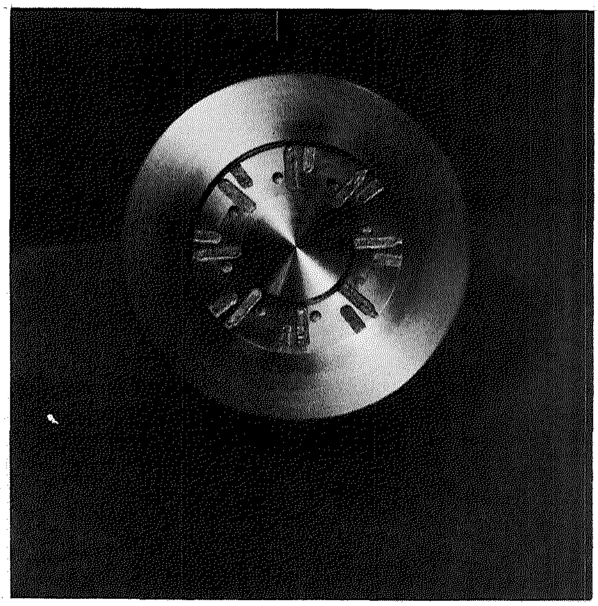
INJECTOR MANDREL ASSEMBLY

FIG. 6



RADIAL FUEL MANIFOLD

FIG. 7

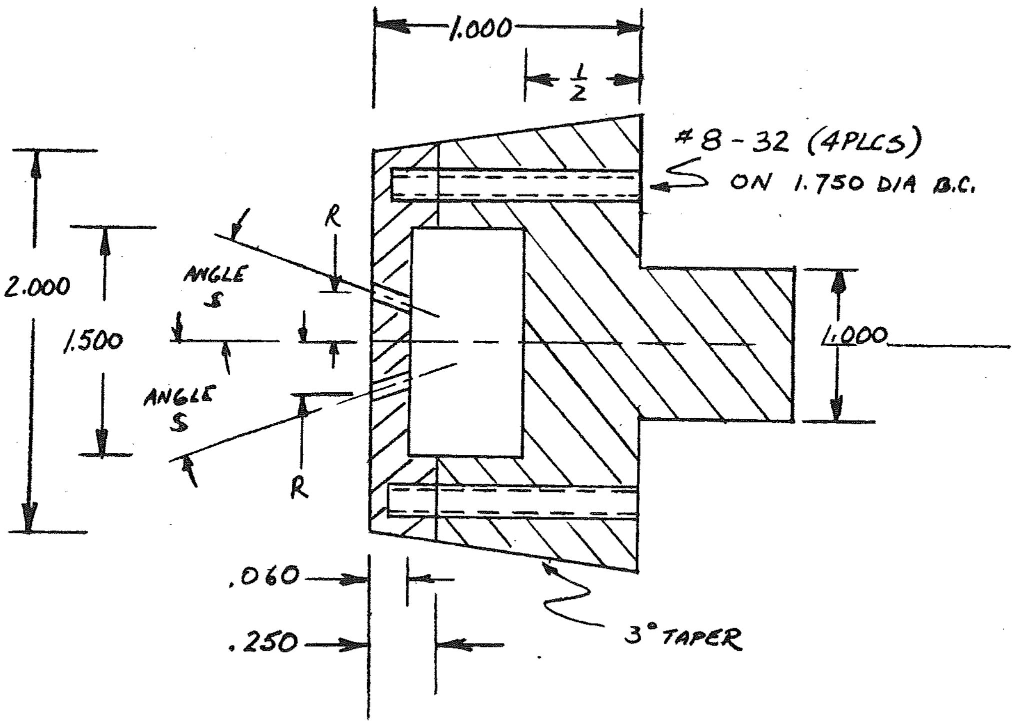


OXIDIZER MANIFOLD

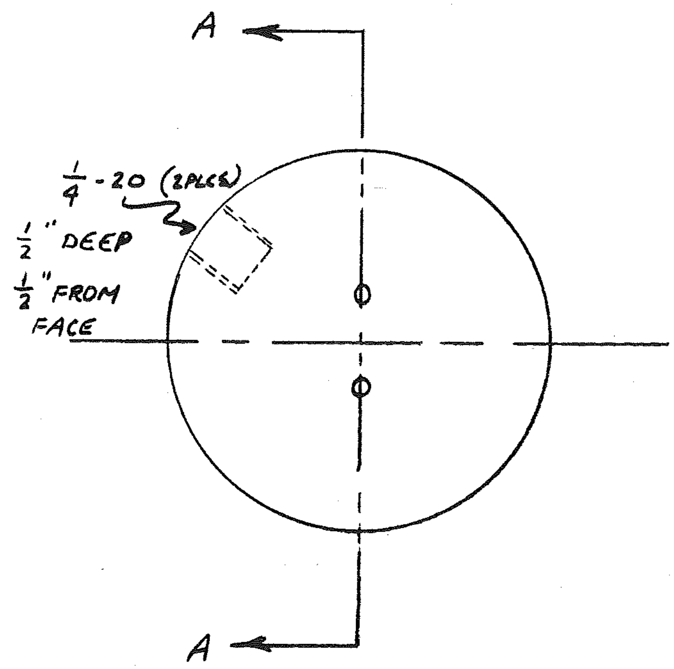
FIG. 8

1000 LBF. THRUST
ELECTROFORMED INJECTOR

FIG. 9



SECTION A-A



PART NO.	HOLE	R	S	BUSHING DIA.	ORIFICE DIA ±.0002
1	1	.045	30°	.015	.0078
	2	.045	30°	.015	.0078
2	1	.078	45°	.015	.0058
	2	.078	45°	.015	.0058
3	1	.030	15°	.015	.0078
	2	.030	15°	.015	.0058

