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FINAL REPORT

DEVELOPMENT OF LOW COST FABRICATION TECHNIQUES FOR LARGE SOLID ROCKET NOZZLES

CASE FILE COPY

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Aerojet Solid Propulsion Company
Advanced Technology
Sacramento, California

September 1971

Prepared for:

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

Technical Management
J. J. Notardonato, Project Manager

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FOREWORD

The research and development work described herein was performed by the Advanced Technology Operations of Aerojet Solid Propulsion Company under NASA Contract NAS3-12064. The work was done under the management of the NASA Project Manager, Mr. J. J. Notardonato, NASA Lewis Research Center, Cleveland, Ohio.

This program was conducted at the Advanced Technology Operations under the management of J. J. Warga, who also served as project engineer. Principal investigators were R. L. Knapp in the area of heat transfer analysis and H. Efron in structural analysis. Nozzle fabrication was performed at the San Rafael Plastics Company, San Rafael, California.

ABSTRACT

Low-cost fabrication techniques for the manufacture of large solid rocket nozzles were investigated. Property measurements and fabrication characteristics were determined and the performance in subscale (Minuteman Wing II second stage) motors was evaluated. It was demonstrated that the incorporation of low cost fabrication techniques in a full-scale 260-in. nozzle could result in savings of $149,000 when compared with an identical design using tape-wrapped components throughout.

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I. INTRODUCTION

Since 1966, there has been a continuing effort to reduce the cost of the reinforced ablative composite nozzle for the 260-in. (6.6 m) dia solid rocket motor. The Aerojet-General Corporation has conducted programs in behalf of NASA and the Air Force to evaluate low-cost materials and fabricating techniques. Both the Air Force and NASA have sponsored the development and testing of low cost materials systems. The potential cost savings can be visualized by reference to the overall dimensions of the nozzle. The submerged type most often proposed has an 89.1-in. (2.26 m) dia throat and an expansion ratio of 9.0 to 1. The overall length of the nozzle is approximately 300 in. (7.62 m), the maximum diameter of the nozzle liner is in excess of 6.6 meters, and the ablative material weight exceeds 20 tons (18,140 kg).

This latest in the series of evaluation programs was initiated in June 1969 with the objective of developing fabrication techniques with an optimum combination of cost and performance. This objective was to be achieved by accomplishing the following three tasks.

A. TASK I - LOW COST FABRICATION CONCEPTS

In which low cost fabrication concepts for large ablative nozzles were to be selected and subjected to preliminary evaluation.

B. TASK II - SUBSCALE NOZZLE EVALUATION

In which the most promising low cost fabrication concepts developed in Task I were to be evaluated by fabricating and testing subscale ablative nozzles.

C. TASK III - FULL SCALE NOZZLE DESIGN AND FABRICATION PLANNING

In which the preliminary design and fabrication planning needed for the production of a full-scale, low-cost ablative nozzle were to be performed.

II. SUMMARY

The Low-Cost Fabrication Techniques Development Program performed under Contract NAS3-12064, was initiated for the purpose of acquiring processing and performance data on promising techniques suitable for fabricating large solid-propellant rocket nozzles. To accomplish this objective, six subscale (8-in. [20.3 cm] dia throat) nozzle assemblies were fabricated, attached to obsolescent Minuteman Wing II second-stage motors and evaluated for performance. Selection of the fabricating techniques and ablative materials incorporated into each of the subscale nozzles was made as a result of screening tests conducted on small (1.8-in. [4.6 cm] dia throat) nozzle assemblies.

The program effort was organized into three tasks, as indicated.

A. TASK I - LOW COST FABRICATION CONCEPTS

A survey of available material and fabrication concepts was performed in order to establish a suitable test matrix to screen candidate concepts. Twenty suppliers of materials and/or developers of low cost fabrication concepts were consulted. As a result of the survey, molding, casting, wrapping, trowelling and spraying techniques were selected for investigation.

A solid rocket motor was designed to operate at 600 psi (414 N/cm^2) chamber pressure for a minimum duration of 30 sec. A converging-diverging nozzle assembly containing a throat insert with a minimum dia of 1.8-in. (4.57 cm) was also designed. Twenty-one nozzle assemblies were fabricated for use in screening candidate materials and fabrication techniques and exposed to a 15% aluminum-containing propellant developed for use in 260-SL motors.

The results of the screening tests indicated that materials fabricated by casting, molding, and wrapping exhibited the necessary combinations of performance and low cost to make them suitable candidates for use in the subscale motor evaluations of Task II of this program. Castable formulations based on furfuryl, phenolic, and silicone resins with carbon and graphite reinforcements; moldable formulations based on furfuryl and phenolic resins with carbonaceous and graphite particle reinforcements; and a low-cost fabric prepreg for wrapping, consisting of an 87% carbon reinforcement, were selected for use.

B. TASK II - SUBSCALE MOTOR EVALUATION

The subscale nozzle assemblies for use in evaluating the efficiency of low-cost fabrication techniques were designed for attachment to obsolescent Minuteman Wing II second-stage motors. Two basic designs were provided: one for fabricating by tape-wrapping techniques, the second for use with casting and molding techniques. In both design versions, the throat dia was 8.00 in. (20.32 cm), the exit cone half-angle was 17.5 degrees (0.31 rad), and the area ratio at the exit plane was 8:1. Six subscale nozzle assemblies (total) were evaluated.

Five nozzle assemblies were fabricated using procedures applicable to components for full-scale 260-in. motors. Processing characteristics were recorded, and the properties of the raw materials and cured composites were determined. After fabrication, the nozzle assemblies were attached to the motors and tested in the horizontal position. Measurements of axial thrust and chamber pressure were made and recorded for each motor, and motion picture coverage was maintained during test. After static test, the nozzle assemblies were removed from the motors and the components removed from the support shell for examination of the ablative performance. Cost/performance evaluations were determined, and a sixth nozzle assembly was fabricated using those materials considered to exhibit the optimum combination of characteristics.

The sixth subscale nozzle assembly consisted of the following:

Throat Approach	- Castable Carbon
Entrance Section	- Castable Carbon
Nosecap	- Molded Graphite Particle
Throat	- Molded Graphite Particle
Exit Cone "A" Section	- Molded Graphite/Carbon
Exit Cone "B" Section	- Low Cost Carbon Fabric Shingles
Exit Cone "C" Section	- Canvas Shingles

After fabrication, the nozzle assembly was attached to the test vehicle and statically test fired. Analysis of the performance after test indicated that the castable carbon and shingled materials performed satisfactorily, whereas the molded graphite particle materials exhibited severe spallation on the surface.

It was concluded as a result of the six subscale nozzle tests that the full-scale nozzle could best meet performance and cost requirements if the throat were molded of a conventional chopped-carbon fabric preimpregnated with polyphenylene or phenolic resin. The outboard portions of the submerged nozzle were to be fabricated of castable carbon and the inboard portions of molded carbonaceous material (CFA). The forward exit cone was planned to be wrapped using low-cost carbon and canvas duck prepregs; the aft exit cone was to be molded from canvas duck fabrics.

C. TASK III - FULL SCALE NOZZLE DESIGN AND FABRICATION PLANNING

The full scale nozzle design was based on a 260-FL motor containing 3.4 million lb (1.54 million Kg) of propellant, with a web action time of 147.5 sec, an MEOP of 764 psia (526 N/cm^2), and an average thrust of 6.34×10^6 lbf (28.2 MN). The design was verified by heat transfer and structural analysis.

The nozzle components and the aft exit cone were designed to be fabricated by casting or molding. The forward exit cone was designed to be fabricated by wrapping. All cast or molded components, with the exception of the throat, were designed to be of segmented construction. Use of such construction ensures that final assembly can be performed at AD-D. Structural support to the exit cone will be provided by glass/polyester roving.

The unit cost of a full-scale nozzle assembly fabricated as above will be $767,992, of which $442,762 is for the nozzle and $325,230 is for the exit cone. This is $149,000 less than for a tape-wrapped design.

III. TASK I - LOW COST FABRICATION CONCEPTS

Task I was accomplished by designing and fabricating ablative nozzle assemblies with 1.8-in. (4.57 cm) dia throats using low-cost materials processed by molding, casting, trowelling, spraying and wrapping techniques. The ablative performance and mechanical properties of the materials were evaluated. Cost/performance assessments were made, and candidate material systems were selected for continued investigation.

A. SURVEY OF MATERIAL AND FABRICATION CONCEPTS

Prior to the fabrication of the test nozzle assemblies, a survey of ablative materials and fabrication techniques was performed. The material suppliers or fabricators listed in Table III-1 were consulted and the available literature was examined with the objective of preparing a matrix for evaluating ablative performance. The major criteria employed in the selection of material systems were that they be suitable for use in large ablative nozzles and that they have the potential for reducing the cost and complexity of fabrication.

1. Compression Molding

In compression molding, the partially polymerized, resin-reinforcement mixture is placed in a heated mold cavity. The mold is closed, heat and pressure are applied, and the material flows and fills the mold cavity. Heat completes the polymerization, and the mold is opened to remove the cured part.

Compression molding has been used in the manufacture of nozzle components up to 36 in. (0.91 m) in diameter. Molding pressures up to 8000 psi (5515 N/cm^2) have been employed at curing temperatures up to 350°F (449.8K). Steam coils or electric resistance strip heaters imbedded in the metal dies are the usual heat sources; the molding compound can be loaded, in accurately weighed batches, into either a hot or cold mold.

In general, any broadgoods materials that can be tape wrapped can also be compression-molded by modifications in resin content and resin advancement. The fabric reinforcement, however, is chopped into 1/4 or 1/2 in.

(6.35 or 12.7 mm) squares so that it will flow into the cavity during molding. In addition, compression-molding compounds are prepared using chopped roving, filament or fiber reinforcements, granules, pellets, and powdered particles.

In the manufacture of a molded part, the ability of the molding compound to fill the mold cavity and produce a sound, homogeneous cross section is measured by its flow characteristics and its bulk factor. In ablative molding compounds the flow ranges from 4 to 20% and the bulk factor from a low of 4 to 1 to a high of 20 to 1. Because of the ratio of length to section thickness in the 260 in. (6.6 M) nozzle components, it is questionable that any parts but the throat inlet and throat could be made as single-piece moldings.

While it is true that molding pressures as high as 8000 psi (5515 N/cm^2) have been employed for nozzle parts, it has been found that carbon fiber-reinforced molding compounds performed satisfactorily after having been molded at 500 psi (345 N/cm^2)[1]*. Graphite particle molding compounds have exhibited satisfactory performance when molded in the range of 850-1000 psi (586-689 N/cm^2)[2]. Molding at these reduced pressures decreases the need for large press capacity and reduces facility expenditures. This, coupled with the possibility of fabricating a billet in 48 to 72 hours instead of 4 to 7 weeks, makes molding the throat in one piece very attractive.

Facility and tooling costs may also be reduced if the nozzle design can be optimized so that only a few molds are used to produce segments that can be assembled into an interlocking pattern to form the full-sized components. Subscale exit cones and throats with this type of joint pattern have been evaluated.[2, 3]

Should compression molded parts be demonstrated to be more effective with respect to cost and performance than wrapped parts, then it may be possible to reduce the curing time drastically by the use of radio frequency (RF) heating. The method has been used for ablative heat shields[4] and appears to be feasible.

*Numbers in raised parentheses designate references.

Compression molding compounds that were evaluated for possible use are shown in Table III-2.

2. Tape Wrapping

Molding tape for use in wrapping is manufactured by impregnating a fabric or mat reinforcement with a selected ablative plastic resin that has been diluted with a compatible solvent. Powdered or hollow fillers may be added to the resin mix. The impregnated reinforcement is passed through temperature-controlled towers to remove the solvent and to polymerize the resin to some intermediate stage suitable for storage, handling and further fabrication. The material (called prepreg) is slit into tapes and broadgoods and shipped to the component fabricators.

Part fabrication is performed by wrapping the prepreg tapes on a metal mandrel, with plies of tape aligned at some desired angle to the flame surface of the finished part. For mechanical retention of each ply and for simplicity in fabrication, nozzle components in the entrance and throat sections have ply orientations close to 45 degrees to the flame surfaces, while those in the exit sections have ply orientations parallel to the nozzle center line. Angled wraps require the use of a bias-fabric tape to produce the desired deformation and compaction during wrapping; the parallel wraps employ straight tapes.

Wrapping may be performed in either the horizontal or vertical positions. During wrapping, the prepreg tape is heated prior to lay-up using hot-air jets or radiant heaters. This softens the resin for interply bonding and makes the prepreg more formable under the pressure rollers. The tape temperature, roller pressure, rotational speed, and billet temperature are held within fairly narrow limits to control the as-wrapped density.

After the preform has been wrapped, it is covered with a porous fabric (bleeder cloth), enclosed in an impervious bag and cured by one of two alternative procedures. If the flame liner is to be overwrapped with another ablative prepreg of greater thermal insulating value, the preform is "debulked" (compacted and partially cured at full pressure and temperatures between 165 and 180°F (347-355.4K)) so that a smooth surface may be machined prior to application

of the overwrap. If the flame liner is not to be further insulated, the preform is cured at full pressure and the temperature required for resin-polymerization. During curing (and debulking) vacuum is maintained in the enveloping bag and the polymerization reactants are drawn off through the bleeder cloth.

Pressure during debulking and curing may be applied by any one of several means. Hydroclaves, using hot water at pressures of up to 1000 psi (689 N/cm^2); autoclaves using heated gas at pressures of up to 350 psi (241 N/cm^2); and nylon shrink tapes exerting hoop tensions to 150 psi (103 N/cm^2) have all been used.

Analysis of the separate steps involved in fabrication by tape wrapping points the way for cost reductions. One obvious step is to reduce the wrapping time by increasing the tape speed, by applying multiple layers of tape, or by using thicker tapes than normal. This last approach has been successfully demonstrated with both carbon and silica fabric prepregs[1, 2]. Wrapping times have been reduced by as much as 55% by using double-thick tapes.

Economies can be effected in capital equipment costs by reducing the cure-pressure requirements. Based on the attainment of a minimum char density of 64 lb/cu ft (1.025 g/cc), autoclave curing at a pressure of 125 psi or less could be used for the high-angled wraps in and near the throat[4]. In the nozzle exit section, where heat fluxes are lower and the ply orientations are parallel to the center line, the regression rate is unaffected by density and it appears that vacuum pressures of 25-27 in. (635-686 mm) Hg are suitable for curing. In this case, the heat for curing is furnished by a recirculating hot air oven, which is less costly than are autoclaves.

Table III-3 shows the tape wrapping materials that were considered for use in this program.

3. Casting

In casting, as in compression molding, the ablative nozzle part is formed in a cavity. Unlike molding, however, pressurization is not employed during curing nor is the cavity heated during fill. The casting compounds are

ordinarily mixed with a separate catalyst prior to pouring in order to promote polymerization. The compounds are viscous, and heated molds would tend to polymerize the resin before the cavity is completely filled.

The viscosity of the casting compounds requires that molds be simple in design and that they be filled under a direct, static head. Vacuum may be used during mixing and pouring to aid in the removal of entrapped air and to promote complete cavity fill.

The concept has been used to fabricate nozzle parts[2] and chamber insulation. Although it can be used for integral parts, additional development would appear to be required to produce defect-free full-size nozzle components.

The casting compounds that were considered are shown in Table III-4.

4. Trowelling and Spraying

In both the trowellable and sprayable concepts of fabricating large nozzle liners, the material is applied directly onto the structural shell to the required thickness. Facility and equipment costs for these fabricating techniques are low since pressures during cure do not exceed 27 in. (685.8 mm) Hg and the cure temperatures are adjusted by catalysis to occur between 3 and 4 hours in the range of 110 to 150°F (316.5 to 338.7K)[5, 6, 7].

Ablative materials for use with these techniques range from phenolic base to furfuryls to silicones, acrylonitriles, and polysulfides blended with epoxies and polyamides. Resin fillers include carbon, graphite, glass, silica, rayon, and coke in the form of powders, granules, fibers, and microspheres.

Trowelling and spraying systems that were considered are shown in Table III-5.

5. Test Matrix

A matrix of 20 test nozzle assemblies for use in solid rocket motor screening tests was prepared and submitted to NASA for approval. Candidate materials were selected for the inlet (entrance), the throat and the exit areas. The bases for selection were threefold: (a) projected material cost, (b) projected processing cost, and (c) past experience or probable performance. After discussion of alternate materials and considering the developmental aspects of IIT Research Institute's castable carbon, it was decided to add an additional test nozzle to evaluate process improvements made as the result of the evaluation of the first IIT nozzle. The test matrix, as approved by NASA, is shown in Table III-6.

The test matrix includes provisions for evaluating molded versions of chopped fabric materials (SP-8030, SP-8057, MXS-198, 4C1686, MXK-418, and WB-8251). It also includes provisions for evaluating chopped fiber molding compounds, which are inherently less expensive than chopped fabric grades (CA-2216, CA-8502, Pyrolarex 200 and FM-5700). Castable carbons from four different sources (IIT Research Institute, Atlantic Research, Ironsides Resins, and Thiokol Chemical) are included. Trowellable and sprayable materials (DC-93-104, Plastonium, and AGC-CS) are evaluated. And finally, provision is made to compare the ablative performances of phenolic, polyphenylene, and epoxy-novolac resins.

B. TEST MOTOR DESIGN AND FABRICATION

The subscale solid rocket motors for evaluating the preliminary performance of the candidate materials were required to conform to the following:

Throat Diameter	1.8 in (4.57 cm), min.
Chamber Pressure	600 $\pm$ 50 psig (414 $\pm$ 34.5 N/cm^2)
Firing Time	30 sec, minimum
Propellant Aluminum Content	15 $\pm$ 1 pbw*

The above requirements were met by modifying an existing motor.

*Parts by weight

1. Motor

The existing motor was modified by the addition of another short-length cylindrical chamber section, shown as solid black in Figure III-1. The new chamber section was similar in material and identical in flange and seal design to the existing section.

2. Propellant Grains

In order to meet the required firing duration and pressure it was necessary for the propellant grains to be 17-in. (43.18 cm) dia by 27.5-in. (69.85 cm) long. Four such grains, cast from ANB-3254 propellant, were available. The remaining grains were originally planned to be machined from a 120-degree (2.1 rad) segment of a full-scale 260-in. (6.6 m) dia grain, 6 ft (1.83 m) long, cast from ANB-3350 propellant. This latter propellant has the same ballistic and mechanical properties as ANB-3354 and the same aluminum content of 15%. During the actual machining of the grains, however, only 12 of the desired 17 grains could be obtained. Accordingly, the last five grains were manufactured by bonding available propellant slabs or cylinders and machining to size. Bonding was effected using the following procedure:

a. Clean and scrape both surfaces to be joined.

b. Apply excess of ANB-3285 propellant to both surfaces.

c. Join surfaces, press together, and squeeze out ANB-3285 propellant

d. Remove excess ANB-3285 propellant from joint and cure 24 days at 135°F (330.38K).

e. Apply restriction to propellant grain surface as required.

C. NOZZLE DESIGN AND FABRICATION

1. Design

The aft end closure (Figure III-1) also served as the nozzle structural support. The test nozzle assembly is shown in Figure III-2. The throat was sized to 1.8 in. (4.57 cm) dia. The contour of the converging and diverging sections was a circle of 13-in. (33 cm) radius, fairing into a 17.5 degree (0.3 rad) cone in the nozzle exit. Forward of the ablative nozzle, the steel closure was insulated with IBT-100 trowellable insulation.

Two alternate nozzle configurations were designed. In one design, the nozzle consisted of three separate sections; in the other design the entrance and throat sections were combined. The ply orientations in the wrapped parts were 60-65 degrees in the entrance, 40-45 degrees in the throat, and parallel-to-center line in the exit.

2. Fabrication

a. Tape Wrapping

In general, tape wrapping was performed without difficulty. All as-wrapped densities were 90% of the theoretical density (arbitrarily selected as equal to that produced by hydroclaving at 1000 psi (689 N/cm^2) or higher). Curing pressure of wrapped parts did not exceed 125 psig (86.2 N/cm^2) except for the throat insert fabricated of MXSC-195 prepreg, which was cured at 300 psig (207 N/cm^2) to eliminate delaminations. Roller pressures, tape temperatures, billet temperatures, and curing conditions were all within normal limits for the type of reinforcement being fabricated.

Handling and fabricating procedures for SP-8057 high resin-content Pluton H carbon prepreg were practically identical with those for MXC-199B1 high-resin-content Pluton B1 carbon prepreg.

The MXC-12449 and MXS-12450 were experimental grades of material designated by Fiberite as "extruded fibertapes." These consisted of epoxy novolac resins and carbon or silica fiber reinforcements that were blended and extruded into tapes, were cut into segments, laid-up to form the desired billet, and cured in a vacuum bag at 27 in. (685 mm) Hg. After curing, the surface appearance was indicative of a molded composite (see Figure III-3).

b. Molding

The majority of the molding compounds presented little or no difficulty during fabrication, although several parts finished undersize because the shrinkage was greater than expected. Figure III-4, which shows the CA-8502 carbon fiber composite throat after machining, illustrates the type of surfaces that were attained.

Difficulty was experienced in molding several of the less commonly used materials. The chopped paper (XR-2920) exhibited delaminations and lack of bonding even though it was cured at 5000 psi (3447 N/cm^2). The wood chips (CA-2216) did not cohere when molded at the supplier's recommended pressure of 1000 psi (689 N/cm^2) and it was necessary to mold as high as 10,000 psi (6894 N/cm^2), which produced a composite density higher than desired. The forward edge of the KYNOL (linear phenolic) exit cone cracked upon removal from the mold; fortunately, it was repairable (Figure III-5).

The Pyrolarex 200 (and all the Pyrolarex series) are sold by Hitco in the finished condition. No details are available on the fabrication of the two throat inserts that were evaluated. From examination of the publicly released information, it appears that the Pyrolarex fibers were blended with phenolic resin and compression molded in the usual manner. Porosity in the Pyrolarex 200 throat insert was comparable to that in some of the castable carbons (see Figure III-6).

c. Casting

Three types of castable carbon materials (from Atlantic Research Corporation, IIT Research Institute, and Thiokol Chemical Corporation) were supplied as cured composites. While they are described as "castable," all of them employ tamping during mold fill and two of the three employ some degree of pressurization during curing, from the nearly 1000 psi (689 N/cm^2) for LCCM-2626 to the 20 psi (1318 N/cm^2) for one of the IIT composites. Porosity and void content varied almost directly with the pressure used during molding. The LCCM-2626 material had the appearance of a bulk graphite and the ARC and IIT materials had large irregular voids dispersed throughout the cross-section. Figures III-7 and -8 show the appearance of machined IIT and ARC materials, respectively.

One castable carbon was available from a commercial supplier (DP5-161, Ironsides Resins). Supplied as a two-component system, liquid resin plus powdered reinforcement with a surface coating of catalyst, it was fully castable although of high viscosity. It was found that vacuum-assisted casting yielded better mold fill, and all DPC-161 nozzle components were cast under vacuum. The resin, when mixed in accordance with the supplier's recommendations was susceptible to surface crazing during cure. This led to chipping at the corners, clearly visible in Figure III-9. The surface crazing was eliminated by the addition of 5 pbw carbon (Figure III-10) or silica (Figure III-11) fibers, both of which contributed to increased porosity. Figure III-12 shows the surface appearance of unloaded DP5-161 cast into a honeycomb skeleton under vacuum. All DP5-161 components were cured by releasing the vacuum and heating for 24 hrs at 110°F (316.5K), after which they were removed from the oven and cooled to room temperature.

The DC93-104 silicone material was also supplied as a two-component system. The base and catalyst were mixed and poured into the mold under vacuum, and 5 minutes after the pour was completed the vacuum was released. The mold and casting were held 48 hours at room temperature (70°F = 294K), then heated to 125°F (324.8K), held for 2-1/2 hours, and then cooled to room temperature. Figure III-13 shows the SN 001 entrance cap fabricated of DC93-104 material.

d. Troweling and Spraying

The Plastonium components were supplied as finish-machined nozzle components. Beyond the fact that they were machined from a troweled billet, which was radiographed and found free of gross porosity, nothing is known. Two Plastonium entrance caps are shown in Figure III-14.

One sprayable composition was made up and fabricated into an exit cone. The resin mixture consisted of 31 pbw of Epotuf 37-619 hardener added to 100 parts of Epotuf 37-17 resin. To this was added 50 pbw of 1/2-in. (1.3 cm) long chopped GSCY-2-30 carbon fibers. This mixture was vacuum-bag cured under 27 in. (685 mm) Hg by heating 1 hour at 175°F (352.6K), 1 hour at 250°F (394.3K), 3 hours at 350°F (449.8K), and cooling to 150°F (338.7K). Figure III-15 shows SN 020 exit cone after fabrication. The outer ring is glass fabric, which was used to contain the resin-reinforcement mixture during cure.

3. Assembly

The nozzle was assembled to the steel support structure with Epon 921 adhesive. PR-1910 sealing compound was used as a joint filler between adjacent ablative nozzle components. In assembly, the exit cone was first bonded to the steel closure, after which the throat and entrance caps were installed. Finally, the IBT-100 was troweled on the closure and swept to contour. After firing, the IBT-100 was chipped off the closure sufficiently to remove the entrance cap and throat.

D. STATIC TEST FIRING

1. Procedure

Twenty-one test motors with attached nozzle assemblies containing candidate ablative materials that were fabricated by molding, casting, tape-wrapping, troweling, and spraying were statically test fired in the nozzle-up condition during the period December 1969 through June 1970. Measurements were made of chamber pressure only.

The motor was prepared for firing by loading the ANB-3254 (or ANB-3350) propellant grains into the motor chamber. The motor aft closure, containing the ablative nozzle inserts, was then bolted to the chamber and the loaded motor stored in a conditioning cell at 75 $\pm$ 10°F (297K) overnight, or longer if the test bay was not free.

In the test bay, pressure transducers were attached to tapped holes in the flange between the chamber and closure (see Figure III-1) and checked out. The igniter was then lowered into the motor through the nozzle throat opening and rested on the end of the propellant grain.

After each test firing, the motor was disassembled and the chamber and aft closure were examined to determine the effect of the test on the chamber insulation. The aft closure, with the nozzle inserts, was dimensionally inspected to determine the surface material loss and, after measurement, was refurbished for the next test firing.

2. Motor Ballistic Performance

Table III-7 summarizes the 21 firings, showing the average pressure and the duration of each firing. The pressure-time curves are shown in Figures III-16 through III-36.

The first four test firings employed the ANB-3254 cast cylindrical propellant grains. Except for Test No. 2, the pressure-time curves were normal, showing a gradual decay in pressure as the throat eroded. It appeared that the grain in Test No. 2 had some defect since the peak pressure was 745 psi (514 N/cm^2), well above normal, and the pressure decay was delayed to 13 sec after fire switch.

Tests No. 5 through 17 employed the ANB-3350 grains machined from the full-scale grain segment. The pressure-time curves were essentially normal. Tests No. 18 through 21 employed bonded grains; those for 18 and 19 were comprised of four slices of ANB-3350 and those for 20 and 21 of two

half-cylinders of ANB-3254. The pressure-time curves were normal, but exhibited a pressure drop through each of the bonded joints.

3. Ablative Material Performance

The surface regression of the test nozzle components was determined by measuring the dimensions of the nozzles before and after firing. Tables III-8 through III-10 show the surface regression in the entrance, throat, and exit materials, respectively, averaged for three separate angular locations in the nozzle, and normalized to a common base of 600 psi (414 N/cm^2) chamber pressure.

Among the materials evaluated in the entrance section, the five most resistant to surface regression were the LCCM-2626 and IIT graphite particle molding compounds, the ARC castable carbon, the MXC-12449 extruded fibertape, and the 4C 2585 AVCERAM/polyphenylene. Figure III-37 shows the surface appearance of the IIT material after firing and is illustrative of the best-performing materials. Three materials (Plastonium, XR-2029 paper, and CA-2216 wood pulp) were completely eroded away during firing. Figure III-38 shows the appearance of the aft closure insulation and the void formerly occupied by the Plastonium entrance.

The five most erosion resistant throat materials were the LCCM-2626 and IIT Research Institute graphite-particle molding compounds, the SP-8057 molded carbon phenolic, the 4C 1686 wrapped and molded carbon/polyphenylene, and the CA-8502 molded carbon fiber. Figure III-39 shows the rough, irregular surface that was representative of even the best molded materials after firing.

The five most erosion resistant among the exit section candidate materials were the MXC-12449 extruded carbon fibertape, the LCCM-4120 graphite particle material, the Ironsides castable carbon reinforced with silica fibers, the ARC castable carbon, and the MXK-418 canvas material.

Figure III-40 shows the smooth, regular surface of the extruded fibertape; it is representative of the best-performing materials. Figures III-41

and 42 show how the performance of the ARC castable carbon was improved by the addition of silica fibers. The Plastonium exit section was almost completely eroded away during firing, and several other materials were gouged severely. Figures III-43 shows an example of severe, localized material removal (the AGC/CS sprayed exit section).

E. MATERIAL COSTS

1. Prepregs

In the past[1, 2] cost/performance indexes may have been erroneous because some of the material prices that were used were not realistic. A "realistic" price is one that is currently being quoted on actual production buys and it includes a reasonable contingency and certification cost; it is not a one-time price intended to "buy" into a program. Generally, all like products and grades sell within a narrow price range in a freely competitive market, perhaps within $\pm$ 5% of each other. For this reason, the prices of the commercially available tape and molding grades used in this program are listed against generic systems rather than specific trade names. The prices shown in Table III-11, are based on the purchase of 5,000 lbm (2273 kg) minimum lots and delivery in 1000 lbm (455 kg) releases.

2. Castable-Moldable Materials

The pricing situation with regard to the majority of the castable and moldable grades of ablative materials is uncertain at this state of process development. While the ARC, TCC, and IIT Research Institute materials are all based on low-cost reinforcements and resins, the actual costs at the moment do not reflect this. Because of the continued process development, technical and supervisory costs must be added to the basic material costs. Accordingly, fixed prices have been assumed for the castable carbon grades, based on the published composition and an estimate of the most probable direction of further development leading to improved performance. In the case of DP-5-161 and DC93-104 materials, the prices are those quoted for commercial sale.

Table III-12 shows the prices of castable grades; the prices were estimated to fall within the range of U.S. $0.45 and U.S. $4.00 per lbm (0.45 kg).

F. MATERIAL PROPERTIES

1. Density

Composite densities were calculated from specific gravities determined by the displacement of water (Method 5011 of Federal Test Method Standard 406) except for the IIT Research Institute materials, which were determined by weight-volume procedures (Method 5012). The densities are shown in Table III-13. In general, the molded forms of material were denser than their wrapped counterparts. Among the castable carbon materials, the LCCM-2626 had the highest density (about the same as ATJ graphite) and the DP5-161 had the lowest. The CFA grades (IIT Research Institute) could apparently be varied over the widest range since one grade was as dense as 1.58 gr/cc and another only 1.14 gr/cc.

2. Compressive Properties

Compressive strengths and moduli of selected materials were determined at room and elevated temperatures in accordance with the procedures of FTMS 406, Method 1021, using specimens of square cross section.

Elevated temperature tests at 600°F (589K) and above were conducted in an atmosphere of flowing argon. The specimens tested at 300°F (442K) and below were virgin material; those tested at 600°F (589K) and 1700°F (1200K) were charred at 750°F (672K) and 2100°F (1422K), respectively, prior to test. The test results are listed in Tables III-14 and 15.

At room temperature, the highest compressive strength and modulus (35.5 ksi and 2.65 x 10^6 psi) were observed in the 4C 1686 molded composite. The lowest room temperature strength (7.8 ksi) was observed in the

LCCM-4120 graphite particle material and the lowest room-temperature moduli (0.72×10^6 and 0.99×10^6 psi) in the KF-418 and 4K9502 canvas composites. At 1700°F (1200K), the highest compressive properties (10.7 ksi and 1.39×10^6 psi) were observed in the charred 4K9502 canvas composite, and the lowest (1.1 ksi and 0.18×10^6 psi) in the ARC 100 castable carbon.

G. COST/PERFORMANCE EFFECTIVENESS OF TEST MATERIALS

The cost of the ablative nozzle material that is consumed in thrust vector control has been described (1) as the product of the volume of degraded material and the sum of the unit material and fabrication costs.

$$\text{Cost} = \text{PEV}\ (M+F) \qquad \text{Equation (1)}$$

In determining the suitability of the test materials for continued evaluation, a simplified form of this relationship was used.

The performance effective volume (PEV) was confined to a 1 in. band at area ratio 3.24 in the entrance (at the minimum throat) and at area ratio 4 in the exit section. Further, the eroded material only was considered. Finally, because it was intended that molded and wrapped parts would be evaluated separately, there was no need to apply unit fabrication costs at this phase of the program.

The materials are listed in order of increasing cost in Tables III-16, -17, and -18 after exposure in the entrance, throat, and exit sections, respectively. The PEV was based on 40 seconds exposure (since this was the planned duration of the test motor) and was the volume of a tore generated by rotating the eroded area about the nozzle center line at a radius equal to its center of mass. The volume was multiplied by the density of the material under test and the cost of the material in dollars per lb. The calculations are illustrated by those for the ARC 100 entrance section at area ratio 3.24 (R = 3.25 in.), which are shown in Figure III-44.

In the entrance section, the low-cost carbonaceous materials (LCCM, ARC, CFA, and DP5) are the most effective from the standpoints of cost and performance, as indicated in Table III-16. In the exit section, the wrapped canvas-phenolic composite was rated first, solely on the basis of its material cost of $1.80 per lb, since the five most erosion resistant materials all exhibited shrinkage at area ratio 4, and cost-ratings of the components could not be established (see Table III-18). The ARC 100, although shown in the compilation of surface regression in Table III-10, was not listed in the cost ratings because the severe gouging observed would make it a poor risk.

In the throat section, low-cost ratings are not the sole criterion for continued evaluation of the material. Additional weight must be assigned to its erosion resistance, since this changes the throat area and alters the ballistic performance of the motor. Compensating changes would then be required in the propellant grain and these could lead to weight and cost penalties in the propellant grain and motor case. Consequently, a cut-off was established at 10 mils/sec (0.254 mm/sec), with those materials exhibiting higher rates being excluded from further consideration for use in the throat inserts of the subscale 44-in.-dia motors. This decision eliminated two low-cost carbonaceous materials (ARC and DP5), a molded carbon (Pyrolarex 200), an AVCERAM C/S grade (MXSC-195), and two silica grades (MXS-198 and SP-8030).

TABLE III-1

SUPPLIERS OF MATERIAL SYSTEMS SURVEYED

Supplier	System
American Polytherm, Inc. Sacramento, California	Castable and Trowelable Materials
American Reinforced Plastics (Furane) Los Angeles, Calif.	Molding Compounds, Trowelable Materials, Sprayable Materials
Armour Coated Products Saugus, California	Molding Compounds, Tape Materials
Atlantic Research Corp. Alexandria, Va.	Castable Materials
Carborundum Corp. Sanborn, New York	Linear Phenolic Reinforcements
Coast Mfg. & Supply (Hexcel) Livermore, Calif.	Tape and Molding Compounds
Dow Corning Burlingame, Calif.	Trowelable and Sprayable Compounds
Dyna-Therm Corp. Los Angeles, California	Trowelable Compounds
Fiberite Corporation Winona, Minn.	Extruded Fibertape, Molding Compounds
Haveg-Reinhold Sante Fe Springs, Calif.	Trowelable Materials
Hexcel Corporation Livermore, California	Honeycomb Reinforcements
Hitco Materials Division Gardena, California	Felted Materials, Extra-thick Tapes, Molding Compounds
IIT Research Institute Chicago, Illinois	Castable, Trowelable and Moldable Materials
Insulation Systems, Inc. Los Angeles, Calif.	Sprayable Materials, Trowelable Materials
Ironsides Resins Columbus, Ohio	Trowelable and Sprayable Materials
Kureha Chemicals Los Angeles, Calif.	Spun Pitch (Carbon) Reinforcements
McDonnell Douglas Santa Monica, Calif.	Moldable Concepts
Thiokol Corporation Brigham City, Utah	Castable and Moldable Compounds
U. S. Polymeric Corp. Santa Ana, California	Tape and Molding Compounds
Western Backing Division Los Angeles, California	Tape and Molding Compounds

TABLE III-2

MOLDING COMPOUNDS SURVEYED

Supplier	Designation	Composition	Remarks
Armour	SP-8050	CCA-1 Carbon Fabric and EC-201 Phenolic Resin	Chopped broadgoods molding compound.
	SP-8057	Pluton H-1 Carbon Fabric and EC-201 Resin.	Chopped broadgoods molding compound. Specified by NASA.
	SP-8060	AVCERAM C/S Fabric and EC-201 Resin	Not available from stock.
	SP-8030	C-100-48 Silica Fabric and EC-201 Resin.	Chopped broadgoods molding compound. Specified by NASA.
Atlantic Research	ARC-100	Coke and Furfuryl Alcohol	Low pressure molding material.
Coast (Hexcel)	4C-1686	CCA-1 Carbon Fabric and Polyphenylene Resin.	Chopped broadgoods molding compound. Specified by NASA.
	None	KAYA (Japanese) Carbon Phenolic or Polyphenylene Resin	Chopped carbon fibers. Price indeterminate but low.
	None	KYNOL (Linear Phenolic) Fibers and SC-1008 Phenolic Resin	Chopped fiber molding compound.
	4C-2530	AVCERAM C/S Fabric and EC-201 Resin	Chopped broadgoods molding compound.
	4C-2585	AVCERAM C/S Fabric and Polyphenylene Resin	Chopped broadgoods molding compound.

TABLE III-2, MOLDING COMPOUNDS SURVEYED (cont.)

Supplier	Designation	Composition	Remarks
Coast (Hexcel)	4S-5107	C-100-96 Silica Fabric and SC-1008 Resin	Chopped double-weight broadgoods molding compound.
	4K-9502	Loose Weave Canvas Duck and SC-1008 Resin.	Chopped broadgoods molding compound.
Fiberite	MXS-198	C-100-48 Silica Fabric and Epoxy Novolac Resin	Chopped broadgoods. Specified by NASA.
	MXK-418	Canvas Duck and SC-1008 Resin	Chopped broadgoods molding compound. Specified by NASA.
HITCO	Pyrolarex 200	Proprietary	Carbonaceous, fibrous composite of low density.
HITCO	Pyrolarex 300	Proprietary	Carbonized composite. Density less than that of Pyrolarex 200.
IIT Research Institute	CFA	Proprietary	A low cost carbonaceous material suitable for molding and casting.
McDonnell-Douglas	None	Any molding compound	A segmented fabricating concept in which the segments are joined and cured in vacuum bags.
Thiokol	LCCM-2626	Graphite Particles and SC-1008 Resin	A low cost carbonaceous material.
U.S. Polymeric Corp.	FM-5020	C-100-48 Silica Fabric and SC-1008 Resin	Chopped broadgoods molding compound.
	FM-5059	CFA-1/4 Carbon Fibers and 91LD Phenolic Resin	Standard carbon molding compound.
	FM-5272	Kraft Paper and USP100 Phenolic Resin.	Chopped paper molding compound. Specified by NASA.

TABLE III-2, MOLDING COMPOUNDS SURVEYED (cont.)

Supplier	Designation	Composition	Remarks
U.S. Polymeric Corp.	X-5571	AVCERAM C/S Fabric and USP100 Resin	Chopped broadgoods molding compound.
	FM-5700	Glass strands 1/4-in.-long and SC-1008 Resin	Standard glass molding compound.
	XR-2029	Kraft Paper and Elastomeric Modified Phenolic Resin.	Chopped paper molding compound. For reduced shrinkage compared to FM-5272.
Western Backing	CA-2213	Loose Weave Canvas Duck and EC-201 Resin.	Chopped broadgoods molding compound.
	CA-2216	Wood Pulp and Melamine Resin	Inexpensive molding compound.
	CA-8502	KUREHA (Japanese) Carbon and Phenolic Resin	Chopped carbon fibers. Price indeterminate, but low.
	WB-8517	CFA-1/4 Carbon Fibers and Phenolic Resin	Standard carbon molding compound.
	WB-8251	AVCERAM C/S Fabric and WB-2233 High Char Phenolic Resin	Chopped fabric molding compound. Specified by NASA.
	ACFX	Any Reinforcement and ACFX Resin System	ACFX resin system less expensive than other phenolic systems.

TABLE III-3

PREPREG TAPE MATERIALS SURVEYED

Supplier	Designation	Composition	Remarks
American Polytherm, Inc.	40 CA 40 SA	Carbon or Silica Fibers in Urethane	For hand lay-up and vacuum bag cure up to 110°F (316.5K). In development.
Americal Reinforced Plastics (Furane)	Adlock	Fabric and Most Reinforcements and MIL-R-9299 Phenolic Resins	Standard line of ablative tape laminating grades.
Armour	SP-8052	CCA-42 Carbon Fabric and C5802 Phenolic Resin	Double weight carbon fabric.
	SP-8057	Pluton H-1 Carbon Fabric and C5802 Resin	High resin content laminating grade.
	SP-8060	AVCERAM C/S Fabric and C5802 Resin	Carbon-Silica laminating grade.
Coast (Hexcel)	4C-2585	AVCERAM C/S Fabric and Polyphenylene Resin.	Carbon-Silica laminating grade.
	4K-9502	Loose weave canvas Duck and SC-1008 Resin	More formable laminating grade than KF-418.
	4S-4186	G100-48 or -96 Silica Fabric and Polyphenylene Resin.	Silica laminating grade.
Fiberite	MXC-199B1	Pluton B1 Carbon Fabric and Epoxy-Novolac Resin	Low cost, high-resin-content prepreg for vacuum bagging cure.
	MXK-198	Canvas Duck and Epoxy-Novolac Resin	For vacuum-bagging.

TABLE III-3, PREPREG TAPE MATERIALS SURVEYED (cont.)

Supplier	Designation	Composition	Remarks
Fiberite	MXSC-195	AVCERAM C/S and SC-1008 Resin	Carbon-silica laminating grade
	MXC-113	Carbon Fibertape on Scrim and SC-1008 Resin	Low density laminating grades for exit cones.
	MXC-12449	Carbon Fibers and Epoxy-Novolac Resin	Extruded tape for vacuum bagging cure.
HITCO	B-1570	Needle Felted Silica Batting 0.20 in. (0.56 cm) thick.	For hand lay-up operations when impregnated with suitable resin.
	CF-2507 Felt	Carbon Felts up to 0.5 in. (1.27 cm) thick. Standard thickness is 0.22 in. (0.56 cm).	For low-density hand lay-up operations.
U. S. Polymeric Corp.	FM-5272	Kraft Crepe Paper and USP100 Resin	Has been proven in MM test motors. Shrinkage during cure is high.
	XR-2029-25	Kraft Crepe Paper and Elastomerized Phenolic Resin	To reduce danger of cracking during cure and removal of billet from mandrel.
	FM-5042	Glass Fabric and Phenolic Resin	For use in back-up insulation and exit cones.
Western Backing	CA-2213	Loose Weave Canvas Duck and EC-201 Resin	More formable laminating grade than KF-418.
	CA-8201	KUREHA (Japanese) Fabric and Phenolic Resin	Potentially low-cost carbon laminating tape.

TABLE III-4

CASTABLE MATERIALS SURVEYED

Supplier	Designation	Composition	Remarks
Atlantic Research	ARC-100	Coke and Furfuryl Alcohol with and without Added Silica Fibers	Cured under vacuum.
Dow Corning	DC93-104	Silicone Rubber with or without Added Fibers	Two-component material that can be catalyzed at room and near room temperatures. Can be sprayed and troweled also.
IIT Research Institute	CFA	Proprietary	A low cost carbonaceous material.
Insulation Systems, Inc.	Plastonium	Sulfates with Carbonaceous Forming, Water-Based, Resin System and with or without Added Fibers	Extremely low-cost material. can be troweled or sprayed. Use for exit cones.
Ironsides Resins, Inc.	DP5-161	Phenolic Resin with or without Added Fibers	Two-component material that can be catalyzed at room and near room temperatures. Can be troweled also.
Thiokol	LCCM-4120	Graphite Particles and Durez 10694 Resin	A low-cost carbonaceous material. Cured under vacuum at near room temperatures.

TABLE III-5

SPRAYABLE AND TROWELABLE MATERIALS SURVEYED

Supplier	Designation	Composition	Remarks
American Reinforced Plastics (Furane)	Epo-Cast 38	Two-Component Epoxy-Based System	For troweling. Has been used in Glas-Craft Gun (chop and spray.
Dow Corning	DC93-104	Silicone	Dilute with Freon TF (Freon 113) and add catalyst.
Dyna-Therm Corp.	E-340	Two-Component, Epoxy-Based System	For troweling. Room temperature curing.
	DE-350	Three-Component, Silicone Modified, Epoxy Polyamide	For spraying. Can also be transfer molded. Cures at near room temperatures.
Aerojet	None	Chopped Roving and Epoxy Novolac Resin	For spraying. Use Glas-Craft gun.

TABLE III-6

1.8 DIA NOZZLE TEST MATRIX

No.	Description	Entrance	Throat	Exit
001	Low Cost Tape Wrapped	DC93-104	MXC-199B1	MXK-198
002	Molded Control	SP-8030	SP-8057	MXK-418
003	Castable Carbon (Illinois)	IIT Matl.	IIT Matl.	IIT Matl.
004	Castable Carbon (Atlantic)	ARC Matl.	ARC Matl.	ARC Matl.
005	Castable Carbon (Ironsides)	DP5-161	DP5-161	ARC/Si Matl.
006	Castable Carbon (Thiokol)	LCCM 2626	LCCM 2626	LCCM 4120
007	Castable Carbon Honeycomb Reinforced	DP5-161 HC	DP5-161-HC	DP5-161/Si
008	Molded Polyphenylene	4C2585	4C1686	MXC-12449
009	Molded Carbonaceous	Plastonium	Pyrolarex 200	KYNOL
010	Castable Carbon Fiber Reinforced	XR-2029	DP5-161/C	MXS-198
011	All-White Phenolic	WB-8251	WB-8251	4K9502
012	All-White Phenolic	SP-8030	SP-8030	FM-5700
013	All-White Epoxy-Novolac	MXS-198	MXS-198	FM-7111
014	Tape Wrapped Control	XR-2029-25	SP-8057	Plastonium
015	Tape Wrapped Polyphenylene	LCCM 2626	4C 1686	MXC-113
016	Tape Wrapped, All White Phenolic	MXK-418	MXSC-195	FM-5042
017	Molded Carbonaceous	SP-8030	Pyrolarex 200	MXK-418
018	Tape Wrapped, All-White Polyphenylene	4S4186	4C 2585	4E 0285
019	Molded Fiber	CA 2216	CA-8502	MXS-12450
020	Molded Fiber	MXC-12449	CA-8502	AGC/CS
021	Castable Carbon (Illinois)	IIT Matl.	IIT Matl.	IIT Matl.

TABLE III-7

SUMMARY OF 1.8-IN.-DIA THROAT FIRINGS

Test No.	Nozzle Assy.	Throat	Average Pressure, psi	Average Pressure, N/cm^2	Duration, sec
1	004	Atlantic Research	298	205	47.8
2	006	Thiokol	654	451	35.6
3	012	SP-8030 (M)*	238	164	62.9
4	013	MXS-198 (M)	326.5	225	49.7
5	011	WB-8251 (M)	390	269	44.7
6	018	4C2585 (W)**	409	282	44.5
7	002	SP-8057 (M)	472	325	39.3
8	005	DP5-161	194	134	72.2
9	007	DP5-161-HC	187	129	72.8
10	008	4C 1686 (M)	505.5	348	40.0
11	009	Pyrolarex 200	279	192	54.7
12	001	MXC-199 B1 (W)	474.5	327	39.6
13	010	DP5-161/C	302	208	52.4
14	014	SP-8057 (W)	424	292	44.3
15	020	CA-8502 (M)	508	350	34.2
16	017	Pyrolarex 200	384.5	265	41.2
17	015	4C 1686 (W)	529	365	36.8
18	003	IIT Research Inst.	384	265	48.2
19	016	MXSC-195 (W)	297	205	48.7
20	019	CA-8502 (M)	502	346	40.3
21	021	IIT Research Inst.	515	355	39.1

*Molded
**Wrapped

TABLE III-8

SURFACE REGRESSION OF ENTRANCE MATERIALS

Material	Fabrication Method	Regression Rate, mils/sec (mm/sec) at Area Ratio 4.0		3.24		2.6	
LCCM-2626 (3)*	Molding	(-)	(-)	(-)	(-)	(-)	(-)
LCCM-2626 (15)*	Molding	2.09	(0.053)	0.95	(0.024)	0.67	(0.017)
ARC	Casting	2.00	(0.051)	3.37	(0.086)	5.79	(0.147)
IIT - CFA (21)*	Molding	2.30	(0.058)	3.40	(0.086)	4.70	(0.119)
MXC-12449	Extrusion	2.19	(0.056)	6.52	(0.166)	9.44	(0.240)
DP5-161	Casting	7.17	(0.182)	9.15	(0.232)	14.97	(0.380)
4C-2585	Molding	6.08	(0.154)	9.32	(0.237)	8.53	(0.217)
WB-8251	Molding	6.10	(0.155)	9.50	(0.241)	8.40	(0.213)
IIT - CAF (3)*	Molding	10.58	(0.269)	9.88	(0.251)	14.67	(0.373)
4S-4186	Wrapping	9.41	(0.239)	10.07	(0.256)	12.43	(0.316)
DP5-161 HC	Casting	7.61	(0.193)	12.32	(0.313)	17.62	(0.448)
XR-2029-25	Wrapping	12.80	(0.325)	13.30	(0.338)	16.50	(0.419)
MXS-198	Molding	11.69	(0.297)	14.31	(0.363)	15.71	(0.399)
SP-8030 (2)*	Molding	14.12	(0.359)	14.42	(0.366)	13.97	(0.355)
DC93-104	Casting	12.63	(0.321)	14.82	(0.376)	14.82	(0.376)
MXK-418	Wrapping	13.88	(0.353)	15.22	(0.387)	17.72	(0.450)
SP-8030	Wrapping	15.49	(0.393)	17.60	(0.447)	17.79	(0.452)
SP-8030 (12)*	Molding	18.42	(0.468)	20.21	(0.513)	20.75	(0.527)
Plastonium	Troweling	Completely Removed					
XR-2029	Molding	Completely Removed					
CA-2216	Molding	Completely Removed					

* Numbers in parentheses refer to nozzle assembly in which duplicate material was tested.

TABLE III-9. - SURFACE REGRESSION OF THROAT MATERIALS

Material	Fab. Method	Regression Rate, mils/sec (mm/sec) at Area Ratio						
		1.48	1.15	1.02	Throat	1.05	1.28	1.76
LCCM-2626	Molding	1.07 (0.027)	1.52 (0.039)	1.80 (0.046)	1.65 (0.042)	1.66 (0.042)	0.59 (0.015)	( ) ( )
SP 8057	Molding	5.55 (0.141)	5.69 (0.146)	6.17 (0.157)	2.75 (0.070)	4.63 (0.118)	2.67 (0.068)	1.55 (0.039)
4C 1686	Molding	4.73 (0.120)	3.63 (0.092)	3.95 (0.100)	4.10 (0.104)	3.53 (0.090)	2.15 (0.055)	0.88 (0.022)
IIT-CFA (21)*	Molding	5.30 (0.135)	5.30 (0.135)	6.10 (0.155)	4.80 (0.122)	4.70 (0.119)	3.10 (0.079)	1.20 (0.030)
CA-8502 (19)*	Molding	3.40 (0.086)	4.00 (0.102)	4.60 (0.117)	5.19 (0.132)	3.90 (0.099)	3.60 (0.091)	1.00 (0.025)
4C 1958	Wrapping	4.95 (0.126)	4.95 (0.126)	5.49 (0.139)	5.75 (0.146)	4.95 (0.126)	3.40 (0.086)	1.06 (0.027)
SP-8057	Wrapping	7.09 (0.180)	7.25 (0.184)	6.46 (0.164)	6.25 (0.142)	5.58 (0.142)	3.63 (0.092)	1.85 (0.047)
CA 8502 (20)*	Molding	3.68 (0.093)	5.96 (0.151)	5.96 (0.151)	6.25 (0.159)	4.95 (0.126)	6.20 (0.157)	2.25 (0.057)
IIT-CFA (3)*	Molding	7.86 (0.200)	8.84 (0.225)	7.95 (0.202)	7.00 (0.178)	6.83 (0.173)	4.54 (0.115)	1.93 (0.049)
MXC-199B1	Wrapping	6.31 (0.160)	7.27 (0.185)	5.96 (0.151)	7.20 (0.183)	4.67 (0.119)	3.21 (0.082)	1.84 (0.047)
4C 2585	Wrapping	9.55 (0.243)	8.49 (0.216)	8.76 (0.222)	8.40 (0.213)	7.48 (0.190)	8.94 (0.227)	10.47 (0.266)
WB-8251	Molding	9.62 (0.244)	8.61 (0.219)	10.10 (0.256)	10.10 (0.256)	7.45 (0.189)	9.06 (0.230)	10.07 (0.256)
MXS-198	Molding	15.49 (0.393)	15.49 (0.393)	12.99 (0.330)	11.80 (0.300)	10.16 (0.258)	9.81 (0.249)	6.32 (0.160)
Pyrolarex 200 (9)*	Molding	7.49 (0.190)	10.35 (0.263)	16.08 (0.408)	13.50 (0.343)	17.64 (0.448)	10.55 (0.268)	3.78 (0.096)
DP5-161/C	Casting	17.42 (0.442)	13.78 (0.350)	15.04 (0.382)	13.70 (0.348)	12.73 (0.323)	11.47 (0.291)	6.87 (0.174)
ARC	Casting	9.52 (0.242)	11.65 (0.296)	16.23 (0.412)	14.70 (0.373)	16.10 (0.409)	14.04 (0.357)	9.52 (0.242)
MXSC-195	Wrapping	20.10 (0.510)	20.00 (0.508)	16.65 (0.423)	15.30 (0.389)	14.89 (0.378)	12.51 (0.318)	7.64 (0.194)
Pyrolarex 200(17)*	Molding	19.41 (0.493)	21.59 (0.548)	21.07 (0.535)	15.70 (0.399)	16.58 (0.421)	12.21 (0.310)	7.86 (0.200)
SP-8030	Molding	21.31 (0.541)	21.21 (0.539)	19.54 (0.496)	21.60 (0.549)	16.41 (0.417)	13.43 (0.341)	9.23 (0.234
DP5-161	Casting	19.65 (0.499)	21.09 (0.536)	24.54 (0.623)	23.50 (0.597)	22.79 (0.579)	18.73 (0.476)	13.84 (0.352)
DP5-161 HC	Casting	21.01 (0.534)	25.65 (0.652)	24.49 (0.622)	24.80 (0.630)	23.30 (0.592)	19.61 (0.498)	14.90 (0.378)

*Numbers in parenthesis refers to nozzle assembly in which duplicate material was tested.

TABLE III-10

SURFACE REGRESSION OF EXIT MATERIALS

Material	Fabrication Method	Regression Rate, mils/sec (mm/sec) at Area Ratio 2.6		4.0		5.65	
MXC-12449	Extrusion	(-)	(-)	(-)	(-)	(-)	(-)
LCCM-4120	Molding	(-)	(-)	(-)	(-)	(-)	(-)
DP5-161/Si	Casting	7.15	((0.182)	(-)	(-)	(-)	(-)
ARC-100	Casting	8.47	(0.215)	(-)	(-)	0.48	(0.012)
MXK-418	Wrapping	18.71	(0.475)	(-)	(-)	(-)	(-)
MXC-113	Wrapping	3.37	(0.086)	0.30	(0.008)	0.16	(0.004)
ARC/Si	Casting	5.82	(0.148)	0.41	(0.010)	(-)	(-)
IIT - CFA(3)*	Molding	2.41	(0.061)	0.81	(0.021)	0.60	(0.015)
IIT - CFA (21)*	Molding	1.60	(0.041)	0.90	(0.023)	0.40	(0.010)
MXS-198	Molding	7.77	(0.197)	3.65	(0.093)	0.44	(0.011)
4K 9502	Molding	8.50	(0.216)	5.25	(0.133)	2.70	(0.069
MXK-418	Molding	7.91	(0.201)	6.00	(0.152)	2.87	(0.073)
FM-5042	Wrapping	10.37	(0.263)	6.06	(0.154)	2.09	(0.053)
MXS-12450	Extrusion	8.70	(0.221)	6.90	(0.175)	4.50	(0.114)
KYNOL	Molding	9.38	(0.238)	7.31	(0.186)	5.56	(0.141)
4E 0285	Wrapping	10.17	(0.258)	7.73	(0.196)	2.38	(0.060)
FM-5711	Molding	9.39	(0.239)	8.93	(0.227)	4.67	(0.119)
AGC/CS	Spraying	10.38	(0.264)	10.79	(0.274)	4.64	(0.118)
FM-5700	Molding	12.33	(0.313)	10.99	(0.279	6.23	(0.158)
MXK-198	Wrapping	15.28	(0.388)	22.85	(0.580)	26.44	(0.672)
Plastonium	Troweling	44.6	(1.133)	Completely Removed			

*Number in parentheses refers to nozzle assembly in which duplicate material was tested.

TABLE III-11

PREPREG PRICES USED IN THIS PROGRAM*

Reinforcement	Resin	Price $ U.S./lbm
98% Carbon Fabric	Phenolic	20.00
98% Carbon Fabric Chopped	Phenolic	20.00
98% Carbon Fibers, Chopped	Phenolic	14.50
98% Carbon Fibers, Chopped	Epoxy-Novolac	12.50
98% Carbon Fabric	Polyphenylene	21.00
98% Carbon Fabric, Chopped	Polyphenylene	21.00
98% Carbon Fabric	Epoxy-Novolac	22.00
86% Carbon Fabric	Epoxy-Novolac	14.25
C-100-48 Silica Fabric	Phenolic	5.50
C-100-96 Silica Fabric	Phenolic	5.00
Silica Fabric, Chopped	Phenolic	6.00
Silica Fabric, Chopped	Epoxy-Novolac	9.50
C-100-96 Silica Fabric	Polyphenylene	5.00
AVCERAM C/S Fabric	Phenolic	15.00
AVCERAM C/S Fabric, Chopped	Phenolic	16.00
AVCERAM C/S Fabric	Polyphenylene	16.00
AVCERAM C/S Fabric, Chopped	Polyphenylene	16.00
Canvas	Phenolic	1.80
Canvas	Epoxy-Novolac	1.80
Canvas, Chopped	Phenolic	1.80
Glass Fabric	Phenolic	2.90
Glass Fabric, Chopped	Phenolic	2.00
KYNOL Fabric	Phenolic	3.00

*Based on 5000 lbm (2273 kg) lots.

TABLE III-12

LOW COST CARBONACEOUS MATERIAL
USED IN THIS PROGRAM

Material	Price, $ U.S./lbm
ARC-100/Si	0.45
DC93-104	4.00
IIT Research Institute Grade CFA	2.00
DP5-161	3.00
TCC-LCCM Grades	0.75
Pyrolarex 200	8.00

TABLE III-13

DENSITIES OF CANDIDATE ABLATIVE MATERIALS

Material	Fab. Method	Density	
		gm/cu cm	lb/cu in.
MXK-198	Wrapping	1.31	0.047
MXK-418	Wrapping	1.35	0.049
MXK-418	Molding	1.41	0.051
4K 9502	Molding	1.40	0.051
MXKF-418	Vacuum Bag	1.40	0.051
4C 1686	Molding	1.51	0.055
4C 1686	Molding	1.41	0.051
4C 1686	Wrapping	1.41	0.051
SP 8057	Wrapping	1.39	0.050
SP 8057	Molding	1.48	0.053
CA 8502	Molding	1.41	0.051
MXC 199B1	Wrapping	1.47	0.053
MXC-113	Wrapping	1.37	0.049
MXC-12449	Extrusion	1.32	0.048
MXC-12449	Extrusion	1.18	0.043
MXC-12450	Extrusion	1.48	0.053
LCCM-2626	Molding	1.78	0.064
ARC-100	Casting	1.56	0.056
ARC-100/Si	Casting	1.58	0.057
LCCM-4120	Casting	1.51	0.055
IIT CFA	Molding	1.14	0.041
ITT CFA	Molding	1.58	0.057
MXSC-195	Wrapping	1.51	0.055
WB-8251	Molding	1.51	0.055
4C 2585	Wrapping	1.51	0.055

TABLE III-13 (cont.)

