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AEROSPIKE THRUST CHAMBER PROGRAM

FINAL REPORT

by J. Campbell, Jr. and S. M. Cobb

ROCKETDYNE DIVISION
ROCKWELL INTERNATIONAL

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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16. Abstract

An existing, but damaged, 25,000-pound thrust, flightweight, oxygen/hydrogen aerospike rocket thrust chamber that was available from a previous Air Force sponsored program was disassembled and partially repaired. A brief description is presented of the aerospike chamber configuration and of the damage it had suffered. Techniques for aerospike thrust chamber repair were developed, and are described, covering repair procedures for lightweight tubular nozzles, titanium thrust structures, and copper channel combustors. The contract effort was terminated prior to completion of the repairs and conduct of a planned hot fire test program when it was found that the copper alloy walls of many of the thrust chamber's 24 combustors had been degraded in strength and ductility during the initial fabrication of the thrust chamber. The degradation is discussed and traced to a reaction between oxygen and/or oxides diffused into the copper alloy during fabrication processes and the hydrogen utilized as a brazing furnace atmosphere during the initial assembly operation on many of the combustors.

The effects of the H_2/O_2 reaction within the copper alloy are described. The significance relative to the aerospike thrust chamber concept of the repair techniques developed, and of the H_2/O_2 reaction problem is discussed.

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SUMMARY

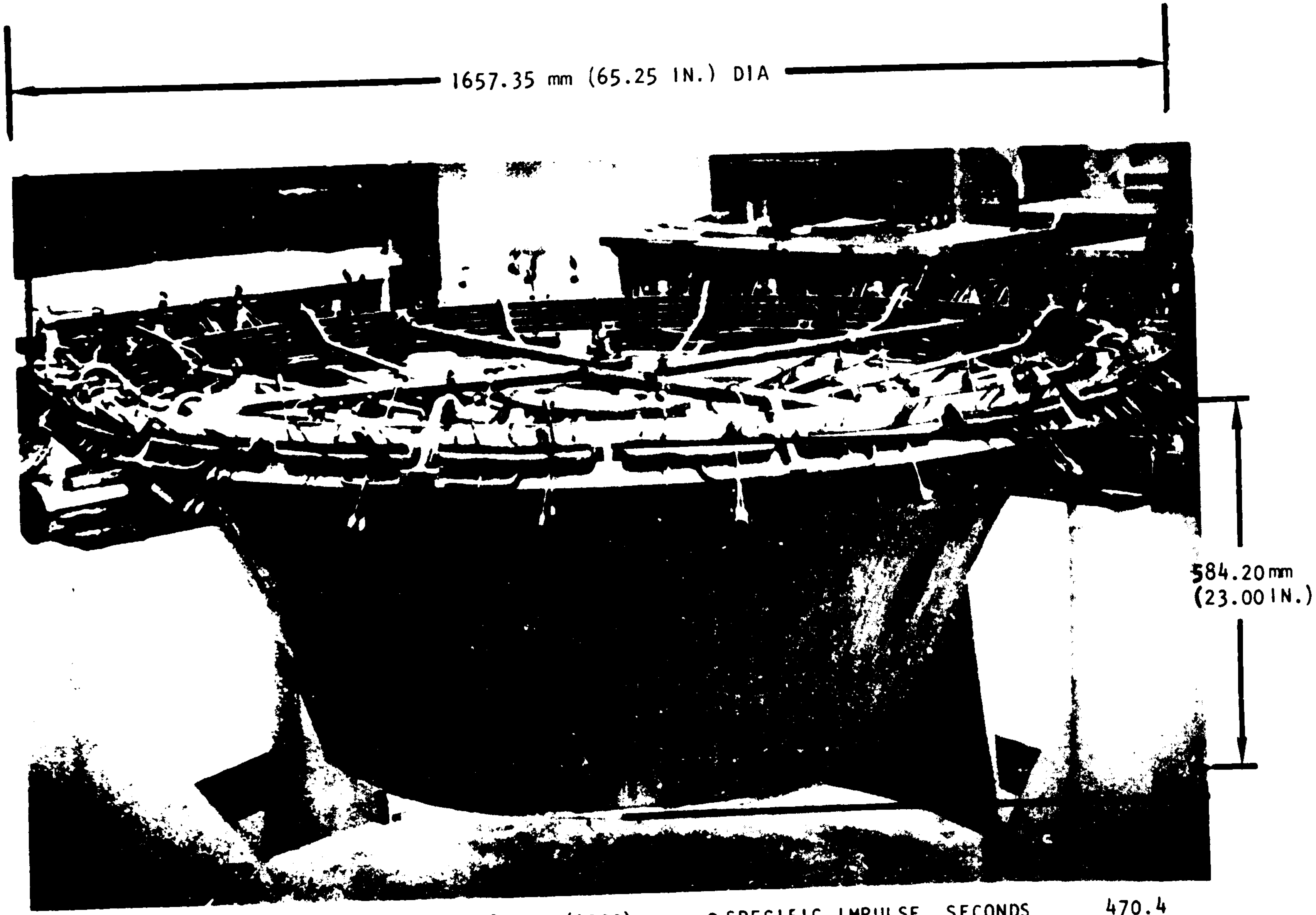
The 111 kN (25K) aerospike thrust chamber project, Contract No. NAS3-20076, was conceived as a means of carrying out an aerospike thrust chamber feasibility demonstration project. A similar project had been previously funded under Air Force auspices. The Air Force contract, No. F04611-67-C-0016, resulted in the design, fabrication, and initial testing of a 111 kN (25,000-pound) thrust hydrogen/oxygen aerospike thrust chamber for possible space tug application. The Air Force contract was terminated in 1975 after the chamber was extensively damaged in a test stand fire. The NASA retained an interest in the possible application of the aerospike thrust chamber concept to space propulsion and contracted with Rocketdyne under Contract NAS3-20076 for the purpose of repairing the existing 111 kN (25K) aerospike thrust chamber and conducting altitude firings to determine the chamber's performance, cooling capability, and structural integrity.

While the planned program included both the repair of the thrust chamber and a hot-fire testing series, all effort actually expended on the program was confined to the repair of the thrust chamber components. This condition came about because a fundamental problem with the material processes utilized in the initial fabrication of the combustors was uncovered during the repair effort. Thus, the content of this report, and of this summary, covers the repair and fabrication procedures developed to permit repair of aerospike chambers.

The 111 kN (25K) aerospike thrust chamber assembly consisted of 24 regeneratively cooled combustor segments arranged around the periphery of a regeneratively cooled nozzle and base closure assembly so as to discharge their gases against the nozzle. A view of the thrust chamber assembly is shown in Fig. 1 together with a summary of the thrust chamber design and operating parameters.

The damage that was incurred during thrust chamber test 74-005 on the Air Force contract was assessed by disassembly and cleaning of those components that had been assembled with fasteners, i.e., the ducting and unboltable support structure. An assessment of the damage indicated that it would be necessary to replace five of the combustors, the inner backup support ring, the ignition manifolding and propellant feedlines, and some of the thrust chamber support structure. Additionally, it would be necessary to repair the outer titanium backup ring, the thrust cone, and approximately 30% of the nozzle tubes.

The nature of the aerospike thrust chamber assembly is such that it is possible to effect repairs by replacing damaged components with functional components, i.e., unbolt or cut out the damaged component and replace it with a good one. The thrust chamber combustors, while brazed and welded assemblies, also were judged to be repairable in this manner. As there were a number of combustors available that had some usable parts, a plan was devised for combustor replacement which involved cannibalization of portions of the existing spare combustors so as to utilize them in combination with new components to produce viable combustors suitable for welding



● CHAMBER PRESSURE, kPa (PSIA)	6895 (1000)	● SPECIFIC IMPULSE, SECONDS	470.4
● EXPANSION AREA RATIO	200:1	● WEIGHT, kg (LB)	180.5 (398)
● MIXTURE RATIO	5.5:1		

Figure 1. 25,000-Pound O_2/H_2 Aerospike Engine

in-place on the existing thrust chamber assembly. This is believed to be the first time that dissection and reassembly of such welded combustors was attempted. It was made possible by the unique fabrication scheme of the 111 kN (25K) aerospike chambers which is illustrated in Fig. 2. Table 1 lists the five rebuilt combustors from which replacements for the assembly were to be obtained, and indicates the scheme for utilization of existing parts.

TABLE 1. COMBUSTOR BODY-INJECTOR USAGE

Combustor Segment Identification Unit No.	Injector Unit No.	Inner Liner Unit No.	Outlet Liner Unit No.
507R	506	507	507
510R	518	510	510
509R	New	New liner, coolant panel, cover sheet, and end plates	509
515R	New	↓	515
535(N)	New		New liner, cover sheet, and end plate

R = rebuilt
N = new

Three of the rebuilt combustors, units 509R, 515R, and 535, were dependent upon new inner liners for completion. The rework of the existing details and the fabrication of the new liner assemblies for these combustors was satisfactorily carried through, but was halted in the second quarter of the program to concentrate efforts on completing combustor units 507R and 510R.

Combustor units 507R and 510R were planned to utilize existing inner and outer liners, and had been partially completed under the sponsorship of the previous Air Force contract. Both of these combustors encountered problems with cover-sheet cracking during their final assembly operation. A photo of a typical cover-sheet crack is shown in Fig. 3 . The cracking was at first attributed to the unusual strains associated with the assembly operations, and repairs were effected by both furnace braze and tungsten inert gas brazing with Nioro braze alloy. These repair efforts were generally unsuccessful in that further cracking of the material occurred, either in the heat-affected zone of the TIG-brazed areas, or during the cryogenic shock cycling employed for evaluation of repair effectiveness.

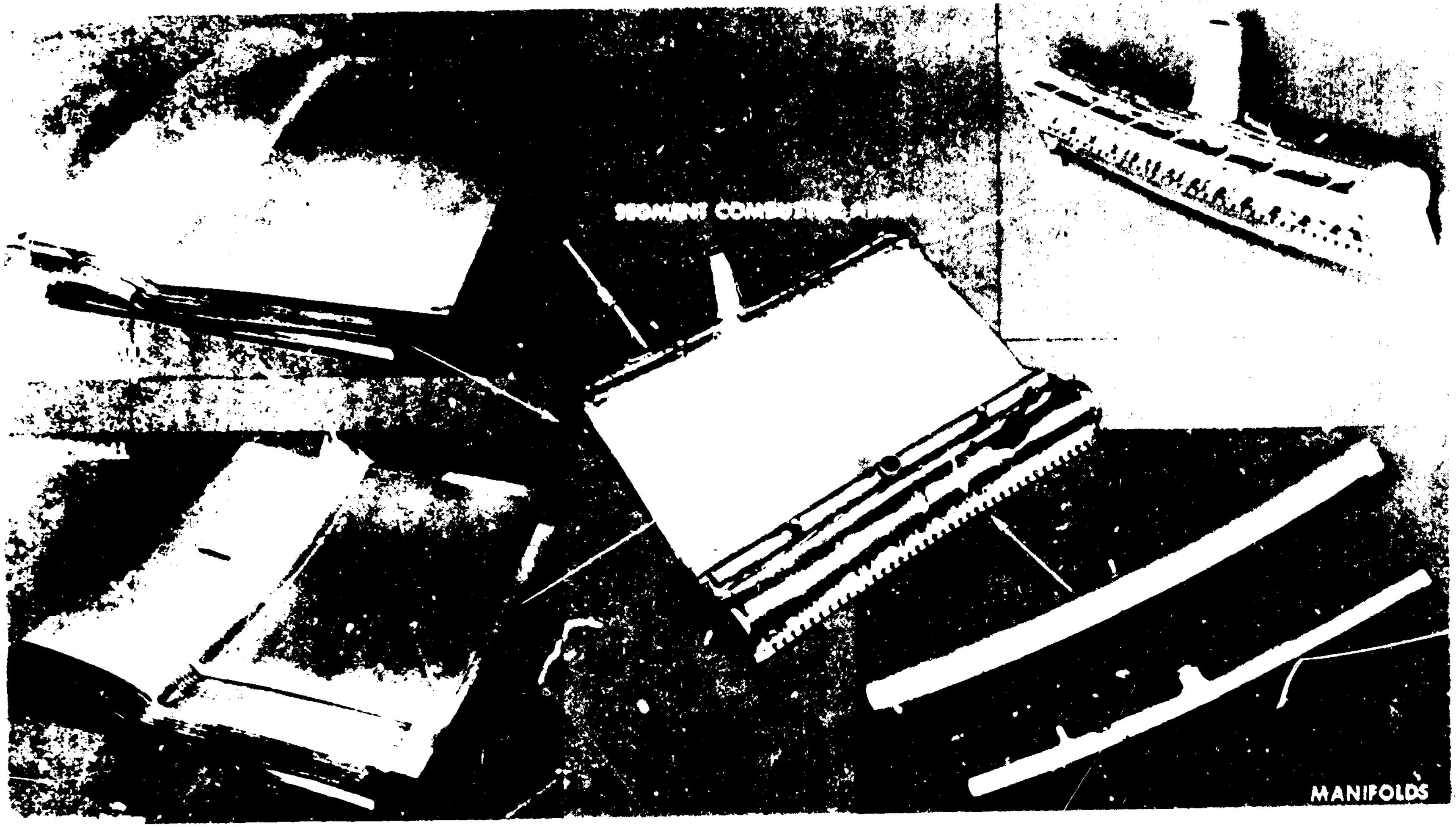


Figure 2. Segment Combustor Fabrication

Figure 3. Photo of Crack in Unit 507R LOX
Cover Sheet (10X Magnification)

It became evident after repeated attempts at repair of the cover-sheet cracking experienced on units 507R and 510R, that a condition existed that was not consistent with the ductility normally displayed by NARloy-A. Investigations were undertaken to find the reasons for the nontypical cracking, and also to find some way to bring units 507R and 510R to successful completion.

A repair concept was developed for the NARloy-A cover-sheet cracks of units 507R and 510R which involved dishing out the cracked areas and electrodepositing copper into the groove. Both cell plating, in which a small electroplating cell is clamped to the side of the part to be repaired rather than submerging the whole part in plating solution, and tank plating were successfully employed on the crack areas of the cover-sheets that were accessible. However, on completion of the repairs, and the conduct of cryogenic shock testing and hydrostatic pressure testing, it was found that additional cracking had occurred. On the basis of this experience, it was determined that neither 507R nor 510R was suitable for assembly to the thrust chamber.

The NARloy-A cracking encountered on units 507R and 510R was so nontypical that it engendered a metallurgical and historical investigation, concurrent with the repair effort on 507R and 510R, to understand the problem and to assess its implications for all the combustors. Methods of removing samples from existing combustors were developed which permitted metallurgical examination of the NARloy material and, if necessary, replacement of the removed sample so as to be able to fire the combustor. Microscopic examination of these samples indicated that the fundamental cause of the cracking of 507R and 510R was that the NARloy material properties had been degraded by the reaction of hydrogen with previously dissolved oxygen. Figure 4 is a photomicrograph of material removed from unit 510R. It shows the voids along the grain boundaries that result when steam is formed. The source of hydrogen was readily ascribed to the hydrogen atmosphere furnace brazing that had been utilized during the initial fabrication of the combustors. An investigation was conducted as to the source of oxygen and it was determined that the most probable source was oxidation of the inner surfaces of the liners and cover-sheets during the initial fabrication (i.e., in 1974). This inner surface oxidation had apparently occurred despite the utilization of inert atmospheres during these operations and despite the imposition of well-developed disciplines for the maintenance of cleanliness.

The results of the metallurgical examination of all combustors sampled are presented in Table 2, which indicates a correlation between the presence of embrittled NARloy-A and the conduct of final brazing cycles in a hydrogen atmosphere. On the basis of the data displayed in Table 2, the conclusion appears inescapable that a large majority of the combustors have been affected by the hydrogen/oxygen phenomenon during their initial fabrication (prior to the start of this contract), and will display substantially reduced ductility under conditions of thermal strain. As it had been demonstrated during the repair procedures on 507R and 510R that the thermal strains involved in cryogenic testing did result in cracking of the embrittled NARloy, and as the test program planned for the thrust chamber assembly

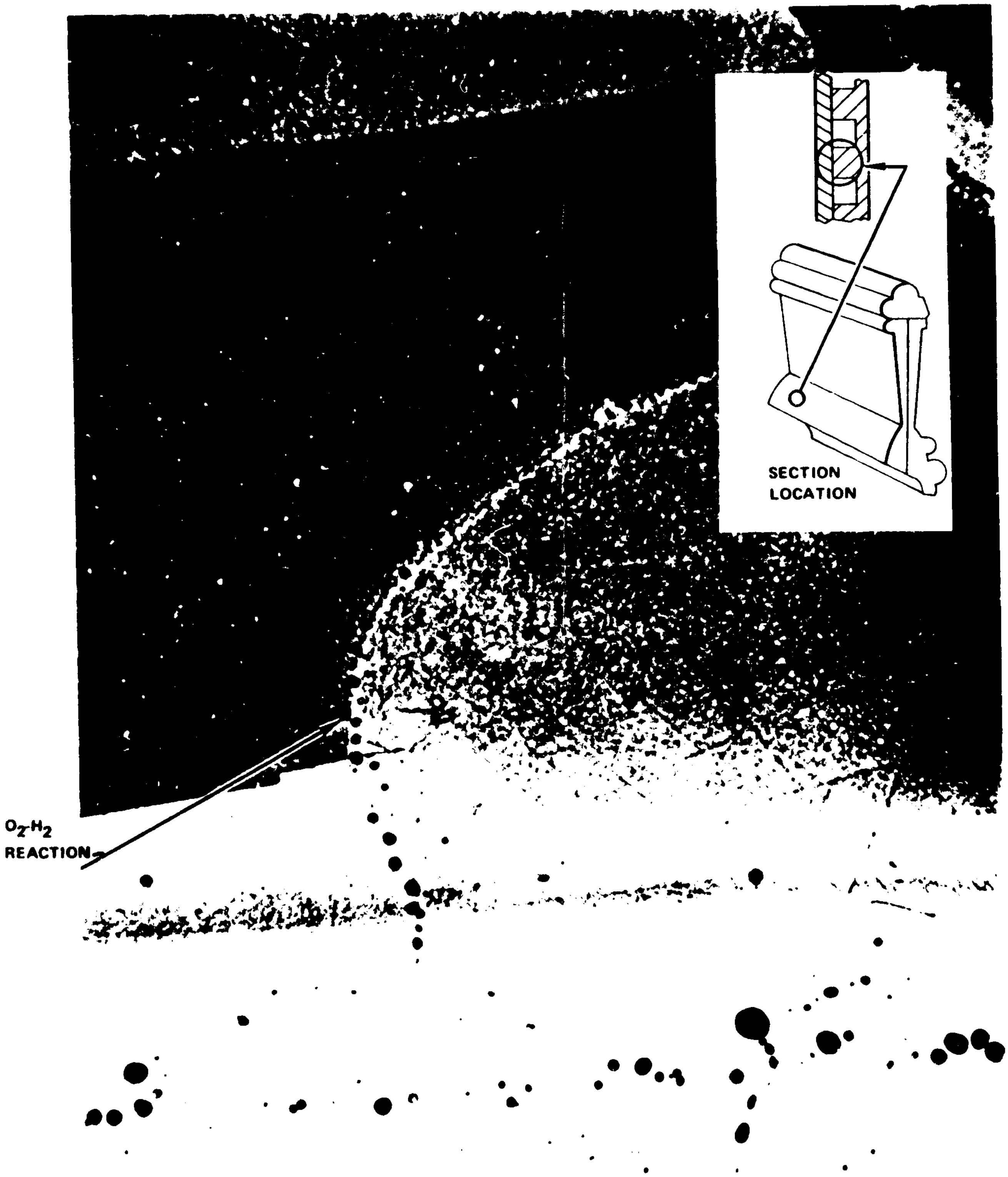


Figure 4. Section Near Crack in Outer Half of Segment 510 (400X)

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OF POOR QUALITY

TABLE 2. AEROSPIKE THRUST CHAMBER REPAIR-SUMMARY OF FURNACE CYCLE HISTORY COMPARED TO METALLURGICAL EXAMINATIONS

	Segment No.	Grain Boundary Voids Found By Examination	Number of Cycles in H_2 Brazing Atmosphere	H_2 on 3rd Cycle or After	Probability of Absence of Embrittlement due to H_2/O_2 Voids at Grain Boundaries
	507	Yes	5	Yes	None
	508		4	Yes	Poor
	9		2	Yes	Poor
	10	Yes	3	Yes	Poor
Segments Used In Thrust Chamber Assembly	11Δ		2	No	Good
	12	Yes	4	Yes	None
	13		4	Yes	Poor
	14Δ	Yes	4	Yes	None
	15Δ		5	Yes	Poor
	16	Yes	4	Yes	None
	17		3	Yes	Poor
	18Δ	Yes	1	Yes	None
	19		2	No	Good
	20		1	No	Good
	21		2	Yes	Poor
	22	No	1	No	Good
	23	No	1	No	Good
	24		1	Yes	Poor
	25	No	0	No	Very Good
	26		1	Yes	Poor
	27Δ		1	Yes	Poor
	28		1	Yes	Poor
	29		1	Yes	Poor
	30		1	Yes	Poor
	31		1	Yes	Poor
	32		1	Yes	Poor
	33		2	Yes	Poor
	34		1	Yes	Poor

ΔRemoved from assembly after fire

did involve numerous strain cycles, it was concluded that the majority of combustors available for the assembly were not sufficiently reliable to permit their utilization in the firing program.

During the test stand fire which terminated the Air Force program, the nozzle had suffered localized overheating on its interior portions (i.e., the "cold" side), because it was sprayed with molten titanium from the burning inner combustor support ring. Repairs to this type of tubular nozzle had not previously been attempted on the scale represented in this instance. Because of a general need for developing the technology for repairing complex lightweight tubular nozzles, a company-sponsored technology program was undertaken which utilized the 111 kN (25K) aerospike nozzle for development purposes. Two basic methods of repair were developed, the saddle-patch repair and the inserted tube repair as defined in Fig. 5. When properly applied, these two methods sufficed to repair all of the damage that had been incurred by the 111 kN (25K) aerospike nozzle.

A photograph of the repaired nozzle is shown in Fig. 6. A total of 1,053 saddle patches was applied together with 155 tube insert patches, the tube inserts being applied in 18 different window locations. The nozzle repair effort was successfully concluded during the second quarter of this program with every expectation that the repairs would have proved adequate for the scheduled hot-firing program.

The chamber support structure of the aerospike thrust chamber includes two titanium rings, between which the 24 combustors are sandwiched. The rings accept the thrust generated by the combustors and nozzle and transmit that thrust to a central gimbal bearing through angled struts and a central cone. The repair and refurbishment effort of the subject contract included the redesign of the inner titanium support ring to a more easily fabricated configuration than the original ring, and the completion of its fabrication. Additionally, a repair procedure was devised for the more moderately damaged outer titanium backup ring and checked out by preparation of weld samples in the same configuration. Section examination and tensile tests indicated that the welded-in section would be sufficiently strong for the service, but all fabrication effort was stopped prior to the actual repair of the outer backup ring. The thrust cone and support struts were also reworked during the active portion of the repair effort and had been largely completed by the time fabrication effort was terminated.

Several positive results were obtained during the disassembly and repair procedures:

1. The tubular nozzle repair effort brought out that large-scale repairs on lightweight tubular nozzles are feasible.
2. The structure repairs indicate that it is feasible to repair such complex structures as the outer titanium backup ring.

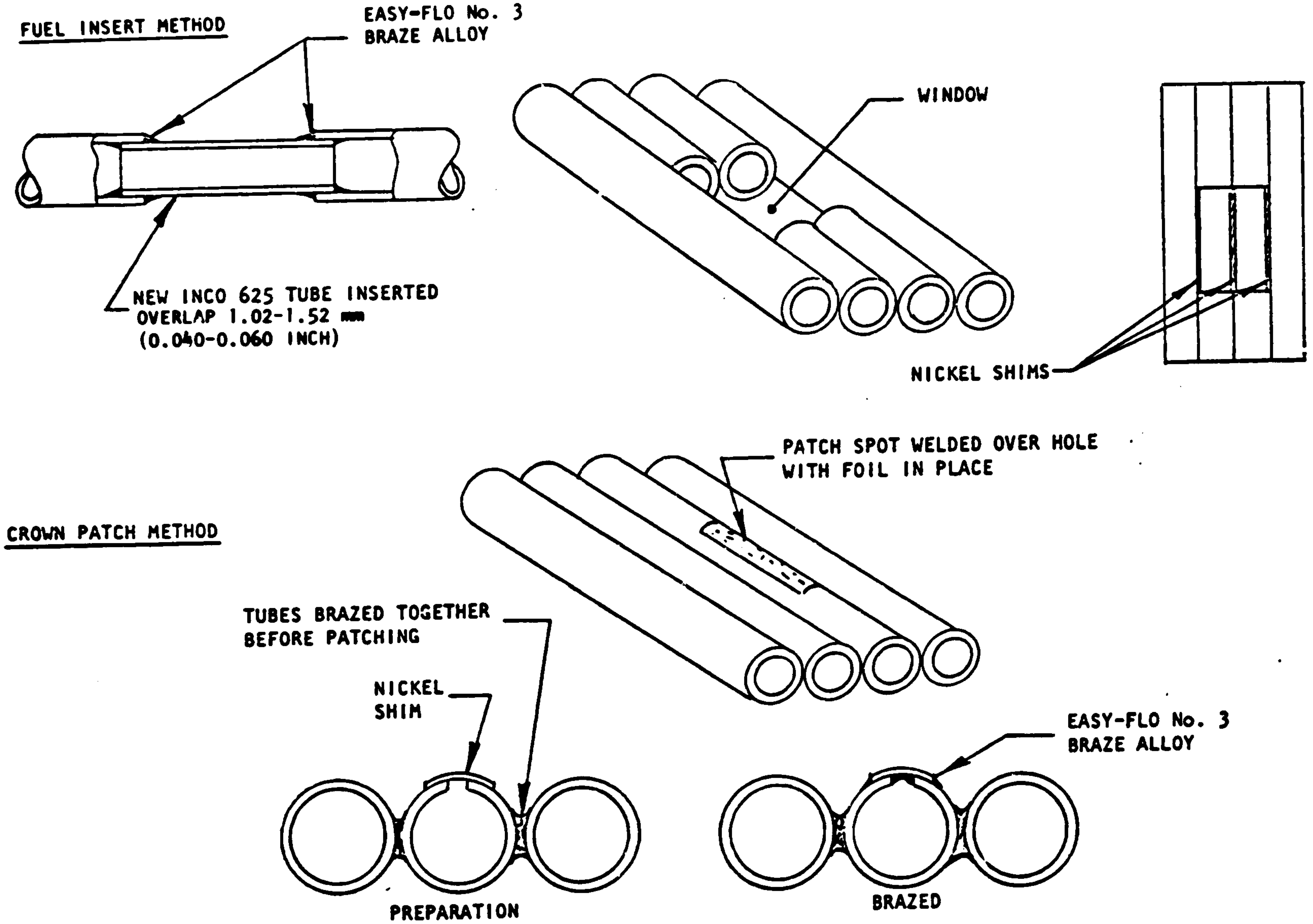

Figure 5. Tube Repair Methods

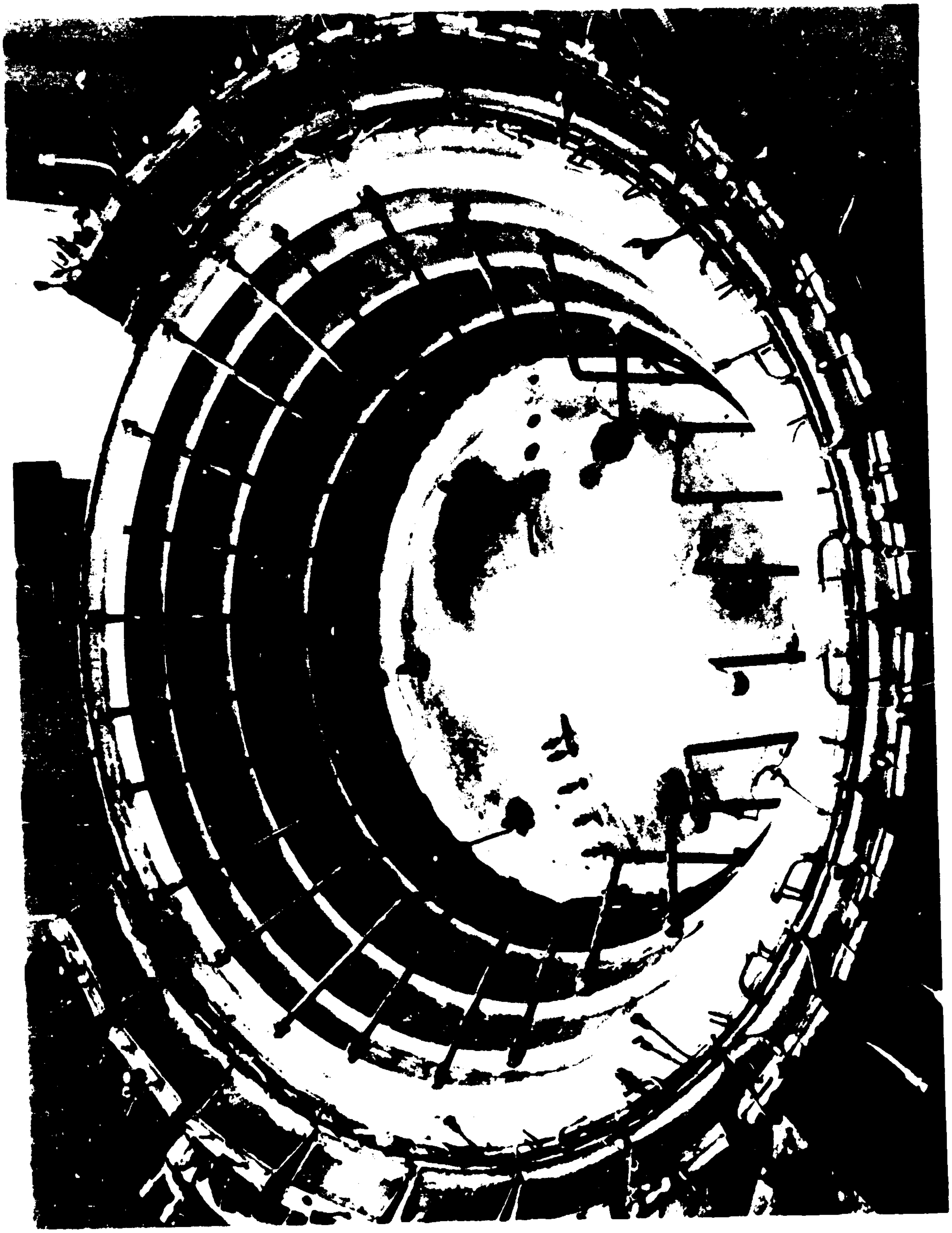

Figure 6. Completed Nozzle Repair

3. The work conducted with combustor dissection and reassembly bears out the basic validity of the concept of the repair of such complex copper channel cooling structures by the method of excising the damaged areas and brazing properly configured replacements in their place.

The basic success of these repair techniques must be considered a positive factor in future evaluations of the aerospike thrust chamber concept. Aerospike configurations tend to be relatively expensive and the concept is favored by the possibility of repair as opposed to replacement of such chambers when the almost inevitable damage which occurs during development programs is suffered.

In assessing the overall results of the program, one must keep in mind that the hydrogen/oxygen reaction problem encountered with the NARloy-A combustor material does not have any special significance for the aerospike thrust chamber concept. Aerospike thrust chambers are fabricated of the same materials as bell thrust chambers. The problem was a materials processing problem, not an aerospike problem. The program did have several positive results for the aerospike concept although it was not possible to carry it through to the hot-firing phase. On balance, the aerospike must still be regarded as a contender for length-limited, space propulsion application. The developmental programs previously conducted have demonstrated the concept's performance and length advantages. The previous Air Force program demonstrated that an aerospike thrust chamber roughly 20% of the length of an equivalent bell chamber could be designed and fabricated to a competitive weight, and the present NASA contract demonstrated that maintenance and repair procedures will be available for aerospike thrust chambers that will permit cost-effective repairs to their assemblies.

INTRODUCTION

The liquid fuel aerospike rocket engine concept has been under development for approximately 15 years. Its thrust chamber configuration consists of a truncated annular spike nozzle (radial in-flow type), which is provided with a number of discrete combustion chambers arranged around the periphery of the nozzle so as to discharge their gases along the nozzle surface. A diagram illustrating the aerospike thrust chamber concept is presented in Fig. 7.

The aerospike thrust chamber concept has several advantages relative to more conventional nozzles. It automatically provides "altitude compensation," and thus may increase the overall impulse supplied in a booster application. It may be arranged to utilize a larger portion of the boattail area than a multiple engine conventional installation. Development has demonstrated that it is feasible to truncate a spike nozzle severely, and by utilizing a small amount of secondary flow introduced into the nozzle base region, to retain excellent nozzle C_f efficiency. This attribute of the aerospike rocket engine has led to its consideration for those space propulsion applications in which engine length is especially significant. A comparison of the thrust chamber lengths of several different types of rocket thrust chamber is presented in Fig. 8, indicating that the aerospike thrust chamber can be on the order of 20% of the length of a bell nozzle of equivalent expansion ratio.

In 1970, a design and development project was undertaken at Rocketdyne to design, fabricate, and test a 111 kN (25,000-pound) thrust hydrogen/oxygen aerospike thrust chamber under Air Force Contract No. F04611-67-C-0116. The objective of this program was to demonstrate, through the fabrication and testing of a flightweight thrust chamber, that the aerospike engine concept was competitive in both weight and performance to conventional bell nozzle-type engines. A thrust chamber with a nozzle area ratio of 200:1, and of competitive weight, was designed, fabricated, installed in the test stand and fired. However, during the first mainstage test, a propellant line leaked, and caused a fire that severely damaged the test hardware. A posttest examination of the hardware indicated that the thrust chamber was repairable and, under Air Force instruction, the resources remaining in the contract were utilized to begin the repairs to the thrust chamber. The Air Force contract was concluded on 31 December 1975. All residual hardware and tooling from the Air Force program were made available to the NASA. The results of the Air Force program are summarized in the Final Report (Ref. 1) and in the Materials Research and Development Report (Ref. 2).

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1. AFRPL-TR-76-05, O_2/H_2 Advanced Manuevering Propulsion Technology Program, Final Report, Rocketdyne Division, Rockwell International, Febraury 1976.
2. AFRPL-TR-76-06, O_2/H_2 Advanced Maneuvering Propulsion Technology Program, Materials Research and Development Report, Rocketdyne Division, Rockwell International, February 1976.

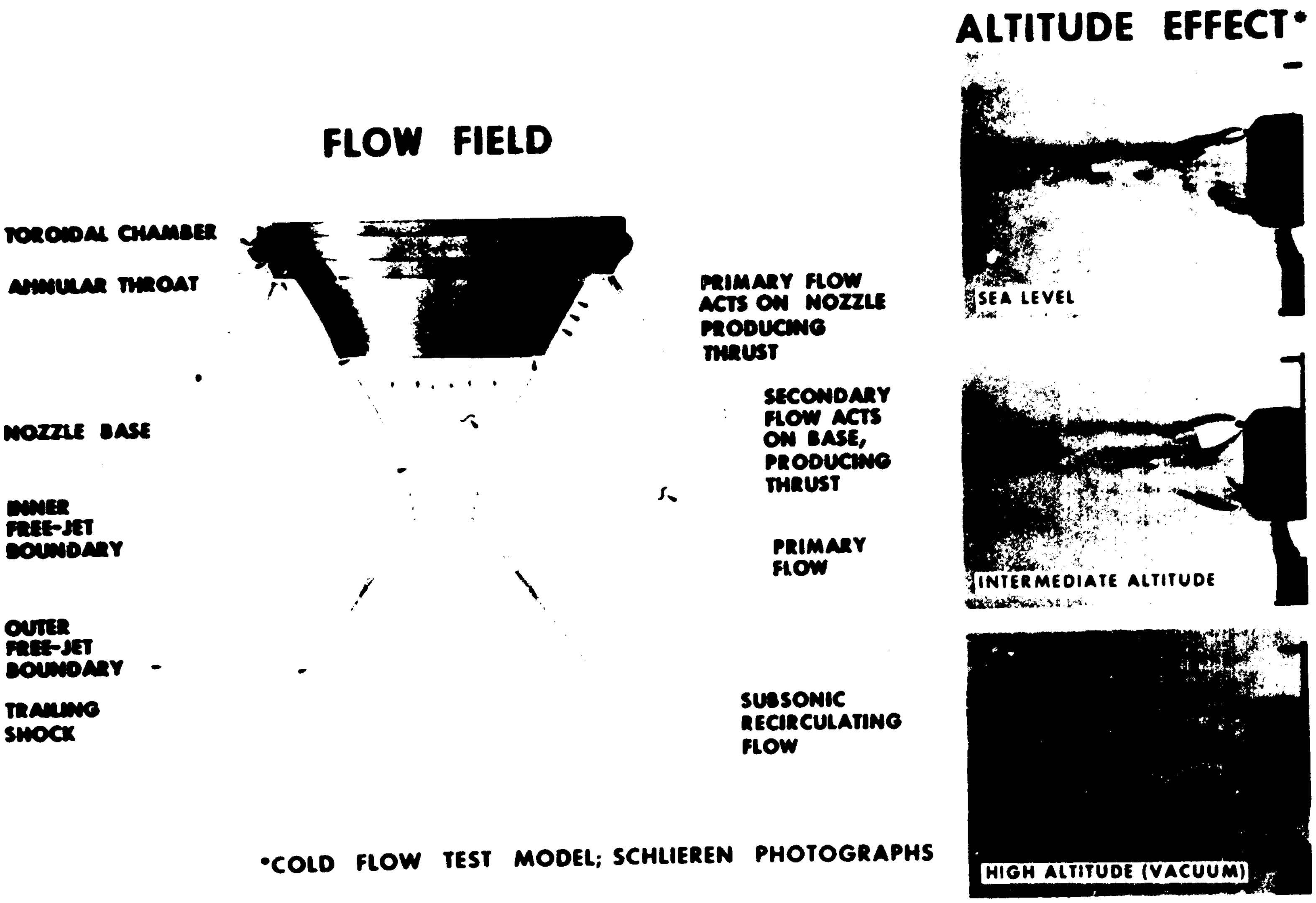

Figure 7. Aerospike Nozzle

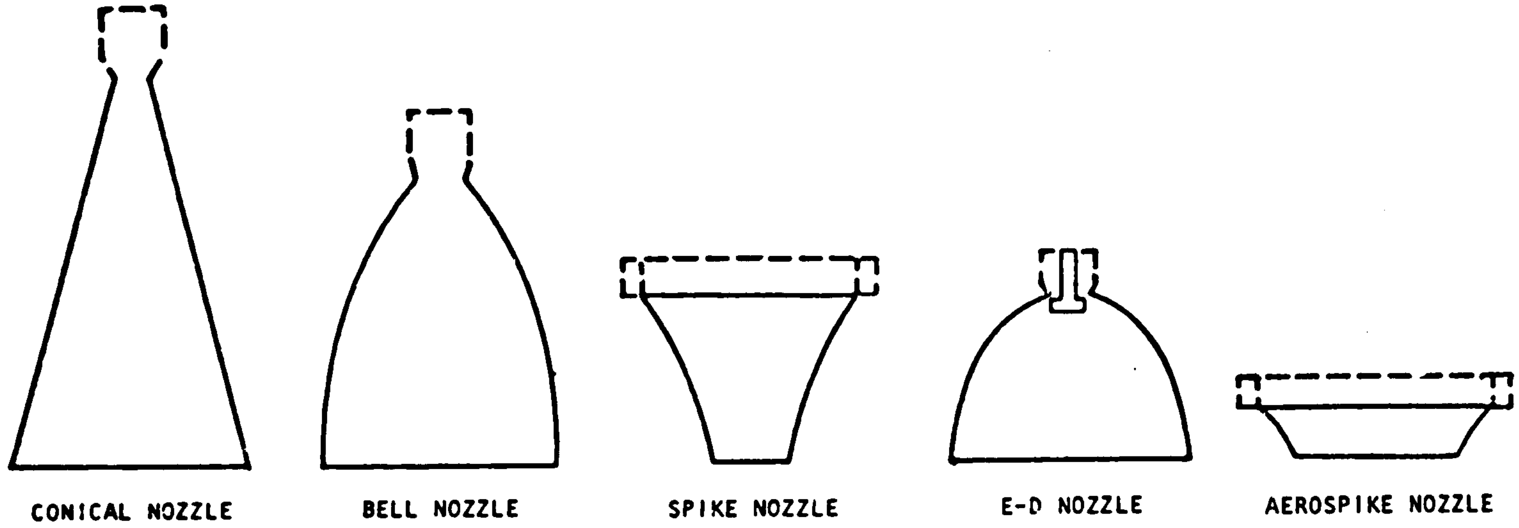

Figure 8. Nozzle Type and Size Comparison

The NASA retained an interest in the aerospike engine concept because of its possible application to the main propulsion system of the full capacity space tug. The principal aerospike engine feature of interest was its very short length which, in application to the tug,would result in a shorter stage and provide more space for payload. The Air Force program had shown that the application of advanced fabrication techniques and materials to the aerospike engine made it possible to fabricate a thrust chamber that was consistent in weight with a high-performance-type engine. However, the program had been concluded short of demonstrating the performance and the structural integrity of the complete flightweight assembly.