NOTES:

DRILL HOLE IN MANDREL TO BUSHING DIA.
BUSHING I.D. EQUAL TO ORIFICE O.D.
ELECTROFORM .100 THICK PLATE
ASSEMBLE PER EFM JPL 002

DATE	1/27/70	CAMIN LABORATORIES BROOKLYN, N.Y.
DRAWN	mm	
APP'D	SBA	
TOL. DEC. ±.001 FRAC ± 1/64 ANGLE ± 0°10'		MICRO-ORIFICE IMPINGING JET ELEMENT MANDREL
		EFM-JPL-70-01

FIG. 10

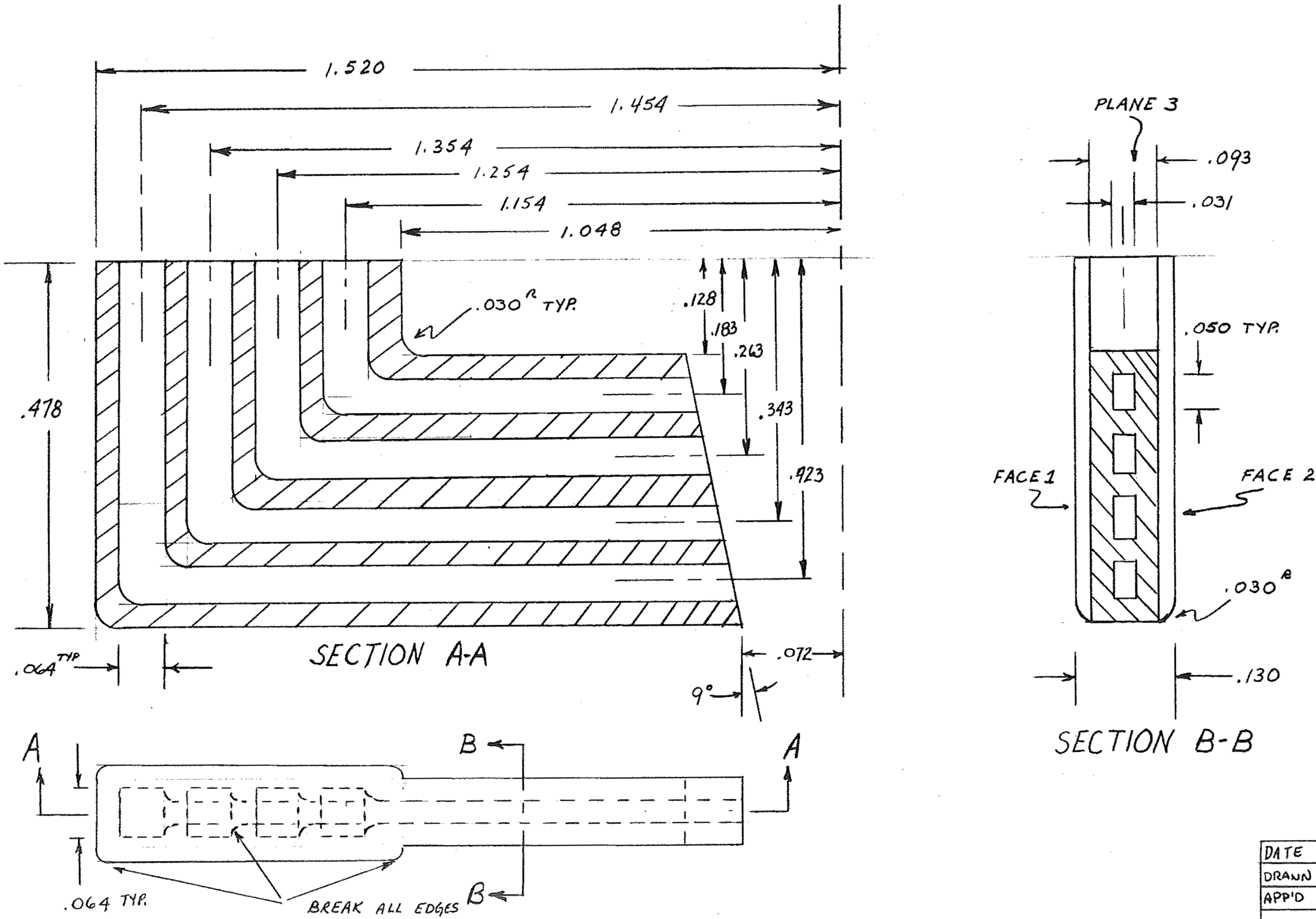
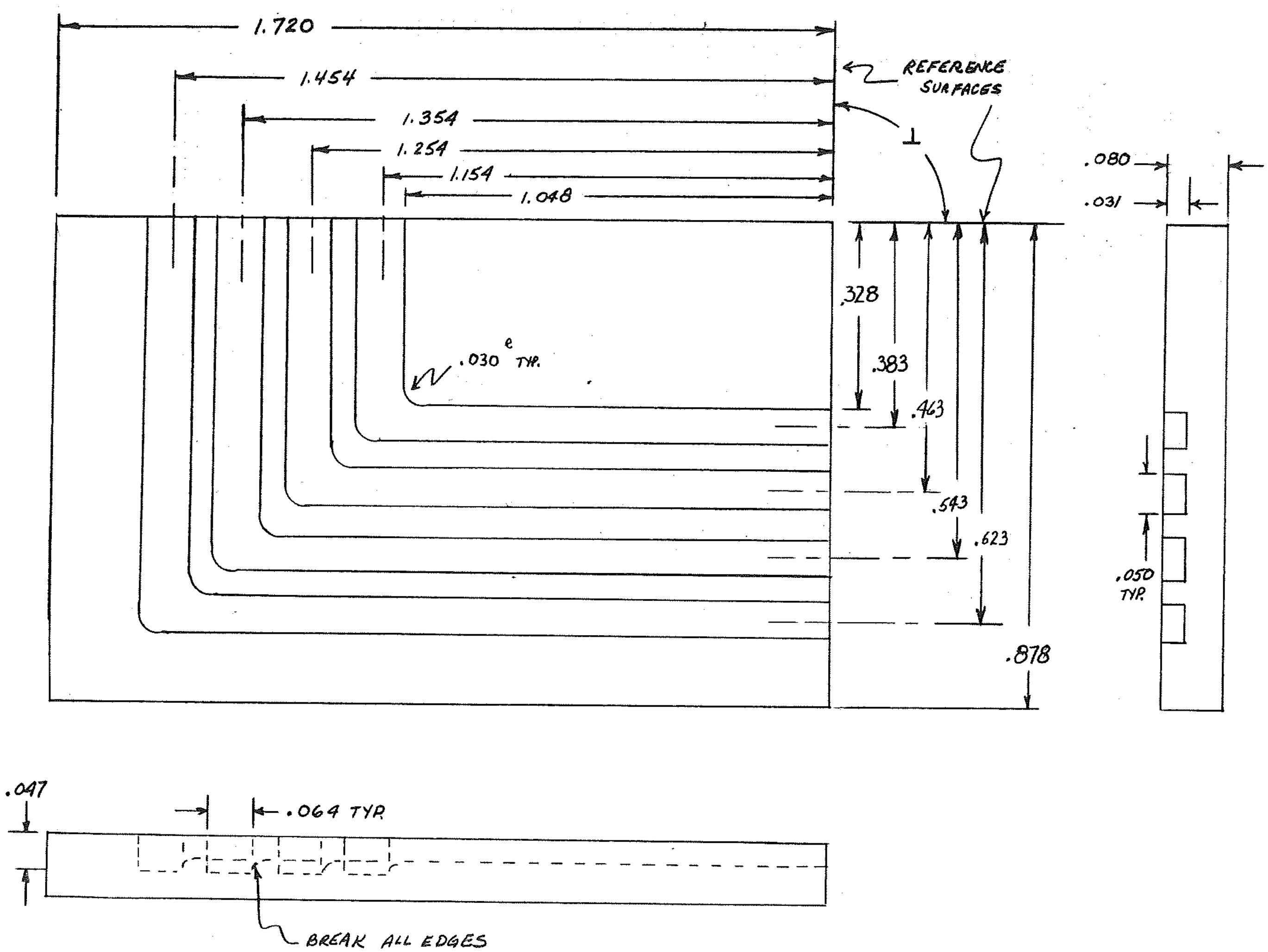