DENSITIES OF CANDIDATE ABLATIVE MATERIALS

Material	Fab. Method	Density	
		gm/cu cm	lb/cu in.
4C 4186	Wrapping	1.71	0.062
SP 8030	Molding	1.80	0.065
SP 8030	Molding	1.77	0.064
SP 8030	Wrapping	1.67	0.060
MXS-198	Molding	1.61	0.058
4E 0285	Wrapping	1.85	0.067
FM 5700	Molding	1.93	0.07
FM 5042	Wrapping	1.73	0.062
FM 5711	Molding	1.76	0.064
Plastonium	Troweling	1.19	0.043
Plastonium	Troweling	1.28	0.046
CA 2216	Molding	1.35	0.049
CA 2216	Molding	1.39	0.050
XR-2029	Molding	1.21	0.044
XR-2029-26	Wrapping	1.26	0.045
KYNOL	Molding	1.28	0.046
DC93-104	Casting	1.46	0.053
DP5-161	Casting	1.18	0.043
Pyrolarex 200	Molding	1.35	0.049
DP5-161/Si	Casting	1.21	0.044
DP5-161-HC	Casting	1.10	0.040

TABLE III-14

COMPRESSIVE STRENGTHS OF SELECTED ABLATIVE MATERIALS

Material	Orientation	Strength in ksi (KN/cm^2) at Temperature							
		75°F	(297°K)	300°F	(422°K)	600°F	(589°K)	1700°F	(1200°K)
ARC-100	Random	12.6	(8.7)	6.5	(4.5)	2.0	(1.4)	1.1	(0.8)
CA-8502	Random	30.2	(20.8)	18.7	(12.9)	12.1	(8.3)	7.5	(5.2)
KF-418	Parallel-to-Ply	18.1	(12.5)	7.6	(5.2)	2.0	(1.4)	6.2	(4.3)
LCCM-2626	Random	12.3	(8.5)	5.6	(3.9)	5.2	(3.6)	3.3	(2.3)
LCCM-4120	Random	7.8	(5.4)	7.3	(5.0)	5.5	(3.8)	6.6	(4.6)
MXC-199B1	45 Deg.-to-Ply	29.3	(20.2)	3.9	(2.7)	7.3	(5.0	6.0	(4.1)
MXC-12449	Random	28.1	(19.4)	18.1	(12.5)	11.6	(8.0)	7.6	(5.2)
4C 1686	Random	35.5	(24.5)	19.3	(13.3)	6.6	(4.6)	4.3	(3.0)
4K 9502	Random	25.5	(17.6)	9.2	(6.3)	2.3	(1.6)	10.7	(7.4

TABLE III-15

COMPRESSIVE MODULI OF SELECTED ABLATIVE MATERIALS

Material	Orientation	Modulus in psi x 10^6 (MN/cm^2) at Temperature							
		75°F	(297°K)	300°F	(422°K)	600°F	(589°K)	1700°F	(1200°K)
ARC-100	Random	1.77	(1.22)	0.76	(0.52)	0.30	(0.21)	0.18	(0.12)
CA-8502	Random	1.26	(0.87)	0.56	(0.39)	0.35	(0.24)	0.61	(0.42)
KF-418	Parallel-to-Ply	0.72	(0.50)	0.21	(0.14)	0.07	(0.05)	0.69	(0.48)
LCCM 2626	Random	1.26	(0.87)	0.18	(0.12)	0.42	(0.29)	0.31	(0.21)
LCCM 4120	Random	1.18	(0.81)	0.80	(0.55)	0.68	(0.47)	0.67	(0.46)
MXC-199B1	45 Deg.-to-Ply	1.77	(1.22)	0.08	(0.06)	0.57	(0.39)	0.24	(0.17)
MXC-12449	Random	1.02	(0.70)	0.45	(0.31)	0.11	(0.08)	0.57	(0.39)
4C 1686	Random	2.65	(1.83)	1.71	(1.18)	0.52	(0.36)	0.52	(0.36)
4K 9502	Random	0.99	(0.68)	0.31	(0.21)	0.02	(0.01)	1.39	(0.96)

TABLE III-16

COST RATINGS OF ENTRANCE
MATERIALS AT AREA RATIO 3.24

Material	Volume, cu in.				Density lbm/cu in.	Matl Cost, $/lbm	Cost Rating, $
LCCM-2626 (15)	0.00095	40	6.284	3.2690	0.064	0.75	0.037
ARC 100	0.00337			3.3174	0.056	0.45	0.071
CFA (21)	0.00340			3.318	0.054	2.00	0.306
CFA (3)	0.00988			3.4476	0.041	2.00	0.702
DP5-161	0.00915			3.433	0.043	3.00	1.019
MXK-418	0.01522			3.5544	0.049	1.80	1.199
XR-2029-25	0.01330			3.516	0.045	2.75	1.451
4S 4186	0.01007			3.4514	0.062	5.00	2.708
DC 93-104	0.01482			3.5464	0.053	4.00	2.801
MXC-12449	0.00652			3.38	0.048	12.50	3.324
DP5-161 HC	0.01232			3.4964	0.040	8.00	3.465
SP 8030 (2)	0.01442			3.5384	0.065	6.00	5.002
SP 8030	0.0176			3.602	0.060	5.50	5.259
MXS-198	0.01431			3.5362	0.058	9.50	7.008
4C 2585	0.00932			3.4364	0.055	16.00	7.054
SP 8030 (12)	0.02021			3.6542	0.064	6.00	7.129
WB 8251	0.0095	40	6.284	3.44	0.055	16.00	7.431

TABLE III-17

COST RATINGS OF THROAT
MATERIALS AT MINIMUM THROAT

Materials	Volume, cu in.				Density lbm/cu in.	Matl Cost, $/lbm	Cost Rating, $
LCCM-2626	0.00165	40	6.284	0.933	0.064	0.75	0.019
CFA (21)	0.0048			0.996	0.056	2.00	0.136
CFA (3)	0.007			1.040	0.0495	2.00	0.181
SP 8057 (M)	0.00275			0.955	0.051	20.00	0.700
CA-8502	0.00519			1.0038	0.056	14.50	0.968
4C 1686	0.0041			0.982	0.051	21.00	1.084
CA 8502	0.00625			1.025	0.051	14.50	1.191
MXC-199B1	0.0072			1.044	0.053	14.25	1.426
4C 1686	0.00575			1.015	0.051	21.00	1.571
SP 8057 (W)	0.00625			1.025	0.050	20.00	1.610
4C 2585	0.0084			1.063	0.055	16.00	2.037
WB 8251	0.010	40	6.284	1.120	0.055	15.00	2.346

TABLE III-18

COST RATINGS OF EXIT MATERIALS
AT AREA RATIO 4.0

Material	Volume, cu in.				Density lbm/cu in.	Matl Cost $/lbm	Cost Rating, $
MXK-418 (W)	-	40	6.284	-	-	1.80	-
LCCM-4120	-			-	-	0.75	-
DP5-161/Si	-			-	-	3.25	-
MXC-12449	-			-	-	12.50	-
ARC/Si	0.00041			3.608	0.057	0.45	0.01
CFA (3)	0.00081			3.6162	0.0459	2.00	0.068
CFA (21)	0.0009			3.618	0.057	2.00	0.094
MXC-113	0.0003			3.606	0.049	22.50	0.299
4K 9502 (M)	0.00525			3.705	0.051	1.80	0.449
MXK-418 (M)	0.006			3.72	0.051	1.80	0.515
KYNOL	0.00731			3.7462	0.046	3.00	0.982
FM-5042	0.00606			3.7212	0.062	2.90	1.019
4E 0285	0.00773			3.7546	0.067	2.90	1.418
FM 5700	0.01099			3.8198	0.070	2.00	1.477
AGC-CS	0.01079			3.8158	0.050	3.00	1.553
FM-5711	0.00893			3.7786	0.064	2.90	1.574
MXS-198	0.00365			3.673	0.058	9.50	1.857
MXK-198	0.02285			4.057	0.047	2.25	2.464
MXS-12450	0.0069	40	6.284	3.738	0.053	11.00	3.78

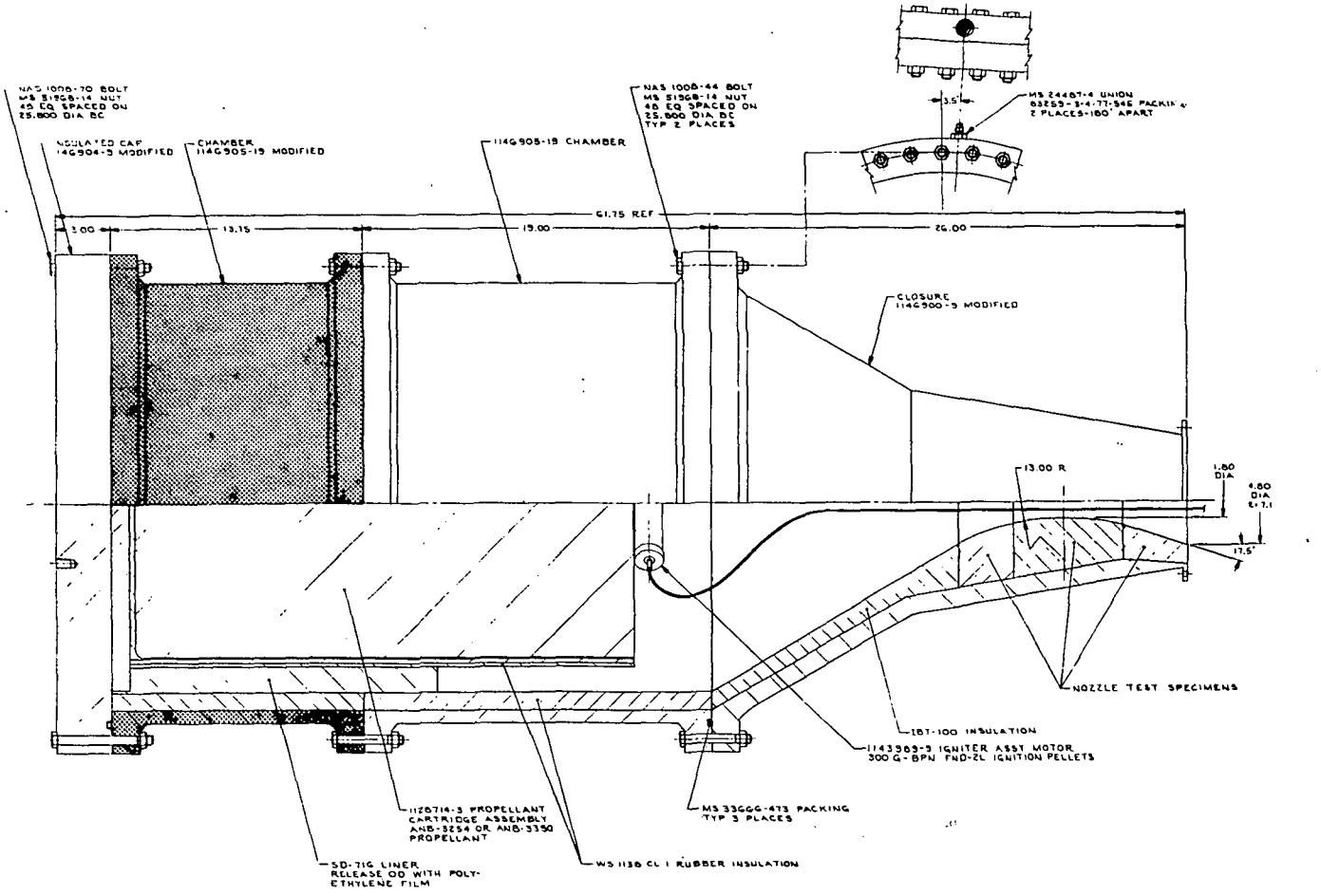


Figure III-1. - Screening Test Motor Configuration

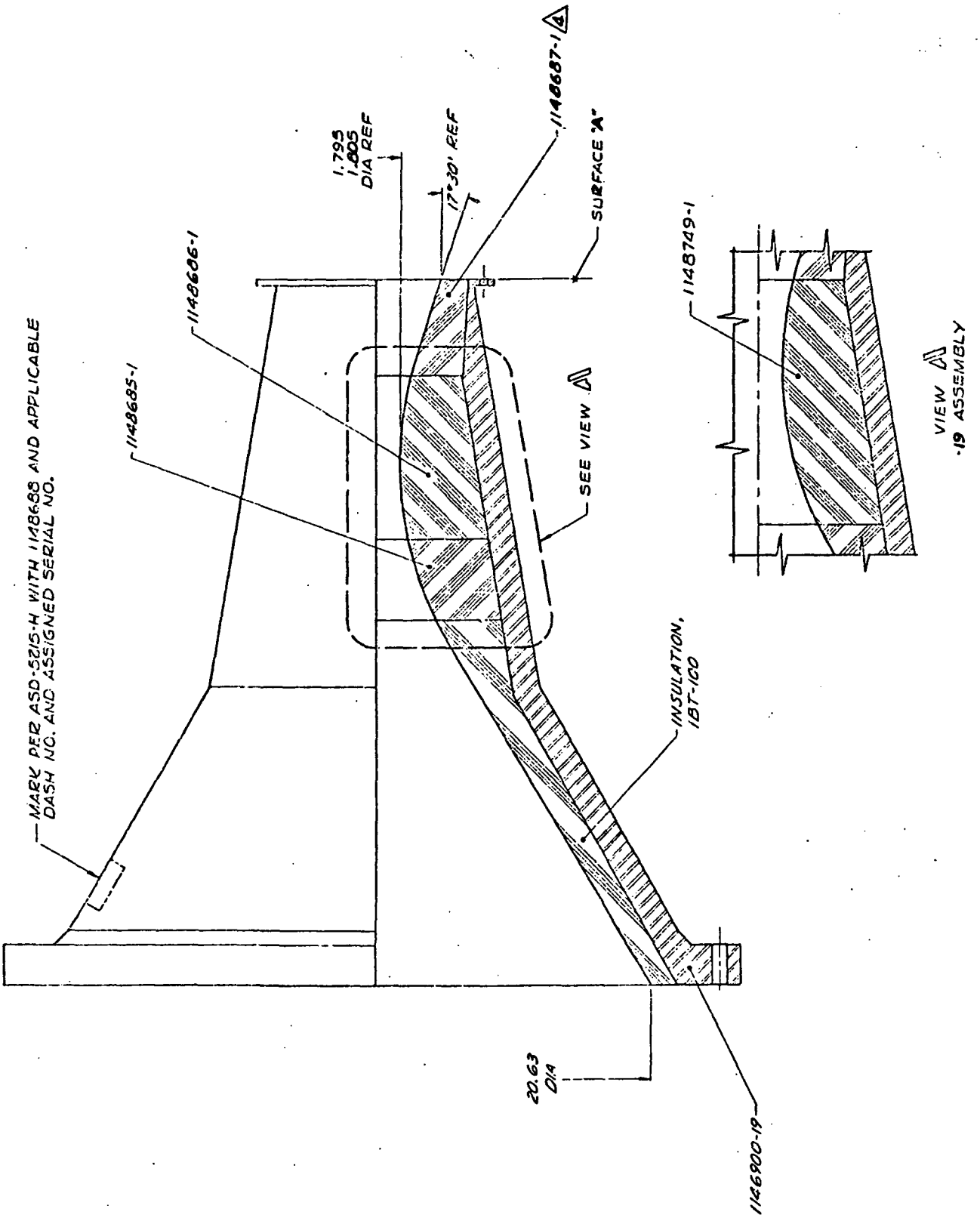


Figure III-2. - Test Nozzle Assembly



Figure III-3. - Extruded Fibertape Exit Cone

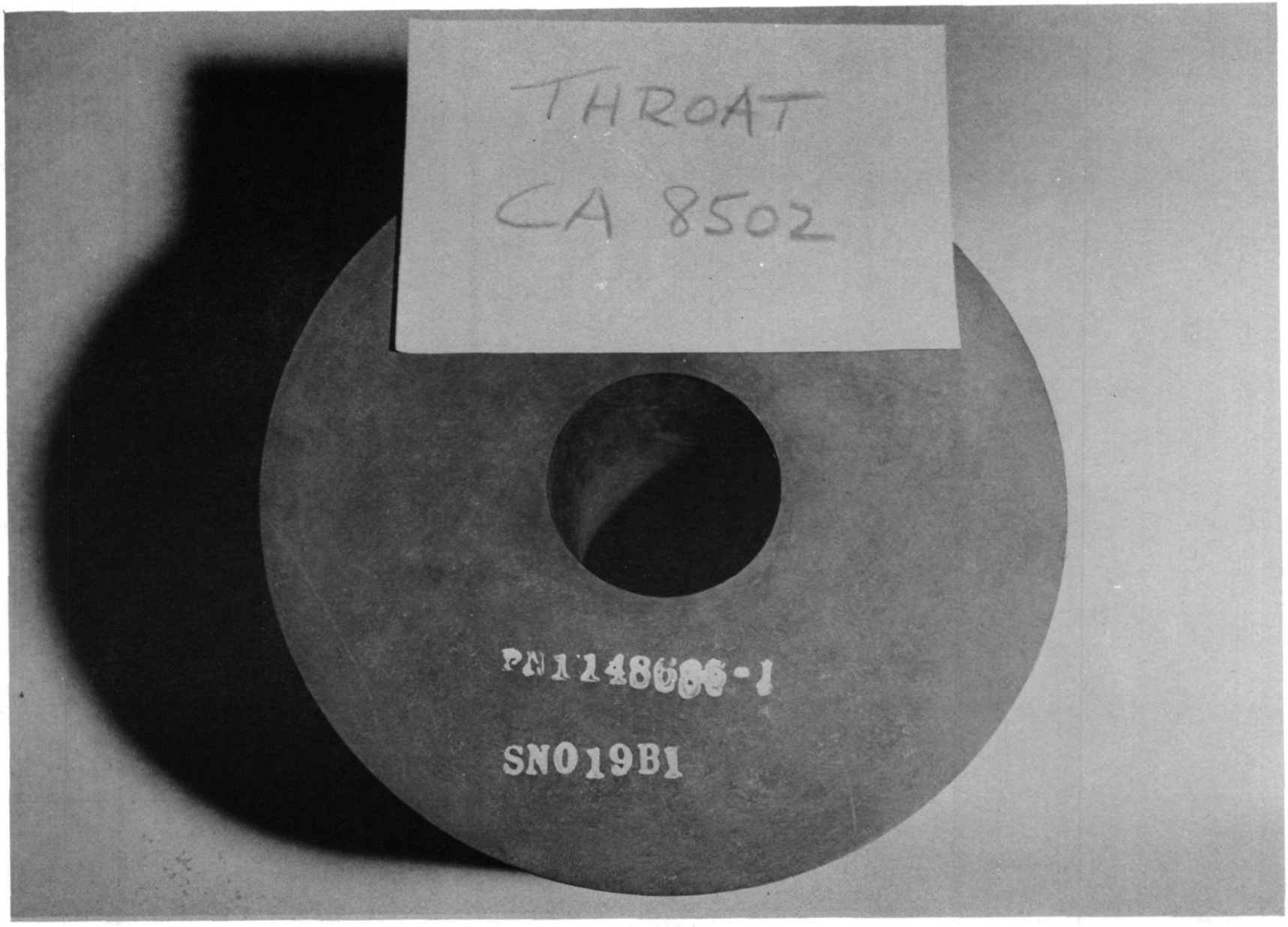


Figure III-4. - Molded Carbon Fibers Throat



Figure III-5. - Molded Linear Phenolic Exit Cone

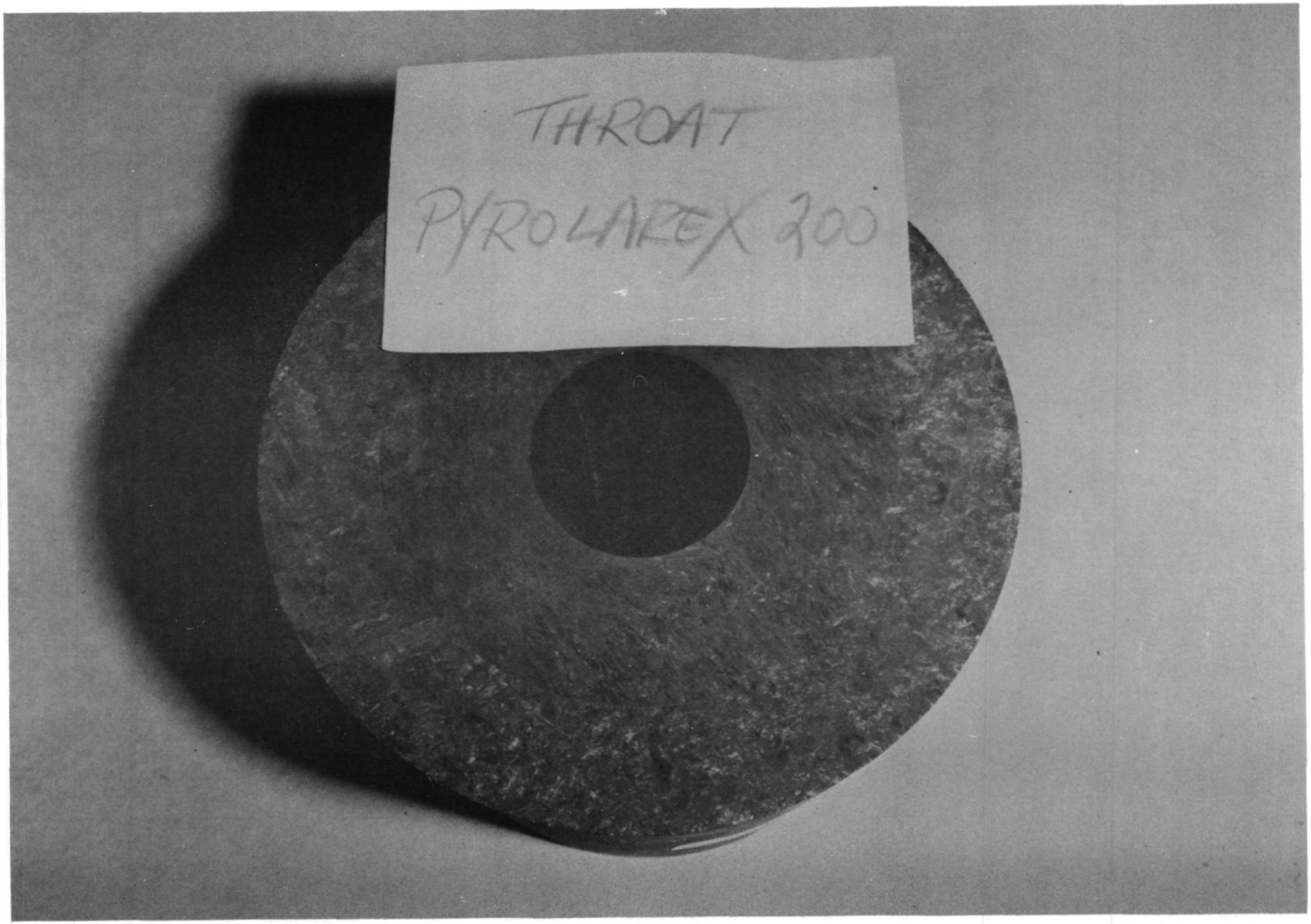


Figure III-6. - Molded Pyrolyzed Carbon Throat

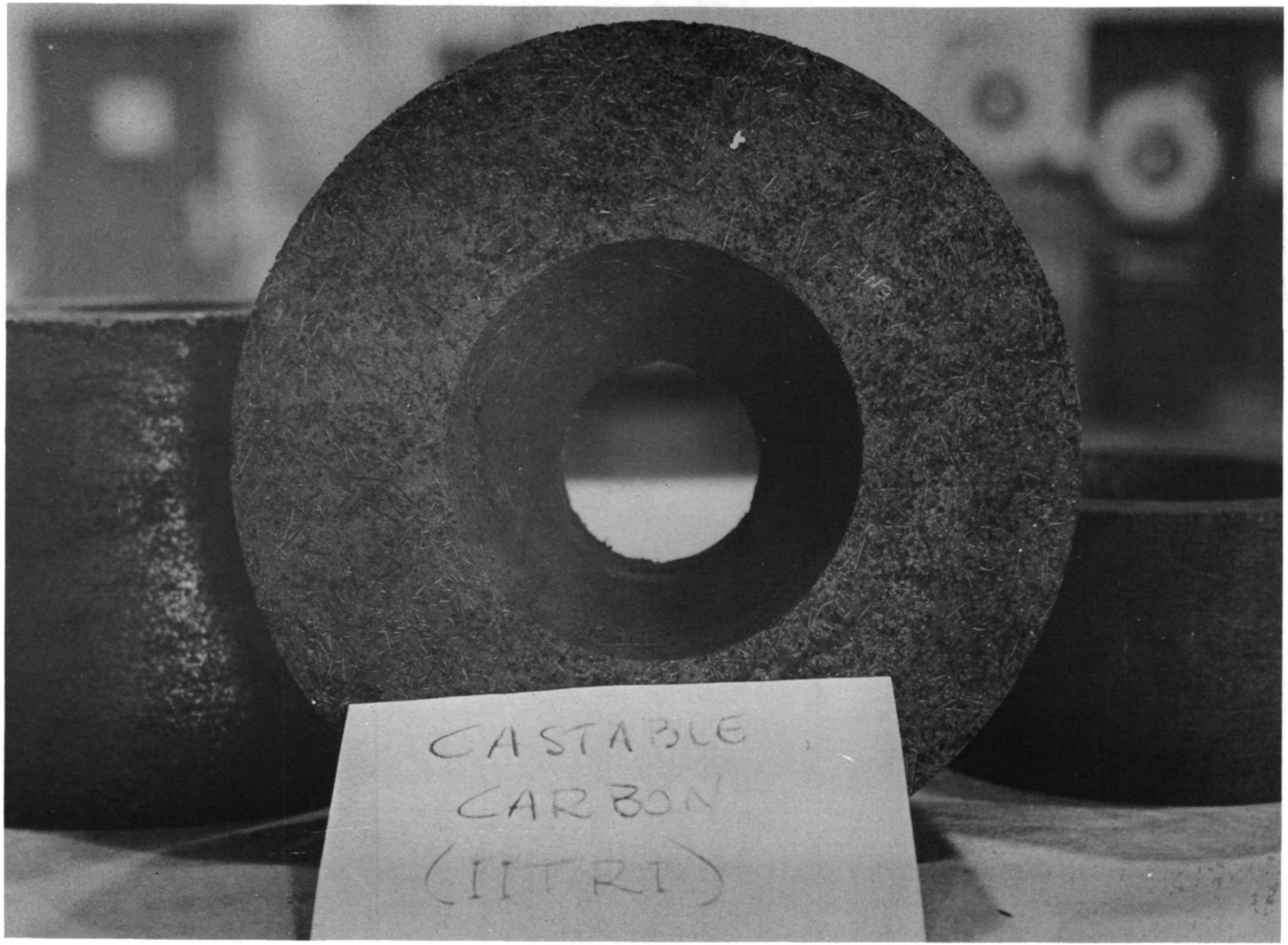


Figure III-7. - Cold Formed Additive Entrance Section



Figure III-8. - Castable Carbon Exit Cone



Figure III-9. - Cast Resin Throat

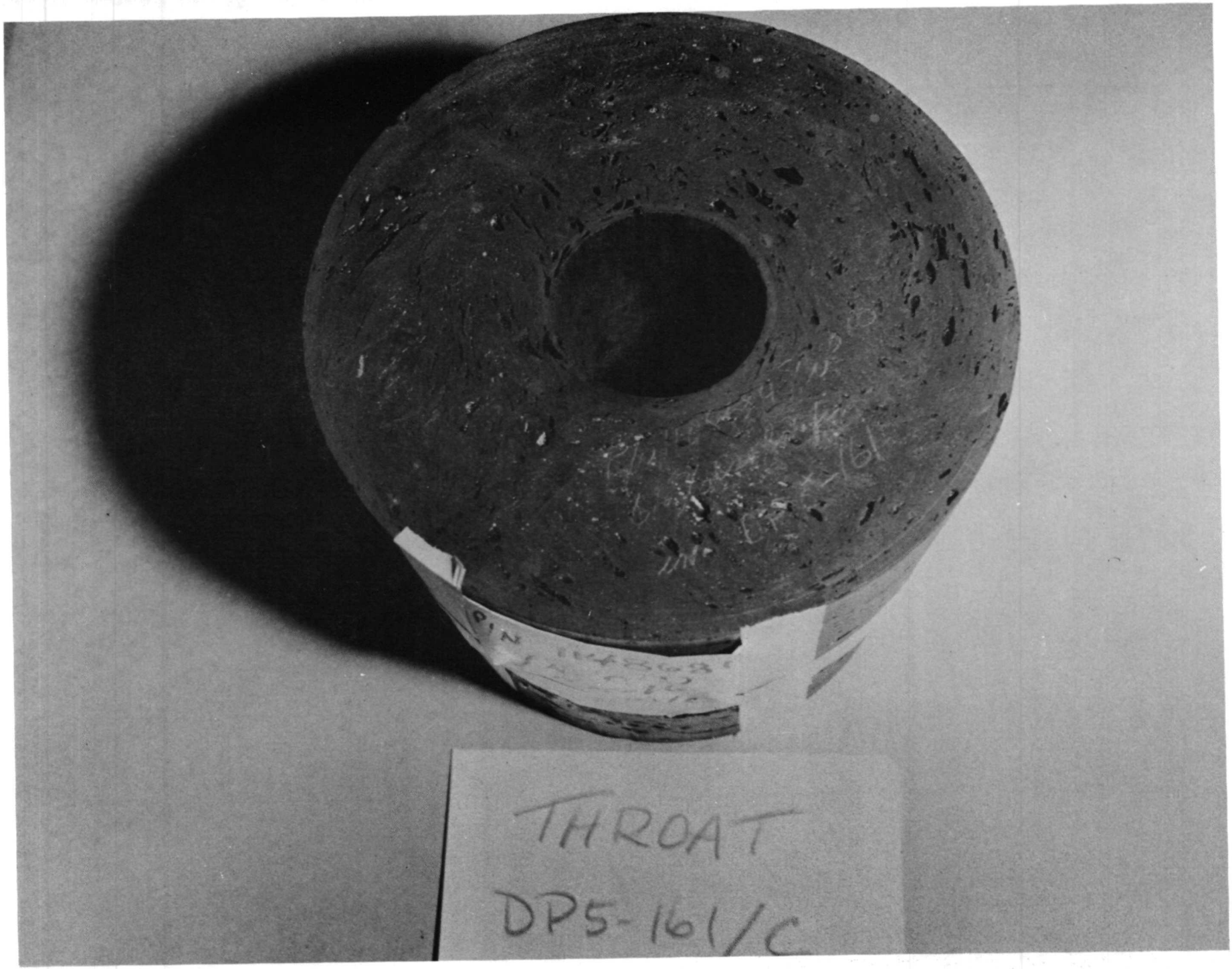


Figure III-10. - Cast Resin, Carbon Added Throat



Figure III-11. - Cast Resin, Silica Added Exit Cone

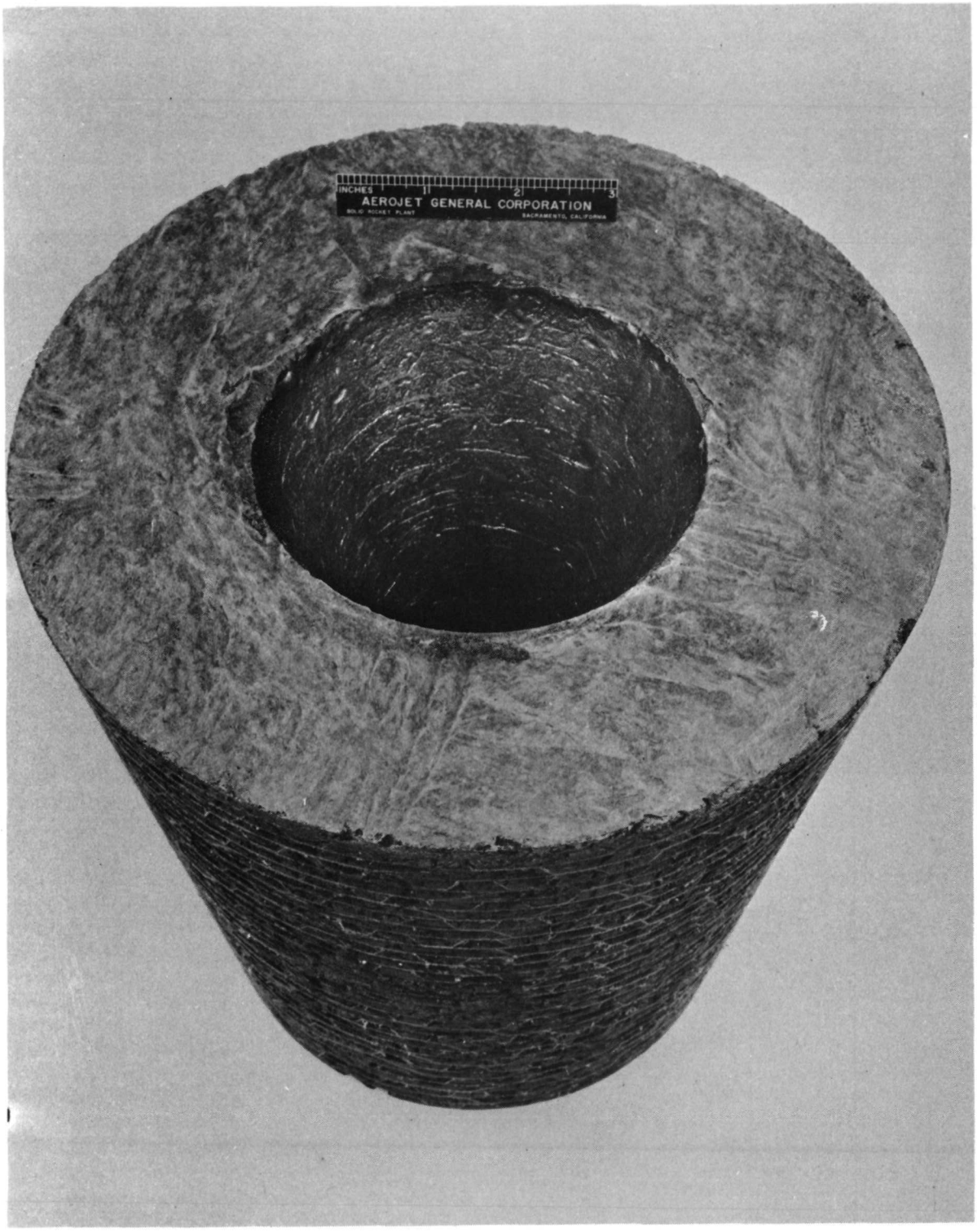


Figure III-12. - Asbestos Honeycomb Reinforced Throat

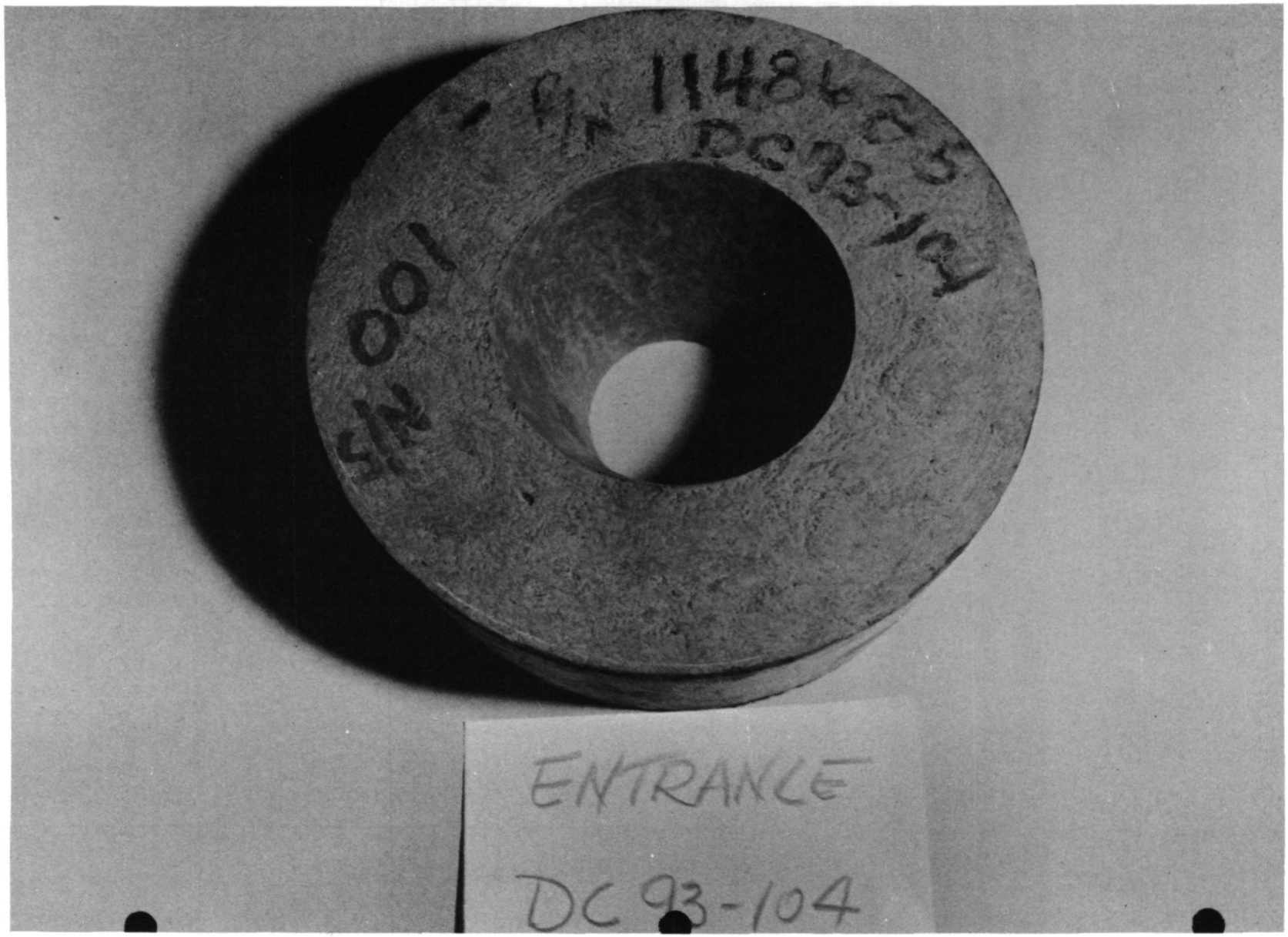


Figure III-13. - Cast Silicone Entrance Section



Figure III-14. - Plastonium Entrance Section



Figure III-15. - Sprayed Epoxy-Novolac Ext Cone

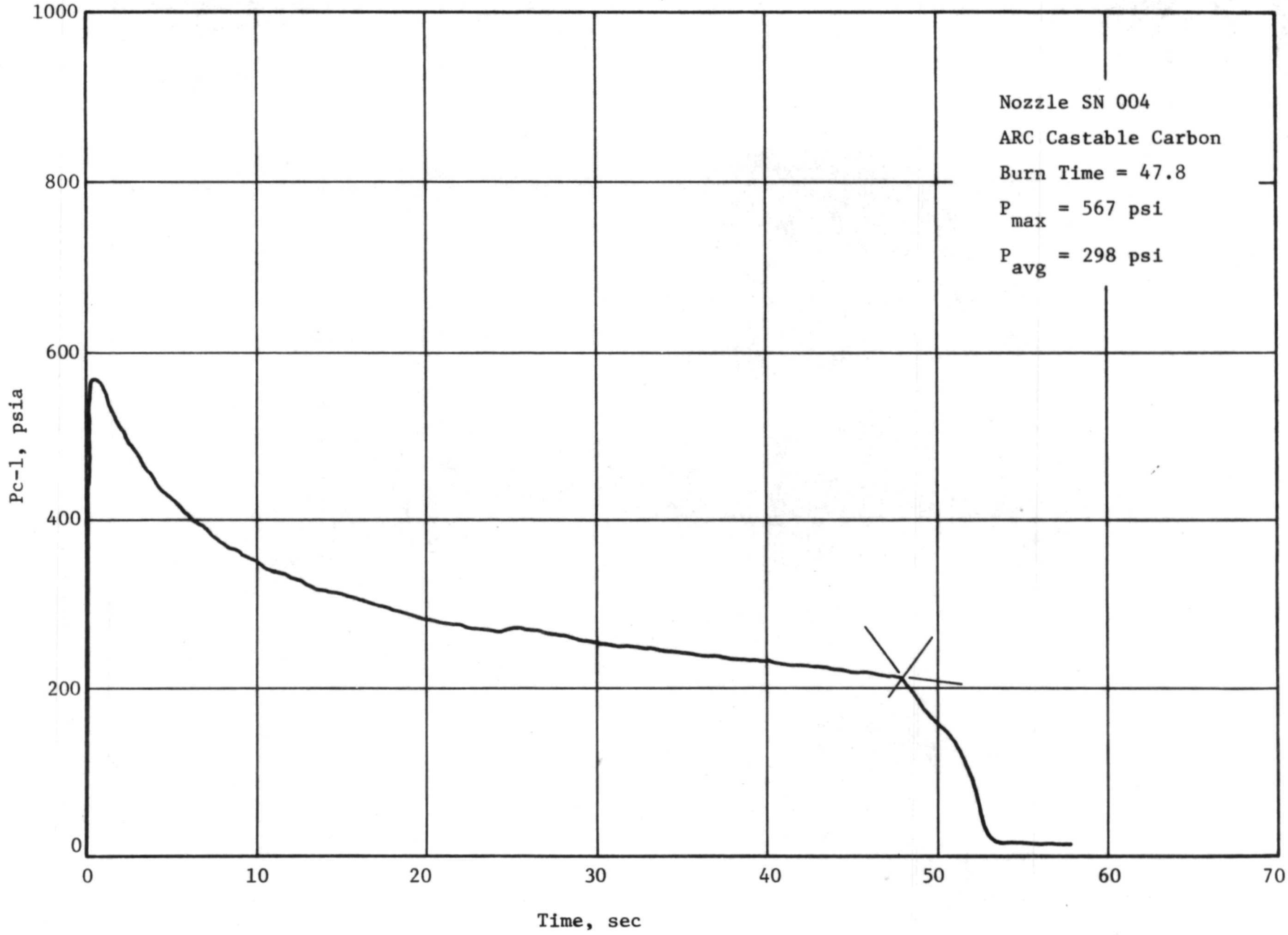


Figure III-16. - Screening Test No. 1 (ARC-100 Throat)

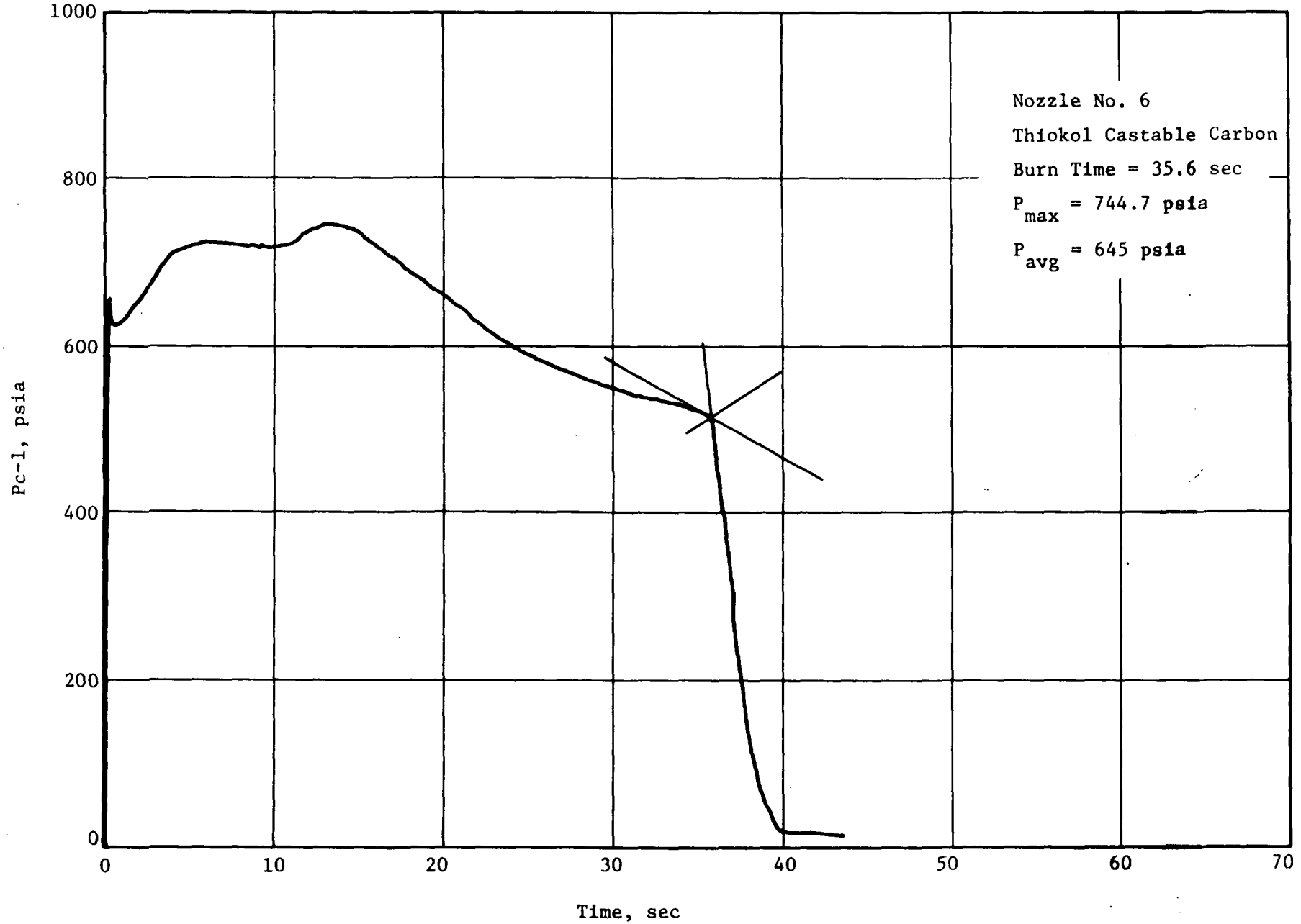


Figure III-17. - Screening Test No. 2 (LCCM-2626 Throat)

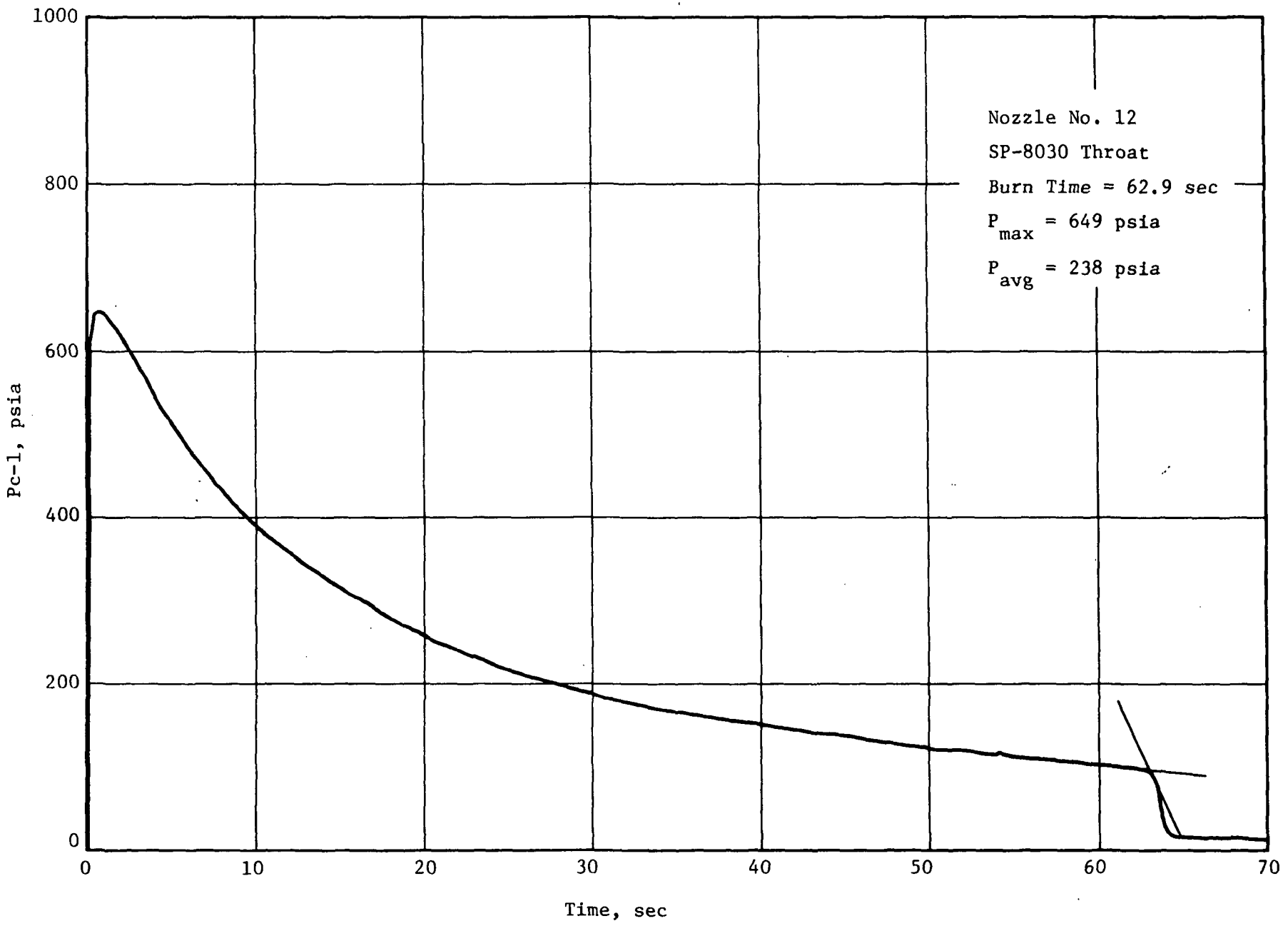


Figure III-18. - Screening Test No. 3 (Molded SP-8030 Throat)

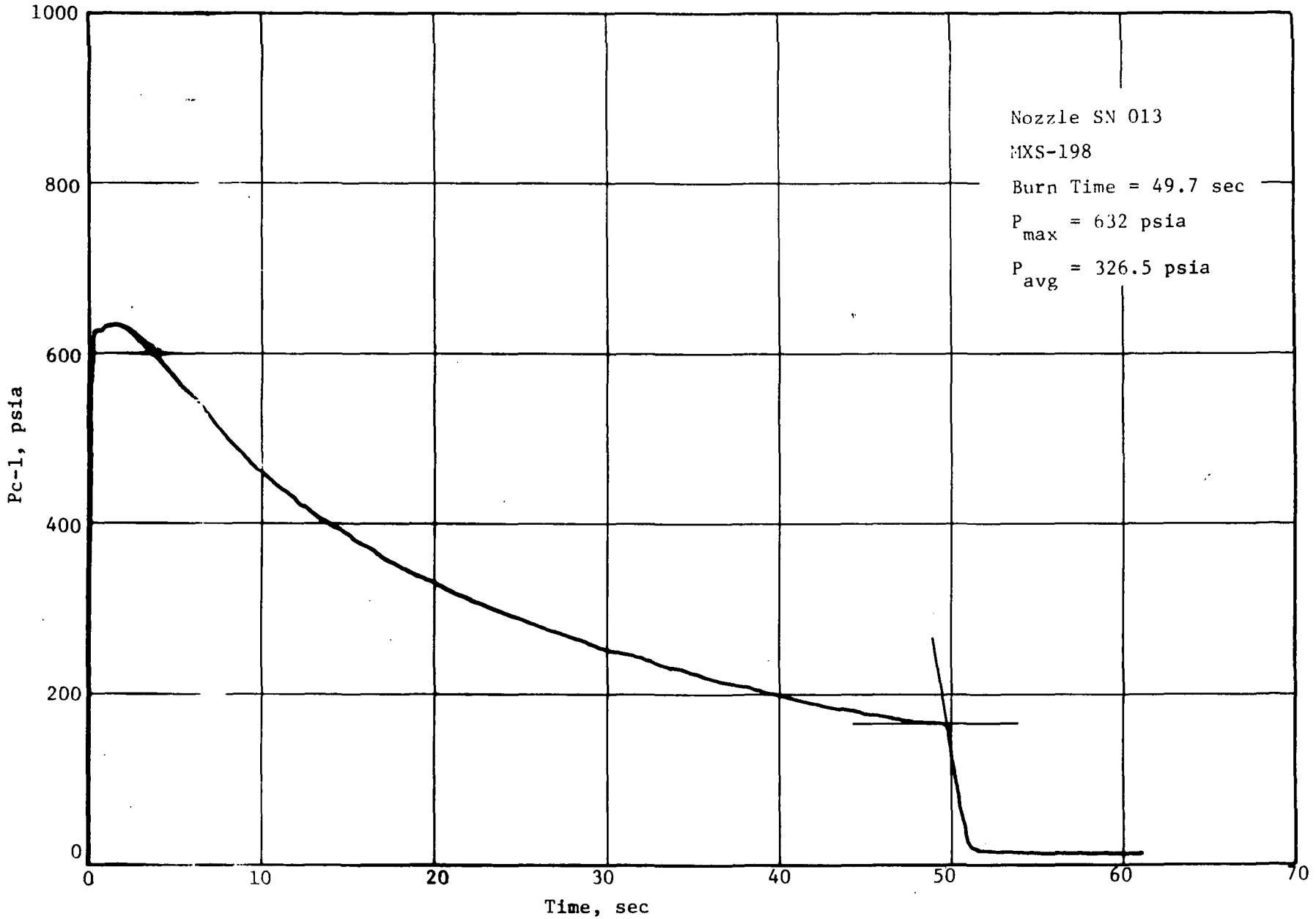


Figure III-19. - Screening Test No. 4 (Molded MXS-198 Throat)

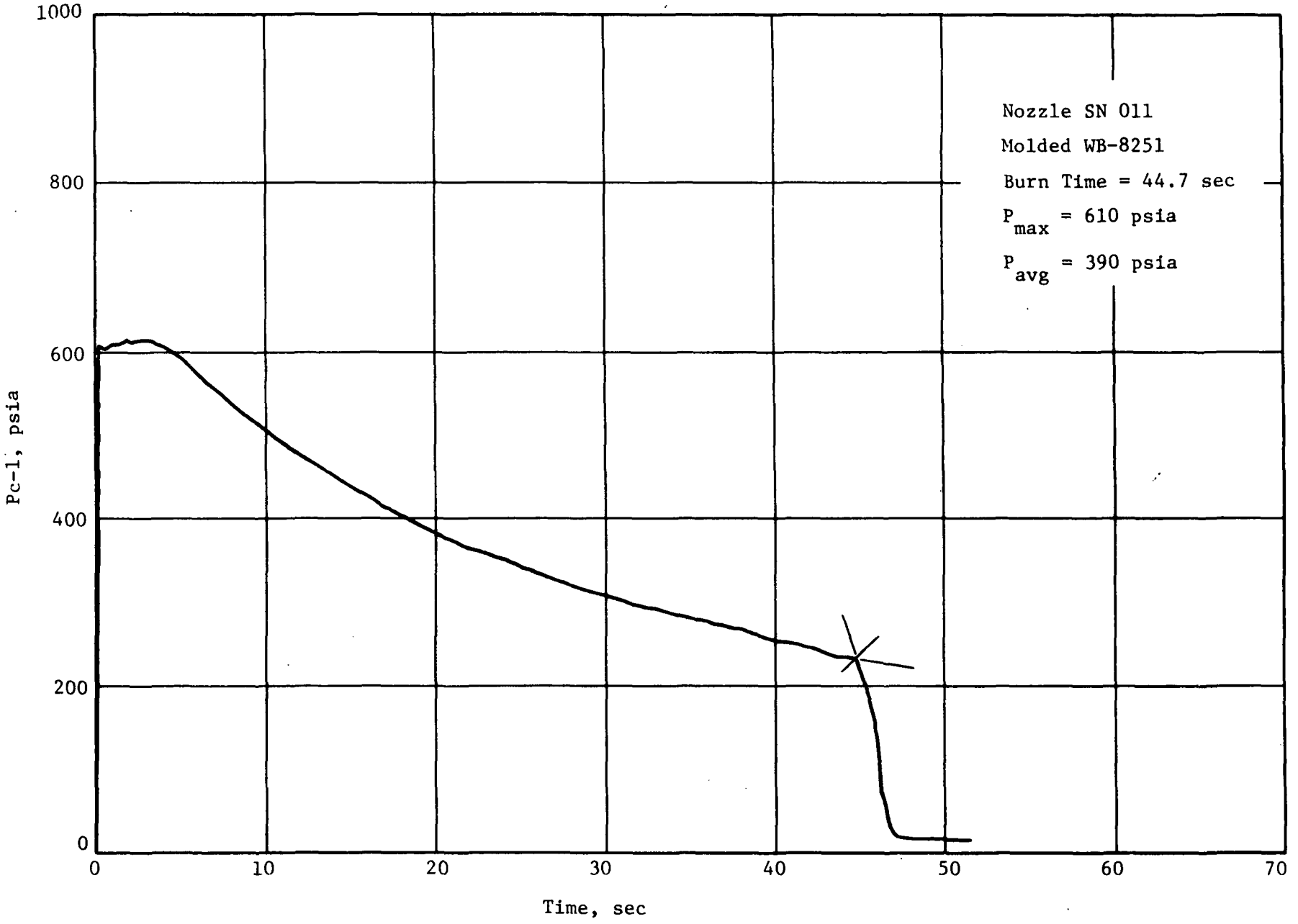


Figure III-20. - Screening Test No. 5 (Molded WB-8251 Throat)

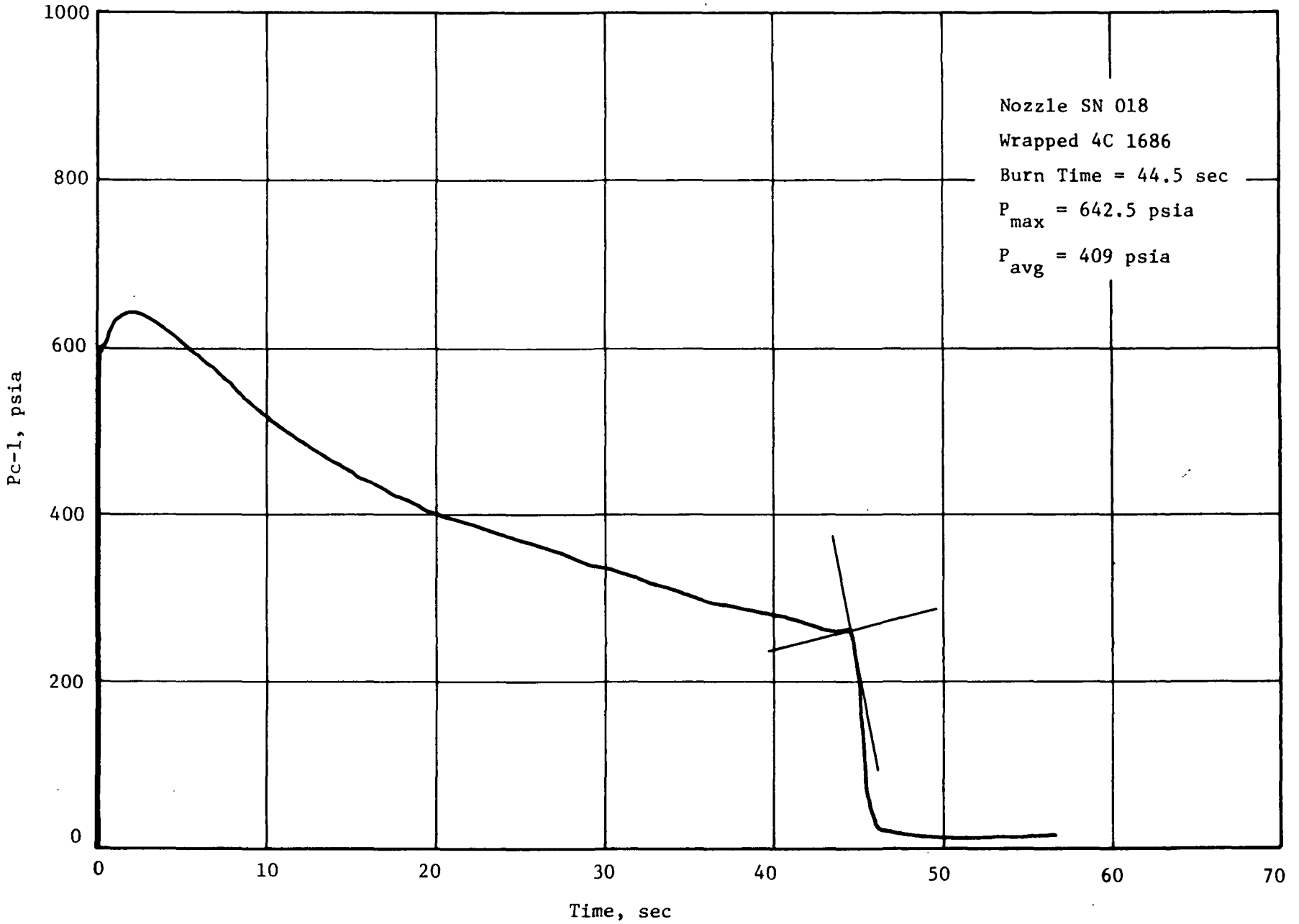


Figure III-21. - Screening Test No. 6 (Wrapped 4C 2585 Throat)

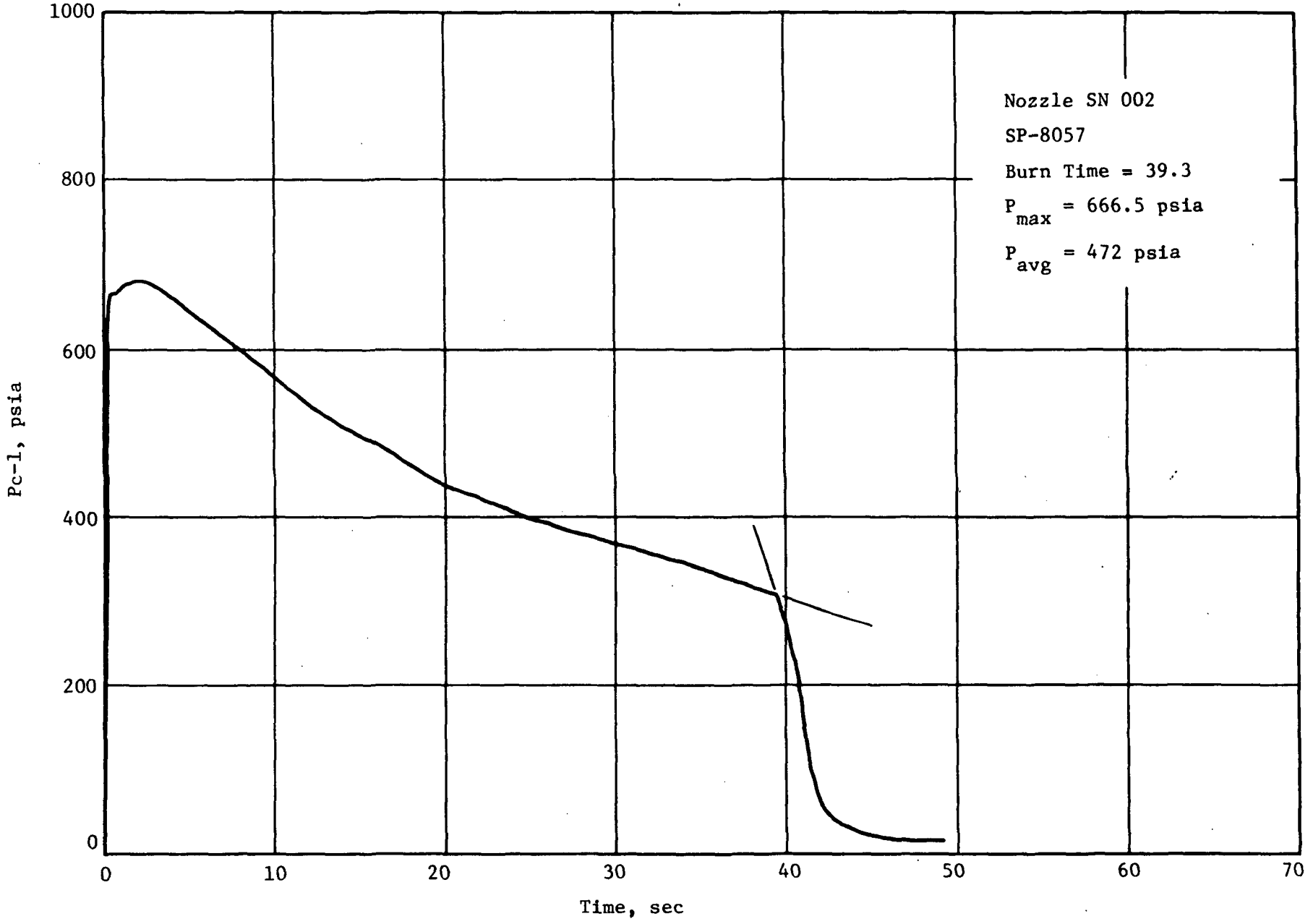


Figure III-22. - Screening Test No. 7 (Molded SP-8057 Throat)

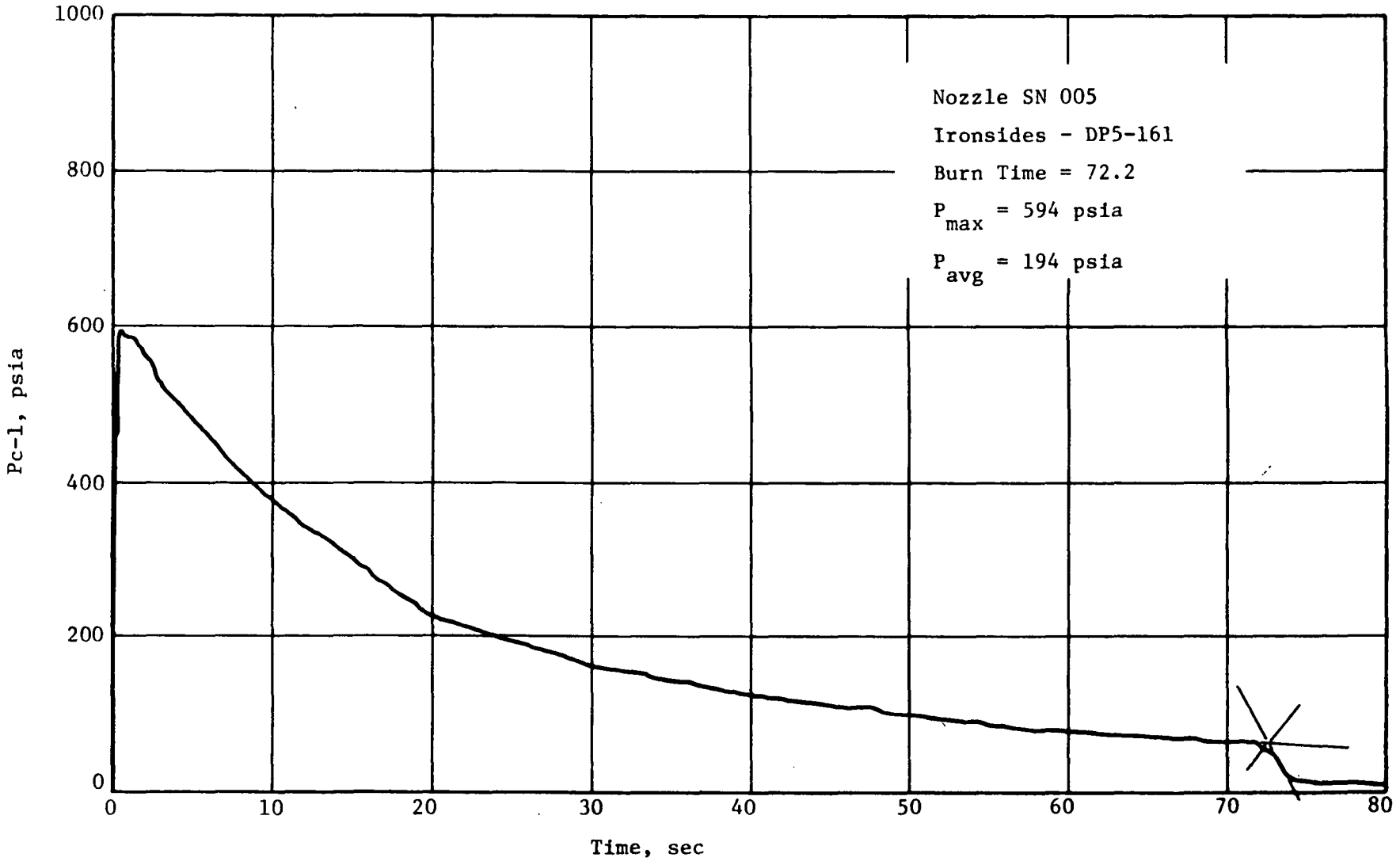


Figure III-23. - Screening Test No. 8 (DP5-161 Throat)

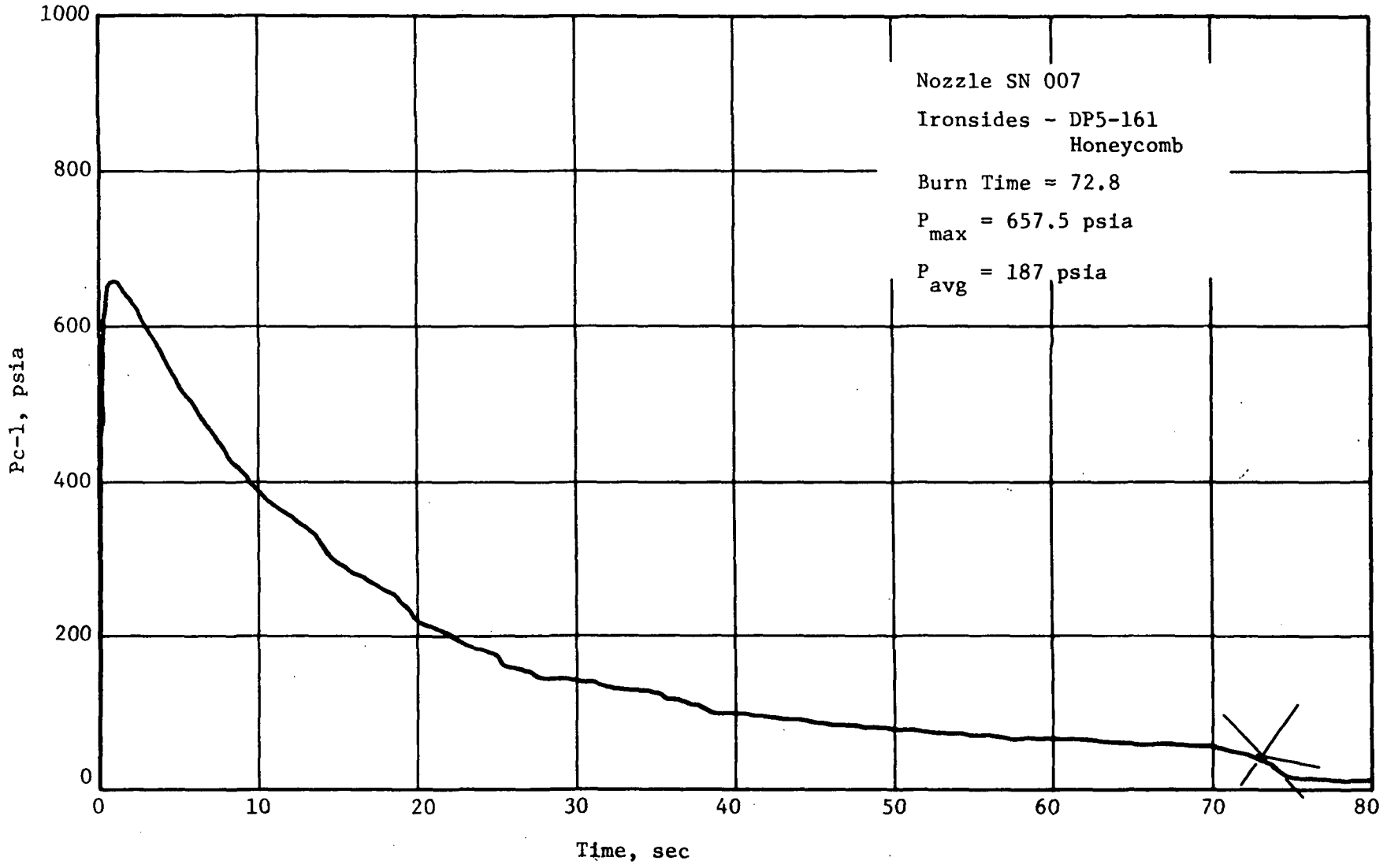


Figure III-24. - Screening Test No. 9 (DP5-161 HC Throat)

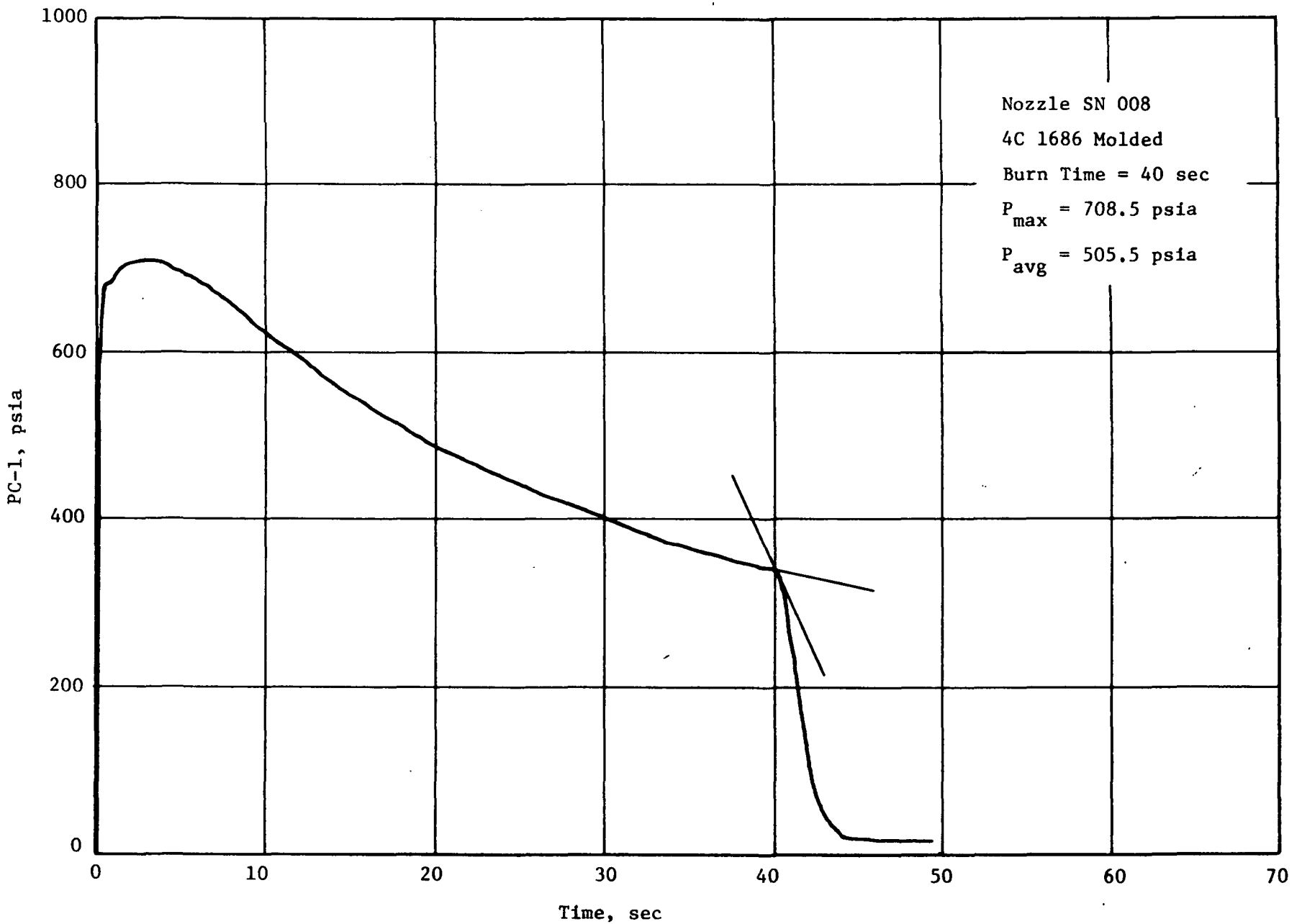


Figure III-25. - Screening Test No. 10 (Molded 4C 1686 Throat)