Under these circumstances, the NASA contracted with Rocketdyne under Contract No. NAS3-20076 for the purpose of repairing the existing 111 kN (25K) aerospike thrust chamber and conducting altitude firings to determine its performance, cooling capability, and structural integrity. It is the effort on Contract NAS3-20076 that is discussed in this report.

The planned program included three technical tasks: (1) thrust chamber disassembly and repair of components, (2) thrust chamber reassembly, and (3) thrust chamber hot-fire testing. All effort actually expended on the program was confined to Task 1, i.e., disassembly of the thrust chamber and repair of its components. This condition came about because a fundamental problem with the material processing utilized in the fabrication of the combustors was uncovered during the repair effort.

This report is thus concerned with a description of the rather unique repair and fabrication procedures developed in connection with the aerospike chamber repair. The material condition which resulted in the program's termination is also discussed.

The principal measurements and calculations of this contract were conducted in the customary United States system of units, as were the calculations and measurements of the preceding Air Force Contract No. F04611-67-C-0116. The SI system of units is used in the text and tables of this report, and the customary United States units given parenthetically following the SI units. However, in the interests of economy, the dimensions of those existing drawings which are included in this report have not been converted to SI units.

PROGRAM PLAN

The plan of the work that was scheduled to be accomplished under the subject contract is summarized in Fig. 9. As can be seen from the figure, the program was divided into three time-phased, hardware-related tasks and two review and reporting tasks. During Task 1, the thrust chamber was to be disassembled to the extent necessary to effect repairs. Individual components were to be either repaired or remanufactured depending on their condition. During Task 2, the repaired and/or remanufactured thrust chamber components were to be reassembled into a complete 24-combustor, 200:1 expansion ratio thrust chamber. Task 3 related to activities occurring during the hot-fire testing, i.e., stand modifications appropriate for receiving the thrust chamber, thrust chamber installation and instrumentation and, finally, ambient and simulated altitude hot-fire testing. Tasks 4 and 5 related to technical reviews and reporting.

The program proceeded approximately on the planned schedule until mid-June 1976. At that time, a serious problem in the rebuilding of two of the combustors came to light. The decision was made to halt technical activity on all areas of fabrication except for the repair of those two combustors. The time interval between mid-June and 30 September 1976 was occupied with determining the nature and extent of the fabrication problem with the combustors. A briefing on the fabrication problem and program status was presented on 7 October at the Lewis Laboratory. It resulted in the decision, taken 12 October, to terminate all technical effort on the subject contract. The status of the activities of the program plan at termination of the effort is indicated by the darkened-in bars of Fig. 9.

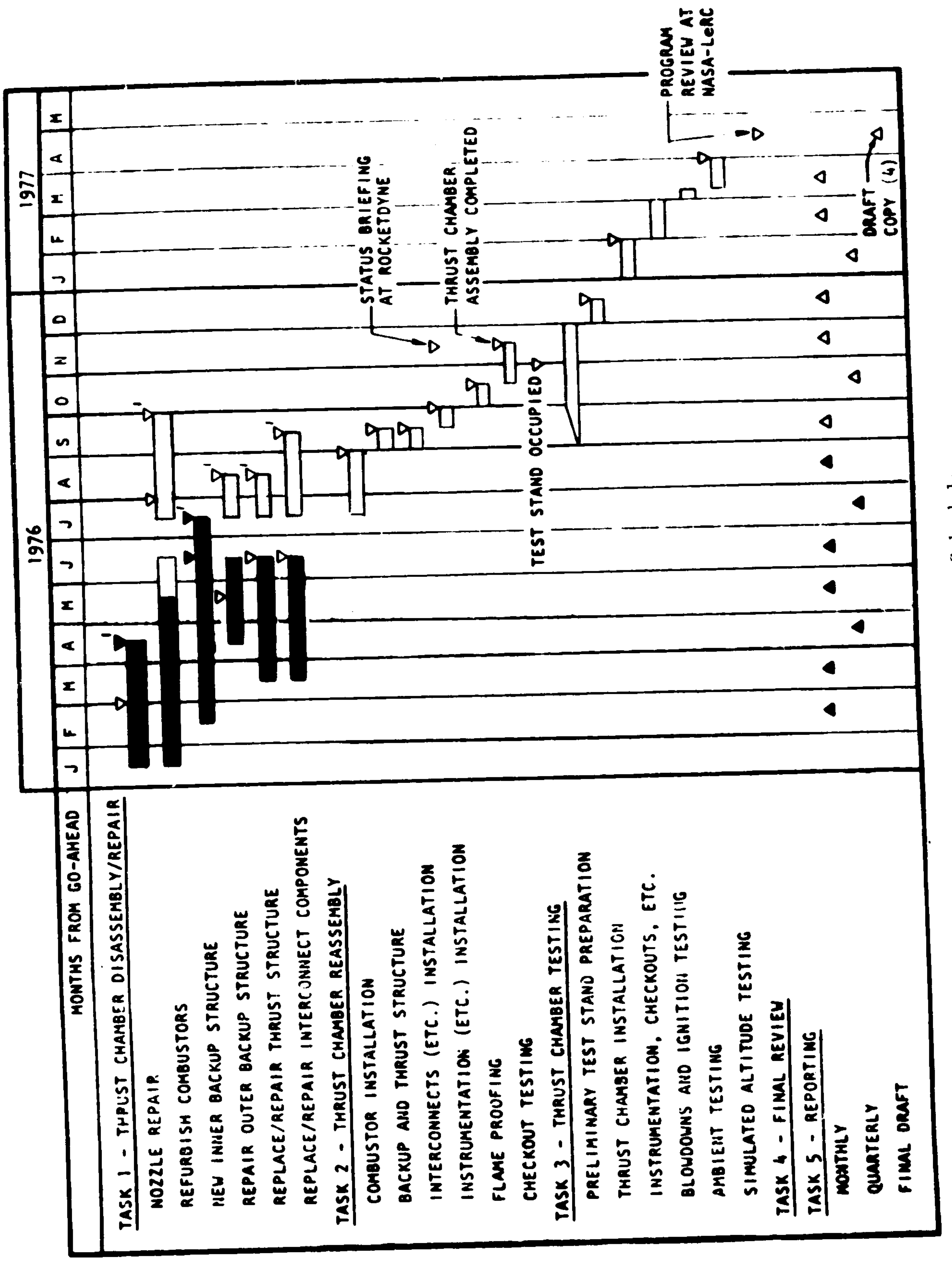

Figure 9. Program Schedule

THRUST CHAMBER ASSEMBLY DESCRIPTION

A complete description of the 111 kN (25K) aerospike thrust chamber assembly is contained in Ref. 1. For the convenience of the reader, a description of the assembly has been condensed from Ref. 1 and is presented below.

OVERALL

The 111 kN (25K) aerospike thrust chamber consisted of an annular combustion chamber assembled from 24 regeneratively cooled combustor segments and a regeneratively cooled nozzle/base closure assembly. Two views of the thrust chamber assembly are shown in Fig. 10 and 11. A summary of the thrust chamber design and operating parameters is presented in Table 3.

TABLE 3. DESIGN CONDITIONS

Propellants	LO_2/LH_2
Maximum Vacuum Thrust, kilonewtons (pounds)	111 (25,000)
Maximum Chamber Pressure, kPa (psia)	6 895 (1000)
Nominal Thrust Chamber Mixture Ratio	5.5/1
Thrust Chamber Mixture Ratio Operating Range	5.0/1 to 6.0/1
Nozzle Expansion Ratio	200/1
Target Vacuum Specific Impulse at Maximum Thrust, seconds	471

The thrust chamber utilized a segmented combustion chamber approach in which 24 combustor segments were clamped between a continuous inner structural ring and a continuous outer structural ring to provide a 6.283 2 radians (360-degree) circular assembly. At each interface between combustor segment assemblies, bolts were installed to connect the inner and outer structural rings as illustrated in Fig. 12. This design approach, also illustrated in Fig. 13, achieved an assembly of the aerospike thrust chamber without bonding the coolant panels to the pressure and thrust restraining structures, thereby reducing thermally induced strains in the structure, and also avoiding the processing associated with furnace braze joining of the segments and the structure. The resulting mechanical assembly allowed removal and replacement of individual segments if required. The adjoining segments were welded together at the joint which occurred at the end of each combustor's low expansion ratio divergent section. The tabular nozzle was welded to the trailing end of each combustor segment inner body, providing a 6.283 2 radians (360-degree) ring joint.

Drawings of the thrust chamber assembly (Fig. 14 and 1[illegible]) present its dimensions and configuration.

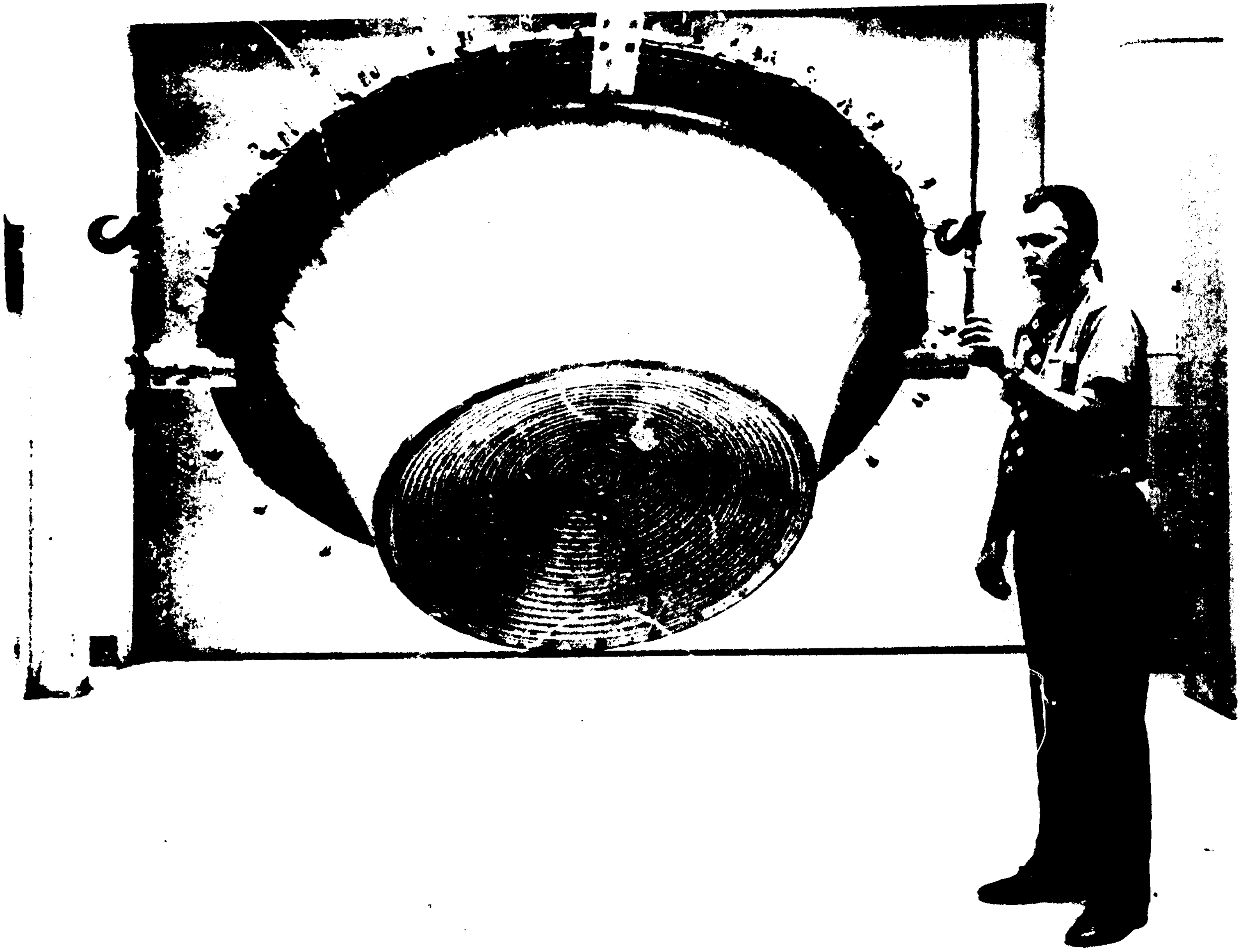

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Figure 10. 111 kN (25K) Aerospike Demonstrator Thrust Chamber Assembly (Side View)

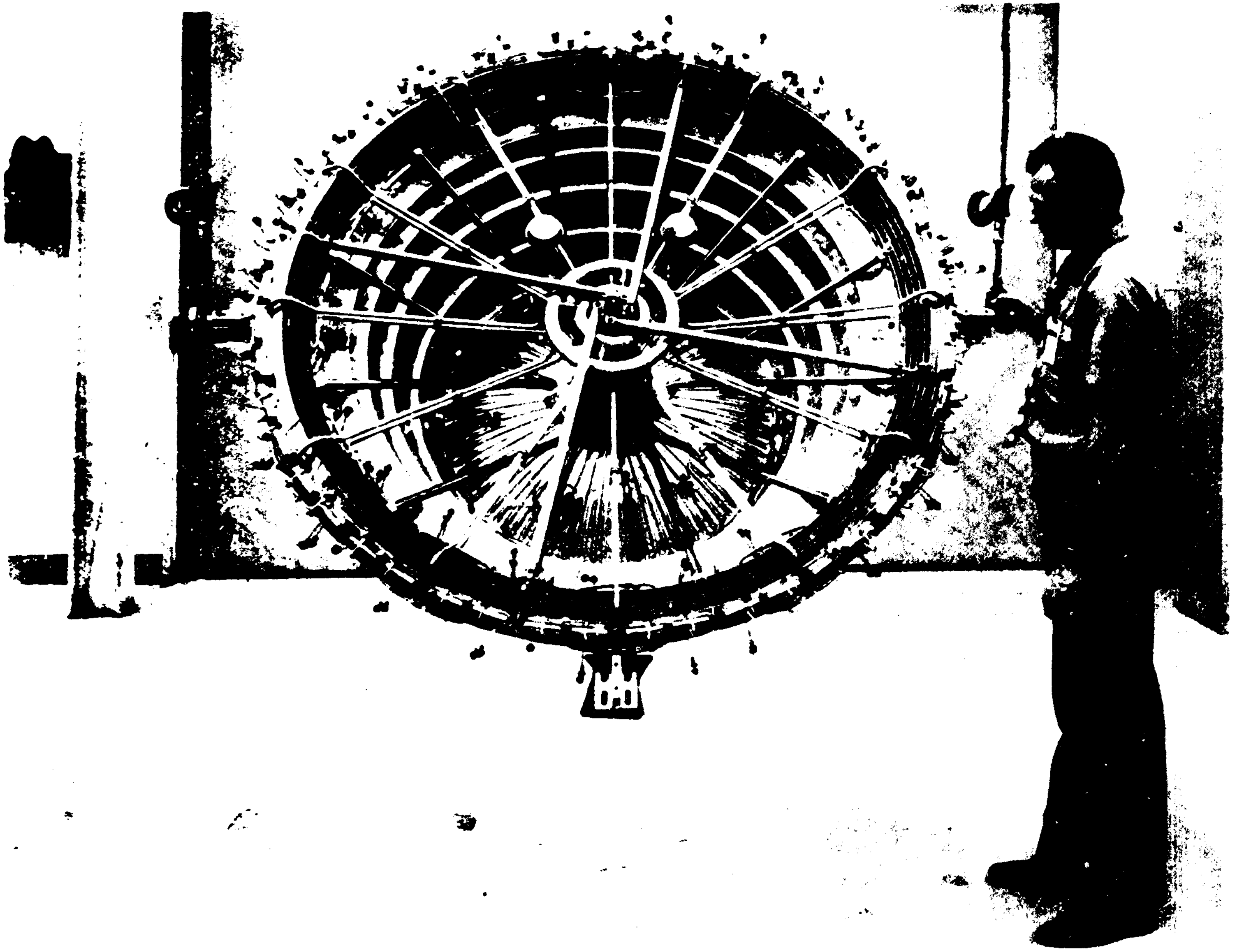

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Figure 11. 111 kN (25K) Aerospike Demonstrator Thrust Chamber Assembly (Top View)

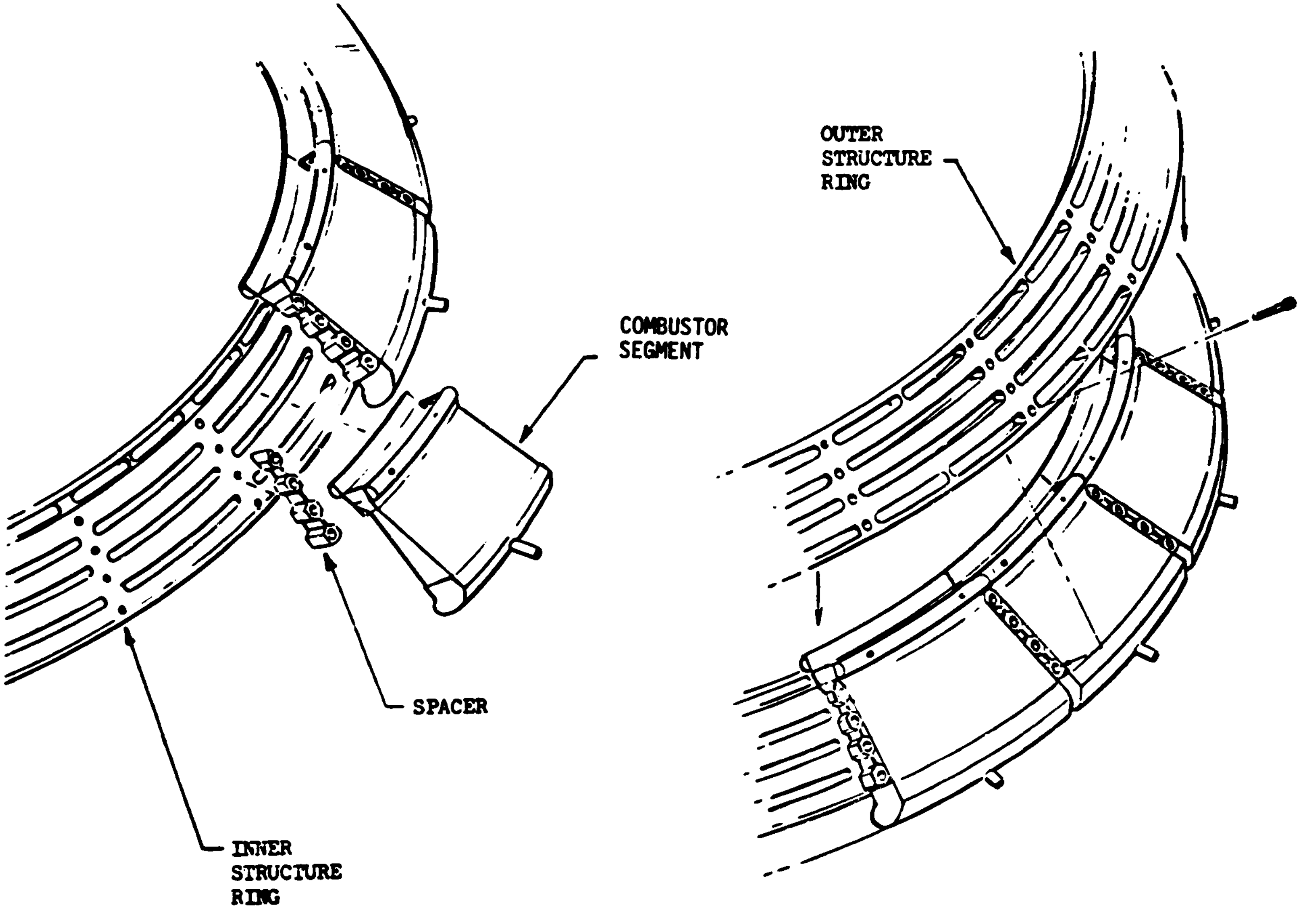


Figure 12. Thrust Chamber Assembly Procedure

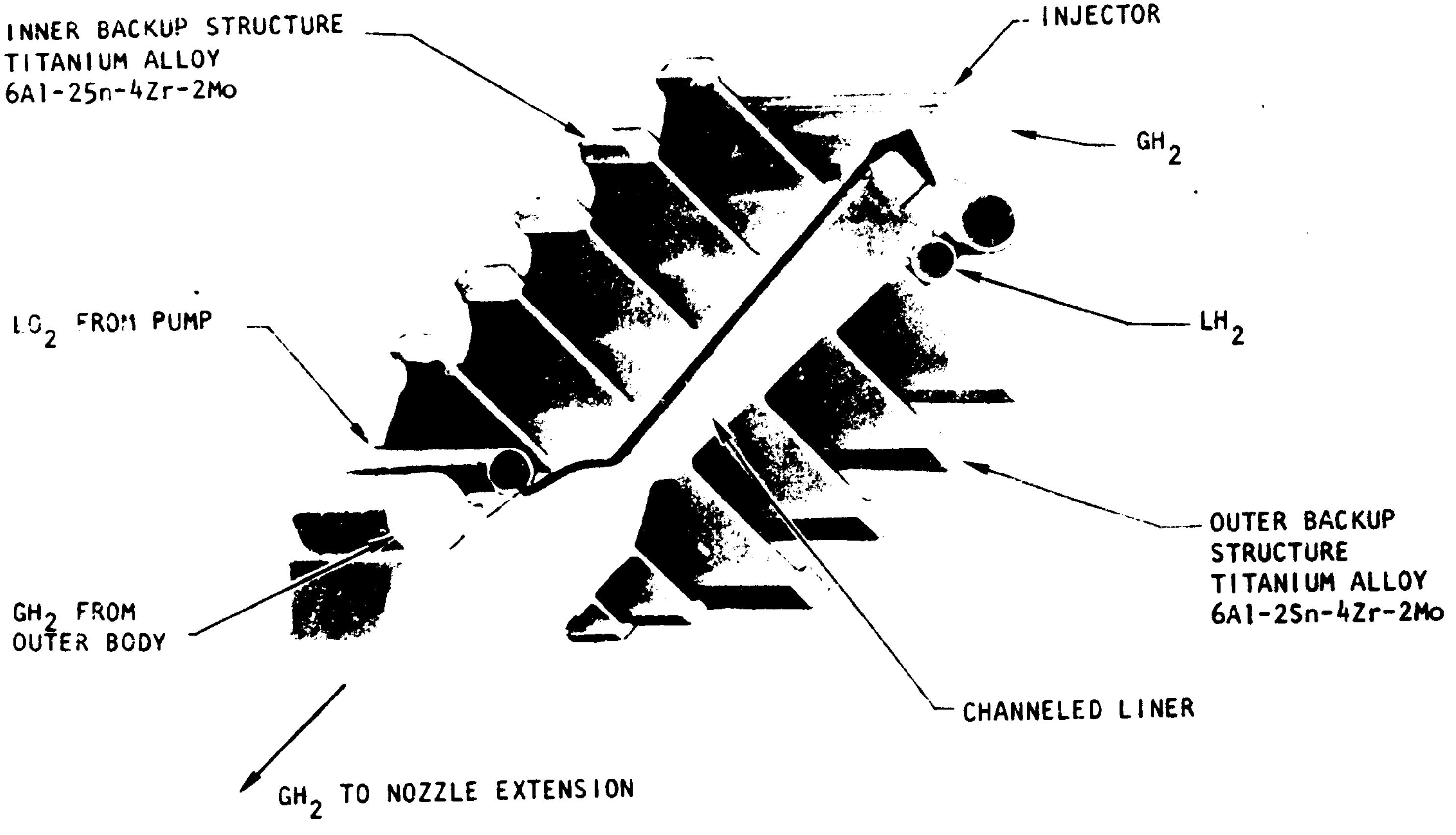
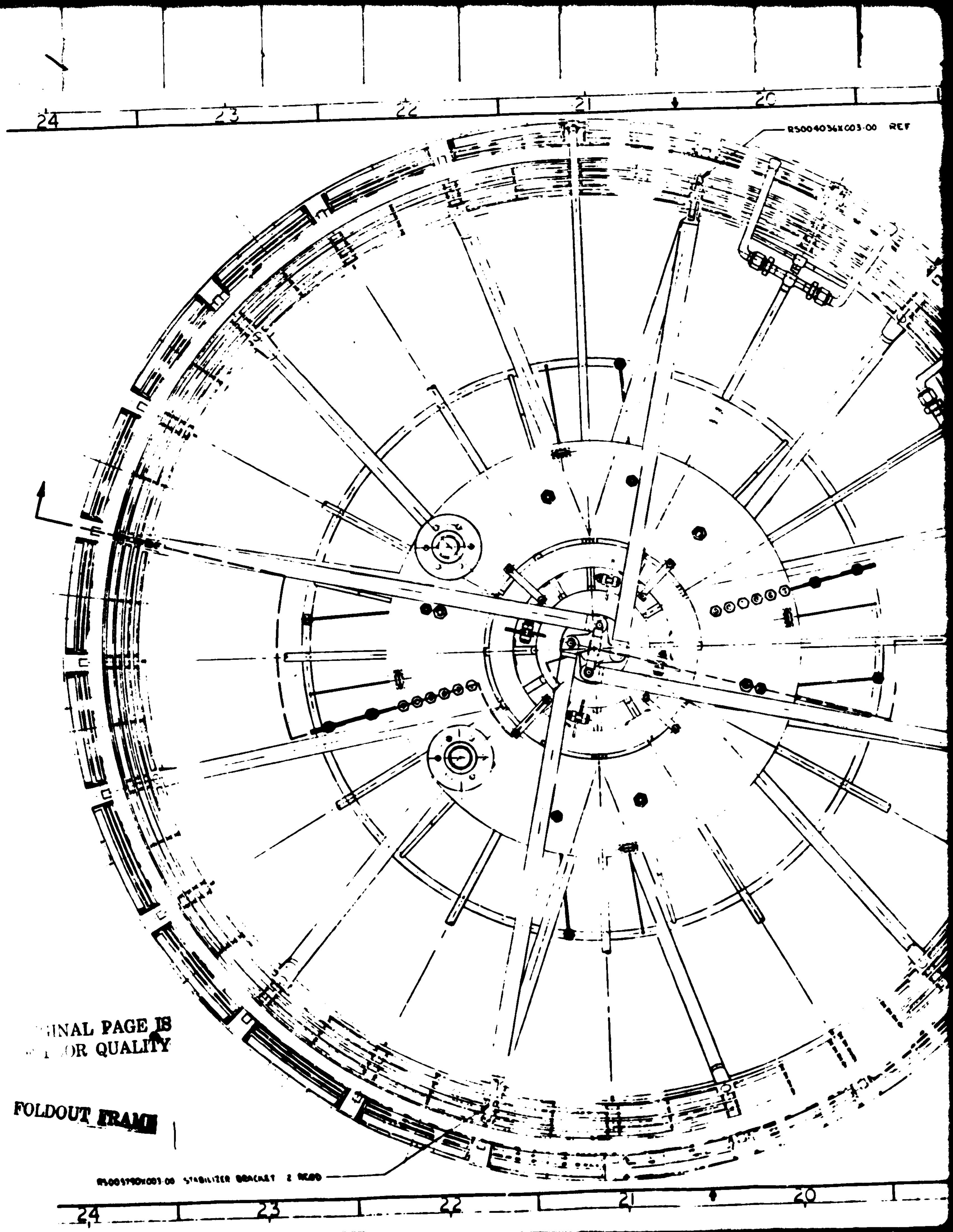


Figure 13. Regeneratively Cooled Lightweight Combustion Chamber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RS003790X003-00 STABILIZER BRACKET 2 REQD
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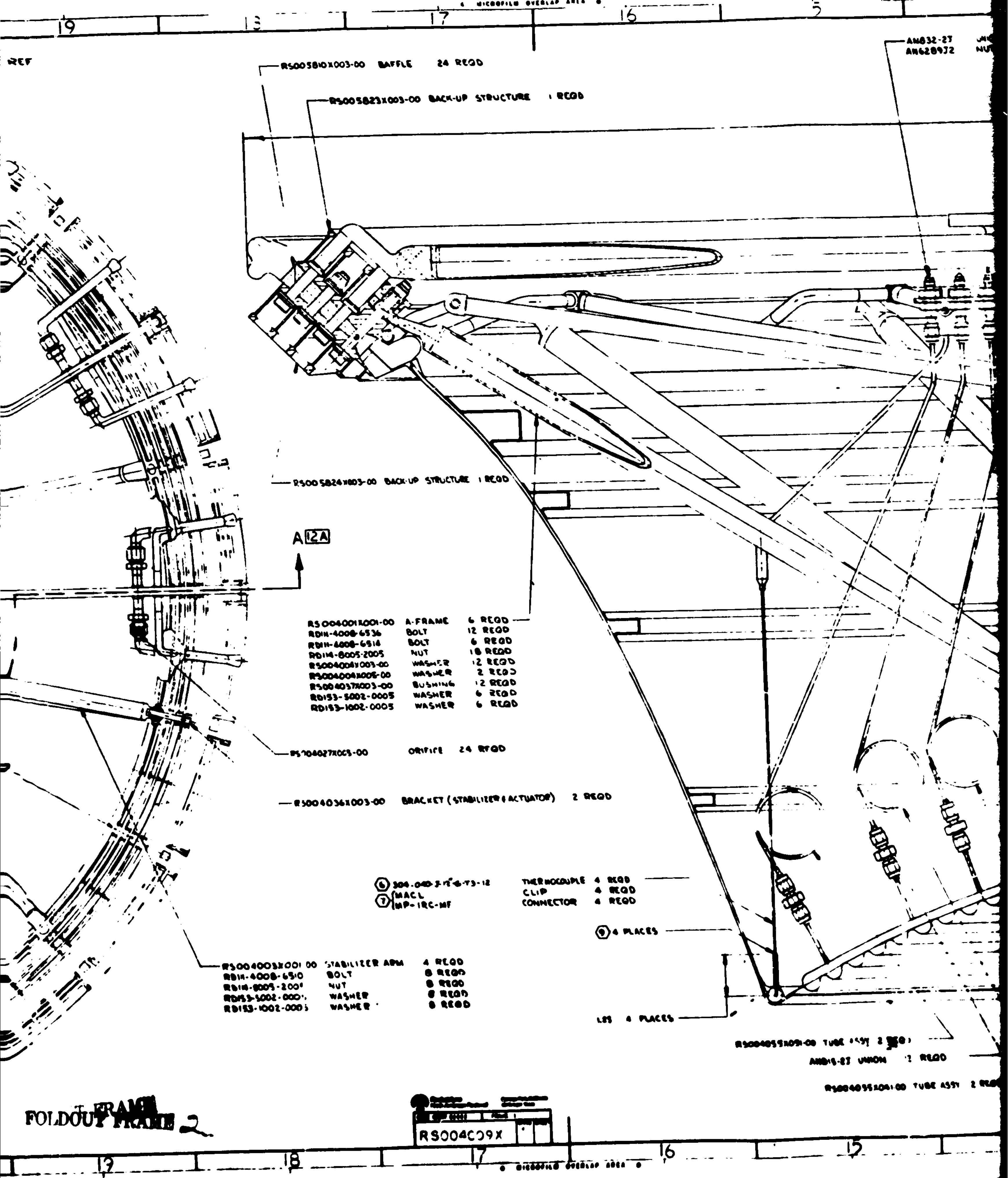

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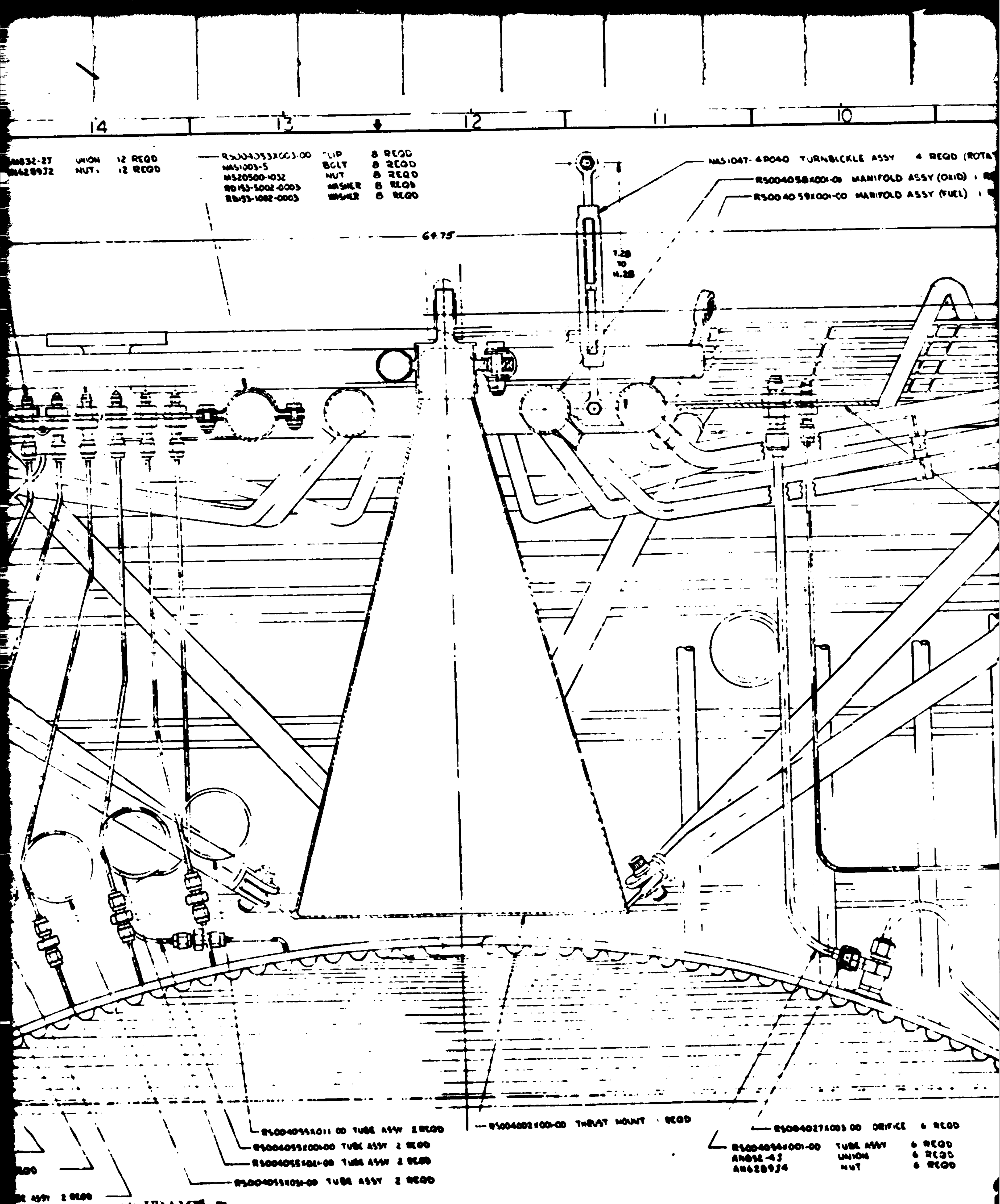