FIG. 11

DATE	2-9-70	CAMIN LABORATORIES BROOKLYN, N.Y.
DRAWN	MM	
APP'D	[illegible]	
TOL. DEC ±.002 FRAC ± 1/64 ANGLE ± 0°10'		BAFFLE SEGMENT
		EFM-JPL-70-02



MAT'L : NICKEL

DATE	2-8-70	CAMIN LABORATORIES BROOKLYN N.Y.
DRAWN		
APP'D		
TOL. DEC ±.002 FRAC ±1/64 ANGLE 0° 10'		BAFFLE SEGMENT MANDREL
		EFM JPL - 70-03

FIG. 12

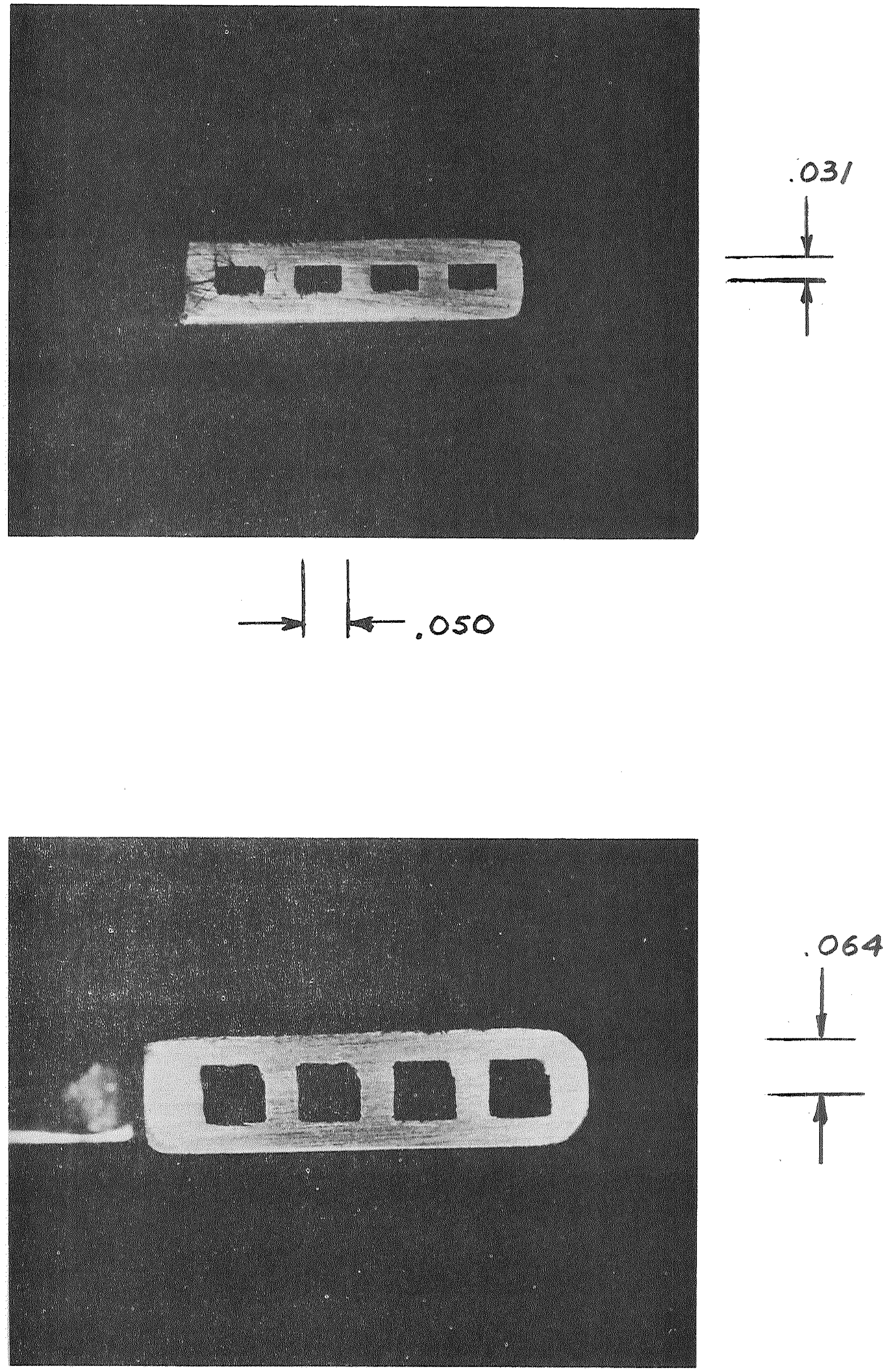
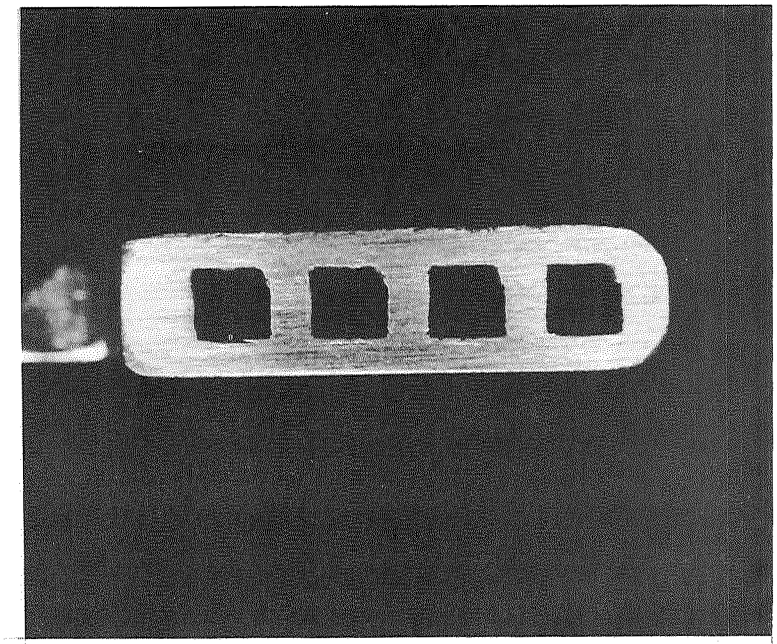
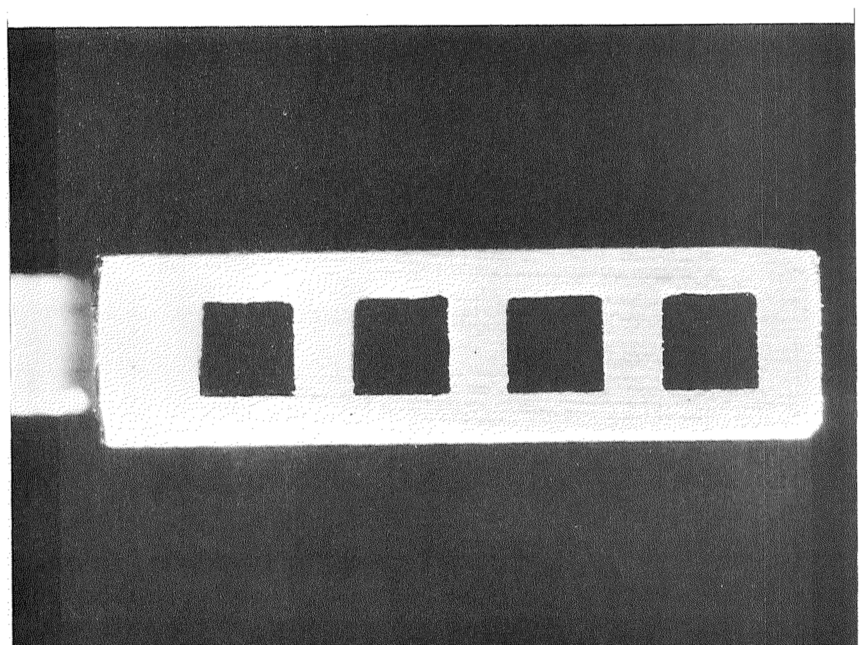