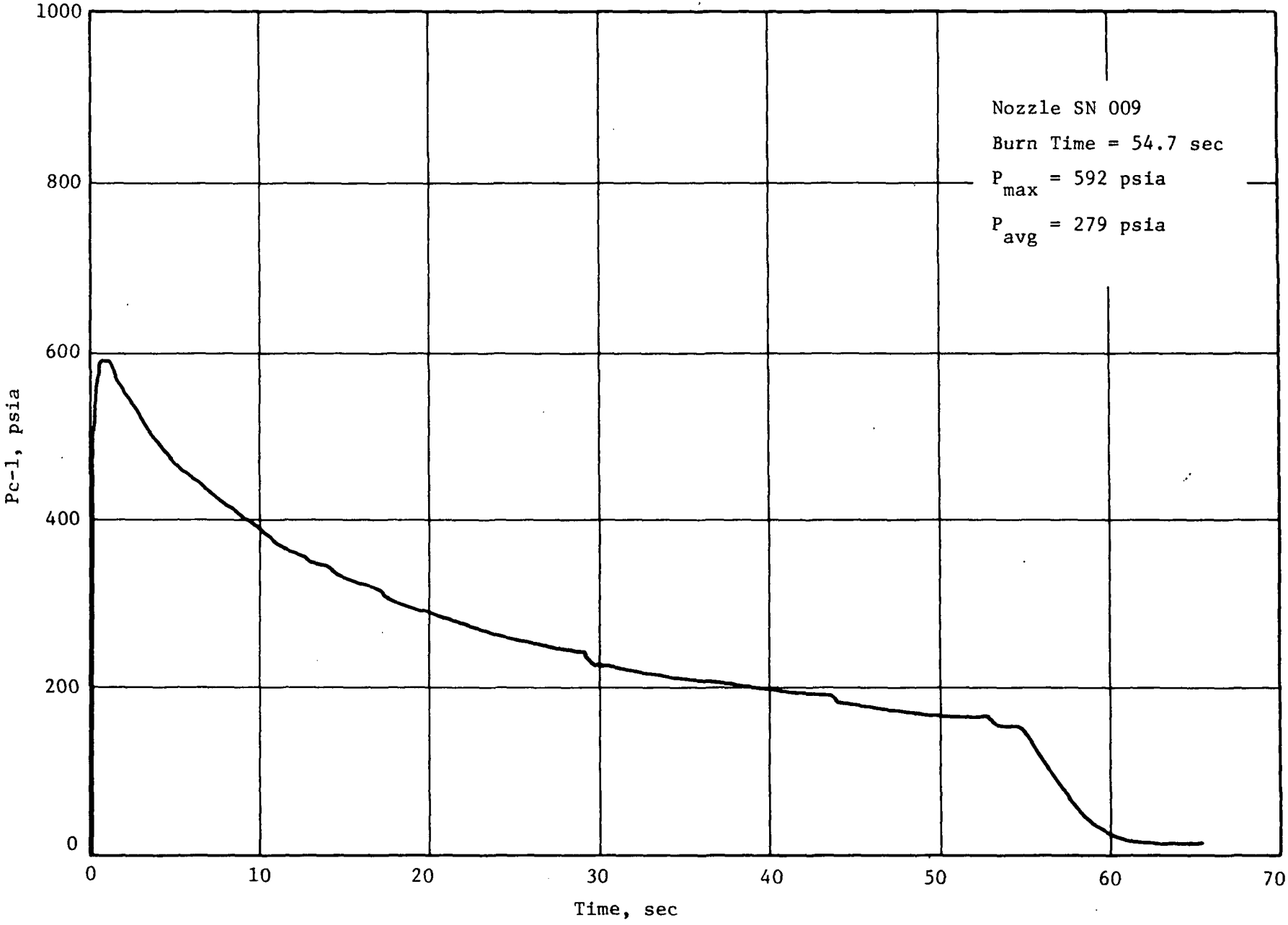


Figure III-26. - Screening Test No. 11 (Pyrolarex 200 Throat)

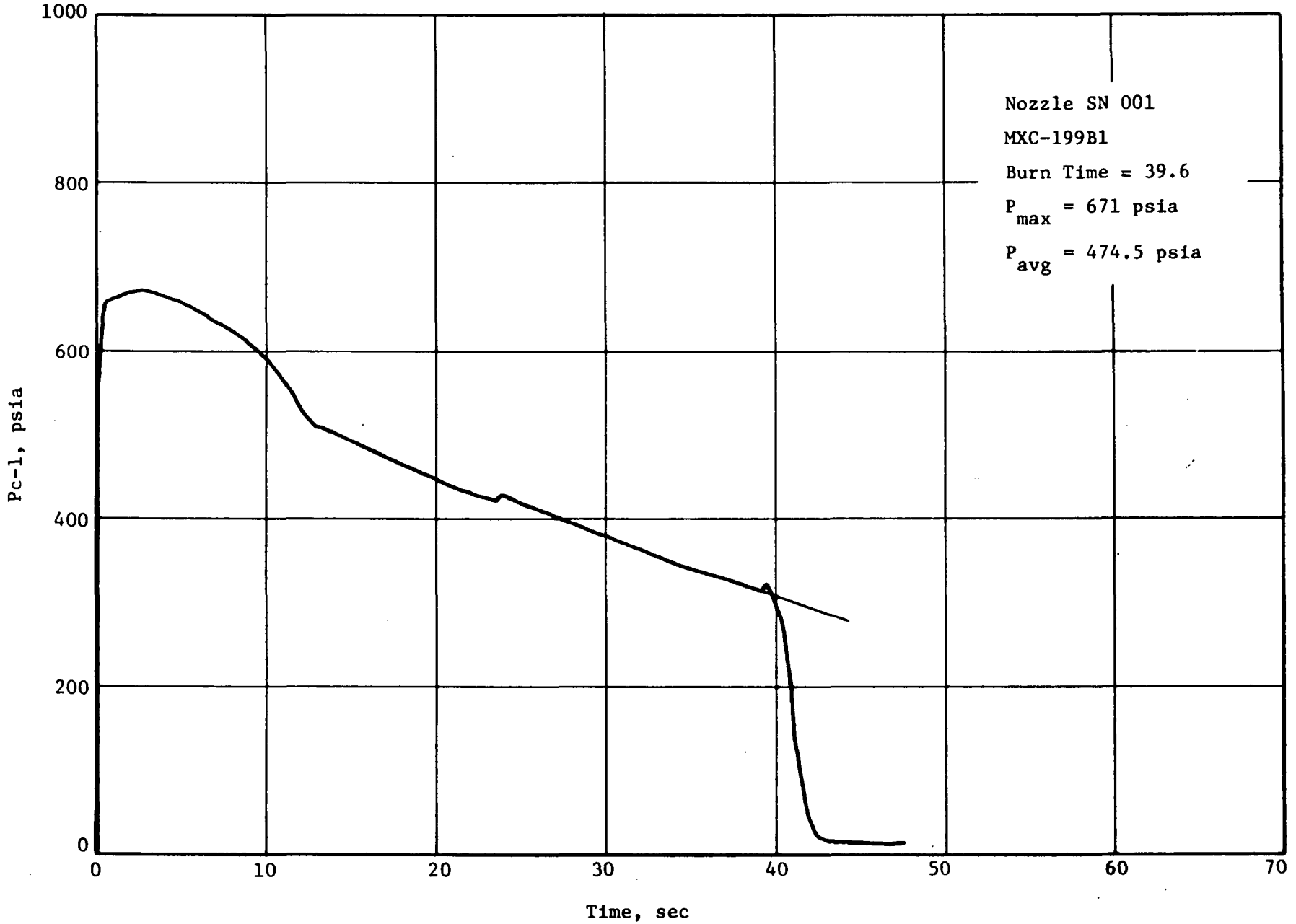


Figure III-27. - Screening Test No. 12 (Wrapped MXC-199 B1 Throat)

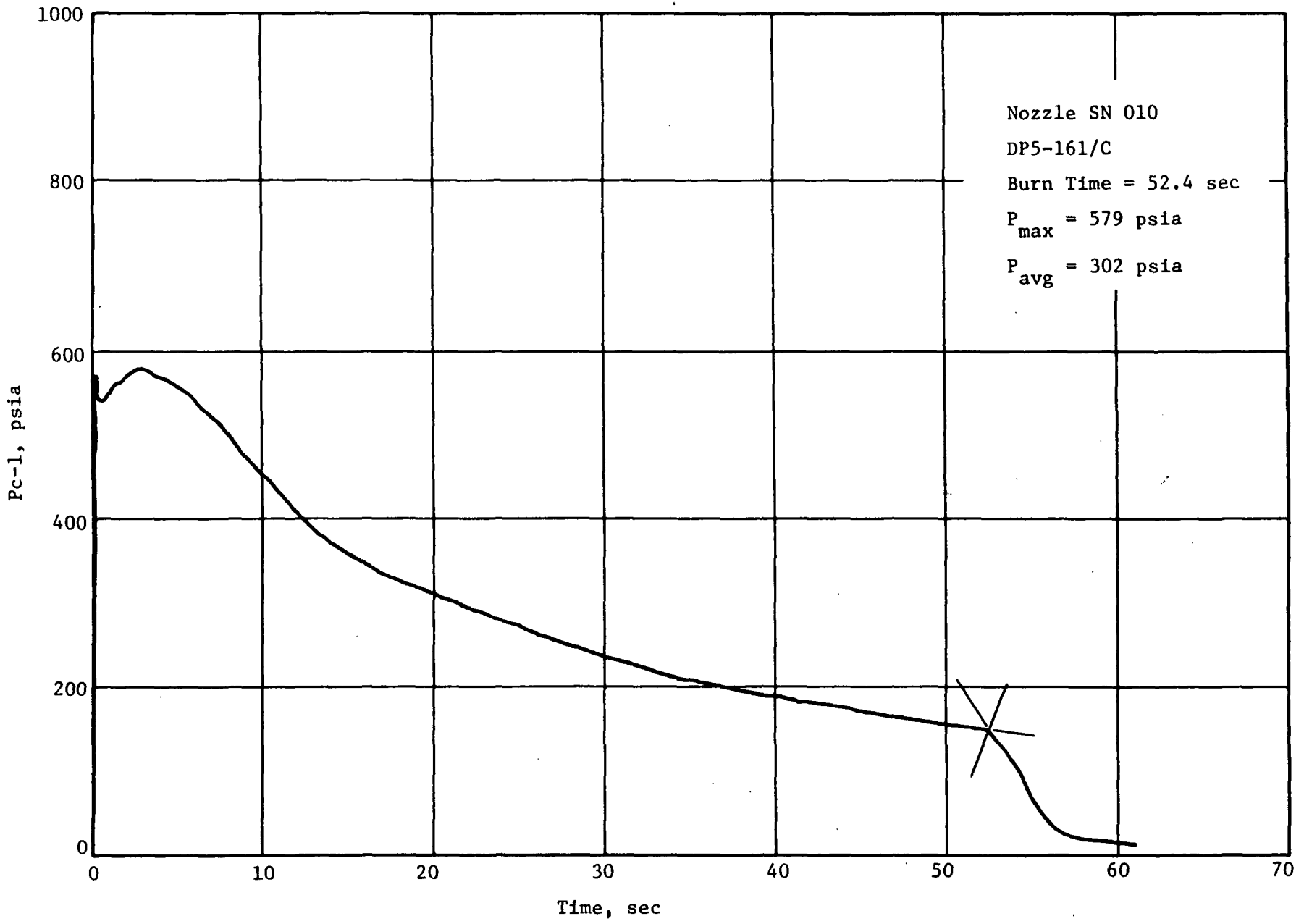


Figure III-28. - Screening Test No. 13 (DP5-161/C Throat)

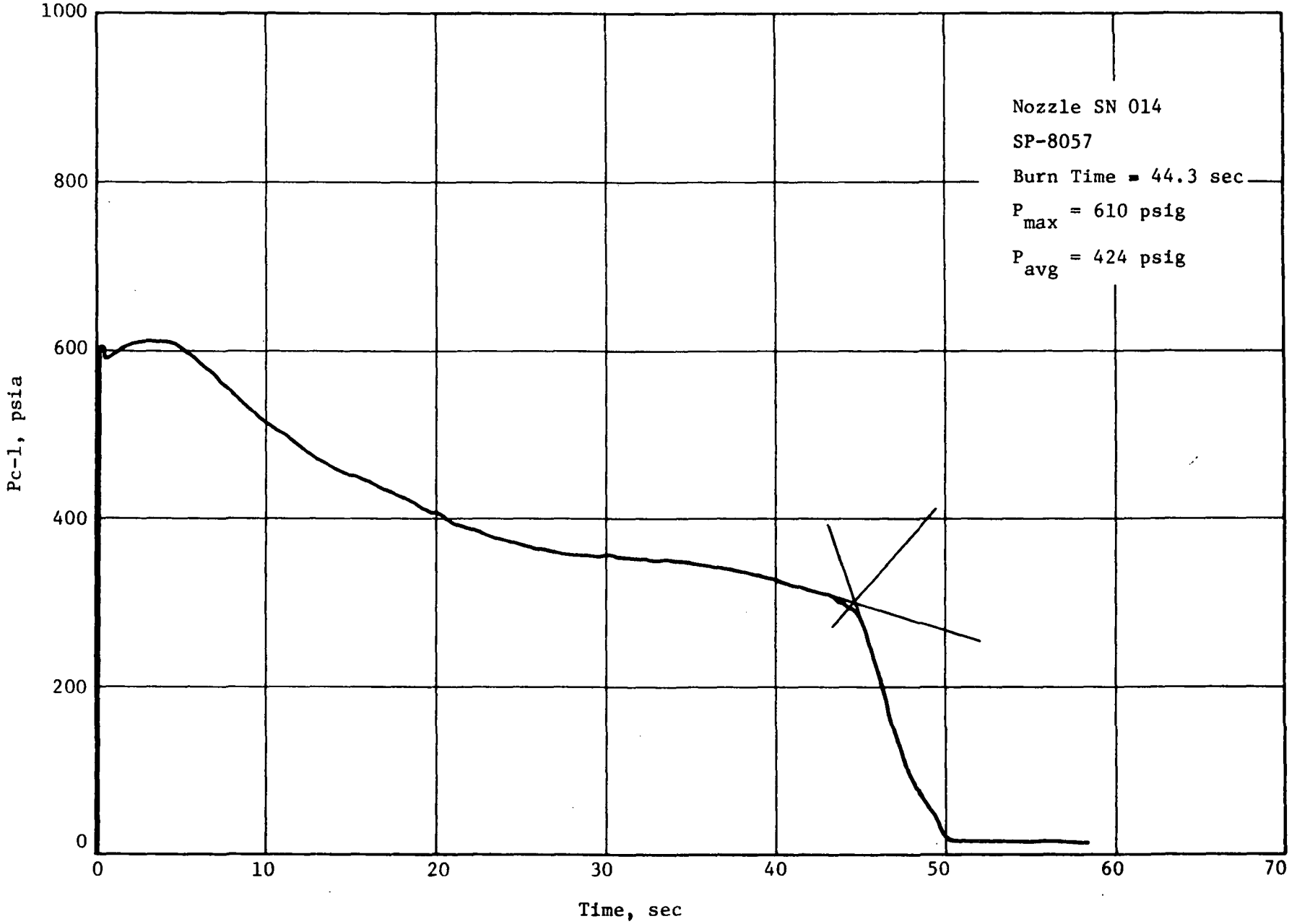


Figure III-29. - Screening Test No. 14 (Wrapped SP-8057 Throat)

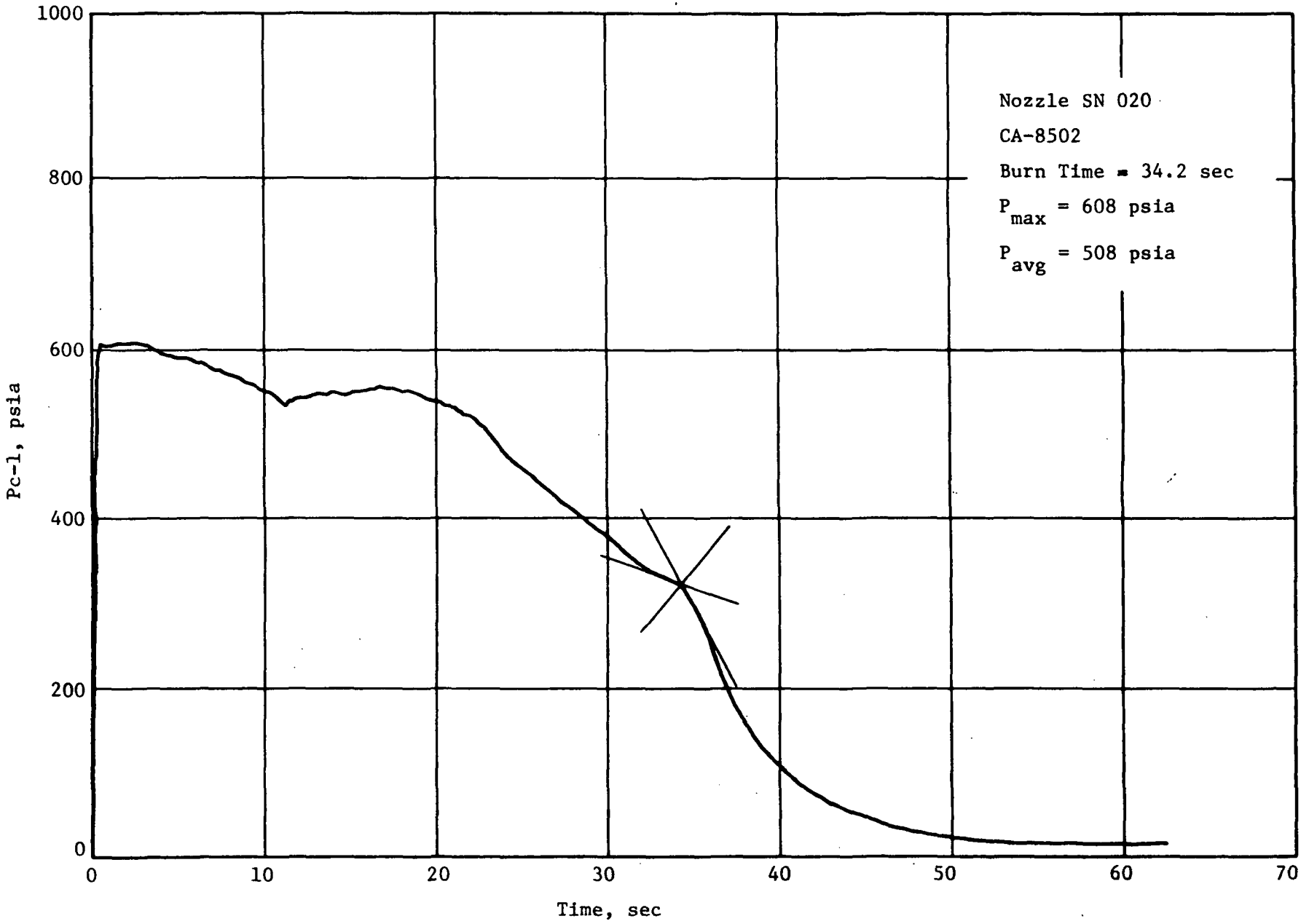


Figure III-30. - Screening Test No. 15 (Molded CA-8502 Throat)

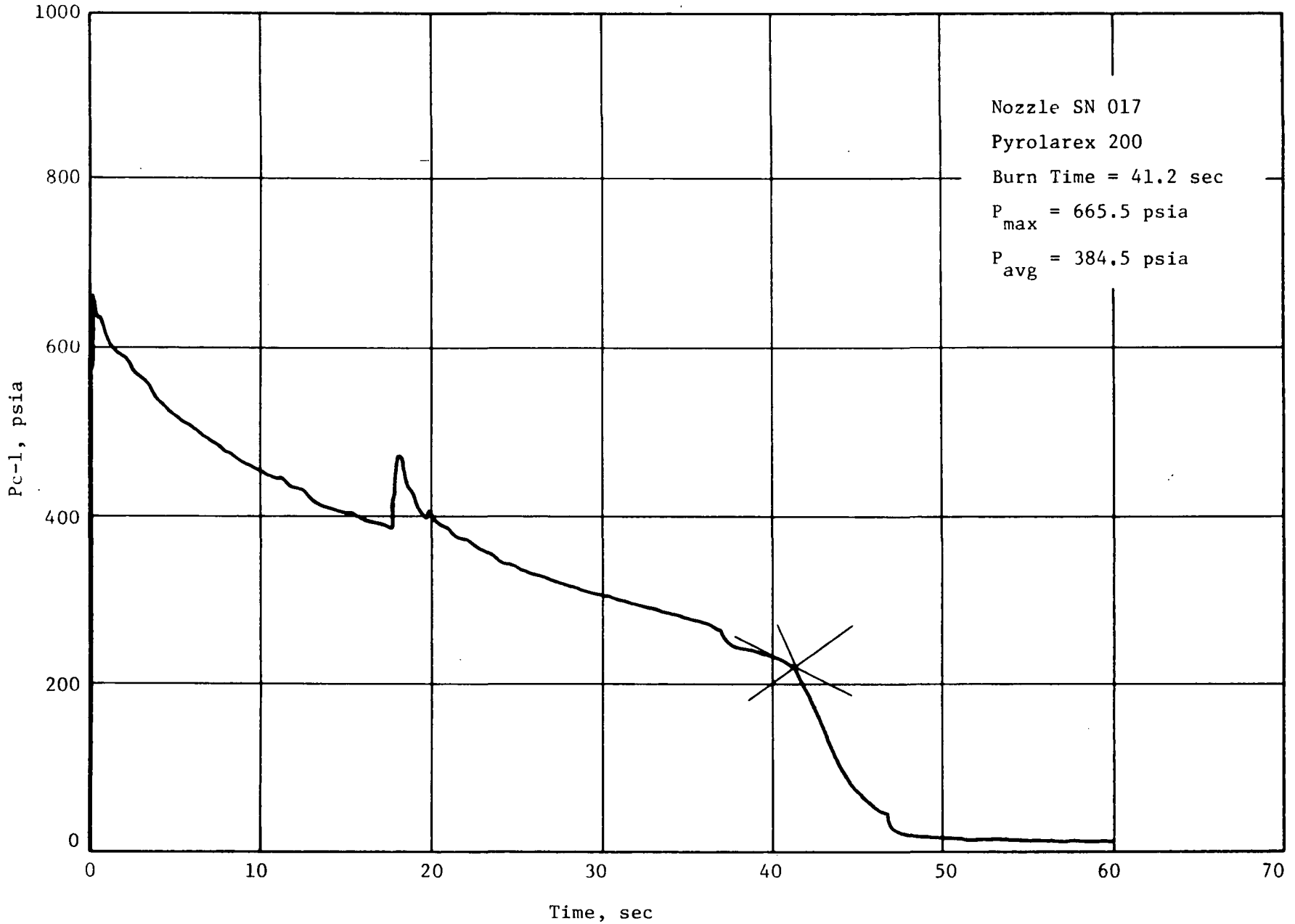


Figure III-31. - Screening Test No. 16 (Pyrolarex 200 Throat)

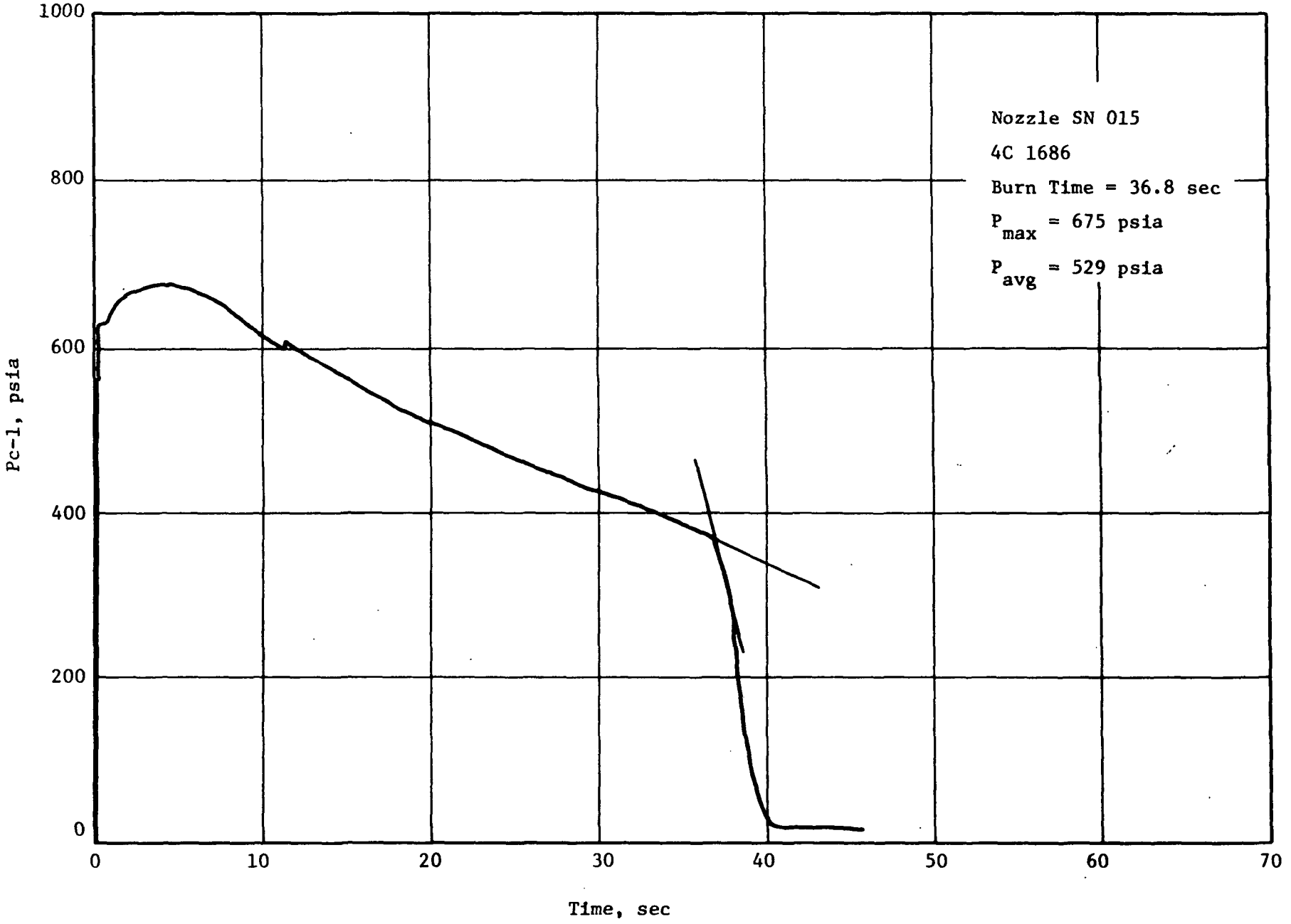


Figure III-32. - Screening Test No. 17 (Wrapped 4C 1686 Throat)

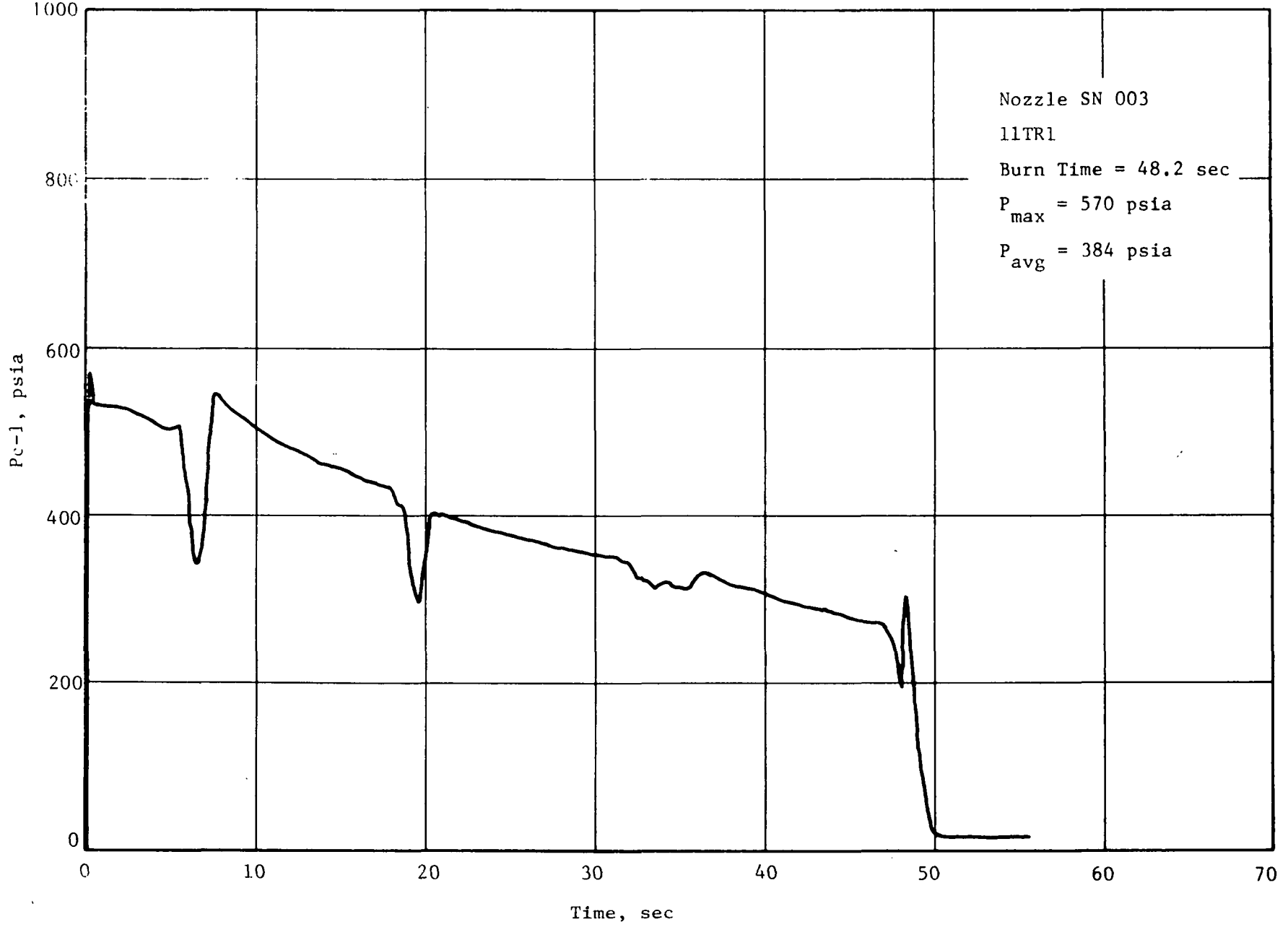


Figure III-33. - Screening Test No. 18 (CFA Throat)

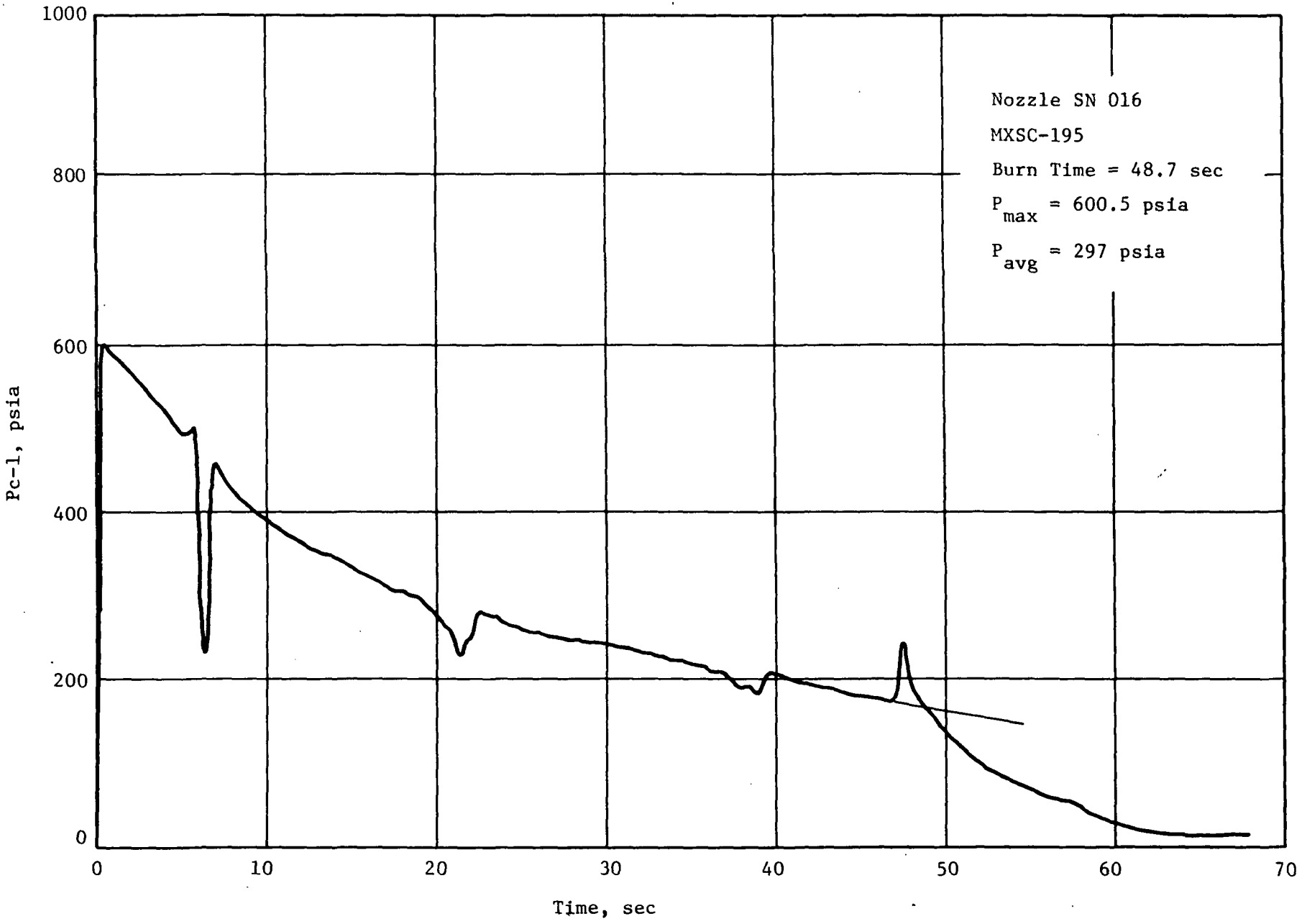


Figure III-34. - Screening Test No. 19 (Wrapped MXSC-195 Throat)

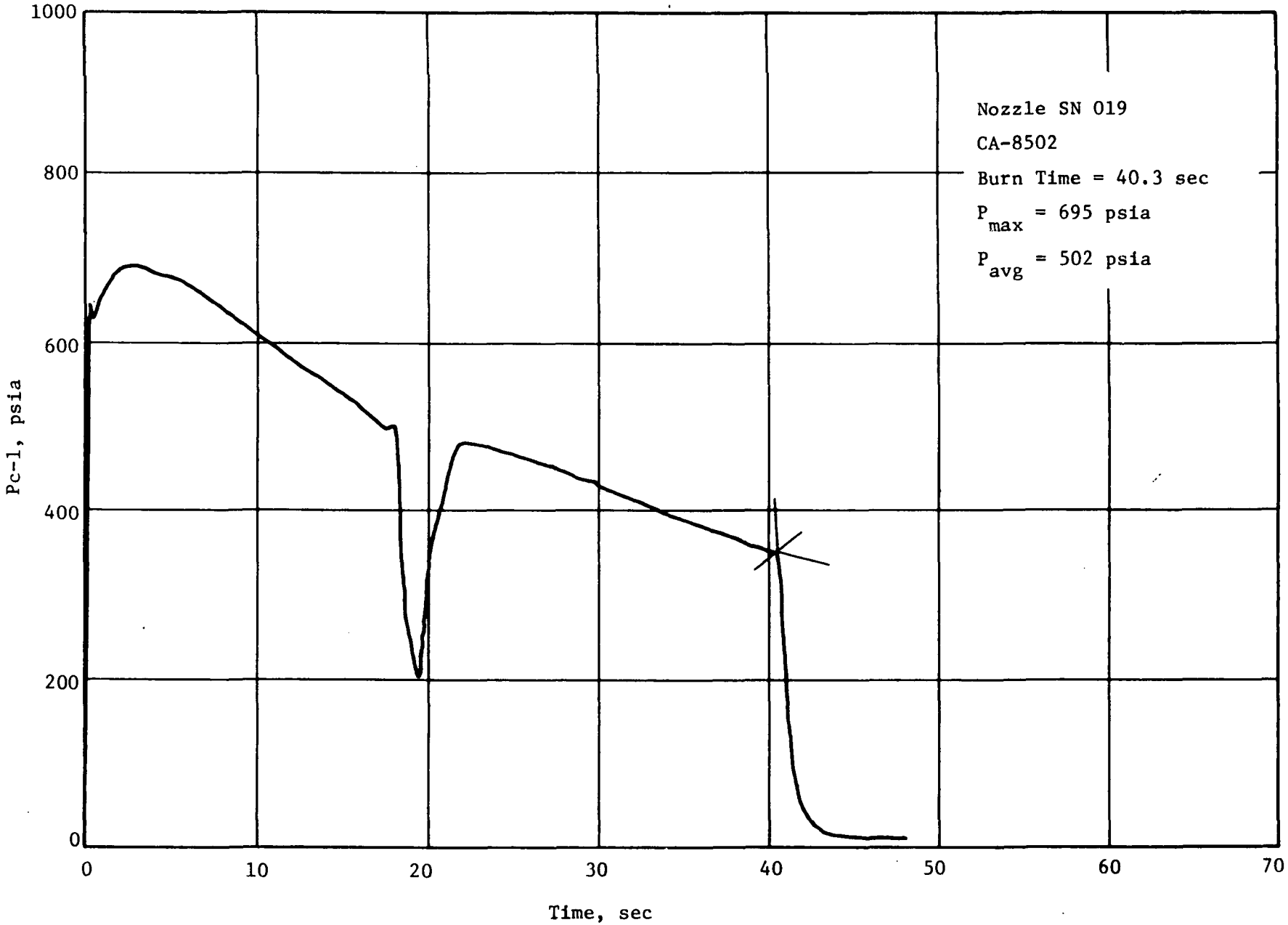


Figure III-35. - Screening Test No. 20 (Molded CA-8502 Throat)

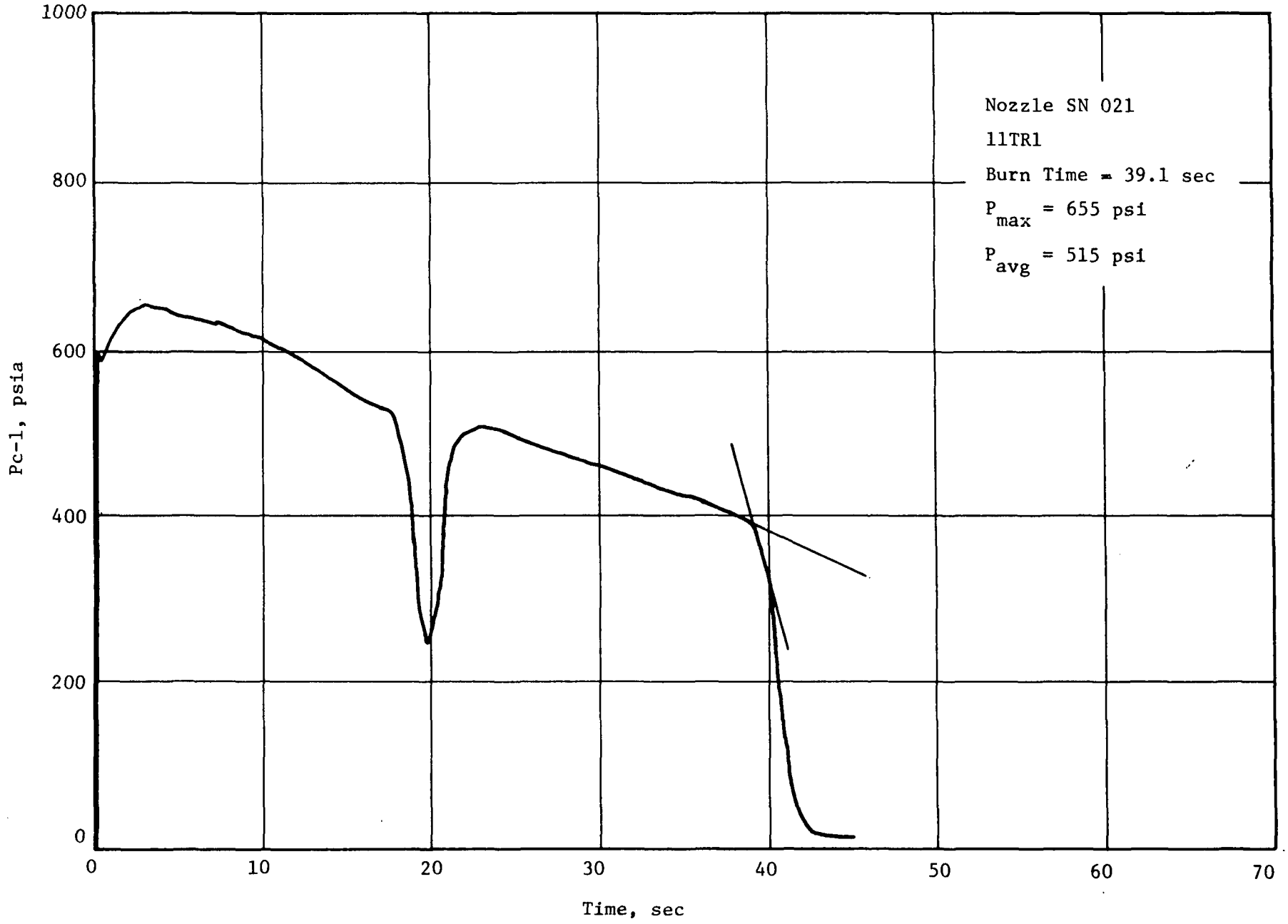


Figure III-36. - Screening Test No. 21 (CFA Throat)

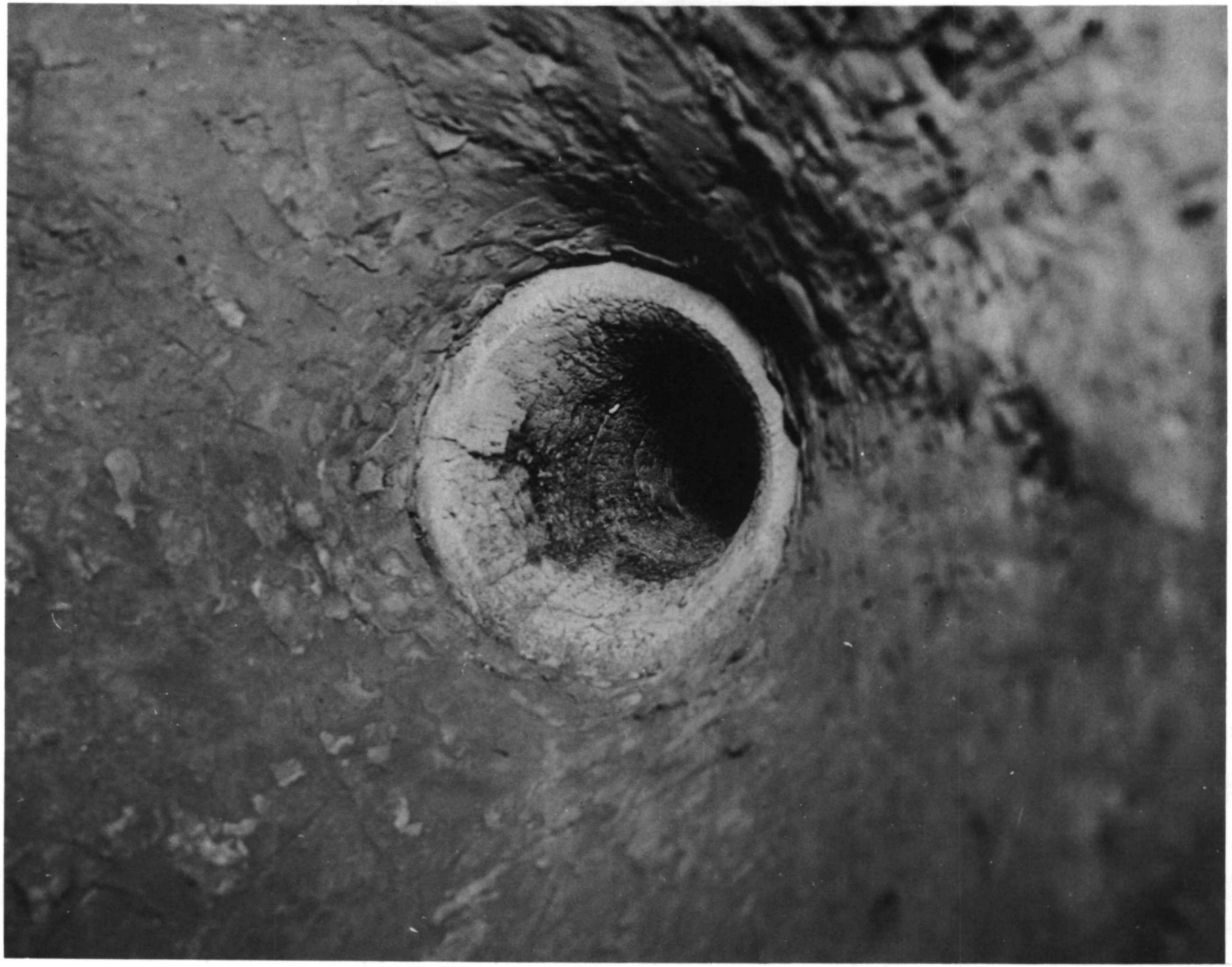


Figure III-37. - Entrance Section of CFA Nozzle



Figure III-38. - Complete Erosion of Plastonium Entrance, Nozzle S/N 009

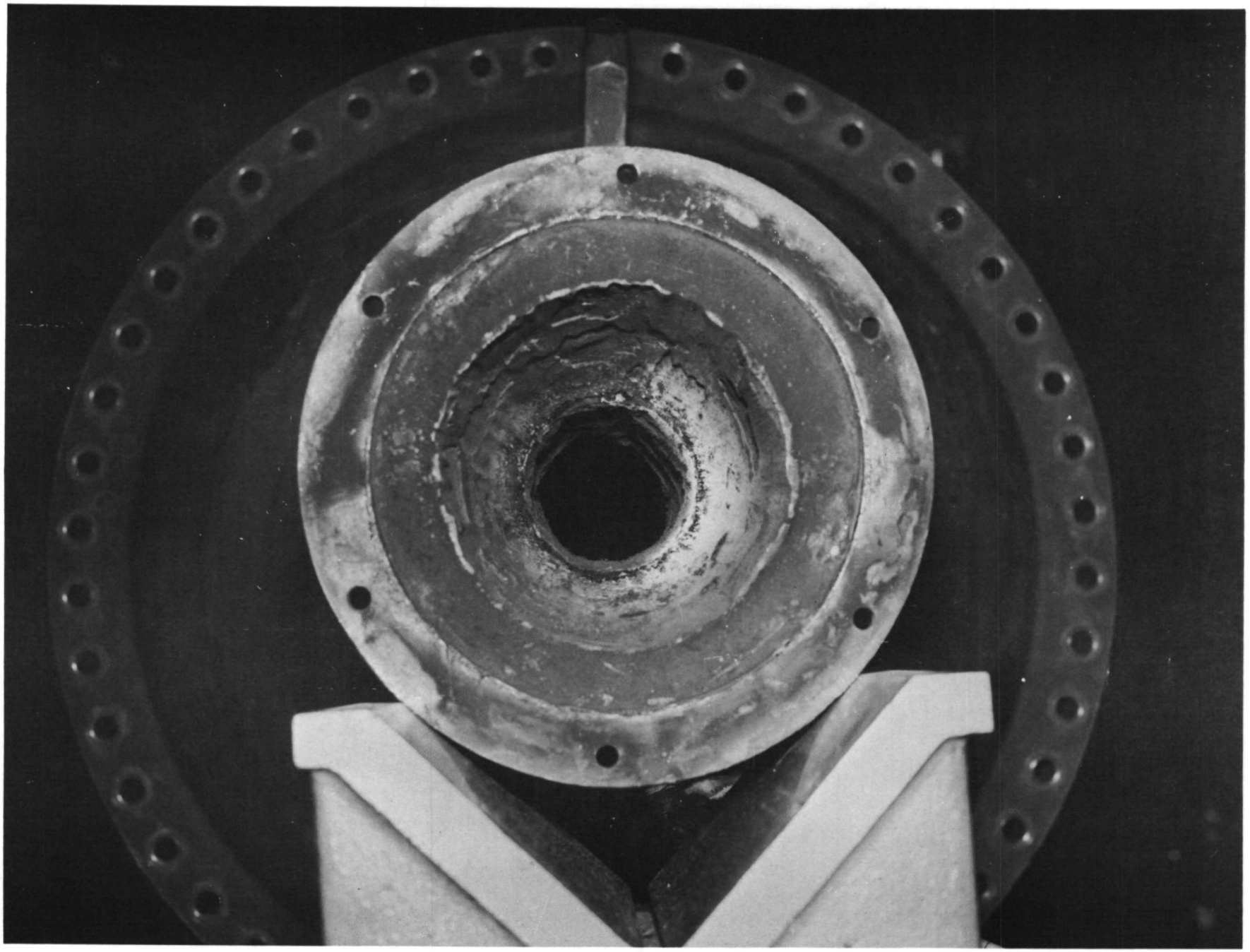


Figure III-39. - CA-8502 Carbon Fiber Throat, Nozzle S/N 019

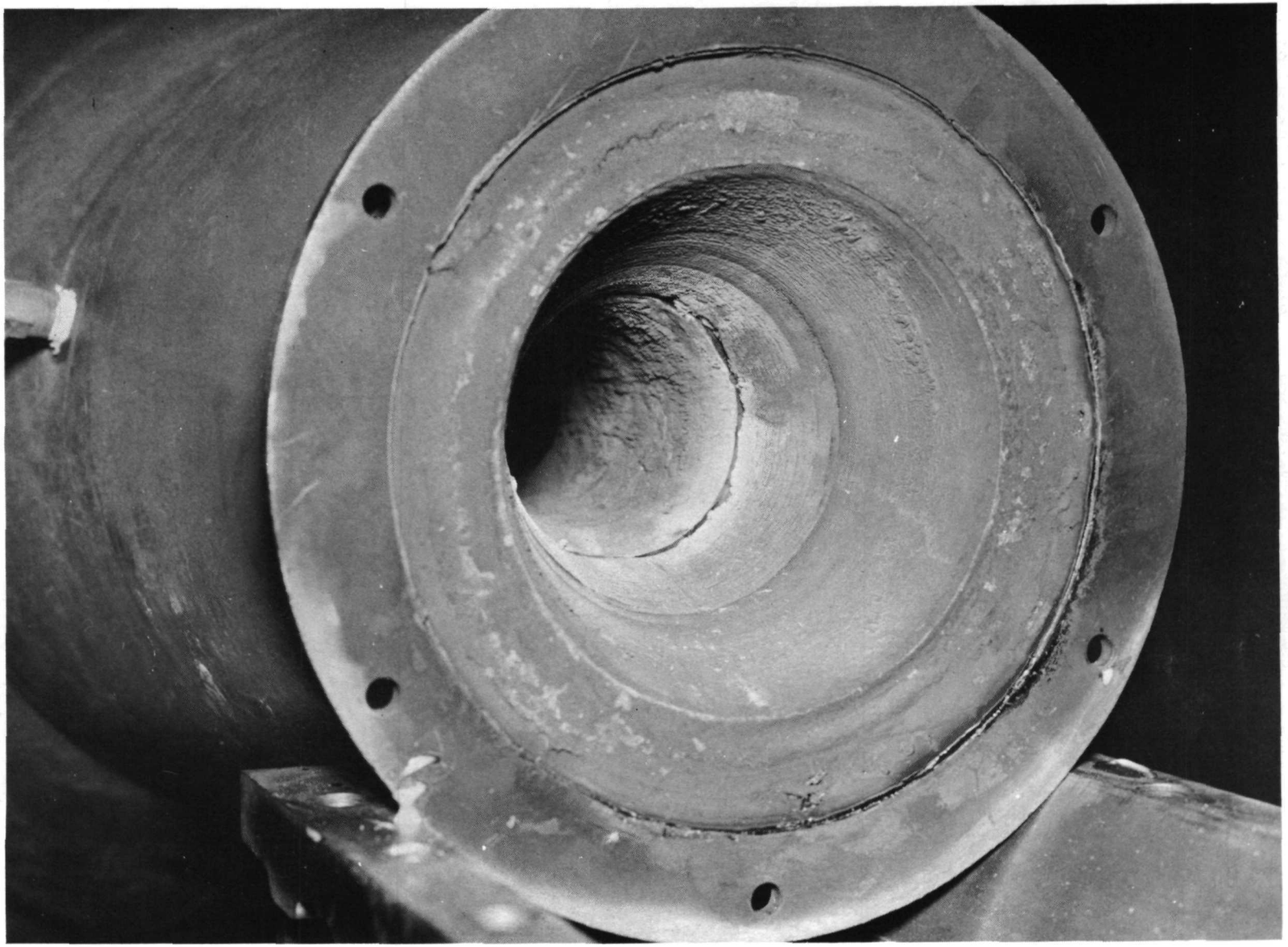


Figure III-40. - Extruded Carbon Fibertape Exit Cone, Nozzle S/N 008

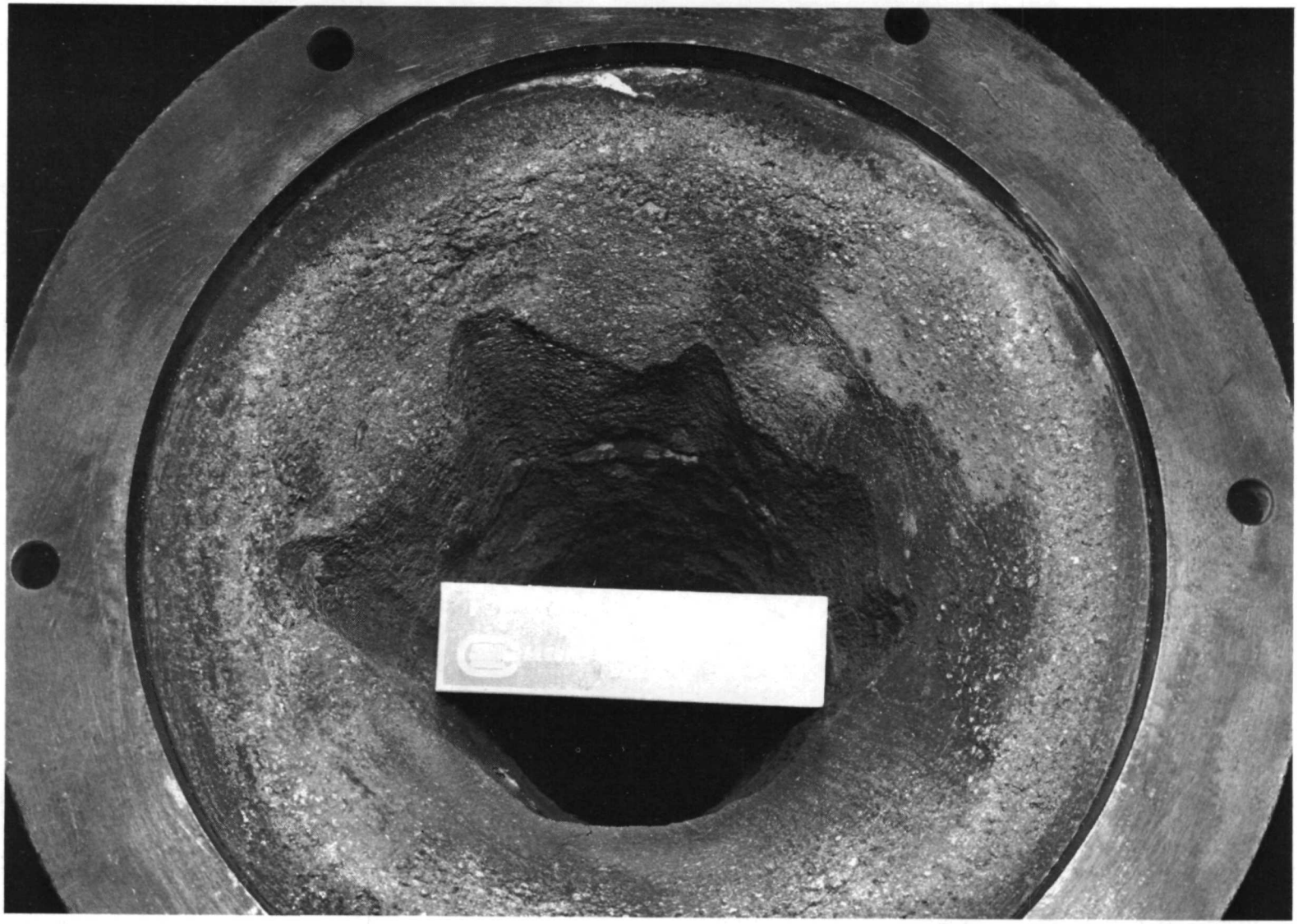


Figure III-41. - Castable Carbon Exit Cone, Nozzle S/N 004



Figure III-42. - Castable Carbon Plus Silica, Exit Cone, Nozzle S/N 005



Figure III-43. - Sprayed Carbon/Silica Exit Cone, Nozzle S/N 020

Cost Rating = Volume x Density x Material Cost

where: Volume is Eroded Area Rotated About Centroidal Radius

or: $\underbrace{(\text{Erosion Rate})\ (\text{Duration})}_{\text{Eroded Area}}\ \underbrace{(2\pi\left[\ r + \frac{\text{Erosion Rate x Duration}}{2}\right])}_{\text{Centroidal Radius}}$

For ARC 100

Erosion Rate (Table III-8) = 0.00337 in./sec at $\varepsilon = 3.25$

Density (Table III-13) = 0.056 lbs/cu in.

Material Cost (Table III-12) = \$0.45/lbm

Cost Rating ARC = $(0.00337 \times 40 \times 6.284)\ (3.25 + \frac{0.00337 \times 40}{2})\ (0.056)\ (0.45)$

= \$0.071

Calculation of Cost Rating of ARC 100
Entrance Section at Area Ratio 3.24

Figure III-44

IV. TASK II - SUBSCALE MOTOR EVALUATION

Task II was accomplished by designing, fabricating, and statically test firing ablative nozzle assemblies with 8.00-in. (20.32 cm) dia throats using the most cost effective materials of Task I. Five nozzle assemblies were fabricated, and the manufacturing characteristics and ablative performances were evaluated. Cost/performance assessments were made of the materials in these five nozzle assemblies, and a sixth assembly was fabricated from those materials considered to exhibit the optimum combination of characteristics for use in full-scale, 260-in. (6.6 m) dia motors.

A. NOZZLE DESIGN

1. Design

Six subscale nozzle assemblies were designed and fabricated. Two steel nozzle supports (shells) and one steel aft closure for attachment to Minuteman Wing II second-stage motors were supplied as GFM by NASA/Lewis Research Center in support of the nozzle manufacturing effort. The test nozzle was designed to meet the following requirements:

Throat Diameter	8.00 in. (20.32 cm)
Exit Cone Half Angle	17.5 deg (0.31 rad)
Exit Plane Area Ratio	8.0

Two basic designs were provided. The first (Figure IV-1a) was designed for fabricating by tape wrapping techniques; the second (Figure IV-1b) was designed for use with those materials that were fabricated by casting, molding, or spraying.

The contour of the convergent section of both nozzles was a 1.5 to 1 ellipse with a major diameter of 9.00 in. (22.86 cm) and a minor diameter of 6.00 in. (15.24 cm). The contour of the divergent section was 8.00 in. (20.32 cm) in dia, blending smoothly into the 35 degree (0.62 rad) conical angle of the exhaust skirt; the exit plane dia was 23.00 in. (58.42 cm), and the area ratio at the exit plane was 8.3.

Seven separate ablative components were included in the nozzle assembly, designated by the nomenclature indicated in Figure IV-1a. The approach, entrance, and inlet were designed for use without insulation and were identical in dimensions regardless of the fabrication technique. The ply orientation angles of the wrapped components were parallel-to-center line in the case of the approach and entrance, and 75 degrees (1.31 rad) in the case of the inlet. The throat liner was overlaid with insulative material. In the tape-wrapped version, the ply orientation was 45 degrees (0.78 rad) and the interface with the exit cone was at area ratio 1.44, whereas in the cast or molded version, the interface was at area ratio 1.24. The exit cone consisted of three separate liners overlaid with insulation material, and the interfaces between the liners occurred at area ratios 3.0 and 5.5. The exit cone liners, which were fabricated by wrapping, all had ply orientations parallel to the nozzle center line.

The steel nozzle shell and aft closure had been designed in a previous program[1] to provide a minimum margin of safety at yield of 1.25 at a chamber pressure of 540 psia. The maximum pressure that was anticipated from the use of the candidate materials was 530 psia.

2. Materials

The subscale nozzle assemblies represent an intermediate step between the evaluation of material properties and the utilization of the materials in full-scale 260-in. (6.6 m) dia motor nozzles. The materials considered for use were those whose cost and performance potential were most highly rated in Task I. The intent was to use the first five assemblies to evaluate the material potential, whereas the sixth nozzle assembly would use the materials determined to be optimum in cost, performance, and ease of fabrication during Task II.

Table IV-1 shows the matrix of materials evaluated in the first five subscale nozzle assemblies. Nozzles SN 001, 002, and 004 were fabricated chiefly of molding or casting compounds, whereas nozzles SN 003 and 005 were

fabricated almost entirely of fabric tapes and broadgoods. Examination of Table IV-1 reveals the presence of some materials that had not been evaluated in Task I. The materials UF1161 and UF1164, for example, are included in nozzle SN 001, and the materials 4C1402 and CA-2213M are included in nozzle SN 005.

UF1161 and UF1164 are graphite particle molding compounds developed to replace the LCCM 2626 and LCCM 4120 materials that were evaluated in Task I. The 4C1402 material is an analog of MXC-199 B1 in which the epoxy-novolac resin impregnant has been replaced by a MIL-R-9299 high temperature phenolic resin. The CA-2213M material is merely another canvas fabric prepreg similar to the 4K9502 and KF-418 materials examined in this and other programs.

B. FABRICATION OF FIRST FIVE SUBSCALE NOZZLES

1. Material Composition and Properties

The compositions of the casting and molding compounds and the properties of the prepregs used in fabricating the components of the first five subscale nozzles are listed in Tables IV-2 through -6. Table IV-2 shows the composition of the ARC-100 casting compound evaluated in nozzle SN 001. Although not indicated, the coke filler was graded with regard to particle size. Table IV-3 shows the composition of the castable DP5-161 resins with and without the silica fiber reinforcements. Table IV-4 shows the composition of the CFA material used in fabricating the components used in nozzle SN 004.

The molding compounds that were used to fabricate the nozzle components are shown in Table IV-5. As indicated in Section IV.A.2, the UF grades replaced the LCCM grades evaluated in Task I and the material prices are assumed to be the same. The 4C1402, supplied by Hexcel, contains Pluton B-1 fabric and phenolic resin and its price was quoted to be the same as that of the MXC-199 B-1 tape.

The properties of the fabric prepregs are shown in Table IV-6. The 4C1402 and CA-2213 materials were supplied in two grades, differing in resin content. The higher resin content material was used for hand lay-up of exit cone No. 5.

2. Fabrication of Nozzle Components

The fabrication parameters for the components of the first five subscale nozzles are shown in Tables IV-7 to -11. In those parts requiring insulation overwraps, 4K9502 canvas tape was applied and vacuum bag-cured. Since the flame liners that were insulated in most cases required curing at pressures greater than 100 psi (69 N/cm^2), the liners were fully cured prior to the application of the insulation.

In general, the fabrication procedures for the wrapped and molded components were conventional and no major problems occurred. All individual flame liners were radiographed subsequent to finish machining. In most cases the liners were clear of defects. The following paragraphs describe the handling characteristics of the materials that were used. Table IV-12 shows the cured composite properties that were measured on tag-ends of the billets.

a. ARC-100 Castable Carbon

Entrance section No. 1 was formed of four segments of ARC-100 castable carbon bonded with epoxy resin. The segments were fabricated by mixing the required amounts of coke filler, carbon fibers, and furane resin binder and pouring the mixture into sheet metal molds. These were loaded into an air oven and heated slowly to 340°F (440°K) to cure. The material was easy to handle. Internally, however, the segments were filled with voids varying in size up to 0.4 in. (10 mm) in greatest extent. Methods of removing the entrapped air that causes these voids are available and could be used if the presence of the voids is objectionable.

b. DC93-104

Approach No. 1 was cast from this two-part, carbon powder-filled silicone material. The two components were mixed and degassed in vacuum. The mixture was then injected into the mold cavity under pressure through a hollow lance whose tip was held below the surface of the flowing mixture to minimize air entrapment. Figure IV-2 shows the forward end of nozzle No. 001; the difference in void content between the DC93-104 approach and ARC-100 entrance is readily visible.

c. DP5-161 and DP5-161/Si

The basic material was prepared by mixing two pbw of the liquid resin with 0.8 pbw of the DP5-161 HC hardener. The DP5-161/Si material was prepared by adding 1 pbw of chopped silica fibers to every 5.6 pbw of resin-hardener mixture. Both the basic and reinforced material were cast into molds at ambient temperature and pressure and cured by holding at ambient conditions for 5 days. Both the basic and reinforced materials were filled with voids caused by entrapped air. These can be seen in Figure IV-3. Removal of the entrapped air is considered to be a minor problem.

d. CFA

In fabricating the components for nozzle No. 004, 55-lb (25 Kg) batches were prepared using a planetary mixer. Powders and liquids were mixed separately and then combined and turned for 30 minutes. The carbon fibers were added last and blended in by hand to minimize splitting and breakage.

The billets were prepared by pressing the CFA mixes between pairs of steel cylindrical containers using pressures between 30 to 50 psig (20.7 to 34.5 N/cm^2). Curing was effected by irradiating the surfaces of the larger (exterior) cylinders with a ring of quartz lamps. Pressure was maintained continuously during 4 hours of heat up and 4 hours at a maximum temperature of 150°C

(302°F) measured at the exterior surfaces. The internal wall temperature was 110°C (230°F). The containers were allowed to cool and the billets were pressed out and postcured in an air oven for 16 hours at 150°C. Heat up to 150°C required 8 hours; cool-down required 6 hours.

All components contained irregular voids that had the appearance of tears and fissures. The exposed fibers appeared to be dry, as if the quantity of resin was not sufficient for complete wetting, or as if mixing was not complete. Figure IV-4 illustrates the worst surface appearance that was observed in the machined components.

e. UF1161 and UF1164

UF1161 is a dry, granular molding compound. No special precautions were required during the fabrication of the nozzle components employing this material and its handling characteristics appeared to be normal.

The UF1164 appeared to have a high loading of fibers. The resin content was also high (on the order of 35%). The exit cone "B" section made from UF1164 was fabricated by loading the as-received compound into the mold and tamping it to fill the cavity. After tamping, the surface of the UF1164 was covered with several layers of porous (bleeder) cloth, the mold was enclosed in a plastic bag, and the assembly was held at ambient temperature over-night at a vacuum pressure of 26 in. Hg (8.8 N/cm^2). The following morning the bagged assembly was inserted into an autoclave and heated to 100°F (38°C) for 1-1/2 hr while maintaining the vacuum inside the bag. Then the autoclave was pressurized to 200 psi (138 N/cm^2), heated stepwise to 310°F (164°C), and held at that temperature for 12 hours.

The surface appearance of both UF grades was dense and fine-grained after machining and both were free of internal voids. The UF1164 had a pepper-and-salt surface that gave it a greyish cast; the UF1161 was almost black. Figure IV-5 shows the two materials in nozzle No. 001 prior to test.

f. MXC-12449

MXC-12449 was originally selected for use because it was amenable to on-site fabrication. The carbon fibers and epoxidized resins were to be mixed and then extruded onto a rotating mandrel, after which the coated mandrel was to be covered with a plastic bag and inserted into an air oven for curing of the ablative liner. This method was not perfected for either the 1.8 in. dia or 8.0 in. dia throat nozzles fabricated in this program. Instead, the material for use in the 8.0 in. dia throat nozzle was supplied as a pre-compacted paper. The carbon fibers for the specific lot of material used for fabricating exit cone "B" section No. 1 were purchased from Kureha Chemical Industry Company, Ltd. (Tokyo, Japan) and were generated from a spun-pitch precursor. (Domestic carbon fibers were generated from synthetic precursors, mostly rayon).

The paper was slit into 7 and 8 in. (17.8 and 20.3 cm) wide tapes and wrapped over a steel mandrel at a temperature of 180°F (82°C) and a roller force of 100 lbf/in. (175 N/cm) of width. The as-wrapped density was 0.75 g/cc, approximately 55% of the cured-composite density (1.32 g/cc) that was measured in the 1.8-in. dia throat components of Task I of this present program. During the vacuum-bag curing, the material sprang back since the as-cured density was lower than the as-wrapped density (see Table IV-12).

In the case of exit cone "B" section No. 003, the spring-back produced heavy ridges and wrinkles (see Figure IV-6). Surface repairs were effected by filling the depressions between the ridges with a mixture of 47.5% by weight of carbon powder, 47.5% Epon 821*, and 5% Diethylamine Triamine (DTA). After the insulation overwraps had been applied to the exit cone and cured, delaminations were observed in the "B" section. These were determined by radiographic inspection to be as deep as 50% of the liner thickness. An epoxy-novolac resin filler** was vacuum-impregnated into the delaminations and cured locally with heat lamps for 8 minutes at 290°F (143°C) after holding the entire exit

* Shell Chemical Company.
** HT-7998, Fiberite Corp.

cone for 12 hours at 140°F (60°C). The filled delaminations are shown in Figure IV-7.

The low density MXC-12449 entrance section (No. 002) was modified by removing the forward 2 in. portion and replacing it with a molded UF1161 nose cap, as shown in Figure IV-8. Additional MXC-12449 prepreg material was laid up and cured at 200 psig (136 N/cm^2) to an as-cured density of 1.24 g/cc. This provided enough cured composite for a 60 degree (1.05 rad) segment, which was bonded into the original low-density MXC-12449 ring and against the UF1161 nose cap. Figure IV-9 is a close-up view of the finished entrance section showing wrinkles in the low density portion of the MXC-12449.

g. Hand Lay-Up Materials

The exit cone for nozzle SN 005 was fabricated by use of a hand lay-up technique designated as "shingle-lap." With this technique, patterns of the ablative prepreg material are cut from broadgoods and arranged over a male mold to form a shingled construction. The patterns overlap each other in the circumferential direction; in the axial direction, the patterns all originate at the forward end of the exit cone and only the ends of the patterns are exposed to the propellant gas flow. Curing is to be effected by vacuum bag pressures and heating is to be accomplished in an air recirculating oven, so that exit cone fabrication can be performed in the final motor assembly area.

In components fabricated by this technique, the most critical area with regard to surface erosion is the forward corner, where the shingle originates and where the fabric along the flame surface has little or no length to resist stresses in the axial direction. In the present nozzle, the solution to this problem was the use of a molded insert. This molding of 4C1402 carbon/phenolic is designated as the "A" Section in Figure IV-10.