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SECTION A-A 8E
SCALE 1

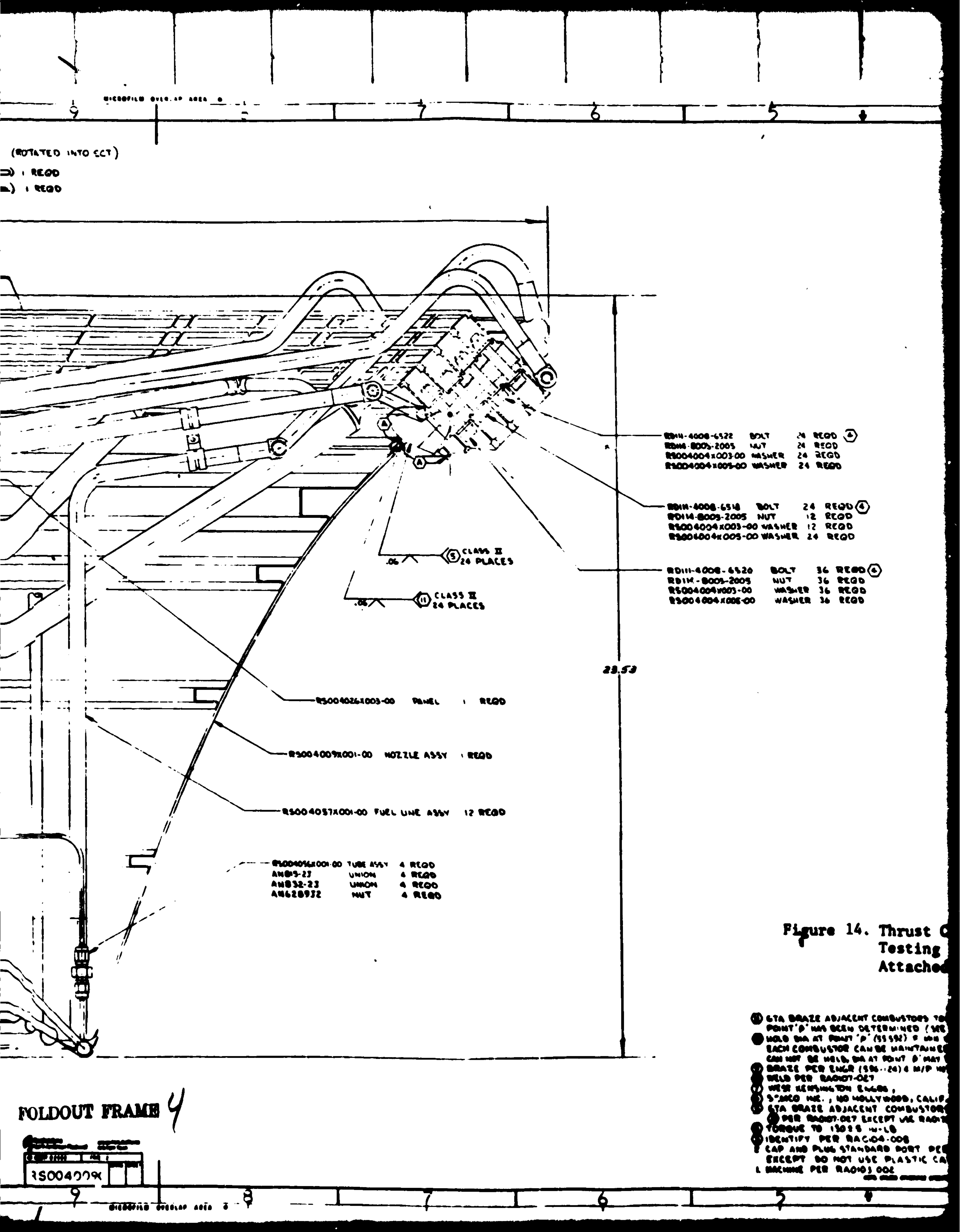


Figure 14. Thrust C
Testing
Attached

FOLDOUT FRAME 4

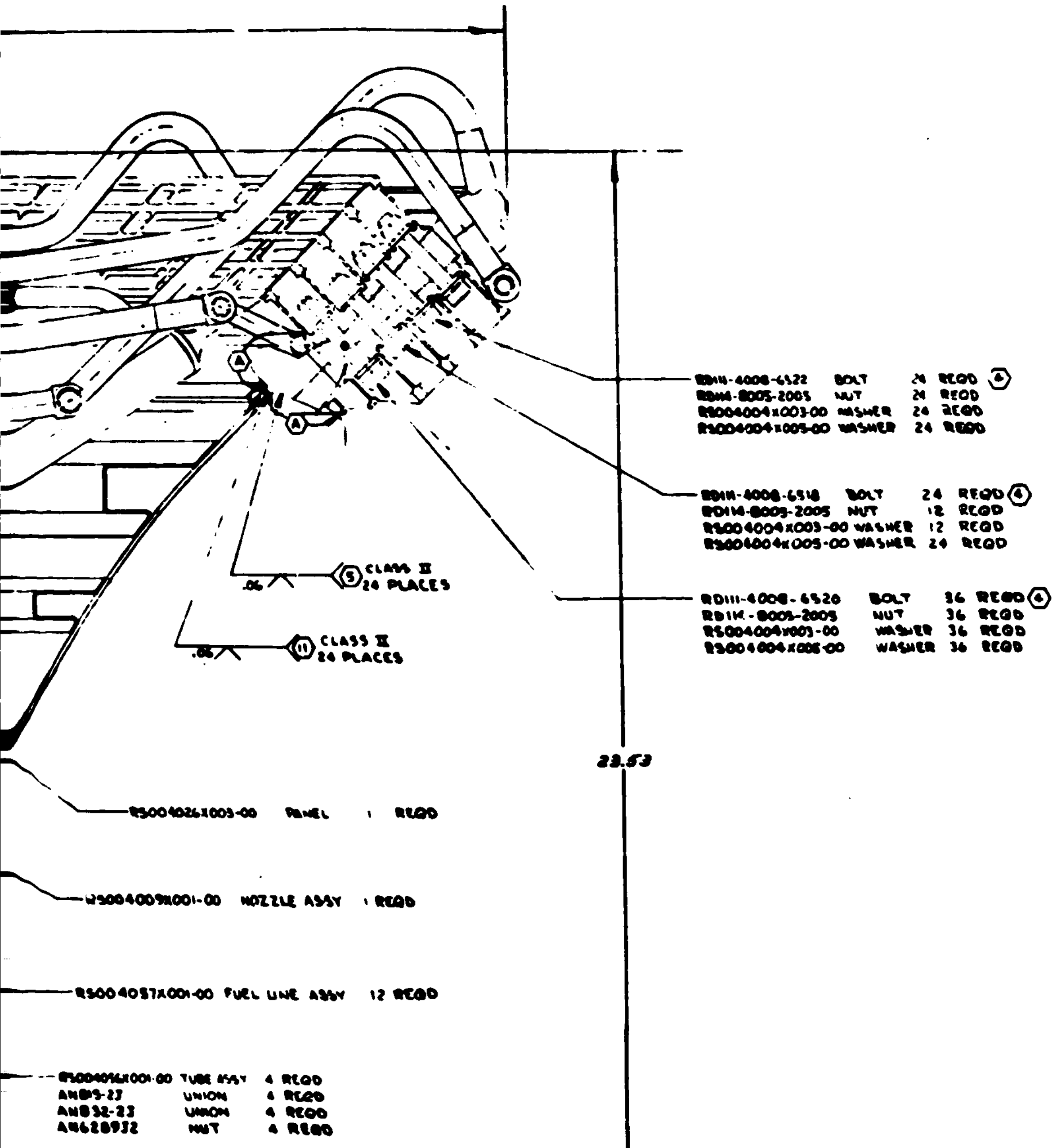
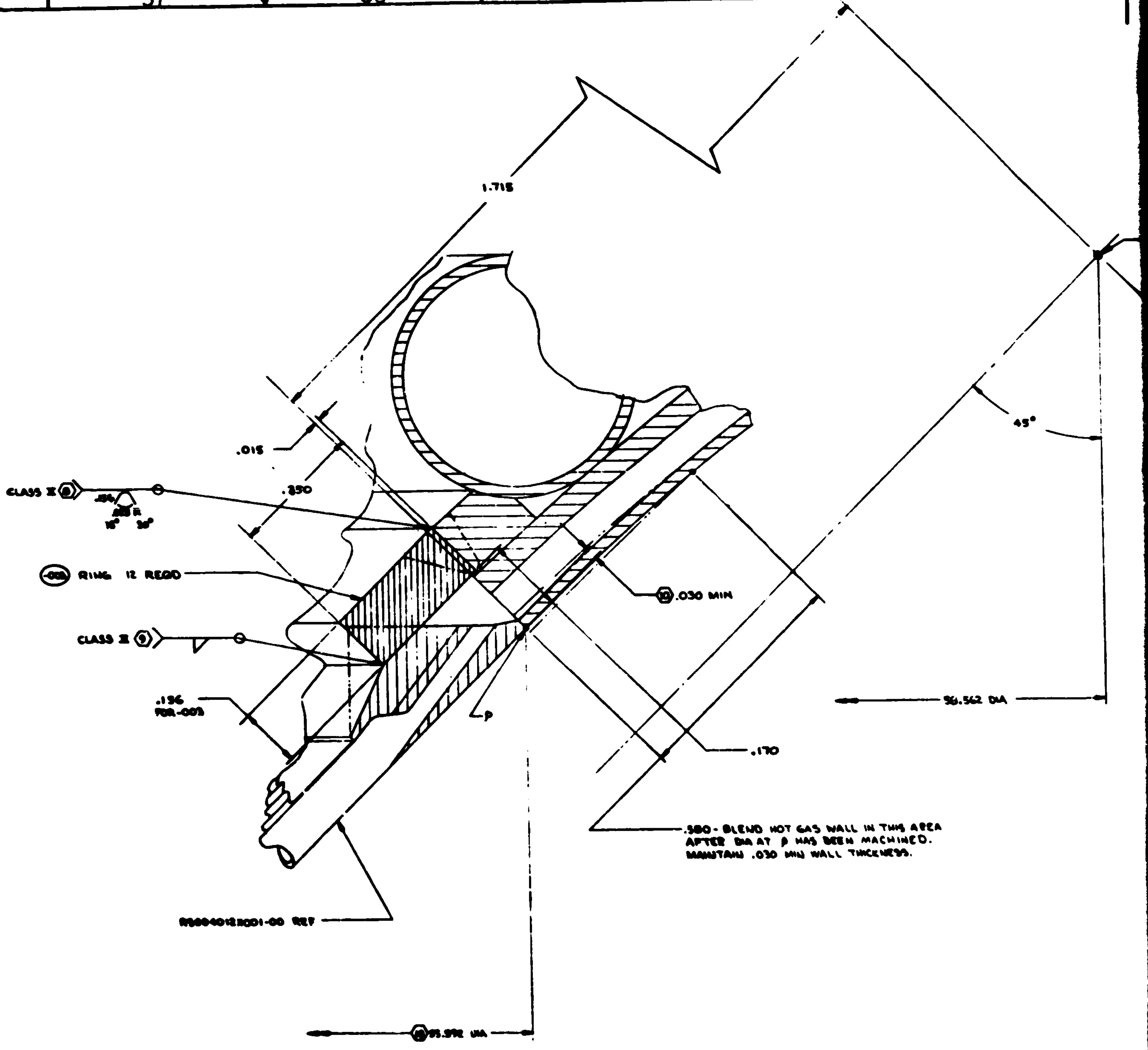


Figure 14. Thrust Chamber Assembly With Testing Instrumentation Attached

FOLDOUT FRAME

⑪ STA BRAZE ADJACENT COMBUSTORS TOGETHER AFTER POINT 'P' HAS BEEN DETERMINED (SEE NOTE 10)
● HOLD DIA AT POINT 'P' (55.50) IF MIN WALL THICKS (.030) OF EACH COMBUSTOR CAN BE MAINTAINED. IF THIS CONDITION CAN NOT BE HELD, DIA AT POINT 'P' MAY BE ADJUSTED
● BRAZE PER ENGR (SPS-124) & M/P INSTRUCTIONS
● WELD PER RA0107-027
● WEST KENSINGTON ENGRG,
● SEMCO INC., NO HOLLYWOOD, CALIF.
● STA BRAZE ADJACENT COMBUSTORS TOGETHER IN AREA ● PER RA0107-027 EXCEPT USE RA0110-004 WIRE FILLER
● TORQUE TO 130±5 IN-LB
● IDENTIFY PER RA0104-008
● CAP AND PLUG STANDARD PORT PER RA0116-094 EXCEPT DO NOT USE PLASTIC CAPS
1 MACHINE PER RA0103-002

001-00
NO.



VIEW C 28E
SCALE 4

OLDOUT FRAME

RSC04009X

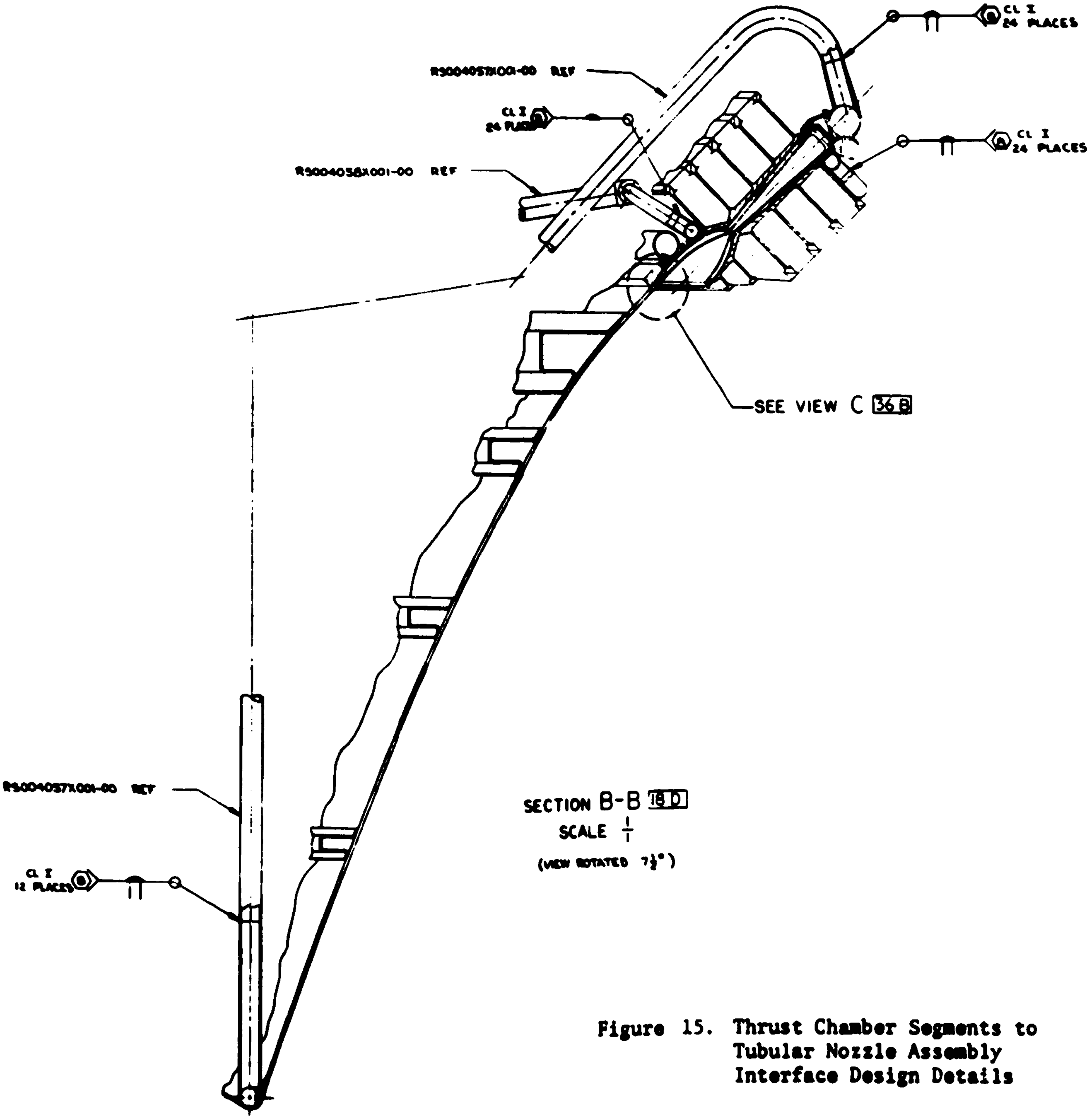


Figure 15. Thrust Chamber Segments to Tubular Nozzle Assembly Interface Design Details

The cooling circuit for the thrust chamber, shown schematically in Fig. 16, consisted of a double-pass, combustor-first/nozzle-last type of circuit. The hydrogen coolant first entered the combustor segment outer body wall as a liquid, at a temperature of 43.89 K (79 R), and completed a downpass and uppass. This was followed by a downpass through the segment end panels, an uppass and downpass through the segment inner body wall, and completion of the circuit by flowing single pass down through the nozzle.

The hydrogen exited the nozzle, and was designed to feed to the injector, as a gas at a temperature of 649.44 K (1169 R). The oxidizer was used for secondary cooling, entering the circuit as a liquid, 97.22 K (175 R), completing a single uppass through the double-paneled inner body wall, and was then fed to the injector as a gas at a temperature of about 199.44 K (359 R). The double-panel thrust chamber heat transfer and pressure loss characteristics are noted in Table 4.

COMBUSTOR SEGMENT DESIGN

The design criteria for the regeneratively cooled combustor segment were established on the basis of extensive development experience gained from single segment test combustors. A sectional sketch of the segment design is shown in Fig. 17.

The segment consisted of a two-piece (i.e., inner and outer liner) NARloy-A* assembly as depicted in Fig. 18. The outer liner had a brazed-on NARloy-A closeout sheet, but the inner liner utilized a brazed-on NARloy-A oxidizer coolant panel closed out with a NARloy-A cover sheet. All material was machined from forgings.

The materials selected for the regeneratively cooled double-panel segment were as follows:

1. Segment Liner - Machined wrought forging NARloy-A material
2. Injector Face - Integral with wrought liner, NARloy-A material
3. Injector Body - Investment casting, 304L corrosion-resistant steel
4. Coolant Channel Closeout, Outer Body Liner - Furnace brazed wrought NARloy-A sheet
5. Coolant Channel Closeout, Inner Body Liner - Furnace brazed NARloy-A oxidizer coolant panel which is closed out with a wrought NARloy-A sheet
6. Injector Body-to-Face Joint - Furnace braze joint
7. Manifold Shells - Minimum wall thickness, corrosion-resistant steel

---

*NARloy-A is a silver-copper alloy (Rockwell International trademark)

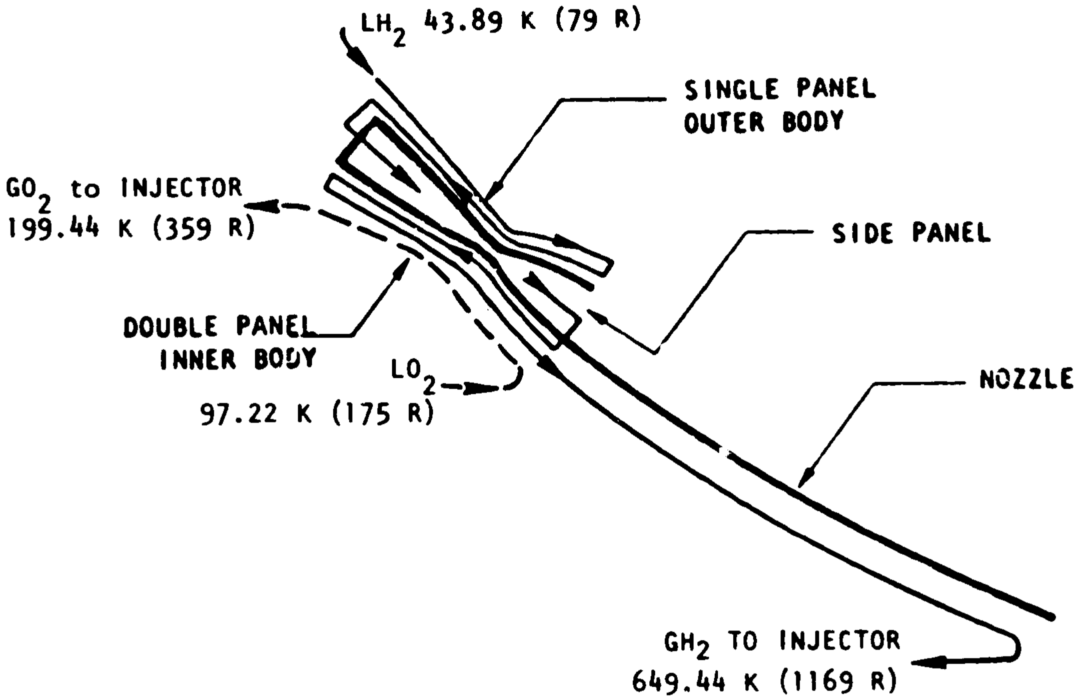


Figure 16. Thrust Chamber Cooling Circuit

TABLE 4. THRUST CHAMBER HEAT TRANSFER

Thrust Chamber Location	Chamber Pressure = 6895 kPa(1000 psia); Mixture Ratio = 5.5			
	ΔT, K (R)	Q, kW(Btu/sec)	ΔP, kPa(psi)	Pressure, kPa(psia)
Cooling Circuit Exit Pressure				12 900 (1871) 8 239 (1195)*
Nozzle Exit Loss			145 (21)	
Nozzle Tubes	96.67 (174)	5 246 (4976)	427 (62)	
Nozzle Entrance			7 (1)	13 479 (1955)
Inner Body Exit and Manifold Loss			221 (32)	
Inner Body Channels and Return	208.89 (376) 102.22 (184)	11 374 (10,788) 4 322 (4099)	4 192 (608) 3 792 (550)	12 031 (1745)
Inner Body Entrance			269 (39)	269 (2634)
Side Panel Exit and Manifold Loss			97 (14)	
Side Panel Fin Turning Loss			234 (34)	
Side Panel Channels	27.22 (49)	1 502 (1425)	931 (135)	
Side Panel Entrance			152 (22)	19 574 (2839)
Outer Body Exit and Manifold Loss			186 (27)	
Outer Body Channels and Return	276.67 (498)	16 314 (15,473)	1 634 (237)	
Outer Body Entrance			34 (5)	21 429 (3108)

*( ) Denotes values for oxygen

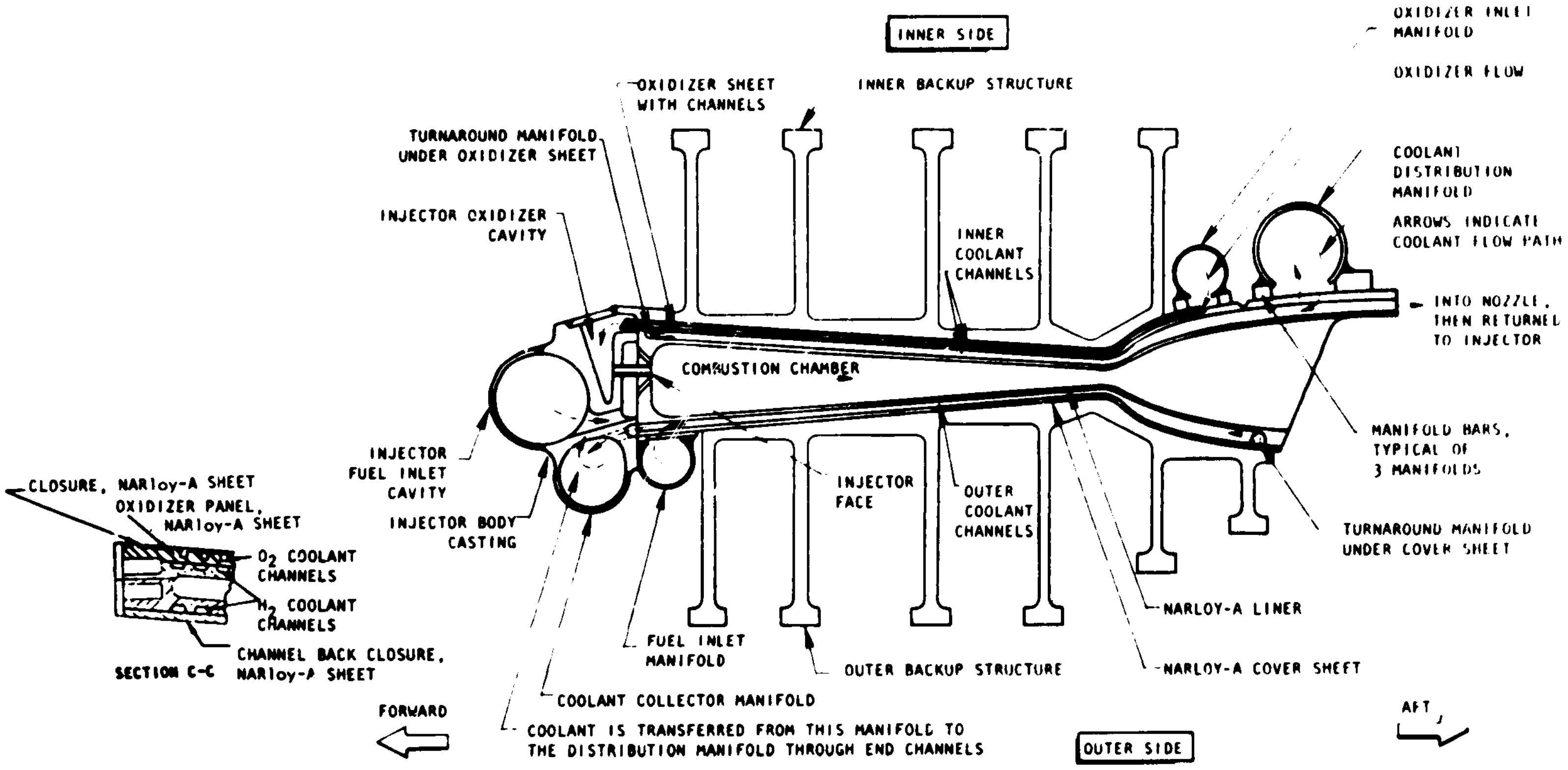


Figure 17. Double Panel Segment Design

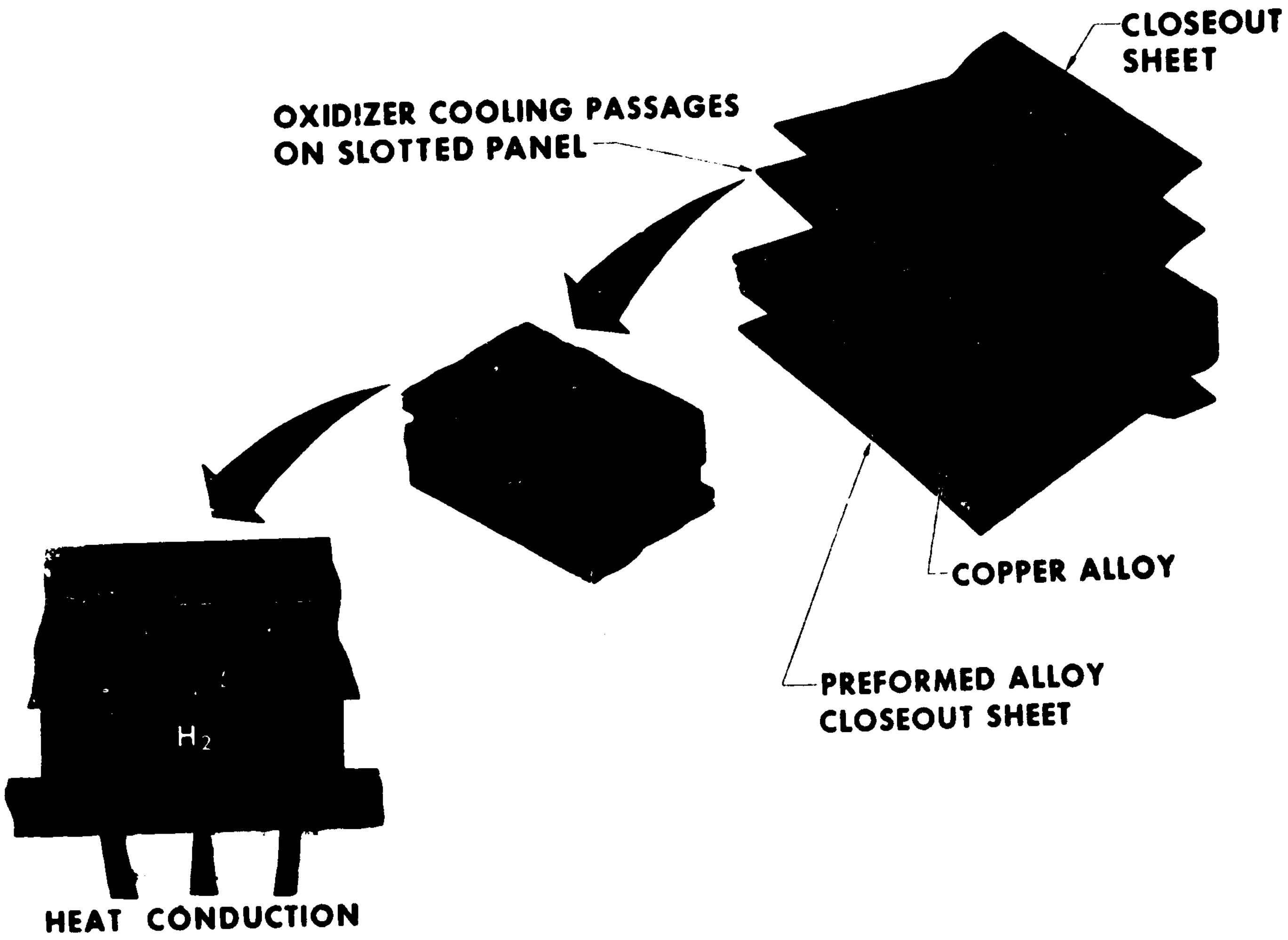


Figure 18. Double-Panel Cooling Concept

The details of this design are described below.

Each NARloy-A liner had 74 regenerative coolant passages machined into its exterior wall. A preformed wrought NARloy-A sheet 0.64-mm (0.025-inch) thick was brazed into position to form the coolant channel closeout for the outer liner. An oxidizer coolant panel, 1.14-mm (0.045-inch) thick, with 73 machined, regenerative-coolant passages along with a closeout sheet, 0.38-mm (0.015 inch) thick, was brazed into position to form the closeout for the inner liner. The inner and outer liner assemblies were then brazed together. The injector face was made integral with the liner halves so that a flat surface injector body-to-injector face joint could be furnace brazed.

The design criteria for the segment geometry were established by development segment testing and are presented in Table 5 .

DESIGN OF THRUST CHAMBER ASSEMBLY

The complete thrust chamber assembly consisted of a combustor segment subassembly attached to a truncated aerospike tubular nozzle as described below.

Combustor Subassembly

The combustor subassembly consisted of 24 combustor segments, a lightweight backup structure for positioning these combustor segments, spacers, and assorted brackets and bolts as illustrated in Fig. 17. The outer backup structure ring was positioned to begin the initial build (Fig. 19). Stacking of the combustor segments was next. Each segment was fitted to the ring. At each of the 24 segment junctions, a TIG weld was applied to form a ring of the combustor trailing edges. Next, the inner backup structure along with the spacers, bolts, nuts, and bracketry was installed. The subassembly was then machined at the end of each combustor to form the transition joint for hookup to the nozzle assembly.

The inner and outer backup structures were designed for minimum weight through the use of titanium alloy ring forgings (6Al-2Sn-4Zr-2Mo) and high section modulus with a continuous support surface in contact with segment combustors. The backup structures were designed to provide for mounting all the combustors together in a sandwich effect. Easy ON/OFF situations were also considered. These backup structure designs are presented in Fig. 20 and 21.

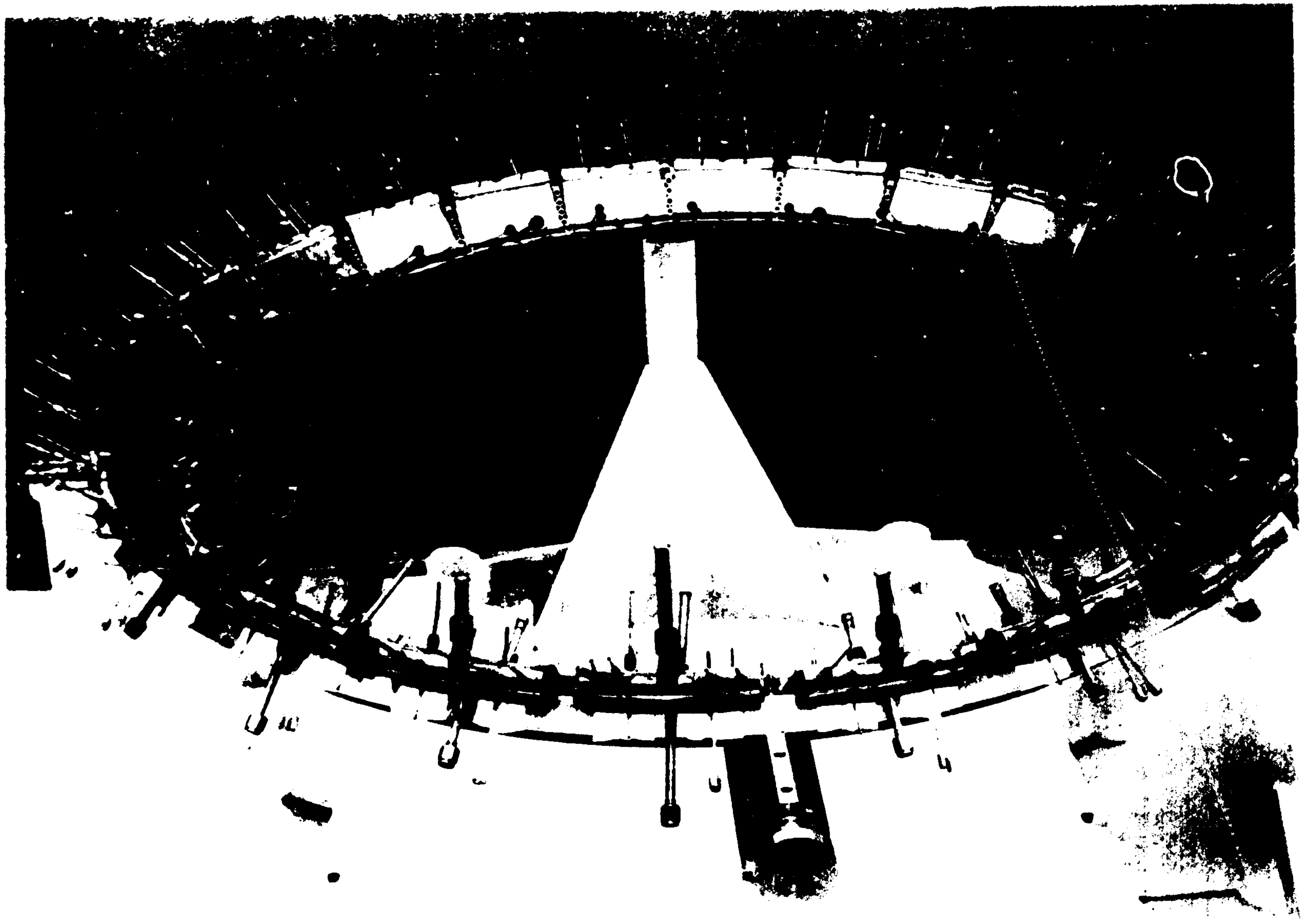
Nozzle-Base Closure Subassembly

The nozzle-base closure subassembly consisted of a nozzle extension and a base closure assembly.

The nozzle extension was a tubular assembly regeneratively cooled by a single downpass of hydrogen coolant introduced at the upper end nozzle-to-combustor transition manifold ring. The nozzle extension was constructed

TABLE 5. COMBUSTOR DESIGN CRITERIA

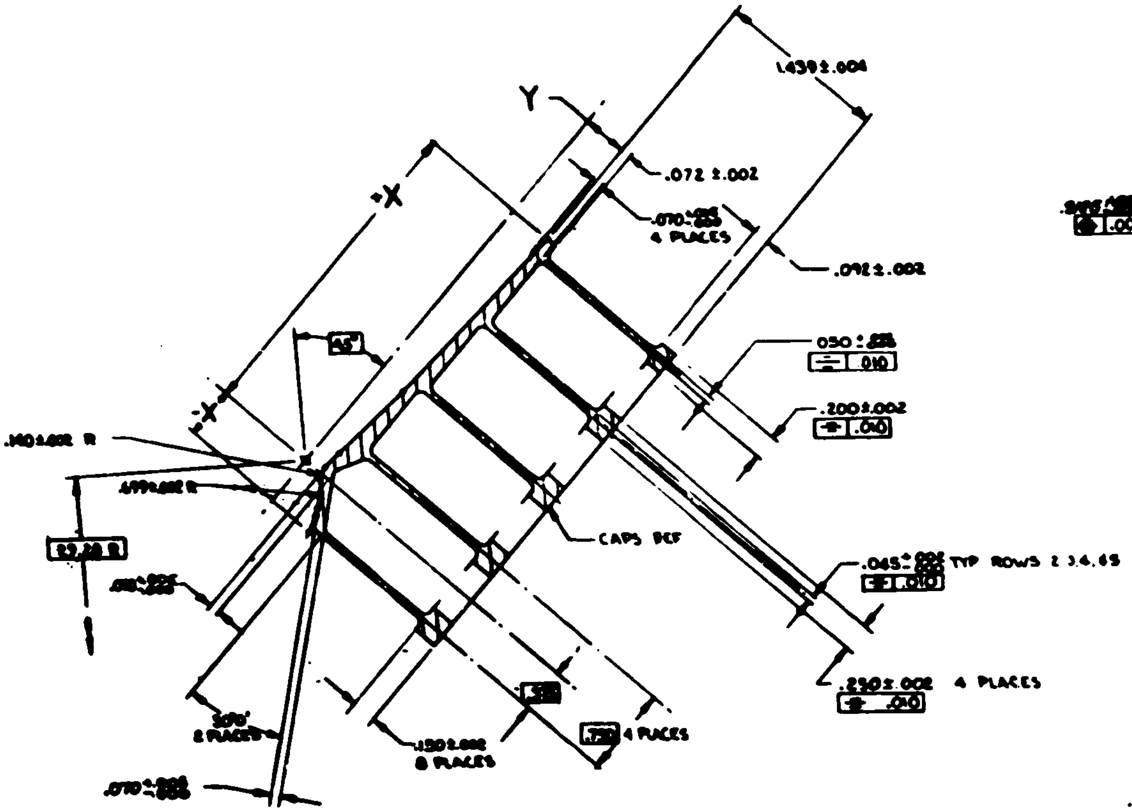
Design Parameters	Values
Chamber Length (side plate-to-side plate at injector end), Chord Length, mm (inches)	169.57 (6.676)
Chamber Length (side plate-to-side plate at throat), Chord Length, mm (inches)	169.57 (6.676)
Width at Injector End, mm (inch)	12.70 (0.500)
Throat Gap, mm (inch)	2.16 (0.085)
Throat Area, mm^2 (sq in.)	(0.570)
Contraction Ratio (A_{inj}/A_t)	5.88
Expansion Ratio (Ae/A_t)	8.8
Combustion Zone Wall Configuration	
Side Plates	Straight, straight
Chamber Walls	Straight, convergent
Combustion Zone Wall Convergence Half Angle, radians (degrees)	0.07 (4 degrees, 5 minutes)
Combustion Zone Length (L_C), Injector Face to Throat, mm (inches)	76.2 (3.0)
Characteristic Chamber Length (L^*) mm (inches)	259.08 (10.2)
Chamber Pressure Range, kPa (psia)	6 900 to 1 379 (1000 to 200)
Hot-Gas-Side Wall Temperature at the Throat Region (maximum), C (F)	676.7 (1250)