FIGURE 13



ORIGINAL METHOD



ALTERNATE METHOD

ELECTROFORMED BAFFLES

FIG. 14

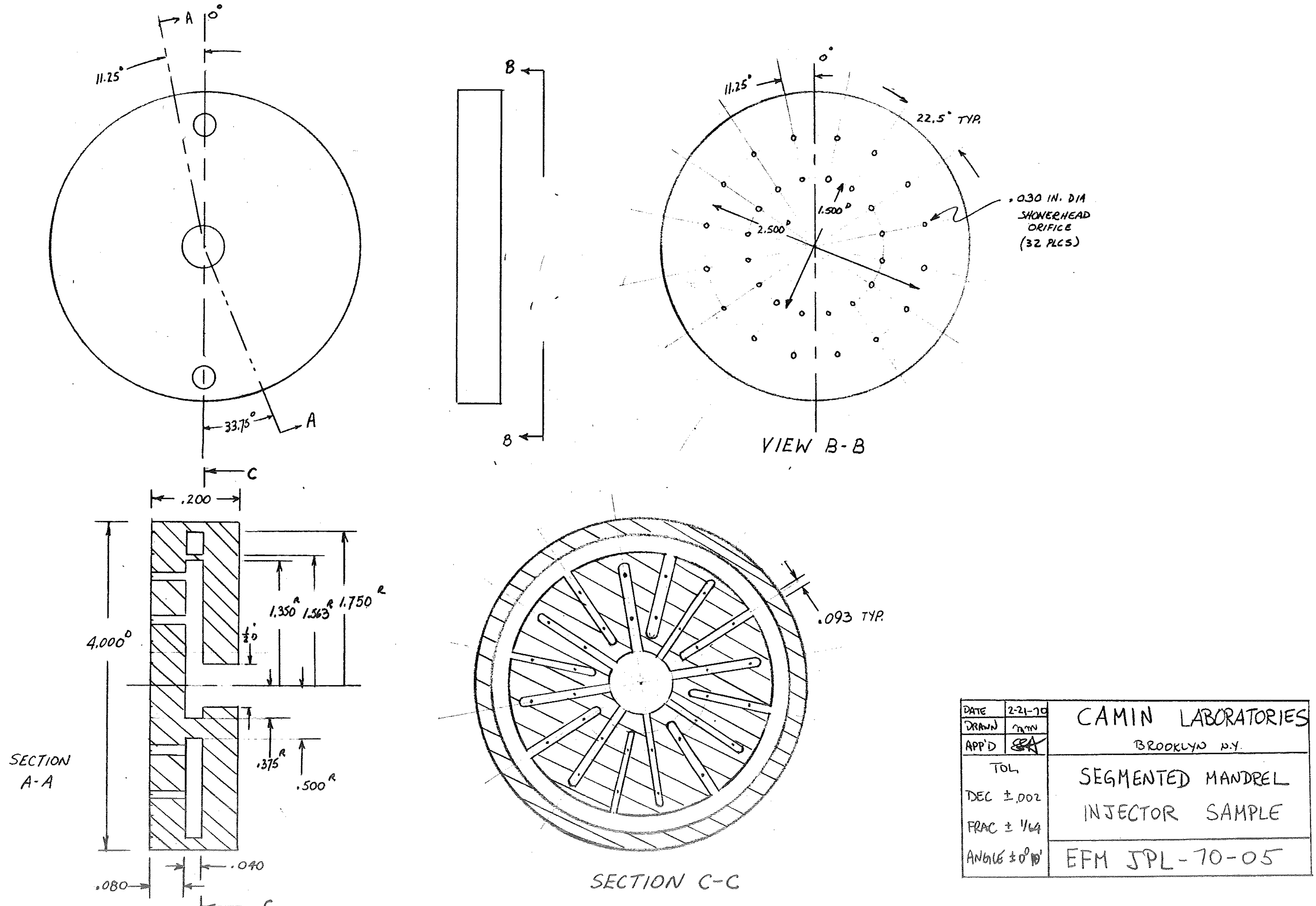