A sheet metal form was used in fabricating the exit cone. The outer surfaces were sprayed with a mold release material and buffed. The

machined "A" section was slipped over the form and accurately positioned. Then the exterior surface of the molding was coated with phenolic resin. The cut patterns of the "B" section were laid over the molding one at a time, and the fabric rolled against the form to squeeze the resin toward the edges of the pattern. Each individual pattern was lapped over the preceding one, using a hot air gun to tack the patterns. After all patterns had been rolled out and tacked together the fabric covered surface was covered with several layers of bleeder cloth and the entire subassembly enclosed in an impervious plastic bag. A vacuum was drawn, then the bagged subassembly was loaded into an electrically heated, recirculating air oven for curing.

In the full-scale nozzle assembly, the structural overwrap would have been applied directly to the exterior surfaces as part of the shingle. In this component, because of the necessity of assembling into the steel nozzle shell, the exterior surface was built up with parallel-to-surface wraps of canvas tape prepreg and the entire assembly was again enclosed in a bag, a vacuum was then drawn and the bag was placed in an air oven. The finished exit cone is shown assembled into the steel nozzle shell in Figure IV-11. The alternating grey and while plies midway along the cone result from an attempt to decrease the erosion step between carbon and canvas by interleaving the two materials.

Both the 4C1402 carbon and CA-2213 canvas-fabric prepregs were found to be unusable in the as-received condition. An additional 10% of resin solids was sprayed onto the fabric prior to cutting the patterns and subsequent lay-up. The prepreg properties reported in Table IV-6 are estimates based on this addition of resin.

3. Assembly

Nozzle assemblies were prepared for evaluation by bonding the fabricated components to the steel shells using a room-temperature curing, two-part epoxy adhesive. Interfaces between adjacent nozzle components were filled with a room-temperature vulcanizing silicone elastomer.

The aft closure was prepared for the first evaluation test firing by cleaning and priming the internal surface and bonding to it the required amount of IBT-100 insulation (Specification AGC-36520). This was troweled in and swept to contour prior to bonding. After each test the fired closure was prepared for re-use by removing the char from the surface of the insulation and applying sufficient IBT-100 material to restore the initial contour.

The nozzle assembly and aft closure were bolted together and installed on the test motors. These were then transported from the assembly area to the test stand.

C. STATIC TEST OF FIRST FIVE SUBSCALE NOZZLES

The nozzle-closure-motor assemblies were tested in the horizontal position at the Aerojet Solid Propulsion Company test facilities in Sacramento, California. Axial thrust and forward head chamber pressure were measured during test. The initial nozzle throat and exit plane diameters were measured at 45-degree (0.79 rad) intervals.

Motion picture coverage with both black-and-white and color film was provided during test. Figures IV-12 through -14 show the motor from the same relative positions as the motion picture cameras. After firing, the motors were quenched with gaseous nitrogen and the nozzles were visually examined to determine the condition of the exit cone, throat, and inlet liners. The nozzle throat and exit-plane diameters were again measured at the same locations as before and photographs of the exit cone were taken. The fired motors were removed from the test stand, loaded into the transporters, and returned to the motor assembly area for removal of the closure and nozzle and eventual disassembly of the fired nozzle components.

The average web pressures and the web times of the first five subscale motor tests are listed in Table IV-13. The average web pressure ranged from 427

to 479.5 psia (294.5 to 330.5 N/cm^2), and the spread in web time was from 57.1 to 59.6 sec. The pressure-time envelope for the first five motor tests is shown in Figure IV-15.

D. PERFORMANCE ANALYSIS OF FIRST FIVE SUBSCALE NOZZLES

The fired nozzle assemblies were removed from the closure, and photographs were taken of the sections that were submerged during test. In addition, close-up photographs were taken of any unusual features. The nozzle assembly was then placed in an air oven and heated to 500°F (260°C) overnight to destroy the epoxy bond between the nozzle shell and ablative components. Unfortunately, the canvas overwrap insulations charred and burned on the first two nozzle assemblies that were heated at 500°F and valuable dimensional information was lost. Accordingly, the temperature was lowered to 450°F (232°C).

The disassembled nozzle components were sectioned axially at zero, 135, and 240 degrees (zero, 2.4 and 4.2 rad), corresponding to a propellant grain valley, a peak, and an intermediate point. These sections were smoothed carefully to show the char depths and the sections were keyed against accurate replicas of the original nozzle designs. Erosion depths were traced and the char depths were measured and plotted on the nozzle cross-sections. Figures IV-16 through -30 are plots of the erosion and char depths in the first five nozzle assemblies. The erosion and char depths were measured from the original flame surfaces and tabulated (Tables IV-14 through -18).

The following paragraphs compare materials in each of the first five subscale nozzles one to another with regard to performance and cost. To place the material performance on an equal basis, the actual erosion and char measurements were converted to those that would occur at a common value of 600 psia chamber pressure. This was accomplished by the use of the following relationship:

$$\frac{A^\circ_{600}}{A^\circ_i} = \left(\frac{600}{P_i}\right)^{0.8}$$

where A° is the regression or char depth and the subscript "i" refers to the actual measurements in the subscale motor tests. Erosion and char rates were calculated on the basis of a web action time of 57.5 sec. These "normalized" rates are shown in Tables IV-19 through -25.

1. Approach

Of the materials evaluated in the approach sections of the first five test nozzle assemblies, three were approximately equal in performance. As indicated in Table IV-19, no measurable erosion was observed for the DP5-161 castable resin and only minor amounts for the DC93-104 and CFA materials. After test, the heat-affected surface layers of these materials were visibly expanded and there were numerous checks and fissures. The three materials were visibly free of spallation, although posttest handling removed the char from the surface of the DP5-161 material. Figures IV-31, -32, and -33 show the surface appearance of the DP5-161, DC93-104, and CFA approach sections, respectively. The DC93-104 appeared to have the densest, most adherent char.

The two canvas-duck approach sections, which were fabricated to lower than the normal density of 84.2 lbm/cu ft (1.35 gm/cc), exhibited an erosion rate of between 7 and 8 mils/sec (0.18 and 0.20 mm/sec), slightly higher than that observed in previous programs[1, 2]. The charring rate of 13 to 18 mils/sec (0.33 to 0.45 mm/sec) was appreciably higher than observed previously.

2. Entrance

The normalized regression and char rates of the entrance sections of the first five nozzle assemblies are listed in Table IV-20. Examination of the values indicates that two distinct zones of performance were present. The first extends aft and outboard from the forward end of the entrance for a distance of approximately 1 in. to Station -3.6. This is a region of particle impingement and the rate of material removal from the flame surface is between three and 10 times greater than it is aft of this region. Aft of Station -3.6, the regression rate for the acceptably performing materials decreases to less than 2 mils/sec (0.05 mm/sec).

The average total erosion of the first five entrance sections at the forward end was as follows:

Material	Avg Erosion, in. (mm)	
UF1161 (2)	0.282	(7.16)
UF1161 (3)	0.380	(9.65)
4C 1402	0.445	(11.30)
ARC-100	0.548	(13.92)
CFA	0.666	(16.92)

The UF1161 exhibited the best performance in the nose region. The measured erosion rate at the forward end was 6.2 and 8.1 mils/sec (0.16 and 0.21 mm/sec), compared with 11.4 mils/sec (0.29 mm/sec) for the ARC-100 and 14.15 mils/sec (0.36 mm/sec) for the CFA. The wrapped Pluton B-1/phenolic 4C 1402 material experienced an erosion rate of 10.46 mils/sec (0.27 mm/sec) and a charring rate almost double that.

Aft of Station -3.6, the UF1161 and ARC-100 carbonaceous materials were equal in erosion rate, about half that of the CFA and the 4C 1402. The extruded carbon fiber-tape material, MXC-12449, displayed erosion rates between 4.9 and 11.56 mils/sec (0.12 and 0.29 mm/sec) as a result of the extremely low as-fabricated density. The charring rate was also higher than is normal for this type of composite.

3. Inlet

A carbon fiber/phenolic molding compound, CA-8502, exhibited the least amount of erosion at the forward end of the inlet section. The erosion depths of the first five inlets are shown below:

Material	Avg Erosion, in. (mm)	
CA-8502	0.214	(5.44)
4C 1402	0.449	(11.40)
MXC-199 B-1	0.452	(11.48)
UF-1161	0.610	(15.49)
CFA	0.661	(16.79)

The erosion rate of the CA-8502 (from Table IV-21) was measured at 4.7 mils/sec (0.12 mm/sec), an exceptionally low value at this location. The tape-wrapped inlet No. 3, fabricated from MXC-199 B-1, eroded at the forward end at the rate of 9.65 mils/sec (0.25 mm/sec). The molded 4C 1402 material, also a Pluton B-1 reinforced composite, eroded at the rate of 10.25 mils/sec (0.26 mm/sec). The erosion rates of the UF1161 and CFA low cost carbonaceous materials were both approximately the same at the forward end [14 mils/sec (0.36 mm/sec)].

The uniformity of material removal varied greatly from one material to another. The CA-8502 exhibited uniform erosion over the flame surface, as shown in Figure IV-34. Some spalling was observed on the surface of the UF1161 inlet (Figure IV-35) and scouring on the surface of the CFA inlet (Figure IV-36).

4. Throat

The average total erosion of the first five throat inserts at the minimum diameter (Station 0) were as follows:

Material	Avg Erosion, in. (mm)	
4C 1686	0.531	(13.49)
MXC-199 B-1	0.581	(14.76)
CFA	0.605	(15.37)
CA-8502	0.677	(17.20)
4C 1402	0.895	(22.73)

The normalized erosion rate of the molded 4C 1686 carbon/polyphenylene composite, as abstracted from Table IV-22, was 10.50 mils/sec (0.27 mm/sec); that of the tape wrapped MXC-199 B-1 Pluton B-1/epoxy novolac was 12.58mils/sec (0.32 mm/sec). The CFA throat exhibited a normalized erosion rate of 13.09 mils/sec (0.322 mm/sec); the molded CA-8502 carbon fiber/phenolic exhibited a disappointing 15.26 mils/sec (0.39 mm/sec); and the molded 4C 1402 Pluton B-1/phenolic showed a disastrous 20.41 mils/sec (0.52 mm/sec).

The most uniformly eroding throat insert was the tape-wrapped MXC-199 B-1, in which the total spread between high and low diameters was 0.064 in. (1.63 mm). The molded CA-8502 throat insert was almost as uniform, its spread in diameters measuring 0.071 in. (1.80 mm). The least uniform in erosion was the 4C 1402 molded material, which had a total spread of 0.573 in. (14.55 mm). This large spread was caused by gouges, several of which are visible in Figure IV-37; the deepest of these gouges was approximately 0.4 in. (10 mm). While determining reasons for the presence of gouges was not within the scope of this particular effort, they appear to be associated with the high resin content ($\sim$ 51%) combined with included water from the phenol-formaldehyde condensation reaction. The MSC-199 B-1 also contains approximately 50% resin, but the resin in this case is an epoxy novolac, which cures without the formation of water.

5. Exit Cone "A" Section

None of the materials used in the exit cone "A" section was completely satisfactory. All of them, with the exception of the tape-wrapped MXC-199 B-1 flame liner used in nozzle 3 exhibited some spalling and/or gouging Figures IV-38 through IV-42 show the five exit cones after the evaluation firings. For UF1161 (Figure IV-38), spalling was of a relatively minor nature confined to a band about 1 in. wide and 20 degrees of arc. The CA-8502 used in "A" section No. 2 also exhibited minor spalling (Figure IV-39), whereas the 4C 1402 used in "A" section No. 5 was deeply gouged (Figure IV-40). The CFA used in "A" section No. 4 was scoured in the same manner as the CFA throat (Figure IV-41). The uniform erosion of the surface of the tape-wrapped "A" section, as shown in Figure IV-42, contrasts with the severe erosion in the remainder of the exit cone.

The normalized erosion rates of the "A" section materials, with the exception of the UF1161, are shown in Table IV-23. No measurements could be made of the UF1161 because the canvas overwrap insulation was consumed during the disassembly operations and the flame liner was cracked and broken. The range of measured values [5.83 to 11.05 mils/sec (0.148 to 0.281 mm/sec)] at Station +4.0 is an indication of the inadequate performance that was observed.

6. Exit Cone "B" Section

The normalized erosion and char rates of the materials evaluated in the "B" sections of the first five nozzle assemblies are shown in Table IV-24. Only one of the five materials (MXC-12449) was unsatisfactory in performance; this was a result of the very low density, the severity of the wrinkles that occurred during fabrication, and the use of carbon-epoxy filler to produce an initially smooth surface. The MXC-12449 "B" section after firing is shown in Figure IV-42.

While no measurements could be made of the erosion of the UF1164 used in "B" section No. 1 because of the loss of the canvas overwrap, the visual examination after firing indicates that, subjectively, the material is at least equal in performance to the CFA and DP5-161/Si materials and was not subject to spallation or grooving at this location. The posttest appearance of the UF1164 is shown in Figure IV-43.

7. Exit Cone "C" Section

With the exception of the low-density, tape-wrapped canvas duck used in nozzle No. 3, the materials used in the "C" section performed acceptably. Table IV-25 shows the normalized erosion and char rates. The canvas materials (4K9502 and CA-2213) both exhibited surface regression; the castable resin (DP5-161/Si) and the low cost carbonaceous material (CFA) exhibited negative surface regression because of the expansion of the decomposed surface layer.

E. COST/PERFORMANCE EFFECTIVENESS

1. Baseline Motor and Nozzle

The materials that were evaluated in the first five test nozzles are intended for use in the nozzle assembly of a full-scale, 260-in. (6.6 m) dia solid rocket motor. Their relative costs and performances, therefore, should be compared with some baseline nozzle design to determine whether their use would

prove economical. The baseline nozzle selected for comparative purposes is a low-cost design, fabricated from carbon fabric and cotton canvas reinforced tapes[8].

The low-cost nozzle design is based on the 260-FL motor defined in the Douglas 260/SIVB Study[9]. The motor contained 3.4 million lbm (1.54 x 10^6 kg) of propellant and its operating characteristics were as follows:

Action Time	147.5 sec
MEOP	764 psia (526 N/cm^2)
Thrust, Avg (web)	6.34 x 10^6 lbf (28.2 NM)
Flame Temperature	5742°F (at 1000 psia)
	3440K (at 689 N/cm^2)

The baseline nozzle design is shown in Figure IV-44. The nozzle is of the submerged type, using flexible seals for thrust vector control. The throat diameter is 89.1 in. (2.26 m). The nose and approach section have a 3:2 elliptical contour with the major axis equal to 75% of the throat radius and the leading edge located at an area ratio of 1.81:1. This configuration provides a streamlined, gas-flow transition into the throat and has been shown by analysis and test to be a very efficient design. The two-piece exit cone has a bell-shaped contour with an exit plane diameter of 267.30 in. (6.78 m) and an overall length of 247.16 in. (6.27 m). The bell shape results in economy of material usage over that of a conventional conical exit cone of equivalent thrust coefficient.

A wrapped carbon fabric/phenolic composite forming the throat of the baseline nozzle assembly attached to the 260/SIVB motor would have a predicted erosion rate of 6.0 mils/sec (0.015 cm/sec). Trajectory analyses of the above motor[8] indicate that it would be capable of inserting a 94,675 lbm (43,030 Kg) payload into a 105 nautical mile (195 Km) circular earth orbit. The use of throat materials with higher erosion rates would decrease the payload that could be inserted into orbit. As Table IV-26 indicates, this same motor with a nozzle throat eroding at the rate of 15 mils/sec (0.038 cm/sec) would have a payload capability of 92,451 lbm (42,023 Kg), which is 2224 lbm (1007 Kg) less than that of the baseline. The trajectory analyses also established the increase in motor weight required to achieve the baseline vehicle payload with the higher throat erosion rates. These

increases in motor weight together with the corresponding cost increases are shown in Table IV-27. The cost figures provide a basis for judging the economic worth of the low-cost nozzle materials, since any savings realized through the use of the low-cost material must be traded against the added cost resulting from increased motor size.

2. Evaluation of Cost and Performance

To evaluate the cost and performance factors of the low-cost materials, studies were conducted in which the throat of the full-scale nozzle employed the materials of the first five subscale throats. The erosion rates of these materials (as determined by heat transfer analyses scaled from the respective test runs) are shown in Table IV-28 together with the increased motor cost necessary to maintain full payload capability in orbit.

The overall savings from the use of these throat materials is the sum of both materials savings and fabrication savings. In the case of the MXC-199 B-1 material, only the material savings can be used in the trade study since it would be fabricated by wrapping identical to the baseline carbon tape material. As shown in Table IV-29, the material savings resulting from the use of MXC-199 B-1 bias tape at a cost of $15.40 per lbm ($33.88 per Kg), as compared with standard carbon bias tape at a cost of $21.50 per lbm ($47.30 per Kg), is $10,047. There are no direct labor or tooling savings, but there would be an administrative saving of $854 because of the decreased material cost. Also, there would be a decreased profit of $1090. Opposed to these savings (total, $11,991) there would be an added motor cost of $49,900 because of the increased erosion rate of the MXC-199 B-1 composite compared with that of the baseline material. Consequently, the use of the lower cost tape material would actually result in a net loss of $37,909 and there would be no incentive to use the MXC-199 B-1 tape in the throat insert.

In comparing the cost and performance of the molded throat materials with the baseline, fabrication and tooling costs must be entered into

the comparison. Table IV-30 shows the savings that can be achieved when the 260-FL throat is molded. The method of computing costs is described below:

a. Material

The material costs for the baseline throat were derived from Table 36 of Reference (8), wherein it was calculated that 1647 lbm (749 Kg) of carbon fabric at $21.50 per lbm ($47.30 per Kg) and 567 lbm (257 Kg) of canvas at $1.80 per lbm ($3.96 per Kg) were required to fabricate the throat insert with a finished weight of 1357 lbm (616 Kg) of carbon and 515 lbm (234 Kg) of canvas. In calculating the weights of the molded billets, approximately 10% overage was added to the weight of the finished throat liner to yield a base weight of 1500 lbm (682 Kg) for a molded carbon fabric throat. This base weight was then adjusted to reflect the differences in specific gravity between the candidate materials (1.67 for UF1161, 1.57 for CFA, and 1.42 for all others) and the baseline composite (1.40). Each of the molded throat liners was overwrapped with 441 lbm (200 Kg) of canvas tape, vacuum-bag-cured to a density of 65.5 lbm/ cu ft (1.05 gm/ cu cm). The material costs for the candidate throats were calculated from the cost data listed in Tables III-11 and -12 (the cost of UF1161 molding compound was considered to be equivalent to LCCM-2626).

b. Labor

The baseline 260-FL nozzle is tape-wrapped throughout. Thus, in estimating the labor cost of the baseline throat insert, the total labor time for the entire nozzle (9488 hr according to Reference 8) was prorated by the ratio of the throat billet weight (2214 lbm/1000 Kg) divided by the total nozzle billet weight, (6598 lbm/2914 Kg). This yielded a total time of 3183 hr required to fabricate the baseline throat insert. These hours were costed at the rate of $5.87 each. Direct labor overhead (DLO) was calculated to be 174%.

In calculating labor costs for the molded throats, it was estimated that half of the 3183 hr required to fabricate the baseline throat insert were required for machining and the remainder for wrapping and curing.

For the molded throats, the maching time was reduced by approximately 20% (to 1287 hr) because of the decreased billet volume, The wrapping time was eliminated except for 300 hr required for the canvas overwrap. The labor required for molding and monitoring the cure cycle was estimated to be 450 hr. Total labor requirements for each of the molded throats were estimated to be 2037 hr.

c. Tooling

Tooling for fabricating the baseline throat has been estimated (see Table IV-31) for a production rate of six nozzles per year for 5 years. The prorated cost of tooling for the baseline throat is $1541 per unit. Tooling cost for the molded throats is less than half that of the baseline throat and the prorated tooling cost is $745 per unit.

d. Administrative Costs and Profits

General and administrative costs on materials, labor, and tooling were figured at 8.5%. The profit margin was figured at 10%. These values are considered to be standard for fabricators of ablative parts.

e. Realized Net Savings

Fabricating costs, general and administrative expenses, and profit were added to determine the unit throat cost. To this was added the increased motor cost resulting from the increased erosion rate of the candidate materials (from Table IV-28). The realized net savings was the difference between the total cost of the baseline nozzle and that of each of the candidate nozzles. Three of the candidate throat materials showed net savings, ranging from $3664 for a molded CFA throat, to $10,332 for a molded 4C 1486 throat, to $31,226 for a molded UF1161 throat.

F. OPTIMUM DESIGN SUBSCALE NOZZLE

1. Design of Nozzle No. 006

Figure IV-44 shows the design details of subscale nozzle No. 6. The low-cost carbonaceous material (UF1161) was selected for use in the throat and throat entrance sections because of its cost and performance advantages over the other candidate materials. Castable carbon (ARC-100) was selected for the submerged outboard liners because of its outstandingly low cost. The exit cone is of shingle-lap construction suitable for build-up at the motor assembly site. This design features a segmented construction since the full-scale components would be too large to be molded economically as one-piece liners. A brief description of the design follows:

a. Throat

The throat flame liner is a one-piece molding of UF1161 low-cost carbonaceous material. The desired density is 1.65 g/cu cm (103 lbm/cu ft). In configuration it is identical with the molded inserts fabricated for the first five throats except that the liner thickness has been increased. The flame liner is overwrapped with canvas tape cured at 300°F (149°C) in a vacuum bag at a mimimum pressure of 27 in. (685 mm) Hg.

b. Nosecap

The nosecap is a newly designed component that combines the former inlet section with the forward 1-in. (25.4 mm) portion of the former entrance section. It is molded from UF1161 material in four circumferential segments. The desired density is the same as that of the throat flame liner.

c. Entrance

As noted above, the forward 1-in. (25.4 mm) portion of the entrance section has been removed to form part of the nosecap. The new entrance

section, which is in the submerged outboard portion of the nozzle, is an eight-segment part fabricated from ARC-100 castable carbon. The desired density is 1.50 g/cu cm (93.6 lbm/cu ft).

d. Approach

The approach section for nozzle No. 6 is unchanged in size and configuration from those used in the first five nozzles. Eight segments of ARC-100 castable carbon are machined and bonded together to form the complete approach section. The desired density is 1.50 g/cu cm (93.6 lbm/cu ft).

e. Exit Cone

The exit cone is designed to be constructed as a shingle-lap assembly, employing a molded "A" section of UF1164 and carbon and canvas broadgoods in the "B" and "C" sections. Since the aim is to assemble or fabricate the aft exit cone at the motor assembly site, it has been designed for segmented construction to be cured by autoclave techniques. Eight segments are bonded together and overwrapped with glass fabric to form the exit cone. The "A" section has only half as many segments as the remainder of the cone and the joints are offset from those in the aft portion.

f. Structural Overwrap

The exit cone is overwrapped with glass fabric impregnated with polyester resin, catalyzed to cure at room temperature. This structure will simulate the design proposed for the full-scale nozzle. Since the liner thickness is designed for a backside temperature of 100°F (38°C), no loss of strength is anticipated in the polyester composite. The use of catalyzed resin eliminates the need for a large pressure vessel for curing the structural overwrap.

2. Fabrication

The goal in fabricating the components for subscale nozzle No. 006 was to simulate as closely as possible the techniques and procedures that would be used in the full-scale nozzle. The fabrication procedures for the nozzle components are given in Table IV-32 and indicate that this goal was met. Because of the size of the components, it was more economical to initiate the fabrication sequence with large one-piece billets rather than with the segments. These one-piece billets were machined, slit into segments, and then rejoined by adhesive pressure bonding.

All subscale components were fabricated without difficulty with the exception of the castable carbon (ARC-100) approach and entrance sections. The approach section contained numerous, large circumferential tears, and the entrance section cracked during machining. The tears in the approach section did not affect the subsequent fabrication. The cracks in the entrance section were repaired by coating the crack surfaces with Ironsides DP5-160 resin and rejoining the cracked pieces under pressure. The circumferential tears in the approach segments and the repairs in the entrance segments are shown in Figures IV-45 and IV-46. Several reasons can be advanced for the cracking in the ARC-100 material. These are:

a. Lack of fiber reinforcement.

b. Lack of, or improper, mold release coating.

c. Insufficient removal of entrapped air at room temperature prior to elevated temperature curing.

Remedial actions for the insufficient dwell time and lack of fiber reinforcement are self-evident. The size and extent of the tears can be greatly reduced by mixing and casting under vacuum conditions and using tamping or vibratory movements in the mold to help remove the entrapped gases.

The properties of the cured composites are listed in Table IV-33. The properties are equivalent to those of the same materials used in the previous subscale nozzle components of this program except that the ARC-100 exhibited a higher specific gravity than in previous measurements (1.64 vs 1.50). The nozzle assembly is shown in Figures IV-45 through IV-49. The bonds between segments may be noted throughout the photographs.

3. Static Test

The nozzle assembly and aft closure were bolted together, installed on one of the Wing II Minuteman second-stage test motors and tested in the horizontal position at the Aerojet Solid Propulsion Company's facility in Sacramento, California. Axial thrust and chamber pressure were measured in the same way as in the first five subscale nozzle assemblies and motion picture coverage was provided as before.

The average web pressure during the test of nozzle No. 006 was 433 psia (299 N/cm^2), the maximum pressure was 509 psia (351 N/cm^2), and the web action time was 58.1 sec. While these values fall within the pressure-time envelope of the first five subscale nozzle test firings, the pressures were lower than anticipated and are indicative of excessive throat recession.

4. Performance Analysis

Visual examination of the nozzle after firing revealed severe and irregular spallation in the molded, graphite-particle throat insert and that all "A" section exit-cone segments had been ejected. No identifiable traces of these segments could be found. Photographs of the exit cone were taken immediately after the static test firing. Additional photographs of the forward end of the nozzle were taken after removal of the nozzle assembly from the aft closure, at which time it was noted that all nosecap segments and two entrance segments had separated from the nozzle shell. These segments were collected intact.

The nozzle assembly was heated to 425°F (218°C) and held overnight (15 hr) to destroy the epoxy bonds. The disassembled nozzle components were then sectioned axially at the 0-, 135-, and 240-degree locations and examined for depth of erosion. No char measurements were made; because of the preponderance of castable carbon and graphite particle materials, a specific char line was not exhibited. Erosion depths are tabulated in Table IV-34 and are plotted in Figures IV-50, IV-51 and IV-52. The following paragraphs describe the results of the performance analysis and their implications for full scale nozzles.

a. Throat Approach (ARC-100)

Figures IV-53 and IV-54 show the appearance of the throat approach and entrance sections after test. In general, the fissured (tear) areas did not survive the test. In both Figures IV-53 and IV-54, for example, it can be seen that substantial surface areas were scoured from the forward edges of throat-approach segments. The material removal from the remainder of the surfaces, however, was minor and amounted to a maximum of only 0.081 in. (0.206 cm). For comparison, this erosion depth is approximately the same as that of the DC93-104 approach evaluated in subscale nozzle No. 001. When transposed to the normalized* basis of 600 psi (413 N/cm^2), the maximum erosion rate was 1.81 mils/sec (0.046 mm/sec).

b. Entrance Section (ARC-100)

The entrance section exhibited scouring at those areas that had been repaired prior to test (see Figures IV-53 and IV-54). In addition, the heat penetration into two segments was sufficient to destroy the adherence of the epoxy bond (Figure IV-53). As in the throat approach, however, the general surface material removal was low, amounting to a maximum erosion rate of 2.82 mils/sec at Station -2.5. This is not as good as the ARC-100 material used in the entrance section of nozzle No. 001.

*See Section IV.D, page 36.

The castable carbon formulation used in nozzle No. 001 was free of cracks and tears. In addition, it contained approximately 3% of 0.25-in. (0.64 cm) long carbon fibers. It appears that the presence of the fibers contributed to the mechanical strength of the composite and prevented the scouring that was observed in the throat approach and entrance section of nozzle No. 006. Accordingly, ARC-100/Si castable carbon is recommended for use in the submerged, outboard portion of the full-scale nozzle, with the provision that it be free of cracks, fissures, and tears.

c. Nosecap (UF1161)

The forward end and outboard surface of the nosecap experienced severe spallation during firing. Figure IV-55 shows the nosecap, and the smoothed appearance of the spalled surfaces indicates that the material fractured, was removed by the gas stream, and the surface scoured during firing. Examination of the motion picture films indicates that pieces of the nozzle were ejected sporadically. Examination of the oscillographic traces show that a large mass was ejected at approximately 22 sec, resulting in a pressure spike.

Figure IV-56 shows cross-sections of the nosecap. The zero-degree section is untouched, as-tested; the 135- and 240-degree sections have been hand polished. The apparent sequence of events is that heating of the flame surface caused expansion of surface layers. The expansion caused tensile stresses that initiated a crack at the inside corner of the nosecap that was in contact with the entrance section. Continued expansion raised the surface and the propellant gas flow (which would be forward at this location) tore off the fractured surface layers. The remainder of the cracks in a branched pattern below and roughly paralleling the flame surface are cooling cracks; this is indicated by Figure IV-57. The small piece was removed by sawing to a uniform depth below the surface, whereupon only a small application of pressure to the end of the piece was sufficient to separate it from the rest of the nosecap. Had these cracks been present during firing, the nosecap would probably have been ejected catastrophically instead of staying in place during the entire duration of the test. An example of excellent surface appearance is shown in Figure IV-58, together with the heating and cooling cracks.

The normalized maximum erosion rate at the forward end of the nosecap was calculated to be 13.45 mils/sec (0.34 mm/sec). This figure includes spallation and compares to previous maximum observed rates for this material of 16.87 mils/sec (0.428 mm/sec), at the forward end of the inlet section of No. 001, and 10.27 mils/sec (0.261 mm/sec), at the forward end of the entrance section of No. 003.

Because of the severe spallation, UF1161 graphite-particle material is not recommended for use in full-scale nozzle inlet sections; these sections will be subjected to over twice the exposure time experienced in the subscale test. Instead, the CFA carbonaceous material is recommended for use.

d. Throat (UF1161)

The throat insert also experienced severe spallation during firing and the sequence of failure was essentially the same as that of the nosecap. Figure IV-59 shows the throat after test. The maximum erosion at the minimum throat diameter was 1.080 in. (2.743 cm), corresponding to a normalized erosion rate of 24.4 mils/sec (0.62 mm/sec). This is much higher than the erosion rates observed in the throats of any of the first five subscale nozzles. As indicated in Table IV-22, the highest average erosion rate among the first five throats was 20.41 mils/sec (0.52 mm/sec), exhibited by the molded 4C 1462 Pluton B-1/phenolic material of nozzle No. 005. The average erosion rate of the throat in nozzle No. 006 was 21.4 mils/sec (0.53 mm/sec).

UF-1161 graphite particle material is not recommended for use in full-scale throats. Because of its severe spallation, no prediction can be made of its probable performance. It can be stated, however, that erosion in the range noted above would lead to high motor costs to maintain the payload capability. It is recommended that 4C 1686 molded chopped squares be employed in the full-scale throat. As noted in Section IV.E, the cost/performance effectiveness was greater than that of a wrapped carbon fabric prepreg.

e. Exit Cone "A" Section (UF1164)

The "A" section was ejected during firing and no remnants could be identified for recovery and analysis. Apparently the excessive removal of material in the throat increased the heat input to the "A" section and destroyed the adhesion between the "A" and "B" sections. A posttest view of the exit cone is shown in Figure IV-60. The shadows in the depression caused by the ejection of the "A" section are visible at the right side of the photograph.

At this time the data for UF1164 are insufficient to warrant use of this graphite particle material in full-scale nozzles.

f. Exit Cone "B" Section (MXC-119 B-1)

The erosion depths of the exit cone "B" section noted in Table IV-34 were calculated to the normalized condition and compared with previous values for subscale nozzle tests. The average erosion rate at Station + 12.0 of the MXC-199 B-1 material in nozzle No. 006 was 4.8 mils/sec (0.12 mm/sec), and the worst erosion rate was 7.0 mils/sec (0.18 mm/sec). The previous shingle-lap exit cone (subscale nozzle SN 005), which had utilized 4C 1402 carbon phenolic material, exhibited an average erosion rate of 0.69 mils/sec (0.018 mm/sec). It is felt that the principal reason for the increased erosion in "B" section of No. 006 is the ejection of the molded "A" section, the function of which was to protect the forward corner plies of the "B" section from peeling off. Examination of Figure IV-60 indicates that peeling was avoided except at the 180-degree location (6 o'clock in the photograph).

While the probability of successful use of a shingle-lap construction in the forward exit cone may be high, additional evaluation is required to confirm this point. Accordingly, a tape-wrapped construction is recommended for use in the full-scale forward exit cone.

g. Exit Cone "C" Section (4K9502)

The erosion rates of the exit cone "C" section were calculated in the normalized condition and compared with previous subscale nozzle values. The average erosion rate at Station +18.0 was 1.5 mils/sec (0.038 mm/sec), and the worst erosion rate, at the bottom of one of the grooves shown in Figure IV-60, was 7.2 mils/sec (0.183 mm/sec).

It is recommended that the shingle-lap construction be employed in the aft exit cone of the full-scale nozzle.

h. Structural Overwrap (Glass/Polyester)

There were no observable signs of failure in the structural overwrap of polyester resin impregnated glass fabric and roving, despite the greater-than-expected exposure to heat. It is recommended, therefore, that the full-scale exit cone be structually reinforced with glass/polyester.

TABLE IV-1

SUBSCALE EVALUATION NOZZLES

Component	S/N 001	S/N 002	S/N 003	S/N 004	S/N 005
Approach	DC93-104	DP5-161	4K 9502	CFA	4K 9502
Entrance	ARC-100	UF 1161 & MXC-12449	UF 1161	CFA	4C 1402
Inlet	UF 1161	CA-8502	MXC-199B1	CFA	4C 1402
Throat	4C 1686	CA-8502	MXC-199B1	CFA	4C 1402
"A" Section	UF 1161	CA-8502	MXC-199B1	CFA	4C 1402
"B" Section	UF 1164	DP5-161/ Si	MXC-12449	CFA	4C 1402
"C" Section	4K 9502	DP5-161/ Si	4K 9502	CFA	CA 2213

TABLE IV-2

COMPOSITION OF ARC-100 CASTING COMPOUND IN NOZZLE 1

Dense Coke Filler	67 w/o
Carbon Fibers (1/4-in.; 6.4 mm)	3
Furane Resin	30

TABLE IV-3

COMPOSITION OF DP5 CASTING COMPOUNDS

	DP5-161	DP5-161/Si
Resin	71.4 w/o	60.7 w/o
Hardener (see below)	28.6	24.3
Reinforcement*	-	15.0

*1/4-in. (6.35 mm) Silica Fibers

Hardener

74.1 w/o Carbon Black Powder
24.7 w/o Powdered Paraformaldehyde
1.2 w/o 1/8-in. (3.2 mm) Carbon Fibers

TABLE IV-4

COMPOSITION OF CFA MATERIAL IN NOZZLE 4

	w/o
Petroleum Coke	49.7
Carbon Black	5.0
Furfuryl Ester Resin	24.6
Furfural	3.4
Pitch	6.9
Carbon Fibers (1/2-in.; 1.27 cm)	8.0
Catalyst	2.4

TABLE IV-5

COMPOSITION AND PROPERTIES OF MOLDING COMPOUND

Material	Resin Content, %	GL-1012 Graphite, %	Volatile Content, %	Flow, %
4K 9502	43.4	-	3.6	N.A
4C 1686	35.2	-	3.2	17.6
UF 1161	40.0	60.0	N.A	N.A
UF 1164	40.0	50.0(1)	N.A	N.A
CA 8502	N.A.	-	N.A.	3.25
4C 1402	49.9	-	6.7	8.1

(1) Ten percent chopped carbon fiber also present.

N.A. - Not available.

TABLE IV-6

PROPERTIES OF FABRIC PREPREGS

Material	Resin Content, %	Volatile Content, %	Laminate Flow, %
MXC-199 B-1	46.9	1.2	11.8
MXC-12449	55.7	2.6	31.6(1)
4K 9502	39.9	3.6	0
4K 9502	43.4	7.3	12.6
4C 1402(2)	50.8	12.6	9.6
4C 1402(3)	61.5	12.5	15.5
CA 2213(3)	62.0	12.5	35.0

(1) At 1000 psi. All others at 150 psi.
(2) Wrapping grade.
(3) Hand lay-up grade.

TABLE IV-7

FABRICATION DATA FOR NOZZLE NO. 001

Component	Material	Mold Temp °F (°C)	Cure Temp. °F (°C)	Cure Pres. psi (N/cm^2)	Cure Time, hrs	Post Cure	Remarks
Approach	DC93-104	RT	RT	14.7	24	No	Continuous stream, vacuum degassing followed by pressure injection into casting mold. Clear of defects.
Entrance	ARC-100	RT	340 (171)	14.7 (10.1)	12	No	Four separate segments cast into sheet metal molds, machined and bonded together. Numerous small voids.
Inlet	UF-1161	RT	310 (154)	1000 (689)	8	No	Closed die molding. Clear of defects.
Throat	4C 1686	RT	310 (154)	1000 (689)	3	Yes	Closed die molding, overwrapped with canvas and vacuum-bag-cured at 310°F (154°C). Clear of defects.
"A" Section	UF-1161	RT	310 (154)	1000 (689)	10	Yes	Closed die molding. All exit cone sections overwrapped with canvas and vacuum-bag-cured at 310°F (154°C) Clear of defects.
"B" Section	UF-1164	RT	310 (154)	200 (138)	12	Yes	Tamped into female cavity, then bagged and autoclave cured. Overwrapped with canvas. Clear of defects.
"C" Section	4K 9502	RT	310 (154)	2000 (1380)	3	Yes	Closed die molding. Overwrapped with canvas. Clear of defects.

TABLE IV-8

FABRICATION DATA FOR NOZZLE NO. 002

Component	Material	Mold Temp. °F (°C)	Cure Temp. °F (°C)	Cure Pres. psi (N/cm^2)	Cure Time, hrs	Post Cure	Remarks
Approach	DP5-161	RT(1)	RT	None	120	No	Material used as supplied by Ironsides. Cast in ring mold. Many small voids.
Entrance	MXC-12449	NA(2)	300 (149	12 (8.3)	3	No	Ring cured under vacuum pressure. 60-degree (1.05 rad) segment removed.
	MXC-12449	NA	300 (149)	200 (138)	3	No	60-degree (1.05 rad) segment cured in autoclave and bonded into vacuum cured ring.
	UF-1161	RT	310 (154)	1000 (689)	8	No	Made from same closed die molding that was used for entrance of nozzle No. 003.
Inlet	CA-8502	RT	320 (160)	1000 (689)	3	No	Closed die molding. Clear of defects.
Throat	CA-8502	RT	315 (157)	1000 (689)	3	Yes	Closed die molding. Overwrapped with canvas and vacuum-bag-cured at 310°F (154°C). Clear of defects.
"A" Section	CA-8502	RT	310 (154)	1000 (689)	3	Yes	Closed die molding. All exit cone sections overwrapped with canvas and vacuum-bag-cured at 310°F (154°C). Clear of defects.
"B" Section	DP5-161/Si	RT	RT	None	120	Yes	"B" and "C" sections cast in one piece. Fifteen percent silica fibers added separately to mix prior to casting.
"C" Section	DP5-161/Si	RT	RT	None	120	Yes	

(1) RT - Ambient room temperature
(2) NA - Not applicable

TABLE IV-9

FABRICATION DATA FOR NOZZLE NO. 003

Component	Material	Wrap Temp., °F (°C)	Wrap Force lb/in. (N/cm)	As Wrapped Density, g/cc	Cure Temp., °F (°C)	Cure Time, hrs	Cure Pres., psi (N/cm^2)	Post-Cure	Remarks
Approach	4K 9502	180 (82)	100 (175)	0.91	310 (154)	4	12.7 (8.75)	No	Wrapped parallel to centerline and vacuum-bag-cured. Clear of defects.
Entrance	UF-1161	N.A.	N.A.	N.A.	310 (154)	8	1000 (689)	No	Closed die molding. Clear of defects.
Inlet	MXC-199 B1	180 (82)	100 (175)	1.25	310 (154)	3	125 (86)	No	Wrapped with bias tape. Free of defects.
Throat	MXC-199 B1	180 (82)	100 (175)	1.25	310 (154)	3	125 (86)	Yes	Wrapped with bias tape and cured. Overwrapped with 4K 9502 tape and vacuum bag cured. Clear of defects.
"A" Section	MXC-199 B1	180 (82)	100 (175)	1.25	310 (154	4	13.0 (8.96)	No	Wrapped parallel to centerline. Clear of defects.
"B" Section	MXC-12449	180	100	0.70					Wrapped into "A" Section. Severe wrinkles and delaminations.
"C" Section	4K 9502	180	100	1.00					Wrapped into "B" Section. Wrinkles. Overwrapped with 4K 9502.

N.A. - Not applicable.

TABLE IV-10

FABRICATION DATA FOR NOZZLE NO. 004

A. MOLDING

Pressure	-	30-50 psi (20.7-34.5 N/cm^2)
Temperature	-	110-150°C (230-302°F)*
Time	-	8 hrs

B. CURE

Pressure	-	Ambient
Temperature	-	150°C (302°F)
Time	-	16 hrs

*Temperature drop through walls of ring mold.

TABLE IV-11

FABRICATION DATA FOR NOZZLE 005

Component	Material	Wrap Temp., °F (°C)	Wrap Force, lb/in. (N/cm)	As-Wrapped Density, g/cc	Cure Temp, °F (°C)	Cure Time, hrs	Cure Pres. psi (N/cm^2)	Post-Cure	Remarks
Approach	4K 9502	180 (82)	100 (175)	0.91	310 (154)	3	12.7 (8.75)	No	Wrapped parallel to centerline and vacuum-bag-cured. Clear of defects.
Entrance	4C 1402	180 (82)	100 (175)	1.30	310 (154)	3	200 (138)	No	Wrapped parallel to centerline and autoclave cured. Canvas insulation bonded to ID surface. Clear of defects.
Inlet	4C 1402	N.A.	N.A.	N.A.	310 (154)	3	1000 (689)	No	Loaded into cold mold and step-cured at 225°F (107°C), 254°F (118°C), 275°F (135°C) and 310°F (154°C). Throat overwrapped with canvas and vacuum-bag-cured. All liners free of defects.
Throat								Yes	
"A" Section								Yes	Carbon "B" section and canvas "C" section laid up and over "A" section and vacuum-bag cured. Backside overwrapped with canvas and vacuum-bag cured. Free of defects.
"B" Section	4C 1402	N.A.	N.A.	N.A.	310 (154)	3.0	12.7 (8.75)	Yes	
"C" Section	CA-2213	N.A.	N.A.	N.A.	310 (154)	3.0	12.7 (8.75)	Yes	

N.A. - Not applicable.

CURED COMPOSITE PROPERTIES

Material	Component	Specific Gravity	Hardness Rockwell M	Uncured Resin, %	Volatile Content, %
ARC-100	Entrance #1	1.50	10	N.A.	N.A.
CFA	Approach #4	1.54	-	N.A.	N.A.
	Inlet-Throat #4	1.57	-	N.A.	N.A.
	"A" Section #4	1.42	-	N.A.	N.A.
	"B" Section #4	1.39	-	N.A.	N.A.
	"C" Section #4	1.33	-	N.A.	N.A.
DC 93-104	Approach #1	1.47	10	N.A.	N.A.
DP5-161	Approach #2	1.35	<10	N.A.	N.A.
DP5-161/Si	"B" Section #2	1.37	<10	N.A.	N.A.
	"C" Section #2	1.37	<10	N.A.	N.A.
UF-1161	Entrance #2	1.66	<10	N.A.	N.A.
	Entrance #3	1.66	<10	N.A.	N.A.
	Inlet #1	1.64	<10	N.A.	N.A.
	"A" Section #1	1.63	10	N.A.	N.A.
UF-1164	"B" Section #1	1.60	10	N.A.	N.A.
CA-2213	"C" Section #5	-	-	-	-
CA-8502	Inlet #2	1.43	115	0.38	0.85
	Throat #2	1.42	117	0.32	0.76
	"A" Section #2	1.42	119	0.35	0.65
4C 1402	Entrance #5	1.41	116	0.41	0.72
	Inlet #5	1.43	116	0.41	0.72
	Throat #5	1.43	115	0.35	0.92
"A"	"A" Section #5	1.43	113	0.30	0.90
	"B" Section #5	-	-	-	-
4C 1686	Throat #1	1.42	116	0.31	0.86
4K 9502	Approach #3	0.91	<10	-	-
	Approach #5	0.91	<10	-	-

TABLE IV-12 (CONT.)

Material	Component	Specific Gravity	Hardness, Rockwell M	Uncured Resin, %	Volatile Content, %
4K 9502 (cont.)	"C" Section #1	1.37	10	0.35	2.7
	"C" Section #3	1.00	<10	-	-
MXC-199 B1	Inlet #3	1.50	112	0.42	0.95
	Throat #3	1.50	112	0.42	0.95
	"A" Section #3	1.25	-	-	-
MXC-12449	Entrance #2	0.69	<10	0.45	1.25
	Entrance #2	1.24	<10	0.41	1.05
	"B" Section #3	0.70	-	-	-

N.A. - not applicable.

TABLE IV-13

SUBSCALE MOTOR PERFORMANCE

Motor No.	Nozzle Throat	Web Pressure, Average		Web Time, sec
		psia	(N/cm^2)	
1	4C 1686 (Molded)	479.5	330.5	57.25
2	CA-8502 (Molded)	447.5	308.5	58.55
3	MXC-199 B-1 (Wrapped)	464.0	320.0	57.3
4	CFA (Molded)	467.0	322.0	57.1
5	4C 1402 (Molded)	427.0	294.5	59.6

TABLE IV-14. - REGRESSION AND CHAR DEPTHS OF NOZZLE 001 (INCHES), Page 1 of 2

Station		Approach (DC93-104) 0	135	240	Entrance (ARC-100) 0	135	240	Inlet (UF 1161) 0	135	240	Throat (4C 1686) 0	135	240
Fwd End	Regr				0.782	0.312	0.550	0.612	0.406	0.811			
	Char												
-3.6					0.281	0.004	0.188	0.657	0.409	0.621			
-3.0					0.135	0.000	0.093	0.671	0.438	0.812			
-2.5					0.031	0.008	0.064				0.688	0.531	0.872
											1.093	0.875	1.125
-2.0					0.001	-0.057	0.065				0.625	0.502	0.660
											1.002	0.846	1.002
-1.75					0.005	-0.062	0.061				0.593	0.512	0.593
											0.935	0.880	0.982
-1.0					0.002	-0.060	0.052				0.540	0.532	0.563
											0.938	0.875	0.968
0 (Throat)					0.055	-0.093	0.038				0.503	0.481	0.531
											0.907	0.869	0.894
+1.0					0.063	0.031	0.060				0.384	0.324	0.406
											0.843	0.742	0.782
+2.0		0.061	-0.010	0.064							0.214	0.125	0.112
		0.320	0.342	0.370							0.634	0.522	0.531
+3.0		0.070	0.031	0.090									
		0.320	0.344	0.402									
+4.0		0.014	0.002	0.070									
		0.219	0.312	0.365									
+5.0		0.002	0.005	0.060									
		0.188	0.257	0.312									

TABLE IV-14. - REGRESSION AND CHAR DEPTHS OF NOZZLE 001 (CENTIMETERS), Page 2 of 2

Station		Approach (DC93-104) 0	135	240	Entrance (ARC-100) 0	135	240	Inlet (UF-1161) 0	135	240	Throat (4C 1686) 0	135	240
Fwd End	Regr.				1.986	0.792	1.397	1.554	1.031	2.06			
	Char				-	-	-	-	-	-			
-3.6					0.714	0.010	0.478	1.669	1.039	1.577			
					-	-	-	-	-	-			
-3.0					0.343	0.000	0.236	1.704	1.113	2.062			
					-	-	-	-	-	-			
-2.5					0.079	0.020	0.163				1.748	1.349	2.215
					-	-	-				2.776	2.223	2.858
-2.0					0.003	-0.145	0.165				1.588	1.275	1.676
					-	-	-				2.545	2.149	2.545
-1.75					0.013	-0.157	0.155				1.506	1.300	1.506
					-	-	-				2.375	2.235	2.494
-1.0					0.005	-0.152	0.132				1.372	1.351	1.430
					-	-	-				2.383	2.222	2.459
0 (Throat)					0.140	-0.236	0.097				1.278	1.222	1.349
					-	-	-				2.304	2.207	2.27
+1.0					0.160	0.079	0.152				0.975	0.823	1.031
					-	-	-				2.141	1.885	1.986
+2.0		0.155	-0.025	0.163							0.544	0.318	0.284
		0.813	0.869	0.940							1.610	1.326	1.349
+3.0		0.178	0.079	0.229									
		0.818	0.874	0.021									
_4.0		0.036	0.005	0.178									
		0.556	0.792	0.927									
+5.0		0.005	0.013	0.152									
		0.478	0.653	0.792									

TABLE IV-15. - REGRESSION AND CHAR DEPTHS OF NOZZLE 002 (INCHES), Page 1 of 2

Station	Approach (DP5-161)			Entrance (UF 1161 & MXC-12449)			Inlet (CA-8502)			Throat (CA-8502)			Exit Cone (CA-8502 & DP5-161/S1)		
	0	135	240	0	135	240	0	135	240	0	135	240	0	135	240
Fwd Regr				0.438	0.219	0.188	0.385	0.102	0.156						
End Char							0.980	0.687	0.695						
-3.6				0.188	0.118	0.125	0.546	0.421	0.470						
							0.809	0.640	0.688						
-3.0				0.066	0.031	0.042	0.565	0.469	0.485						
							0.752	0.657	0.702						
-2.5				0.161	0.191	0.312				0.539	0.530	0.500			
				0.453	0.938	0.660				0.750	0.748	0.875			
-2.0				0.219	0.344	0.411				0.600	0.594	0.560			
				0.438	0.875	0.688				0.813	0.783	0.878			
-1.75				0.245	0.470	0.407				0.606	0.563	0.600			
				0.484	0.875	0.656				0.828	0.781	0.879			
-1.0				0.247	0.605	0.534				0.625	0.615	0.625			
				0.499	1.000	0.640				0.934	0.938	1.000			
0				0.169	0.497	0.575				0.690	0.688	0.704			
(Throat)				0.422	1.024	0.691				0.993	0.963	1.062			
+1.0				0.120	0.688	0.770				0.688	0.656	0.678			
				0.379	1.047	0.969				0.969	0.937	0.928			
+2.0	-0.234	-0.341	-0.219							0.529	0.594	0.408			
	0.156	0.093	0.188							0.953	0.908	0.720			
+3.0	-0.328	-0.437	-0.365										0.368	0.503	0.680
	0.066	0.001	0.020										0.688	0.782	1.045
+4.0	-0.344	-0.375	0.437										0.235	0.381	0.719
	0.031	0.032	0.000										0.531	0.664	0.880
+5.0	-0.281	-0.278	-0.344										0.234	0.411	0.621
	0.095	0.138	0.000										0.503	0.719	0.815
+6.0													0.126	0.478	0.416
													0.407	0.772	0.722
ε = 3.0													0.004	0.160	0.096
													0.281	0.469	0.542
+12.0													0.063	0.156	0.070
													0.185	0.321	0.274
ε = 5.5													-0.031	-0.123	-0.240
													0.089	0.125	-0.125
+18.0													-0.262	-0.230	-0.281
													0.040	-0.120	-0.188
+22.0													-0.437	-0.312	-0.563
													-0.125	-0.002	-0.250

TABLE IV-15. - REGRESSION AND CHAR DEPTHS OF NOZZLE 002 (CENTIMETERS), Page 2 of 2

Station	Approach (DP5-161) 0	135	240	Entrance (UF 1161 & MXC-12449) 0	135	240	Inlet (CA-8502) 0	135	240	Throat (CA-8502) 0	135	240	Exit Cone (CA-8502 & DP5-161/$1) 0	135	240
Fwd Regr.				1.113	0.556	0.478	0.978	0.259	0.396						
End Char				-	-	-	2.489	1.745	1.765						
-3.6				0.478	0.300	0.318	1.387	1.069	1.194						
				-	-	-	2.055	1.626	1.748						
-3.0				0.168	0.079	0.107	1.435	1.191	1.232						
				-	-	-	1.910	1.669	1.783						
-2.5				0.409	0.485	0.792				1.369	1.346	1.270			
				1.151	2.383	1.676				1.905	1.900	2.223			
-2.0				0.556	0.874	1.044				1.524	1.569	1.422			
				1.113	2.223	1.748				2.065	1.989	2.230			
-1.75				0.622	1.194	1.034				1.539	1.430	1.524			
				1.229	2.223	1.666				2.103	1.984	2.233			
-1.0				0.627	1.537	1.356				1.588	1.562	1.588			
				1.267	2.540	1.626				2.372	2.383	2.540			
0. (Throat)				0.429	1.262	1.461				1.753	1.748	1.788			
				1.072	2.601	1.756				2.522	2.446	2.697			
+1.0				0.305	1.748	1.956				1.748	1.666	1.722			
				0.963	2.659	2.461				2.461	2.380	2.357			
+2.0	-0.594	-0.866	-0.556							1.344	1.509	1.036			
	0.396	0.236	0.478							2.421	2.306	1.829			
+3.0	-0.833	-1.110	-0.927										0.935	1.278	1.727
	0.168	0.003	0.051										1.748	1.986	2.654
+4.0	-0.874	-0.953	-1.110										0.597	0.968	1.826
	0.079	0.081	0.000										1.349	1.687	2.235
+5.0	-0.714	-0.706	-0.874										0.594	1.044	1.577
	2.241	0.351	0.000										1.278	1.826	2.070
+6.0													0.320	1.214	1.057
													1.034	1.961	1.834
ε = 3.0													0.010	0.406	0.244
													0.714	1.191	1.377
+12.0													0.160	0.396	0.178
													0.470	0.815	0.696
ε = 5.5													0.079	-0.312	-0.610
													0.226	0.318	-0.318
+18.0													-0.665	-0.584	-0.714
													0.102	-0.305	-1.430
+22.0													-1.110	-0.792	-1.430
													-0.318	-0.005	-0.635

TABLE IV-16. - REGRESSION AND CHAR DEPTHS OF NOZZLE 003
(INCHES) Page 1 of 2

Station		Approach (4K9502) 0	135	240	Entrance (UF-1161) 0	135	240	Inlet (MXC-199B1) 0	135	240	Throat (MXC-199B1) 0	135	240	Exit Cone (MXC-199 B-1 +MXC-12449 + 4K 9502) 0	135	240
Fwd End	Regr.				.481	.218	.441	.582	.261	.512						
	Char							.782	.450	.714						
-3.6					.231	.124	.142	.614	.576	.714						
								.835	.766	.896						
-3.0					.034	.059	-.015	.620	.687	.780						
								.845	.887	.974						
-2.5					.033	.002	-.051				.662	.670	.700			
											.822	.860	.870			
-2.0					.030	.000	-.081				.650	.711	.708			
											.810	.881	.878			
-1.75					.004	-.016	-.064				.638	.721	.712			
											.798	.881	.902			
-1.0					.033	-.020	-.092				.635	.715	.645			
											.805	.870	.855			
0 (Throat)					-.040	-.027	-.122				.557	.587	.623			
											.742	.752	.833			
+1.0					-.008	-.050	-.148				.521	.561	.523			
											.721	.723	.743			
+2.0		.354	.350	.392							.305	.471	.324			
		--	--	--							.575	.681	.624			
+3.0		.361	.325	.418							.254	.416	.218			
		--	--	--							.576	.716	.568			
+4.0		.348	.305	.332										.243	.331	.246
		--	--	--										--	--	--
+5.0		.274	.280	.324										.272	.371	.274
		--	--	--										--	--	--
+6.0														.318	.437	.338
														--	--	--
℄ = 3.0														.547	.408	.502
														--	--	--
+12.0														.928	.818	.748
														--	--	--
℄ = 5.5														1.755	1.114	1.136
														--	--	--
+18.0														2.296	2.292	1.475
														--	--	--
+22.0														1.771	2.298	1.247
														--	--	--

TABLE IV-16. - REGRESSION AND CHAR DEPTHS OF NOZZLE 003 (CENTIMETERS) Page 2 of 2

Station		Approach (4K 9502)			Entrance (UF-1161)			Inlet (MXC-199B1)			Throat (MXC-199B1)			Exit Cone (MXC-199 B1 + MXC-12249 + 4K 9502)		
		0	135	240	0	135	240	0	135	240	0	135	240	0	135	240
Fwd End	Regr.				1.222	0.554	1.120	1.478	0.663	1.300						
	Char				-	-	-	1.986	1.143	1.814						
-3.6					0.587	0.315	0.361	1.560	1.463	1.814						
					-	-	-	2.121	1.946	2.276						
-3.0					0.086	0.150	-0.038	1.575	1.745	1.981						
					-	-	-	2.146	2.253	2.474						
-2.5					0.084	0.005	-0.130				1.681	1.702	1.778			
					-	-	-				2.088	2.184	2.210			
-2.0					0.076	0.000	-0.206				1.651	1.806	1.798			
					-	-	-				2.057	2.238	2.230			
-1.75					0.010	-0.041	-0.163				1.621	1.831	1.808			
					-	-	-				2.027	2.238	2.291			
-1.0					-0.084	-0.051	-0.234				1.613	1.816	1.638			
					-	-	-				2.045	2.210	2.172			
0 (Throat)					-0.102	-0.069	-0.310				1.415	1.491	1.582			
					-	-	-				1.885	1.910	2.116			
+1.0					-0.020	-0.127	-0.376				1.323	1.425	1.328			
					-	-	-				1.831	1.836	1.887			
+2.0		0.899	0.889	0.996							0.775	1.196	0.823			
		-	-	-							1.461	1.730	1.585			
+3.0		0.917	0.826	1.062							0.645	1.057	0.554			
		-	-	-							1.463	1.819	1.443			
+4.0		0.894	0.775	0.843										0.617	0.841	0.625
		-	-	-										-	-	-
+5.0		0.696	0.711	0.823										0.691	0.942	0.696
		-	-	-										-	-	-
+6.0														0.808	1.110	0.859
														-	-	-
ε = 3.3														1.389	1.036	1.275
														-	-	-
+12.0														2.357	2.078	1.900
														-	-	-
ε = 5.5														4.458	2.830	2.885
														-	-	-
+18.0														5.832	5.322	3.747
														-	-	-
+22.0														4.498	5.837	3.167
														-	-	-

TABLE IV-17. - REGRESSION AND CHAR DEPTHS OF NOZZLE 004 (INCHES) Page 1 of 2

	Approach			Entrance			Inlet			Throat			Exit Cone		
Station	0	135	240	0	135	240	0	135	240	0	135	240	0	135	240
Fwd End Regr Char*				0.686 -	0.605 -	0.708 -	0.611 -	0.563 -	0.810 -						
-3.6				0.261 -	0.375 -	0.282 -	0.981 -	0.847 -	1.095 -						
-3.0				0.120 -	0.196 -	0.178 -	0.896 -	0.738 -	0.875 -						
-2.5				0.030 -	0.156 -	0.095 -				0.812 -	0.655 -	0.752 -			
-2.0				0.041 -	0.172 -	0.045 -				0.752 -	0.632 -	0.782 -			
-1.75				0.016 -	0.158 -	0.090 -				0.687 -	0.625 -	0.778 -			
-1.0				0.013 -	0.002 -	0.218 -				0.632 -	0.633 -	0.714 -			
0 (Throat)				0.025 -	0.009 -	0.125 -				0.507 -	0.652 -	0.689 -			
+1.0				0.002 -	-0.034 -	0.058 -				0.435 -	0.572 -	0.584 -			
+2.0	0.031 -	0.030 -	0.041 -							0.378 -	0.431 -	0.508 -			
+3.0	0.000 -	0.003 -	0.012 -										0.700 -	0.563 -	0.412 -
+4.0	-0.038 -	-0.033 -	-0.002 -										0.621 -	0.537 -	0.401 -
+5.0	-0.015 -	0.002 -	-0.005 -										0.558 -	0.345 -	0.163 -
+6.0													0.381 -	0.212 -	0.181 -
ε = 3.0													0.312 -	0.287 -	0.135 -
+12.0 Regr. Char*													0.137 -	-0.125 -	-0.003 -
ε = 5.5													-0.091 -	-0.118 -	-0.156 -
+18.0													-0.188 -	-0.070 -	-0.395 -
+22.0													-0.298 -	-0.130 -	-0.195 -

*Char depths could not be detected.

TABLE IV-17. - REGRESSION AND CHAR DEPTHS OF NOZZLE 004
(CENTIMETERS) Page 2 of 2

Station		Approach			Entrance			Inlet			Throat			Exit Cone		
		0	135	240	0	135	240	0	135	240	0	135	240	0	135	240
Fwd End	Regr.				1.742	1.537	1.798	1.552	1.430	2.057						
-3.6	Char*				0.663	0.953	0.716	2.492	2.151	2.781						
-3.0					0.305	0.498	0.452	2.276	1.875	2.223						
-2.5					0.076	0.396	0.241				2.062	1.664	1.910			
-2.0					0.104	0.437	0.114				1.910	1.605	1.986			
-1.75					0.041	0.401	0.229				1.745	1.588	1.976			
-1.0					0.033	0.005	0.554				1.605	1.608	1.814			
0 (Throat)					0.064	0.023	0.318				1.288	1.656	1.750			
+1.0					0.005	0.086	0.147				1.105	1.453	1.483			
+2.0		0.079	0.076	0.104							0.960	1.095	1.290			
+3.0		0.000	0.008	0.030										1.778	1.430	1.046
+4.0		-0.097	-0.084	-0.005										1.577	1.364	1.019
+5.0		-0.038	0.005	-0.013										1.417	0.876	0.414
+6.0														0.967	0.538	0.460
ε = 3.0														0.792	0.729	0.343
+12.0														0.348	-0.318	-0.008
ε = 5.5														-0.231	-0.300	-0.396
+18.0														-0.478	-0.179	-1.003
+22.0														-0.759	-0.330	-0.495

*Char Depths could not be detected.

TABLE IV-18. - REGRESSION AND CHAR DEPTHS OF NOZZLE 005
(INCHES) Page 1 of 2

	Approach-4K 9502			Entrance-4C 1402			Inlet-4C 1402			Throat-4C 1402			Exit Cone-4C 1402 & CA-2213		
Station	0	135	240	0	135	240	0	135	240	0	135	240	0	135	240
Forward Regr.				0.625	0.308	0.441	0.565	0.344	0.437						
End Char				0.997	0.682	0.822	0.882	0.721	0.813						
-3.6				0.421	0.192	0.283	0.585	0.516	0.563						
				0.760	0.501	0.563	0.875	0.812	0.810						
-3.0				0.188	0.156	0.128	0.567	0.565	0.585						
				0.452	0.356	0.438	0.845	0.824	0.762						
-2.5				0.184	0.125	0.076				0.615	0.570	0.595			
				0.419	0.344	0.378				0.922	0.841	0.844			
-2.0				0.156	0.075	0.045				0.625	0.688	0.625			
				0.425	0.284	0.390				1.023	0.968	1.000			
-1.75				0.101	0.135	0.060				0.640	0.738	0.640			
				0.431	0.284	0.375				1.035	1.041	1.035			
-1.0				0.093	0.158	0.034				0.791	0.802	0.840			
				0.433	0.350	0.415				1.128	1.185	1.072			
0 (Throat)				0.125	0.141	0.042				0.906	0.875	0.901			
				0.456	0.425	0.467				1.231	1.189	1.124			
+1.0				0.094	0.129	0.002				0.781	0.750	0.784			
				0.462	0.432	0.442				1.275	1.072	1.007			
+2.0	0.467	0.384	0.241							0.563	0.430	0.437			
	0.748	0.533	0.570							0.911	0.835	0.695			
+3.0	0.524	0.341	0.192										0.438	0.219	0.295
	0.784	0.549	0.561										0.565	0.503	0.548
+4.0	0.500	0.300	0.218										0.440	0.154	0.268
	0.782	0.563	0.554										0.500	0.444	0.620
+5.0	0.375	0.281	0.219										0.409	0.112	0.380
	0.675	0.529	0.532										0.527	0.478	0.705
+6.0													0.200	0.220	0.312
													0.471	0.429	0.620
ε = 3.0													0.156	0.067	0.219
													0.291	0.315	0.493
+12.0													0.027	0.063	0.000
													0.248	0.312	0.188
ε = 5.5													0.078	0.090	0.031
													0.231	0.221	0.218
+18.0													0.082	0.156	0.057
													0.250	0.315	0.218
+22.0													0.068	0.011	0.031
													0.164	0.162	0.157

TABLE IV-18. - REGRESSION AND CHAR DEPTHS OF NOZZLE 005 (CENTIMETERS) Page 2 of 2

Station		Approach (4K 9502) 0	135	240	Entrance (4C 1402) 0	135	240	Inlet (4C 1402) 0	135	240	Throat (4C 1402) 0	135	240	Exit Cone (4C 1402 & CA 2211) 0	135	240
Fwd	Regr.				1.588	0.782	1.120	1.435	0.874	1.110						
End	Char				2.532	1.732	2.088	2.240	1.831	2.065						
-3.6					1.069	0.488	0.719	1.486	1.311	1.430						
					1.930	1.273	1.430	2.223	2.062	2.057						
-3.0					0.478	0.396	0.325	1.440	1.435	1.486						
					1.148	0.904	1.113	2.146	2.093	1.935						
-2.5					0.467	0.318	0.193				1.562	1.448	1.511			
					1.064	0.874	0.960				2.342	2.136	2.144			
-2.0					0.396	0.191	0.114				1.588	1.748	1.588			
					1.080	0.721	0.991				2.598	2.459	2.540			
-1.75					0.257	0.343	0.152				1.626	1.875	1.626			
					1.095	0.721	0.953				2.629	2.644	2.629			
-1.0					0.236	0.401	0.086				2.009	2.037	2.134			
					1.100	0.889	1.054				2.865	3.010	2.723			
0 (Throat)					0.318	0.358	0.107				2.301	2.223	2.289			
					1.158	1.080	1.186				3.127	3.020	2.855			
+1.0					0.239	0.328	0.005				1.984	1.905	1.991			
					1.173	1.097	1.123				3.239	2.723	2.558			
+2.0		1.186	0.975	0.612							1.278	1.092	1.110			
		1.900	1.354	1.448							2.314	2.121	1.765			
+3.0		1.331	0.866	0.488										1.113	0.556	0.749
		1.991	1.394	1.425										1.435	1.289	1.392
+4.0		1.270	0.762	0.554										1.118	0.391	0.681
		1.986	1.430	1.407										1.270	1.128	0.575
+5.0		0.953	0.714	0.556										1.039	0.284	0.965
		1.715	1.344	1.351										1.339	1.214	1.791
+6.0														0.508	0.559	0.792
														1.196	1.090	1.575
ε = 3.0														0.396	0.170	0.556
														0.739	0.800	1.252
+12.0														0.069	0.160	0.000
														0.630	0.792	0.478
ε = 5.5														0.198	0.229	0.079
														0.714	0.561	0.554
+18.0														0.183	0.396	0.145
														0.635	0.800	0.554
+22.0														0.173	0.028	0.079
														0.417	0.411	0.399

TABLE IV-19

NORMALIZED* REGRESSION AND CHAR RATES OF APPROACH MATERIALS
MILS (MM) PER SECOND

Material	Measurement	Station +2.0		+3.0		4.0		+5.0	
DC93-104	Avg. Regr.	0.79	(0.020)	1.33	(0.034)	0.60	(0.015)	0.46	(0.012)
	Char	7.16	(0.182)	7.38	(0.187)	6.22	(0.158)	5.26	(0.134)
	Worst Regr.	1.33	(0.034)	1.87	(0.047)	1.46	(0.037)	1.25	(0.032)
	Char	7.70	(0.196)	8.36	(0.212)	7.59	(0.193)	6.49	(0.165)
DP5-161	Avg. Regr.	(-)		(-)		(-)		(-)	
	Char	3.21	(0.082)	0.64	(0.016)	0.46	(0.012)	1.71	(0.043)
	Worst Regr.	(-)		(-)		(-)		(-)	
	Char	4.13	(0.105)	1.45	(0.037)	0.70	(0.018)	3.03	(0.077)
4K 9502	Avg. Regr.	7.795	(0.198)	7.859	(0.200)	7.005	(0.178)	6.258	(0.159)
	Char	-	-	-	-	-	-	-	-
	Worst Regr.	8.372	(0.213)	8.927	(0.227)	7.432	(0.189)	5.980	(0.152)
	Char	-	-	-	-	-	-	-	-
CFA	Avg. Regr.	1.828	(0.046)	0.276	(0.007)	(-)		0.106	(0.003)
	Char	No Char		-	-	-	-	-	-
	Worst Regr.	2.210	(0.056)	0.638	(0.016)	(-)		0.106	(0.003)
	Char	No Char		-	-	-	-	-	-
4K 9502	Avg. Regr.	8.31	(0.211)	8.04	(0.204)	7.74	(0.197)	6.67	(0.169)
	Char	14.09	(0.358)	14.41	(0.366)	14.45	(0.367)	13.22	(0.336)
	Worst Regr.	10.66	(0.271)	11.97	(0.304)	11.42	(0.290)	8.56	(0.217)
	Char	17.08	(0.434)	17.90	(0.455)	17.86	(0.454)	15.41	(0.391)

*Normalized to 600 psig (413.6 N/cm2) chamber pressure and 57.5 seconds.