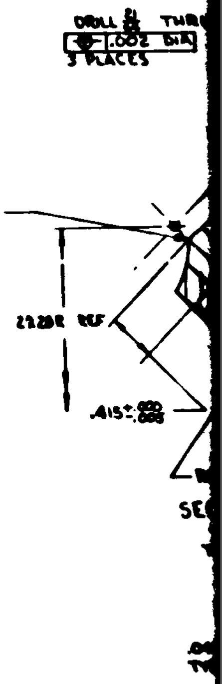
1EH32-4/17/74-C1D*

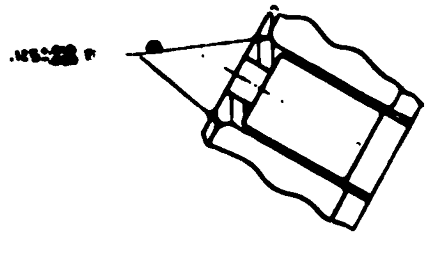
Figure 19. Combustor Segment Stacking

X ±.002	Y ±.002
2.760	381
.990	.262
.240	.178
.064	.166
-.040	.203
-.245	.334
-.300	.358
-.400 REF	395 REF
-.429	.404

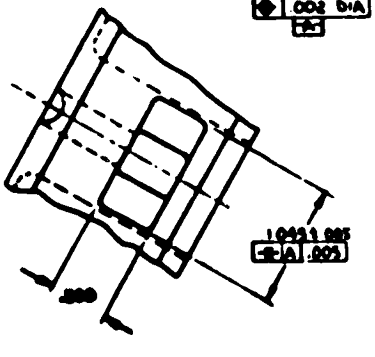


SECTION C-C
SCALE 4
TYP 11 PLACE

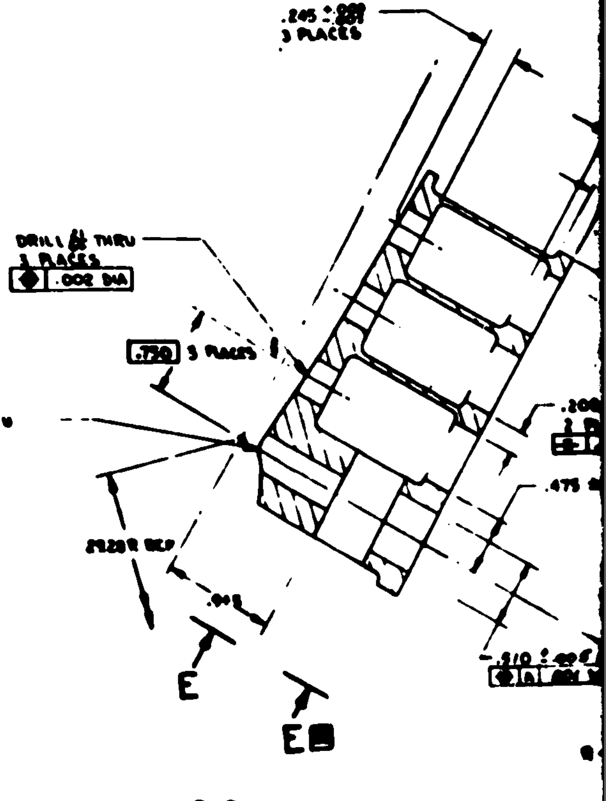




SECTION D-D
SCALE 4
TYP 40 PLACES

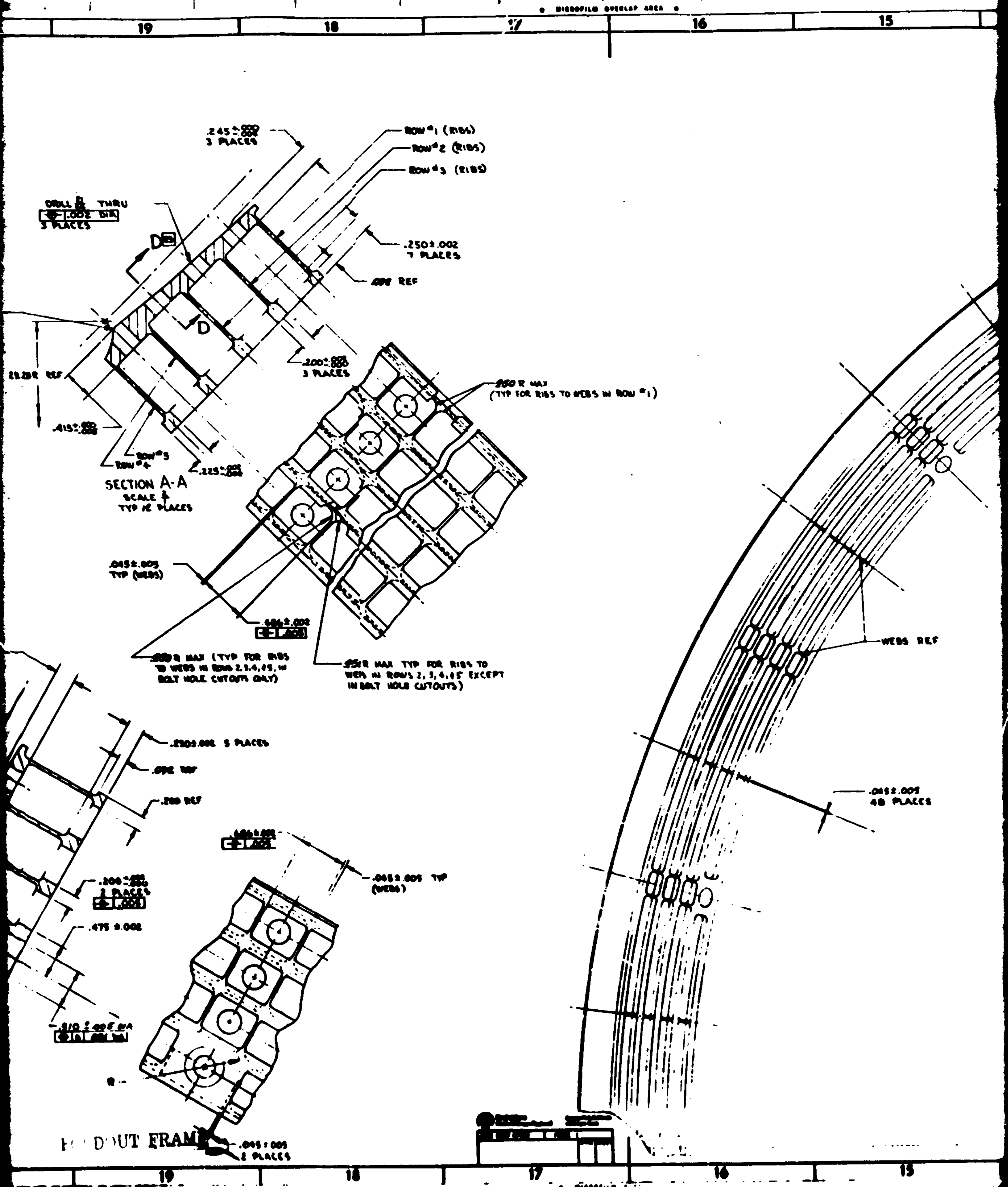


VIEW E-E



SECTION B-B
SCALE 4
TYP 12 PLACES

FOLDOUT FRAME 1



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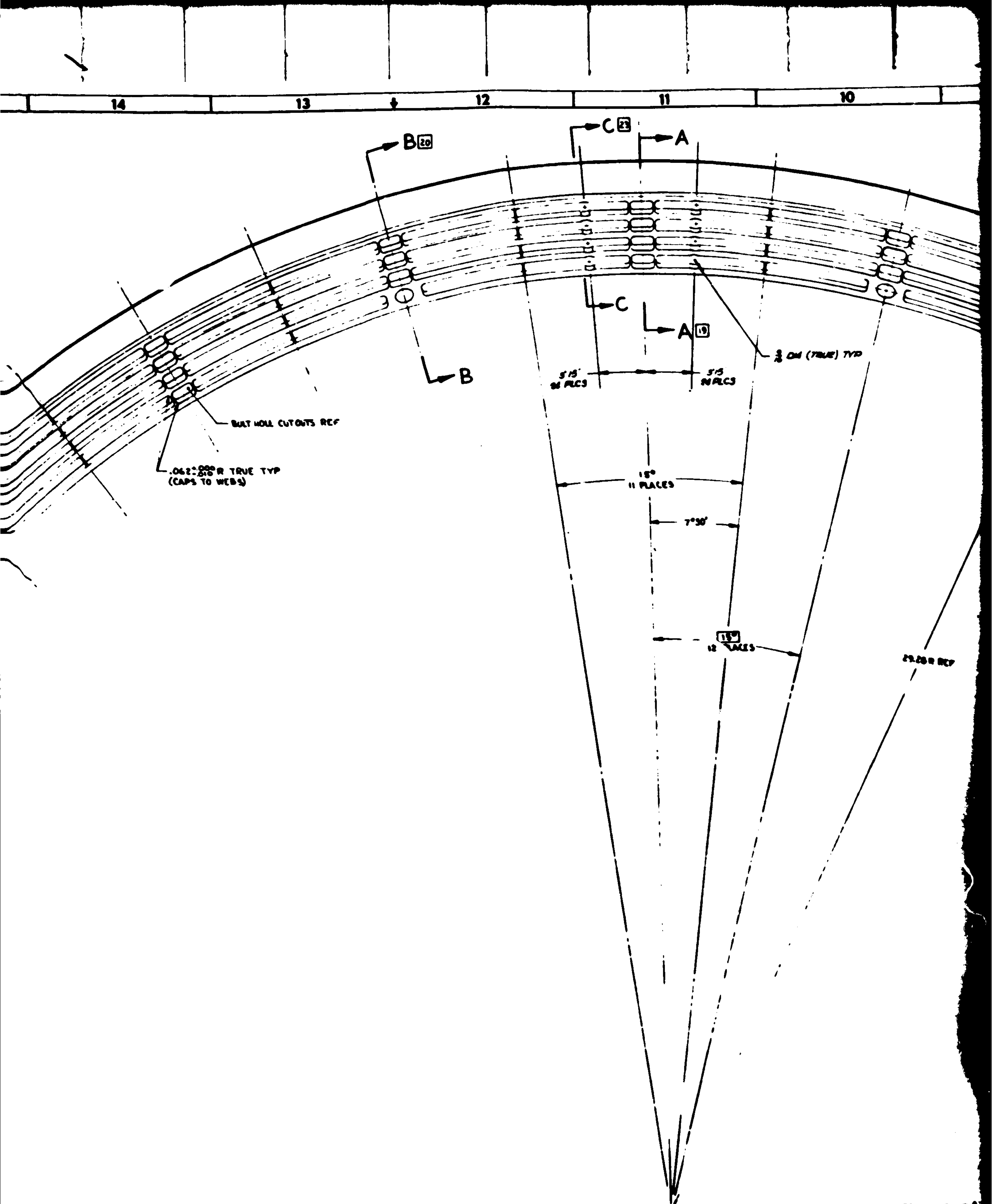
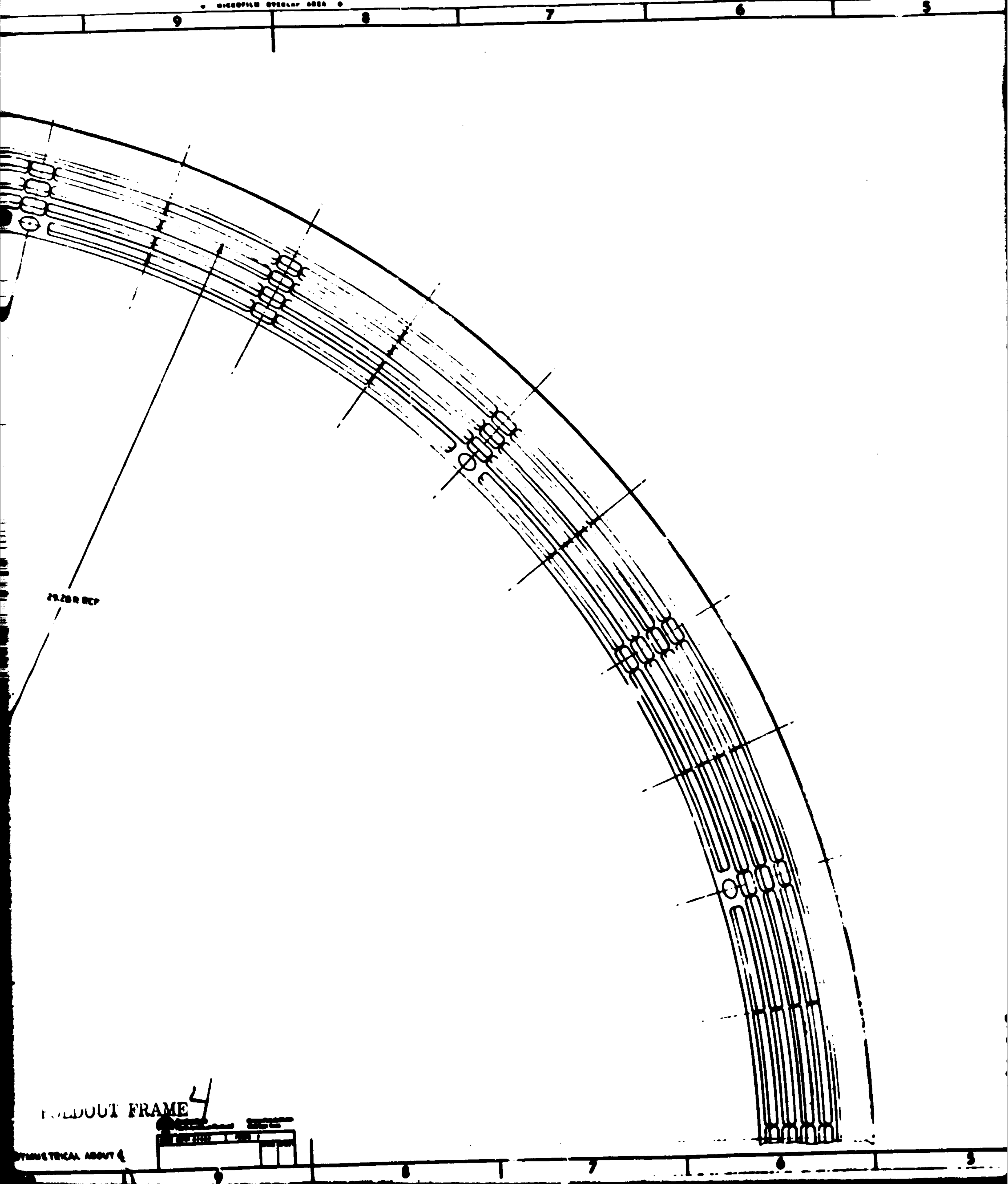


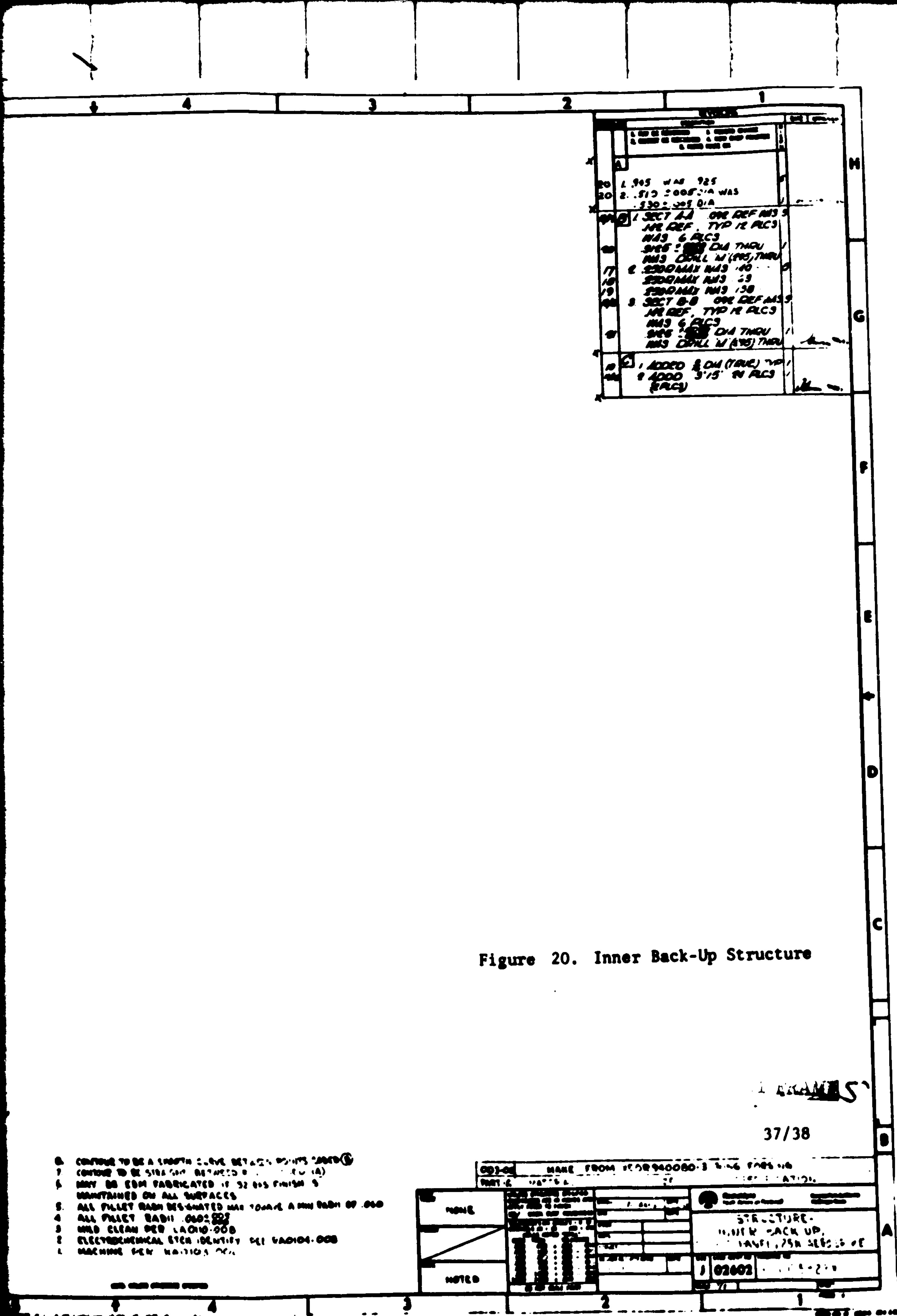
FOLDOUT FRAME

MICROFILM OVERLAY AREA



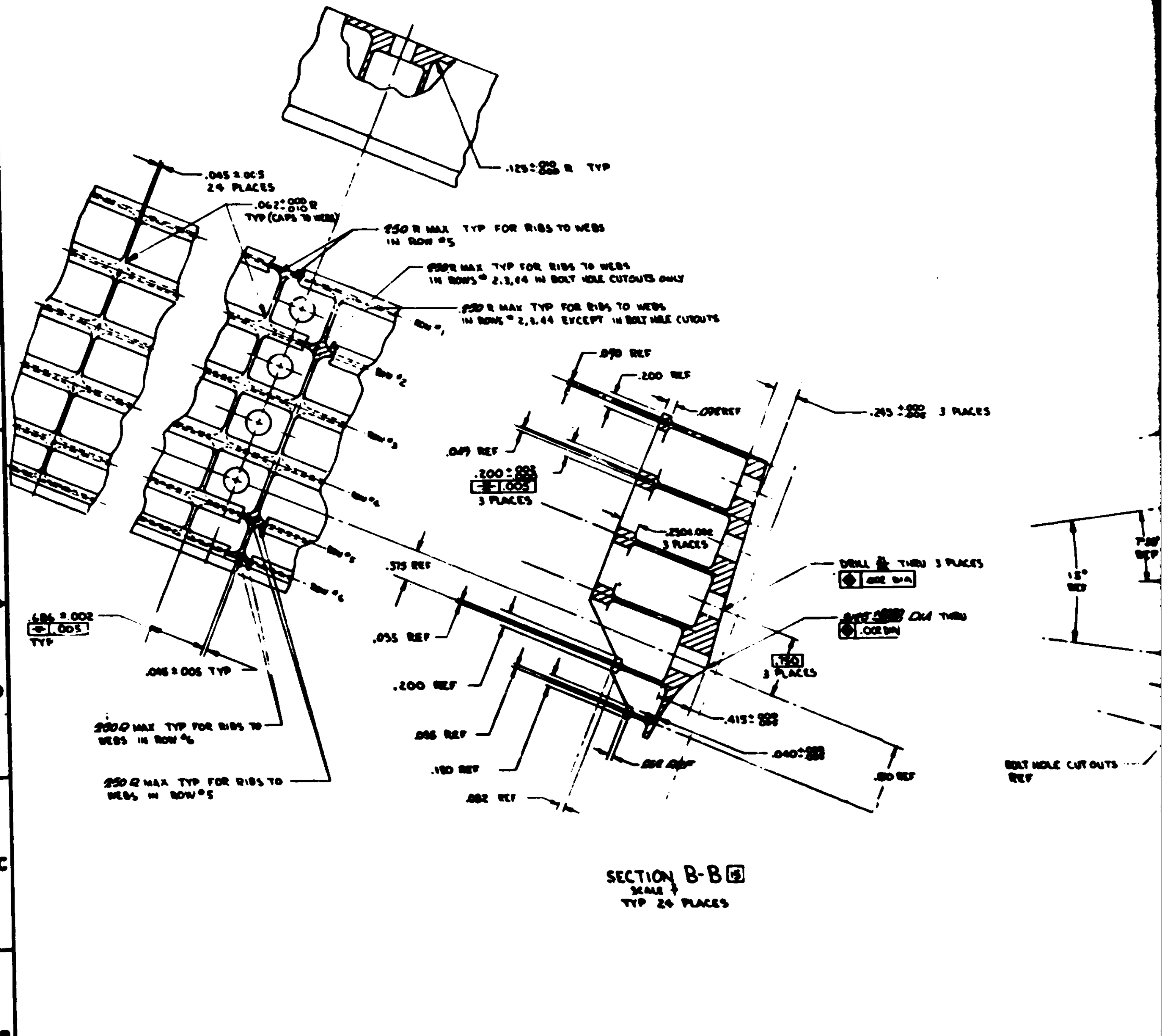
FOLDOUT FRAME 4

YMMETRICAL ABOUT ℄



8. CONTOUR TO BE A SMOOTH CURVE BETWEEN POINTS NOTED
7. CONTOUR TO BE STRAIGHT BETWEEN (A)
6. MAY BE EDM FABRICATED IF 32 RMS FINISH IS MAINTAINED ON ALL SURFACES
5. ALL FILLET RADII DESIGNATED MAX TO HAVE A MIN RADII OF .060
4. ALL FILLET RADII .060±.005
3. VAPOR CLEAN PER LAC010-008
2. ELECTROCHEMICAL ETCH IDENTIFY PER LAC0104-008
1. MACHINE PER NOTATION

Figure 20. Inner Back-Up Structure



SECTION B-B 15
SCALE
TYP 24 PLACES

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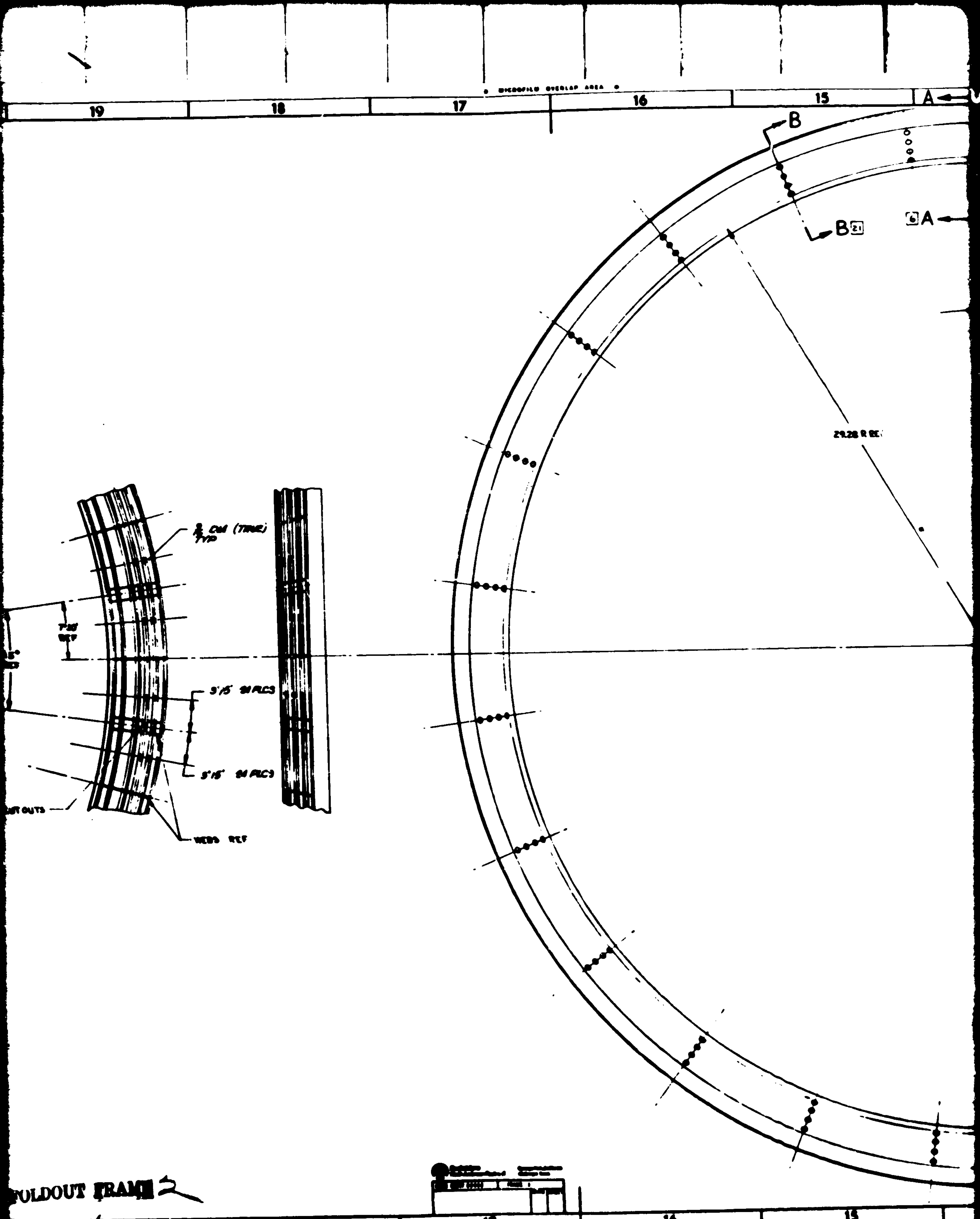
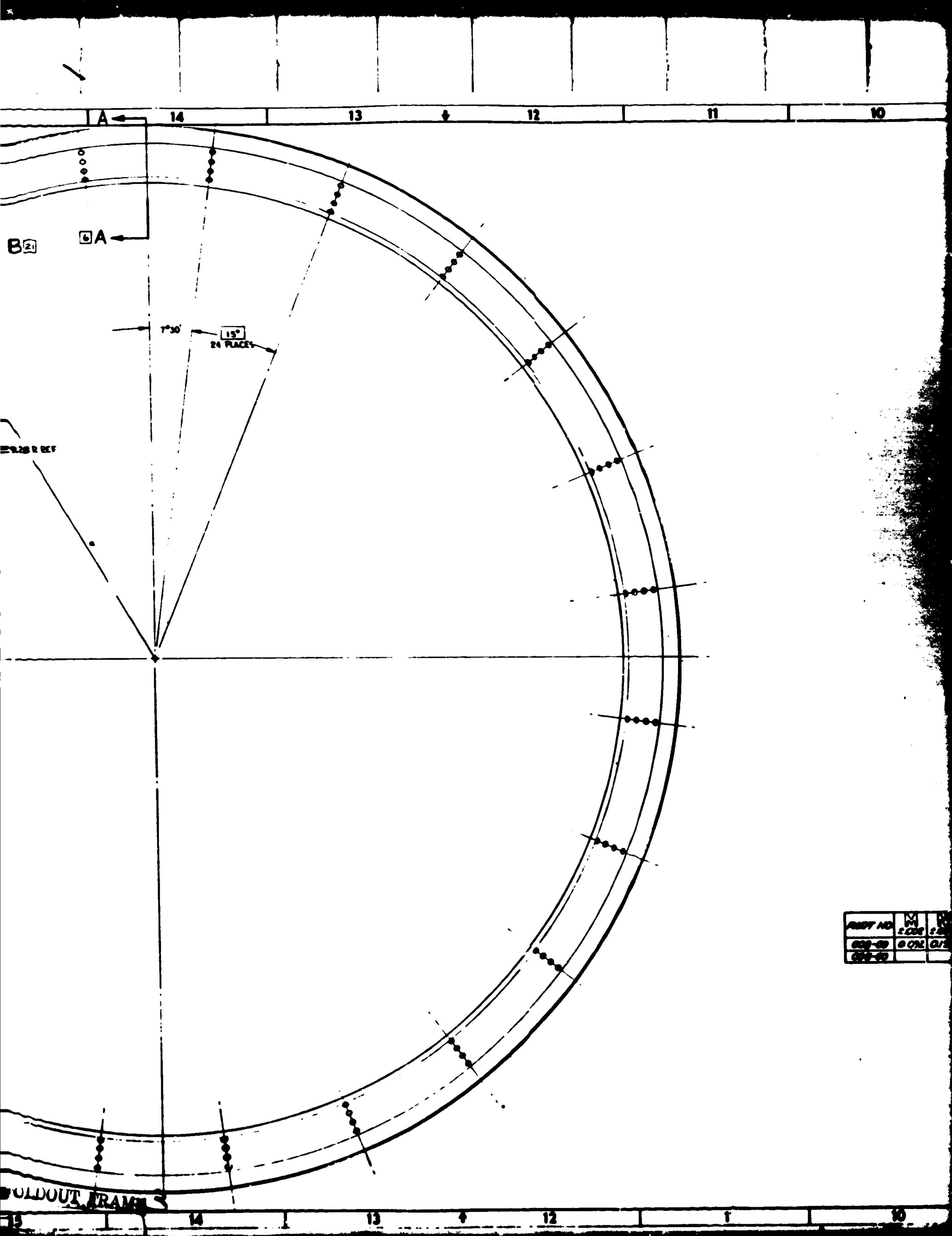
OF POOR QUALITY

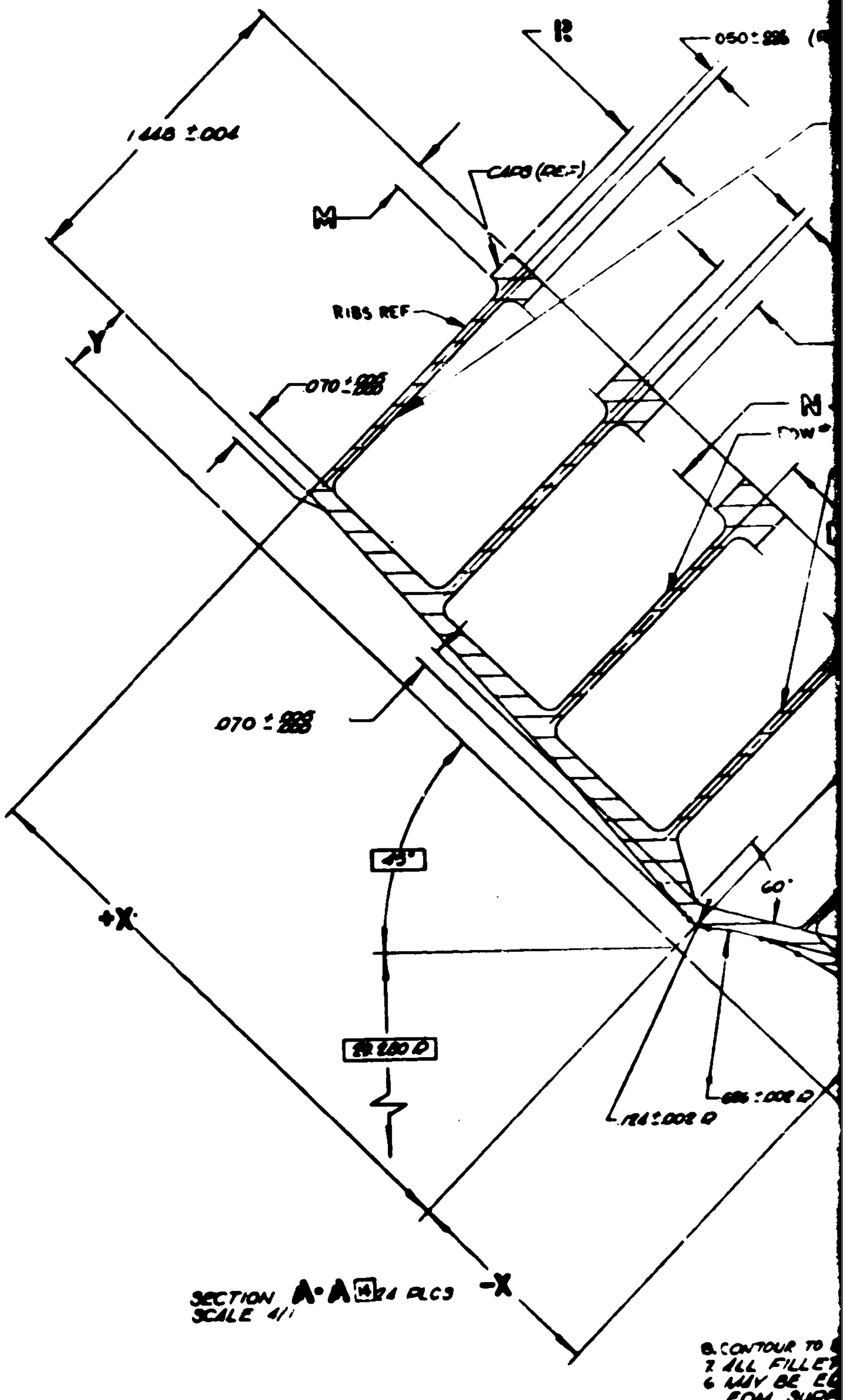
FOLDOUT FRAME



FOLDOUT FRAME 2



[illegible] NO	M ±.008	N ±[illegible]
[illegible]	0.0[illegible]	0.1[illegible]
[illegible]		

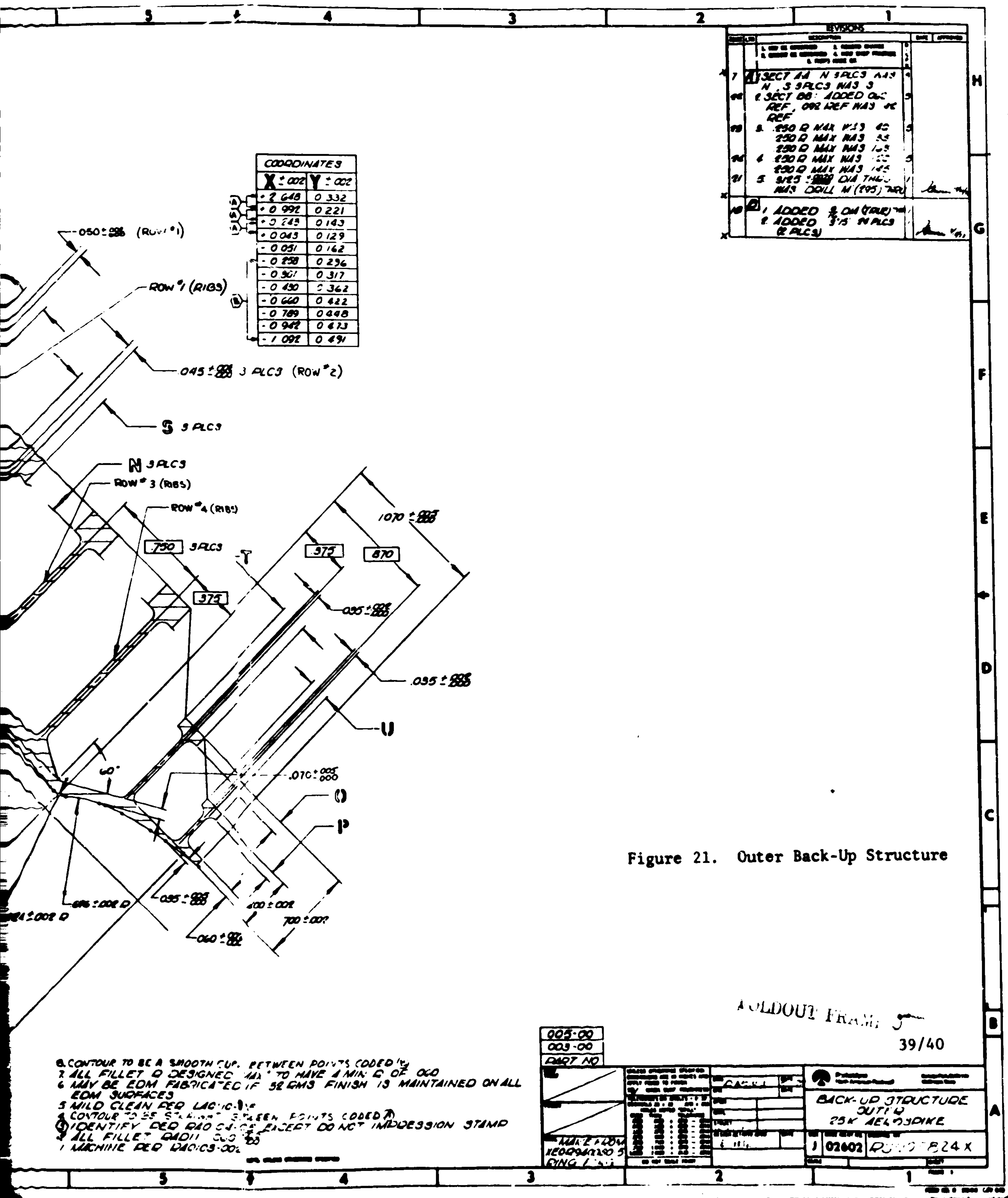


SECTION A-A 24 PLCS
SCALE 4/1

PART NO	M ±.002	N ±.002	O ±.002	P ±.002	R ±.002	S ±.002	T ±.002	U ±.002
C09-00	0.092	0.150	0.082	0.062	0.200	0.250	0.200	0.150
006-00								

8 CONTOUR TO
7 ALL FILLET
6 MAY BE E
EDM SUR
5 MILD CLE
4 CONTOUR TO
IDENTIFY
3 ALL FILLE
1 MACHINE

FOLDOUT FRAME 4



COORDINATES	
X ± .002	Y ± .002
+ 2 648	0 332
+ 0 992	0 221
+ 0 243	0 143
+ 0 043	0 129
- 0 051	0 162
- 0 258	0 296
- 0 301	0 317
- 0 450	0 362
- 0 660	0 422
- 0 789	0 448
- 0 942	0 473
- 1 092	0 491

7 A 1 SECT AA N 3 PLCS WAS N, S 3 PLCS WAS S
2 SECT BB: ADDED .062 REF, .092 REF WAS .06 REF
3. .250 R MAX WAS
.250 R MAX WAS
.250 R MAX WAS
4 .250 R MAX WAS
.250 R MAX WAS
5 .3125 DIA THRU WAS DRILL N (.295) THRU

10 B 1 ADDED OM (TRUE)
2 ADDED .375 N PLCS (2 PLCS)

8 CONTOUR TO BE A SMOOTH CURVE BETWEEN POINTS CODED
7 ALL FILLET R DESIGNED MAX TO HAVE A MIN R OF .060
6 MAY BE EDM FABRICATED IF 32 RMS FINISH IS MAINTAINED ON ALL EDM SURFACES
5 MILD CLEAN PER
4 CONTOUR TO BE STRAIGHT BETWEEN POINTS CODED A
3 IDENTIFY PER EXCEPT DO NOT IMPRESSION STAMP
2 ALL FILLET RADII
1 MACHINE PER

Figure 21. Outer Back-Up Structure

FOLDOUT FRAME 5

of 1590 Inconel 625 tubes. These tubes had a wall thickness of 0.13 mm (0.005 inch) and were tapered from 2.79 mm (0.110 inch) OD at the transition joint down to 1.78 mm (0.070 inch) OD at the nozzle base manifold. The hot-gas-side transition ring was made of OFHC copper while the cold-gas side was made of Inconel 625, as was the base manifold.

The coolant tubes were assembled on a brazing fixture, alloyed, and then furnace brazed.

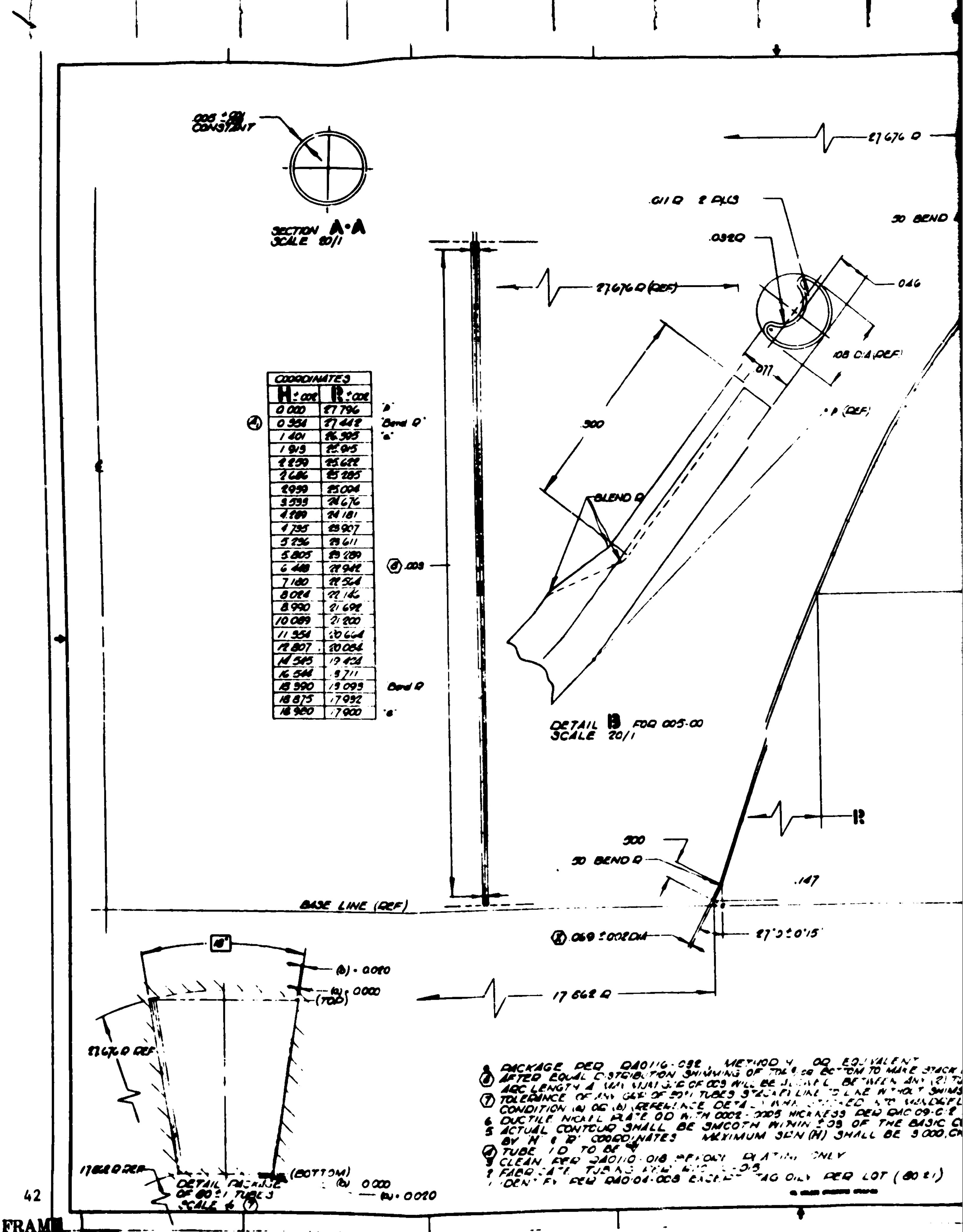
The nozzle tube dimensions are shown in Fig. 22 .