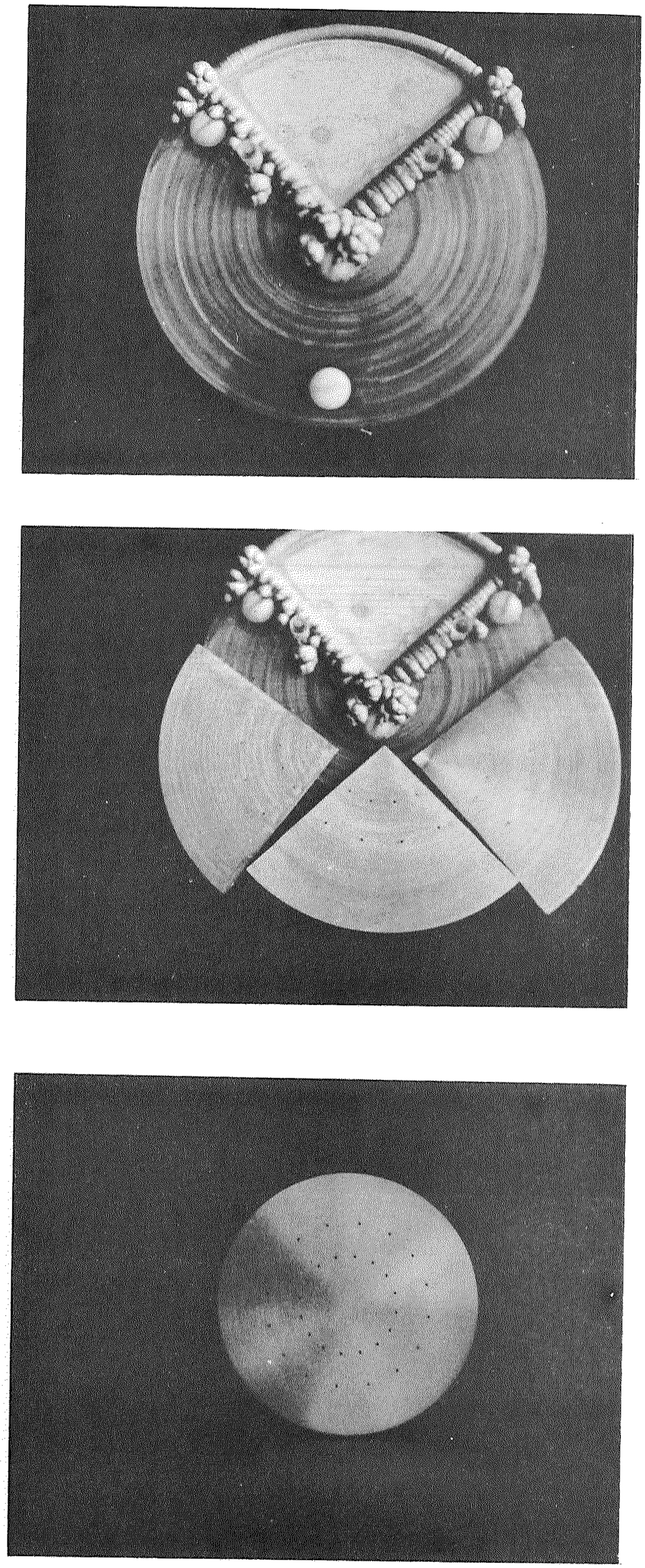
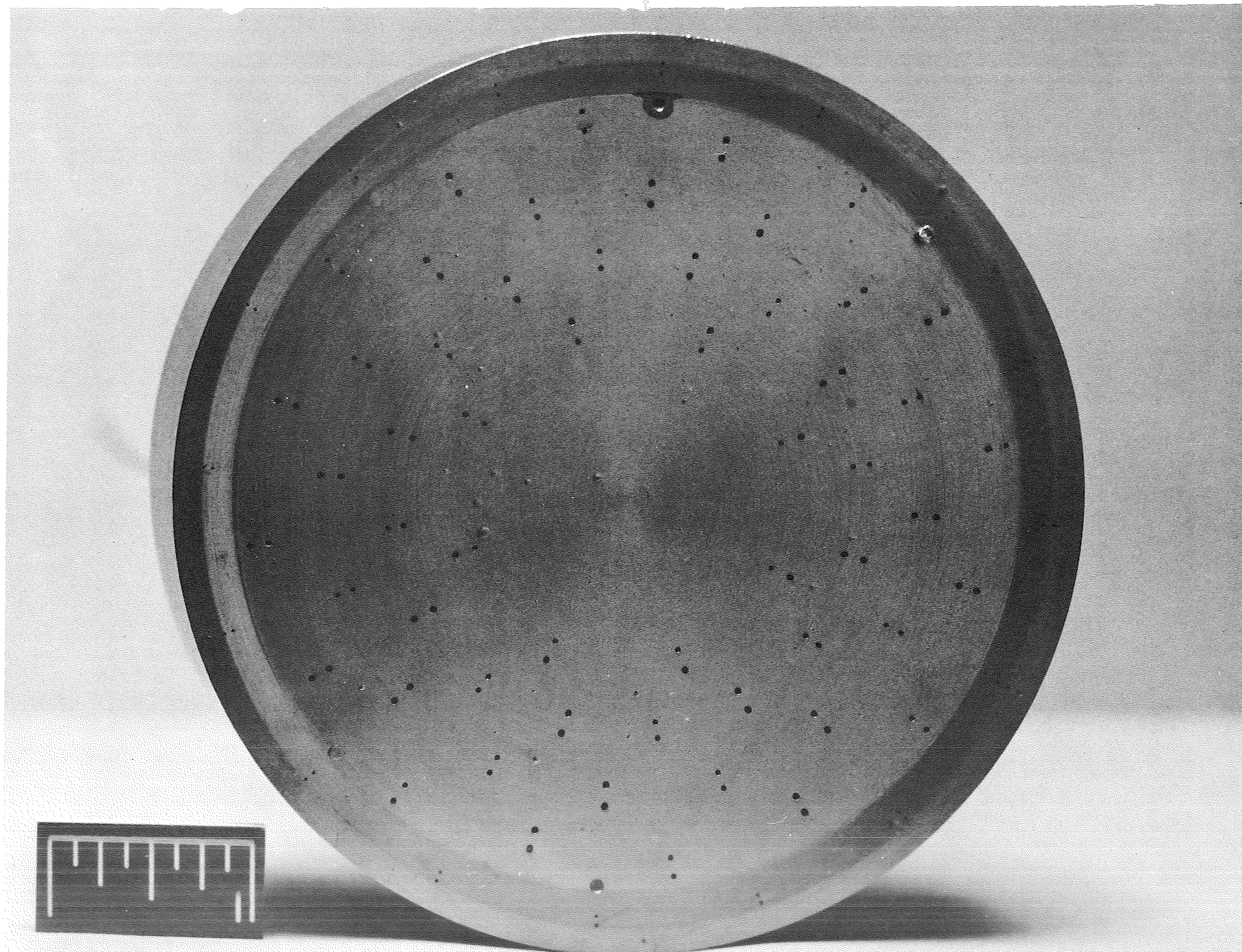