TABLE IV-20. - NORMALIZED* REGRESSION AND CHAR RATES OF ENTRANCE MATERIALS, MILS (MM) PER SECOND

Material	Measurement	Fwd End	Station -3.6	-3.0	-2.5	-2.0	-1.75	-1.0	Throat	+1.0
ARC-100	Avg. Regr	11.40 (0.290)	3.29 (0.084)	1.58 (0.040)	0.71 (0.018)	0.06 (0.002)	0.02 (0.001)	(-) (-)	(-) (-)	1.06 (0.27)
	Char	No Char								
	Worst Regr	16.27 (0.413)	5.84 (0.148)	2.81 (0.071)	1.33 (0.034)	1.35 (0.034)	1.27 (0.032)	1.08 (0.027)	1.14 (0.029)	1.31 (0.033)
	Char	No Char								
UF 1161 & MXC-12449	Avg. Regr	6.20 (0.157)	3.17 (0.081)	1.10 (0.028)	4.88 (0.124)	7.14 (0.181)	8.22 (0.209)	10.16 (0.258)	9.10 (0.231)	11.56 (0.294)
	Char	No Char	- -	- -	15.04 (0.382)	14.66 (0.372)	14.77 (0.375)	15.67 (0.398)	15.65 (0.398)	17.41 (0.442)
	Worst Regr	9.63 (0.245)	4.13 (0.1.05)	1.45 (0.037)	6.86 (0.174)	9.04 (0.230)	10.33 (0.262)	13.30 (0.338)	12.64 (0.321)	16.93 (0.430)
	Char	No Char	- -	- -	20.62 (0.524)	19.24 (0.489)	19.24 (0.489)	21.98 (0.558)	22.51 (0.572)	23.02 (0.585)
UF-1161	Avg. Regr	8.12 (0.206)	3.55 (0.090)	0.56 (0.014)	(-) (-)	(-) (-)	(-) (-)	(-) (-)	(-) (-)	(-) (-)
	Char	No Char								
	Worst Regr	10.27 (0.261)	4.93](0.125)	1.26 (0.032)	0.70 (0.018)	0.64 (0.016)	0.09 (0.002)	0.7- (0.018)	(-) (-)	(-) (-)
	Char	No Char	(-) (-)	(-) (-)	(-) (-)	(-) (-)	(-) (-)	(-) (-)	(-) (-)	(-) (-)
CFA	Avg. Regr	14.15 (0.359)	6.50 (0.165)	3.51 (0.089)	2.00 (0.051)	1.83 (0.046)	1.87 (0.047)	1.66 (0.042)	1.13 (0.029)	0.19 (0.005)
	Char	No Char								
	Worst Regr	15.05 (0.382)	7.97 (0.202)	4.17 (0.106)	3.32 (0.084)	3.66 (0.093)	3.36 (0.085)	4.63 (0.118)	2.66 (0.068)	1.23 (0.031)
	Char	No Char								
4C 1402	Avg. Regr	10.46 (0.266)	6.83 (0.266)	6.83 (0.173)	3.58 (0.091)	2.92 (0.074)	2.10 (0.053)	2.17 (0.055)	2.35 (0.060)	1.71 (0.043)
	Char	19.04 (0.484)	13.88 (0.353)	9.48 (0.241)	8.68 (0.220)	8.36 (0.212)	6.92 (0.176)	9.11 (0.231)	10.25 (0.260)	10.16 (0.258)
	Worst Regr	14.27 (0.362)	9.61 (0.244)	4.29 (0.104)	4.20 (0.107)	3.56 (0.090)	3.08 (0.079)	3.61 (0.092)	3.22 (0.082)	2.95 (0.075)
	Char	22.77 (0.578)	17.35 (0.441)	10.32 (0.262)	9.57 (0.243)	9.70 (0.246)	9.84 (0.250)	9.89 (0.251)	10.66 (0.271)	10.55 (0.268)

*Normalized to 600 psia (413.6 N/cm^2) chamber pressure and 57.5 seconds.

TABLE IV-21

NORMALIZED* REGRESSION AND CHAR RATES OF INLET MATERIALS, MILS (MM) PER SECOND

Material	Measurement	Station Fwd End		-3.6		-3.0	
UF-1161	Avg. Regr.	14.06	(0.357)	11.69	(0.297)	13.31	(0.338)
	Char	No Char		-		-	
	Worst Regr.	16.87	(0.428)	13.67	(0.347)	16.89	(0.429)
	Char	No Char		-		-	
CA-8502	Avg. Regr.	4.70	(0.119)	10.53	(0.267)	11.12	(0.282)
	Char	17.30	(0.439)	15.65	(0.398)	15.48	(0.393)
	Worst Regr.	8.46	(0.215)	12.00	(0.305)	12.42	(0.315)
	Char	21.54	(0.547)	17.78	(0.452)	16.53	(0.420)
MXC-199 B-1	Avg. Regr.	9.65	(0.245)	13.56	(0.344)	14.86	(0.377)
	Char	13.86	(0.352)	17.77	(0.451)	19.26	(0.489)
	Worst Regr.	12.43	(0.316)	15.25	(0.387)	16.66	(0.423)
	Char	16.70	(0.424)	19.14	(0.486)	20.80	(0.528)
CFA	Avg. Regr.	14.05	(0.357)	20.70	(0.526)	17.77	(0.451)
	Char	No Char		-		-	
	Worst Regr.	17.21	(0.437)	23.27	(0.591)	19.04	(0.484)
	Char	No Char		-		-	
4C 1402	Avg. Regr.	10.25	(0.260)	12.57	(0.322)	13.06	(0.332)
	Char	18,38	(0.467)	19.00	(0.483)	18.50	(0.470)
	Worst Regr.	12.90	(0.328)	13.36	(0.339)	13.36	(0.339)
	Char	20.14	(0.512)	19.98	(0.507)	19.29	(0.490)

*Normalized to 600 psia (413.6 N/cm^2) chamber pressure and 57.5 seconds.

TABLE IV-22. - NORMALIZED* REGRESSION AND CHAR RATES OF THROAT MATERIALS, MILS (MM) PER SECOND

Material	Measurement	Station -2.5	-2.0	-1.75	-1.0	Throat	+1.0	+2.0	+3.0
4C 1686	Avg. Regr.	14.50 (0.368)	12.40 (0.315)	11.77 (0.299)	11.34 (0.288)	10.50 (0.267)	7.72 (0.196)	3.12 (0.079)	
	Char	21.44 (0.545)	19.76 (0.502)	19.39 (0.493)	19.28 (0.490)	18.51 (0.470)	16.41 (0.417)	11.69 (0.297)	
	Worst Regr.	18.14 (0.461)	13.73 (0.349)	12.33 (0.313)	11.71 (0.297)	11.04 (0.280)	8.44 (0.214)	4.45 (0.113)	
	Char	23.40 (0.594)	20.84 (0.529)	20.43 (0.519)	20.13 (0.511)	18.87 (0.479)	17.53 (0.445)	13.19 (0.335	
C\-8502	Avg. Regr.	11.50 (0.292)	12.86 (0.327)	12.97 (0.329)	13.59 (0.345)	15.26 (0.388)	14.82 (0.376)	11.21 (0.285)	
	Char	17.39 (0.442)	18.14 (0.461)	18.22 (0.63)	21.04 (0.534)	22.11 (0.562)	20.77 (0.528)	18.91 (0.480)	
	Worst Regr.	11.85 (0.301)	13.19 (0.335)	13.32 (0.338)	13.74 (0.349)	15.48 (0.393)	15.12 (0.384)	13.06 (0.332)	
	Char Char	19.24 (0.489)	19.30 (0.490)	19.32 (0.491)	21.98 (0.558)	23.35 (0.593)	21.30 (0.541)	20.95 (0.532)	
MXC-199-B-1	Avg. Regr.	14.46 (0.367)	14.74 (0.374)	14.74 (0.394)	14.20 (0.361)	12.58 (0.320)	11.43 (0.290)	7.84 (0.199)	6.32 (0.161)
	Char	18.17 (0.462)	18.28 (0.464)	18.37 (0.467)	18.00 (0.457)	16.57 (0.421)	15.57 (0.395)	13.39 (0.340)	13.24 (0.336)
	Worst Regr.	14.95 (0.380)	15.18 (0.386)	15.40 (0.391)	15.27 (0.388)	13.31 (0.338)	11.98 (0.304)	10.06 (0.256)	8.88 (0.226)
	Char	18.58 (0.472)	18.82 (0.478)	19.26 (0.489)	18.58 (0.472)	17.79 (0.452)	15.87 (0.403)	14.54 (0.369)	15.29 (0.388)
CFA	Avg. Regr.	15.73 (0.400	15.34 (0.390)	14.81 (0.376)	14.03 (0.356)	13.09 (0.372)	11.26 (0.286)	9.33 (0.274)	
	Char	No char							
	Worst Regr.	17.26 (0.438)	16.62 (0.422)	16.53 (0.420)	15.17 (0.385)	14.64 (0.372)	12.41 (0.315)	10.80 (0.274)	
	Char	No char							
4C 1402	Avg. Regr.	13.54 (0.344)	14.75 (0.375)	15.37 (0.390)	18.52 (0.470)	20.41 (0.518)	17.63 (0.448	10.44 (0.265)	
	Char	19.84 (0.504)	22.77 (0.578)	23.68 (0.601)	25.76 (0.654)	26.97 (0.685)	25.53 (0.648)	18.59 (0.472)	
	Worst Regr.	14.04 (0.357)	15.71 (0.399)	16.85 (0.428)	19.18 (0.487)	20.69 (0.526)	17.90 (0.455)	11.49 (0.282)	
	Char	21.05 (0.535	23.36 (0.593)	23.77 (0.604)	27.06 (0.687)	28.11 (0.714)	29.11 (0.739)	20.80 (0.528)	

*Normalized to 600 psia (413.6 N/cm^2) chamber pressure and 57.5 seconds.

TABLE IV-23

NORMALIZED* REGRESSION AND CHAR RATES OF "A" SECTION MATERIALS,
MILS (MM) PER SECOND

Material		Station +3.0	+4.0	+5.0	+6.0	ε = 3.0
UF-1161	Avg. Regr.	No measurements made. Consumed in disassembly of nozzle components from shell.				
	Char					
	Worst Regr.					
	Char					
CA-8502	Avg. Regr.	11.37 (0.289)	9.78 (0.248)	9.28 (0.236)	7.47 (0.190)	1.91 (0.049)
	Char	18.42 (0.468)	15.21 (0.386)	14.93 (0.379)	13.94 (0.354)	9.50 (0.241)
	Worst Regr.	14.95 (0.380)	15.81 (0.402)	13.65 (0.347)	10.51 (0.267)	3.52 (0.089)
	Char	22.97 (0.583)	19.34 (0.491)	17.92 (0.455)	16.97 (0.431)	11.91 (0.303)
MXC-199 B-1	Avg. Regr.		5.83 (0.148)	6.54 (0.166)	7.77 (0.197)	10.4 (0.264)
	Char		- -	- -	- -	- -
	Worst Regr.		7.07 (0.180)	7.92 (0.201)	9.33 (0.237)	11.68 (0.297)
	Char		- -	- -	- -	- -
CFA	Avg. Regr.	11.86 (0.301)	11.05 (0.281)	7.54 (0.192)	5.48 (0.139)	5.21 (0.132)
	Char	No Char				
	Worst Regr.	14.88 (0.378)	13.20 (0.335)	11.86 (0.301)	8.10 (0.206)	6.63 (0.168)
	Char	No Char				
4C 1402	Avg. Regr.	7.24 (0.184)	6.55 (0.166)	6.85 (0.174)	6.07 (0.154)	3.36 (0.085)
	Char	12.31 (0.313)	11.90 (0.302)	13.02 (0.331)	11.58 (0.294)	8.36 (0.212)
	Worst Regr.	10.00 (0.254)	10.05 (0.255)	9.34 (0.237)	7.12 (0.181)	5.00 (0.127)
	Char	12.90 (0.328)	14.16 (0.360)	16.10 (0.409)	14.16 (0.360)	11.26 (0.286)

*Normalized to 600 psi (413.6 N/cm^2) chamber pressure and 47.5 sec.

TABLE IV-24

NORMALIZED* REGRESSION AND CHAR RATES OF "B" SECTION MATERIALS, MILS (MM) PER SECOND

Material	Measurement	Station +12.0		Station ε = 5.5	
UF-1164	Avg. Regr.	No measurement made. Consumed in disassembly of nozzle components from shell.			
	Char				
	Worst Regr.				
	Char				
DP5-161/Si	Avg. Regr.	2.11	(0.054)	(-)	(-)
	Char	5.72	(0.145)	1.56	(0.040)
	Worst Regr.	3.43	(0.087)	(-)	(-)
	Char	7.06	(0.179)	2.75)	(0.070)
MXC-12449	Avg. Regr.	17.75	(0.451)	28.51	(0.724)
	Char	No measurement made of char			
	Worst Regr.	19.82	(0.503	37.48	(0.952)
	Char	Consumed in disassembly			
CFA	Avg. Regr.	0.98	(0.025)	(-)	(-)
	Char	No char			
	Worst Regr.	2.91	(0.074)	(-)	(-)
	Char	No char			
4C 1402	Avg. Regr.	0.69	(0.018)	1.51	(0.038)
	Char	5.69	(0.145)	5.48	(0.139)
	Worst Regr.	1.44	(0.037)	2.06	(0.052)
	Char	7.12	(0.181)	6.42	(0.163)

*Normalized to 600 psia (413.6 N/cm^2) chamber pressure and 57.5 seconds.

TABLE IV-25

NORMALIZED* REGRESSION AND CHAR RATES OF "C" SECTION MATERIALS, MILS (MM) PER SECOND

Material	Measurement	Station +18.0		Station +22.0	
4K 9502	Avg. Regr.	No measurements made. Consumed in			
	Char	disassembly of nozzle components from			
	Worst Regr.	shell.			
	Char				
DP5-161/Si	Avg. Regr.	(-)	(-)	(-)	(-)
	Char	0.29	(0.007)		
	Worst Regr.	(-)	(-)	(-)	(-)
	Char	0.88	(0.022)		
4K 9502	Avg. Regr.	43.16	(1.096)	37.84	(0.961)
	Char	No measurements made of char.			
	Worst Regr.	49.04	(1.246)	40.08	(1.247)
	Char	Consumed in disassembly			
CFA	Avg. Regr.	(-)	(-)	(-)	(-)
	Char	No char		-	-
	Worst Regr.	(-)	(-)	(-)	(-)
	Char	No Char			
CA-2213	Avg. Regr.	2.17	(0.055)	0.84	(0.021)
	Char	5.96	(0.151)	3.68	(0.093)
	Worst Regr.	3.56	(0.090)	1.55	(0.039)
	Char	7.19	(0.183)	3.74	(0.095)

*Normalized to 600 psi (413.6 N/cm^2) chamber pressure and 57.5 seconds.

TABLE IV-26

EFFECT OF NOZZLE EROSION RATES ON
260/SIVB VEHICLE PAYLOAD CAPABILITY (REF. 8)

Nozzle Throat Erosion Rate, Mils/sec	(cm/sec)	Payload for 105 NM (195 KM) Orbit, lbm	(Kg)	Change in Payload, lbm	(Kg)
6 (Base Case)	(0.015)	94,675	(43,030)	0	
10	(0.025)	93,721	(42,600)	-954	(430)
15	(0.038)	92,451	(42,023)	-2224	(1007)
20	(0.051)	91,206	(41,457)	-3469	(1573)
25	(0.063)	89,954	(40,889)	-4721	(2141)
25 (Modified Grain)	(0.063)	91,045	(41,384)	-3630	(1646)

TABLE IV-27

260-IN.-DIA(6.6 m) MOTOR WEIGHT AND COST
INCREASE REQUIRED TO ACHIEVE BASELINE PAYLOAD (REF. 8)

Nozzle Throat Erosion Rate, mils/sec	(cm/sec)	Motor Weight Increase for Equal Performance, (lbm (kg)		Motor Cost* Increase, $
6 (Base Case)	(0.015)	0		0
10	(0.025)	52,900	(24,000)	98,400
15	(0.038)	121,300	(55,000)	225,600
20	(0.051)	189,700	(86,200)	352,800
25	(0.063)	258,100	(117,300)	480,100
25 (Modified Grain)	(0.063)	181,500	(82,500)	337,600

*Assumes motor cost increase at a rate of $1.86 lbm (4.10 per Kg)

TABLE IV-28

INCREASED 260-IN. (6.6 m) MOTOR COSTS RESULTING FROM USE OF LOW COST THROAT MATERIALS

Material	Fabrication Technique	Erosion Rate, Mils/sec (cm/sec)	Motor Cost Increase, $
4C 1686	Molding	6.69 (0.017)	17,000
CA 8502	Molding	9.73 (0.025)	91,800
MXC-199 B-1	Wrapping	8.03 (0.020)	49,900
CFA	Molding	8.35 (0.021)	57,800
4C 1402	Molding	13.02 (0.033)	105,600
UF 1161	Molding	7.31 (0.019)	32,619

TABLE IV-29

COST AND PERFORMANCE COMPARISON OF
TAPE-WRAPPED MATERIALS FOR THROAT

		260-FL Baseline	MXC-199 B-1
1.	Savings In:		
	Material based on 1647 lbm (748.6 Kg)	None	10,047
	Direct Labor	None	None
	Direct Labor Overhead	None	None
	Tooling	None	None
	G&A, @ 8.5 percent	None	854
	Profit, @ 10 percent	None	1,090
2.	Increased Motor Cost for Equal Payload	None	(49,900)
3.	Realized Net Savings	None	(37,909)

TABLE IV-30

COST AND PERFORMANCE COMPARISON OF MOLDED THROAT MATERIALS

	260-FL Baseline	4C 1486	CA 8502	CFA	4C 1402	UF-1161
Material	36,432	32,735	22,849	4,128	22,468	2,133
Direct Labor	18,684	11,969	11,969	11,969	11,969	11,969
D.L.O. @ 174 percent	32,510	20,826	20,826	20,826	20,826	20,826
Tooling	1,541	745	745	745	745	745
G&A @ 8.5 percent	7,579	5,633	4,793	3,202	4,761	3,032
Profit @ 10 percent	9,675	7,191	6,118	4,087	6,077	3,871
Unit Throat Cost	106,421	79,099	67,300	44,957	66,846	42,576
Increased Motor Cost	None	17,000	91,800	57,800	105,600	32,619
TOTAL COST	106,421	96,099	159,100	102,757	172,446	75,195
Realized Net Savings	None	10,322	(52,679)	3,664	(66,025)	31,226

TABLE IV-31

TOOLING REQUIREMENTS FOR 260-FL THROAT

A.	For Wrapped Component (From Reference 8)	
	Wrap Mandrel	38,400
	Mandrel Handling Aid	2,500
	Ablative Handling Aid	2,740
	Tracer Template (Wrap)	660
	Tracer Template (Mach.) (2 req'd)	1,320
	Ablative Storage Fixture	600
		46,220
B.	For Molded Component	
	Die Set	18,000
	Tracer Template	1,320
	Ablative Handling Aid	2,740
	Ablative Storage Fixture	600
		22,660

TABLE IV-32. - FABRICATION DATA FOR NOZZLE 006

Component	Material	Mold Temp., °F, (°C)	Cure Temp. °F, (°C)	Cure Pressure, psi (N/cm^2)	Cure Time, hrs	Remarks
Approach	ARC-100	R.T.	340 (171)	Ambient	12	Cast in one ring. Machined and slit into 8 separate segments and bonded together. Numerous voids and circumferential tears.
Entrance	ARC-100	R.T.	340 (171)	Ambient	12	Cast, machined and slit as above. Cracked through offsets. Repaired with Ironsides DP5-160H resin. Numerous voids and small tears.
Nosecap	UF 1161	R.T.	310 (154)	1000 (689)	5	Molded one piece. Machined and slit into four segments, then bonded together. Free of defects.
Throat	UF 1161	R.T.	310 (154)	1000 (689)	5	Molded one piece and step cured. Free of defects.
O'Wrap	4K 9502	180 (82)	310 (154)	150 (103)	2	Wrapped over throat insert parallel to O.D. surface. Free of defects.
"A" Section	UF-1164	R.T.	310 (154)	200 (138)	12	Outgassed 12 hr under vacuum, then step cured. Molded one piece, then machined and slit into 4 segments. Free of defects
"B" Section	MXC-199-B1	210 (99)	310 (154)	80 (55)	3	Debulked at 210F (99C) for one hour. Step cured. Molded in one piece, slit into 8 segments. Free of defects.
"C" Section	4K 9502	180 (82)	310 (154)	80 (55)	2	Debulked at 180F (82C) for one hour. Step cured. Molded one piece, slit into 8 segments. Free of defects.

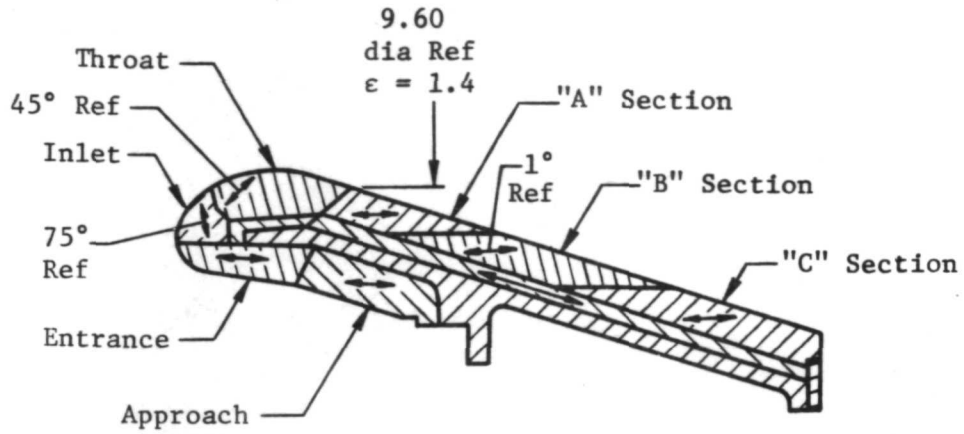
TABLE IV-33

CURED COMPOSITE PROPERTIES, NOZZLE 006

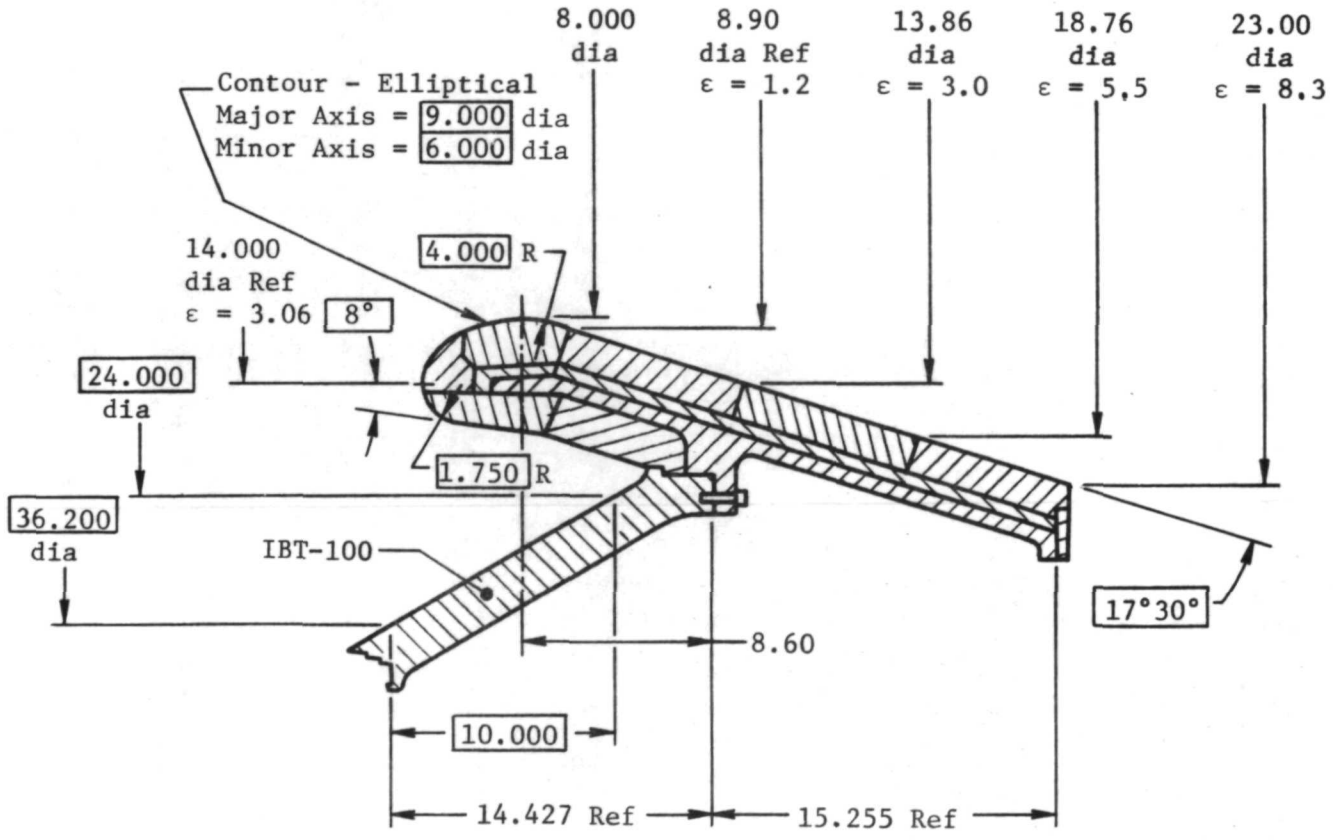
Material	Component	Specific Gravity	Hardness, Rockwell	Uncured Resin, %	Volatile Content, %
ARC-100	Approach Entrance	1.64	<M5	N.A.	N.A.
UF-1161	Nosecap	1.63	<M10	N.A.	N.A.
	Throat	1.58	<M10	N.A.	N.A.
UF-1164	"A" Section	1.60	<M10	N.A.	N.A.
MXC-199-B1	"B" Section	1.44	M113	0.29	0.87
4K 9502	"C" Section	1.32	M110	0.32	0.64

TABLE IV-34. - REGRESSION DEPTHS OF NOZZLE 006

Station	Approach-ARC-100			Entrance-ARC-100			Nosecap-UF-1161			Throat-UF-1161			Exit Cone UF 1164 + C + Canvas		
	0	135	240	0	135	240	0	135	240	0	135	240	0	135	240
Fwd End Inch (cm)							0.596 (1.514)	0.590 (1.499)	0.540 (1.371)						
-3.6 (Inboard)							0.372 (0.945)	0.580 (1.473)	0.595 (1.511)						
-3.0 (Outboard)							0.642 (1.631)	0.260 (0.660)	0.464 (1.179)						
-2.5				0.125 (0.318)	0.035 (0.089)	0.065 (0.165)				0.690 (1.753)	0.600 (1.524)	0.625 (1.588			
-2.0				0.032 (0.081)	0.005 (0.013)	0.055 (0.165)				0.915 (2.324)	0.645 (1.638)	0.720 (1.829)			
-1.75				0.005 (0.013)	-0.050 (-0.127)	0.058 (0.147)				0.905 (2.299)	0.678 (1.722)	0.895 (2.273)			
-1.0				0.008 (0.020)	-0.015 (-0.038)	0.052 (0.132)				1.025 (2.604)	0.702 (1.783)	1.024 (2.601)			
0(Throat)				0.065 (0.165)	0.022 (0.056)	0.045 (0.114)				1.058 (2.687)	0.722 (1.838)	1.080 (2.743)			
+1.0				0.052 (0.132)	0.039 (0.099)	0.064 (0.163)				0.754 (1.915)	0.684 (1.737)	0.752 (1.910)			
+2.0	0.052 (0.132)	0.008 (0.020)	0.064 (0.163)							0.408 (1.036)	0.525 (1,334)	0.524 (1.331)			
+3.0	0.072 (0.133)	0.032 (0.081)	0.081 (0.206)												
+4.0	0.015 (0.038)	-0.015 (-0.038)	0.067 (0.170)												
+5.0	0.002 (0.005)	0.005 (0.013)	0.048 (0.122)												
													EJECTED		
+6.0													0.251 (0.638)	0.312 (0.792)	0.212 (0.538)
= 3.0													0.078 (0.198)	0.259 (0.658)	0.156 (0.396)
+12.0													0.045 (0.114)	0.105 (0.267)	0.078 (0.198
= 5.5													0.094 (0.239)	0.156 (0.396)	0.105 (0.267)
+18.0													0.068 (0.173)	0.097 (0.246)	0.084 (0.213)
+22.0													0.082 (0.209)	0.041 (0.104)	0.072 (0.183)



IV-1a - Fabricated by Tape Wrapping



IV-1b - Fabricated by Casting or Molding

Figure IV-1. - Subscale Evaluation Nozzles



Figure IV-2. - Forward End of Nozzle No. 001, Showing DC 93-104 Approach and Segmented ARC-100 Entrance



Figure IV-3. - Voids in DP5-161 Throat Approach

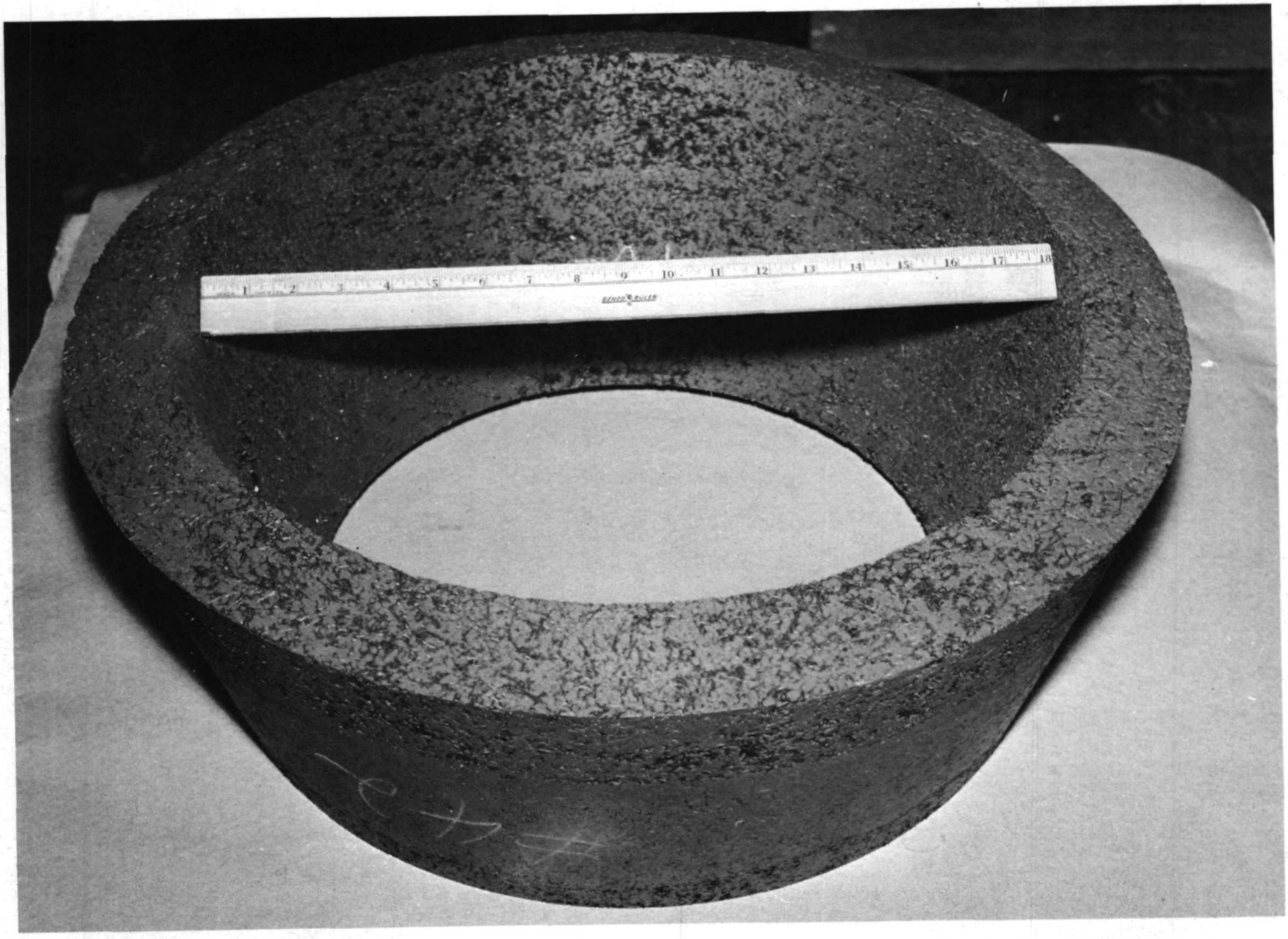


Figure IV-4. - CFA Nozzle Component Showing Exposed Fibers

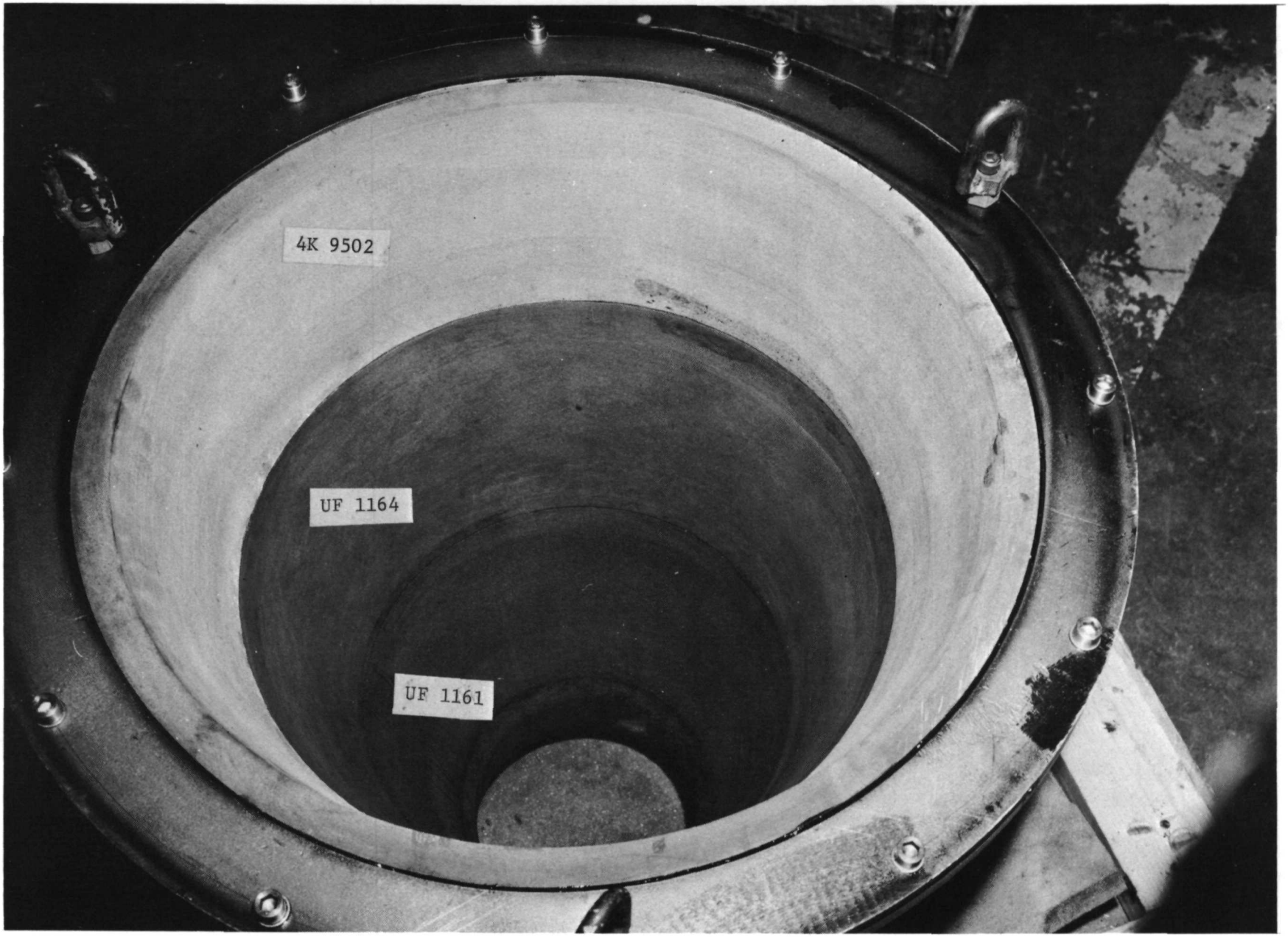
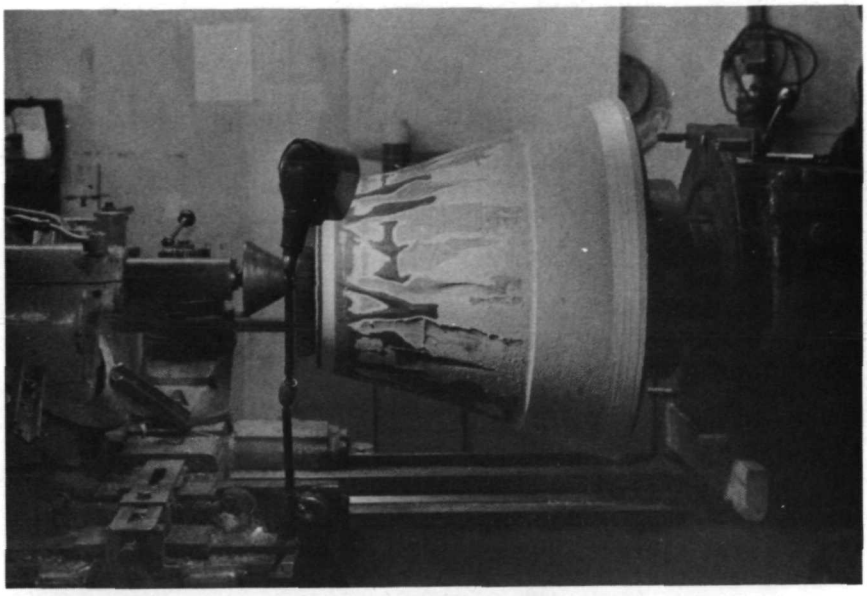


Figure IV-5. - Exit Cone of LCFT Nozzle No. 001 Prior to Test



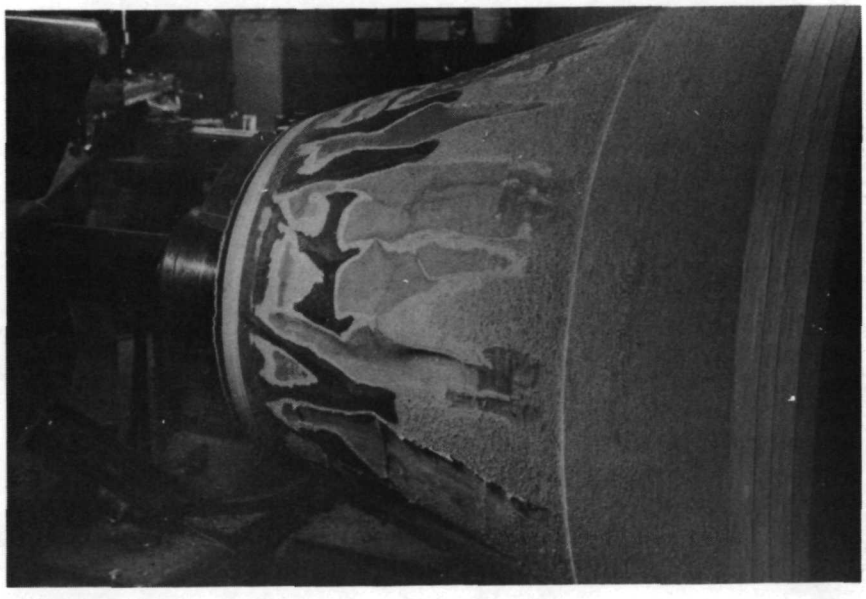


Figure IV-6. - Ridges in Extruded Carbon Fibertape

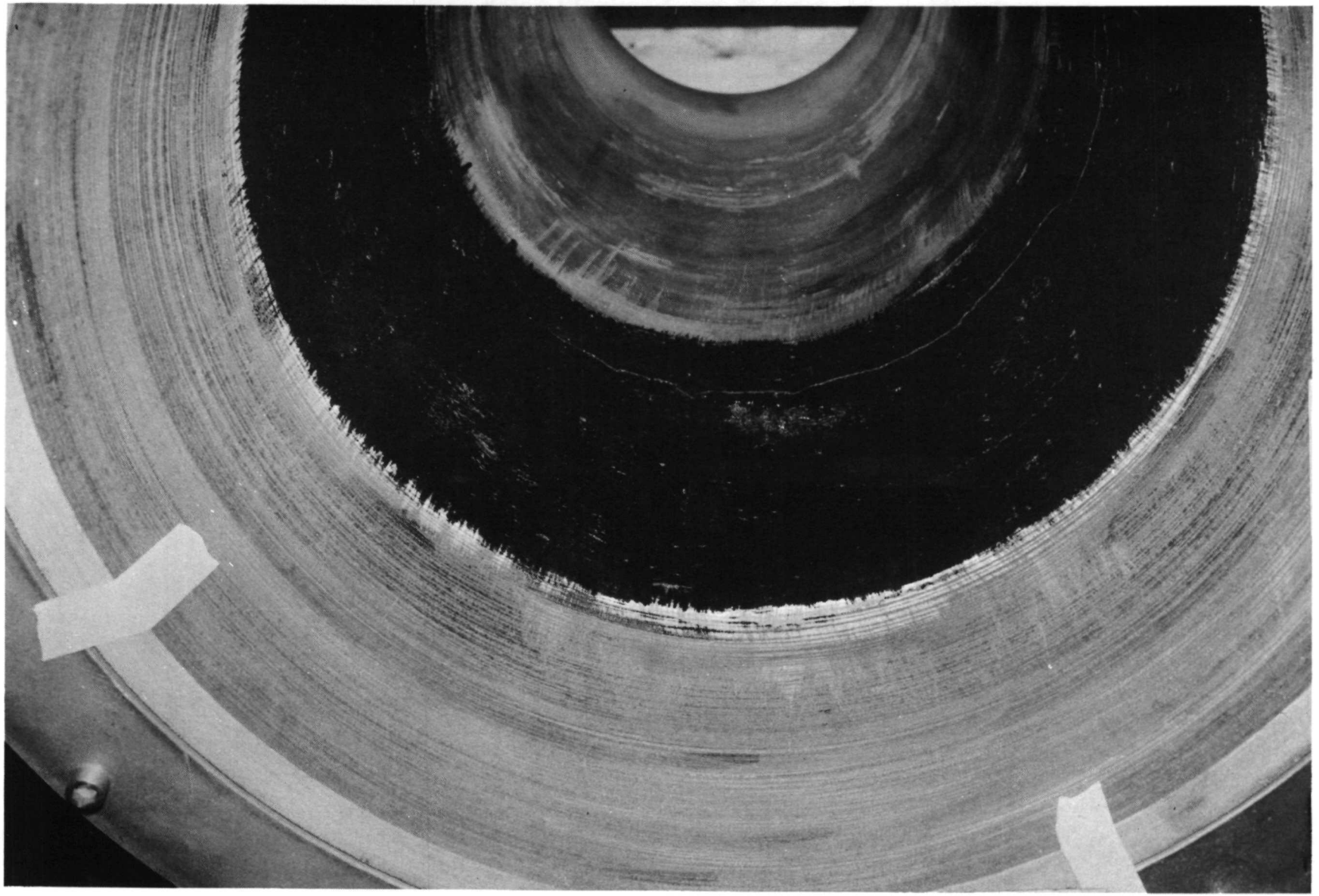


Figure IV-7. - LCFT Nozzle No. 003, Showing Delamination in "B" Section

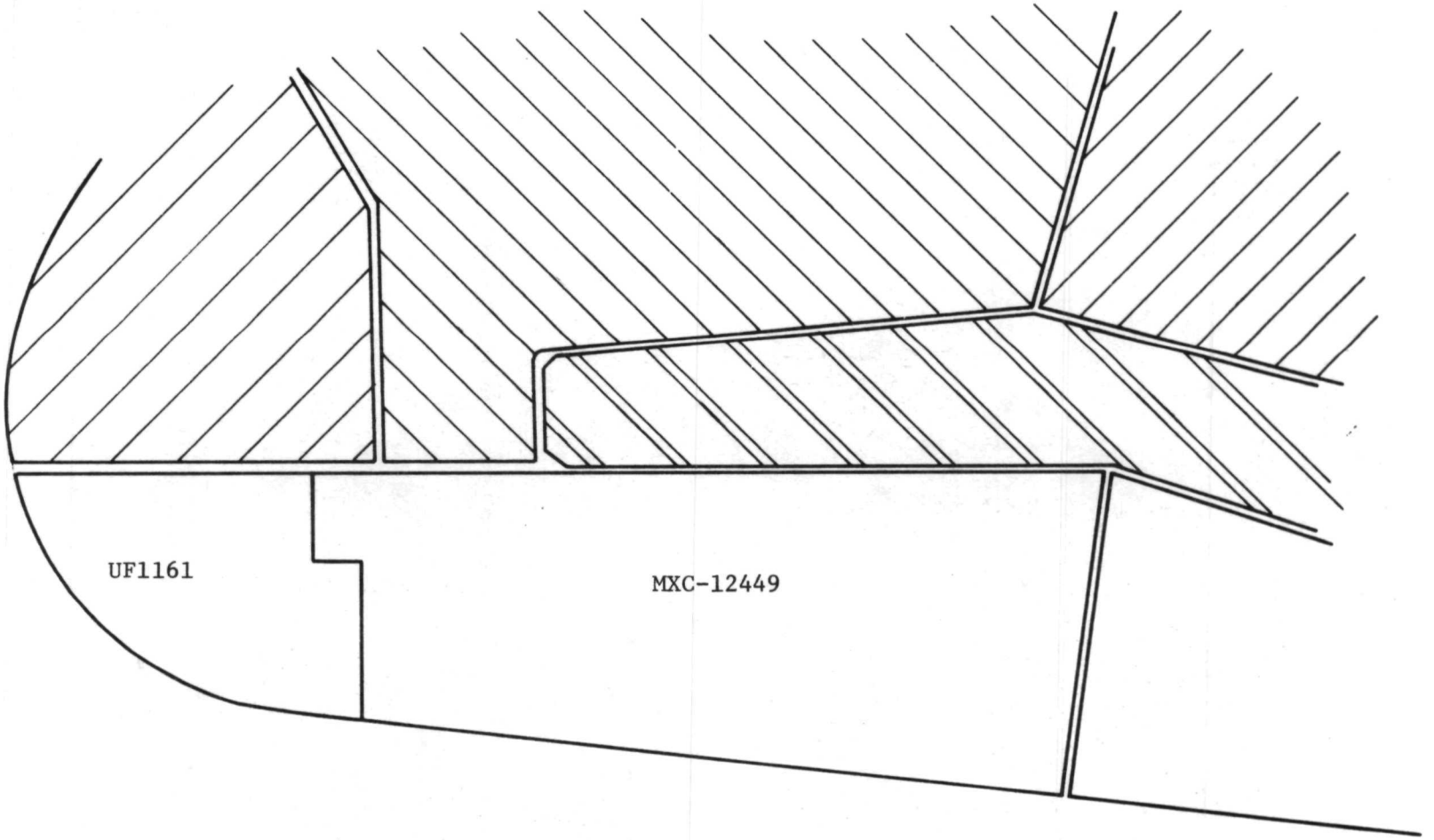


Figure IV-8. - Design of Entrance Section for Nozzle SN 002

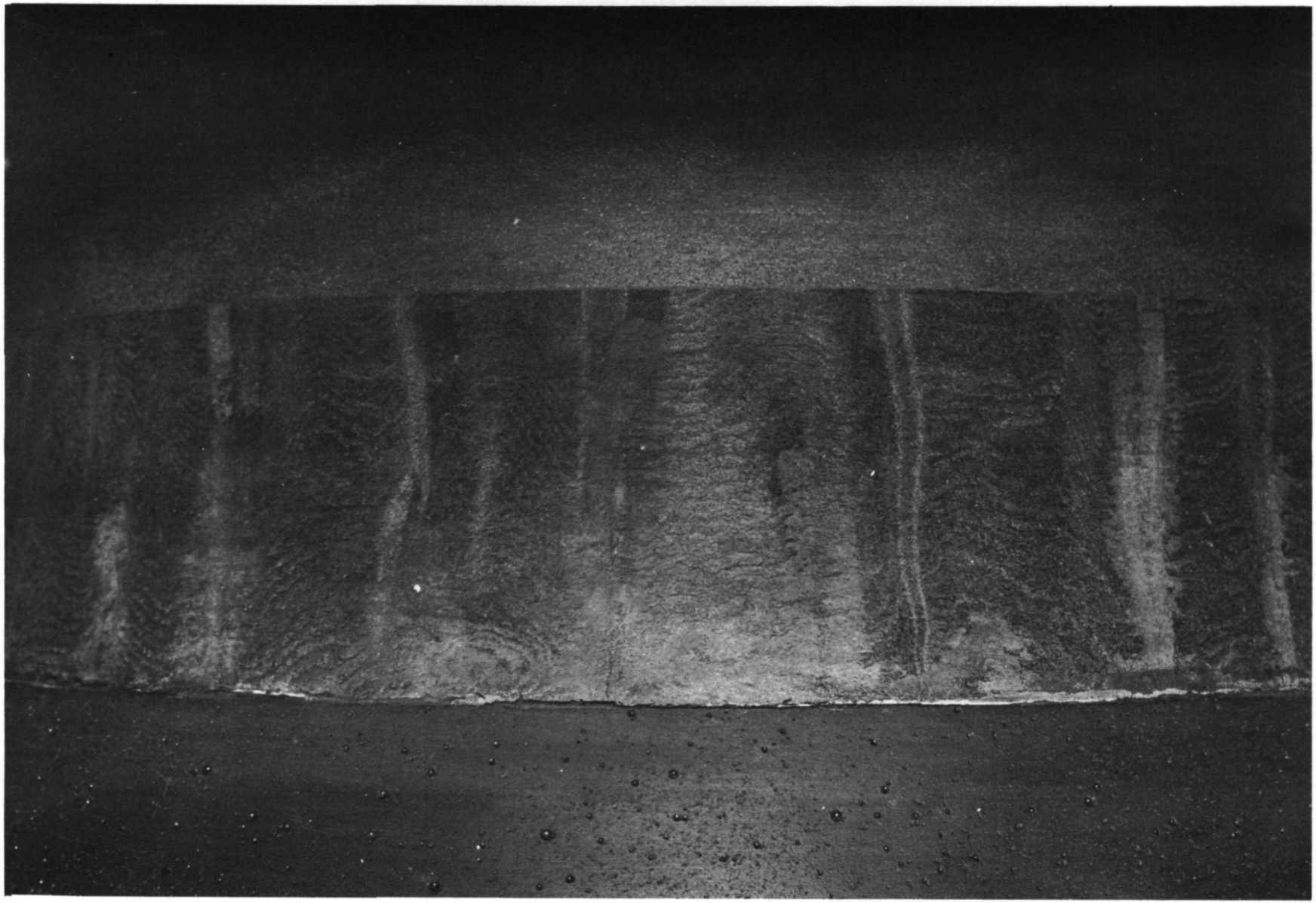
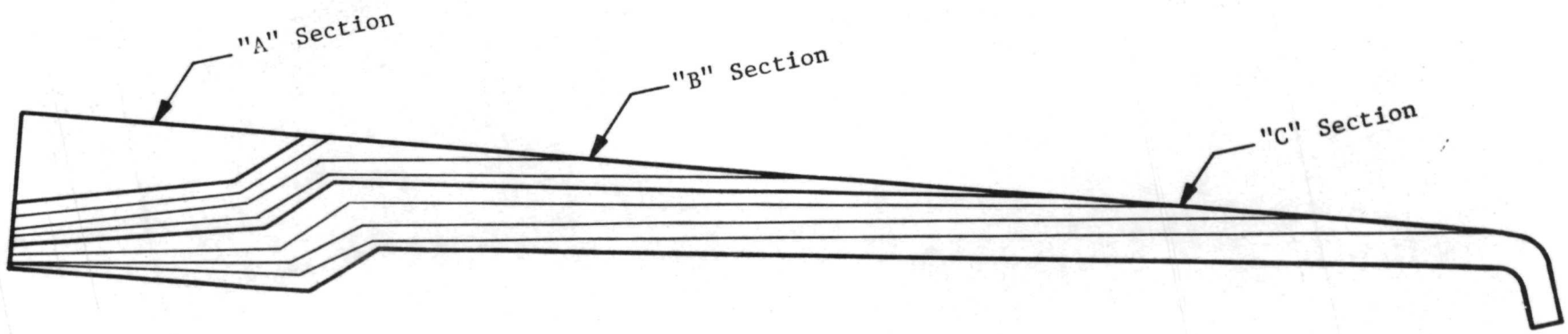


Figure IV-9. - Entrance Section of Nozzle S/N 002. Nose Cap is Molded VF-1161; Remainder is MXC-12449 Fibertape



"A" Section is compression molded.
"B" and "C" Sections are laid over "A" Section on metal form
and cured with vacuum pressure in air oven.

Figure IV-10. - Shingle-Lap Exit Cone for Nozzle 005

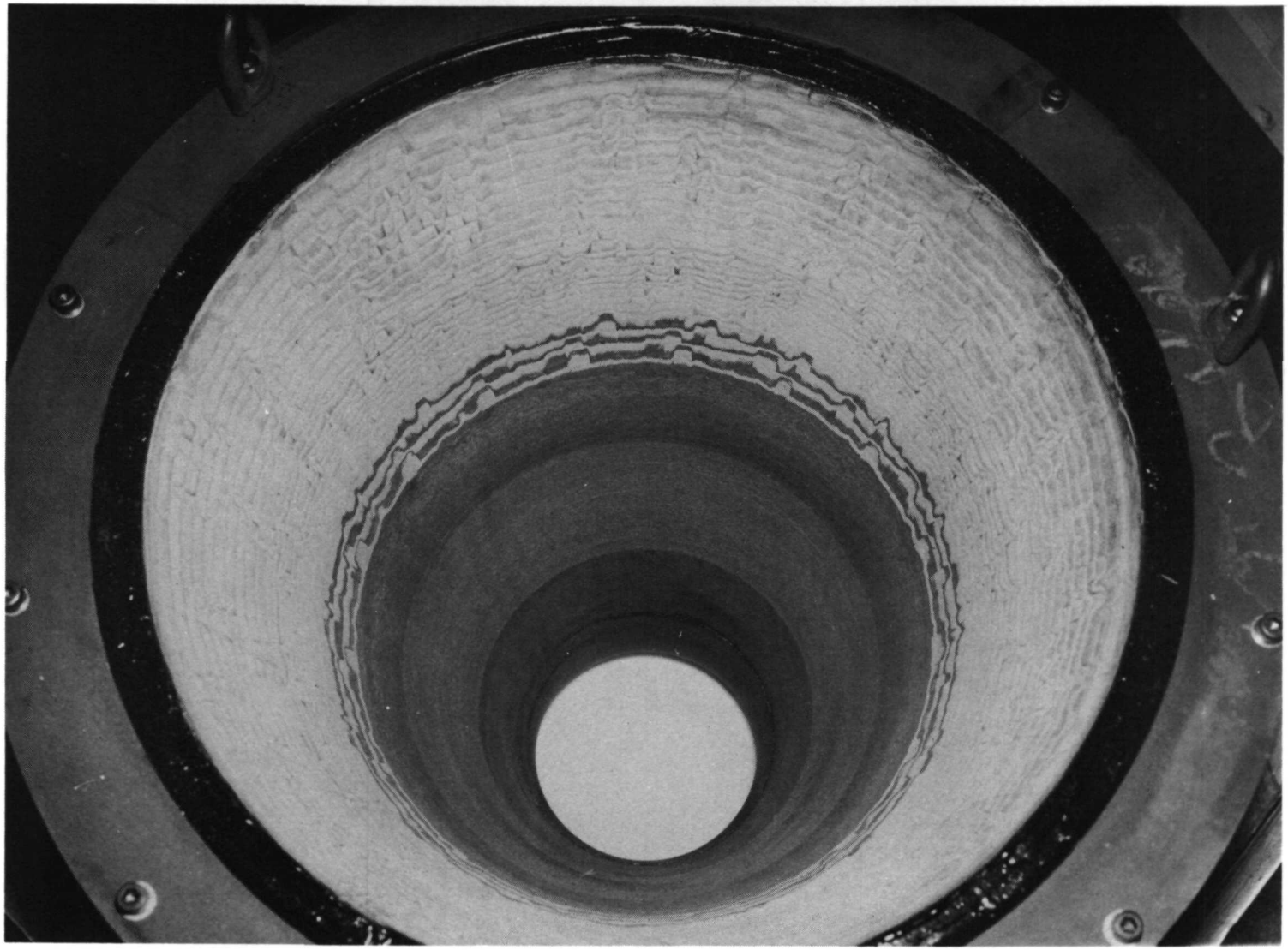


Figure IV-11. - Shingle-Lap Exit Cone of Nozzle 005

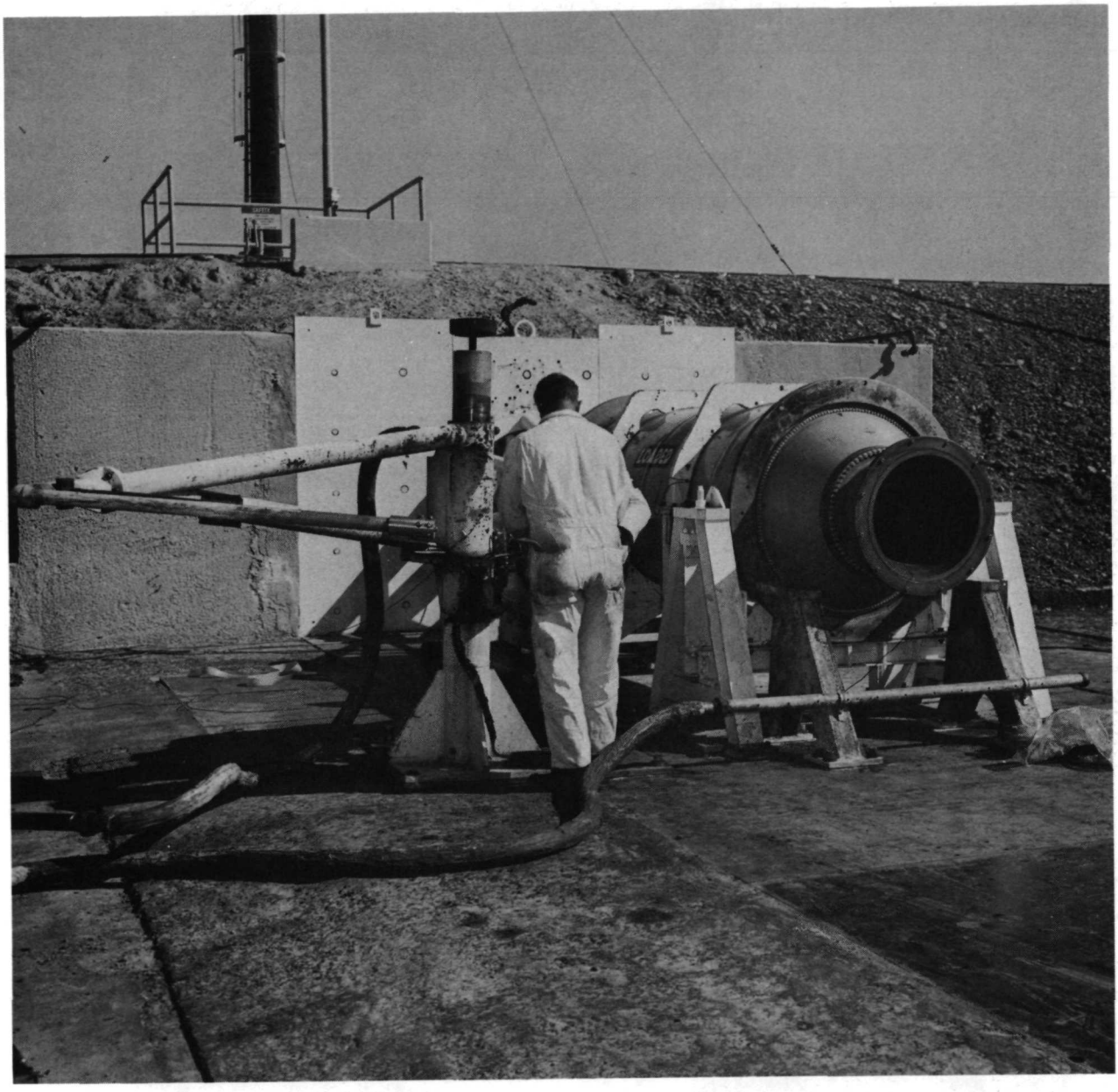


Figure IV-12. - Motor Ready for Test, Seen from Camera Angle 1



Figure IV-13. - Motor Ready for Test, Seen from Camera Angle 2

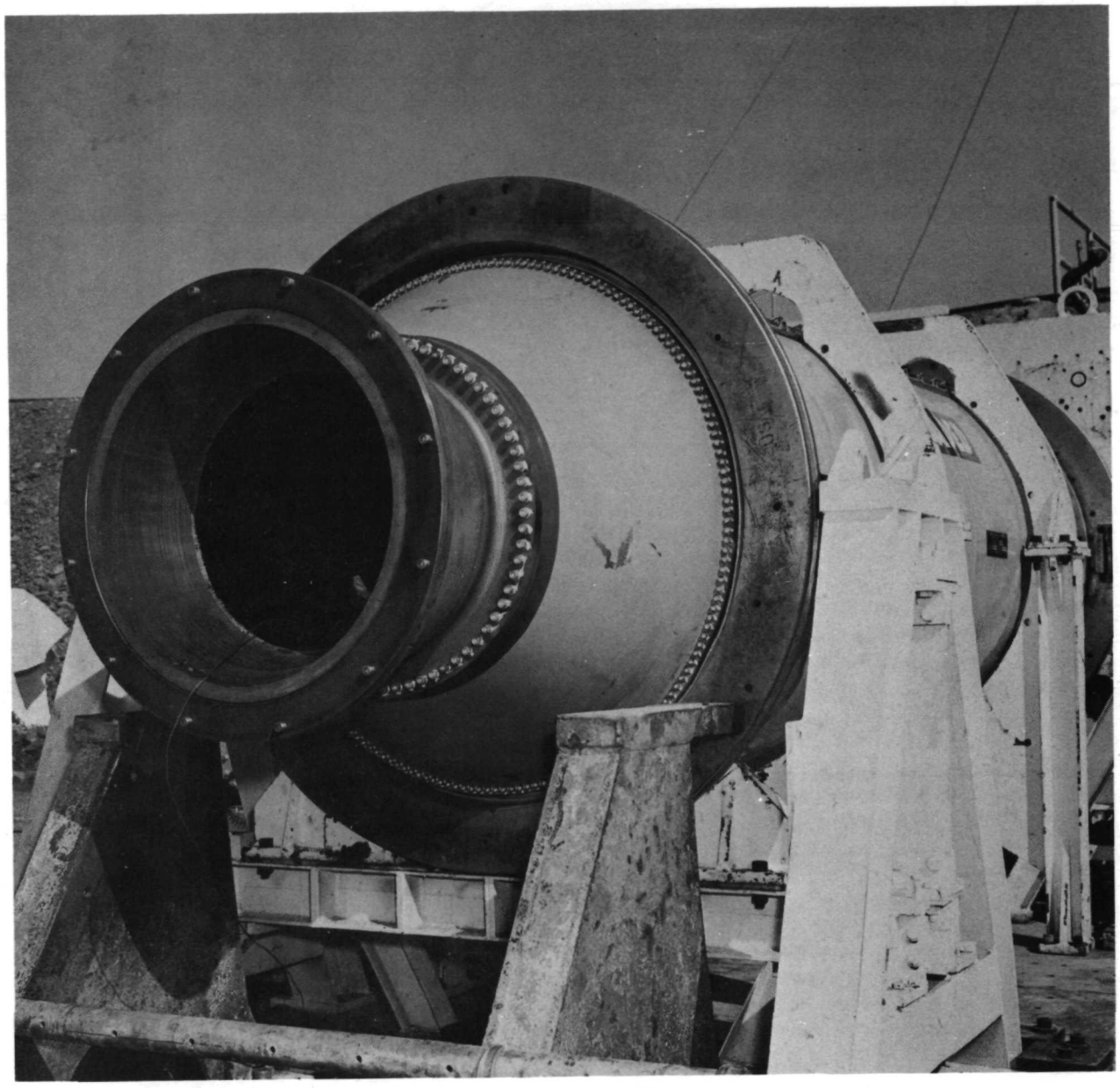


Figure IV-14. - Motor Ready for Test, Seen from Camera Angle 3

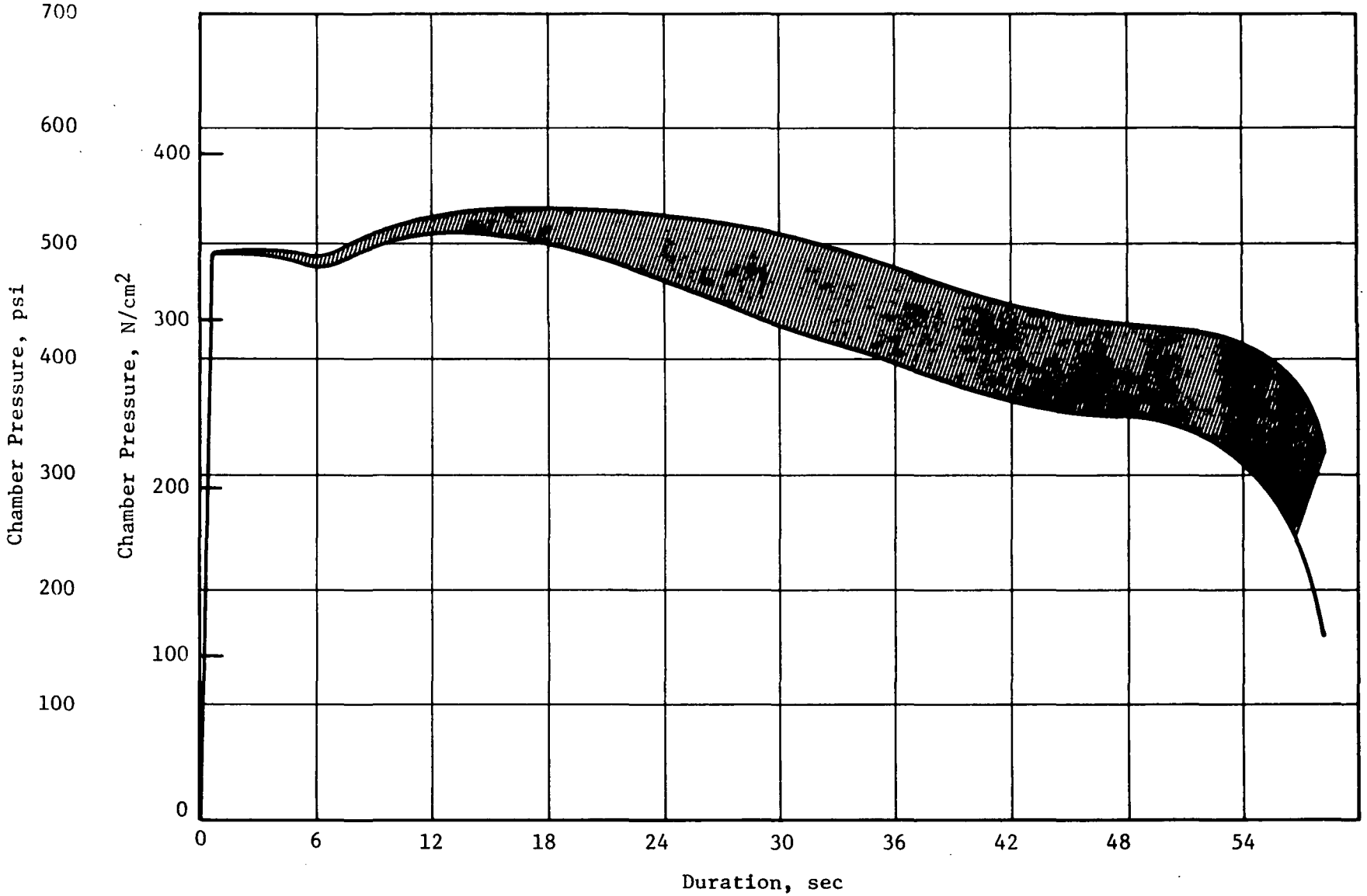


Figure IV-15. - Pressure-Time Envelope for First Five Subscale Motor Firings

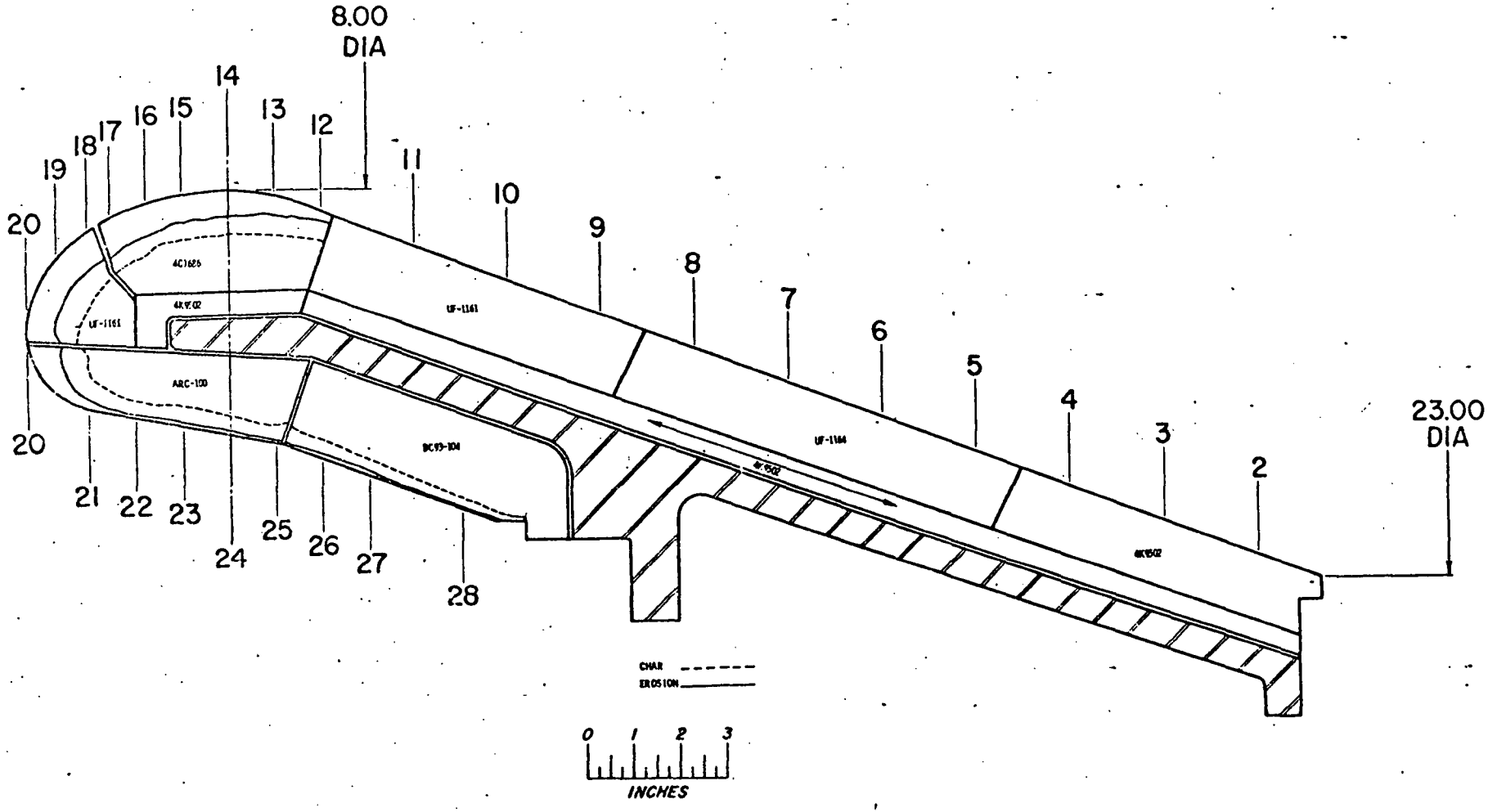


Figure IV-16. - Regression and Char Depths, Subscale Nozzle SN 001, Zero Degree Location