Following machining, the nozzle assembly was welded to a base closure assembly at the welding lip of the base manifold. A design drawing of the base closure assembly is presented in Fig. 23 . The base closure assembly was a thin-shell pressure vessel configuration consisting of two 0.10 mm (0.0)4 inch) waffled 347 CRES sheets joined together by rivets to form a double-walled dome. The small base bleed flow 0.045 kg/s (0.10 lb/sec) is ducted into the cavity between the two walls and then discharged uniformly into the dome base region through bleed holes.

Final Thrust Chamber Assembly

The final thrust chamber assembly consisted of the combustor subassembly, nozzle-base closure subassembly, thrust mount assembly, manifold assembly, and an assortment of brackets, bolts, nuts, etc. The design drawing of the thrust chamber assembly is presented in Fig. 24 , and photographs of the completed assembly are shown in Fig. 10 and 11.

The nozzle-base closure subassembly was joined to the combustor subassembly at the transition joint as shown in Fig. 24. This joint consisted of a wrought NARloy-A-to-OFHC copper TIG braze on the hot-gas side and a 21-6-9 CRES-to-Inconel 625 TIG weld (two places) on the cold-gas side. A small common manifold was utilized to transfer the hydrogen coolant discharge from the 880 channels in the combined 24 combustor segments into the 1590 nozzle tubes.



COORDINATES		
H ±.002	R ±.002	
0.000	27.796	"D"
0.354	27.442	"Bend R" ④
1.401	26.395	"a"
1.919	25.915	
2.259	25.622	
2.686	25.285	
2.959	25.094	
3.539	24.676	
4.289	24.181	
4.795	23.907	
5.296	23.611	
5.805	23.289	
6.448	22.942	
7.180	22.564	
8.024	22.146	
8.990	21.692	
10.089	21.200	
11.354	20.664	
12.807	20.084	
14.545	19.434	
16.544	18.711	
18.390	18.093	Bend R
18.875	17.932	
18.980	17.900	"e"

8 PACKAGE PER QA0116-032, METHOD 4 OR EQUIVALENT
⑧ AFTER EQUAL DISTRIBUTION SHIMMING OF TOP & BOTTOM TO MAKE STACK
ARC LENGTH A MAXIMUM GAP OF .003 WILL BE ALLOWABLE BETWEEN ANY (2) TU
ARC LENGTH A MAXIMUM GAP OF .003 WILL BE ALLOWABLE BETWEEN ANY (2) TUBES STACKED LINE TO LINE WITHOUT SHIMS
⑦ TOLERANCE OF ANY GAP OF 80±1 TUBES STACKED LINE TO LINE WITHOUT SHIMS
CONDITION (a) OR (b) REFERENCE DETAIL ... AT MANDREL
6 DUCTILE NICKEL PLATE OD WITH .0002-.0005 THICKNESS PER QAC 09-012
5 ACTUAL CONTOUR SHALL BE SMOOTH WITHIN ±.03 OF THE BASIC C
BY 'H' & 'R' COORDINATES. MAXIMUM SPAN (H) SHALL BE 3.000, CH
④ TUBE ID TO BE ④
3 CLEAN PER QA0110-018 BEFORE PLATING ONLY
2 FABRICATE TUBING PER ... .015
1 IDENTIFY PER QA0104-008 EXCEPT TAG ONLY PER LOT (80±1)

DOUT FRAM

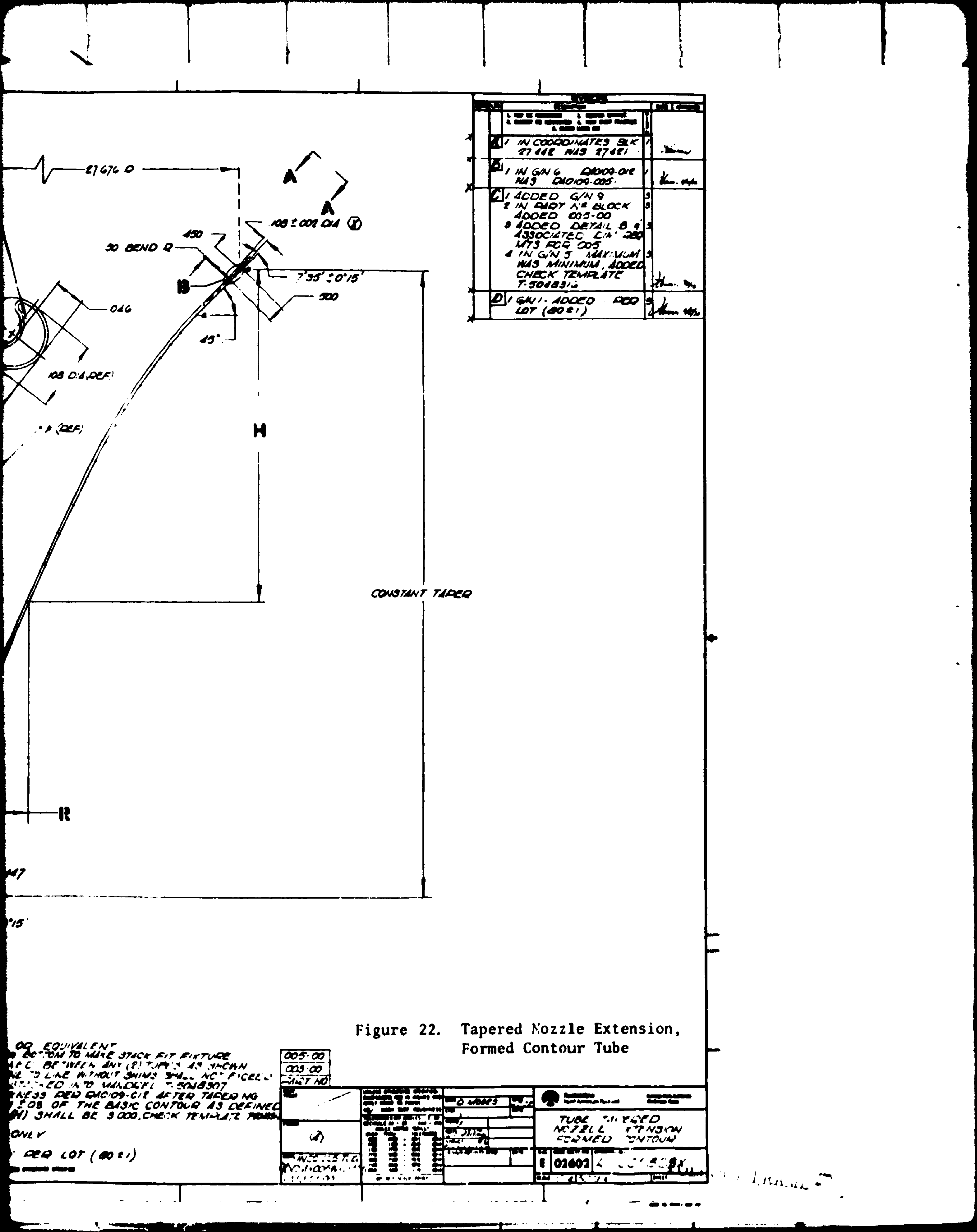
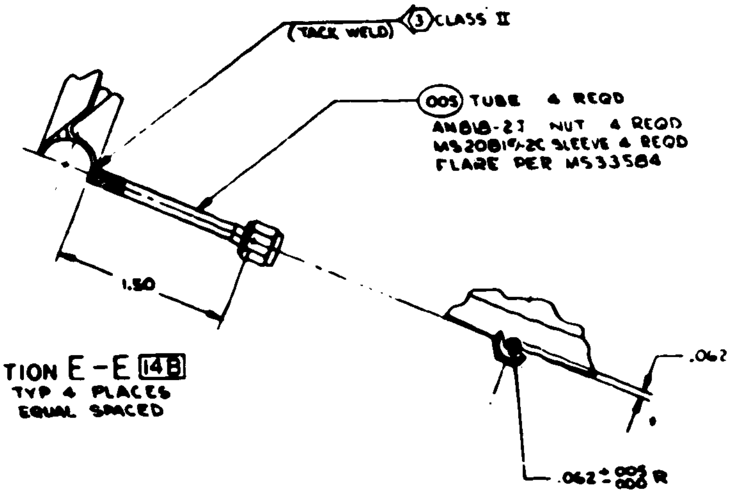
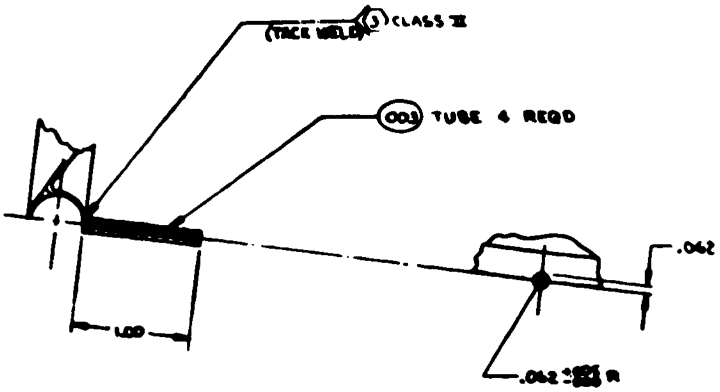


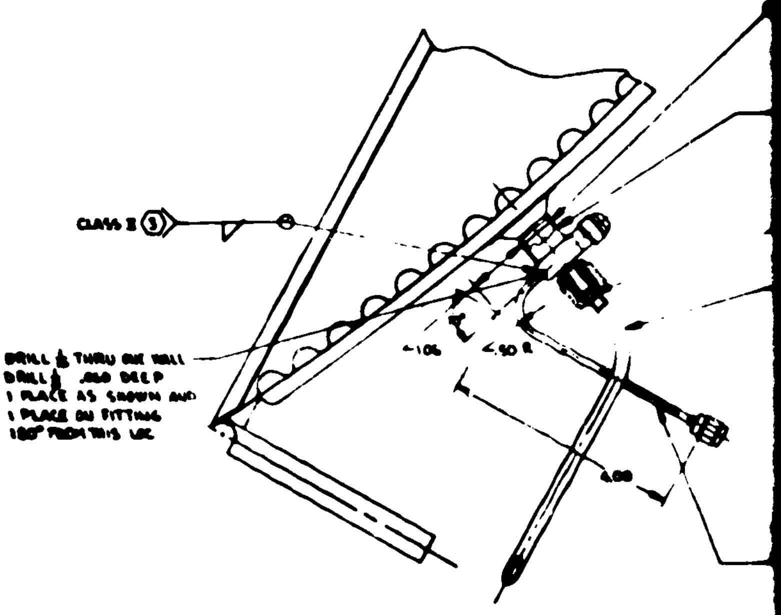
Figure 22. Tapered Nozzle Extension, Formed Contour Tube



SECTION E-E 14B
TYP 4 PLACES
EQUAL SPACED

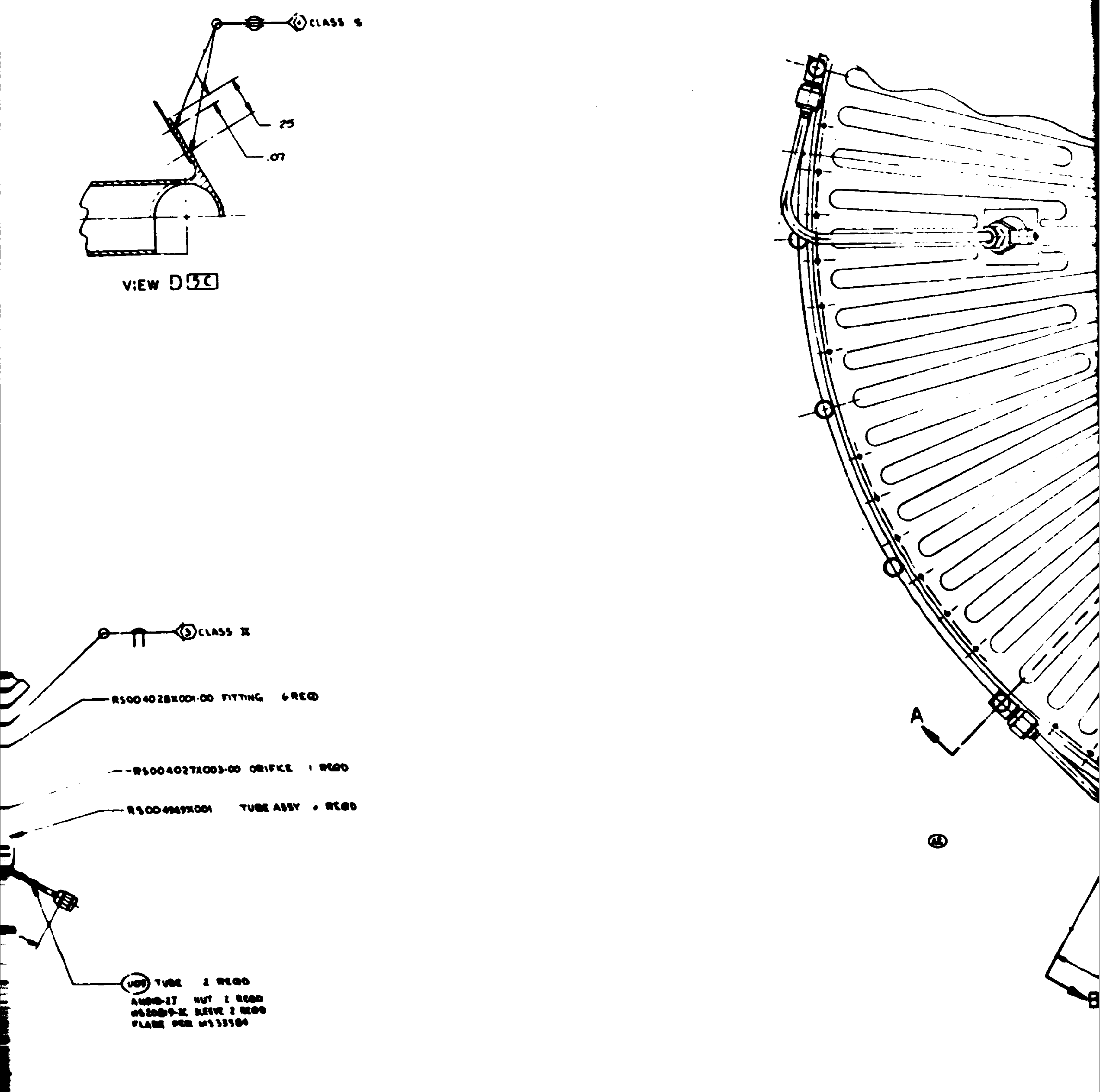


SECTION C-C 13B
TYP 4 PLACES
EQUAL SPACED



SECTION B-B 14B
TYP 6 PLACES

LDOUT FRAME 1



OUT FRAME 2

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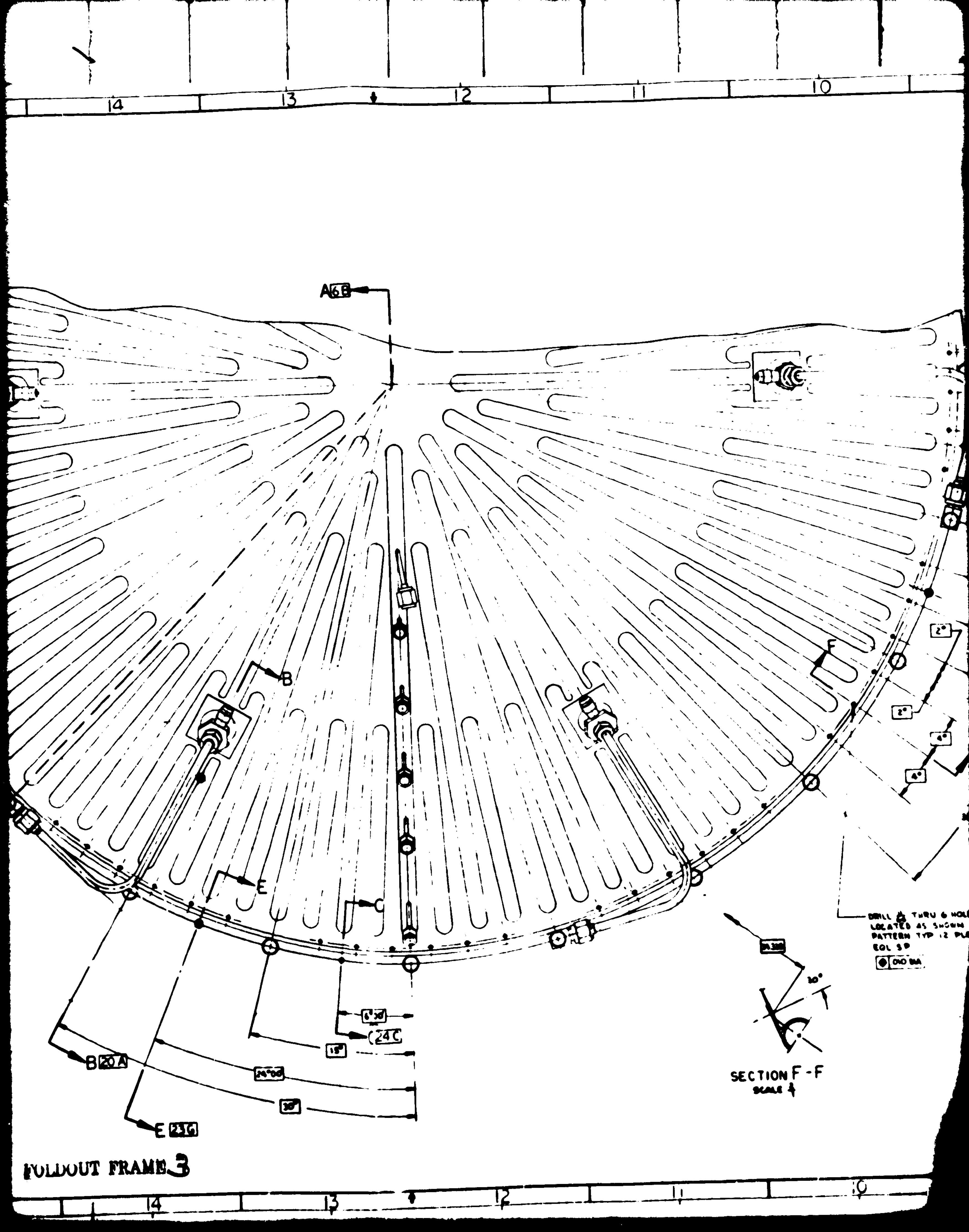
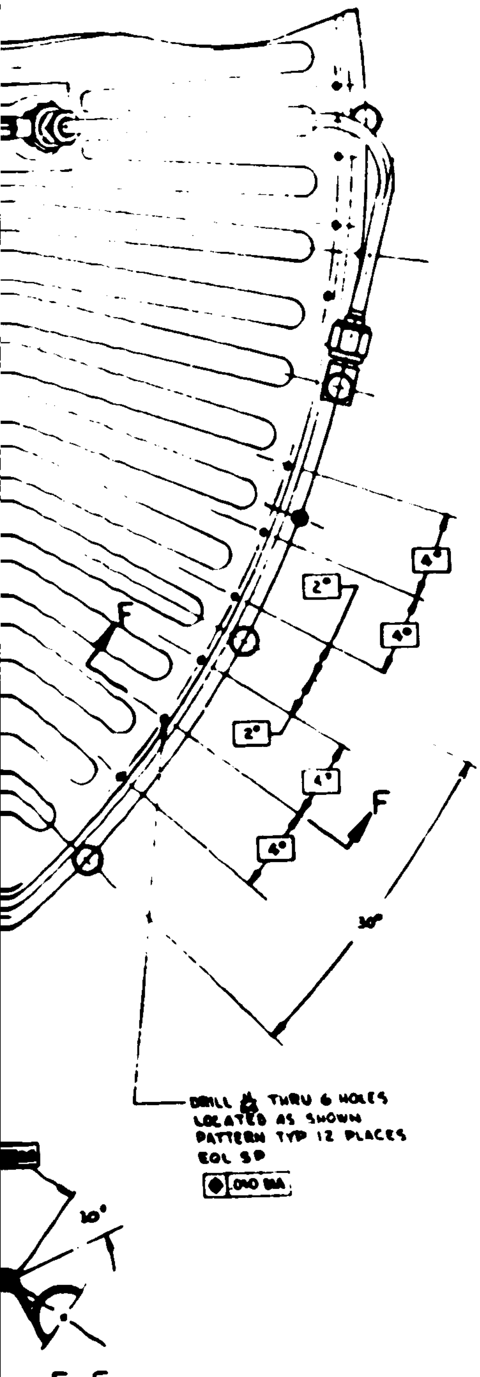
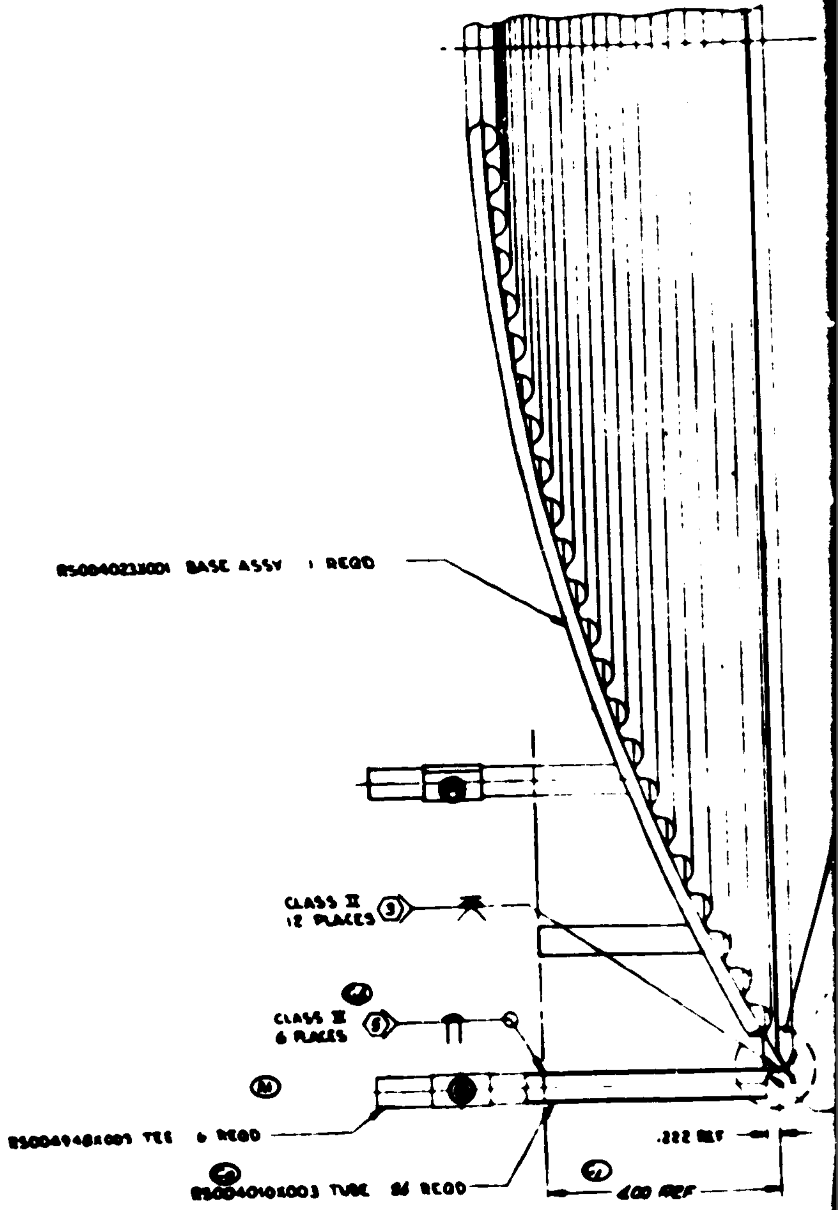


FOLDOUT FRAME 3



ON F-F



SECTION A-A 14 R

FOLDOUT FRAME

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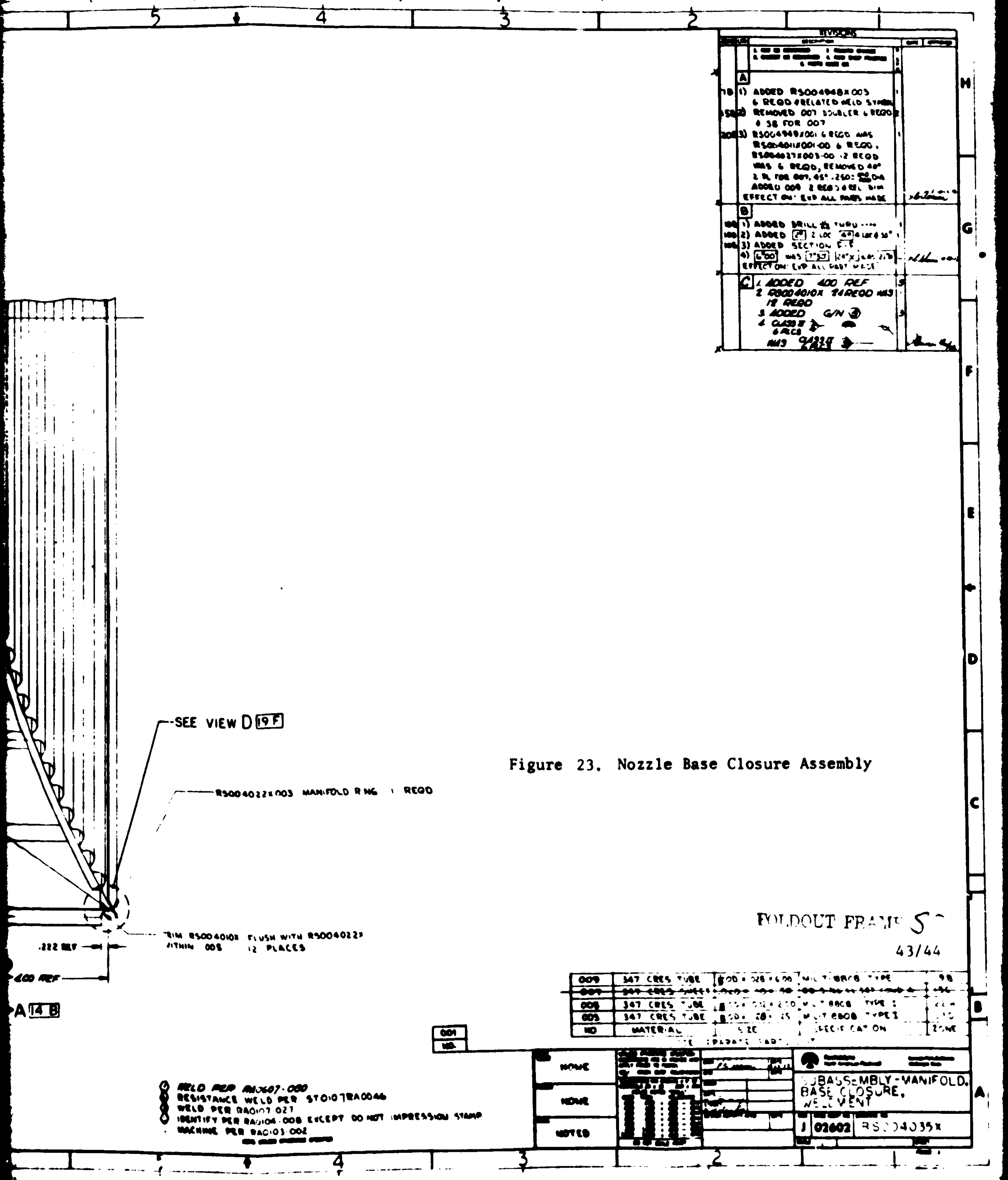
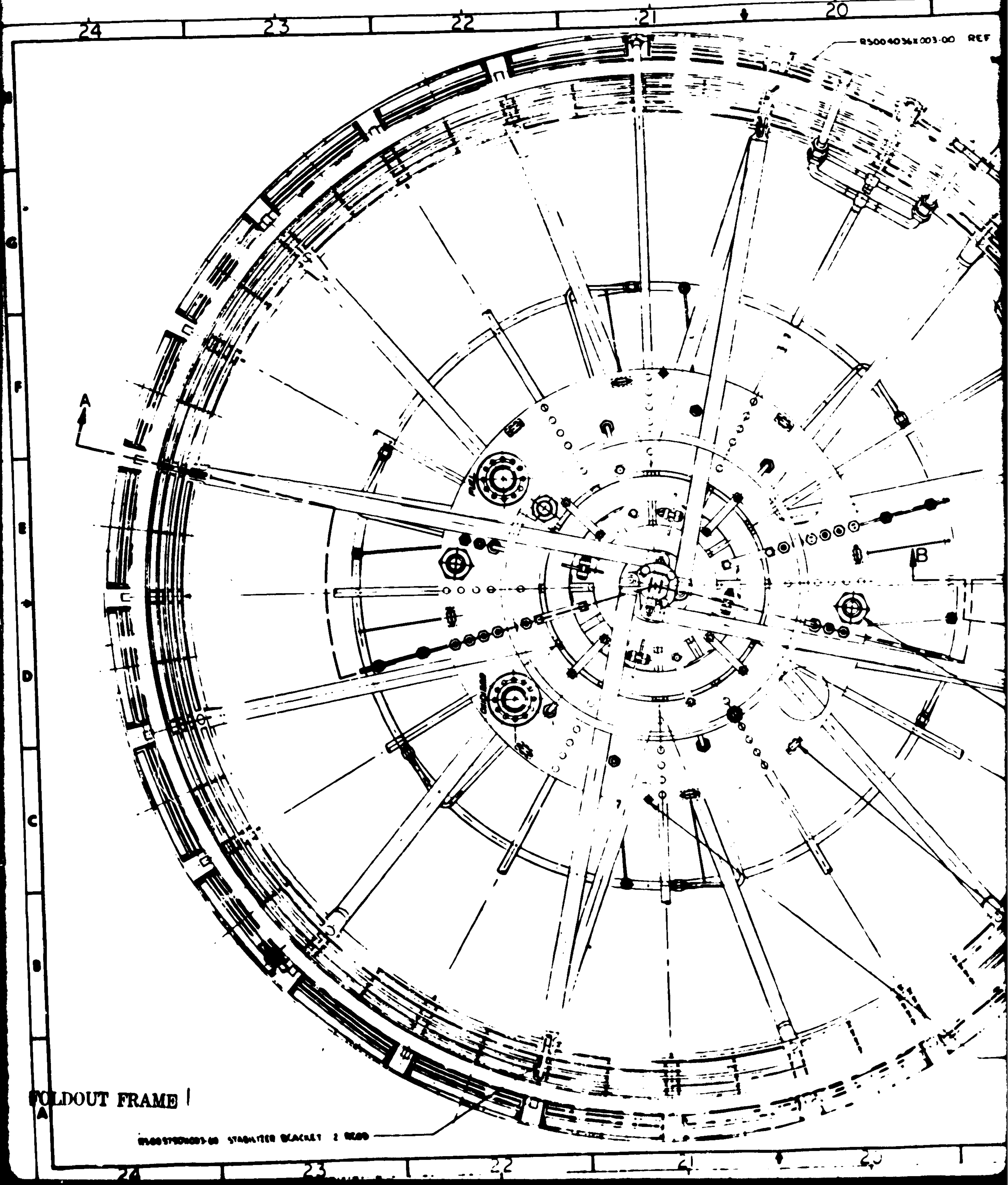
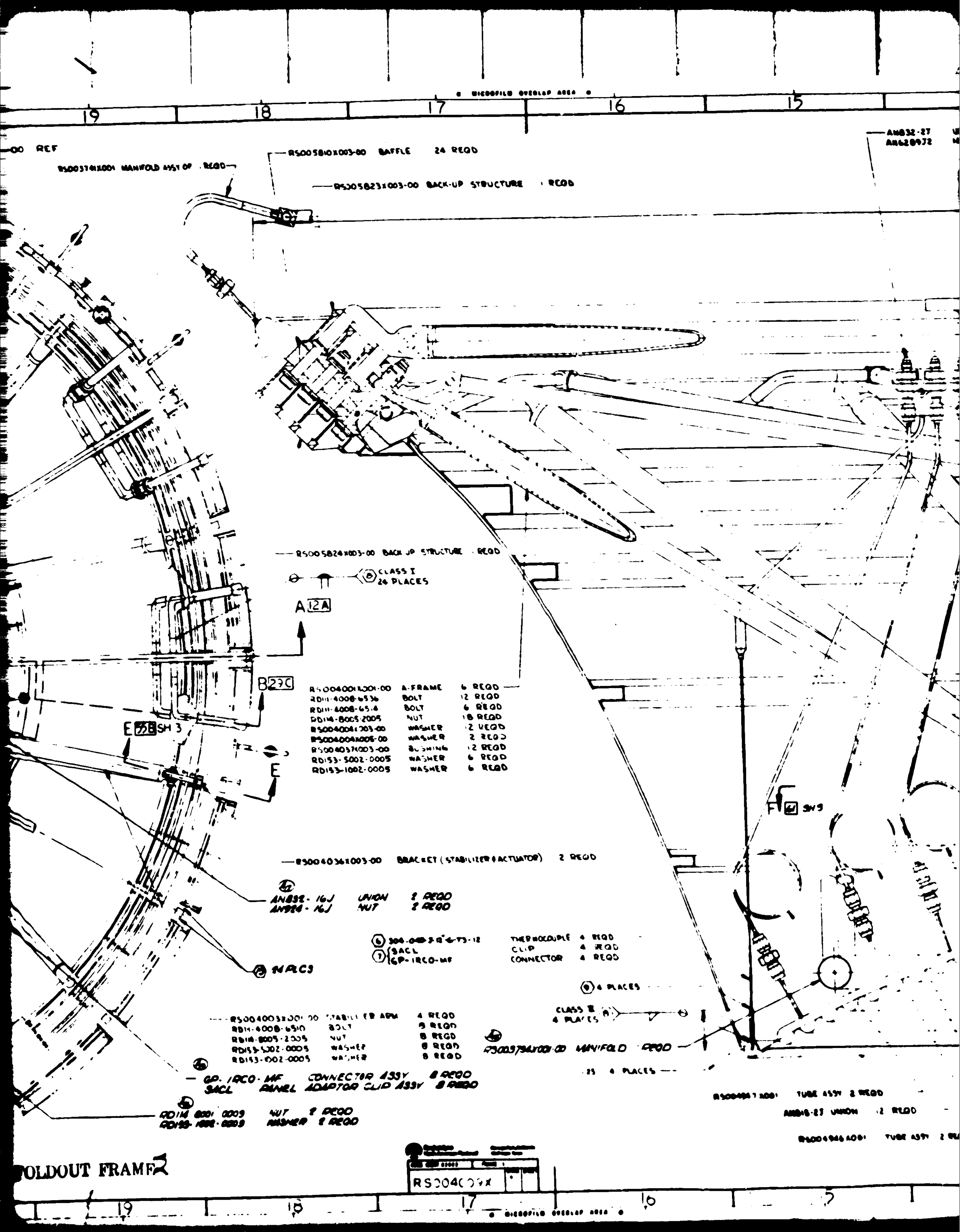