A
0°
11.25°
33.75°
A
C
.200
4.000 D
1.350 R
1.563 R
1.750 R
1/8 D
.375 R
.500 R
.080
.040
C
SECTION A-A
B
B
0°
11.25°
22.5° TYP.
1.500 D
2.500 D
.030 IN. DIA SHOWERHEAD ORIFICE (32 PLCS)
VIEW B-B
.093 TYP.
SECTION C-C
DATE 2-21-70
DRAWN
APP'D
TOL
DEC ±.002
FRAC ± 1/64
ANGLE ±0°10'
CAMIN LABORATORIES
BROOKLYN N.Y.
SEGMENTED MANDREL
INJECTOR SAMPLE
EFM JPL-70-05

FIG. 15



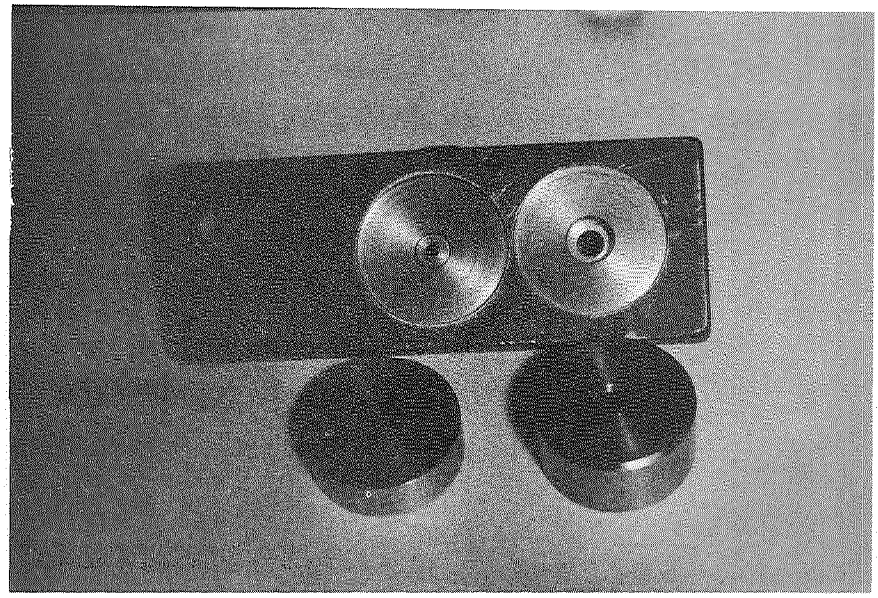
INJECTOR - ELECTROFORMED FROM FOUR 90° SEGMENTS