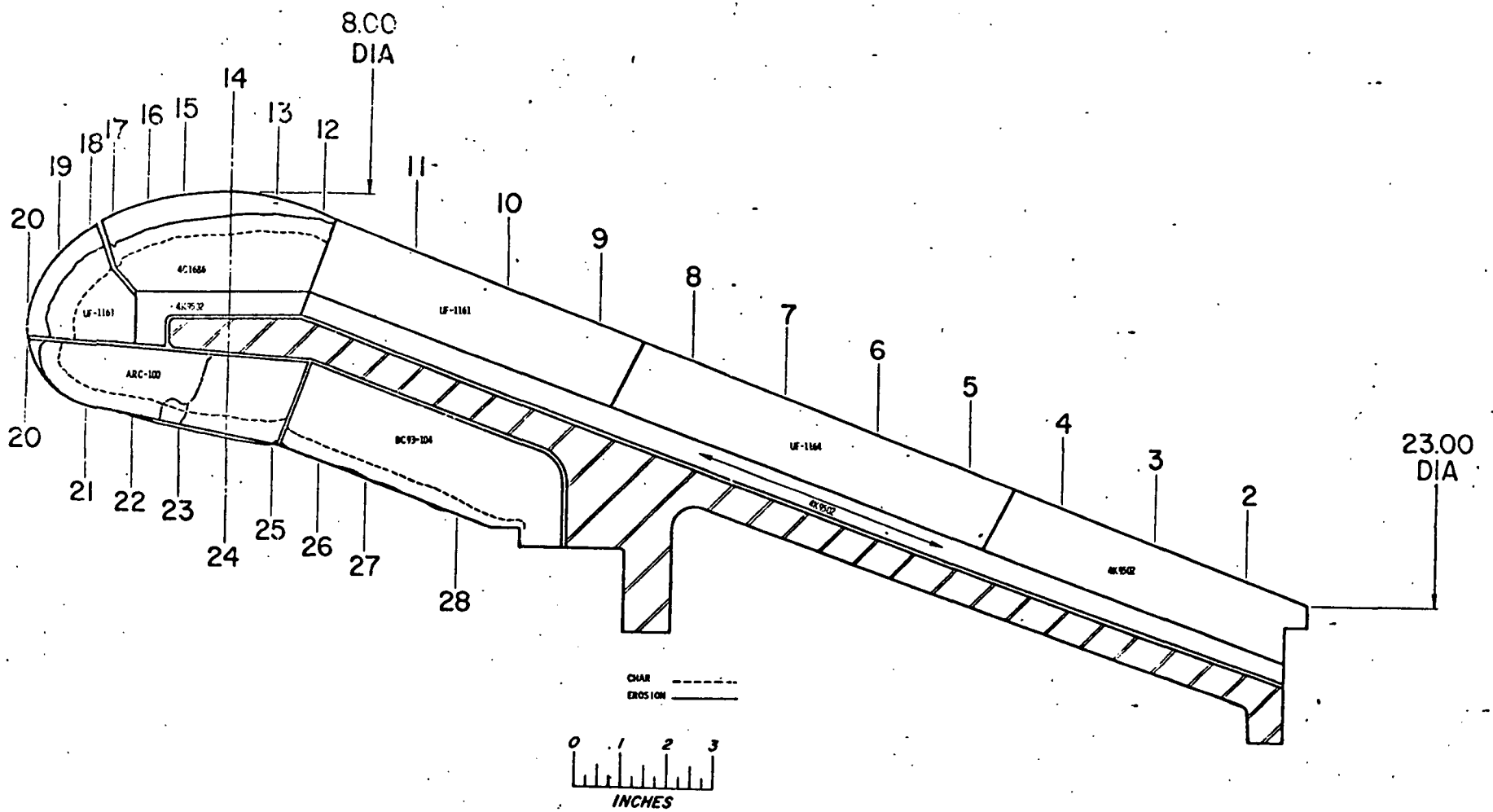


Figure IV-17. - Regression and Char Depths, Subscale Nozzle SN 001, 135-Degree Location

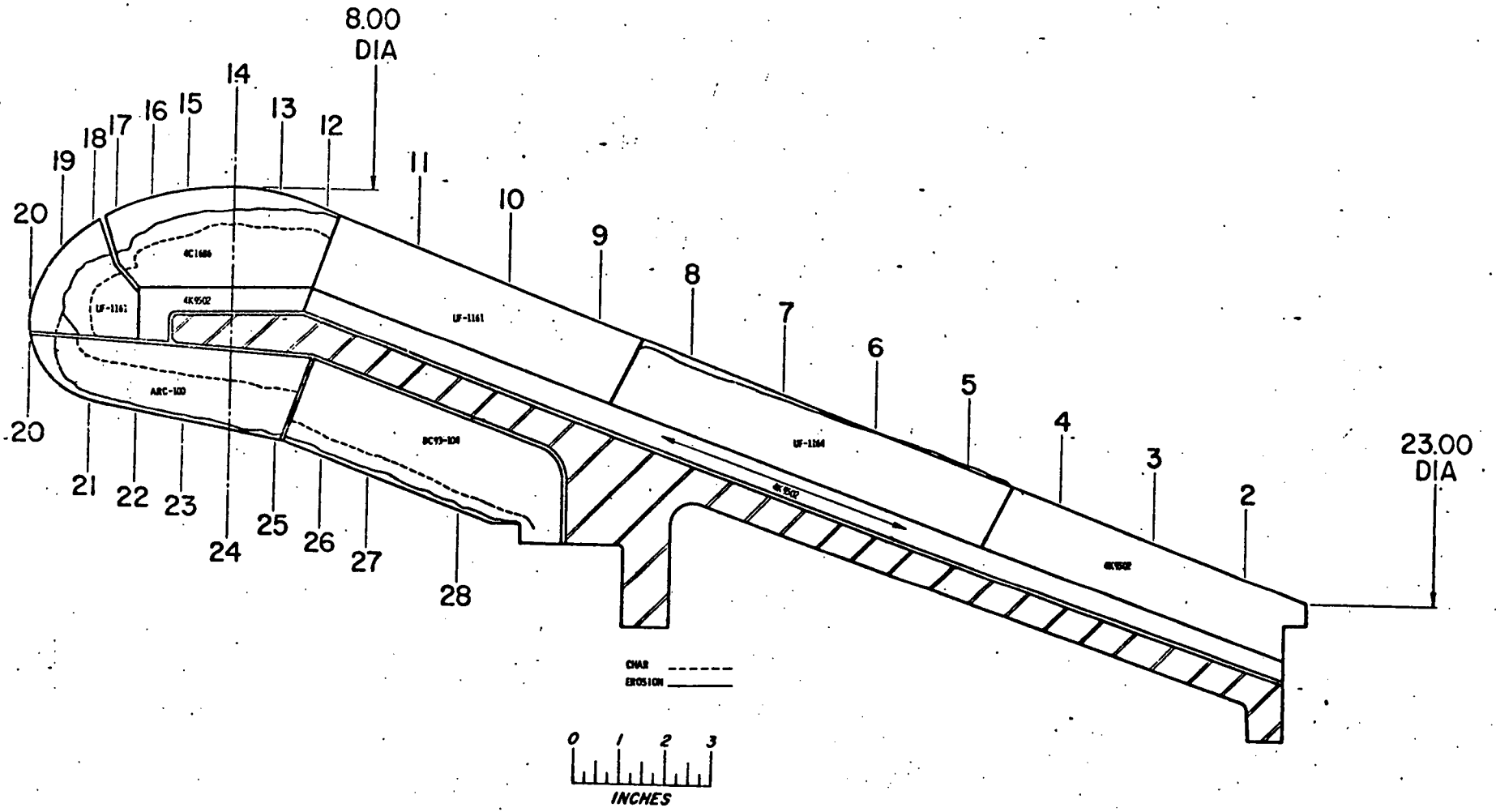


Figure IV-18. - Regression and Char Depths, Subscale Nozzle SN 001, 240-Degree Location

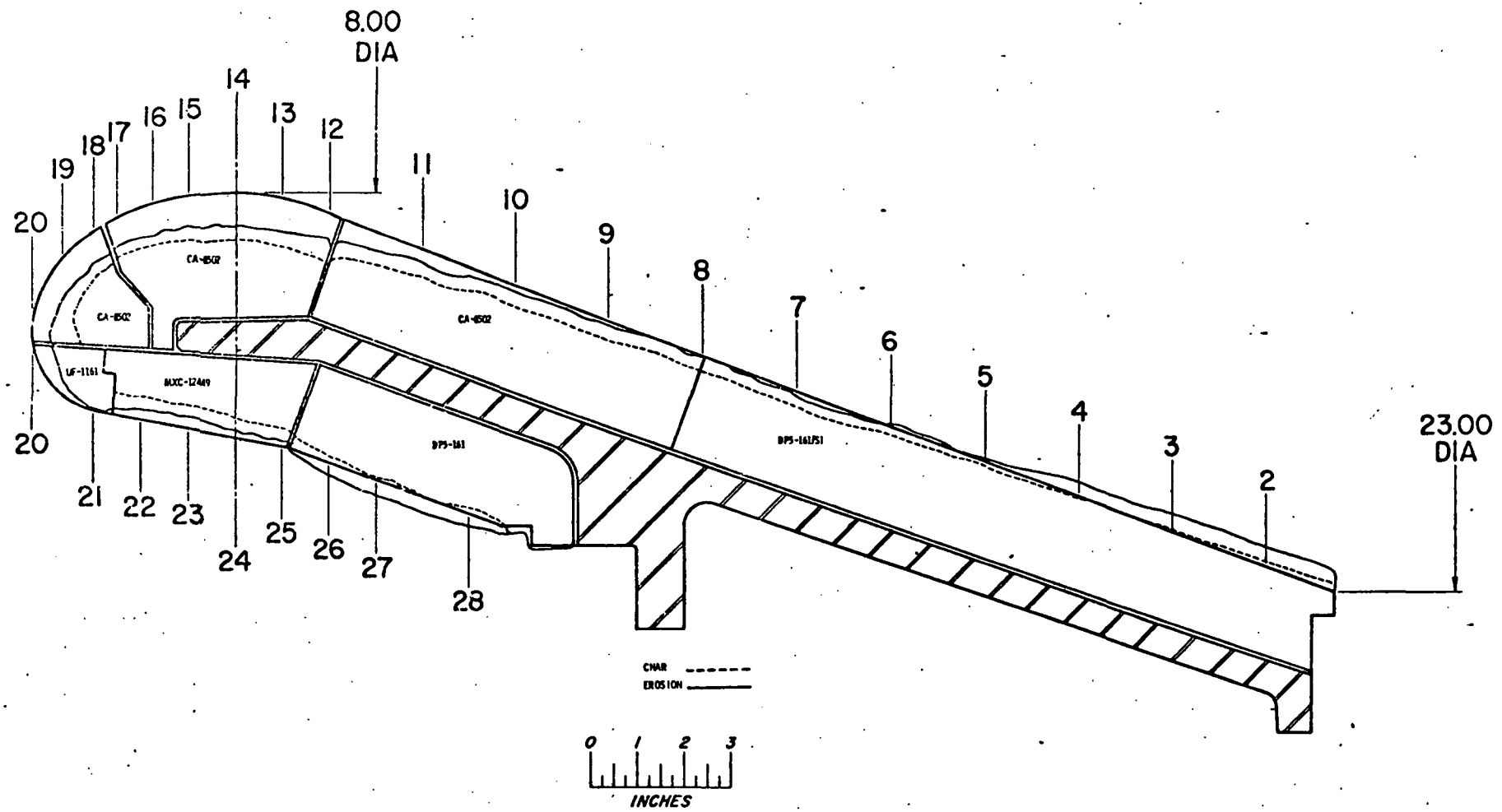


Figure IV-19. - Regression and Char Depths, Subscale Nozzle SN 002, Zero Degree Location

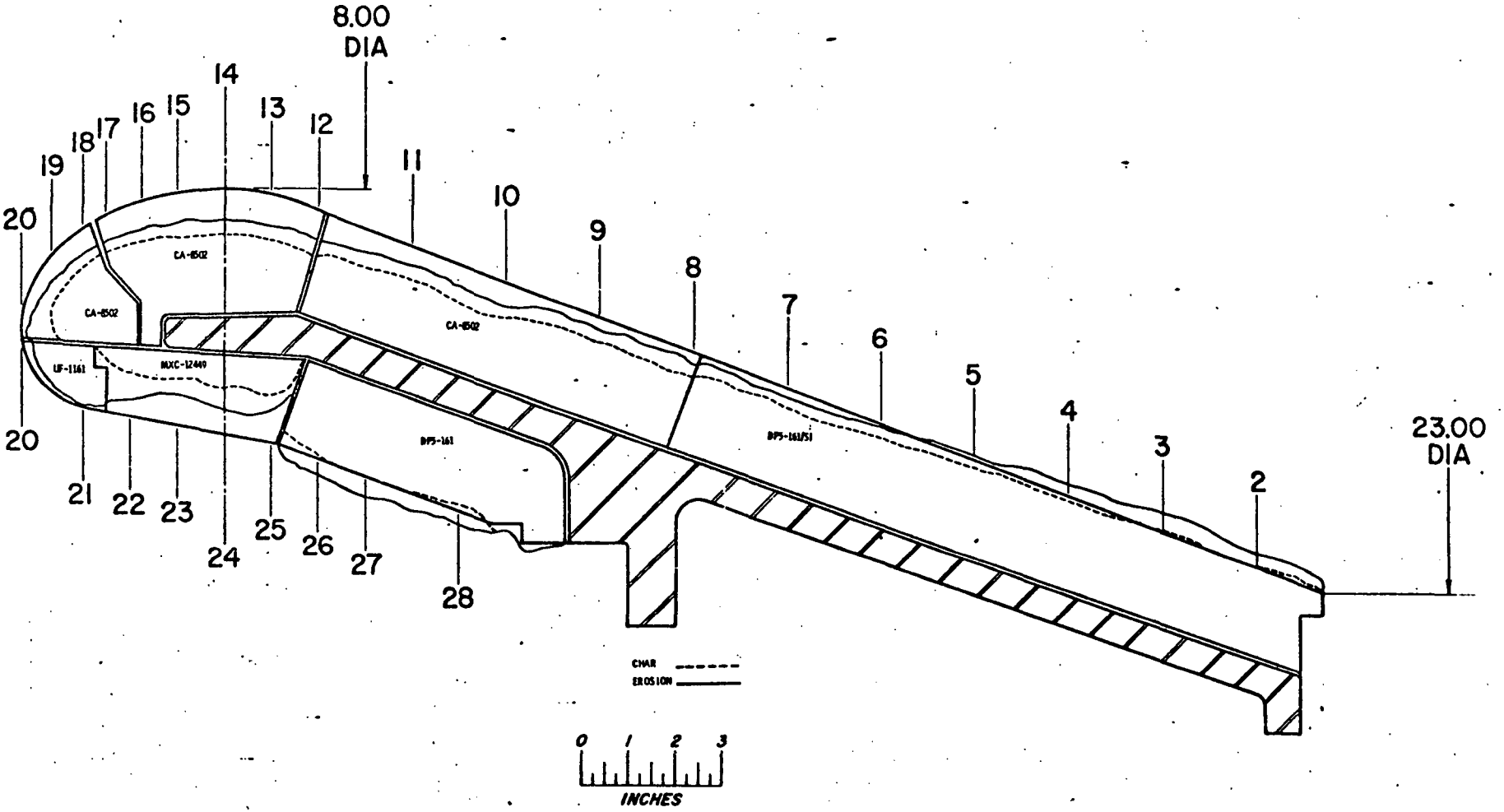


Figure IV-20. - Regression and Char Depths, Subscale Nozzle SN 002, 135-Degree Location

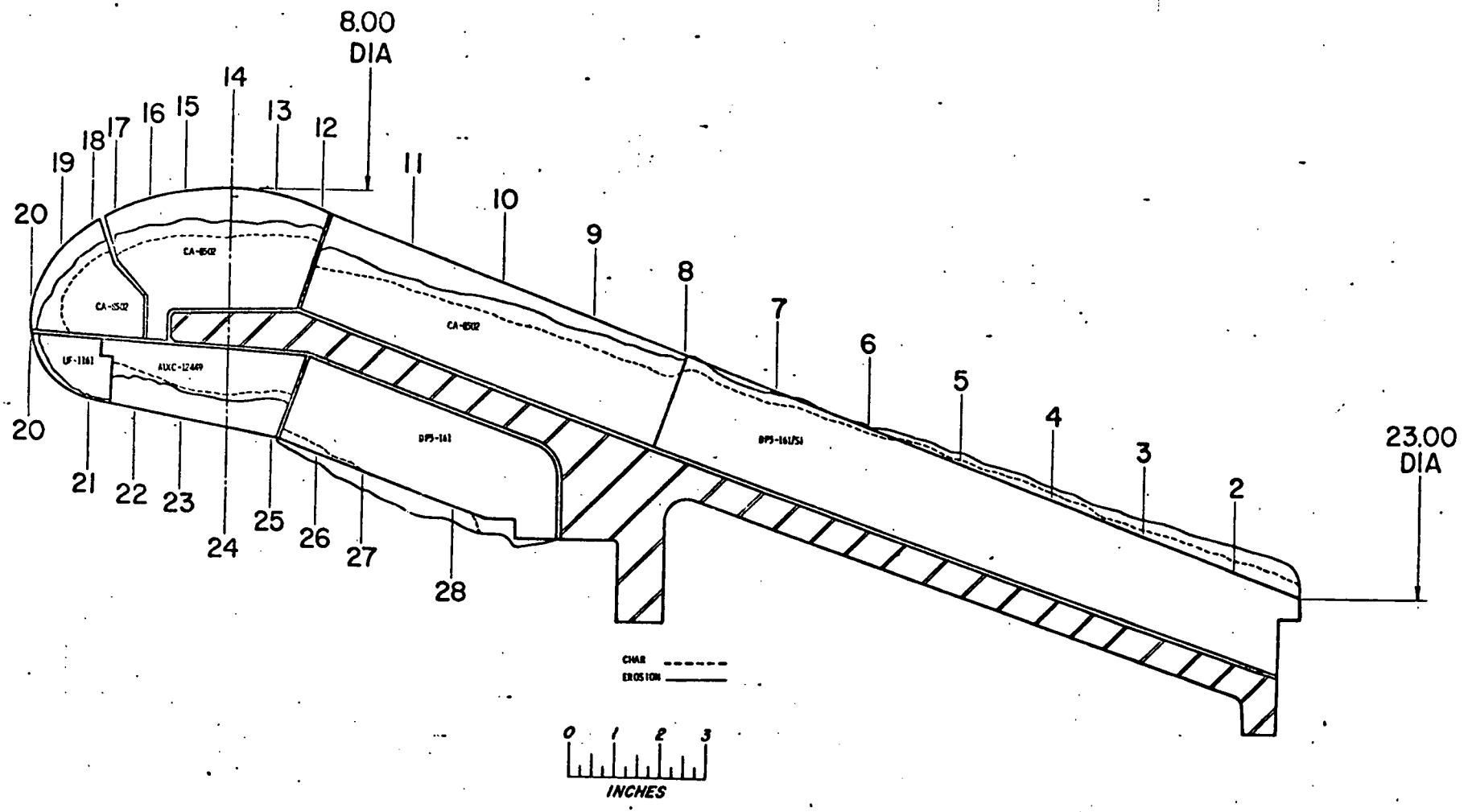


Figure IV-21. - Regression and Char Depths, Subscale Nozzle SN 002, 240-Degree Location

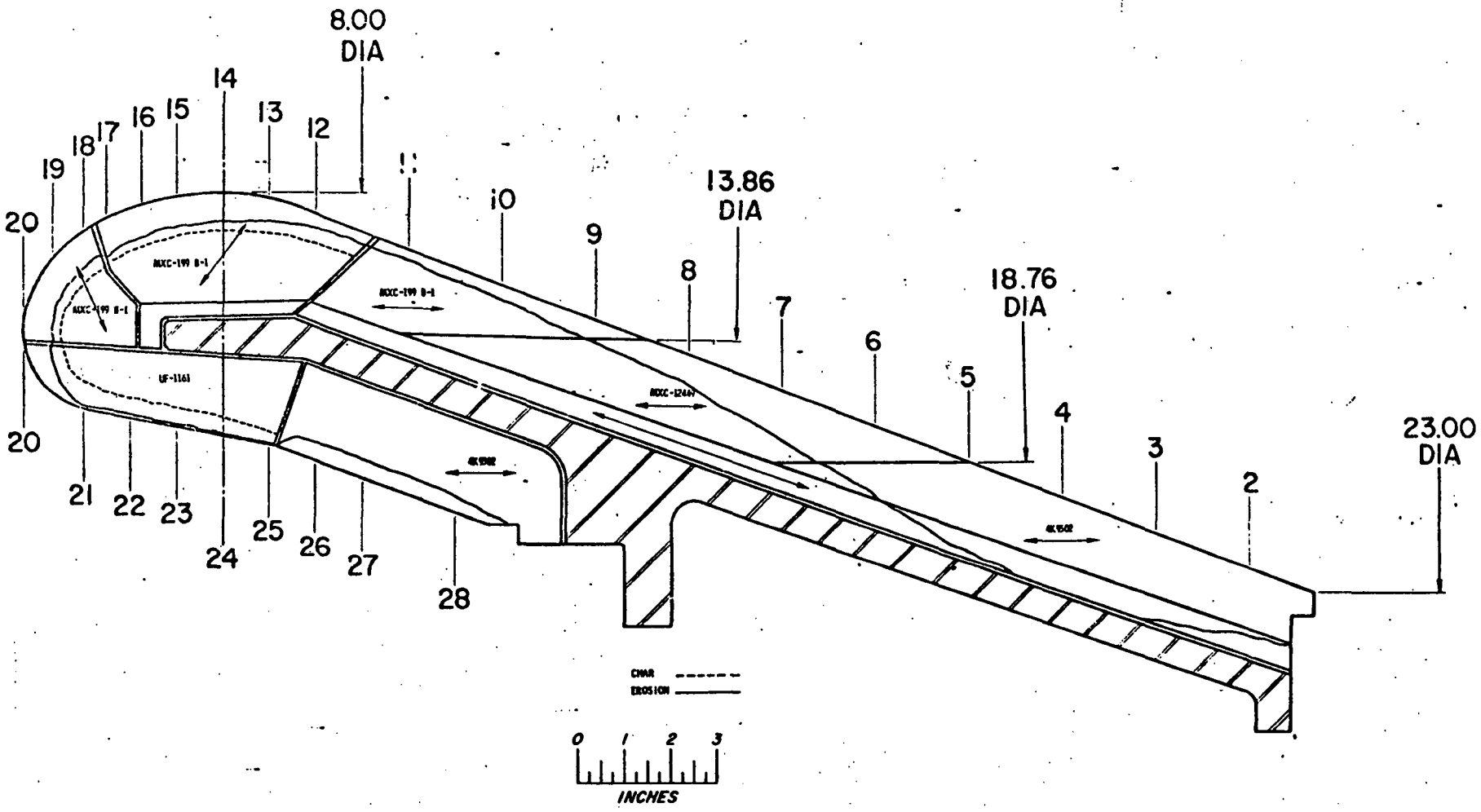


Figure IV-22. - Regression and Char Depths, Subscale Nozzle SN 003, Zero Degree Location

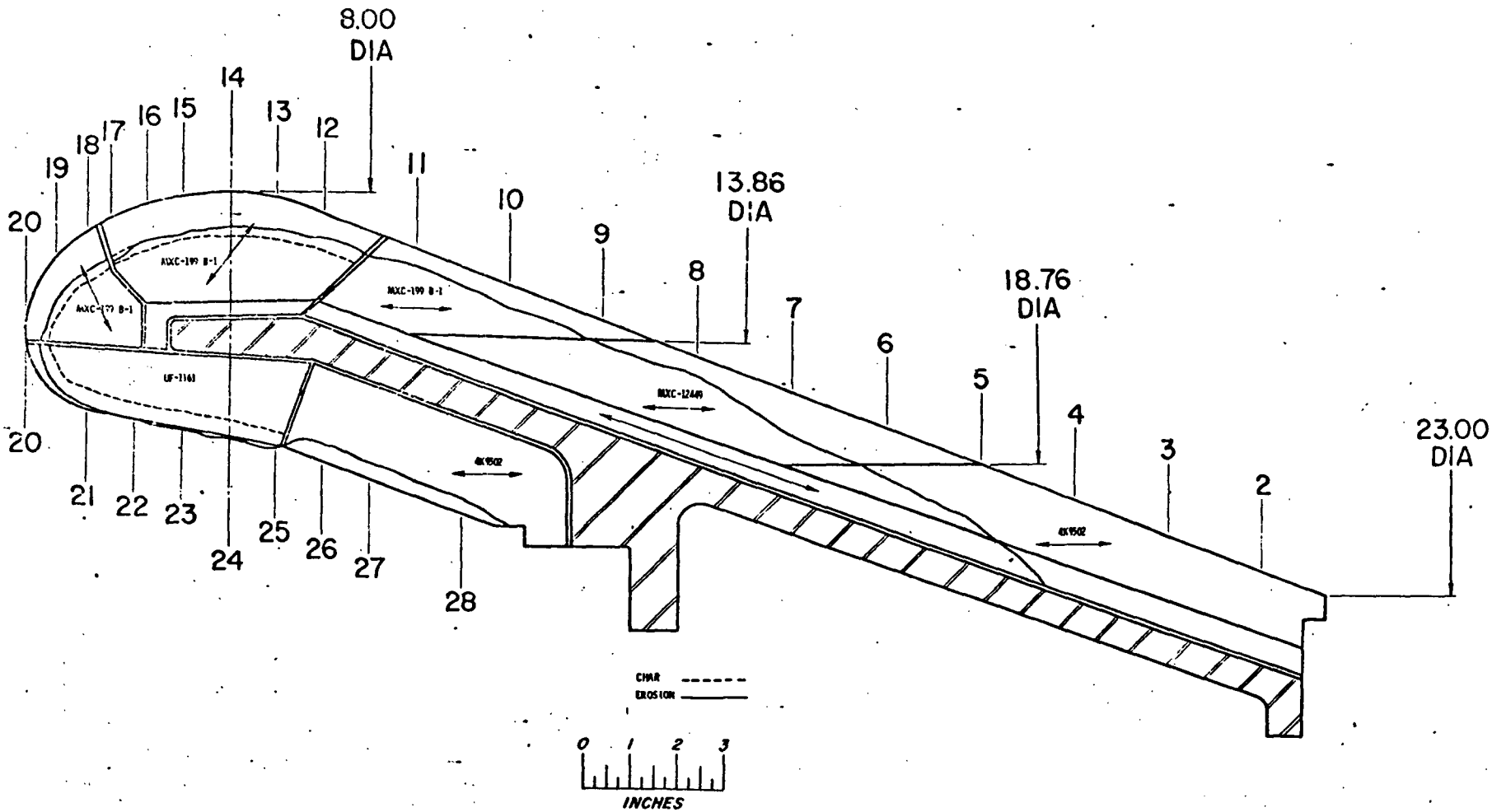


Figure IV-23. - Regression and Char Depths, Subscale Nozzle SN 003, 135-Degree Location

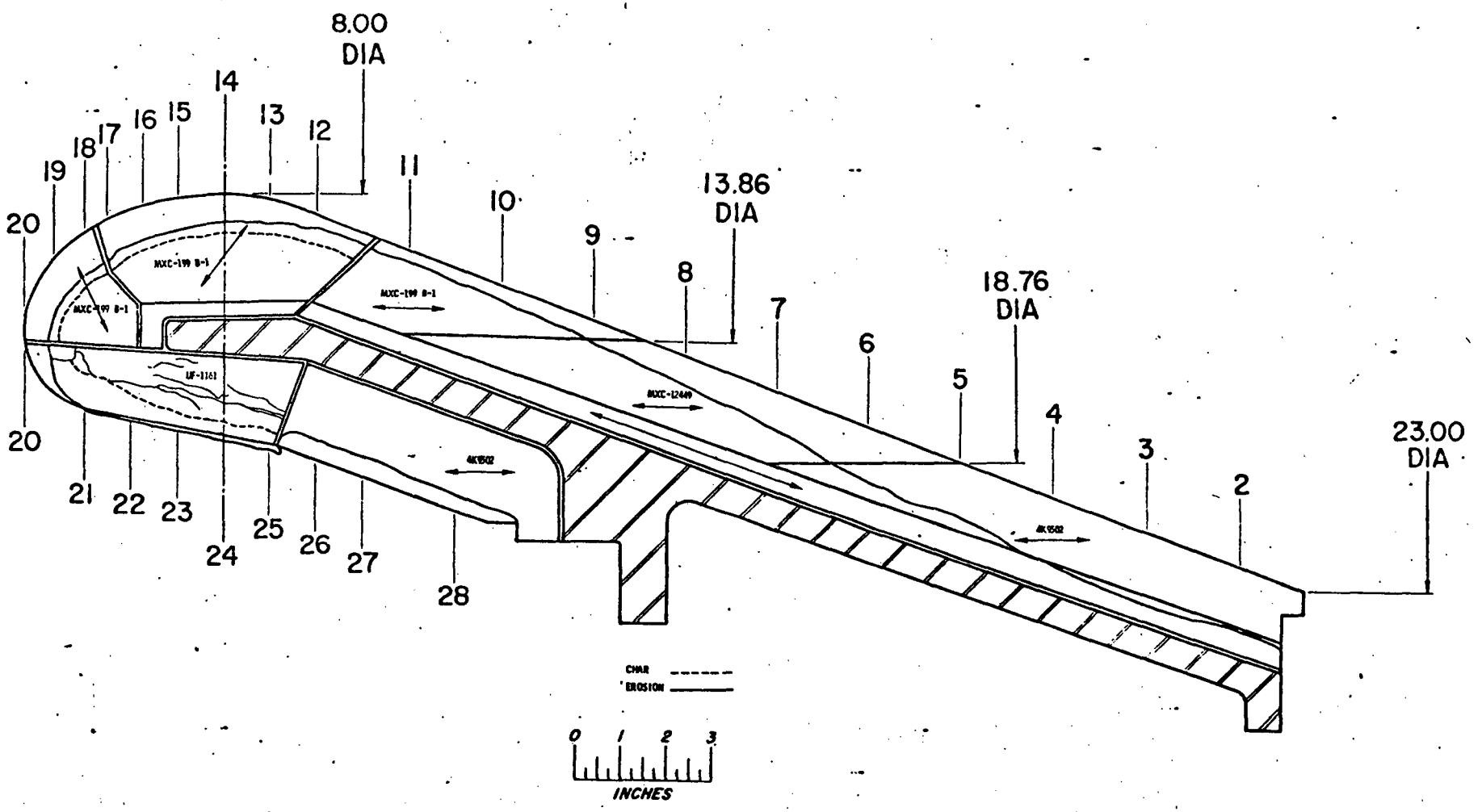


Figure IV-24. - Regression and Char Depths, Subscale Nozzle SN 003, 240-Degree Location

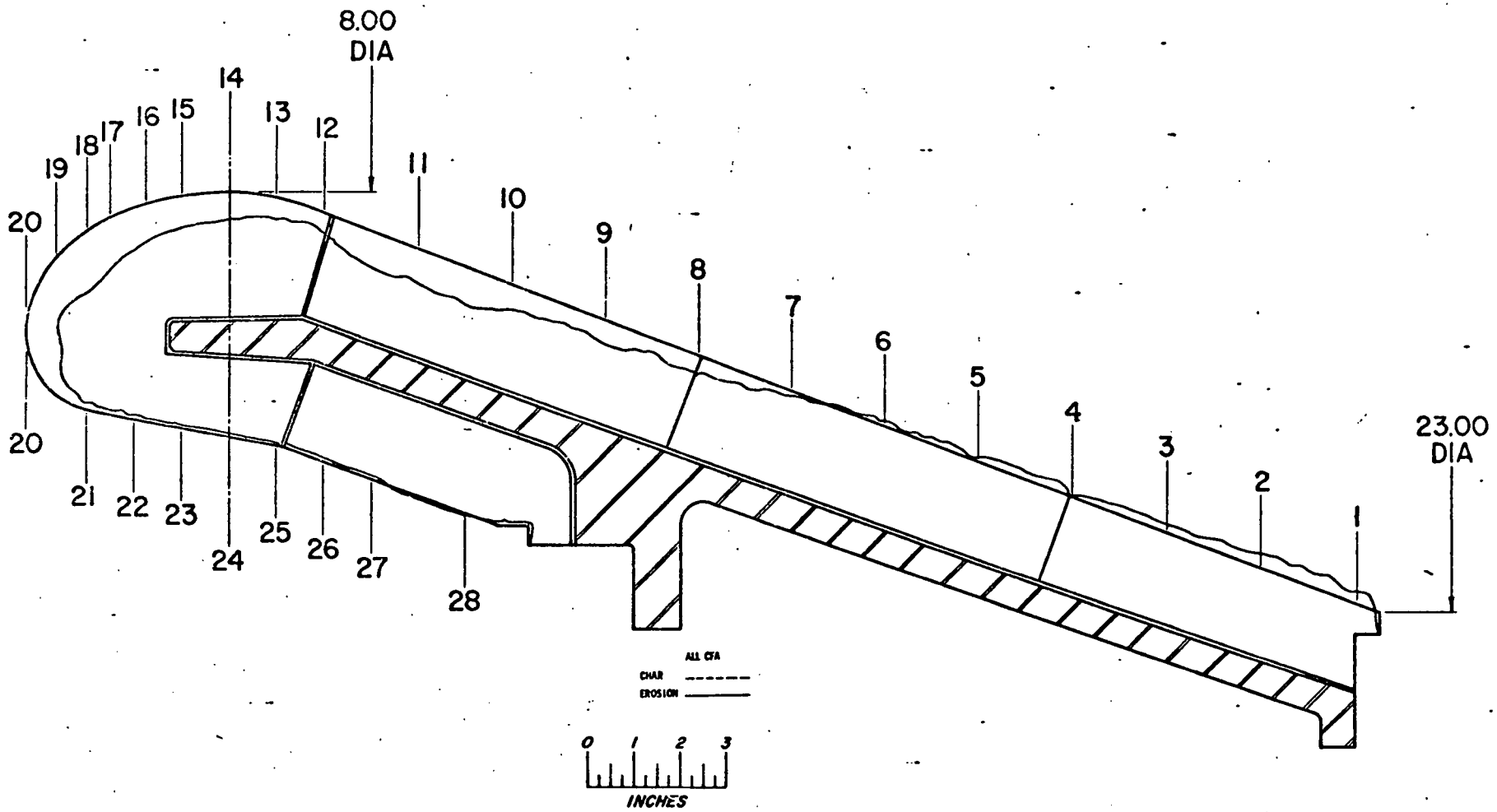


Figure IV-25. - Regression and Char Depths, Subscale Nozzle SN 004, Zero Degree Location

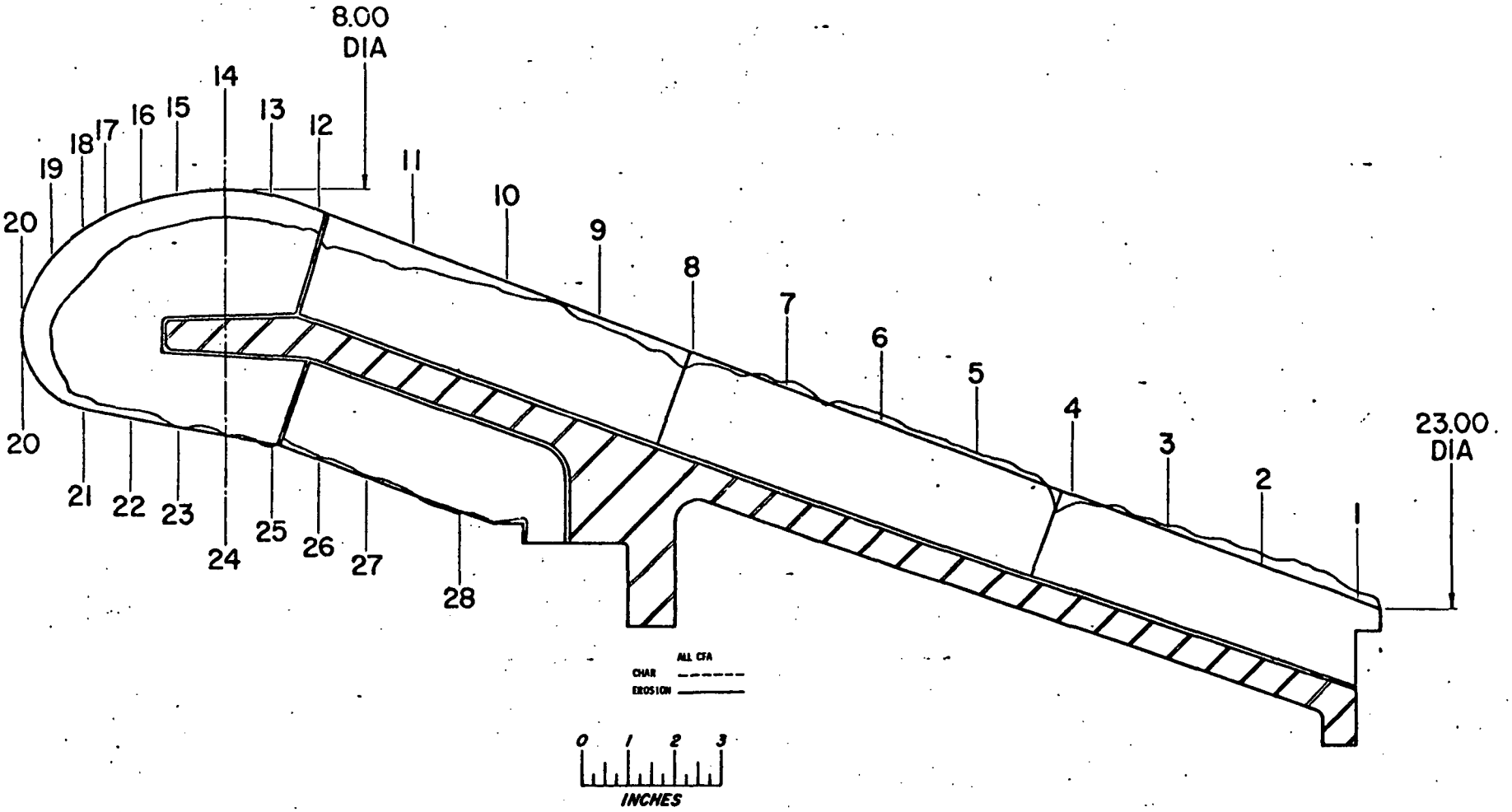


Figure IV-26. - Regression and Char Depths, Subscale Nozzle SN 004, 135-Degree Location

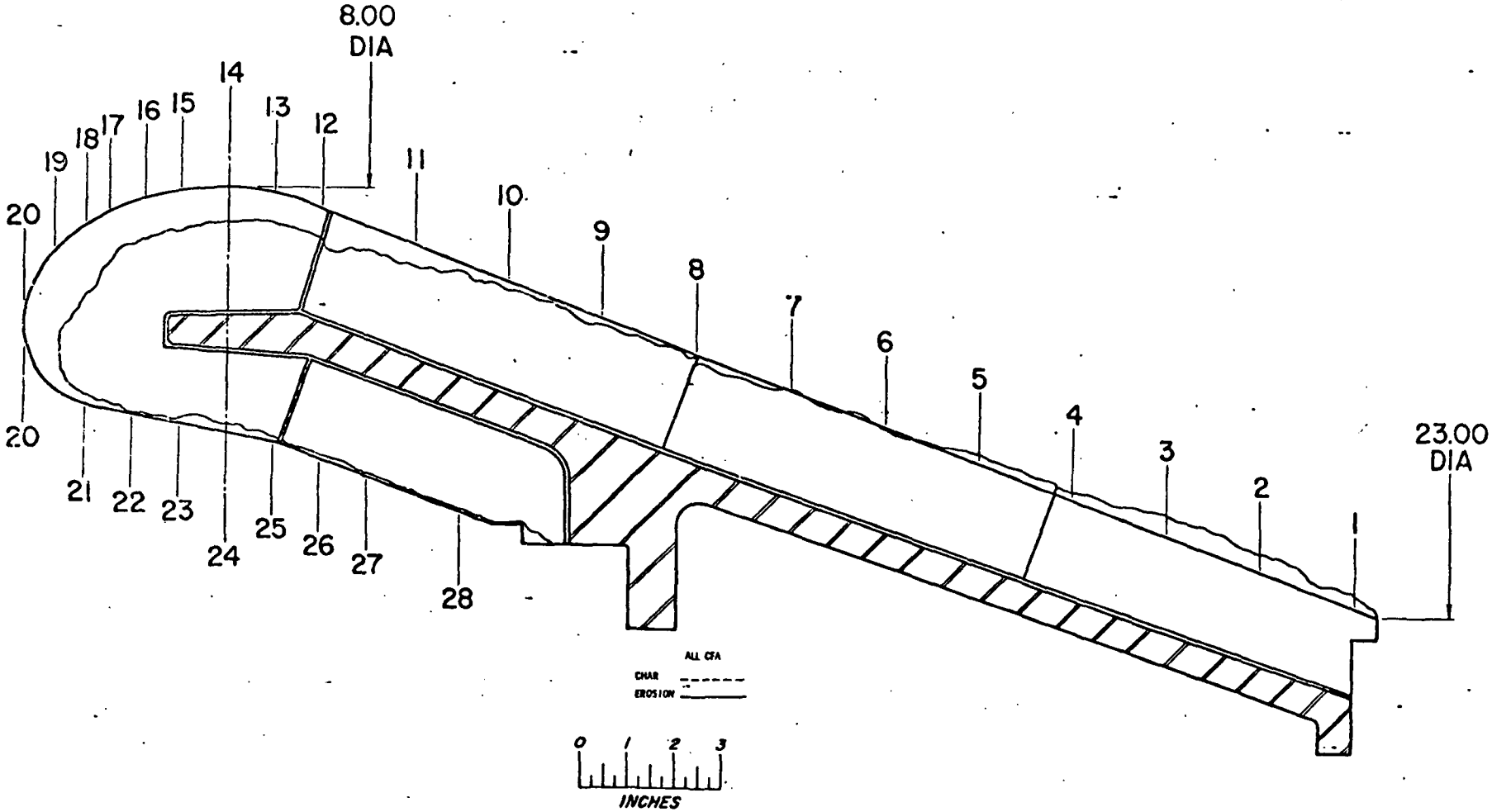


Figure IV-27. - Regression and Char Depths, Subscale Nozzle SN 004, 240-Degree Location

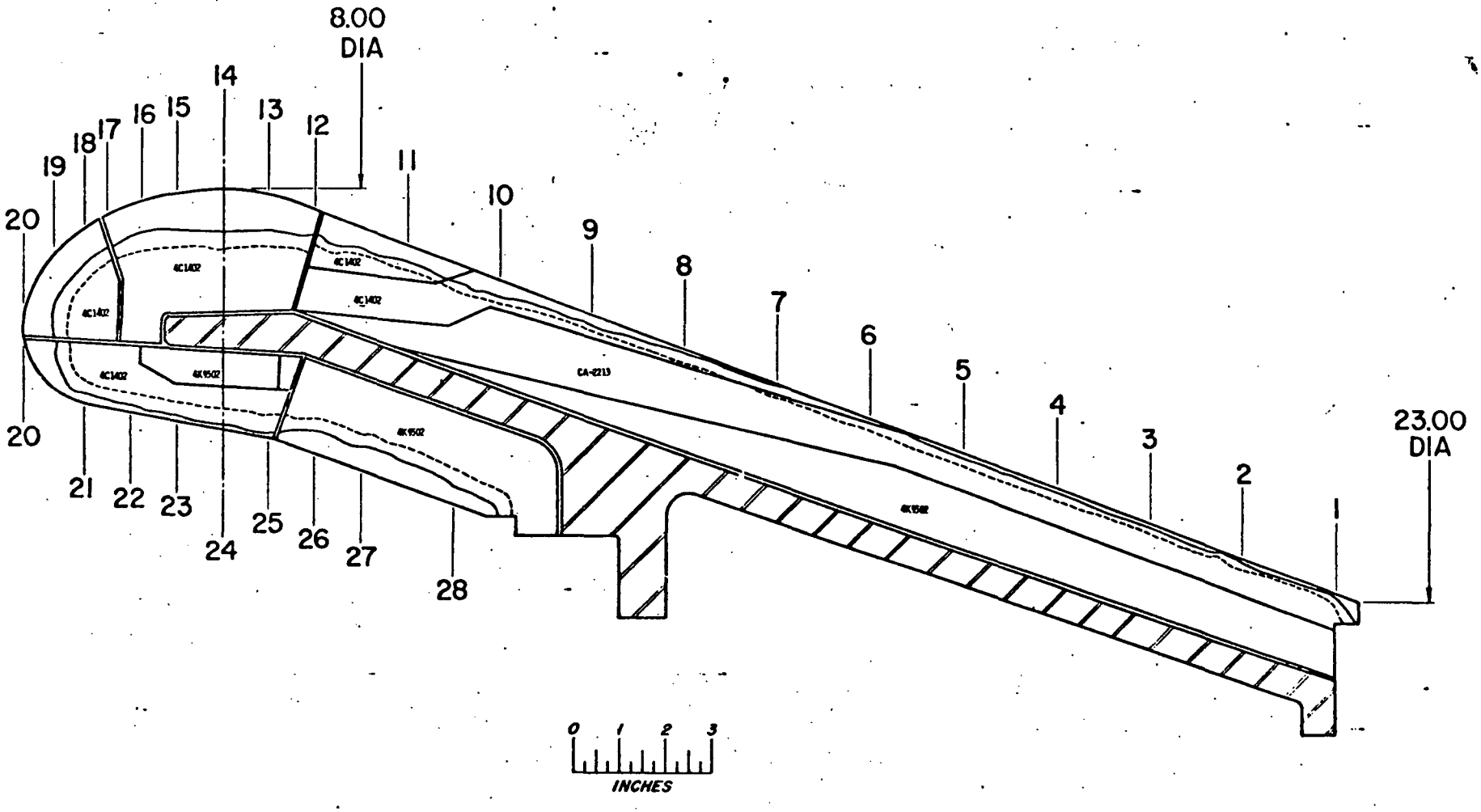


Figure IV-28. - Regression and Char Depths, Subscale Nozzle SN 005, Zero Degree Location

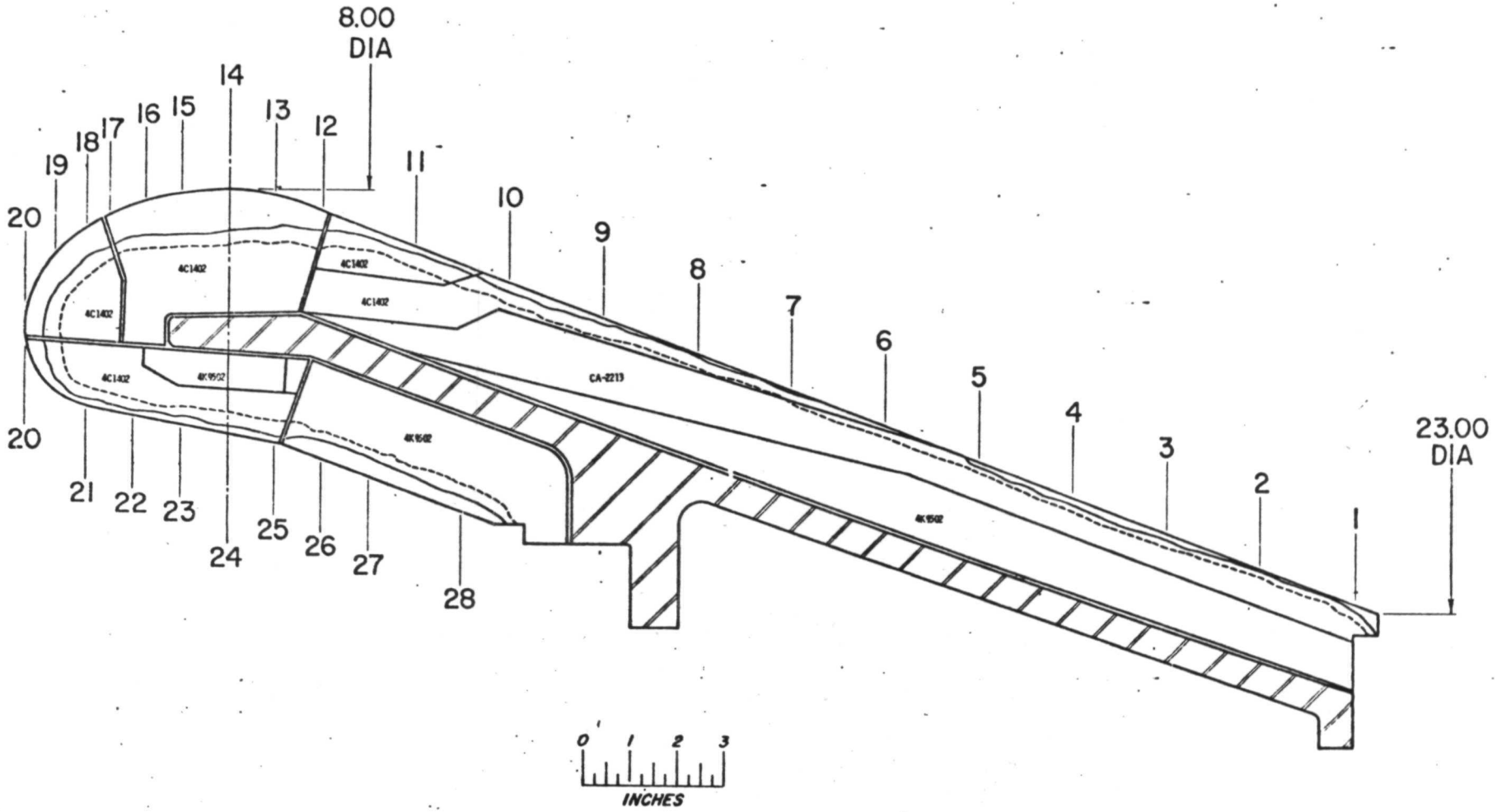


Figure IV-29. - Regression and Char Depths, Subscale Nozzle SN 005, 135-Degree Location

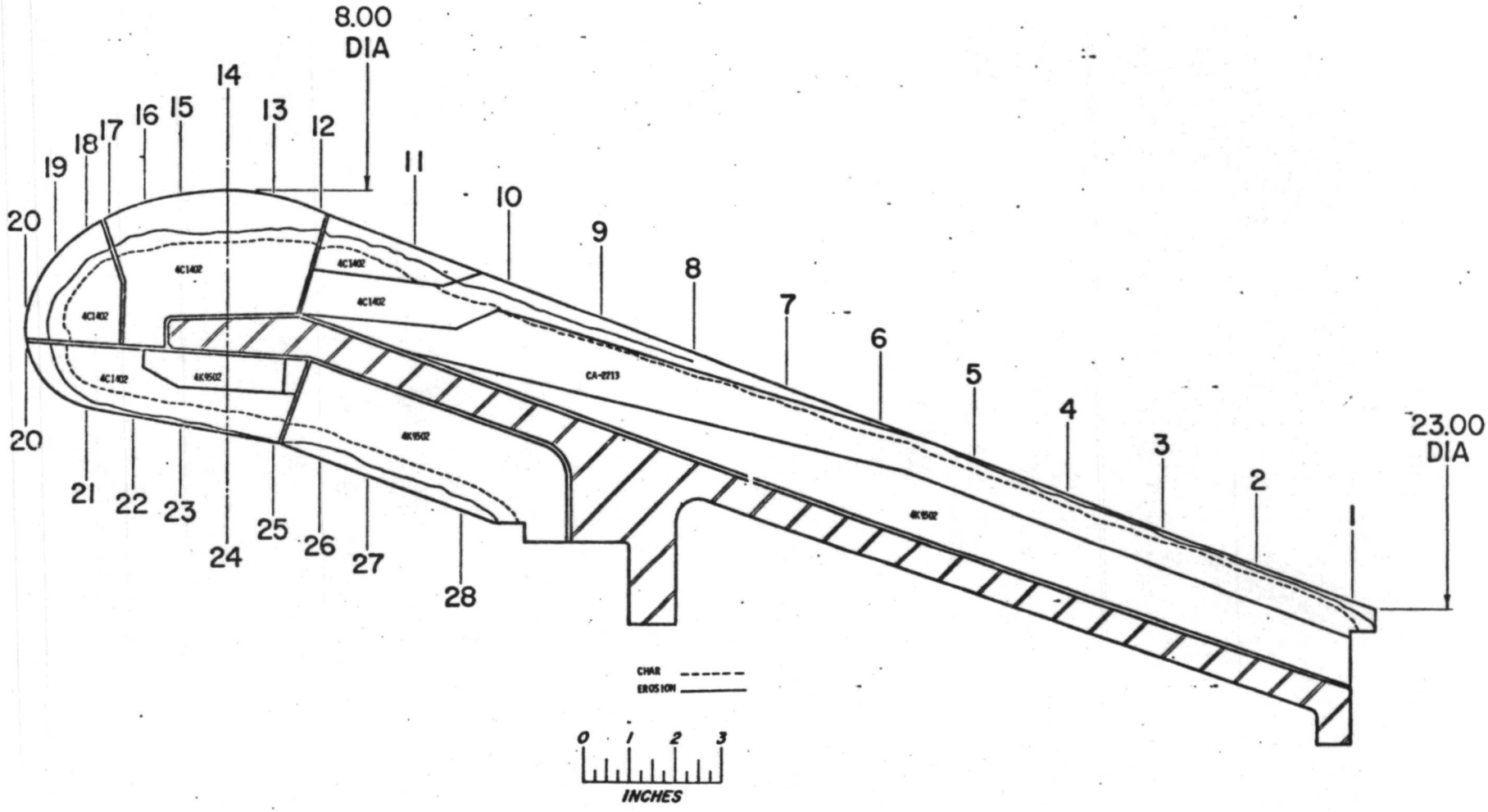


Figure IV-30. - Regression and Char Depths, Subscale Nozzle SN 005, 240-Degree Location



Figure IV-31. - Forward End of Nozzle, S/N 002

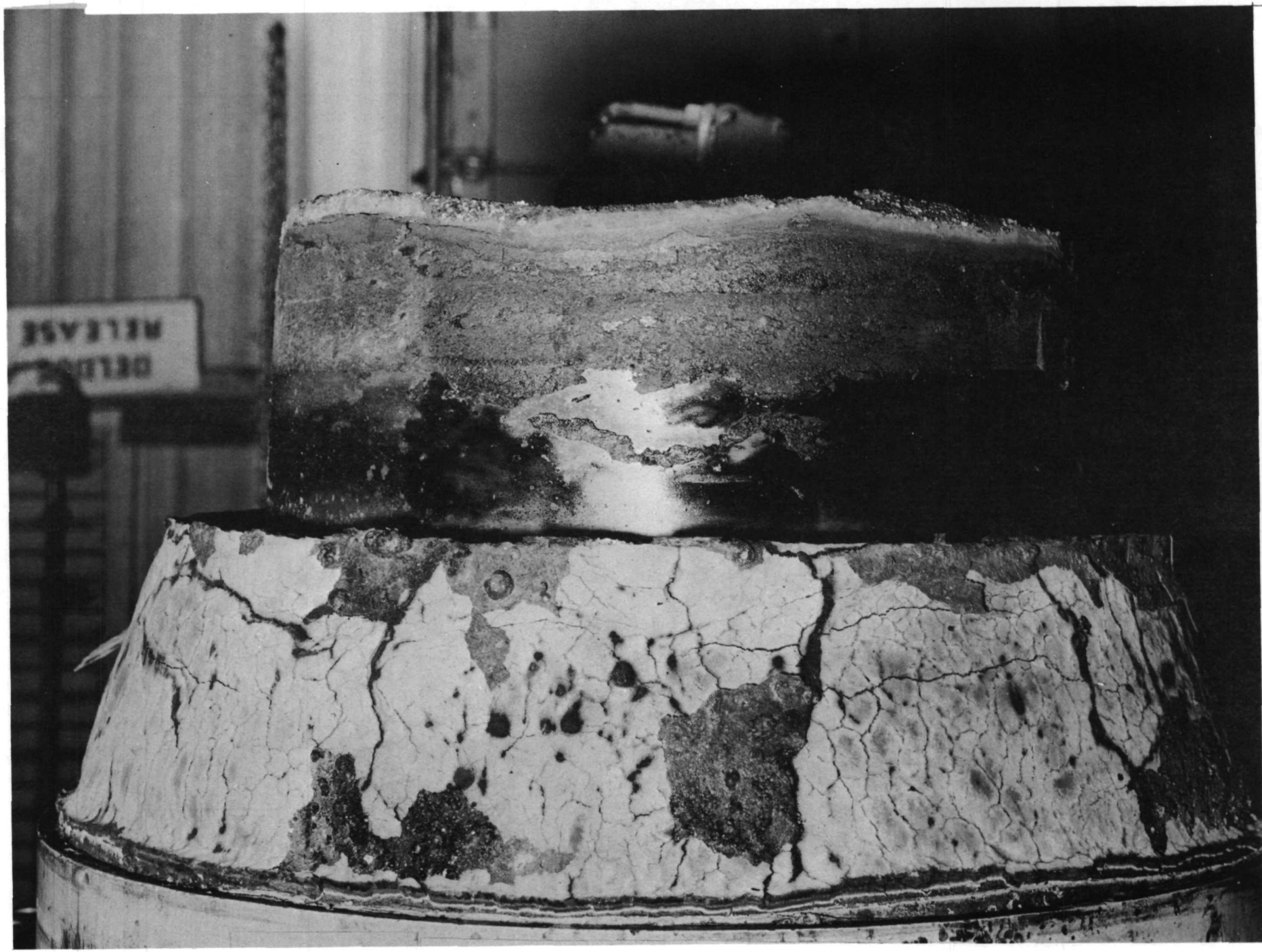


Figure IV-32. - Throat Approach of Nozzle, S/N 001

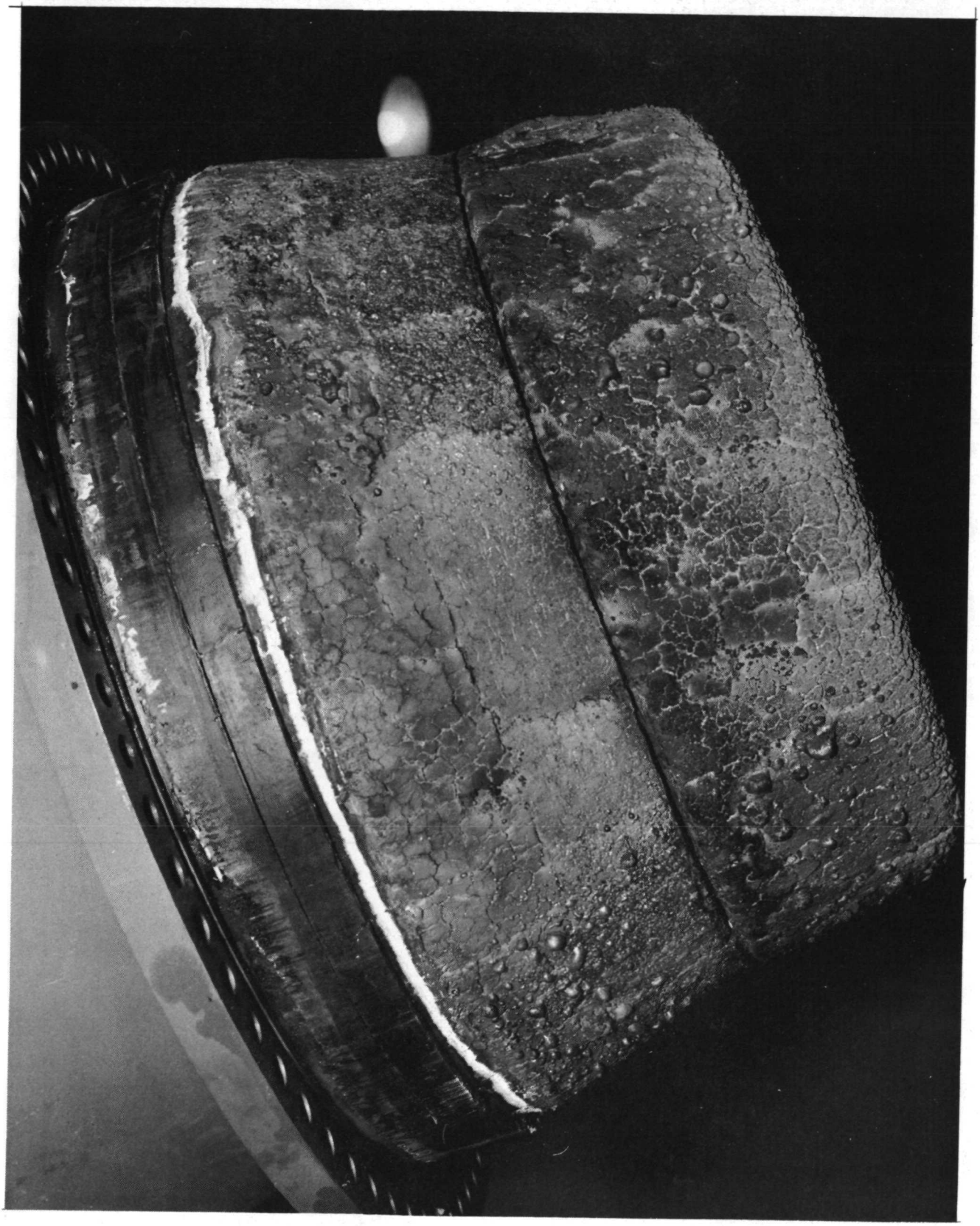


Figure IV-33. - Forward End of Nozzle S/N 004



Figure IV-34. - Inlet and Throat of Nozzle, S/N 002



Figure IV-35. - Inlet and Throat of Nozzle, S/N 001

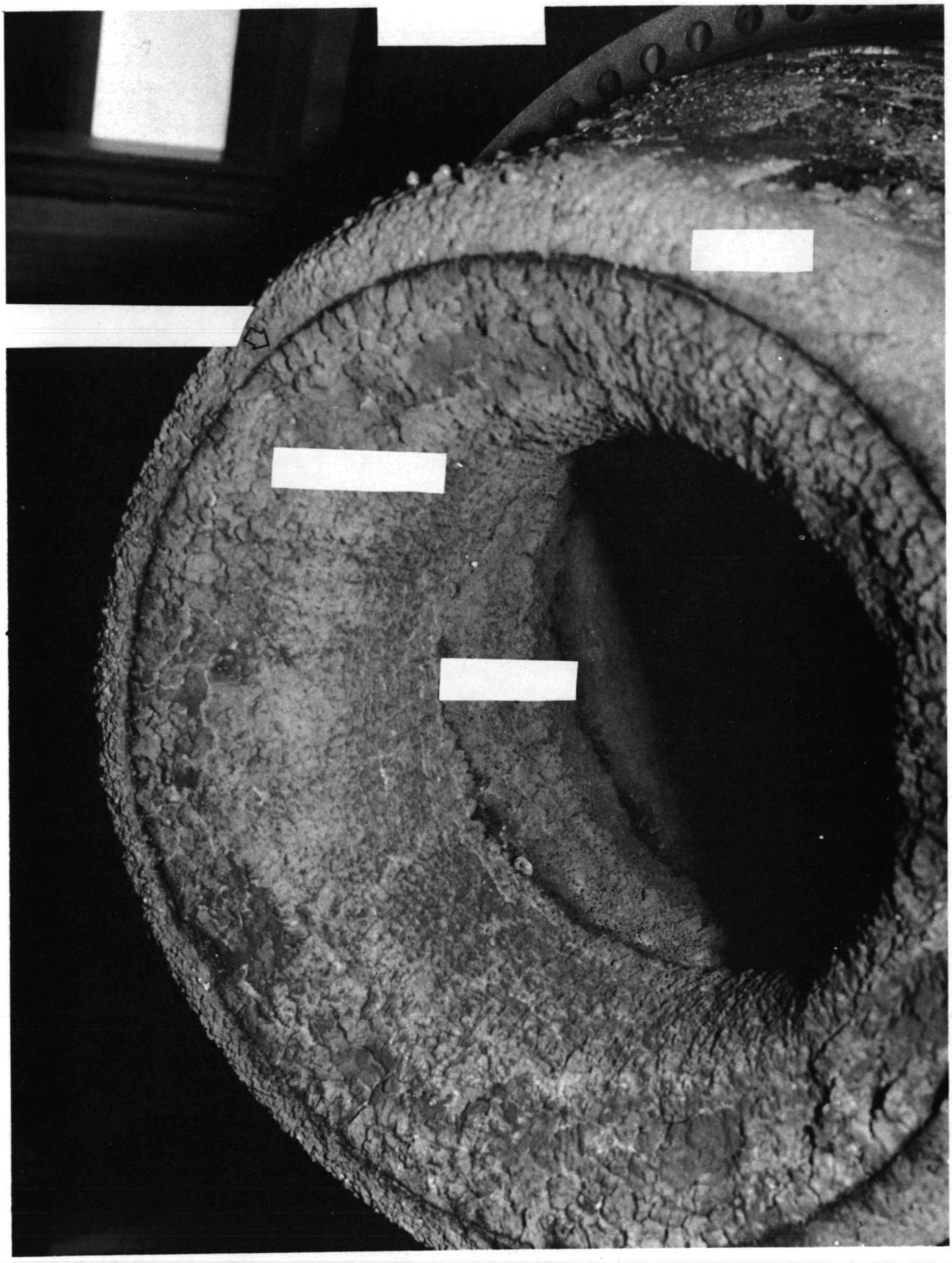


Figure IV-36. - Inlet and Throat of Nozzle, S/N 004



Figure IV-37. - Close-Up of Throat No. 5 Looking Aft



Figure IV-38. - Band of Spallation in UF-1161 "A" Section No. 1

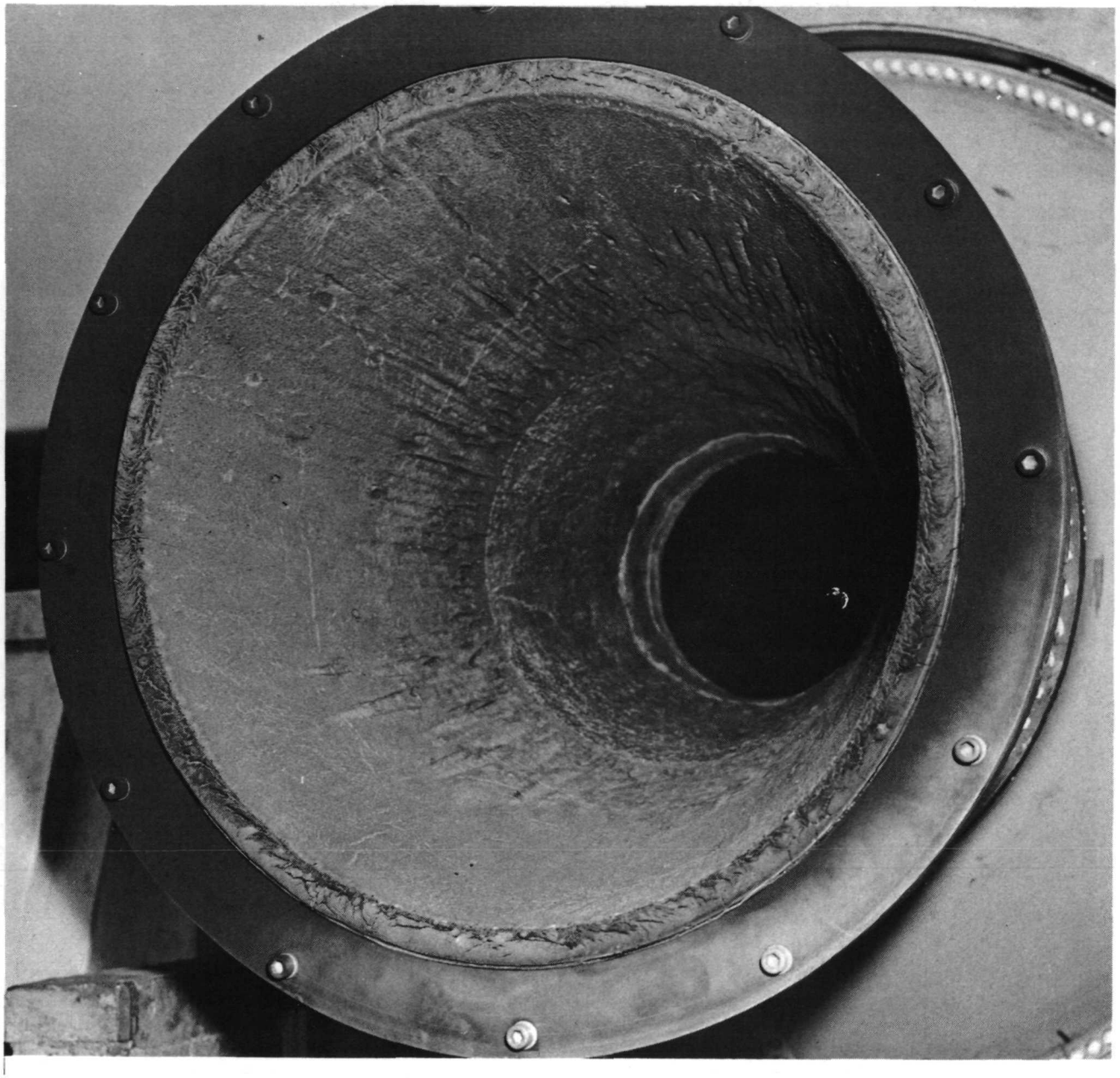


Figure IV-39. - Exit Cone Nozzle S/N 002. Note Spalling in CA-8502 "A" Section and Gouges in DP5-161/Si "B" Section