Figure 23. Nozzle Base Closure Assembly

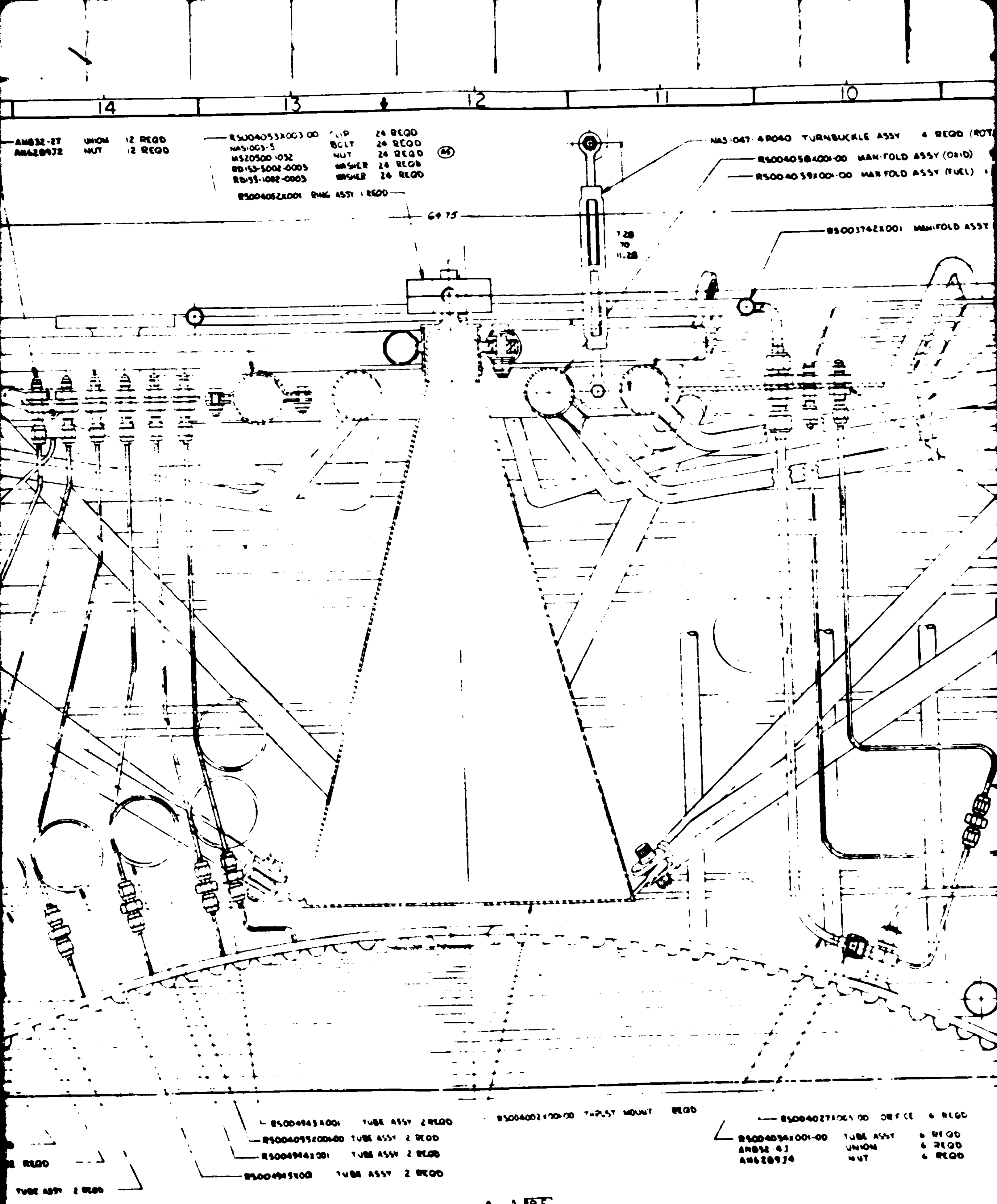
FOLDOUT FRAME 5



FOLDOUT FRAME 1

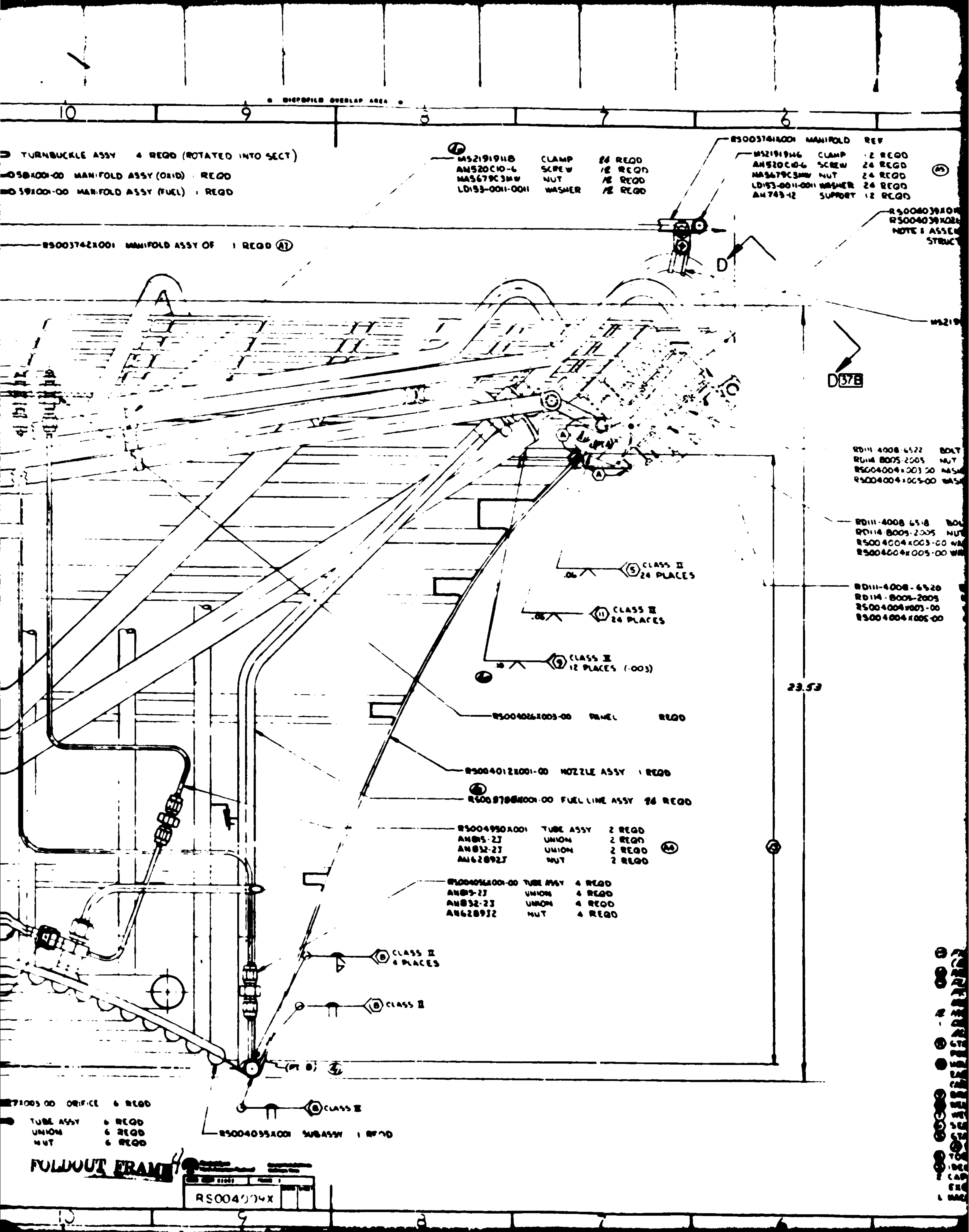


FOLDOUT FRAME 2



SECTION A-A 18F
SCALE 1/4

FOLDOUT FRAME 3



FOLDOUT FRAME

(A1)

01011-00 COMBUSTOR ASSY OF 12 REQD
01021-00 COMBUSTOR ASSY OF 2 REQD (A2)
ASSEMBLE COMBUSTORS & BACK-UP
STRUCTURES BEFORE WELDING & MACHINING

-MS21919WB CLAMP 12 REQD (A3)

BOLT 24 REQD (4)
NUT 24 REQD
00 WASHER 24 REQD
00 WASHER 24 REQD

BOLT 24 REQD (4)
05 NUT 20 REQD
3-00 WASHER 24 REQD
3-00 WASHER 20 REQD

26 BOLT 36 REQD (4)
05 NUT 92 REQD
-00 WASHER 36 REQD
-00 WASHER 92 REQD

REVISIONS

A

1) ADDED SHT 3 DEPICTING REQMTS FOR NOZZLE SUPPORT HARDWARE
SHA 2) RS004039R011-00 & 021-00 BCT-2 REQ WAS RS004048R021-00
3) ADDED RS005741 1 REQD & RELATED SUPPORT HARDWARE
6C 4) ADDED RS004950 2 REQD & RELATED SUPPORT HARDWARE
5) RS004055 4 REQ NOW 24 REQD WAS 12 REQD
6) RS004903 WAS RS004055
RS004904 WAS RS004055
RS004905 WAS RS004055
RS004906 WAS RS004055
RS004907 WAS RS004055
7) ADDED RS005742 1 REQD
8) ADDED REV OF SHT STATUS B.C.
8 9) RS009795X 24 REQD WAS RS004057X 12 REQD
8 10) MS9099WB 64 REQD WAS 48
AN960C10-6 12 REQD WAS 24
MS9 12 REQD WAS 24
LD 12 REQD WAS 24
11) ADDED PT A & PT B
12) (2) WAS
4 13) RD1-8005-1005 20 REQD WAS
RS 21 REQD WAS
RS 20 REQD WAS 24
14) RD1-8005-1005 92 REQD WAS 9
RS 92 REQD WAS 9
15) ADDED RS009794X 1 REQD
16) ADDED RD1-8001-0108 2 REQD
RD95-1001-0005 2 REQD
17) ADDED AN960-16J 2 REQD
AN924-16J 2 REQD
5 18) IN GN4 - 175 IN LBS WAS 190
19) ADDED GP-IRCO-MF 6 REQD
SACL 6 REQD

A	A	A
SH 3	SH 2	SH 1

REVISION STATUS OF SHEETS

FILL WITH DC93-1C PER ENGRG INSTRUCTIONS, NO PRIMER (BONDING AGENT) REQD
WELD PER RA0607-050
PLASMA COAT EXT OUTSIDE SURFACE FROM PT A TO PT B PER ENGRG INSTRUCTIONS AS FOLLOWS UNDERCOAT MO -.0006 MODIFIED COAT 70% ZrO₂ 30% MO .0004; TOPCOAT ZrO₂ .0005
12 HYDROSTATIC PRESS TEST TO 2500 ± 30 PSIG USING DEIONIZED WATER, HOLD FOR 2 MINUTES. LEAKAGE ALLOWANCE TO BE DETERMINED BY ENGRG
(11) GTA BRAZE ADJACENT COMBUSTORS TOGETHER AFTER POINT 'D' HAS BEEN DETERMINED (SEE NOTE 10)
HOLD DIA AT POINT 'D' 592) IF MIN WALL THKNS (.030) OF EACH COMBUSTOR CAN BE MAINTAINED. IF THIS CONDITION CAN NOT BE HELD, DIA POINT 'D' MAY BE ADJUSTED
BRAZE PER ENGR (5.24) & M/P INSTRUCTIONS
WELD PER RA0107-02
WEST KENSINGTON EN,
SEMCO INC., NO HOLLYWOOD, CALIF.
GTA BRAZE ADJACENT COMBUSTORS TOGETHER IN AREA (A) PER RA0107-027 EXCEPT USE RA0110-064 NIORO FILLER
TORQUE TO 175 ± 5 LB
IDENTIFY PER RA0-008
CAP AND PLUG STAND PORT PER RA0106-054 EXCEPT DO NOT USE PLASTIC CAPS
MACHINE PER RA0103

FOLDOUT FRAME 2

Figure 24. Thrust Chamber Assembly

009-00	INCONEL 625 BAR	— —	AMS5666	17 E
NO	MATERIAL	SIZE	SPEC	ZONE

001-00
NO.

NONE

NONE

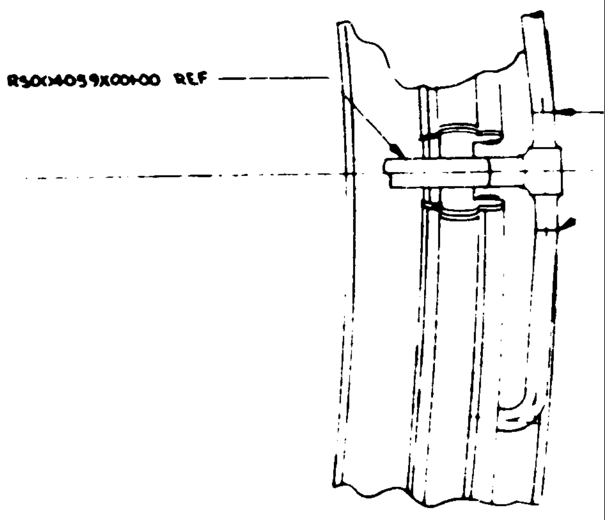
NOTED

THRUST CHAMBER ASSY, 2K AERO

J 02602 A0 98

48 47 46 45 44

H G F E D C B A

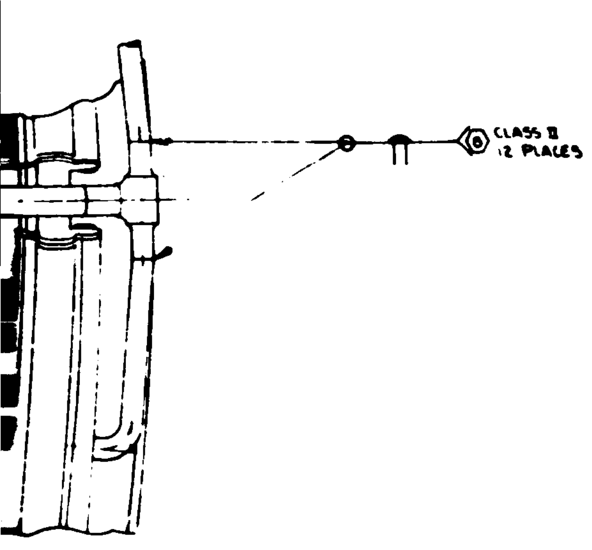


SECTION D-D 6G

48 47 45 44

MICROFILM OVERLAP AREA

43 42 41 40 39

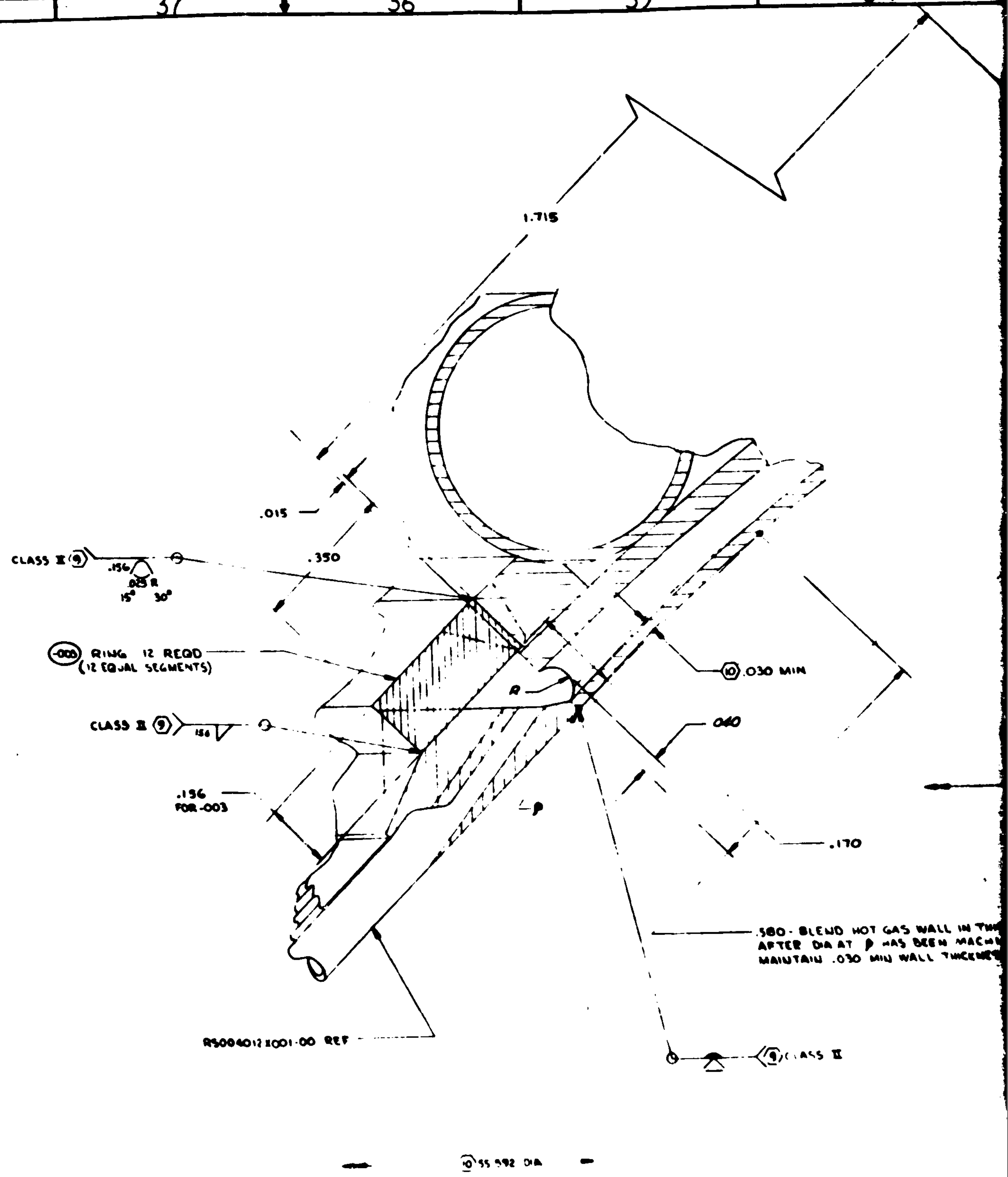


D-D 6G

FOLDOUT FRAME 2

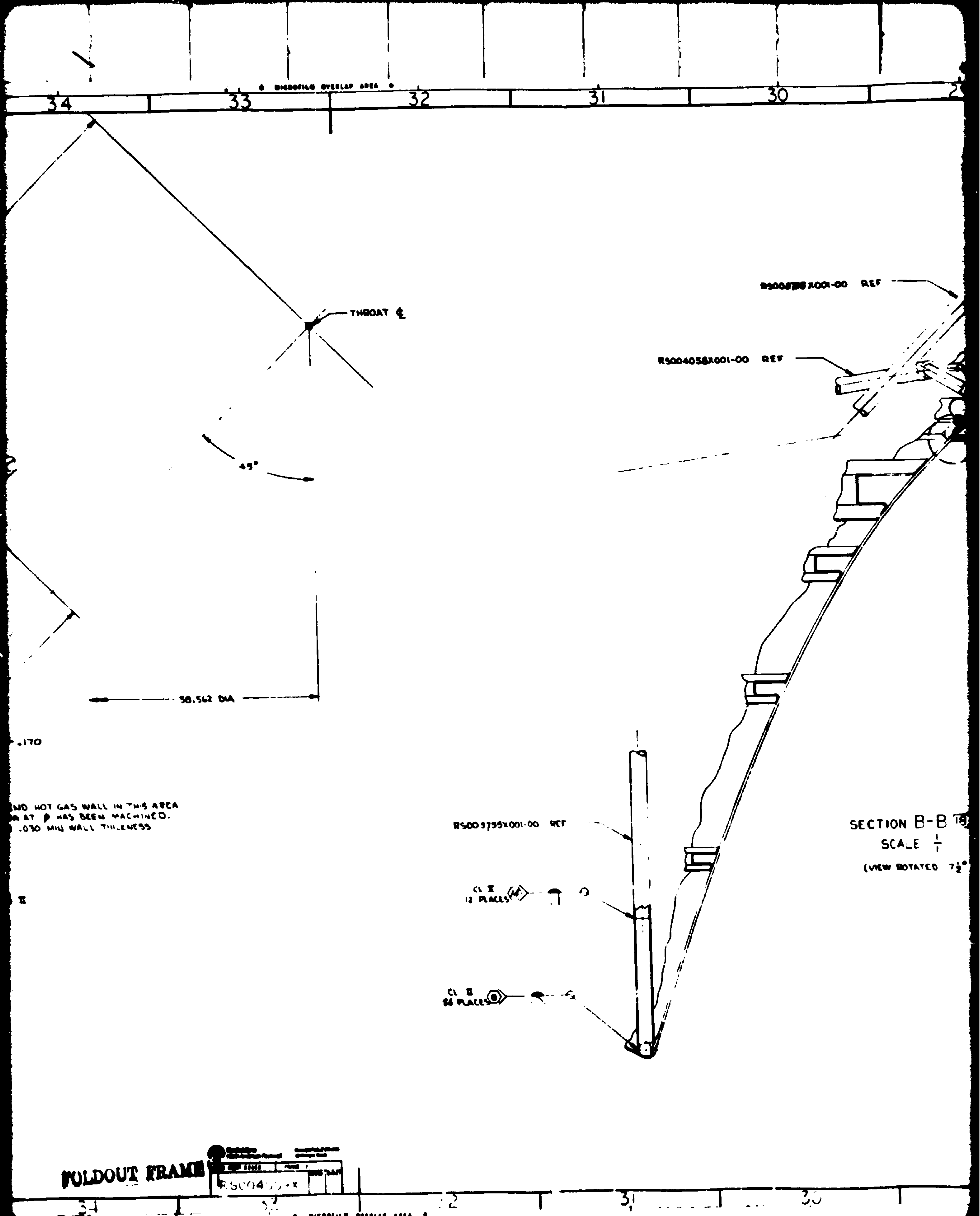
PS0040

43 42 41 40 39



VIEW C 28E
SCALE 4

FOLDOUT FRAME 3



FOLDOUT FRAME

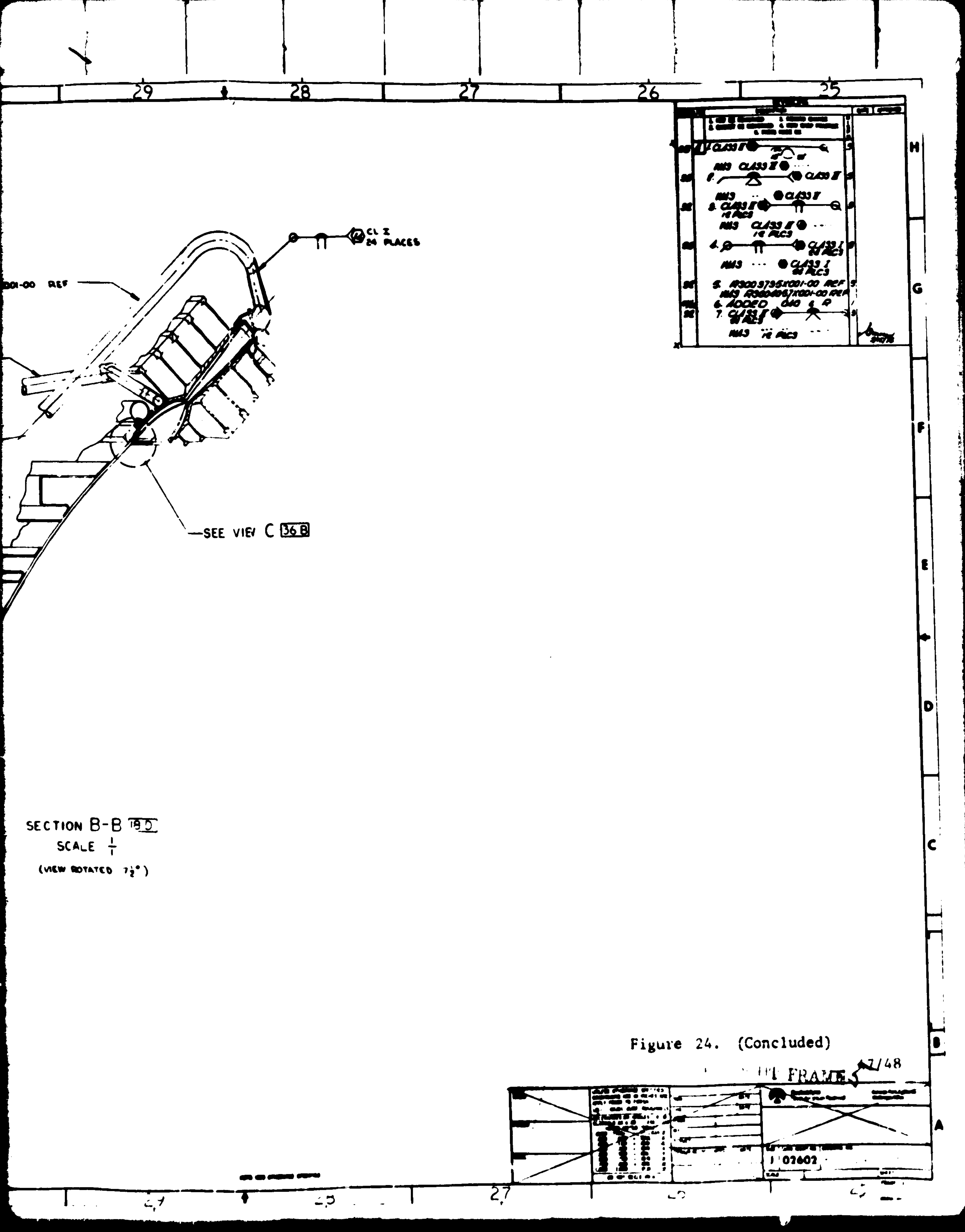


Figure 24. (Concluded)

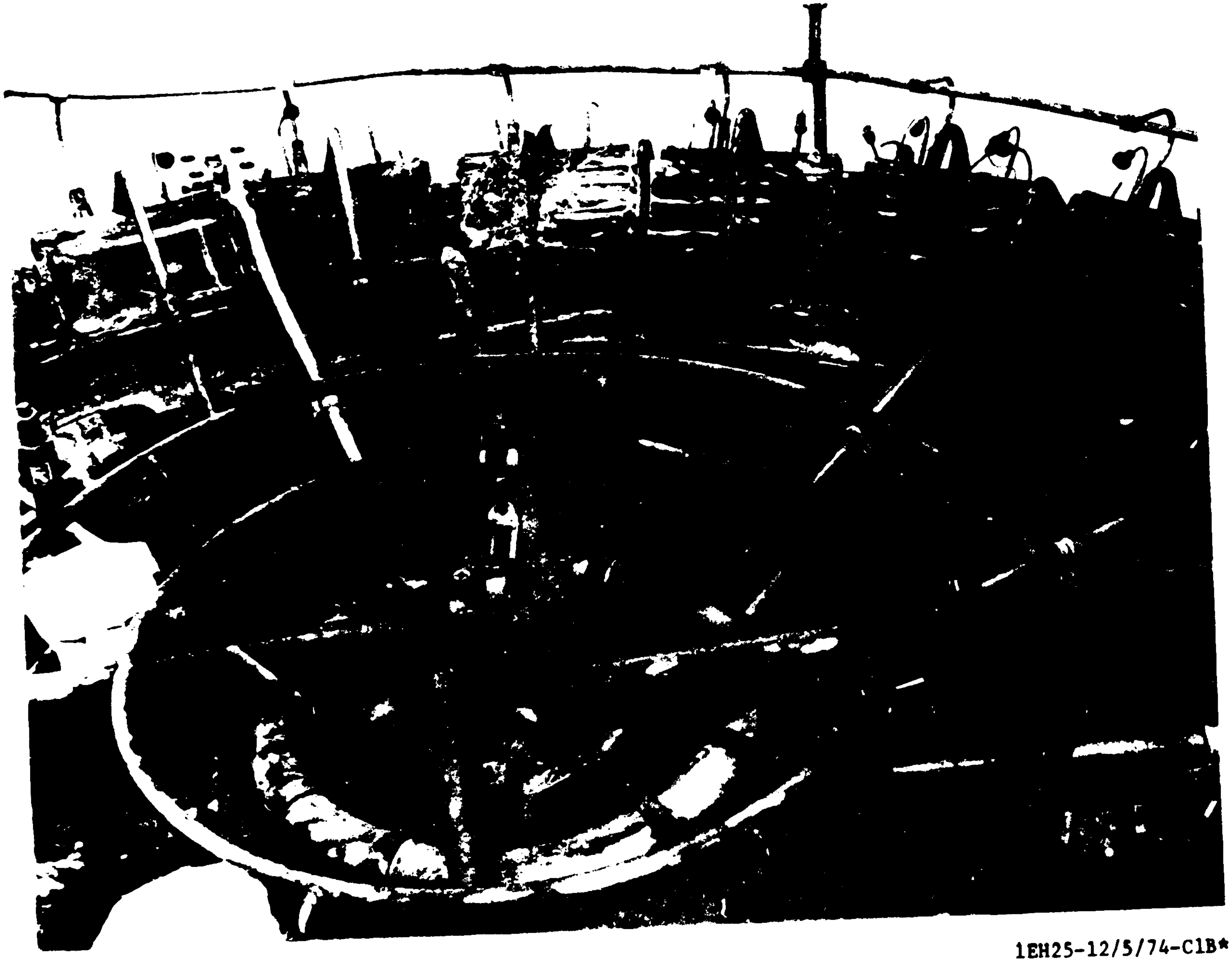
THRUST CHAMBER DAMAGE

This section contains a description of the damage that was incurred by the thrust chamber during test 74-005, the last test firing conducted on Air Force contract F04611-67-C-0116, and of the repair efforts to the thrust chamber that were conducted under the auspices of the U. S. Air Force. A photo of the interior of the thrust chamber assembly after the fire is shown in Fig. 25.

The damage incurred during test 74-005 may be cataloged as follows:

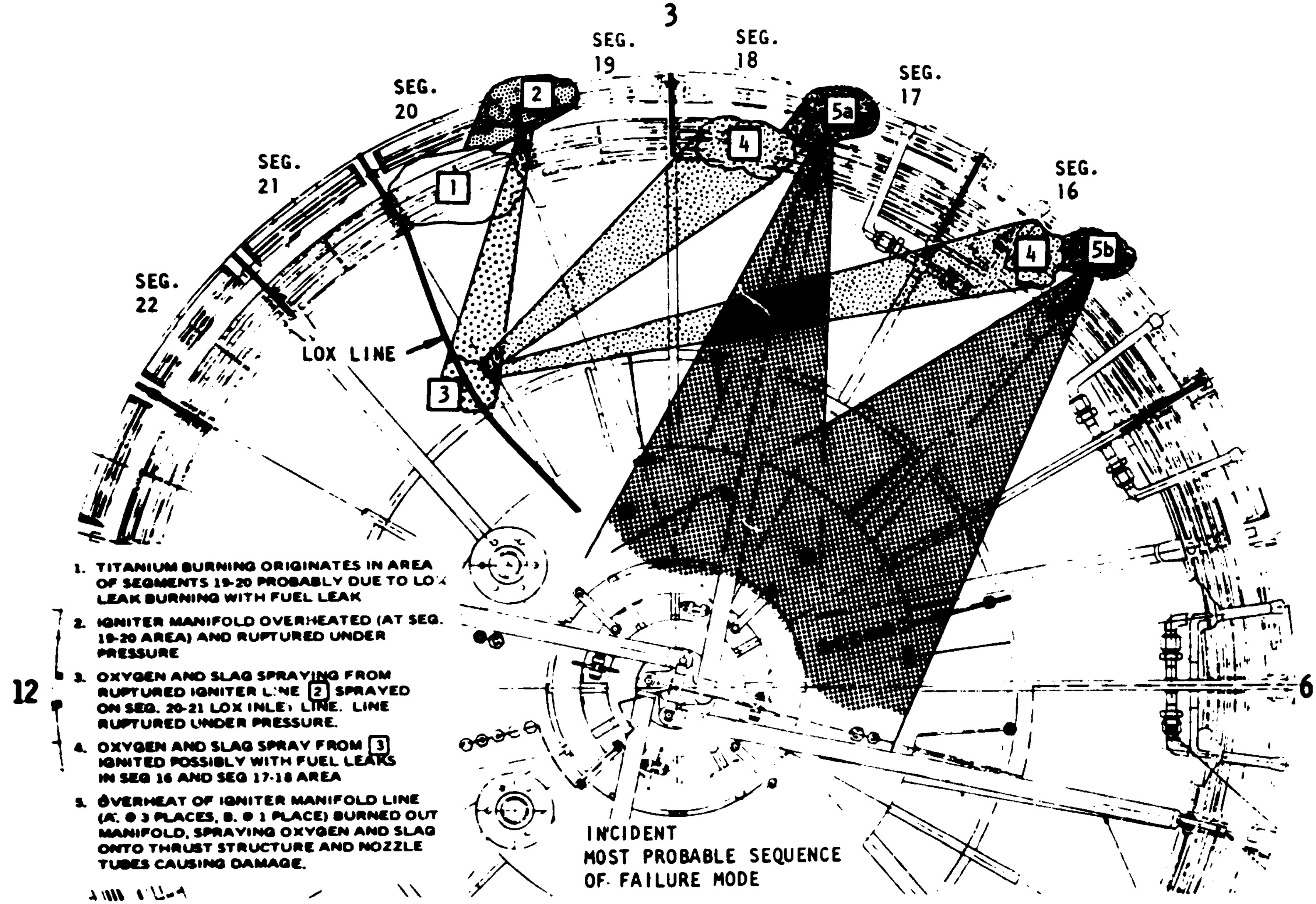
- Five combustors, at locations No. 16 through 20 of Fig. 26, sustained such severe fire damage that they could not be used.
- Approximately one-quarter of the titanium inner backup ring was burned away
- Two small areas of the outer titanium backup ring were sufficiently burned to require metal replacement
- The ignition manifold and the propellant feedlines were burned so as to require approximately 50% replacement
- Components of the thrust mount, i.e., some of the struts and the central cone, suffered burn damage. Some parts required complete replacement and others required repair of damaged areas.
- Approximately 30% of the 1590 nozzle tubes had small areas burned away on the cold side, resulting in leaks in the burned areas
- All of the instrumentation, wiring, and pressure connections were destroyed

After a period of damage assessment, it was determined that all of the damage was repairable. The modular nature of the combustor segments permits the removal of damaged segments, their repair, and replacement. The backup structure and thrust mount components are bolted on, so may be removed for repair and/or replacement. The ignition and propellant feed manifolding is readily accessible for repair and replacement. Finally, a company-sponsored nozzle tube repair program had demonstrated that excellent nozzle tube repairs were feasible, and could return the nozzle to a fireable condition.



1EH25-12/5/74-C1B*

Figure 25. Thrust Chamber Assembly After Fire



1. TITANIUM BURNING ORIGINATES IN AREA OF SEGMENTS 19-20 PROBABLY DUE TO LOX LEAK BURNING WITH FUEL LEAK
2. IGNITER MANIFOLD OVERHEATED (AT SEG. 19-20 AREA) AND RUPTURED UNDER PRESSURE
3. OXYGEN AND SLAG SPRAYING FROM RUPTURED IGNITER LINE 2 SPRAYED ON SEG. 20-21 LOX INLET LINE. LINE RUPTURED UNDER PRESSURE.
4. OXYGEN AND SLAG SPRAY FROM 3 IGNITED POSSIBLY WITH FUEL LEAKS IN SEG 16 AND SEG 17-18 AREA
5. OVERHEAT OF IGNITER MANIFOLD LINE (A. @ 3 PLACES, B. @ 1 PLACE) BURNED OUT MANIFOLD, SPRAYING OXYGEN AND SLAG ONTO THRUST STRUCTURE AND NOZZLE TUBES CAUSING DAMAGE.

Figure 26. Failure Mode Sequence Schematic

THRUST CHAMBER DISASSEMBLY AND REPAIR

DISASSEMBLY

A photograph of the interior of the 111 kN (25K) aerospike thrust chamber is shown in Fig. 27. It is possible to identify on the photograph many of the elements that go to make up the thrust chamber assembly, i.e., the nozzle, the combustors, the inner and outer backup rings, the support structure which carries the thrust from the backup rings to the central gimbal point; the fuel, oxygen, and ignition manifolding; and the instrumentation hookups. Some disassembly effort was funded under the previous Air Force contract and it had been mostly accomplished at the start of the subject NASA contract. The disassembly had made it clear that it would be necessary to refurbish or replace five of the combustors, the inner and outer backup rings, certain other components of the thrust structure, the interior of the nozzle and many of the components of the manifolding.

COMPONENT REPAIR OR REPLACEMENT

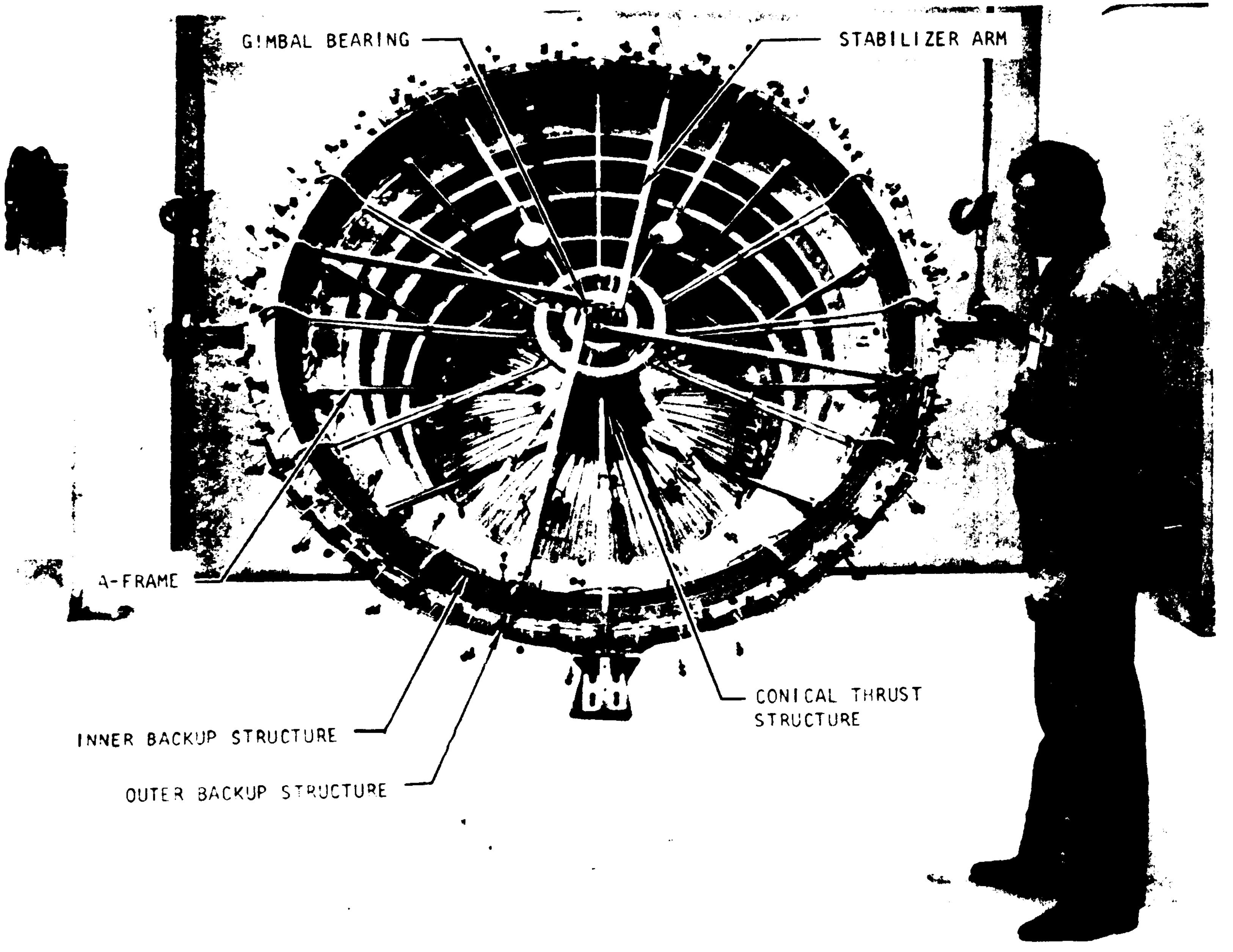
The nature of the aerospike thrust chamber assembly is such that it is possible to effect repairs by replacing damaged components with functional components, i.e., individual components are readily replaced without seriously disturbing the adjacent components. However, where assembly is by brazing or welding, it is necessary to cut the damaged component out, and this may render it unsuitable for further use. The repair and replacement effort is described, by component, in the material below.

COMBUSTOR REPAIR

Background

During the disassembly and inspection of the damaged thrust chamber assembly, it was determined that 5 of the 24 combustors had been so severly damaged that they needed complete replacement. There were no usable complete spare combustors on hand, but there were a number of combustors that had some usable parts. The major elements of a combustor assembly may be visualized as consisting of the injector assembly, the inner liner (which has both a hydrogen and oxygen cooling circuit), and the outer liner (which has only a hydrogen cooling circuit). These three subassemblies are joined by brazing and welding (there are no bolted joints) into an integral combustor.

The plan devised for combustor replacement involved cannibalization of portions of the existing spare combustors so as to utilize them in combination with portions of other combustors, or with new components, to produce viable combustors suitable for welding in place on the existing thrust chamber assembly. This is believed to be the first time dissection and reassembly of such welded combustors was attempted. It was made possible by the unique fabrication scheme of the 111 kN (25K) aerospike **combustors** which is illustrated in Fig. 28.