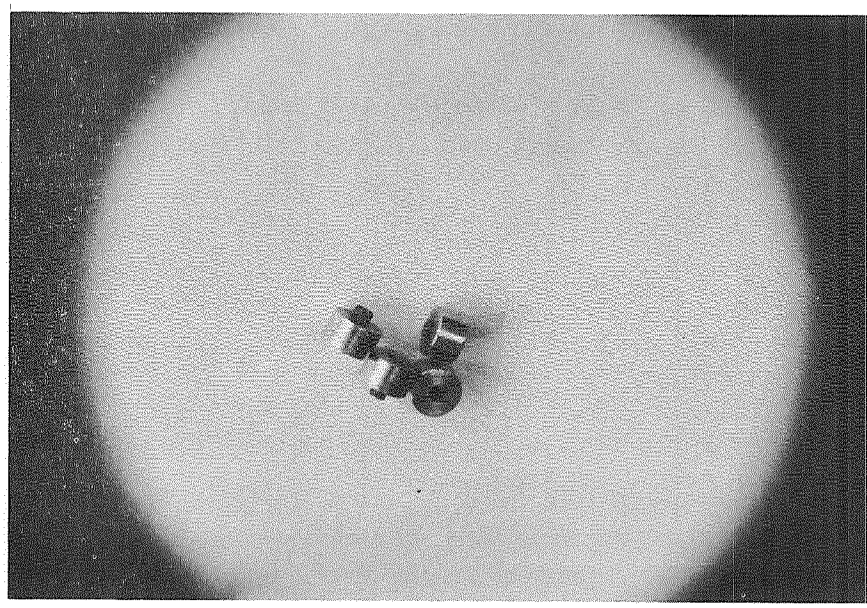
FIG 16



ELECTROFORMED INJECTOR - AFTER BRAZING

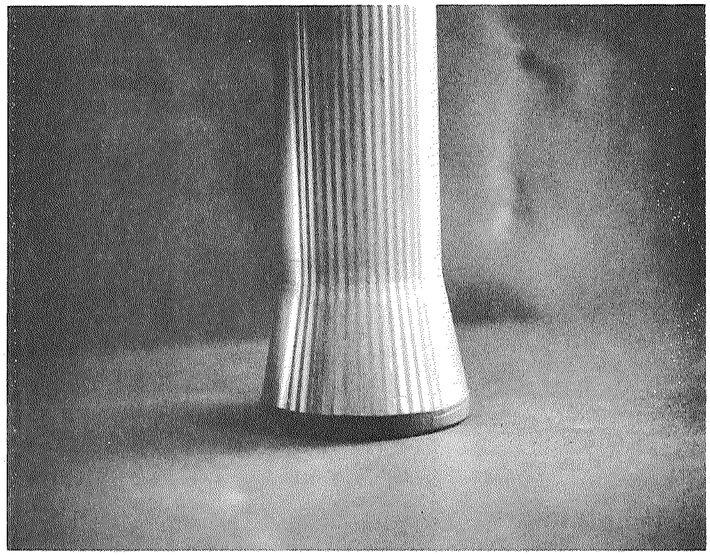
FIG. 17



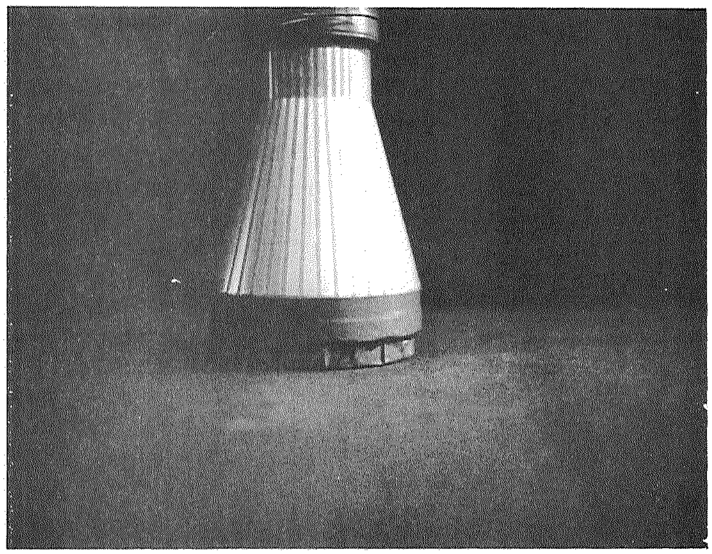


BARRIER MATERIAL ADHESION SPECIMENS

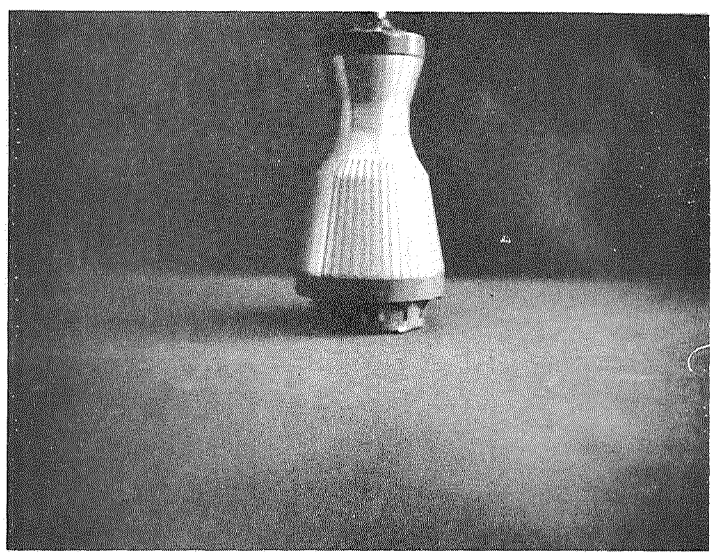
FIG. 18



PYROLYTIC GRAPHITE