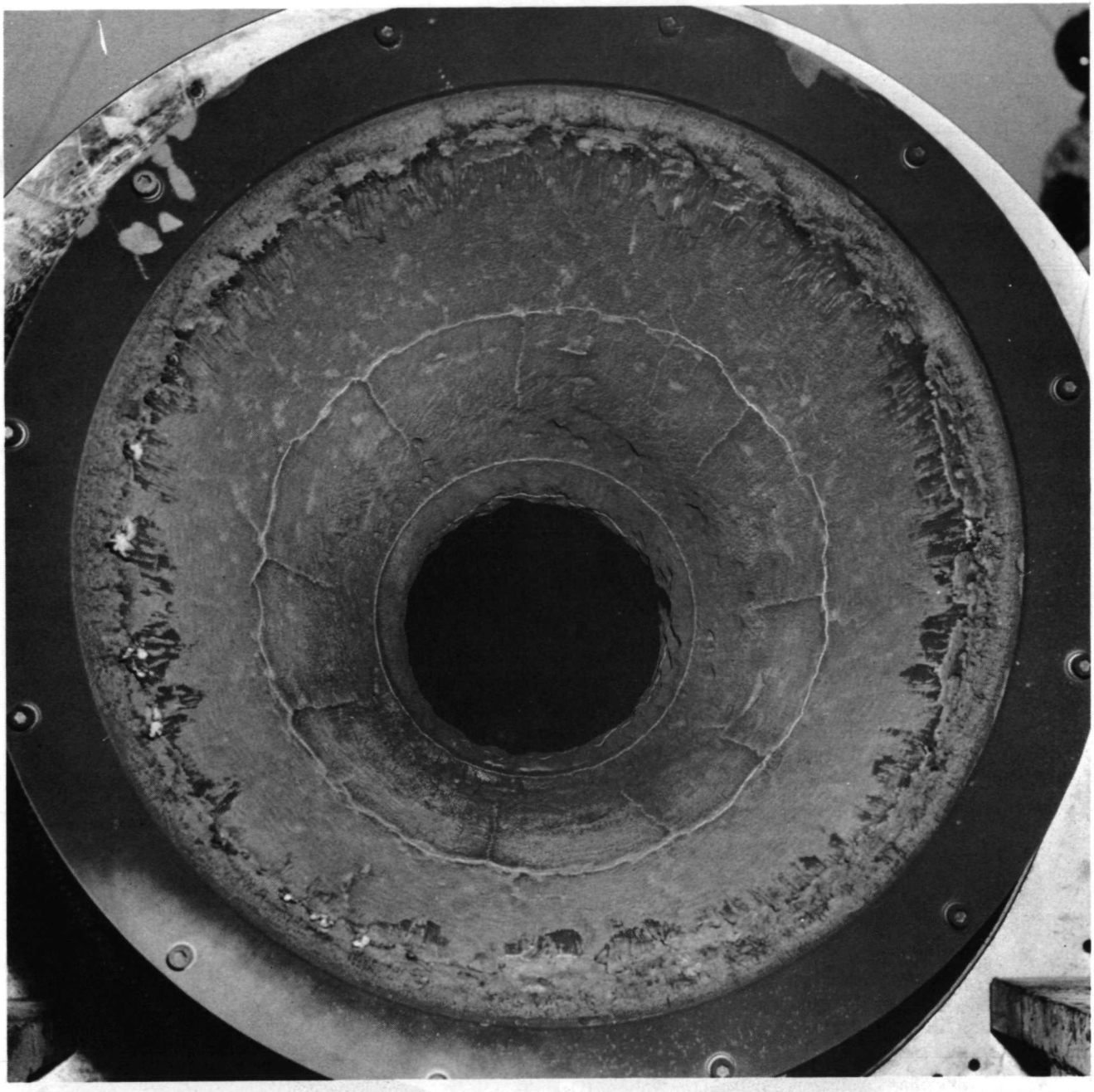


Figure IV-40. - Exit Cone of Nozzle S/N 005 After Firing



Figure IV-41. - Exit Cone of Nozzle S/N 004 After Firing

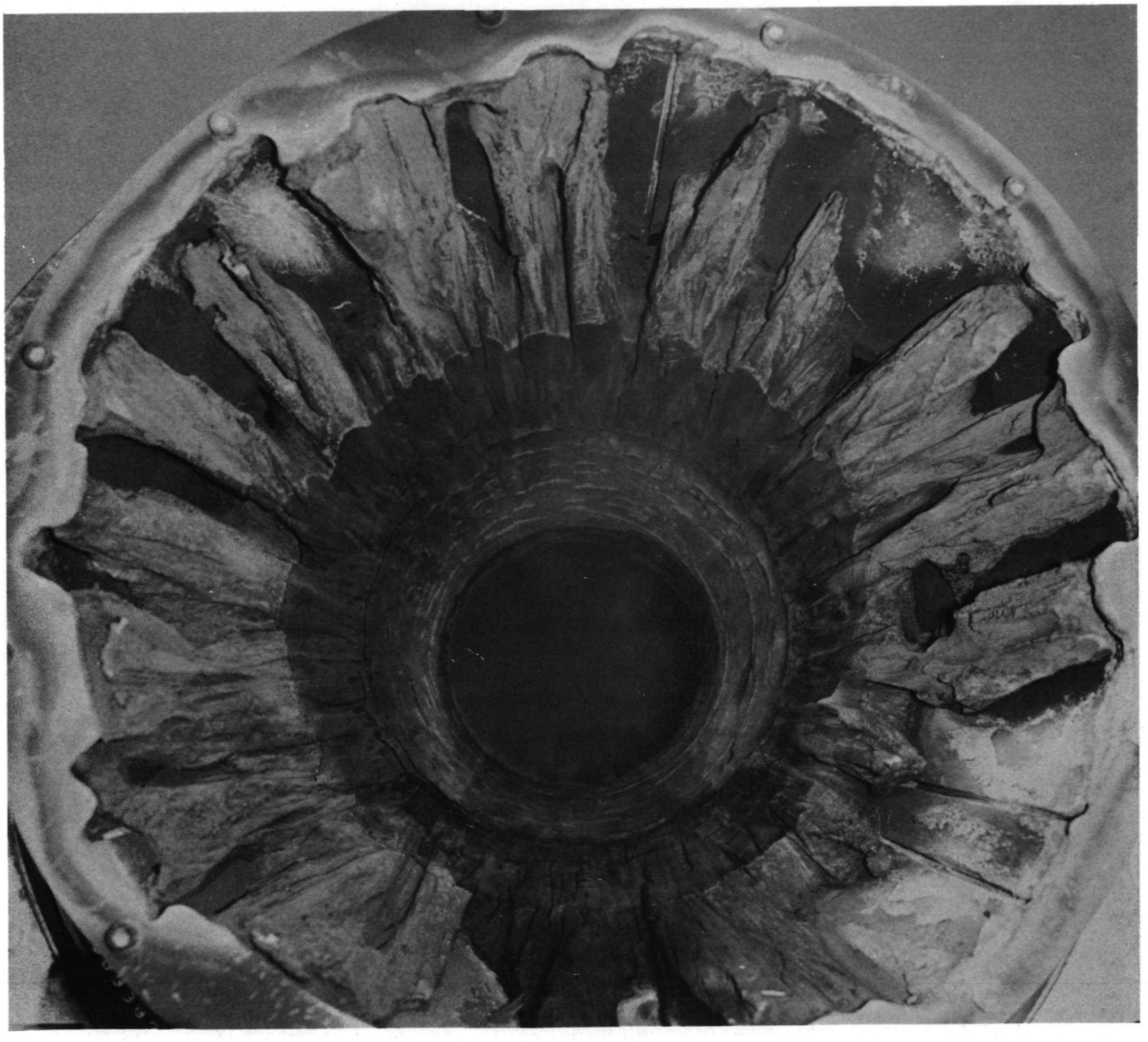


Figure IV-42. - Exit Cone of Nozzle S/N 003 After Firing

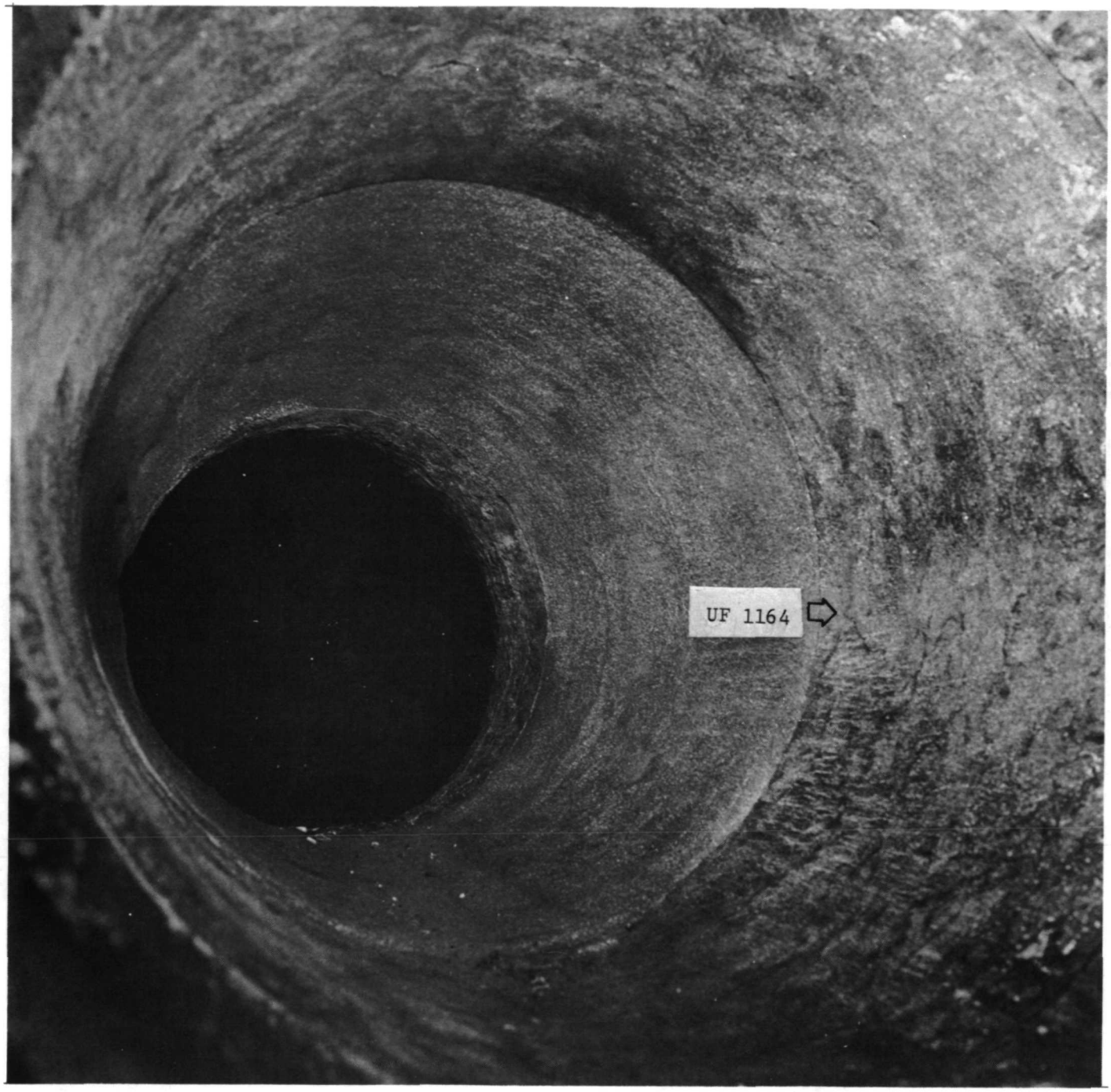


Figure IV-43. - Exit Cone of Nozzle S/N 001 After Firing

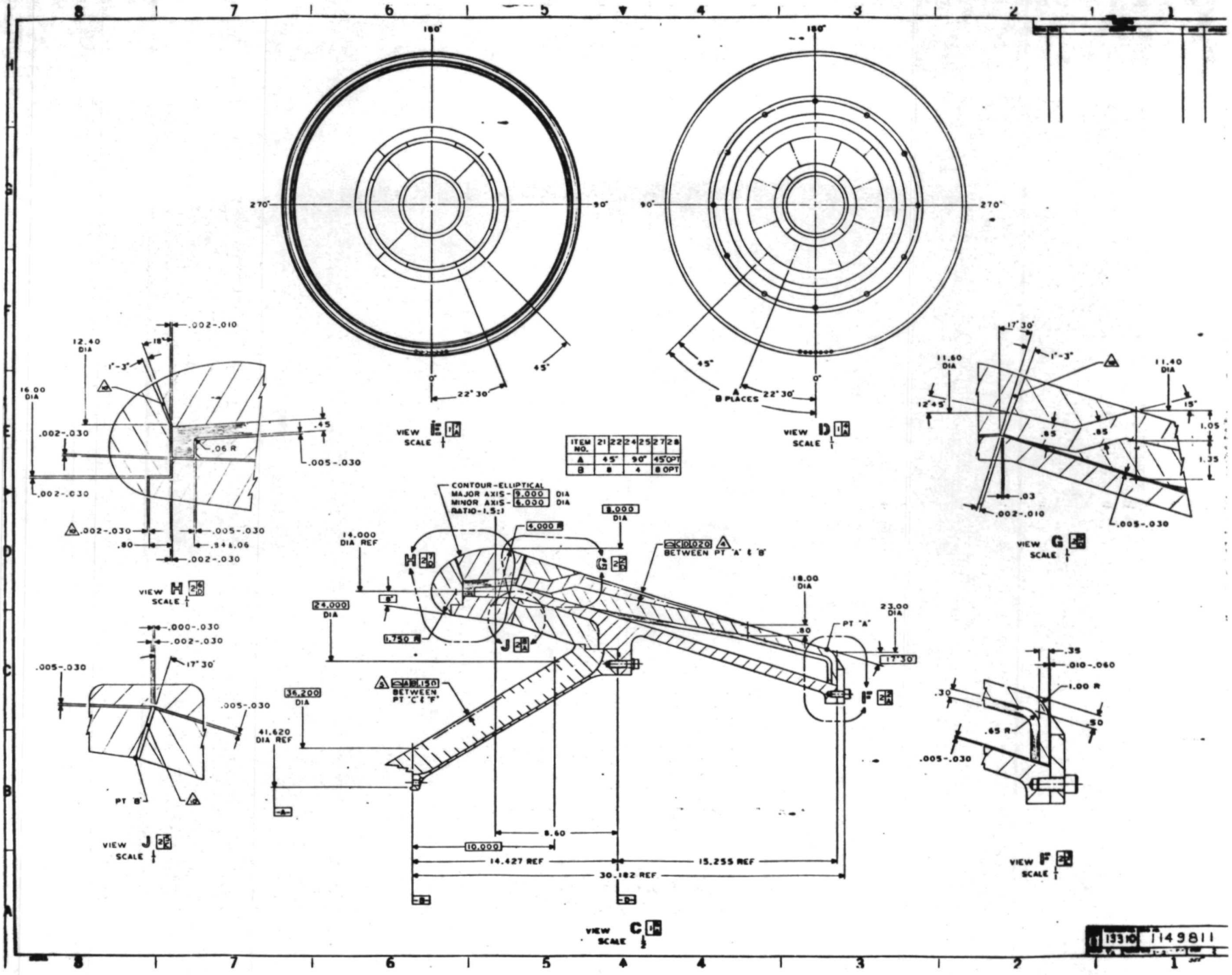


Figure IV-44. - Design Details of Subscale Nozzle SN 006

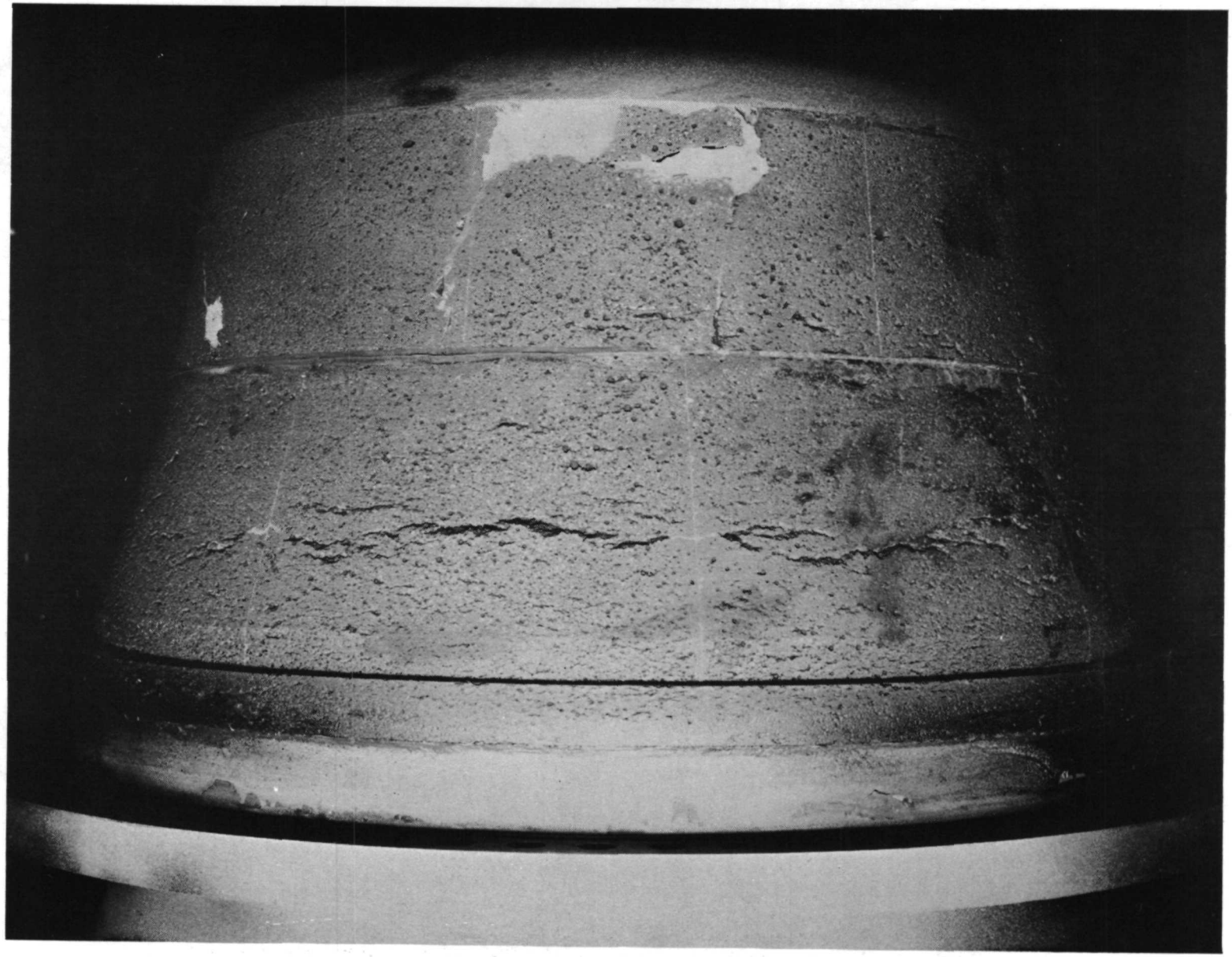


Figure IV-45. - Fissures in Approach and Cracks in Entrance Sections of Nozzle S/N 006



Figure IV-46. - Fissures and Cracks in ARC-100 Components of Nozzle S/N 006



Figure IV-47. - Nosecap (UF-1161) of Nozzle S/N 006

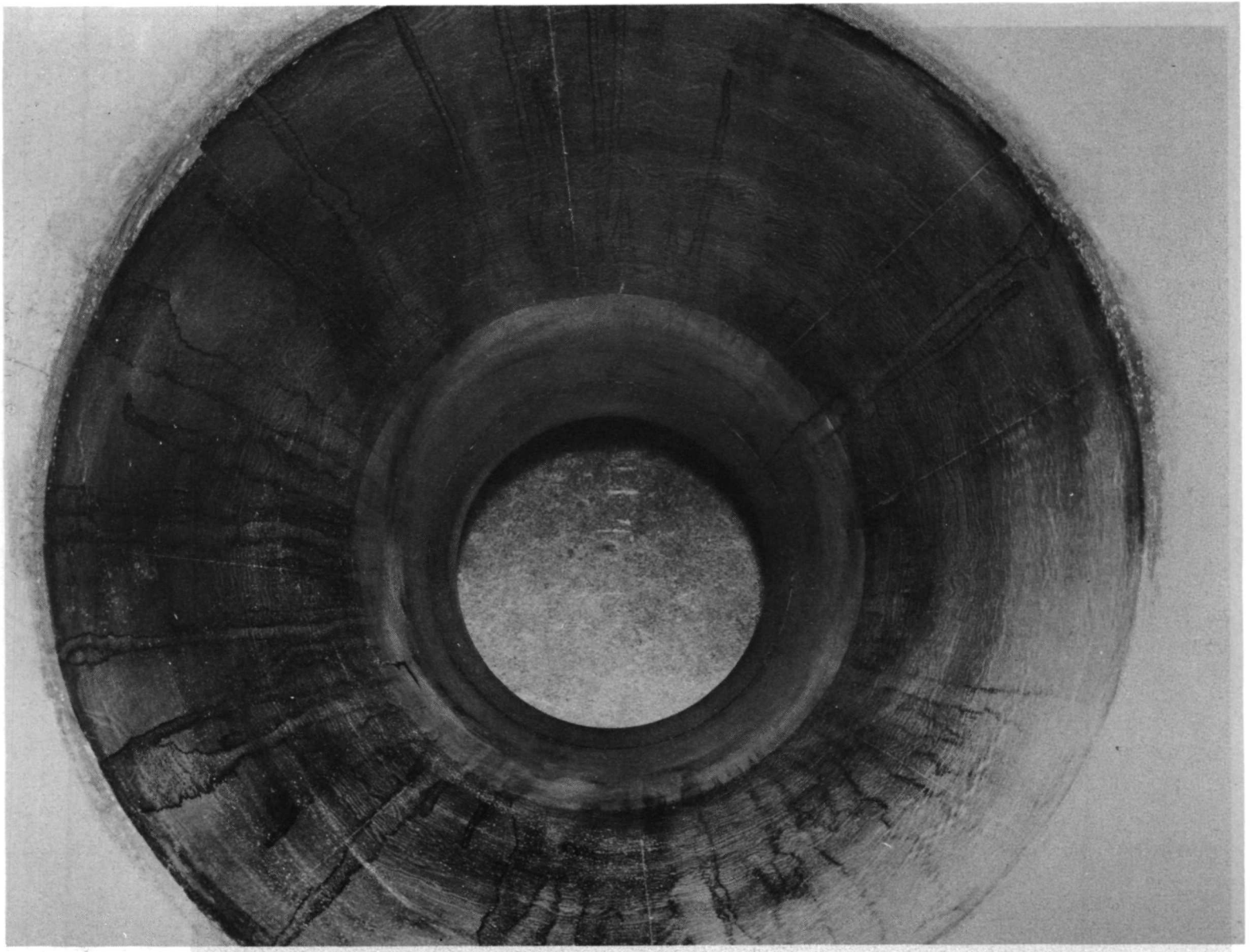


Figure IV-48. - Forward Exit Cone and Throat of Nozzle S/N 006

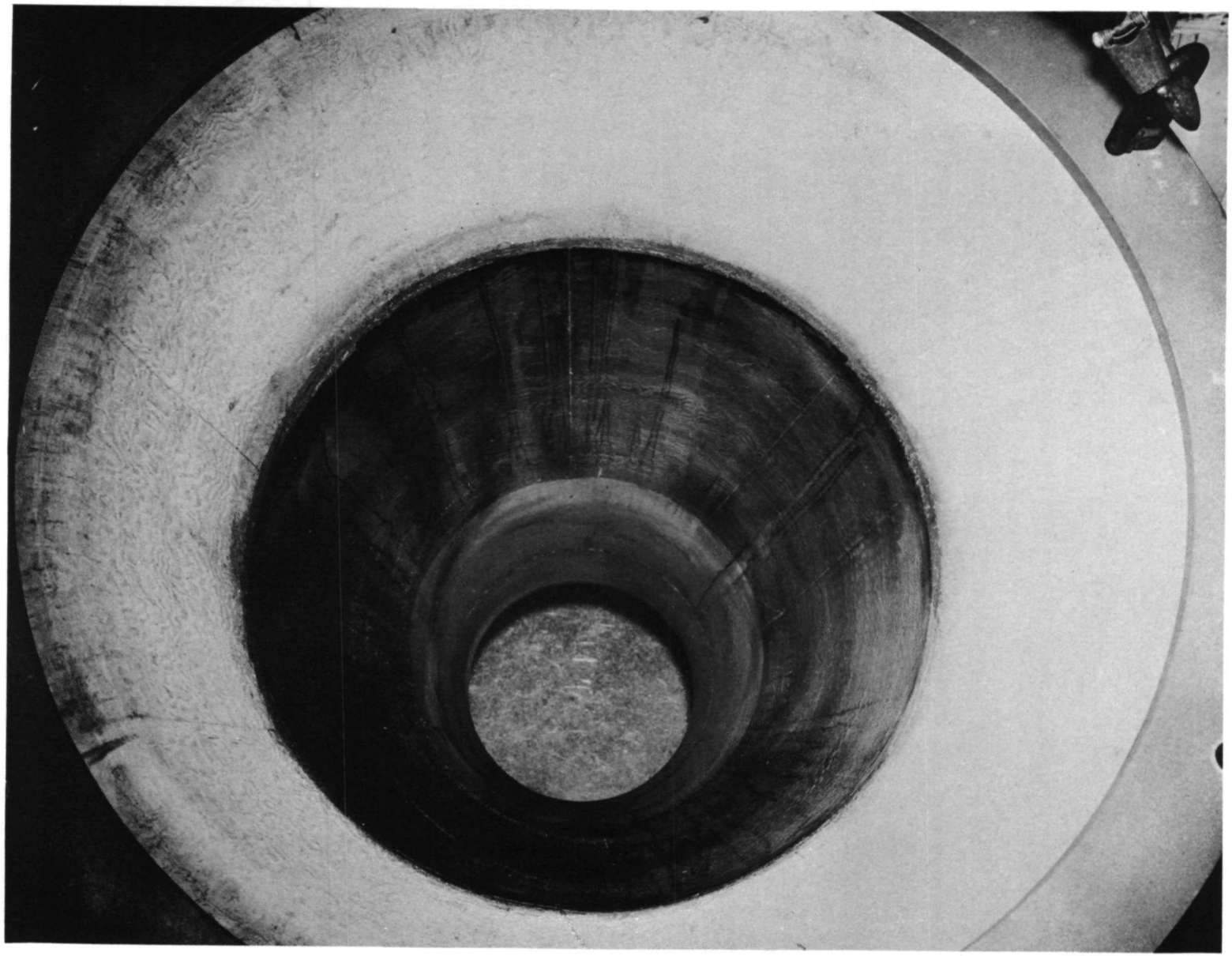


Figure IV-49. - Exit Cone of Nozzle S/N 006

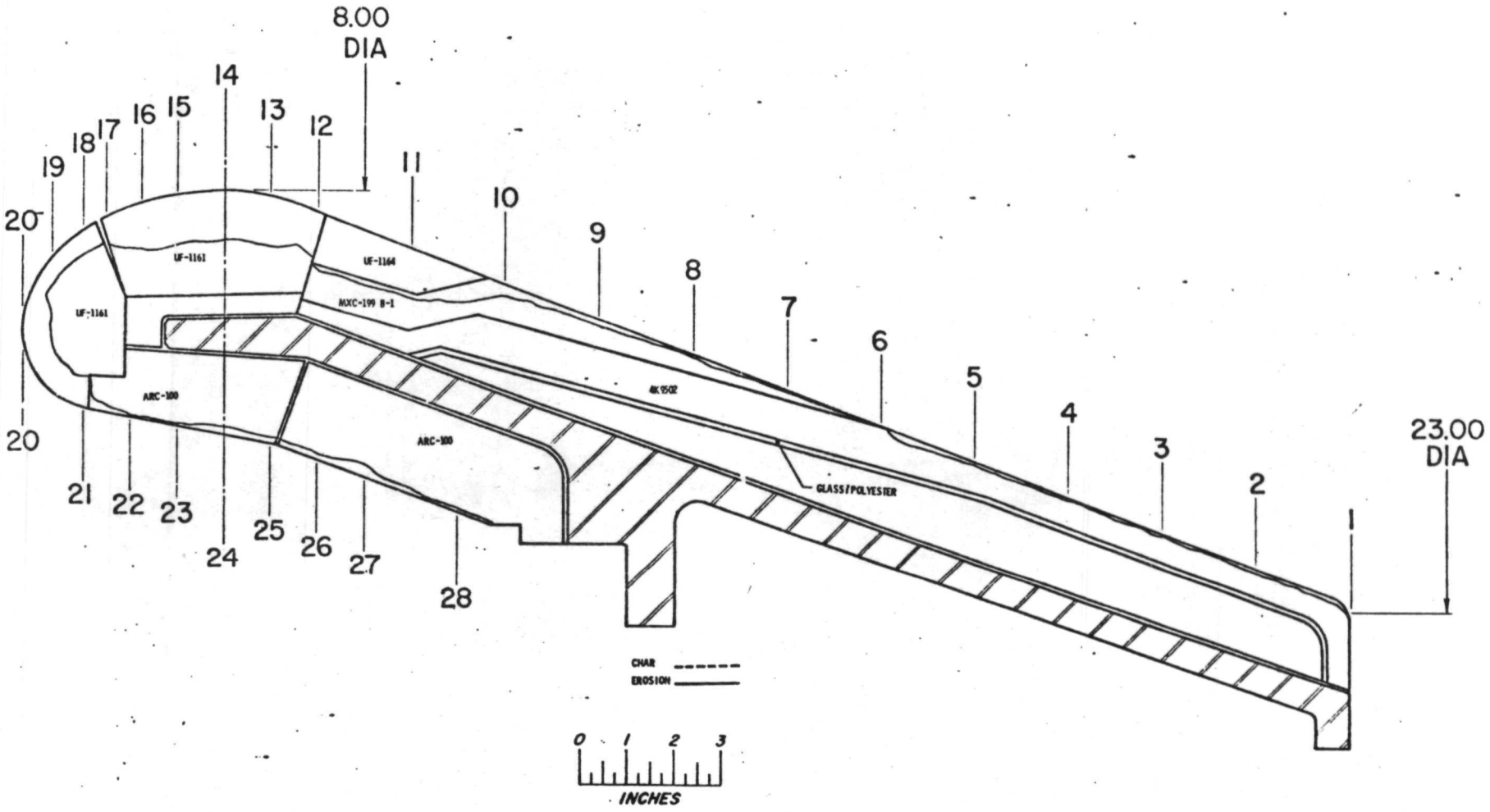


Figure IV-50. - Regression Depths, Subscale Nozzle SN 006,
Zero Degree Location

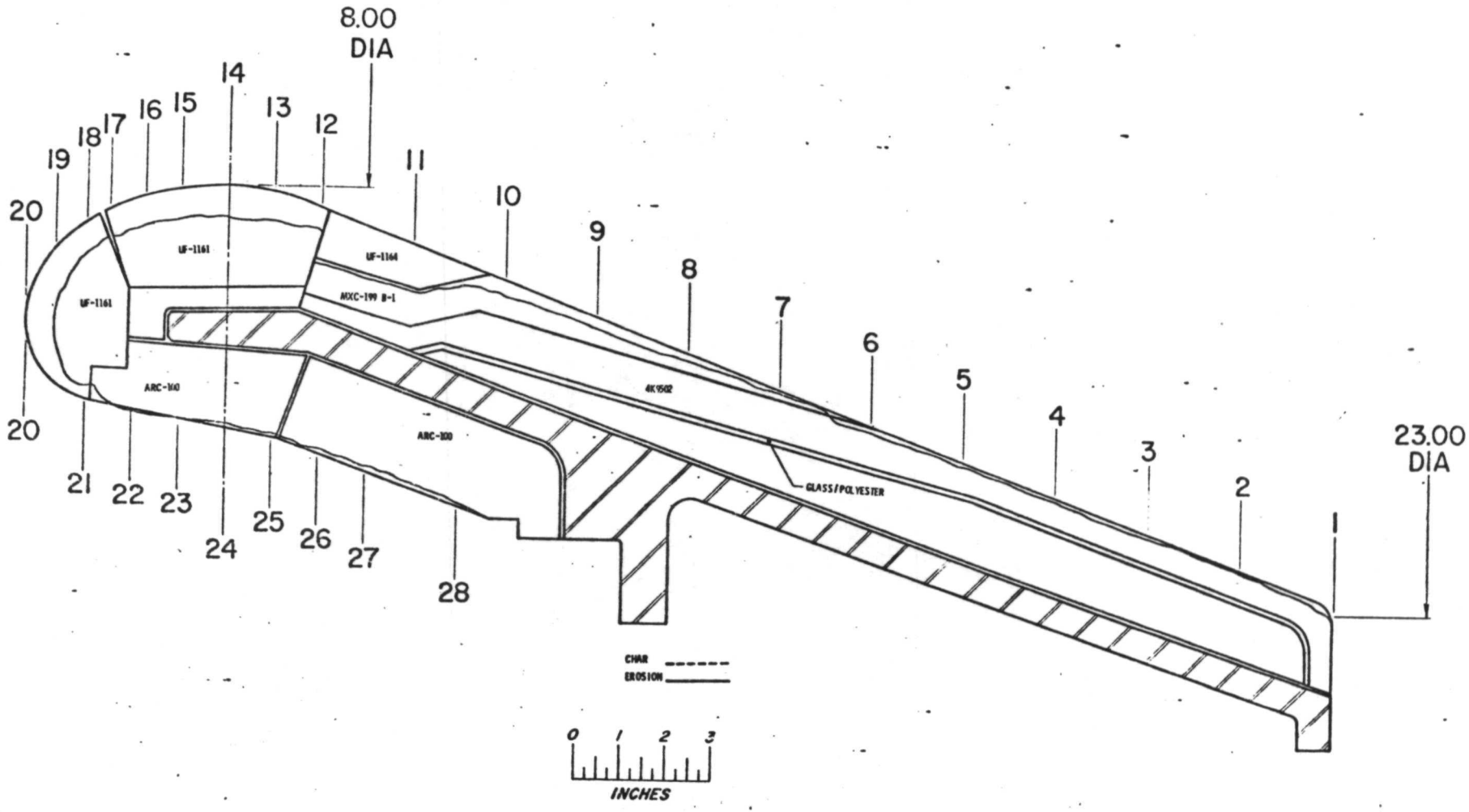


Figure IV-51. - Regression Depths, Subscale Nozzle SN 006,
135-Degree Location

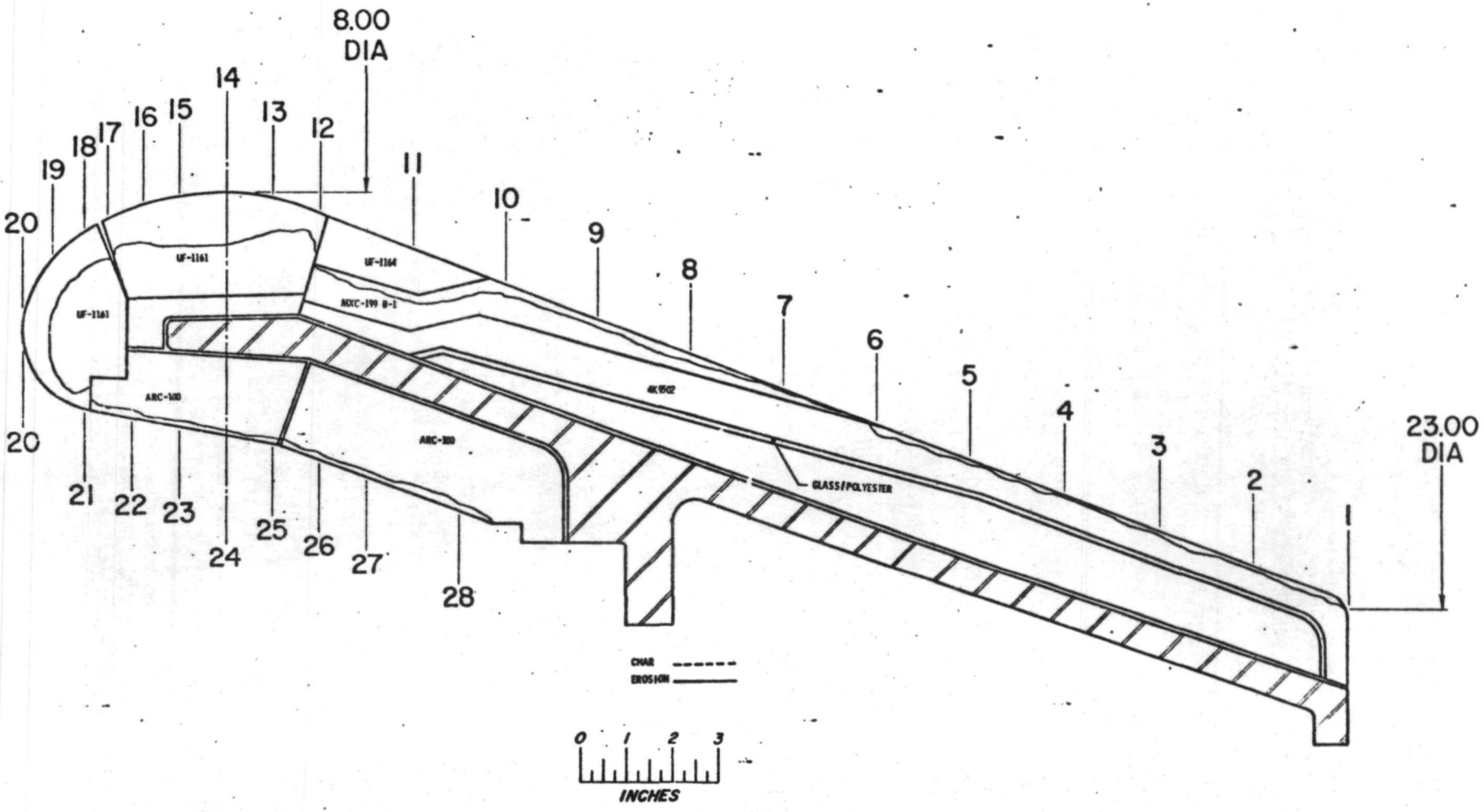


Figure IV-52. - Regression Depths, Subscale Nozzle SN 006,
240-Degree Location



Figure IV-53. - Forward End of Nozzle S/N 006 After Test

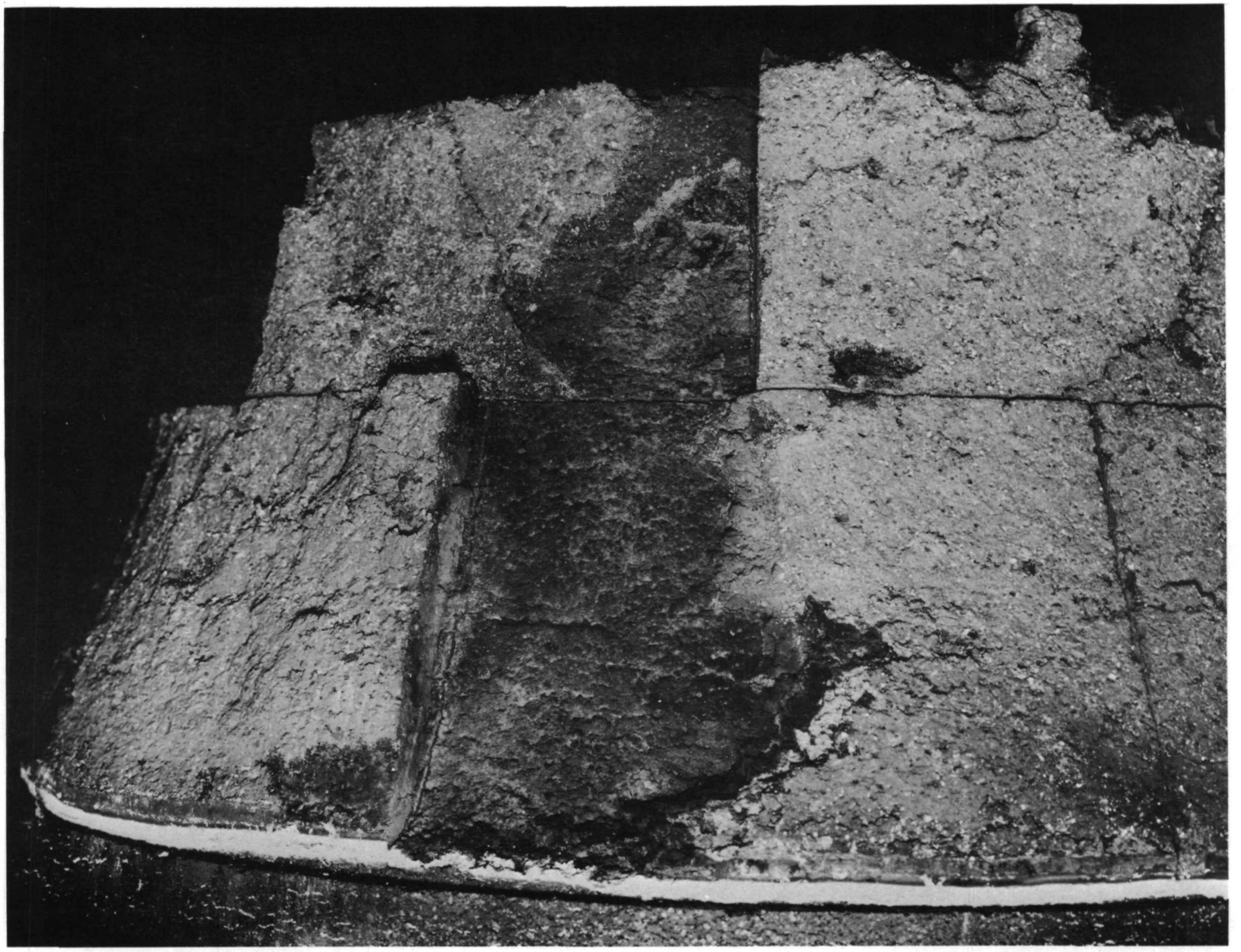


Figure IV-54. - Throat Approach and Entrance Section
of Nozzle S/N 006 After Test

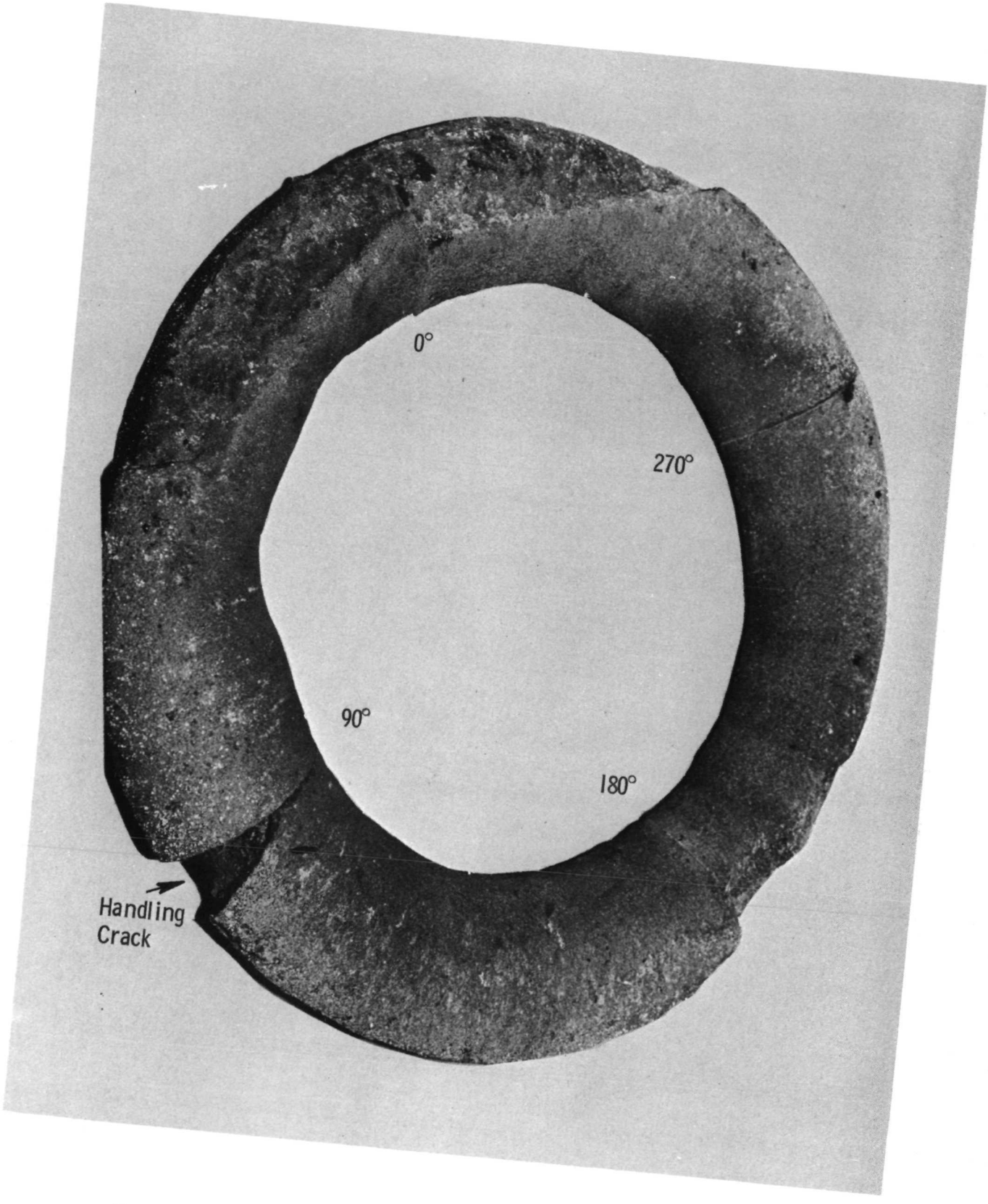


Figure IV-55. - Nosecap of Nozzle S/N 006 After Test

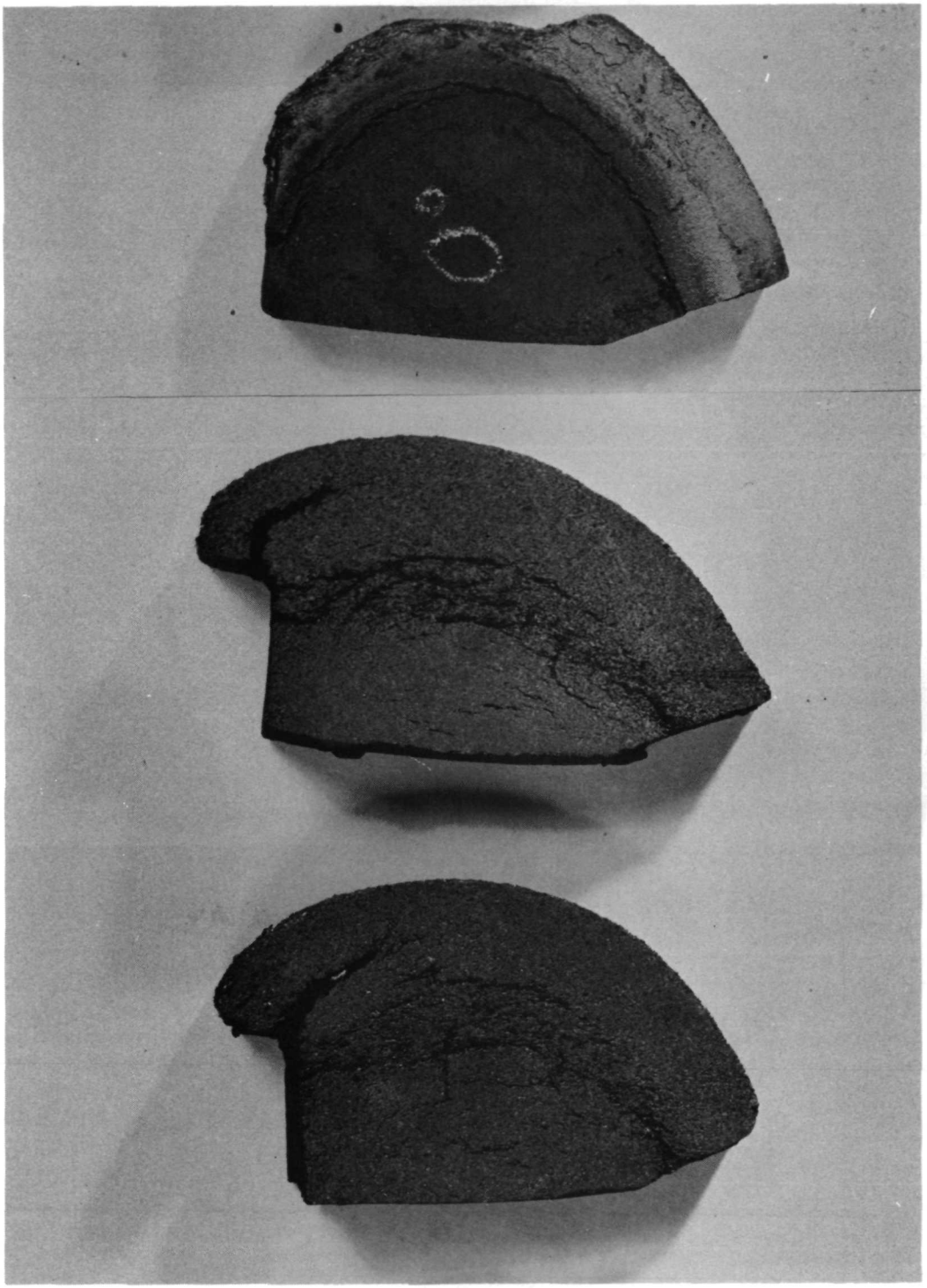


Figure IV-56. - Cross Sections of Nosecap Sections



Figure IV-57. - Fractured Surfaces of Nosecap

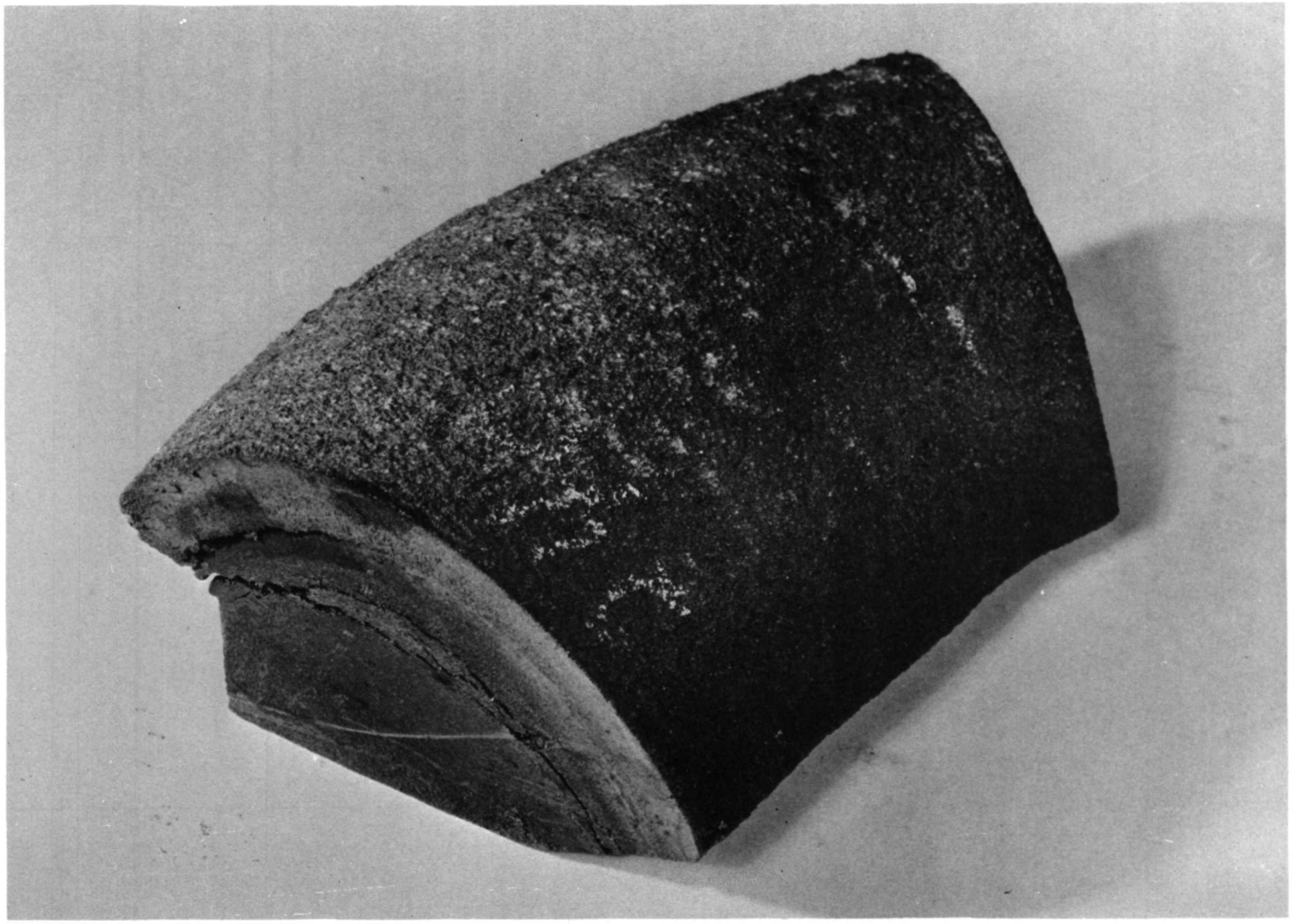


Figure IV-58. - Flame Surface and Cross Section of Nosecap



Figure IV-59. - Throat of Nozzle S/N 006 After Test

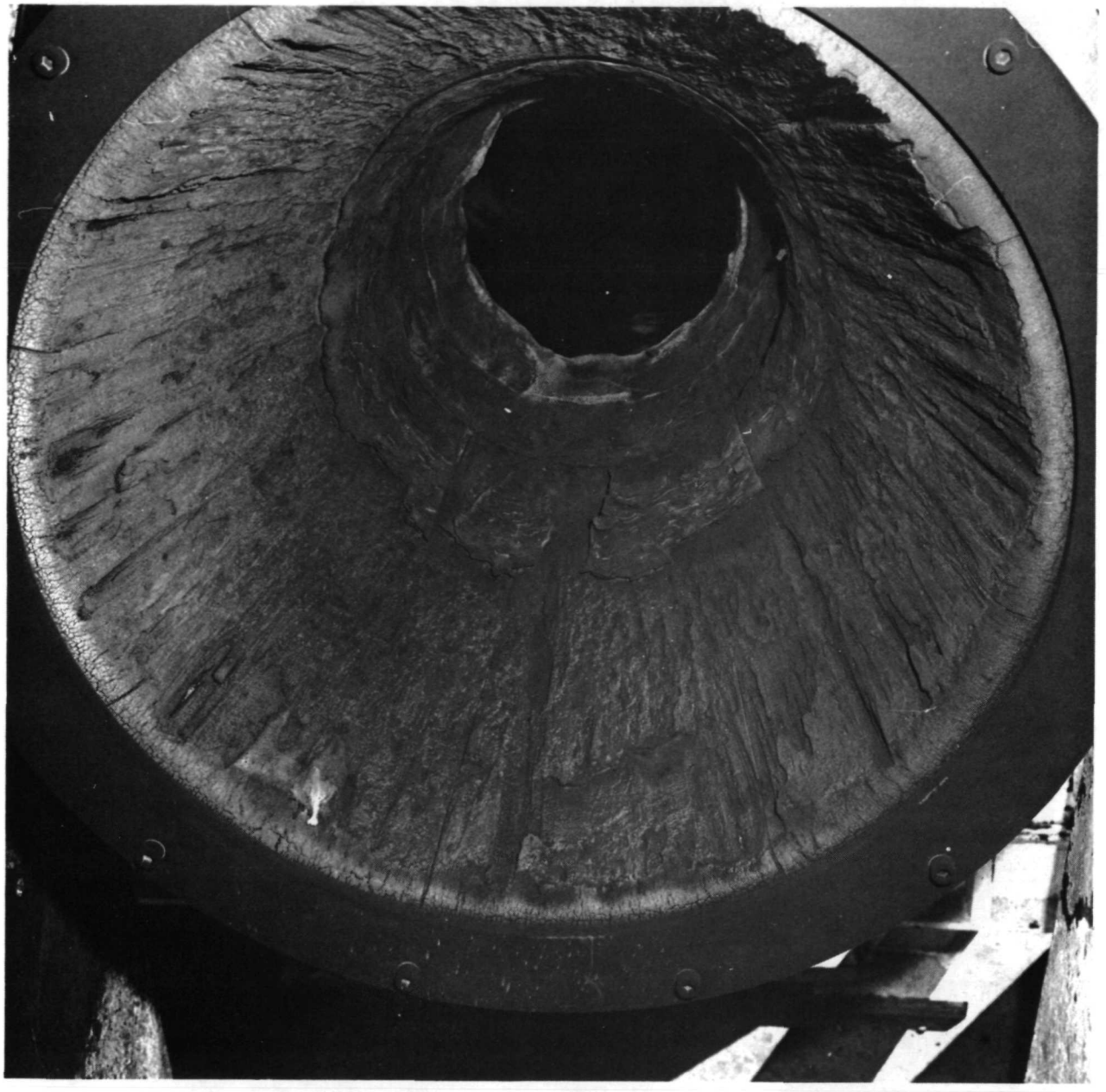


Figure IV-60. - Exit Cone of Nozzle S/N 006 After Test

V. TASK III - FULL-SCALE NOZZLE DESIGN AND FABRICATION PLANNING

A. DESIGN DESCRIPTION

1. Nozzle

The full-scale nozzle design is shown in Figure V-1. The nozzle is of the submerged type, with a throat diameter of 89.10 in. (2.26 m). The nose and approach section have a 3:2 elliptical shape, with the major axis equal to 75% of the throat radius and the leading edge located at an area ratio of 1.81:1. Thrust vector control will be provided by a flexible seal which permits a minimum of $\pm$ 2 degrees (0.035 rad) nozzle deflection. The seal assembly incorporated in this nozzle was designed, structurally analyzed, fabricated and evaluated under Contract NAS3-12049[10].

The throat insert will be molded from a chopped carbon-phenolic fabric. The components forward of the throat will consist of molded carbonaceous and castable carbon grades. The components of the exit cone will consist of carbon and canvas fabric grades.

The nozzle shell and throat support structural fittings will be fabricated of HY-140 steel. Roll-formed and welded assemblies will be employed to reduce fabrication costs, with the thicker flange sections and the forward portion of the throat support machined from ring-rolled forgings.

The ablative components were designed to be assembled into the steel shell at the motor assembly site by the application of adhesive bonding, using an ambient-curing epoxy adhesive. Circumferential joints between the different nozzle components will be filled with a room temperature-vulcanizing elastomeric mixture.

The ablative components are briefly described in the following paragraphs:

a. Aft Closure Insulation

The thermal insulation for the steel aft closure consists of an ARC-100/Si castable carbon inboard section and an outboard section of IBT-100 elastomeric compound. Both of these materials have performed successfully in the subscale motor tests. The silica reinforcement in the castable carbon is employed to reduce the tendency toward cracking and tearing during cure. The inboard (castable carbon) section is built up from 30 individually cast and machined segments that are adhesive bonded to form a ring. The outboard section of IBT-100 is troweled in place after the castable carbon ring is bonded to the steel closure.

b. Submerged Insert

This component provides thermal protection to the flexible seal and the submerged backside of the throat support structure. The submerged insert consists of 24 cast-and-machined segments of ARC-100/Si castable carbon bonded together to form a ring that is cantilevered from the steel shell and extends aft to a position adjacent to the inboard portion of the aft closure insulation.

c. Nosecap

The nosecap covers the entire forward end of the nozzle and consists of 24 molded-and-machined segments of CFA material that have been adhesive bonded to form a ring. The CFA material was selected because of its demonstrated ability to resist cracking and spallation, compared with the UF grade graphite-particle molding compounds, and its low cost potential, compared with chopped carbon fiber or fabric molding compounds. Its erosion resistance is not so high as that of the conventional molding compounds, but the section thickness of the nozzle (because of gas flow considerations) is great enough to permit its use.

During assembly into the steel shell, the joints between the segments of this and the other segmented components are offset from those in adjoining components so that there are no continuous joints extending in the axial direction.

d. Throat Approach

The throat approach is fabricated from CFA material. Fifteen molded-and-macined segments are bonded together to form the complete component that is bonded into the steel shell.

e. Entrance Insert

The entrance insert is also fabricated by adhesive bonding of molded-and-machined segments of CFA material. For this particular component, 18 segments form the finished part.

f. Throat Insert

The throat insert is a one-piece molded flame liner of 4C 1686 carbon/polyphenylene molding compound overwrapped with canvas duck for insulation. The 4C 1686 was selected for use because of its superior erosion resistance compared with the low-cost molding and wrapping materials investigated in this program. Alternative flame liner materials would be any conventional carbon/phenolic chopped fabric molding compound.

A weight summary for the nozzle is provided in Table V-1. The weight of the nozzle, exclusive of the flexible seal assembly is 19,182 lbm (8719 Kg).

2. Exit Cone

The two-section exit cone, also shown in Figure V-1, is a bell-shaped design with an exit plane diameter of 267.3 in. (6.78 m) and an overall

length of 247.16 in. (6.27 m). The expansion ratio of 9:1 provides a thrust coefficient very nearly the same as a conventional conical design with an 11:1 expansion ratio. The two sections of the exit cone are bolted together approximately 95 in. (2.41 m) from the minimum throat diameter.

The flame liner for the forward exit cone is fabricated by wrapping and consists of a low-cost carbon/phenolic tape (4C 1402) between area ratios 1.11 and 2.48 and canvas duck to area ratio 3.76. The flame liner for the aft exit cone is fabricated by autoclave curing and consists of 24 shingle-lap segments of canvas duck that are bonded together after molding.

Both forward and aft sections are separately overlaid with a polyester resin-impregnated glass fabric. In addition, the steel structure is bonded to the glass composite and is, in turn, overwrapped with polyester resin-impregnated glass roving and fabric.

The weight summary for the exit cone is provided in Table V-2. The total weight is 19,983 lbm (9083 Kg).

B. DESIGN VERIFICATION

1. Design Criteria

The full-scale nozzle design incorporating low-cost fabricating techniques was based on the 260-FL motor defined in the Douglas 260/SIVB study[9]. As indicated in Section IV.E.1, the motor contains 3.4 million lbm (1.54 million Kg) of propellant and its operating characteristics are:

Action time	147.5 sec
MEOP	764 psia (526 N/cm^2)
Average Thrust, web	6.34×10^6 lbf (28.2 MN)
Flame Temperature	5742°F at 1000 psia (3440K at 689.4 N/cm^2)

These criteria meet or exceed the reference parameters established in Exhibit "A" to the Contract NAS3-12064 Work Statement.

The exhaust gas composition of ANB-3374 (the HTPB Propellant that is expected to be used in any future large solid boosters) is given in Table V-3. This, along with the pressure-time curve shown in Figure V-2, were used an input for the ablative performance analysis program.

The initial thicknesses of the ablative liner were established using a minimum safety factor of 1.50 over and above the expected surface material loss and char penetration. The location of the 100°F (310K) isotherm further defined the total liner thickness, based on the criterion that the inner surfaces of overwraps do not exceed this temperature. The design safety factor at the nose was increased to 2.0 because analysis is complicated in that area. The safety factor in the aft exit cone was reduced to 1.25 since material loss is minimal and easily defined.

Structural members were designed to prevent strain in the ablative and structural plastic components from exceeding 0.25%. A safety factor of at least 1.25 was imposed on the minimum allowable material properties.

2. Thermal Analysis

A thermal evaluation was conducted of the proposed low-cost, full-scale design. This analysis utilized the estimated ballistic performance and provided analytical predictions of local erosion, char depth, and total thermal zone growth in the ablative flame liners as a function of elapsed firing duration.

The analysis consists of a series of one-dimensional, transient thermal analyses performed at various preselected axial stations of the preliminary nozzle design. These locations receive special attention and are of

sufficient number that a smooth postfiring erosion and thermal gradient contour may be established over the entire nozzle profile. The analytical techniques have been used in previous large motor programs and have been verified for capability. This procedure considers the actual thermal response of a material that reacts at the flame surface with the propellant exhaust products (erosion) and decomposes in depth (charring). The input data for this computer program include material properties, dimensions, and surface heat transfer conditions. The latter are established using a boundary layer growth technique that considers the local flow surface Mach numbers, nozzle contour, and propellant transport properties. The boundary conditions used in this analysis are summarized in Table V-4. In addition, the heat transfer coefficients were varied according to the schedule shown in Table V-5 to account for the chamber pressure variation that occurs during the firing.

Based on the above data, the expected erosion and char depths and the total thermal zone growth were calculated and are listed in Table V-6. In this table, the erosion represents the material surface loss resulting from chemical corrosion. The char depth is defined as the location of the 1100°F (865K) isotherm, while the total thermal zone is represented by the 100°F (310K) isotherm. As indicated in Table V-6, the thermal erosion at the throat is predicted to be 0.93 in. (2.36 cm), which represents a loss rate of 6.69 mils/sec (0.170 cm/sec) over the 139.5 sec of motor web time. This compares to a measured value of 5.8 mils/sec (0.147 cm/sec) for the 75 sec web time of 260-SL-3. The difference is attributed to a higher average chamber pressure and a slightly higher chemical corrosion potential for the HTPB type propellant.

The expected flame liner surface regression and char zone at the end of firing are plotted on the nozzle layout in Figure V-3 for the forward (nozzle) section and in Figure V-4 for the exit cone. Both sections represent nearly optimum design with respect to liner thicknesses. In the exit cone, the 100°F (310K) isotherm is just outboard of the interface between flame liner and structural overwrap. In the nozzle section, the actual minimum safety factor is equal to the target value of 2.0 at the most critical location (ε = 1.80).

The thermal responses at the throat station and at the location determined to be most critical in the forward exit cone are plotted against motor duration in Figures V-5 and V-6, respectively.

3. Stress Analysis

A thermal stress analysis was conducted to determine the design adequacy of the exit cone and of the throat. The Aerojet E11405 finite element computer routine was used for the analysis. The design loads for input into the analysis included the following:

- Motor maximum expected operating pressure (MEOP) of 750 psia (517 N/cm^2).

- Axial ejection force of 1,000,000 lbf (4,45 MN) in the flexible seal.