1EH32-5/28/74-CIE*

Figure 27. Thrust Chamber Assembly With Thrust Mount Components

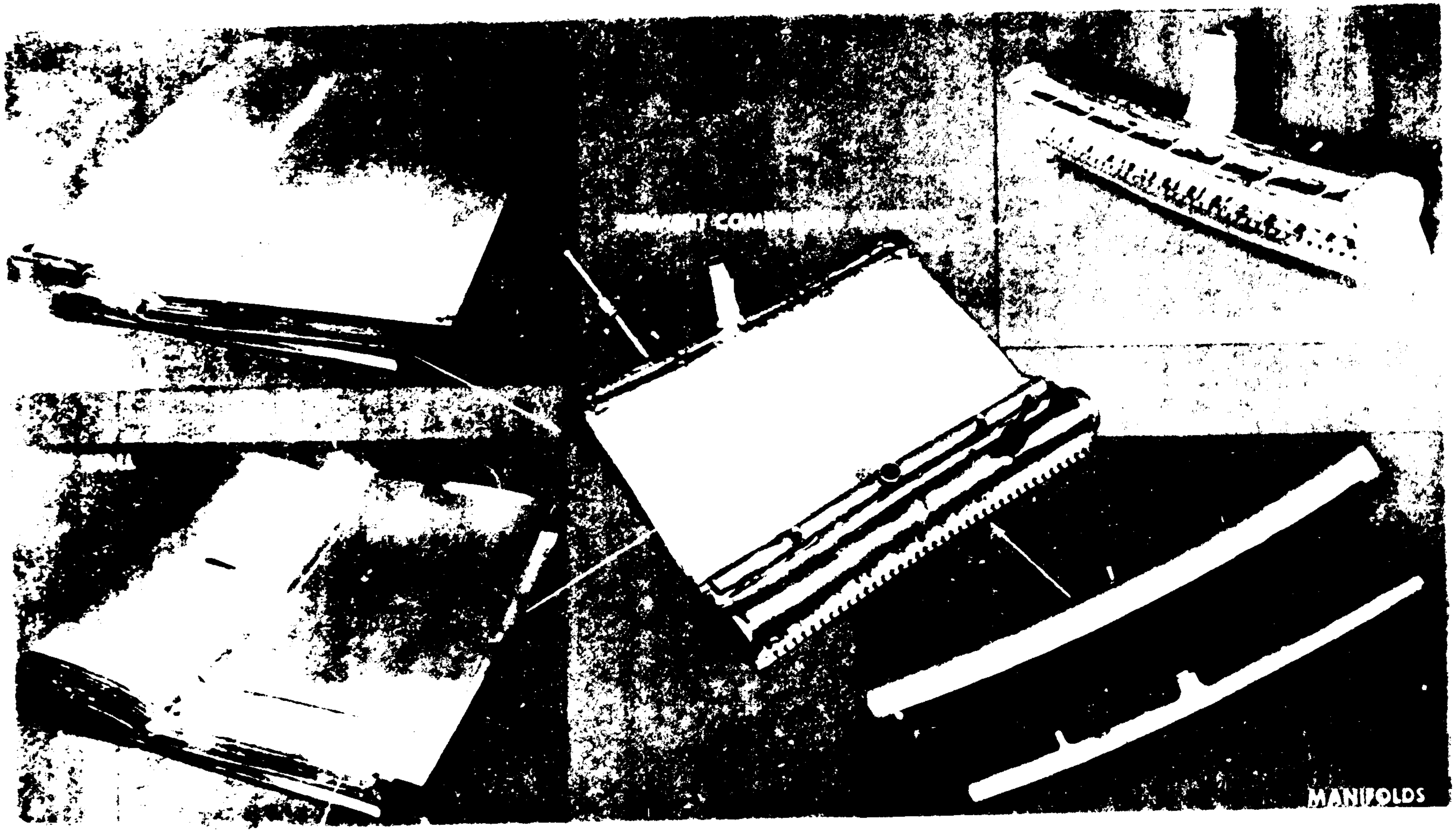


Figure 28. Segment Combustor Fabrication

Work was begun on the fabrication of five combustors, so as to replace the missing five on the thrust chamber assembly. Table 6 lists the five rebuilt combustors from which the replacements for the assembly were to be selected.

TABLE 6. COMBUSTOR BODY-INJECTOR USAGE

Combustor Segment Identification Unit No.	Injector Unit No.	Inner Liner Unit No.	Outer Liner Unit No.
507R	506	507	507
510R	518	510	510
509R	NEW	New liner, coolant panel, cover sheet and end plates	509
515R	NEW	↓	515
535(N)	NEW		New liner, cover sheet, and end plate

R = rebuilt N = new

Interpropellant Leakage

Experience during the initial fabrication of the combustors had shown occasional leakage between the fuel and oxidizer circuits. On the repair program, a gaseous pressure and leak test on the nozzle and the 19 combustors that remain attached to it was conducted prior to initiating repairs. This leak testing was undertaken to assess the extent of any leakage between the hydrogen and oxygen cooling circuits in each of the 19 combustors. The testing was conducted at this time so as to be able to assess the impact of the conditions found upon the schedule and resources required for the chamber repair and hot-fire test program.

The absence of 5 of the 24 combustors on the existing thrust chamber assembly made it impractical to secure a completely leak-free hydrogen cooling circuit and it was therefore not possible to apply hydrostatic pressure by the conventional means of a high-pressure, very-low-volume capacity positive displacement pump. The procedure followed was to plug off the exit of each of the nozzle tubes by dipping the aft nozzle manifold into a pool of melted paraffin and allowing it to solidify. The hydrogen inlet of each combustor was then connected, in turn, to a supply of gaseous nitrogen at approximately 6 895 kPa (1000 psi). Commercially pure methane in an amount sufficient to provide approximately 1% of weight of methane in the pressurizing nitrogen was added to the pressurant just upstream of the combustor inlet. A low-pressure, pure nitrogen purge was also admitted into the oxygen manifold of the injector of the combustor being tested and was exhausted from the oxygen inlet manifold of that combustor. This nitrogen (being purged through the oxygen circuit) was then routed through a combustibles meter and analyzed for methane content. In this manner, it was possible to measure the amount of nitrogen leakage, if any, between the hydrogen and oxygen circuits of the combustor being tested while the circuits were subjected to the same pressure differential as would exist during firing at rated chamber pressure conditions. On the basis of the measured nitrogen leakage, it was then possible to estimate the amount of hydrogen leakage that would exist under firing conditions. The test procedure was capable of measuring minute leakage in a reproducible manner. The results indicated that none of the combustors had sufficient leakage to cause a local concentration of hydrogen in the oxygen of as much as 5 percent of the flammability limit concentration. It was thereby determined that correction of interpropellant leakage in the 19 existing combustors was unnecessary.

Combustors Using New Inner Liners

Three of the rebuilt combustors were dependent on new inner liners for completion. The necessary new combustor liner details, i.e., hydrogen panels, oxygen panels, oxygen panel cover sheets, etc., to support the combustor fabrication plan of Table 6 were requisitioned early in the program. These details were fabricated both in-house and by outside vendors. Deliveries of the details were completed during the second quarter. The three new inner liner assemblies for units 509R, 515R, and 535, were put through their brazing and assembly cycles. One new outer liner for unit 535 was also successfully put through its brazing cycle. The existing outer liners for units 509R and 515R were reworked to braze in new injector face plates. By mid-June, at which point fabrication effort on this hardware was halted, the inner and outer liners for units 509R, 515R, and 535 had been brought to the point where match machining of the inner and outer liners preparatory to their assembly by brazing could be undertaken. The fabrication of these components was satisfactorily accomplished.

Supporting Combustor Details

In addition to the major parts that go into the inner and outer liners in the injector assemblies, there are a large number of supporting details that go to make up each assembly. These too were released and satisfactorily fabricated by mid-June.

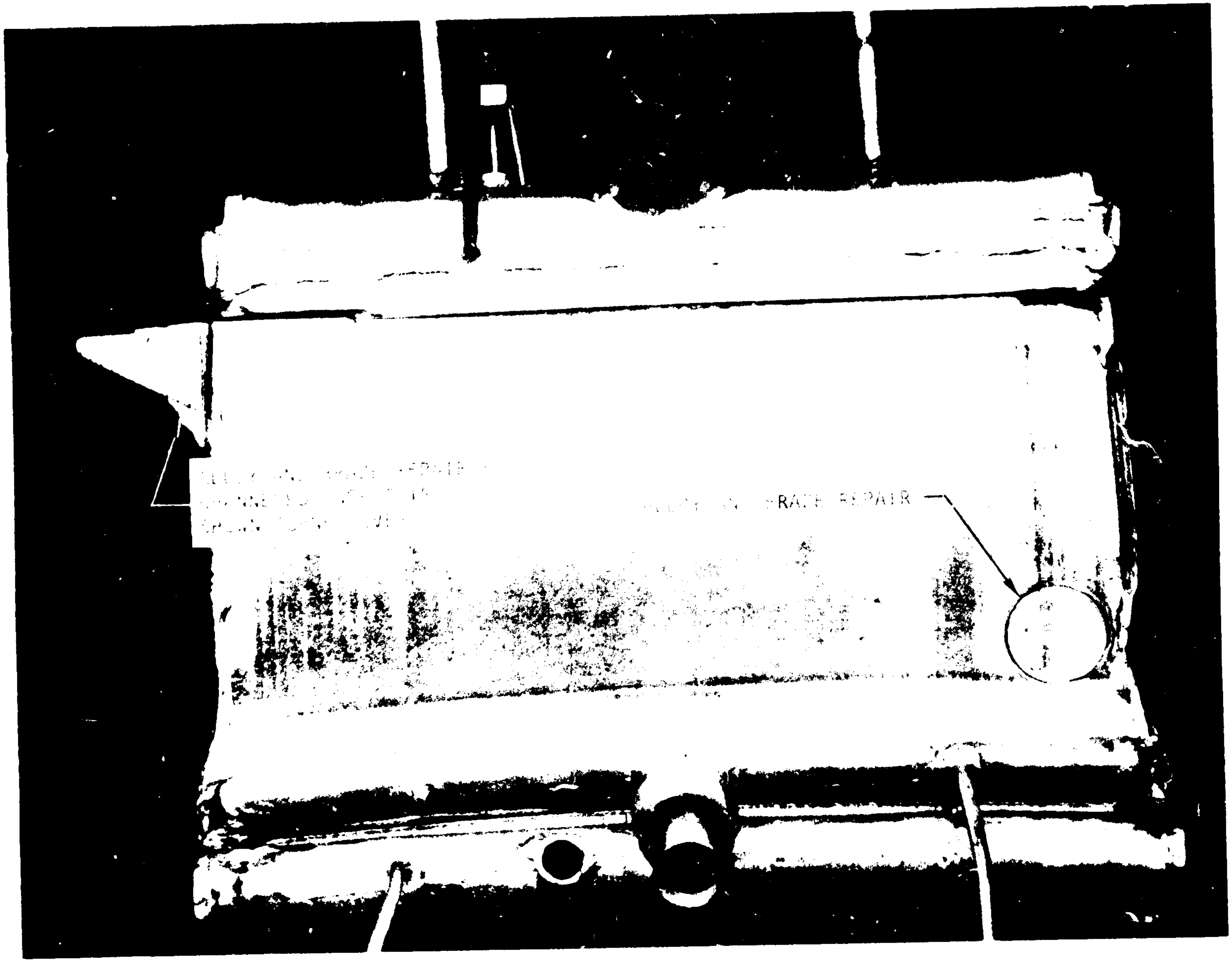
Combustor Units 507R and 510R

These two rebuilt combustors were planned to utilize existing inner and outer liners as indicated in Table 6. They had been partially completed under the sponsorship of the previous Air Force contract. Both of these combustors encountered problems during the first quarter with cover sheet cracking during the final assembly operation on the manifolds of the inner liner. 507R had cracks in the LOX panel cover sheet. 510R developed cracks in the fuel panel closeout sheet between the LOX inlet manifold and the fuel distribution manifold. A repair plan was devised that involved subjecting each combustor to what was intended to be a final furnace braze repair cycle. The metal fitting to prepare for brazing is illustrated in Fig. 29 and 30.

The triangular insert patch of Fig. 29 was successfully brazed to the inner liner of 507R, as illustrated in Fig. 31. However, on hydrostatic pressure test, it was found that a new crack, approximately 50.8 mm (2 inches) long, had occurred just aft of the oxygen outlet manifold on the inner liner LOX cover sheet. A repair to this crack was attempted using TIG brazing with Nioro braze alloy. The repair effort was unsuccessful in that the material cracked at the edge of the fillet formed between the braze alloy and the parent material. Evaluation of this condition indicated that further attempts at TIG braze repairs would likely result in further cracking, so a repair procedure utilizing furnace brazing with the relatively low melting point, "BT" alloy (72% Ag, 28% Cu), was attempted. This final braze repair effort was apparently successful in repairing the crack at the forward joint. 507R was then put through the standard hydrostatic pressure test, which involves a 24 821 kPa (3600 psi) hydrostatic pressure in the fuel side and a 1517 kPa (220 psi) pressure in the oxygen circuit. 507R successfully withstood the fuel side pressure testing without leakage but during the oxygen side pressure testing leakage in the oxygen panel cover sheet was encountered through what appeared to be a series of small cracks in the cover sheet. This condition is illustrated in Fig. 32.

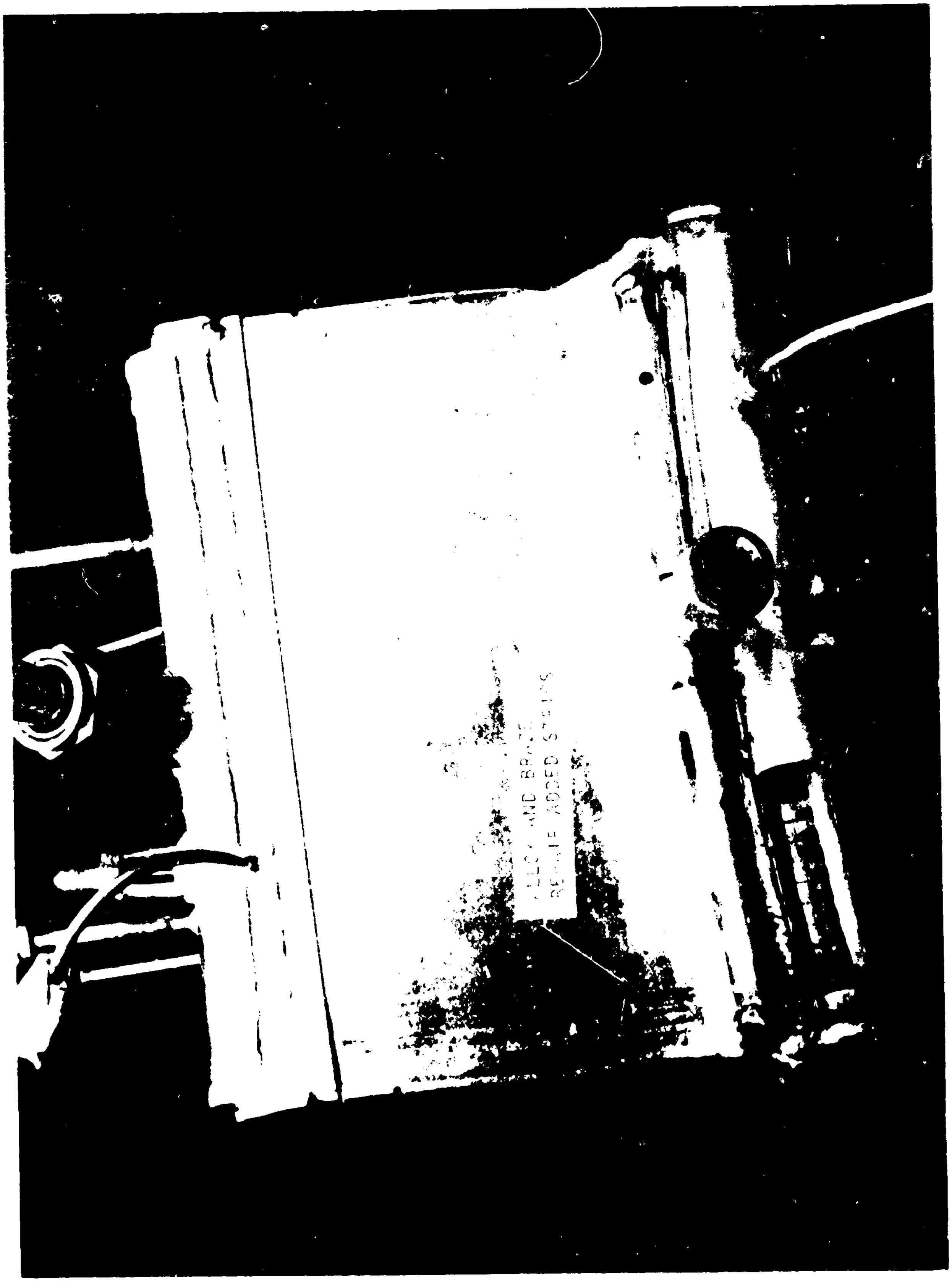
Unit 510R, which had developed cracks in the fuel panel closeout sheet between the LOX inlet manifold and the fuel distribution manifold, and also some small seepage leaks in the oxygen panel cover sheet at locations that had been repaired during initial fabrication (Fig. 30) was also put through a series of repair actions. Leaks between the oxygen inlet manifold and intermediate fuel manifold were successfully repaired by TIG brazing. A furnace braze cycle was employed to correct successfully the oxygen leaks through the oxygen panel cover sheet, with results shown in Fig. 33. Hydrostatic pressure testing of unit 510R on completion of these repairs resulted in detection of a crack in the outer liner fuel panel cover sheet on the right hand side of the bell-shaped nozzle (below the throat). Consistent with standard repair procedures, a TIG braze repair to this crack using Nioro braze alloy was attempted, but resulted in a second crack in the material adjacent to the repaired location.

At this point in the repair procedures, it appeared that a condition existed with units 507R and 510R that was not consistent with previous fabrication experience. The brazing cycles being employed for chamber assembly and repairs were resulting in nontypical cover sheet cracking. An investigation was undertaken to find the reasons for the nontypical cracking and to find some way to bring units 507R and 510R to successful completion. Because of the severe schedule and financial impact on the program in the event it was not possible to complete units 507R and 510R successfully, it was decided at this point (mid-June 1976) that fabrication effort, other than on the two combustors in question, would be halted until the problem was resolved.



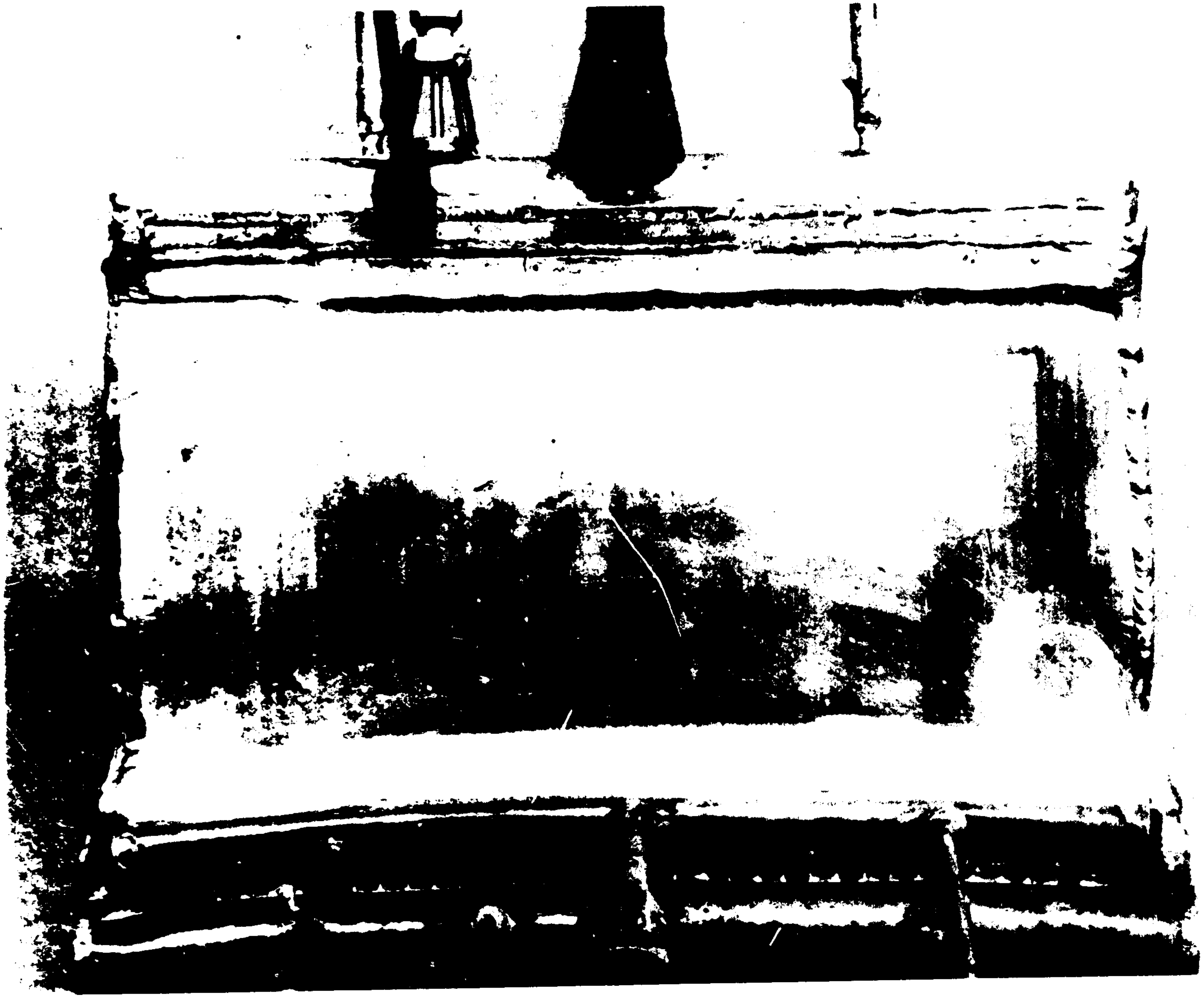
1XE22-4/19/76-C1D

Figure 29. Unit 50'R, Braze Repair Preparation



1XE22-4/19/76-C1C

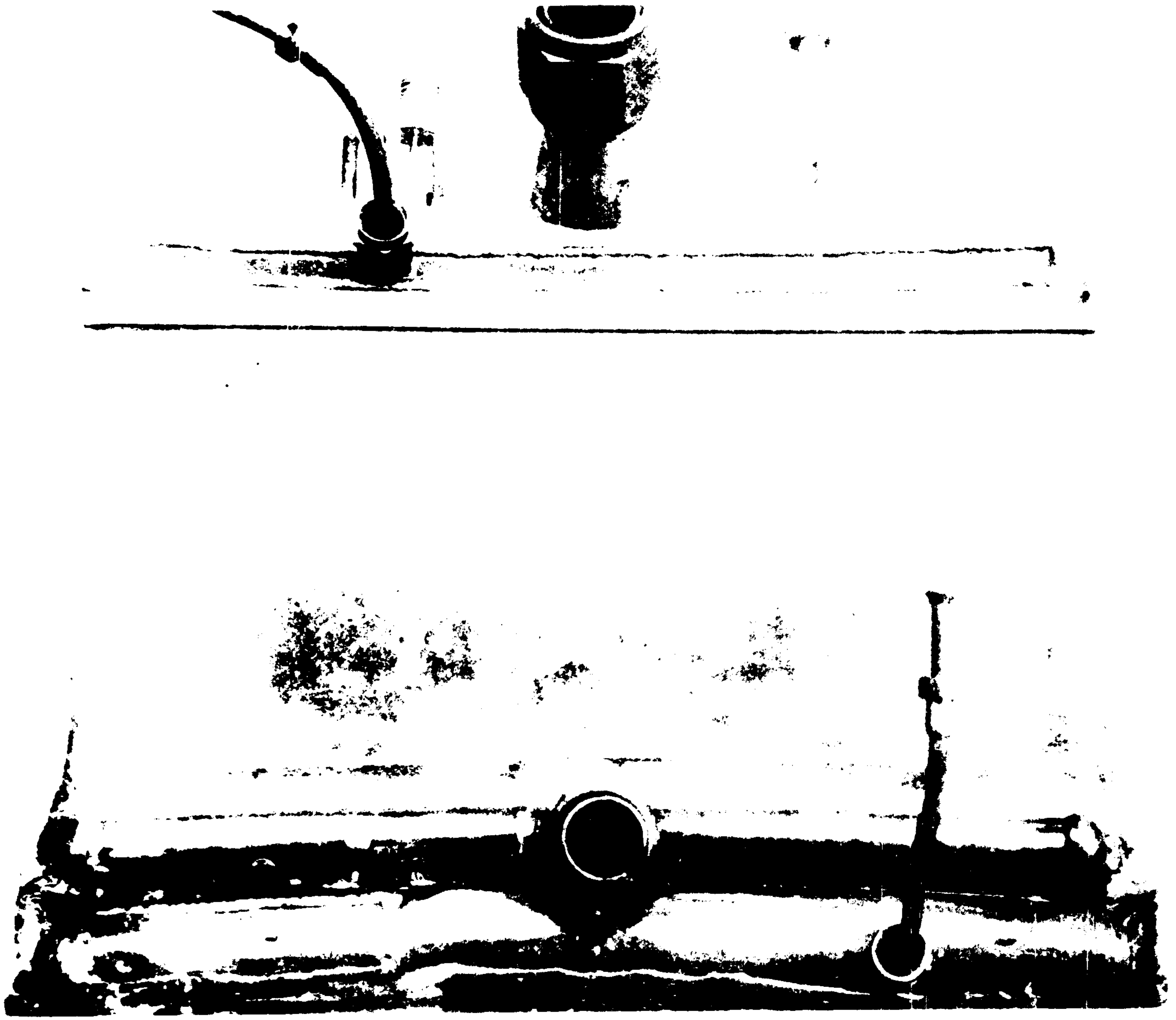
Figure 39. Unit 510R, Braze Repair Preparation



1EH22-5/25/76-C1E

Figure 31. Unit 507R, Braze Repaired

Figure 32. Photo of Crack in Unit 507R LOX Cover Sheet (10X Magnification)



1EH22-5/25/76-C1F

Figure 33. Unit 51CF, Braze Repaired

The investigation took two paths, development of techniques to repair the cover sheet cracks, and research into the causes and significance of the cracks.

Final Repair Efforts on Combustors 507R and 510R

A repair concept was developed for the NARloy-A cover sheet cracks of combustor units 507R and 510R which involved dishing out the cracked area and electrodepositing copper into the groove in sufficient depth to provide the necessary structural strength to contain the internal pressure. The repair concept is illustrated in Fig. 34. Electrodeposited copper has a minimum yield strength of 140 MPa (20K psi) and a minimum ultimate strength of 280 MPa (40K psi) at 21 C (70 F) as compared to 100 MPa (14K psi) and 210 MPa (30K psi), respectively, for aged NARloy-A. The deposition technique used was that of cell plating, in which a small electroplating cell is clamped to the side of the part to be repaired rather than submerging the whole part in the plating solution.

Several NARloy samples were first fabricated to permit experimentation with various methods for activating the NARloy surface to prepare it for copper plating and also to explore means for closing up the crack at the base of the dished area to be plated. The NARloy used for the samples proved to be extremely difficult to crack, indicating that it had not been subjected to embrittlement. The activation procedures investigated included anodic and chemical cleaning. The crack stopping methods included material removal and overplating at the ends. Properly plated samples were achieved with the chemical method of activation and the overplating method of crack stopping, and the samples were found to have excellent adhesion as demonstrated by baking at 537.8 C (1000 F) without blistering.

Combustor unit 510R was then prepared for cell plating. Because the cracked area on 510R had been previously but unsuccessfully repaired with Nioro TIG braze, it was necessary to grind away all the TIG brazed area prior to cell plating. It is generally not possible to activate gold-containing surfaces sufficiently to secure reasonable electroplating adhesion. The opened-up channels on 510R were then filled with Rigidax wax and the surface electroplated until the deposit had grown beyond the original level. A photo showing the setup for cell plating of unit 510R is shown in Fig. 35. Illustrated is the cell pump, copper solution, and power supply.

Unit 510R was then subjected to cryogenic shock testing in which liquid nitrogen was flowed through the chamber until liquid issued from the exit and then permitted to warm up. This procedure was repeated three times. The unit was then subjected to a 24 821 kPa (3600 psi) hydrostatic proof pressure test on the fuel circuit and a 10 342 kPa (1500 psi) hydrostatic proof pressure test on the oxygen circuit. The patched area of the fuel circuit successfully withstood the cryogenic shock testing and the proof pressure test, but leaks were detected at the inner liner fuel and oxidizer

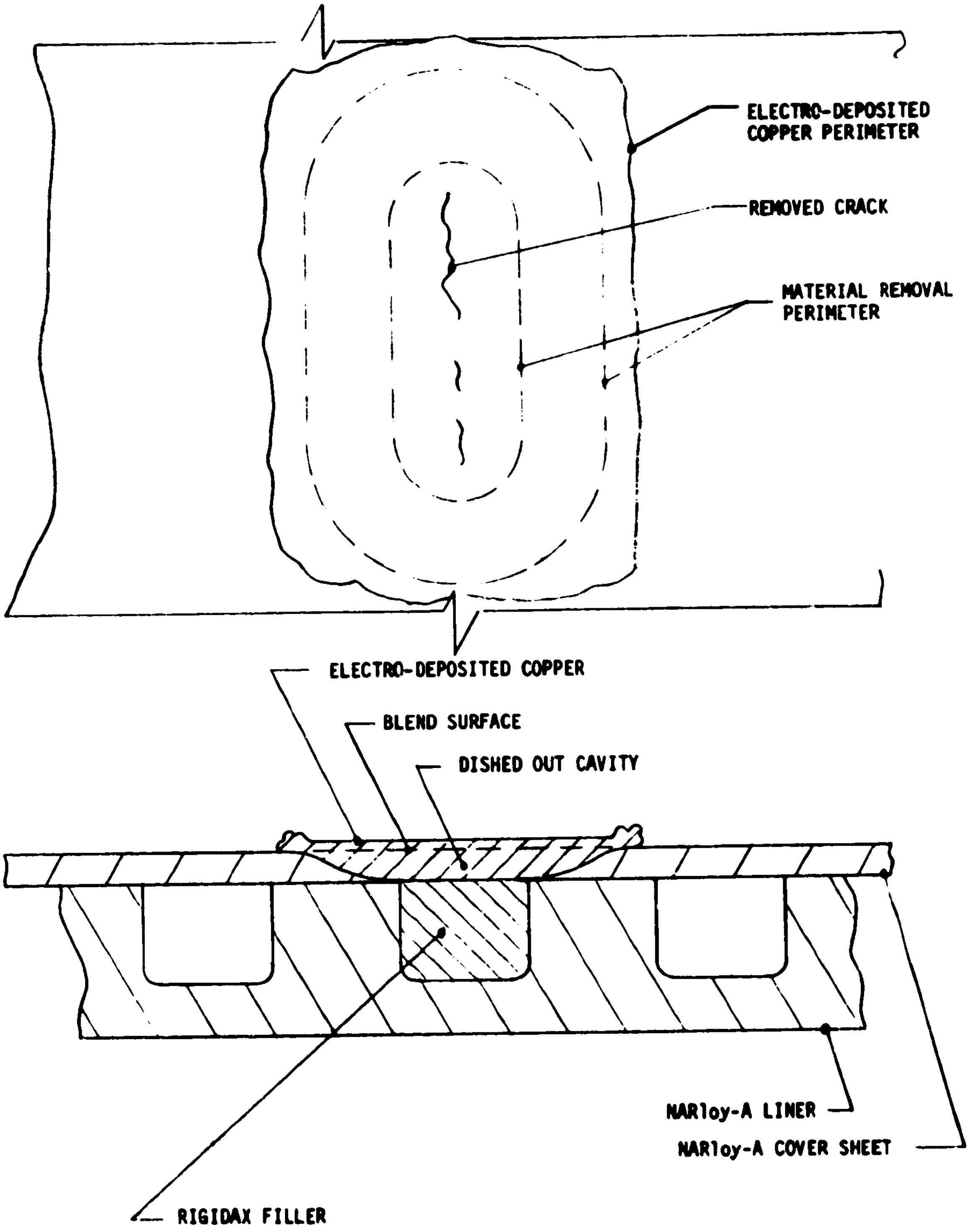
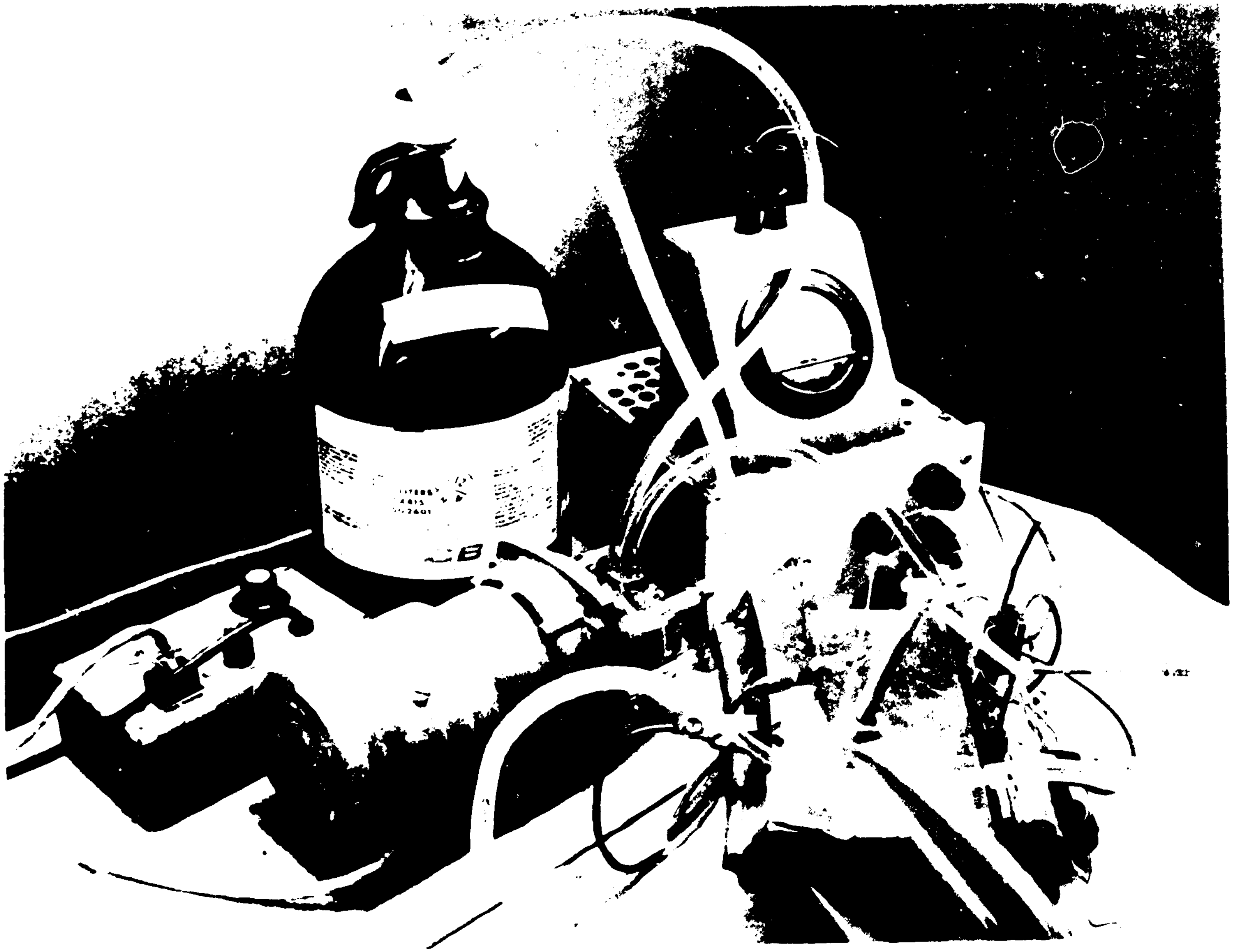


Figure 34. Crack Repair Concept



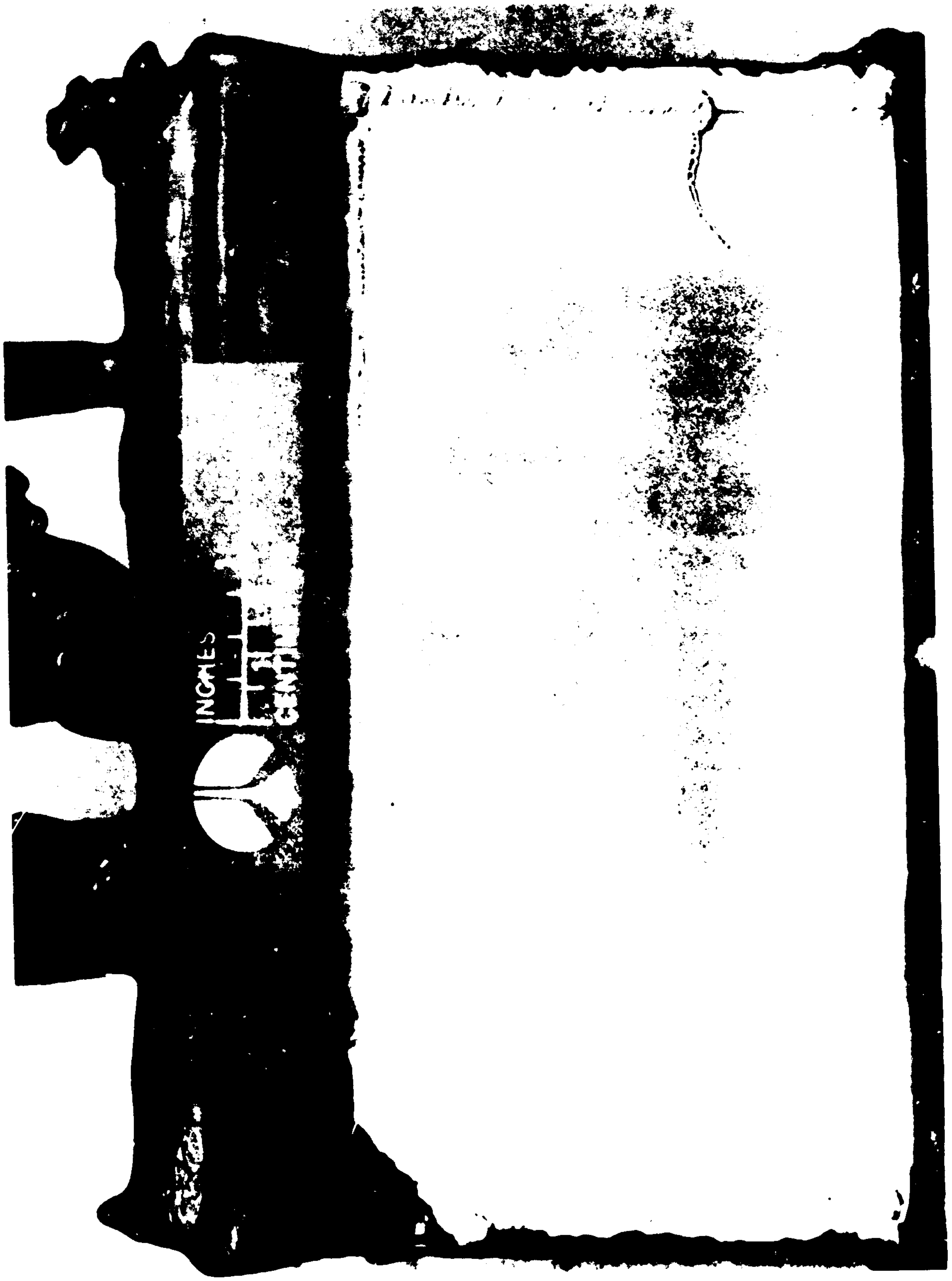
1EH38-7/13/76-C1B

Figure 35. Electrodeposited Copper Apparatus

manifolds. Several unsuccessful attempts at "touch up" repairs were made. The manifold shells in question were then partially removed and it was determined that these fuel and oxidizer manifolds needed extensive repair. Repairs to these manifolds were effected by removing the entire shells of the manifolds, rebuilding the attachment lips on the liner and replacing the shells. These manifold repairs were apparently successful. The assembly was again subjected to a three-cycle cryogenic shock test by passing liquid nitrogen through the fuel side. After the shock test, a fuel side hydrostatic pressure test was conducted, which indicated that another NARloy crack had developed in the outer liner, at approximately the "opposite hand" condition from the previously repaired crack. The area in which the crack appeared is believed to have been only minimally affected by the thermal strains imposed by the manifold repair work, which was conducted on the inner liner. It is believed that the new crack resulted primarily from the additional thermal strains imposed by the cryogenic shock testing. On the basis of this experience, it was concluded that 510R was unlikely to be a suitable combustor for assembly to the thrust chamber.