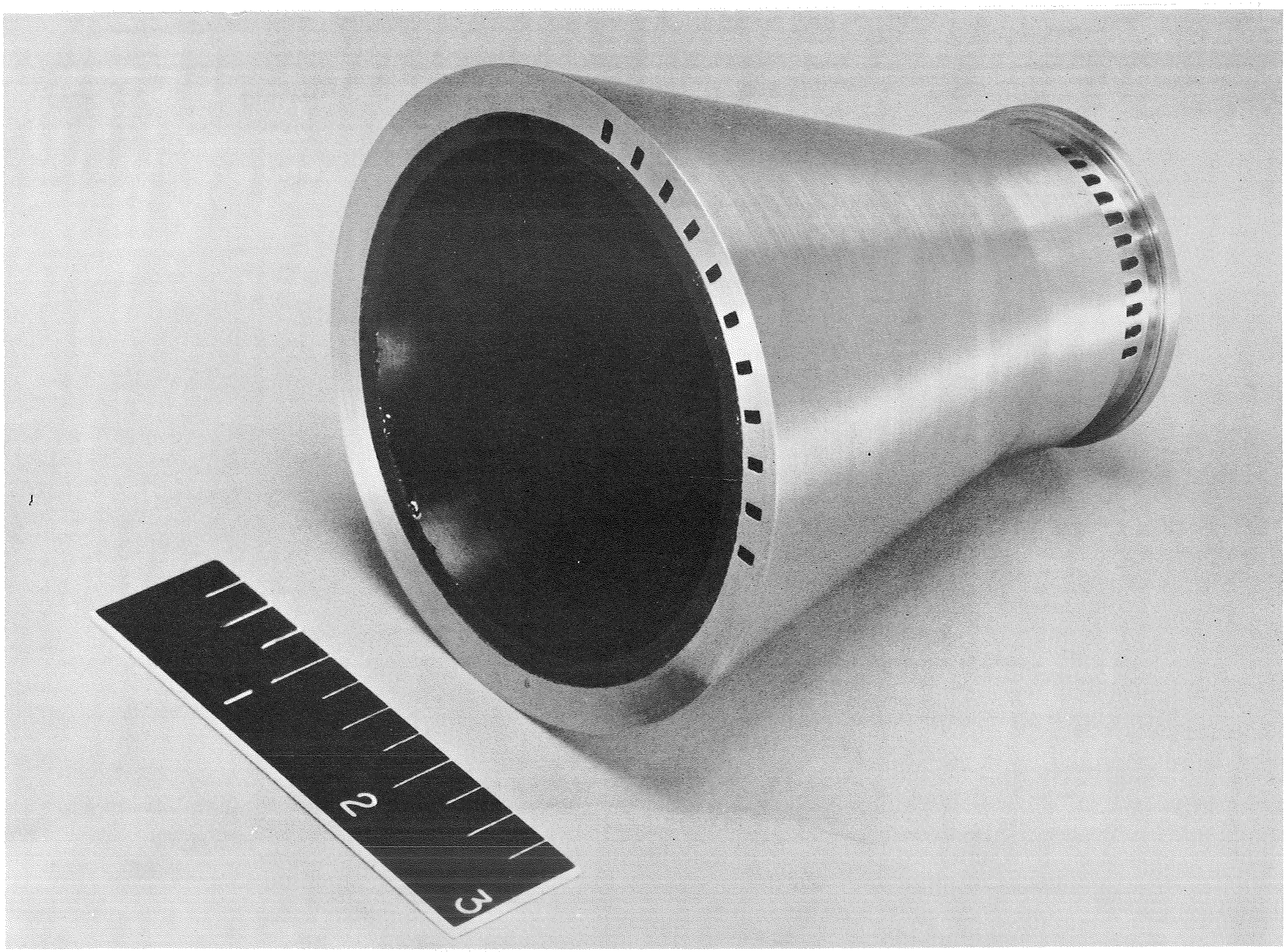
VITREOUS CARBON



ZIRCONIUM CARBIDE
PYROLYTIC GRAPHITE

BARRIER MATERIALS – EF NICKEL COOLING PASSAGES

FIG. 19



VITREOUS CARBON LINER WITH EF NICKEL COOLING PASSAGE AND OUTER JACKET

FIG. 20

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