- Thermal gradient in the nozzle ablators at nozzle burnout as determined by the heat transfer analysis.

On the basis of the design loads, safety factors of 1.25 on structural components and 1.00 on ablative components were imposed. In addition, the strain within the ablative components was limited to 0.25%.

HY-150 steel was selected for the conical aft closure and the throat support structure. Normalized 4130 steel was selected for the exit-cone housing and the attach flanges. The exit-cone structural overwrap was fabricated from 184 glass/polyester resin. Ablative liner materials were as indicated in Table V-6. Structural material properties that were used in the analysis are shown in Table V-7. Properties of the ablative materials are listed in Table V-8.

Detailed analyses were performed by separating the nozzle assembly into three zones as follows: (1) conical aft closure and flexible

seal aft ring, (2) nozzle throat support and flexible seal forward ring, and (3) the exit cone.

a. Conical Aft Closure

Stress analysis of this section was performed under Contract NAS3-12038[8]. Results of the analysis indicated that at the point of maximum stress, the principal stresses were:

Radial stress - 2,250 psi (1550 N/cm^2) in tension
Axial stress - 8 psi (5.5 N/cm^2) in tension
Hoop stress - 63,206 psi (43.5 KN/cm^2) in tension

The margin of safety based on maximum stress theory was plus 0.107. The margin of safety based on the distortional energy failure theory (Von Mises') was plus 0.127.

b. Nozzle Throat

The analyses of Reference 8 had indicated that all stresses in the HY-150 nozzle support shell were below the allowable yield and buckling values of the material. The highest strain calculated to be present in the ablative liner was 0.23%.

c. Exit Cone Assembly

In the stress analysis of the exit cone assembly, the effects of ablation were considered by using the ablated geometry of the liner at web burnout time as predicted by heat transfer analysis. For conservatism, static pressure along the exit cone wall, calculated from compressible isentropic flow and based on MEOP pressure, was combined with the temperature profile at motor burnout in the analysis. Distribution of the maximum stress in the flame liner, the glass/polyester overwrap, and the 4130 steel supports indicated that

the minimum margin of safety was plus 0.58 in the 4C 1402 forward exit cone at area ratio 2.3. The margins of safety throughout the remainder of the exit cone varied from plus 1.77 in the 4130 steel attach fittings to plus 2.4/2.9 in the exit cone overwrap. The results confirm the structural adequacy of the proposed design.

C. FABRICATION PLAN FOR FULL-SCALE COMPONENTS

Detailed requirements for the production of the full-scale nozzle are included in the material and processing specifications that were prepared during the Task III portion of this program and submitted previously to the NASA/LeRC project manager. These specifications are:

Development Specification No.	Title
ASPC-36597 A	Exit Cone Assembly; Process Control of
ASPC-36602	Glass Fabric, Polyester Resin Impregnated; Application of
ASPC-36603	Ablative Components, Molded and Cast; Process Control of
ASPC-36604	Compounds, Ablative; for Molding, Troweling and Casting

Descriptions of the fabrication methods planned for the components of the full-scale nozzle assembly are presented in the following paragraphs. Because of the size of the full-scale nozzle, the fabrication operations have been planned so that subassembly and final nozzle assembly will take place at the motor assembly site.

1. Castable Carbon

The closure insulator and the submerged insert will be fabricated by casting. The maximum section thickness of both as-cast billets is approximately 5 in. (13 cm). The length along the conical surface of the closure insulator is 15 in. (38 cm); the length of the submerged insert is 18 in. (45 cm).

Curing of the ARC-100/Si castable carbon is accomplished by heating slowly to 340°F (171°C). At a heating rate of 60°F (33°C) per hour, the time required to reach the curing temperature is 4.5 hours. Holding at this temperature for 6 hours, and cooling to room temperature after curing will consume the remainder of one full day (24 hours) and so the monthly production rate will be a maximum of 20 to 23 castings of each type. The actual monthly production requirement, on the basis of six nozzle assemblies per year, is 15 of the closure insulator segments and 12 of the submerged insert segments. While one mold for each cast billet would be sufficient, two will provide for greater flexibility in meeting the schedule requirements.

After the castings are cured, they will be machined and inspected to drawing requirements, and shipped to the motor assembly site. There they will be assembled and joined together in a bonding fixture with room temperature-curing epoxy adhesive and machined to finished dimensions. As a final step, the segmented-bonded components will be bonded to the steel nozzle shell.

It would have been possible to bond the machined segments directly into the steel nozzle shell without going through the intermediate step of joining the segments and machining to form the nozzle component. This was evaluated and discarded for use because of the high probability of excessive tolerance buildup in the individual bonding operations and the consequent necessity to machine the last few segments to be bonded.

Bonding of the individual segments to form the closure insulator is shown in Figure V-7.

2. Carbonaceous (CFA) Molding Material

The nosecap and the approach and entrance sections are single-material components and will be fabricated by molding CFA material at approximately 50 psi (34.5 N/cm^2). The section thicknesses of the as-molded billets

will range from 6 in. (15 cm) in the approach insert to 3.5 in. (9 cm) in the entrance insert segments. After molding, the segments are machined and bonded together with epoxy adhesive. Figures V-8 through V-10 show the sequence of operations required to form the respective components in the forward end of the nozzle.

3. Throat Insert

The throat insert is a two-material component consisting of an erosion-resistant carbon/polyphenylene flame liner overlaid with canvas tape for insulation. The flame liner is molded as a single ring, using 1/2 in. (1.25 cm) chopped squares, and molding at 1000 $\pm$ 50 psi (689 $\pm$ 35 N/cm^2) and 300 $\pm$ 10°F (150 $\pm$ 5°C). The mold should be designed so that the fabric squares at the I.D. surface are aligned at approximately 45 degrees (0.785 rad). After molding, the flame liner is machined on the O.D. surface and wrapped with canvas tape. The flame liner and overwrap are then covered with bleeder cloth and enveloped in an impervious bag attached to a vacuum line. The bagged assembly is loaded into a heating chamber, a vacuum of 27 in. Hg (9 N/cm^2) is drawn and the part temperature is raised to 300°F (149°C) to cure the canvas/phenolic overwrap.

Alternatively, the flame liner may be fabricated by bonding together molded segments of the carbon/polyphenylene material. If this is done, the mold must be designed to yield the same orientation of the fabric squares as that in the one-piece mold.

4. Forward Exit Cone

The flame liner of the forward exit cone is fabricated by tape-wrapping. A low cost, low carbon-content fabric (Pluton B-1) impregnated with resin is wrapped parallel to the center line of the nozzle to approximately 140 in. (3.56 cm) dia, at which location canvas tape is wrapped in and continued to 173 in. (4.4 m) dia. The flame liner is cured on the wrap mandrel, using a

pressure of 125 psi (86 N/cm^2). After curing, the flame liner is machined on the O.D. surface to accept the glass-polyester structural wraps and the steel structure fittings.

Alternatively, the forward exit cone may be terminated at 140 in. (3.56 cm) dia, in which case the entire forward exit cone will be fabricated from the low-cost carbon tape prepreg. The effect of this change in attachment upon the applied stresses, however, was not examined in this program.

5. Aft Exit Cone

The flame liner of the aft exit cone is fabricated from canvas duck preimpregnated with phenolic resin. The canvas duck is pre-cut to shape and laid down in a mold in a shingle pattern so that the plies are oriented at a very low angle to the I.D. surface as indicated in Figure V-11. Pressure application during curing will be of the order of 75-125 psi (52-86 N/cm^2).

The canvas flame liner segments of the aft exit cone will be laid on a form and bonded together, then covered with glass/polyester structural fabric in the same manner as the forward exit cone. The steel structural fittings will also be adhesive bonded in the same manner as before.

D. FULL-SCALE NOZZLE COST ESTIMATE

A cost estimate was prepared for the full-scale nozzle design, based on the assumption that 30 motors would be fabricated at the rate of six units per year. Materials, tooling, facility and labor costs were included in the estimate. Transportation costs were not included.

As shown in the full-scale nozzle cost summary, Table V-9, the unit cost is $767,992. Of this amount, $442,762 is chargeable to the nozzle and $325,230 to the exit cone. The addition of a flexseal for thrust vector control

would increase the cost by another $62,300 for a total of $830,292, exclusive of any necessary actuators, hydraulic power systems or related subsystems.

The incorporation of the low-cost materials and fabrication techniques in the full-scale nozzle assembly results in overall savings of approximately $149,000, in comparison with a tape-wrapped design using conventional carbon and silica fabric reinforced phenolics. Compared with a tape-wrapped version comprised of conventional carbon-phenolic prepreg and canvas duck[8], the cost reduction is approximately $69,000.

The cost of the ablative materials now represents less than 12.5% of the total nozzle cost compared with the almost 38% represented by the steel support structure. It is to be noted that the steel components were costed at a rate of $20/lbm ($44 Kg). In view of the cost of the finished ablative parts ($5.5 to $35/lbm; $12 to $77 Kg), this appears to be high for the production rates considered.

The different items in the cost summary are discussed in the following sections:

1. Ablative Material Costs

Table V-10 summarizes the ablative material costs. The total weight of material was obtained by determining the volume of the as-fabricated components (see Tables V-1 and -2). An additional 3% was added for in-process waste to each component except the aft closure insulator, and 5% was added to its final part weight for waste during mixing, handling and troweling.

The costs of the castable carbon and carbonaceous (graphite particle) materials are subject to some uncertainty, since they have not been established by competitive processes. Accordingly, these materials have been priced on the basis of supplier-furnished information[12, 13]. The IBT-100 cost includes the labor required for application. The glass/polyester cost

combines the glass fabric ($1.47/lbm) and resin mix costs, but does not include the labor required for the mixing of resin and application of fabric and resin.

2. Labor Costs

Eight separate components comprise the full-scale assembly, of which six are in the nozzle and two in the exit cone. All components except the throat insert and forward exit cone are separate circular or conical segments bonded together to form the larger part. In the nozzle, the labor mix is primarily in the area of machining since the segments must be accurately aligned prior to bonding and machining to contour after bonding. In the exit cone, the labor mix is primarily in the area of plastics processing.

The unit labor cost was estimated as follows:

a. Nozzle Throat Assembly

900	hours molding and casting
360	hours bonding
900	hours wrapping (for throat)
4,050	hours machining
6,210	hours direct labor
300	hours prorated nonrecurring direct labor
6,510	hours total direct labor per unit

b. Exit Cone Assembly

954 hours wrapping
470 hours molding
200 hours bonding
860 hours structural overwrapping
420 hours machining
2,300 hours direct labor
300 hours prorated nonrecurring direct labor
3,204 hours total direct labor per unit

The direct labor hourly rate of $5.87 and the overhead rate of 174% are Areojet estimates based on information provided by a major nozzle fabricator.

3. Tooling Costs

The identification of the required ablative tooling in Table V-11 is based on the fabrication plan described in Section V.C. The numbers of segments required for each component (15 to 30) and the required production rate of six nozzle assemblies per year justify the use of accurate, permanent tooling. Consequently, the ablative tooling costs represent a total investment of $313,450 of which $152,890 will be used for the nozzle throat section. Prorated over the life of the program, the unit costs are $5,096 for the nozzle ablative components and $5,356 for the exit cone. Unit tooling costs for a tape-wrapped nozzle assembly have been reported[8] to be $8,145 for the nozzle section and $9,639 for the exit cone. The present program costs represent a 41% reduction.

4. Facility Requirements

The fabrication plan for the full-scale nozzle assembly represents a degree of flexibility in procurement that is unmatched by the use of conventional tape-wrapping techniques. The use of molded segments bonded together,

for each component except the throat, allows for procurement either of the segments or of the bonded components. Also, in the former case, the segments may be shipped directly to A-DD or to a separate assembly-machining source. In any event, no problems with respect to facilities requirements are expected with respect to the nozzle throat section.

The throat insert, even though fabricated as an integral ring, does not represent a major facility investment since molding presses are available on the West Coast in the desired size and capacity. In addition, an alternative fabrication procedure may be used; a hydroclave may be employed to supply the pressure required for curing.

Because of the size of the exit cone, the fabrication was planned so that this component would be assembled and finished at A-DD. This will require the additional facilities as indicated in Table V-12. Major justification for the purchase of these facilities can be provided by the savings in transportation cost accrued by not shipping full-size exit cones from the West Coast through the Panama Canal to A-DD.

5. Administrative Costs

General and administrative costs of 8.5% have been applied to the nozzle assembly. Profits of 10% were also applied. These are considered to be average and reasonable.

TABLE V-I

WEIGHT SUMMARY, FULL-SCALE NOZZLE

Component	Material	Calculated Weight			
		As Fabricated		Final Part	
		lbm	Kg	lbm	Kg
Closure Insulator	Castable Carbon	1275	579.5	1,040	472.7
Submerged Insert	Castable Carbon	1100	500.0	930	422.7
Nose Cap	Carbonaceous (CFA)	615	279.5	505	229.5
Throat Approach	Carbonaceous (CFA)	545	247.7	458	208.1
Entrance	Carbonaceous (CFA)	855	388.6	720	327.3
Throat Liner	Carbon Polyphenylene	1500	681.8	1,357	616.8
Overwrap	Canvas Duck	441	200.0	400	181.8
Aft Closure Insulation	IBT-100	-	-	3,208	1458.2
Nozzle Shell	HY-150	-	-	6,614	3005
Throat Support	HY-150	-	-	3,850	1750
Bolts, Adhesive	-	-	-	100	45.5
Miscellaneous					
Basic Nozzle Weight				19,182	8719
Flex Seal Assembly				4,426	2011.8
Total Nozzle Weight				23,608	10,731

TABLE V-2

EXIT CONE WEIGHT SUMMARY

Component	Part	Material	Calculated Weight			
			As-Fabricated		Final	
			lbm	Kg	lbm	Kg
Forward Exit Cone	Housing	4130 Steel			3,558	1,617.3
	Aft Flange	4130 Steel			794	360.9
	Liner, Fwd	Carbon/Phenolic	2050	931.8	1,710	777.2
	Liner, Aft	Canvas	1600	727.2	1,330	604.5
	Insulator/ Overwrap	Glass	1670	759	1,510	686.4
	Adhesive; Misc.	--	--	--	50	22.7
Subtotal					8,952	4,069
Aft Exit Cone	Fwd Flange	4130 Steel	--	--	899	408
	Liner	Canvas	7150	3250	6,810	3,095.4
	Structural Overwrap	Glass	3415	1552.3	3,250	1,477.3
	Adhesive; Misc.	--	--	--	72	32.7
Subtotal					11,031	5,014
EXIT CONE TOTAL WEIGHT					19,983	9,083

TABLE V-3.- EXHAUST GAS COMPOSITION - ANB-3374 PROPELLANT (HTPB)

HCl	0.4971
N_2	0.3030
H_2O	0.7015
H_2	0.8883
O_2	0.0009
O	0.0029
OH	0.0408
Cl	0.0425
NO	0.0032
Cl_2	0.0001
H	0.1113
CO	0.7873
CO_2	0.0772
PN	0.0015
PO	0.0071
Al	0.0002
AlCl	0.0085
$AlCl_2$	0.0213
$AlCl_3$	0.0006
Al_2O_3	0.2626
FeCl	0.0112

*Moles/100 gm of propellant at 1000 psia (690 N/cm^2) chamber pressure and 5742°F (3440°K)

TABLE V-4

THERMAL ANALYSIS STATIONS AND
BOUNDARY CONDITIONS - FULL-SCALE NOZZLE

Nozzle Location				Local Convective Heat Transfer Coefficient*		Local Recovery Temperature	
Radius				Btu/hr-$ft^2°F$	$(W/m^2°K)$	°R	(°K)
in.	(cm)	ε					
59.6	151.4	-1.80		1700	5358	6076	3376
52.67	133.8	-1.40		1222	3852	6058	3366
47.20	119.9	-1.13		1291	4069	6015	3342
44.98	114.0	-1.02		1228	3871	5972	3318
44.55	112.9	1.00	(Throat)	1110	3499	5929	3294
45.78	116.3	1.06		829	2613	5820	3233
47.03	119.5	1.12		728	2295	5783	3213
59.46	151.0	1.79		567	1787	5728	3182
65.12	165.4	2.15		464	1463	5667	3148
70.2	178.3	2.50		390	1229	5648	3138
76.7	194.8	3.00		317	999	5610	3117
99.6	253.0	5.00		173	545	5520	3067
123.9	314.7	8.00		105	331	5445	3025

* At chamber pressure of 514 psia (354 N/cm^2)
**Chamber stagnation temperature = 6094°R (3390°K)

TABLE V-5.- HEAT TRANSFER CORRECTION FACTOR SCHEDULE

Time, sec	Chamber Pressure, psia	Chamber Pressure, (N/cm^2)	Heat Transfer Factor - HTF*
0	620	427	1.161
35	650	448	1.207
55	505	348	0.985
112	700	482	1.280
140	400	276	0.820
148	14.7	10	

*HTF = Ratio of heat transfer coefficient at any desired chamber pressure (P_c) to its value at P_c = 514 psia (354 N/cm^2).

TABLE V-6

EXPECTED PERFORMANCE OF FULL SCALE NOZZLE

Component	Station	Material	Area Ratio	Depth From Original Surface					
				Erosion		Char		100°F (310°K) Isotherm	
				in.	(cm)	in.	(cm)	in.	(cm)
Nose Cap	1	Carbonaceous	-1.80	1.75	(4.45)	1.97	(5.00)	2.70	(6.86)
Entrance	2	Carbonaceous	-1.40	1.22	(3.10)	1.52	(3.86)	2.29	(5.82)
	3		-1.13	1.26	(3.20)	1.54	(3.91)	2.33	(5.92)
Throat	4	Molded	-1.01	1.08	(2.74)	1.37	(3.48)	2.10	(5.33)
	5	Carbon	Throat	0.93	(2.36)	1.25	(3.18)	1.95	(4.95)
	6	Polyphenylene	1.06	0.54	(1.37)	0.99	(2.51)	1.88	(4.78)
Forward	7	Low Cost Car-	1.11	0.62	(1.57)	0.99	(2.51)	1.82	(4.62)
Exit Cone	8	bon Phenolic	2.14	0.43	(1.09)	0.95	(2.41)	1.77	(4.50)
	9	Canvas	2.48	1.16	(2.95)	1.28	(3.25)	1.52	(3.86)
	10	Duck	2.96	0.93	(2.36)	1.08	(2.74)	1.37	(3.48)
Aft Exit	11	Canvas	4.0	0.35	(0.89)	0.59	(1.50)	1.04	(2.64)
Cone	12		5.0	0.27	(0.69)	0.52	(1.32)	1.01	(2.57)
	13		6.5	0.48	(0.48)	0.48	(1.22)	0.97	(2.46)
	14		8.0	0.15	(0.38)	0.45	(1.14)	0.95	(2.41)

TABLE V-7.- STRUCTURAL MATERIAL PROPERTIES

Property	HY-150 Steel	4130 Steel	184 Glass Cloth Polyester Resin
Yield Strength, ksi (KN/cm^2)	136 (93.7)	70 (48.2)	-
Ult. Tensile Strength, ksi (KN/cm^2)	149 (103)	90 (62.0)	47.4 (32.6) (hoop & axial) 40.5 (27.9) (radial)
Ult. Shear Strength, ksi (KN/cm^2)	89.4 (61.5)	54 (37.2)	5.0 (3.5)
Young's Modulus, psi x 10^6 (MN/cm^2)	29.5 (20.3)	29.0 (20.0)	3.9 (2.7) (hoop & axial) 3.3 (2.3) (radial)
Poisson's ratio	0.30	0.30	0.125

TABLE V-8

PROPERTIES OF ABLATIVE MATERIALS

	ARC-100 Castable Carbon	(CFA)* Carbonaceous	4C 1686 (Molded)	Canvas Duck**	
Tensile Str., ksi (K N/cm^2)					
at 75°F (297°K)	N.A.	0.21 (0.14)	N.A.	8.8 (6.1)	11
	-	-	-		1
at 1700°F (1200°K)	N.A.	N.A.	N.A.	1.95 (1.3)	11
Tensile Mod., psi x 10^6 (NM/cm^2)					
at 75°F (297°K)	N.A.	N.A.	N.A.	0.46 (0.32)	11
	-	-	-	0.36 (0.25)	1
at 1700°F (1200°K)	N.A.	N.A.	N.A.	0.44 (0.30)	11
Compressive Str., ksi (KN/cm^2)					
at 75°F (297°K)	12.6 (8.7)	5.1 (3.5)	35.5 (24.5)	21.3 (14.7)	11
	-	-	-	39.7 (27.4)	1
at 600°F (589°K)	2.0 (1.4)	N.A.	6.6 (4.6)	16.0 (11.0)	11
	--	-	-	30.0 (20.7)	1
at 1700°F (1200°K)	1.1 (0.76)	N.A.	4.3 (3.0)	4.4 (3.0)	11
	-	-	-	8.3 ((5.7)	1
Compressive Mod., psi x 10^6 (MN/cm2)					
at 75°F (297°K)	1.77 (1.22)	N.A.	2.65 (1.83)	N.A.	11
	-	-	-	0.42 (0.29)	1
at 600°F (589°K)	0.30 (0.21)	N.A.	0.52 (0.36)	N.A.	11
	-	-	-	0.61 (0.42)	1
at 1700°F (1200°K)	0.18 (0.12)	N.A.	0.52 (0.36)	N.A.	11
	-	-	-	0.52 (0.36	1

NOTES: *From Reference 13
**From Reference 8. (11) and (1) refer to load-ply orientation.

TABLE V-9

FULL-SCALE NOZZLE COST SUMMARY

I.	NOZZLE		
	A.	Ablative Materials (1)	$ 42,320
	B.	Steel Components (@ $20/lbm)	209,020
	C.	Expendable Materials	5,500
	D.	Direct Labor (6510 hrs @ $5.87)	38,214
	E.	Direct Labor Overhead (@ $1.74)	66,492
	F.	Tooling for Ablative Components (2)	5,096
	G.	Tooling for Steel Components (2)	4,520
	H.	Facilities	0
	I.	G&A (@ 8.5 percent)	31,349
		Subtotal	$402,511
		Profit (10 percent)	$ 40,251
		Total	$442,762
II.	EXIT CONE		
	A.	Ablative Materials (3)	61,334
	B.	Steel Components	107,040
	C.	Expendable Materials	4,000
	D.	Direct Labor (3204 hrs @ $5.87)	18,807
	E.	Direct Labor Overhead	32,724
	F.	Tooling for Ablative Components (2)	5,356
	G.	Tooling for Steel Components (2)	2,740
	H.	Facilities	40,500
	I.	G&A	23,163
		Subtotal	$295,664
		Profit	$ 29,566
		Total	$325,230
		Unit Cost	$767,992
		With Flexible Seal	$830,292

NOTES: (1) Includes IBT-100 Insulation
(2) Prorated over 30 Units
(3) Includes glass/polyester structural wrap.

TABLE V-10

ABLATIVE MATERIAL COST SUMMARY

	Material	Total Weight (2) lbm	(Kg)	$/lbm	Cost
Nozzle	IBT-100 (1)	3370	(1531.8)	1.10	$ 3707.0
	ARC-100	2450	(1113.6)	0.45	1102.5
	CFA	2075	(944.0)	2.05	4150.0
	4C 1686	1550	(704.5)	21.00	32,550.0
	Canvas	450	(204.5)	1.80	810.0
					$42,319.5
Exit Cone	4C 1401	2100		14.25	$29,925.01
	Canvas	9015		1.80	16,227.0
	Glass/Polyester	5235	(2379.5)	2.90	15,181.5
					$61,333.5

(1) IBT-100 weight includes 5 percent contingency; cost includes application.

(2) As-fabricated weight plus 3 percent contingency.

TABLE V-11

TOOLING REQUIREMENTS, FULL SCALE NOZZLE FABRICATION

Component	Tool Description	Estimated Cost
Closure Insulator	Mold Casting (2)	$ 4,300
	Machining Fixtures (2)	1,500
	Bonding Fixture (1)	2,800
	Tracer Template (1)	720
	Ablative Handling Aid (1)	2,160
	Ablative Storage Fixture (1)	300
	Subtotal	$11,780
Submerged Insert	Mold, Casting (2)	$ 4,600
	Machining Fixtures (2)	1,500
	Bonding Fixture (1)	2,600
	Tracer Template (1)	720
	Ablative Handling Aid (1)	2,000
	Ablative Storage Fixture (1)	300
	Subtotal	$11,720
Nose Cap	Mold, Compression (1)	$ 5,300
	Machining Fixture (1)	600
	Bonding Fixture (1)	2,400
	Tracer Template (1)	720
	Ablative Handling Aid (1)	1,600
	Ablative Storage Fixture (1)	300
	Subtotal	$10,920
Approach	Mold, Compression (1)	$ 5,750
	Machining Fixture (1)	700
	Bonding Fixture (1)	2,200
	Tracer Template (1)	720
	Ablative Handling Aid (1)	1,400
	Ablative Storage Fixture (1)	300
	Subtotal	$11,070

Table V-11, Tooling Requirements, Full Scale Nozzle Fabrication (cont.)

Component	Tool Description	Estimated Cost
Entrance	Mold, Compression (1)	$ 6,200
	Machining Fixture (1)	700
	Bonding Fixture (1)	2,500
	Tracer Template (1)	720
	Ablative Handling Aid (1)	1,800
	Ablative Storage Fixture (1)	300
	Subtotal	$11,220
Throat	Mold Compression	18,000
	Tracer Template (2)	1,320
	Ablative Handling (2)	2,740
	Ablative Storage Fixture	600
	Subtotal	$22,660
Nozzle Assembly	Assembly Stand	11,600
	Tracer Template	1,100
	Machining Tool	1,440
	Stage Drawings	9,080
	Assembly Aids	3,500
	Inverting Fixture	27,600
	Leak Test Fixture	19,200
	Subtotal	$73,520
Forward Exit Cone	Mandrel Wrap	62,500
	Mandrel Handling Aid	2,800
	Ablative Handling Aid	3,200
	Tracer Template (Wrap)	680
	Tracer Template (Mach) 2 Req'd.	1,400
	Ablative Storage Fixture	680
	Subtotal	$71,260

Table V-11, Tooling Requirements, Full Scale Nozzle Fabrication

Component	Tool Description	Estimated Cost
Aft Exit Cone	Mold	$14,500
	Machining Fixture	2,750
	Bonding Fixture	14,500
	Ablative Handling Aid	3,750
	Tracer Templates (2)	1,400
	Ablative Storage Fixture	1,000
	Dam Ring	2,100
	Subtotal	$40,000
Exit Cone Assembly	Assembly Fixture	$12,500
	Flange Positioning and Bonding Fixture (3)	15,000
	Tilt Stand Adapter	12,600
	Tracer Template (3)	1,200
	Inspection Aids	8,000
	Subtotal	$49,300
	Total Tooling Cost	$313,450

TABLE V-12

NEW FACILITY REQUIREMENTS

280-In.-Dia Vertical Mill	$ 625,000
Inspection Standards	40,000
Q.C. Laboratory Equipment	120,000
Raw Material Storage Building	30,000
Fabrication Building and Crane	400,000
	$1,215,000

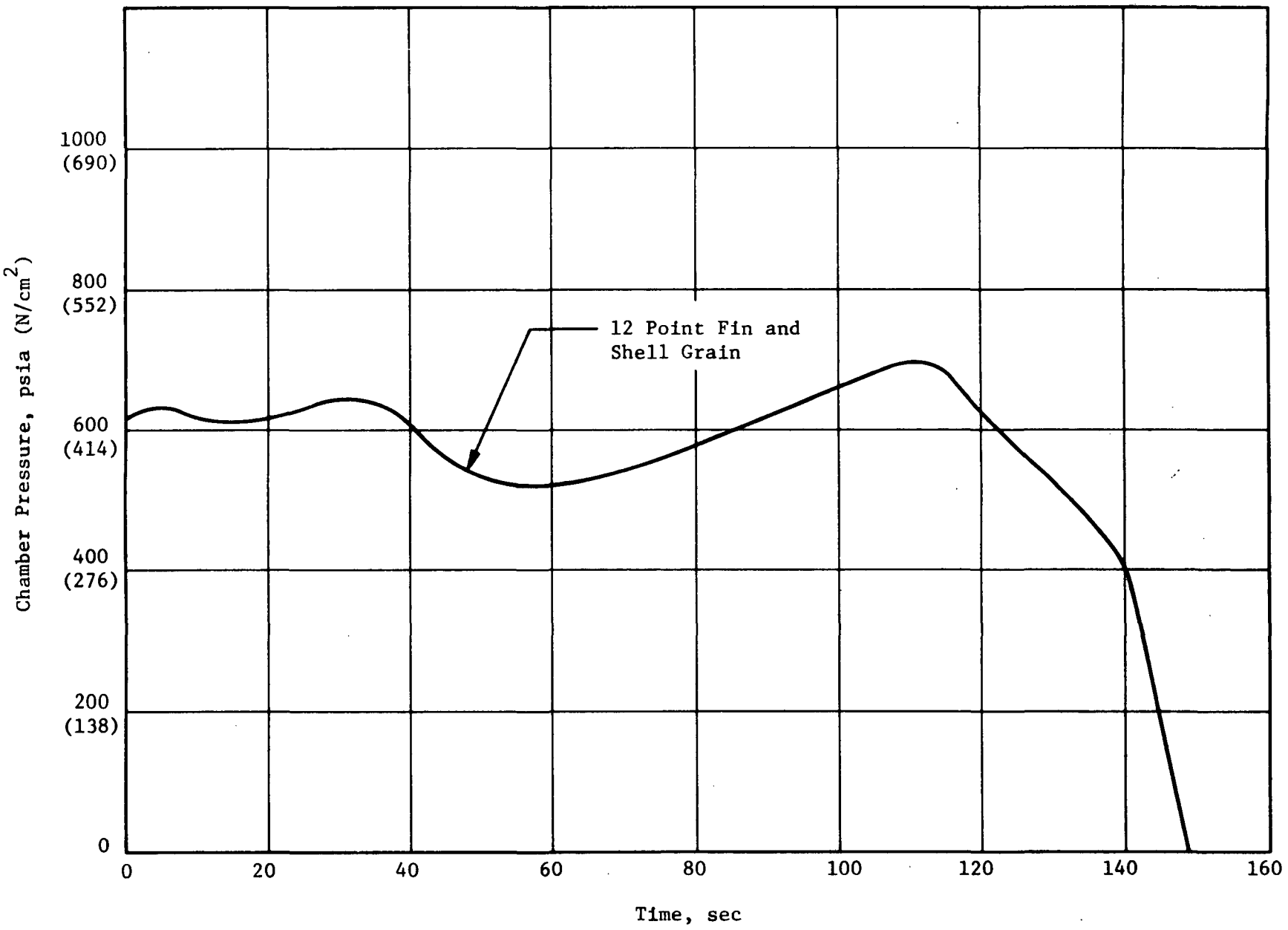


Figure V-2. - Predicted Pressure-vs-Time Performance 260-FL Motor (260/SIVB Study)

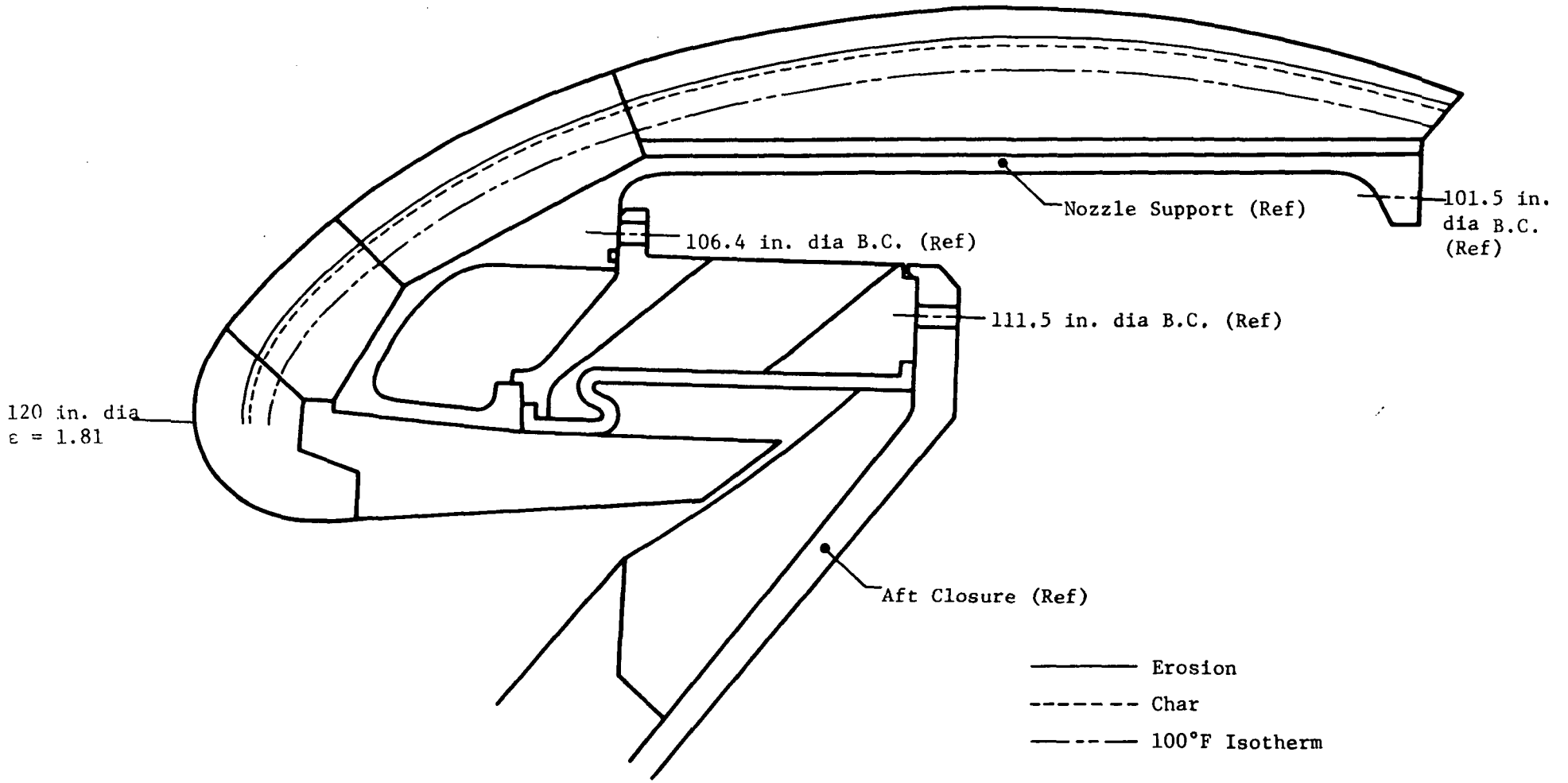


Figure V-3. - Predicted Regression and Char Depths in Forward End of Nozzle

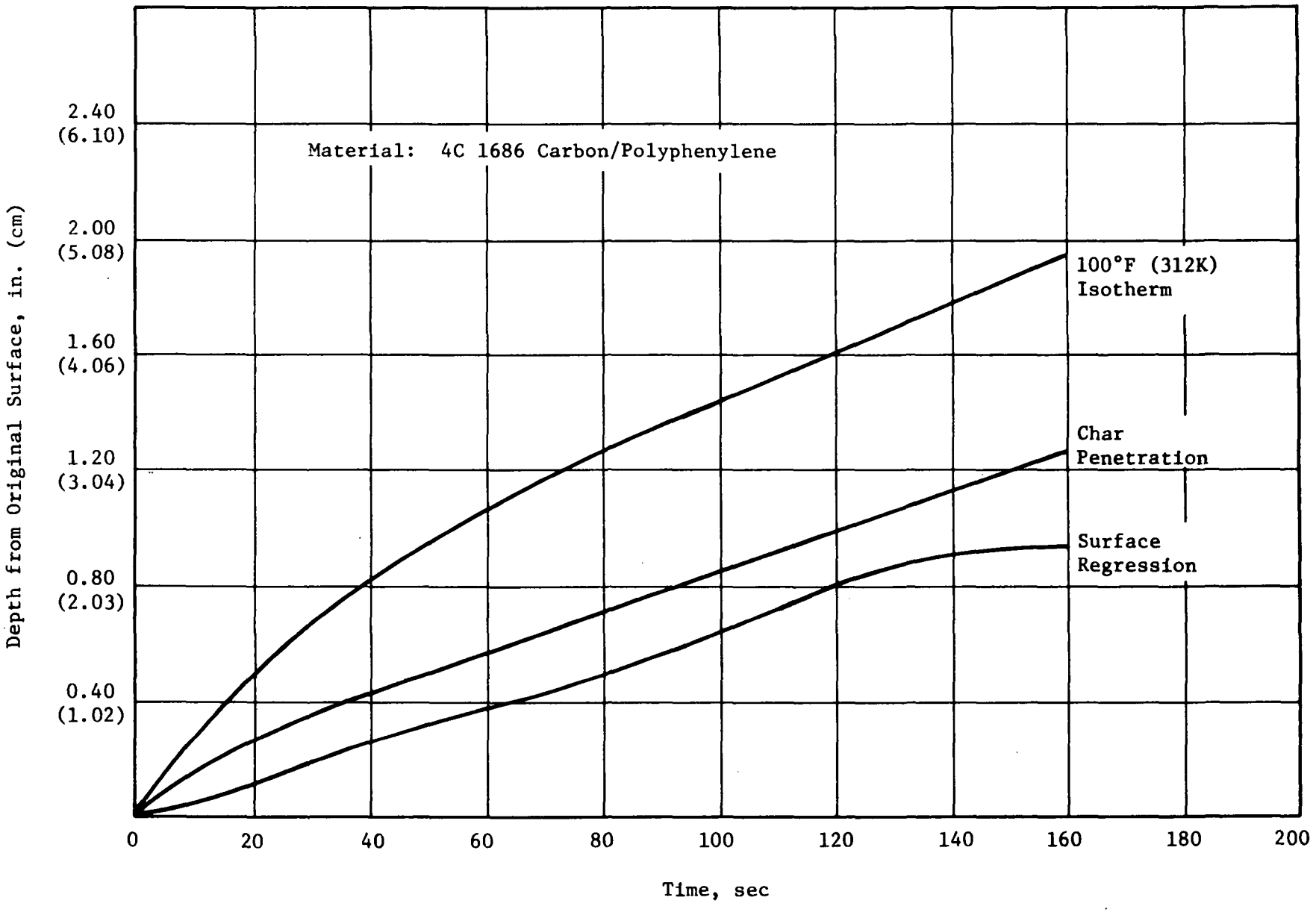


Figure V-5. - Predicted Thermal Response at Throat Station - Full-Scale Nozzle

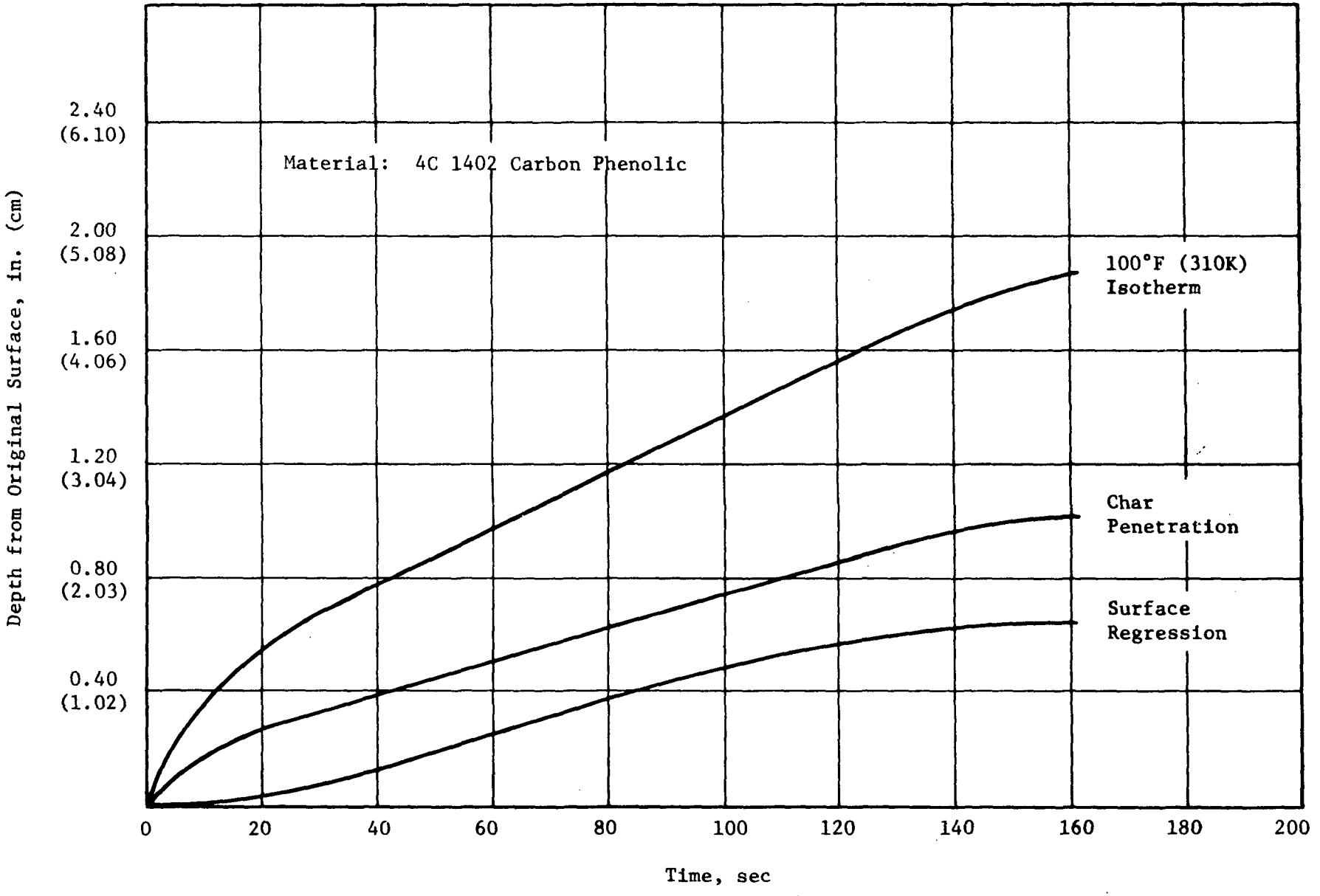


Figure V-6. - Predicted Thermal Response at Exit Cone Station 7

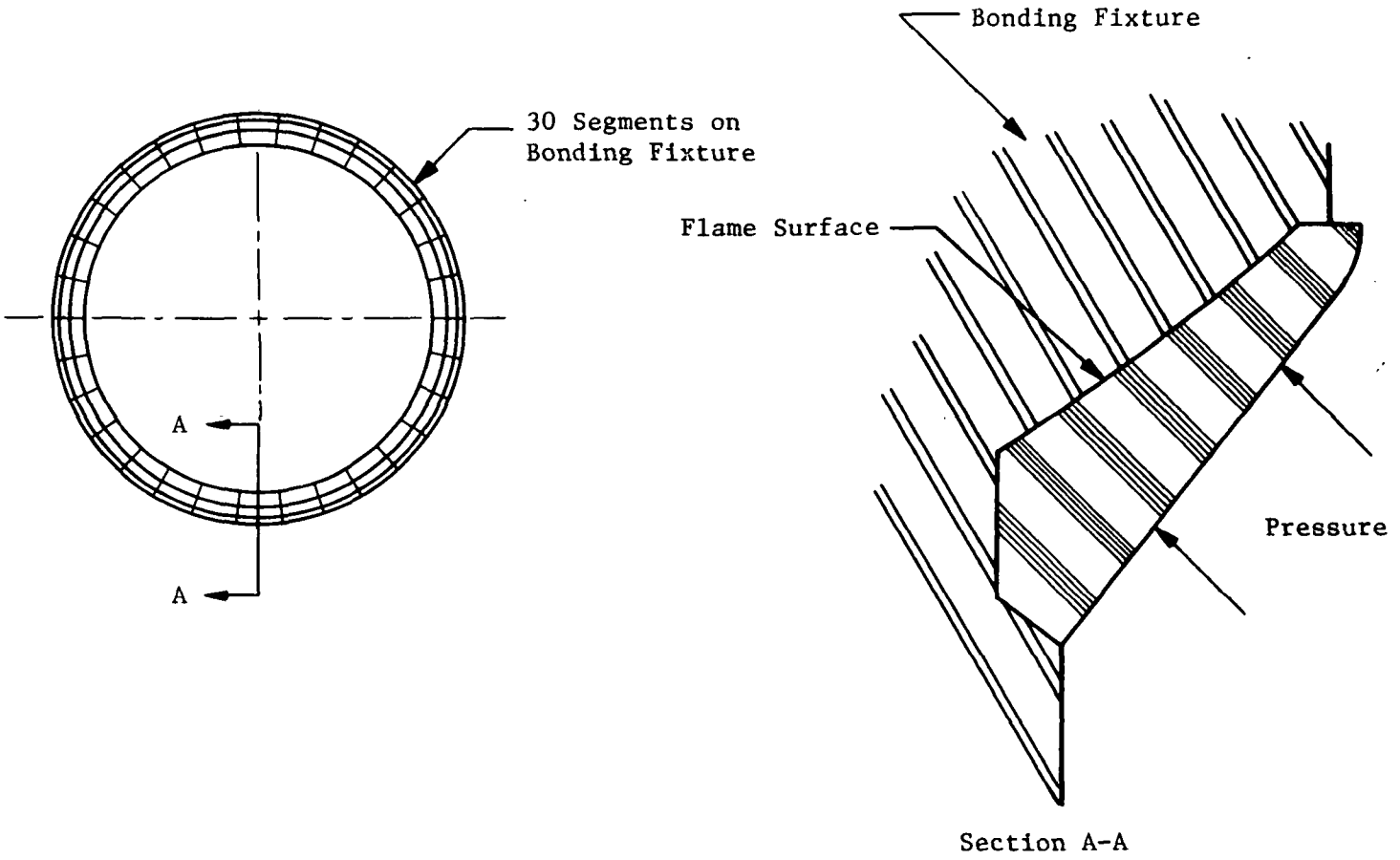


Figure V-7. - Bonding of Closure Insulator Segments

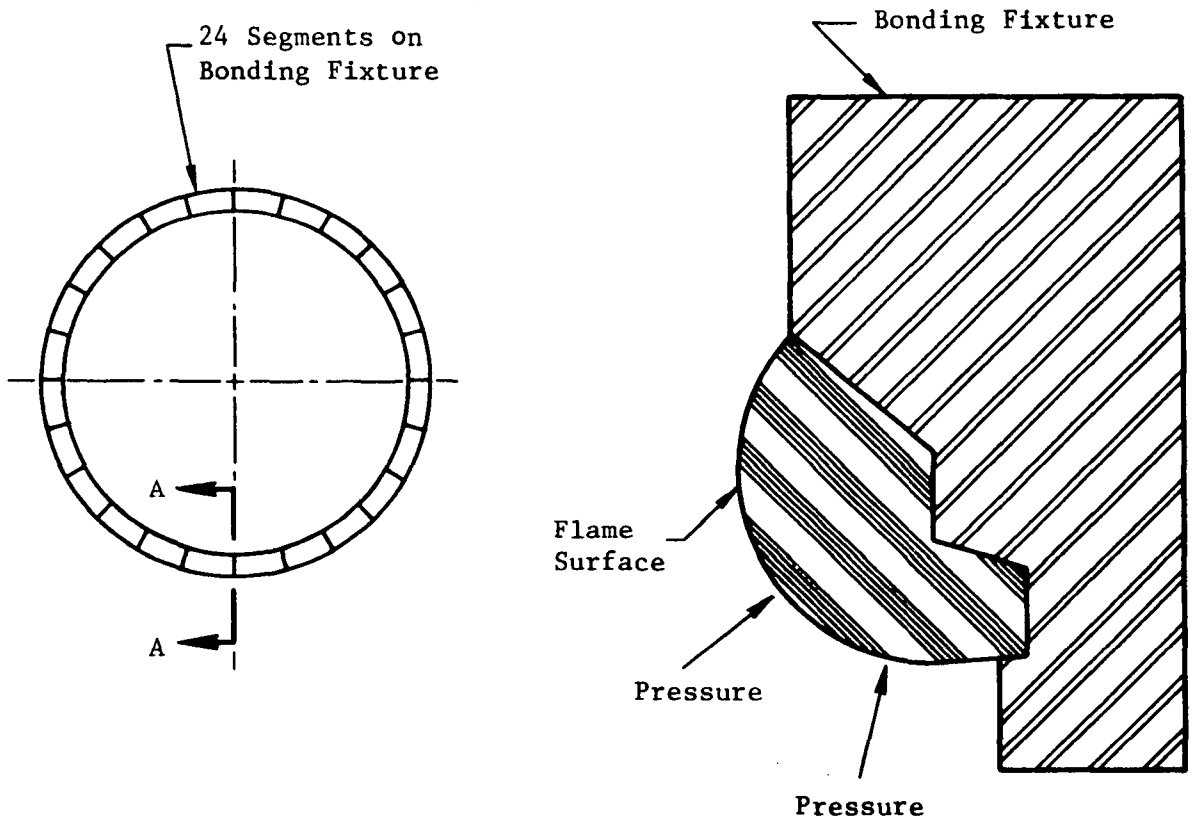


Figure V-8. - Bonding Nose Cap

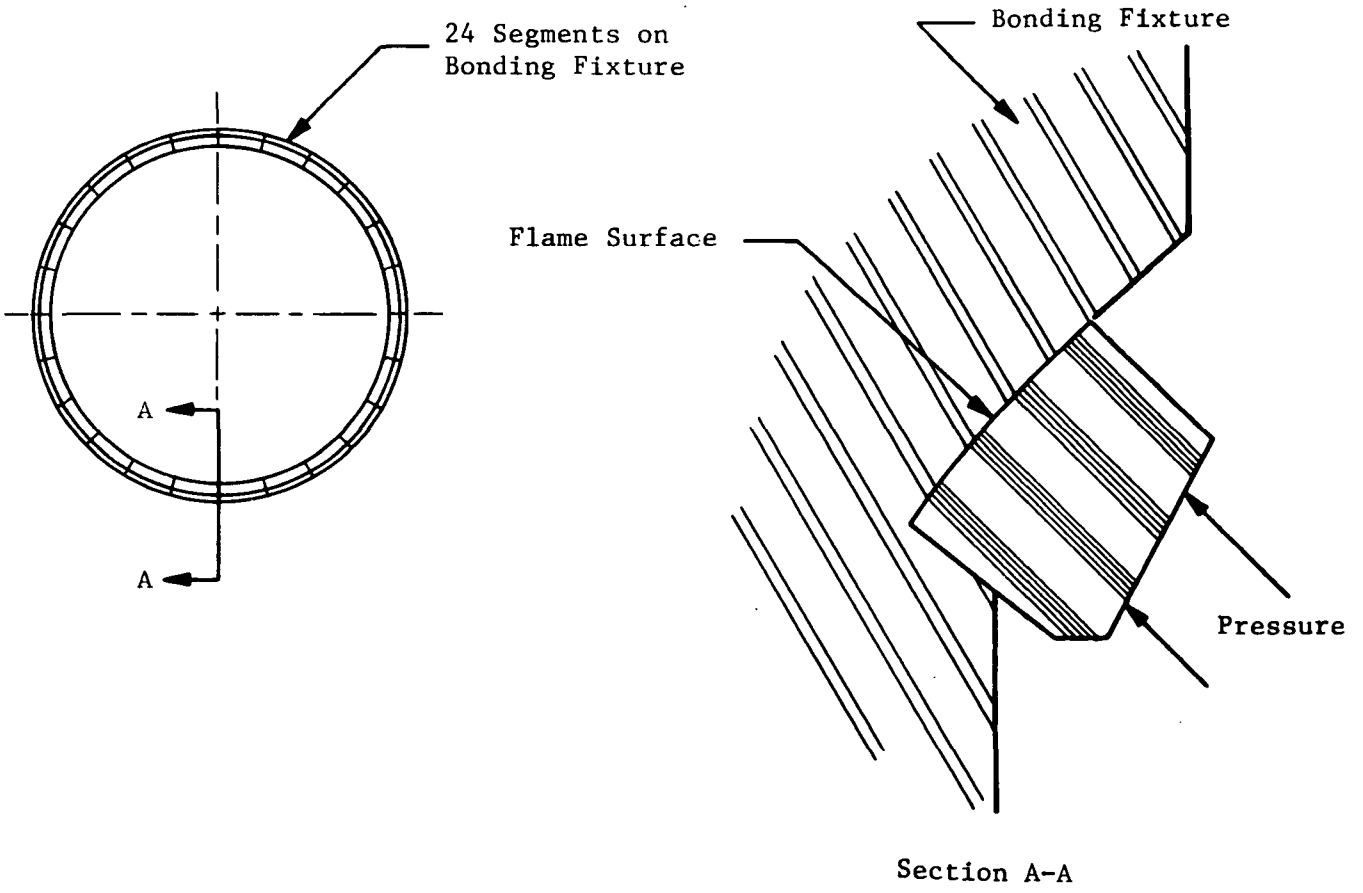


Figure V-9. - Bonding Approach Insert

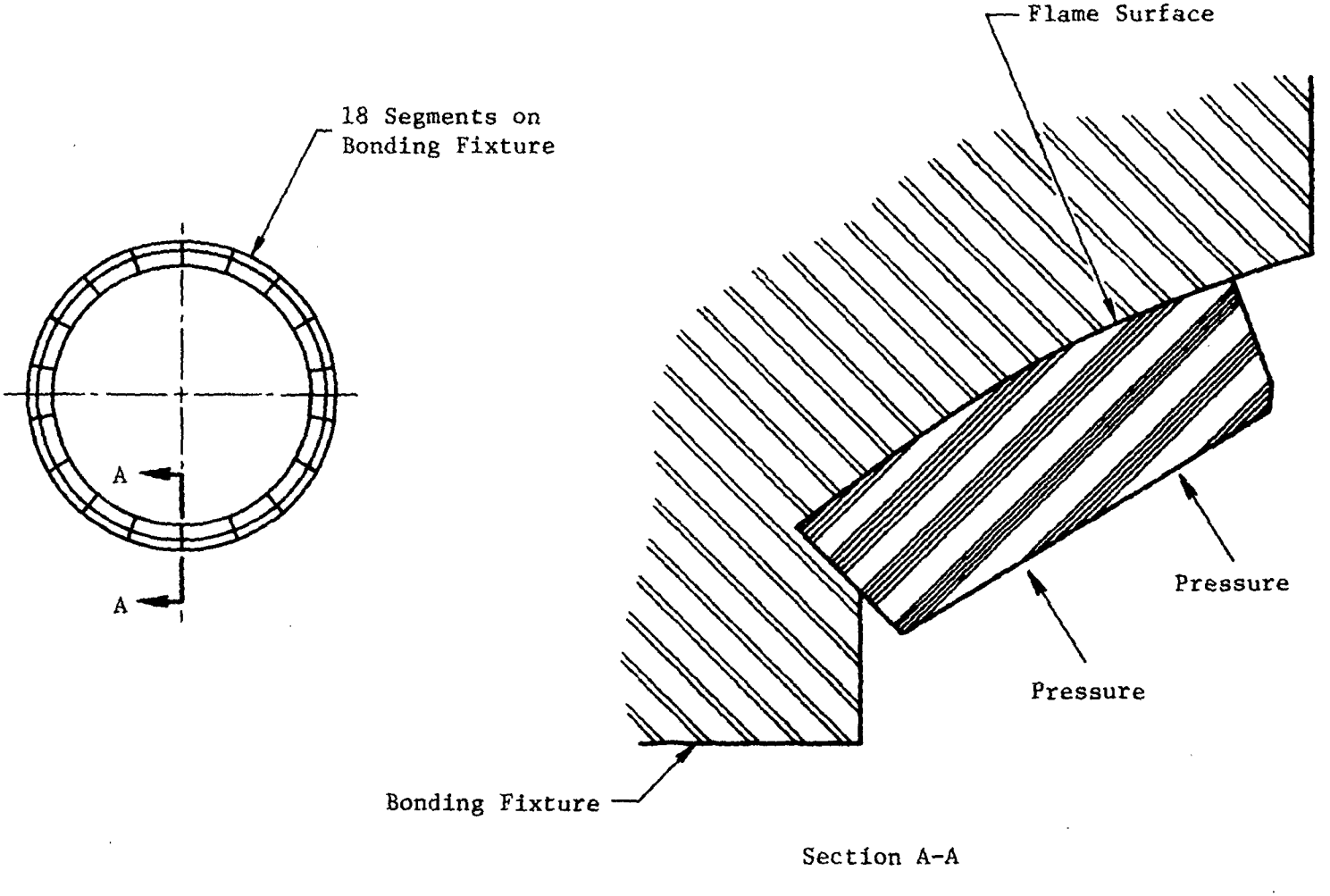


Figure V-10. - Bonding Entrance Insert

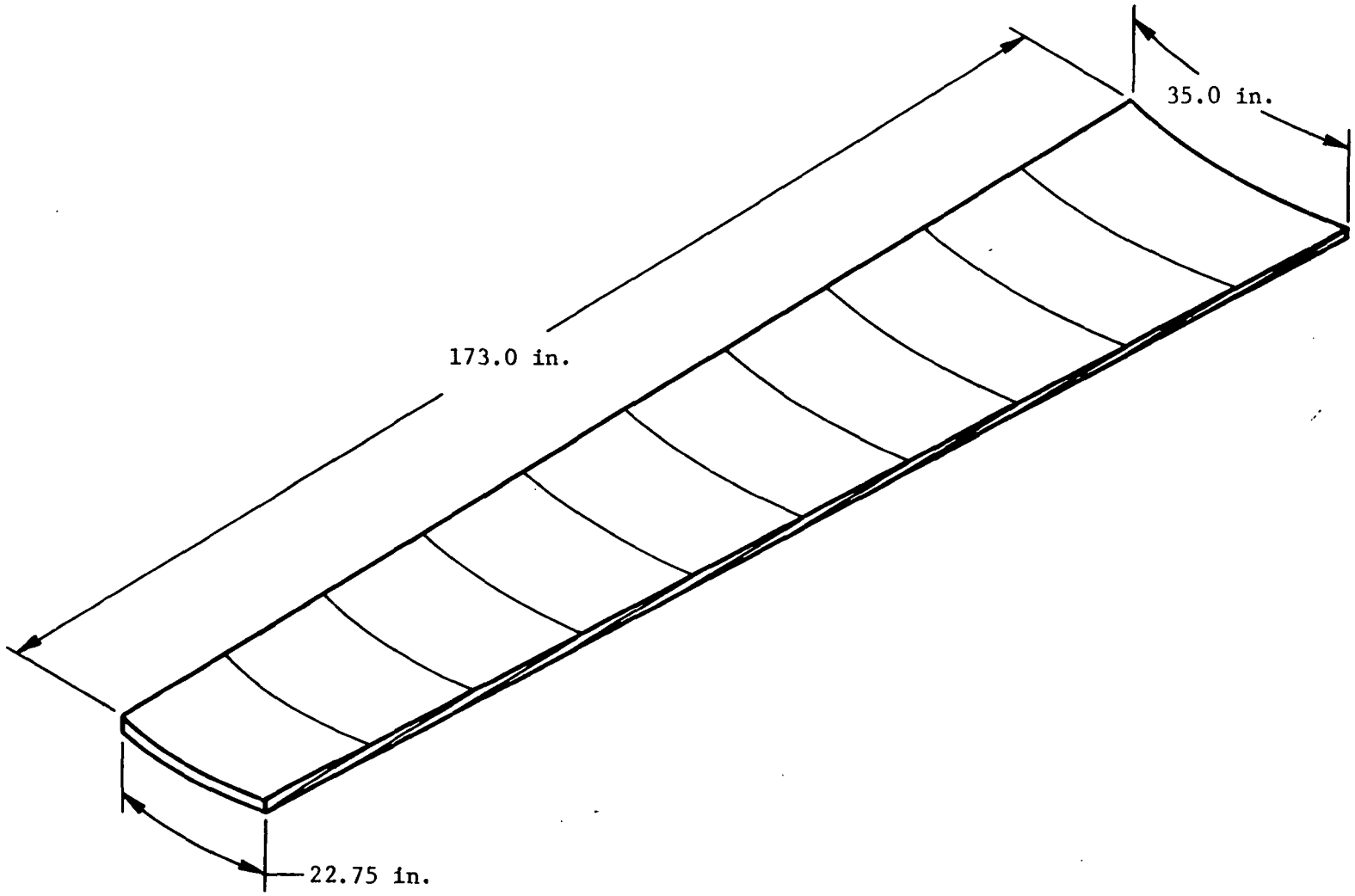


Figure V-11. - Segment of Aft Exit Cone

VI. CONCLUSIONS AND RECOMMENDATIONS

A. Incorporation of low-cost fabrication techniques in large, solid-propellant rocket-motor nozzles can result in cost savings of up to $149,000 when compared to a nozzle of the same design using conventional carbon and silica reinforced ablative composites and wrapping techniques.

B. A flight-weight nozzle for a 260-FL motor may be manufactured for $830,292 including flexseal, based on a 30-unit production contract.

C. It was shown that polyester resin-impregnated glass fabric can be used to provide structural support to the exit cone.

D. It was demonstrated that a segmented construction is feasible for use in fabricating full-scale nozzle components.

E. It is feasible to fabricate full-scale aft exit-cone segments by means of a shingle lay-up technique that employs preshaped fabric patterns.

F. Results of the trade studies and subscale nozzle evaluation show that the most practical low-cost, full-scale design would use a molded carbon/polyphenylene (or equivalent carbon/phenolic) throat insert.

G. It was demonstrated in the screening tests that it is feasible to fabricate large propellant grains by bonding smaller, precast segments.

H. The technology gained in this program on the use and qualities of ablative materials fabricated by low-cost techniques could be advantageously combined with other technology elements in the demonstration of the cost-effectiveness of a "state-of-the-art" solid booster motor for use in the space shuttle.

J. The following recommendations are made for continued development of low-cost, large solid rocket nozzles:

1. Investigations should be conducted to reduce the cost of the nozzle structure. The cost of structural elements has become three times as great as that of the ablative components.

2. Manufacture and marketing of the castable and moldable carbonaceous ablative materials should be arranged with suitable commercial sources of supply so that the design properties and costs can be characterized with confidence.

3. Additional work should be conducted to extend the use of the shingle-lap construction to the forward exit cone of the full-scale nozzle. The use of a shingle-lap forward exit cone could result in an additional saving of $15,000 in the unit nozzle cost.

4. Investigations should be conducted to verify the feasibility of radio-frequency heating to reduce the cure time of molded ablative nozzle parts.

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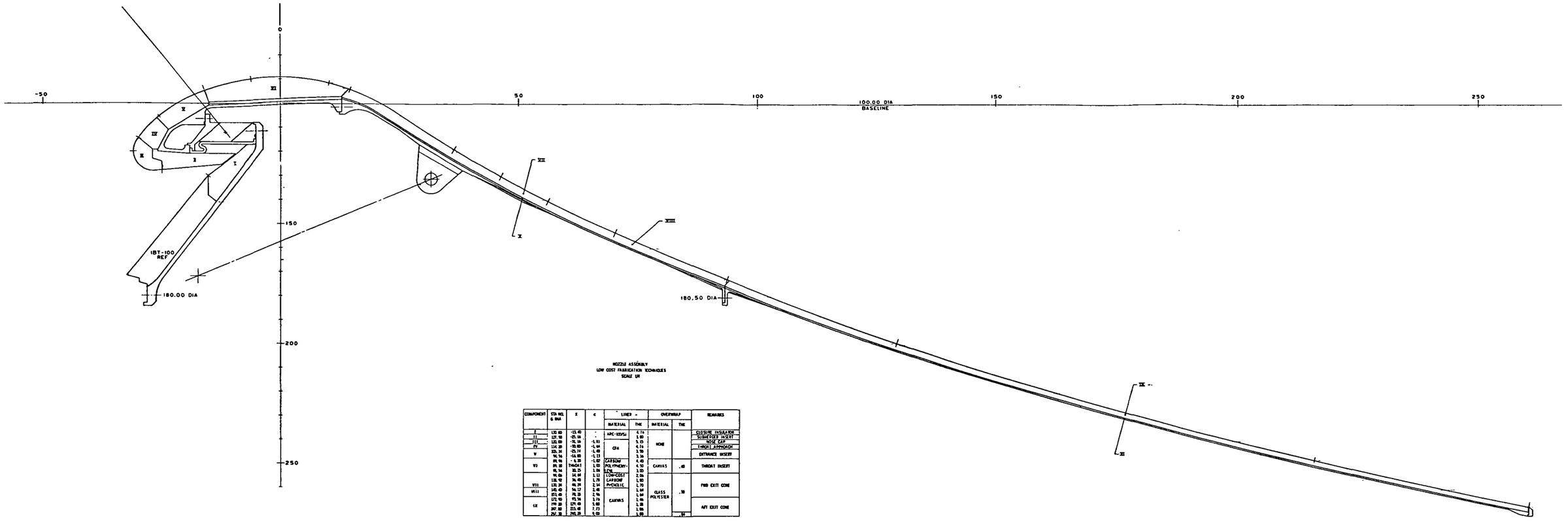
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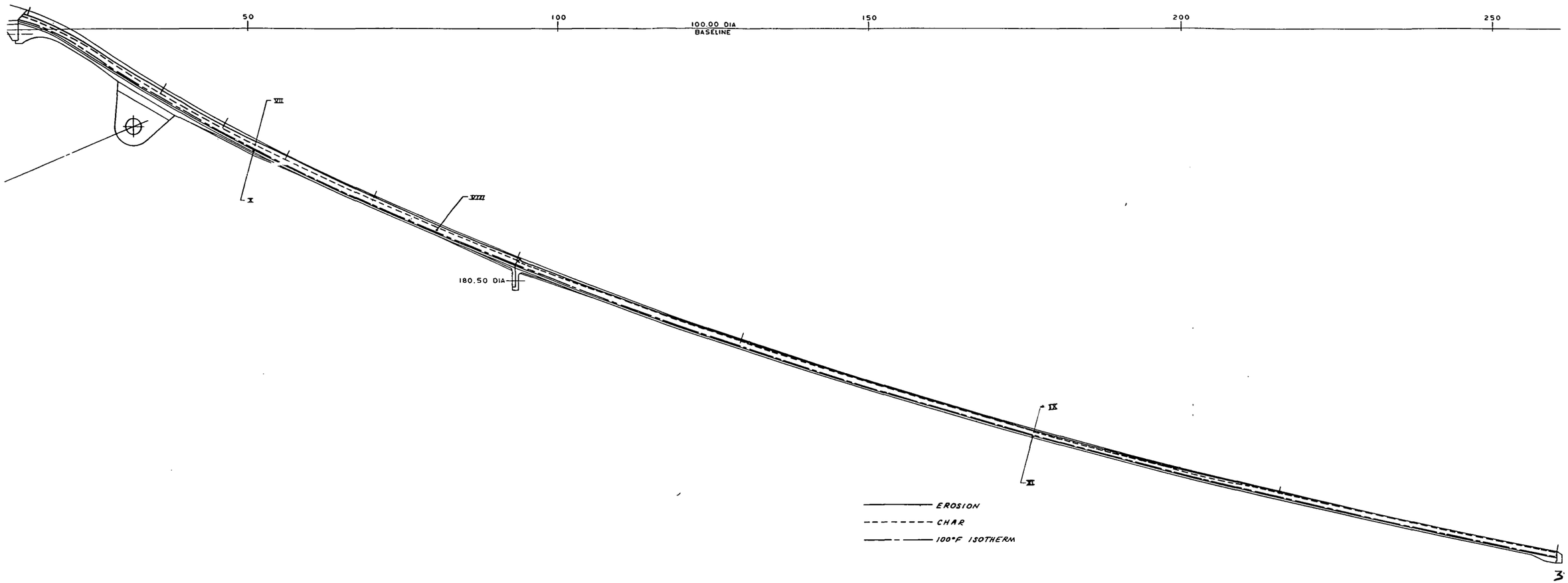


NOZZLE ASSEMBLY
LOW COST FABRICATION TECHNIQUES
SCALE 1/4

COMPONENT	STA. NO. & DIA	X	∠	LINER		OVERWRAP		REMARKS
				MATERIAL	THK	MATERIAL	THK	
I	130.00	-13.40	-	ARC-1035/41	4.74			CLOSURE INSULATOR
II	127.98	-15.14	-		1.80			SUBSERVICE INSERT
III	125.88	-16.14	-1.81		1.15			NOSE CAP
IV	114.20	-10.80	-1.46	CFA	4.74	NONE		THROAT APPROACH
V	103.34	-25.74	-1.48		1.95			ENTRANCE INSERT
	96.96	-14.88	-1.13		3.36			
VI	89.18	- 6.28	-1.82	CARBON	4.40			
	89.18	THROAT	1.80	POLYPHENY-	4.92	CANVAS	.48	THROAT INSERT
	94.94	33.25	1.36	LENE	3.00			
	94.86	34.68	1.13	LOW-COST	2.06			
	122.92	54.40	1.79	CARBON	1.80			
VII	130.24	64.28	2.14	PHENOLIC	1.70			FWD EXIT CONE
	141.60	76.12	2.46		1.64			
VIII	151.60	78.25	2.76	CANVAS	1.44	GLASS POLYESTER	.78	
	172.90	99.96	3.16		1.46			
IX	179.80	179.40	5.80		1.88			AFT EXIT CONE
	207.50	233.68	7.73		1.86			
	247.30	295.29	9.90		1.69		.98	

Full Scale Nozzle Assembly

Figure V-1



Predicted Regression and Char Depths in Exit Cone

Figure V-4