The NARloy cracking problem with unit 507R involved the oxidizer panel cover sheet on the inner liner. Repair of this area was recognized to be more challenging than the repair of unit 510R, so its preparation and plating was held until results with 510R had been obtained. On making a thorough examination of unit 507R preparatory to preparation for plating, it was found that there were relatively large numbers of small cracks, and that cell plating would tend to be quite tedious as many of them would have to be plated in series. Additionally, one could not be certain that all cracks had been identified until some of the larger defects had been covered. For these reasons, it was decided to apply electrodeposited copper (ED) over the entire LOX panel cover sheet of unit 507R. However, ED copper cannot be expected to adhere to the areas that had been TIG braze repaired because of the noble metal content of the braze alloys. These areas were masked off prior to electrodeposition of the copper. The surface was prepared for plating by carefully removing 0.13 mm (0.005 inch) to 0.25 mm (0.010 inch) of the existing NARloy material by hand sanding. Guidance as to the thickness of NARloy material removed and the thickness of the layer of electrodeposited copper applied was obtained by taking caliper measurements of the thickness of the combustor at a relatively fine grid of stations. Approximately 0.76 - 1.02 mm (0.030 - 0.040 inch) thickness of ED copper was then applied by immersing the entire combustor in an electroplating bath. The copper thickness was then hand dressed to provide an average copper surface of 0.51 mm (0.020 inch) above the location of the original NARloy surface. This procedure is acceptable because 0.51 mm (0.020 inch) thick shims are normally applied between the combustor surface and the inner backup ring. A photo of the inner surface of combustor 507R after the application of the ED copper is shown in Fig. 36.

After ED copper application to the inner liner, unit 507R was subjected to a three-cycle cryogenic shock test as previously described for unit 510R and then to a 10 342 kPa (1500 psi) hydrostatic pressure test of the oxidizer circuit. No leaks were observed on the hydrostatic pressure test,



1EH39-7/21/76-C1

Figure 36. Electrodeposited Copper, Unit 507R

but when the unit was subsequently leak tested at 1379 kPa (200 psi) helium pressure, it was found that there were about six leaks around the periphery of the ED copper plating. These leaks did not issue from under the ED copper plating itself but, rather, from beneath the Nioro TIG weld fillet that runs along the upper edge of the LOX cover sheet, from the lower edge of the triangular patch previously installed at the upper left-hand corner of the LOX cover sheet, and from a small crack in the original NARloy at the upper left-hand edge of the ED copper cover. This small NARloy crack had been masked during ED copper plating and, thus, not covered. A repair of these leaks was attempted in which the leaking zones were covered with Nioro braze alloy applied with a TIG torch. Upon pressure checking 507R after this latest repair effort, it was found that while the six leaks appeared to have been repaired, a very large interpropellant leak was now present, apparently caused by the TIG torch repairs. This interpropellant leak was approximately six times the size of the maximum interpropellant leak observed during the interpropellant leak check reported previously. Additionally, the fuel circuit of combustor 507R was put through a hydrostatic pressure test. During that test, the intermediate fuel manifold (located at the aft end of the inner liner) burst at hydrostatic pressure test of approximately 20 684 kPa (3000 psi). It had previously been through two hydrostatic pressure test cycles up to 24 821 kPa (3600 psi). While the fuel manifold could be repaired, the large interpropellant leak in 507R clearly made it unacceptable for utilization on the thrust chamber.

NARloy-A CRACKING INVESTIGATION

Beginning in July 1976, it became evident that the NARloy-A coversheet cracking being experienced on combustor units 507R and 510R was not consistent with the ductile behavior typical of NARloy-A. A metallurgical and historical investigation, concurrent with the repair effort on 507R and 510R, was conducted to understand the problem and its implications for all of the combustors.

A sample of the coversheet and braze joint was removed from segment 510 in the area where cracking had occurred (see Fig. 37 for a view of the crack and Fig. 38 and 39 for photomicrographs of the cracked region). Samples of NARloy-A were also removed from several other combustor segments as the investigation proceeded. All of the samples from useful combustors were taken in a manner permitting replacement of the removed material. All samples examined are listed in Table 7. Several Rocketdyne metallurgists experienced in NARloy-A and copper systems, and Dr. Martin Prager, a consultant, reviewed the mounted sections and agreed that the chains of round voids visible in the grain boundaries were definitely the result of a reaction between hydrogen and oxygen, which formed steam.

The oxygen/hydrogen reaction in pure copper and copper alloys is well known through experience with OFHC copper. If the copper structure contains oxides, or oxygen in solution, in a significant quantity (above 20 ppm), an H_2/O_2 reaction will occur in H_2 atmospheres above 593.3 C (1100 F). The diffusivity of hydrogen in copper is very rapid at these

Figure 37. Cover Sheet Crack in Outer Half of Segment 510 Viewed From Cover Sheet Side (20X)

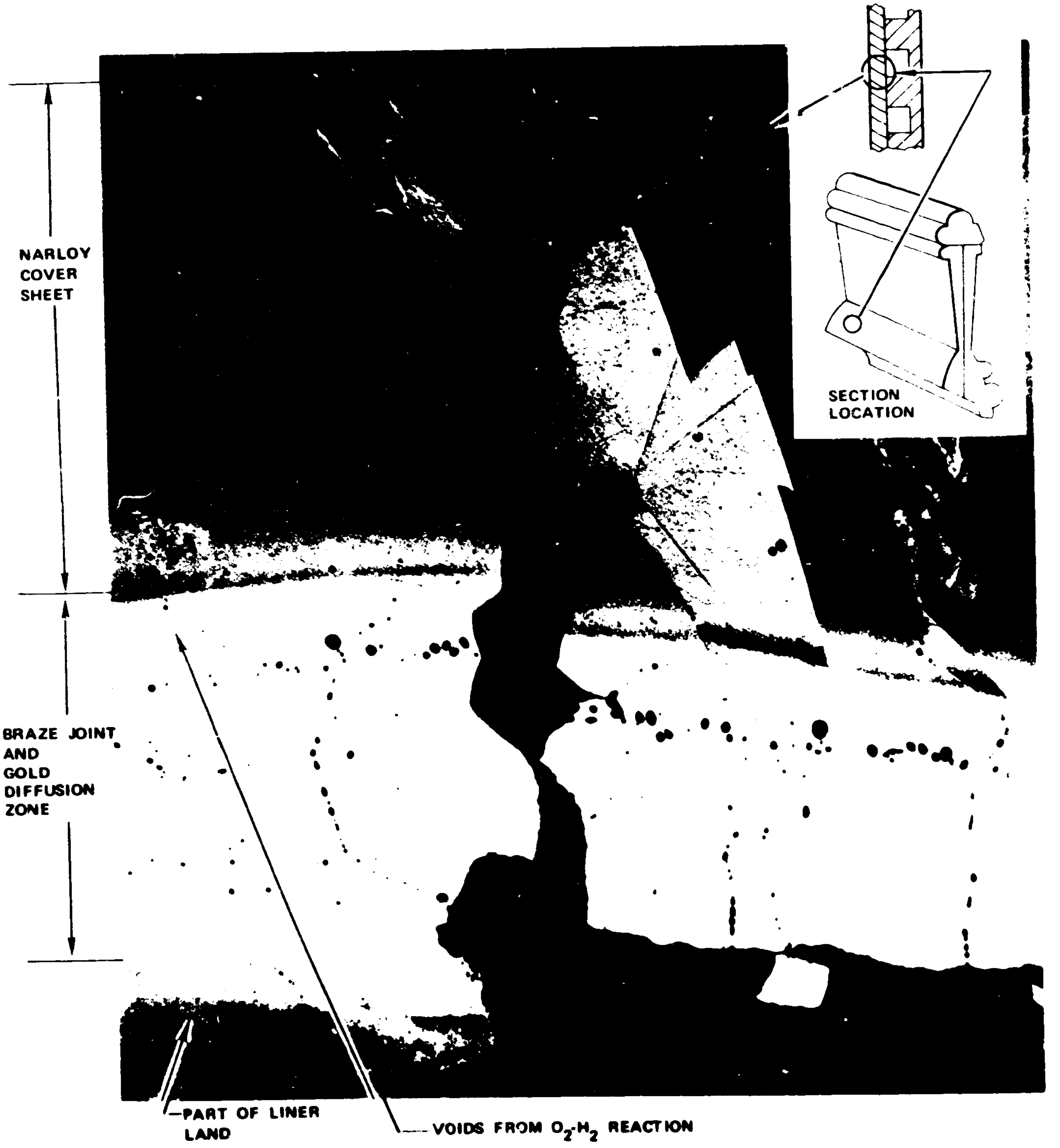


Figure 38. Section Through Crack in Outer Cover Sheet of Segment 510 (200X)

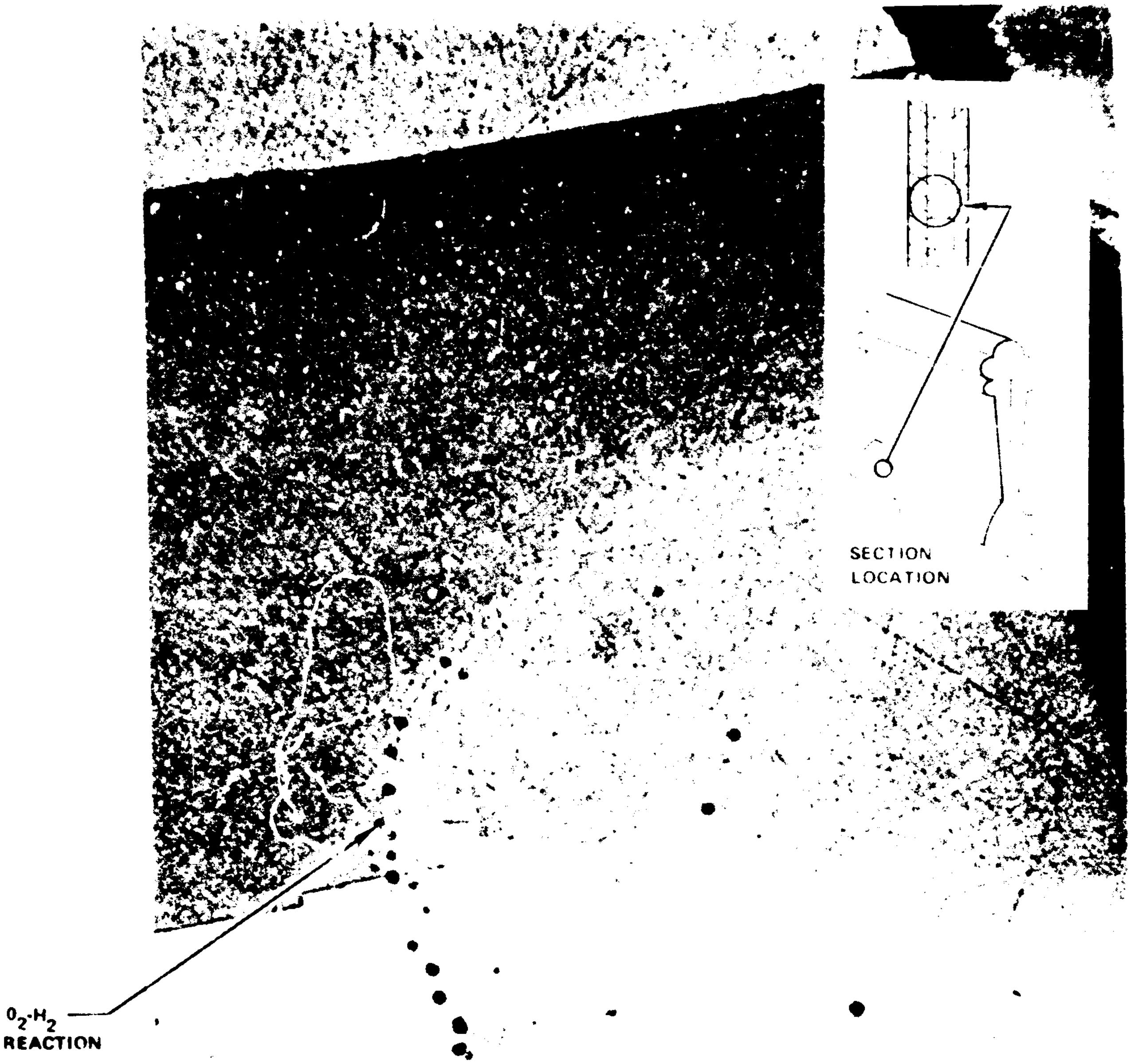


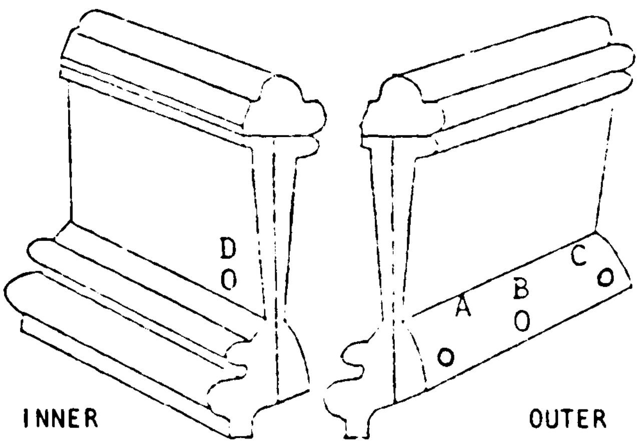
Figure 39. Section Near Crack in Outer Half of Segment 510 (400X)

TABLE 7. METALLOGRAPHIC INVESTIGATION OF SEGMENTS

Segment No.	Test Location	Remarks
504	B	No Gasing[†]
507	B C D	No Gasing No Gasing Cracked-No Micro; Probably Gasing
510	A B C D	Cracked - G.B.* Gasing No Gasing Light G.B. Gasing No Gasing
512	A	Severe G.B. Gasing
514	A	Severe G.B. Gasing
516	C	Slight G.B. Gasing
518	C	Slight G.B. Gasing
522	C	No Gasing
523	A-C	No Gasing
525	C	No Gasing

*G.B. = Grain Boundary

[†] The term gasing refers to voids formed by the O_2-H_2 reaction.



TEST LOCATIONS

temperatures. Heavy sections are penetrated in a few minutes; light sections are penetrated in seconds. When hydrogen is introduced during brazing it enters the copper matrix and reacts with any oxides or oxygen in solution or in oxide form, forming bubbles of H_2O, steam. Table 7 reports the presence of this reaction as "gasing". The steam bubbles cause spherical voids to form within the metal. The voids usually concentrate at grain boundaries. Severe H_2/O_2 reaction may even cause separation of grains, of which Fig. 53 is typical. The effect of the voids is to reduce the strength and ductility of the material.

The question now was, how did the O_2 come to be present in the NARloy of 507R and 510R; was it likely to be present in other combustors; and what was its significance to the program?

Analysis established several possible sources of oxygen in the NARloy-A combustor segments: (1) the oxygen could have been present in the virgin material prior to the fabrication of segments, (2) oxygen could have been trapped in the braze joints during braze assembly or gold plating and diffused into the NARloy-A during furnace operations, (3) NARloy-A oxidizes easily even at room temperature, regardless of the cover gases used during GTA brazing and the cleaning operations between furnace cycles, it was possible that oxides could have accumulated on cooling channel surfaces. The surface oxides could then have diffused into the NARloy at elevated temperatures during furnace operations. All of these possible sources appeared at first to be improbable, as the injurious effects of oxygen on NARloy had been well known all along, and guarded against in material specifications, purchasing procedures, and processing procedures. The actual mechanism was determined by a process of elimination.

The receiving records on the virgin NARloy-A used in the combustors show its oxygen content to be within specification, 20 ppm or less. The quality control steps required by specification on wrought NARloy-A are shown in Table 8. These procedures had been followed, providing considerable confidence that incoming material was oxygen-free. Conceivably, however, local oxygen pickup during forging or rolling could have been missed in the oxygen check samples. As further confirmation of incoming material quality, a new braze sample was made from a gold-plated NARloy-A coversheet from the same lot as the material used for the 24 combustors on the thrust chamber. The sample was brazed in H_2 at 910 C (1670 F) and examined metallographically. The results, shown in Fig. 40, showed no H_2/O_2 reaction. There was also other evidence in samples taken from combustors that the oxygen source was not the virgin material. In several cases where an H_2/O_2 reaction was present, it was noted that both the coversheet and its adjacent liner were contaminated. If the source of oxygen were local pickup during forging or rolling, it is unlikely that adjacent areas of coversheets and liners would both contain excess oxygen, since the liners and coversheets were fabricated from different forgings. A good example of this reasoning is seen in a section taken from segment 514 (Fig. 41). Grain boundary H_2/O_2 reaction is present in both the liner and the coversheet. It might be argued that the original contamination was in the liner

TABLE 8. NARloy-A PROCESSING AND QUALITY CONTROL

Processes	Tests
● Vacuum Induction Melt Ingot ● OFHC Copper ● 99.9% Pure Ag	● Chemical Analysis: ● Ag - 3.2 to 3.7% ● O_2 - 20 ppm maximum ● Cu - balance
● Homogenize Ingot ● 760 C (1400 F), 10 to 24 hours	● Metallographic Examination for Silver Phase
● Scalp Ingot 5 mm (0.2 in.) minimum, all surfaces	● Dimensional
● Forge Ingot to Plate at 760 C (1400 F)	● None
● Stress Relieve Plate 760 C (1400 F), 1 hour 482 C (900 F), 1-2 hour	● Tensile Tests at Room Temperature and 537.8 C (1000 F) ● Heat Treat Test Material: Solution Treat, 898.9 C (1650 F), Water Quench Precipitation Hardened, 482 C (900 F), Air Cool ● Hydrogen Gasing Test at 898.9 C (1650 F) ● Metallographic Examination
● Scalp Plate 2.54 mm (0.1 in.) minimum, all surfaces	● Ultrasonic Inspect per RA0115-012 Class A ● Inspect Dimensionally

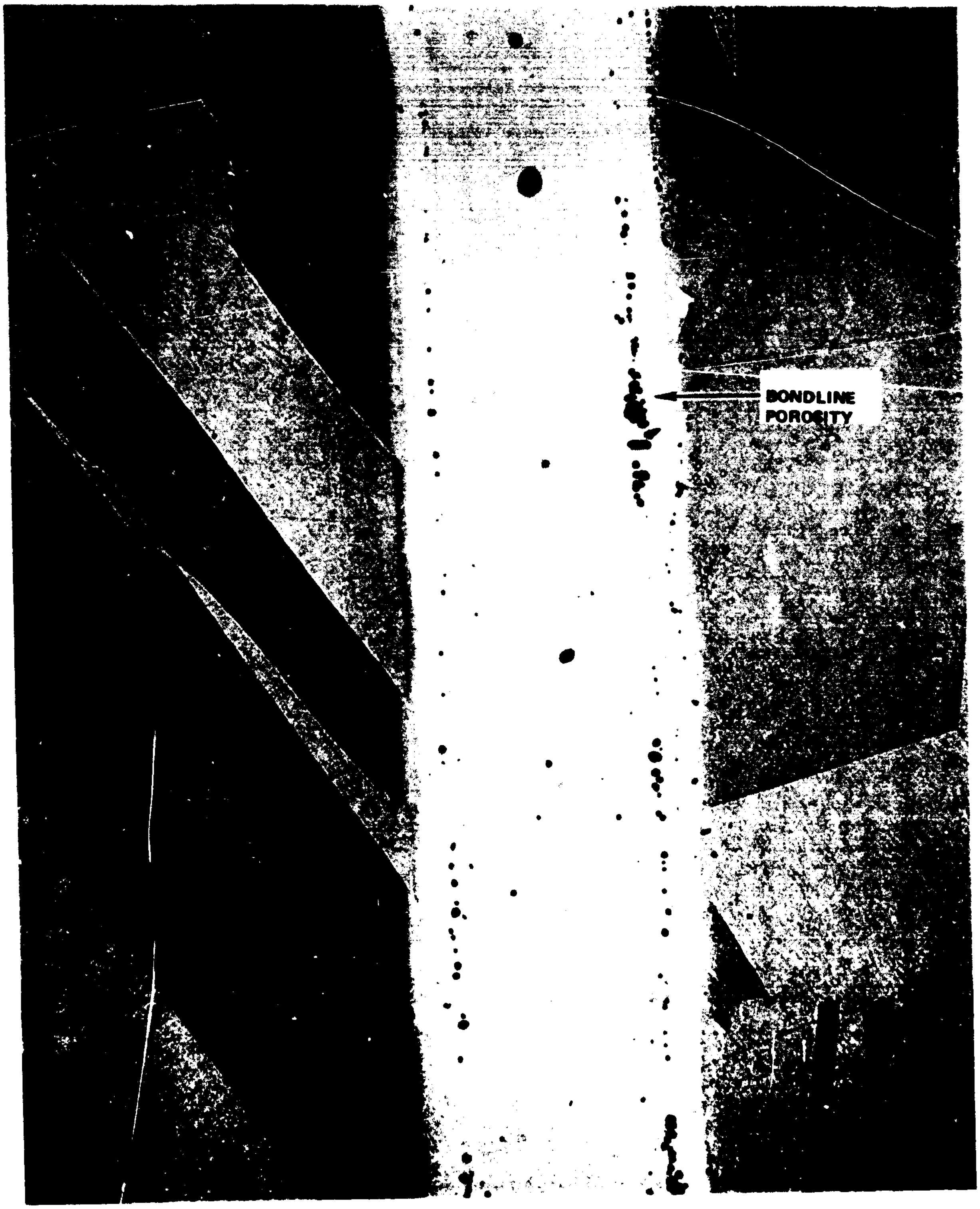


Figure 40. Test Specimen From a Gold-Plated Cover Sheet Subjected to One Braze Cycle in H_2 After Thorough Surface Cleaning (Material is the Same as Segments) (200X)

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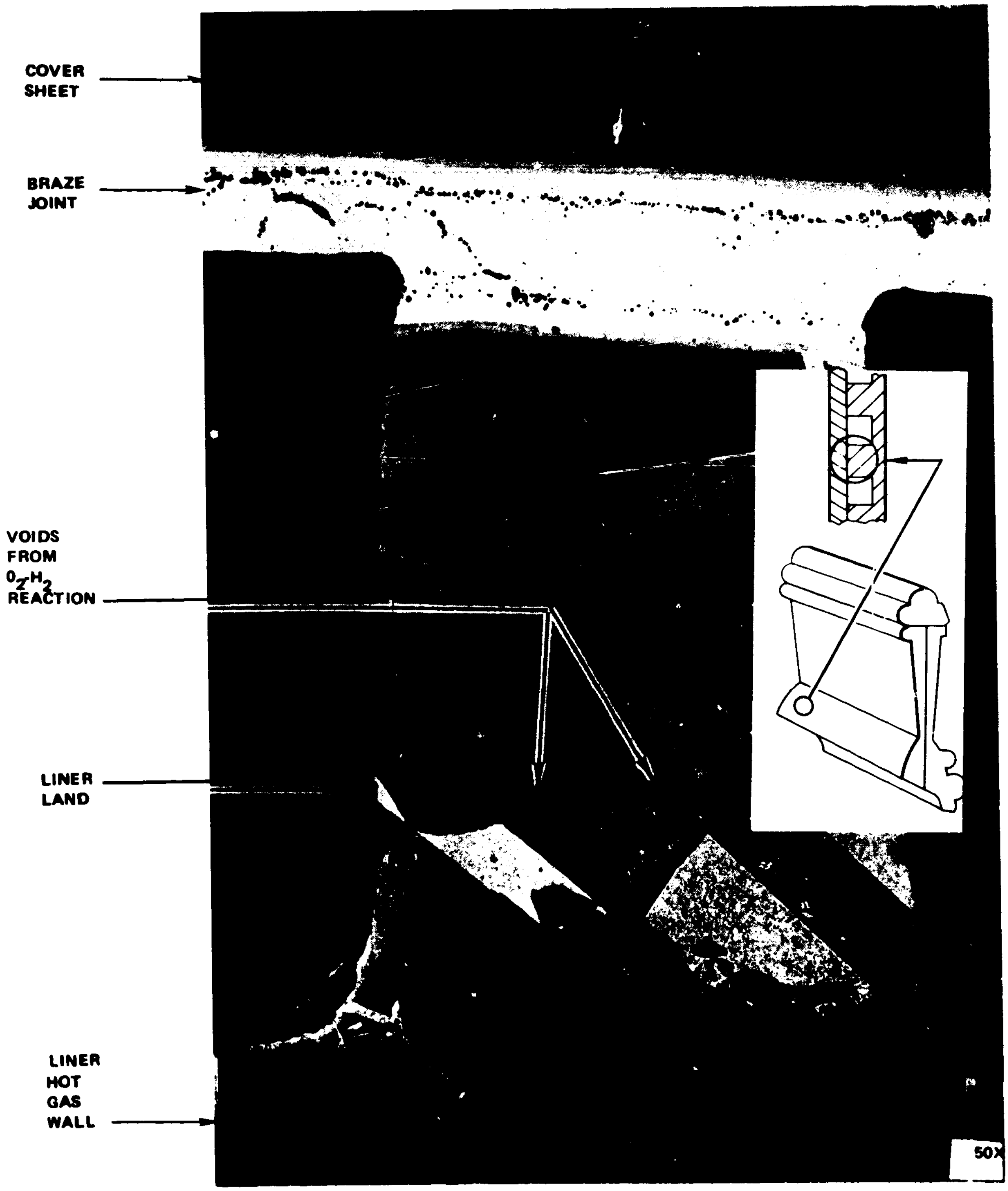

Figure 41. Section From Outer Half of Segment 514 Showing Severe O_2-H_2 Reaction (100X)

only and diffused to the coversheet during furnace operations but, if so, the H_2/O_2 reaction would be continuous across the braze joint between the liner and coversheet reaction areas, which is not the case. Hence, it was concluded that the virgin material could be eliminated as a major source of oxygen.

In most of the sections taken from both segments and experimental samples, porosity was noted in the braze joints. This is a common situation in braze joints due to shrinkage or entrapped gases. Where the braze porosity was oxygen from gases trapped in the joint surfaces at braze assembly, or oxides remaining in the gold-NARloy-A plating bond line, it might be assumed that these oxides could diffuse into the NARloy-A parent metal during thermal cycling and thus be the source of oxygen contamination. Several observations on the sections disproved this assumption. If the braze joint were the major source of oxygen, it would be expected that the H_2/O_2 reaction in the NARloy would be worst near the braze joints, and this was not generally true. Again, combustor 514 (Fig. 41) is a good example. The worst grain boundary condition is in the liner some distance from the braze joint and very little H_2/O_2 reaction occurred near the braze joint. In a section from combustor 516 (Fig. 42 and 43), isolated O_2/H_2 reaction was found in an area remote from a braze joint. There is also evidence that at least part of the braze joint porosity is not the result of the O_2/H_2 reaction. The section in Fig. 44 shows a centerline porosity and traces of bond line porosity in the braze joint, yet this specimen was never exposed to $H2$, so the porosity cannot be steam bubbles from the O_2/H_2 reaction. Additionally, a section from the inner half of segment 510 (Fig. 45) shows considerable bondline porosity in a braze joint with no associated O_2/H_2 reaction in the NARloy. This segment was brazed in hydrogen. The same is true of the specimen shown in Fig. 40.

Dr. Prager stated in his comments about the observed grain boundary conditions that, in his experience, it is not possible to produce major amounts of grain boundary weakening, such as seen in segment 514, from the amount of oxygen available in a braze joint. The braze joint could contribute some oxygen to the system, but not the quantity required for the extensive damage observed. It was therefore concluded that the braze joints were not a significant source of oxygen.

The third possibility, diffusion of surface oxides into the NARloy, was found to fit the observed facts. A review of the fabrication history of the segments brought out several significant points. The diagram in Fig. 46 shows the fabrication sequence in regard to furnace and torch brazing operations. GTA brazing (gas tungsten arc, with a heliarc torch used as a heat source for brazing) with Nioro (82Au, 18Ni), an alloy which brazes at 982.2 to 1010 C (1800 to 1850 F), was performed on all segments as a planned operation at two points in the sequence: the joining of manifold shells to coversheet strips prior to furnace brazing the segment halves together, and a reinforcement Nioro joint over the end plates after furnace brazing the halves together. Since the segments were small, GTA brazing temperatures were high, and NARloy is an excellent thermal conductor, elevated temperatures were experienced in the NARloy during GTA brazing.

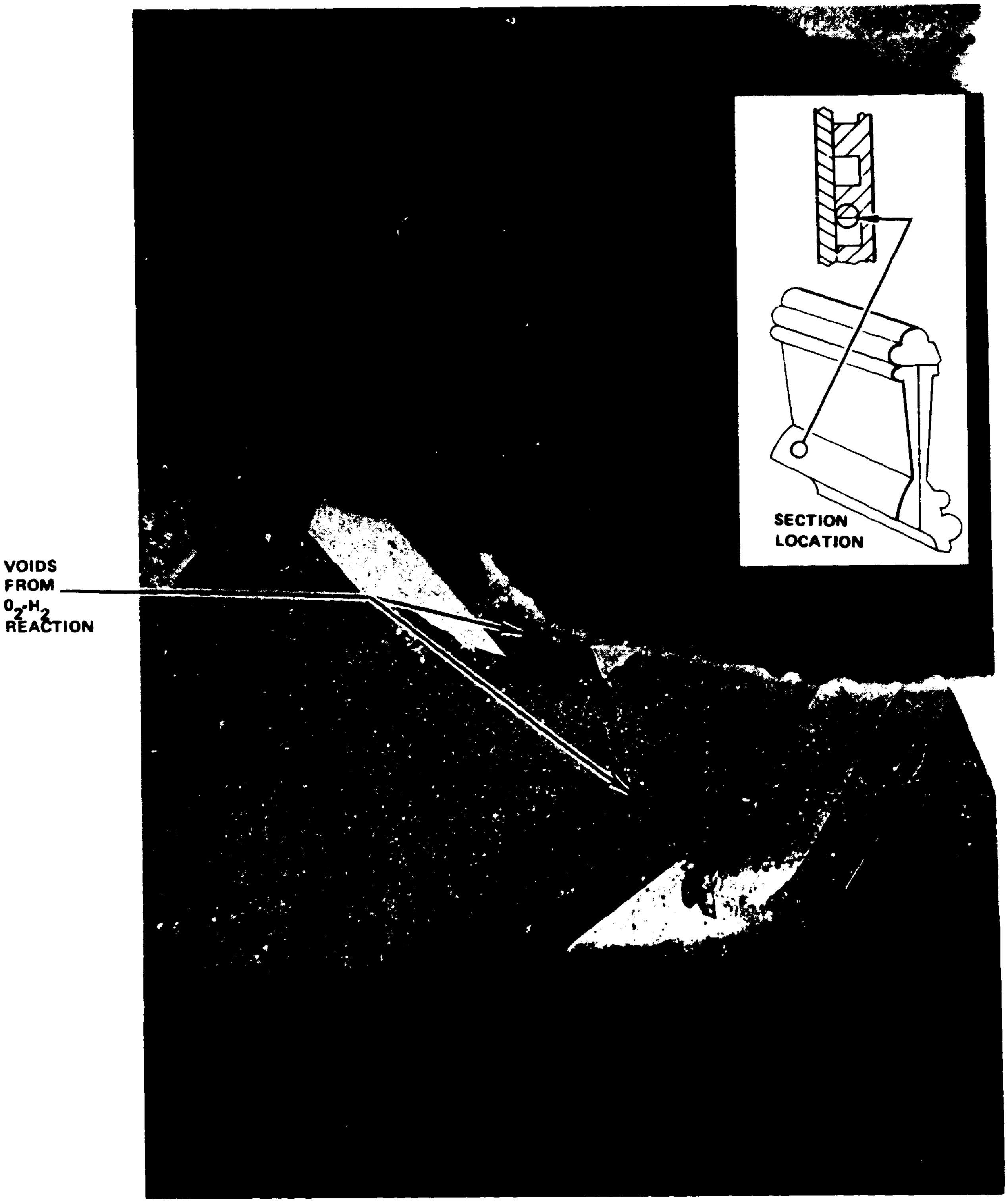

Figure 42. Section From Outer Half of Segment 516, Showing Slight O_2-H_2 Reaction (100X)

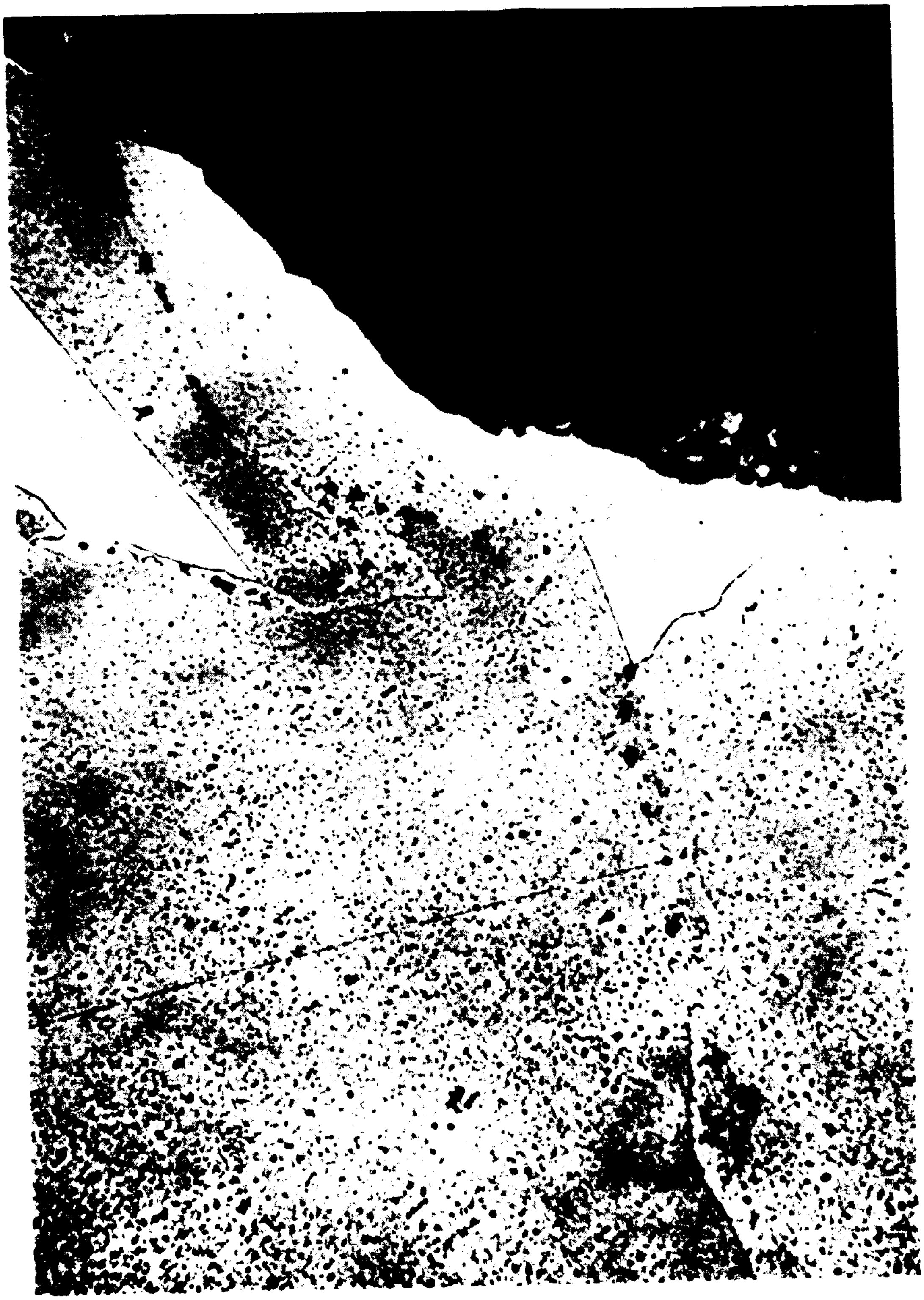

Figure 43. Section From Outer Half of Segment 516, Showing Slight O_2-H_2 Reaction (Blowup of Fig. 42) (400X)

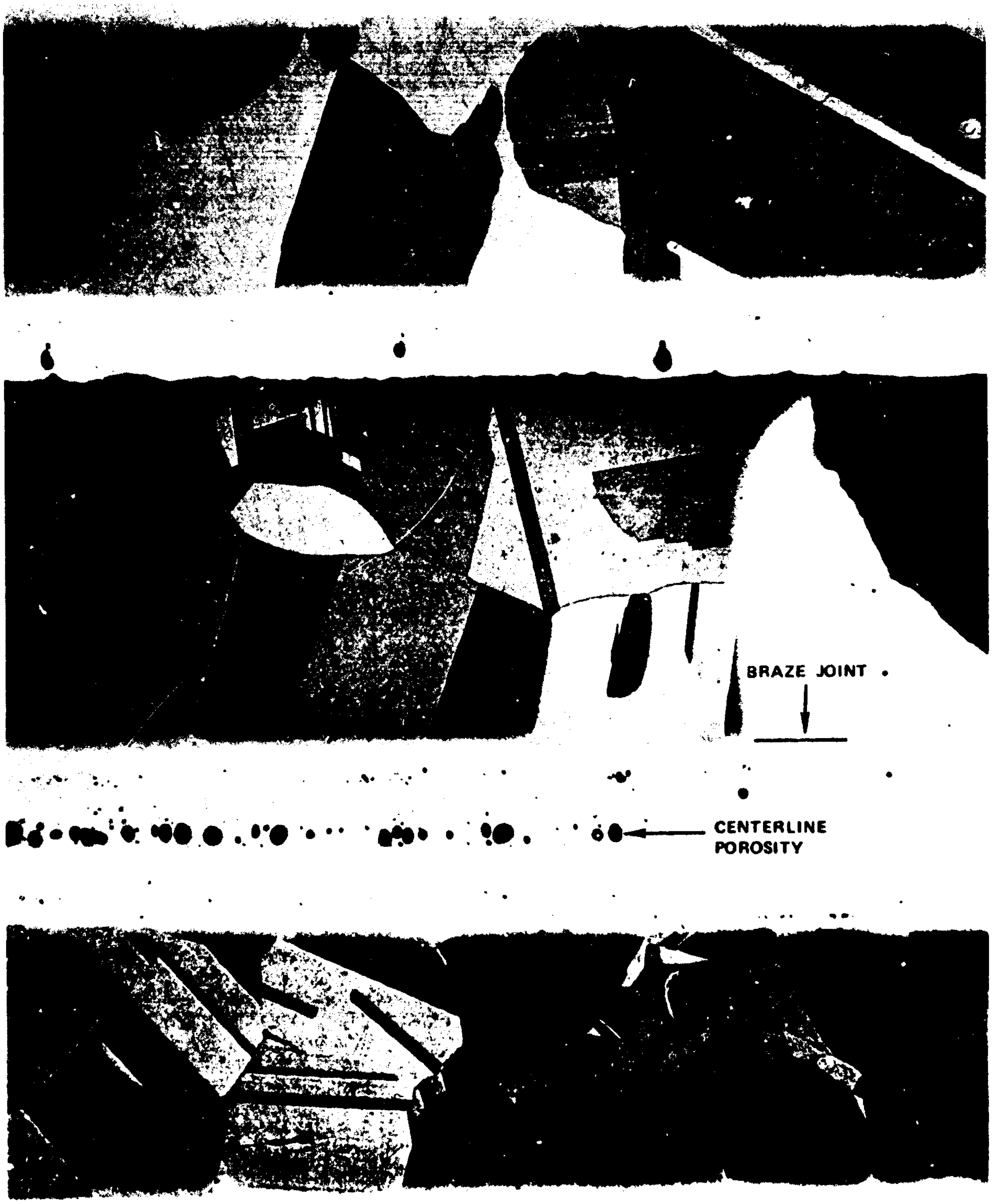

Figure 44. Test Specimen From NARloy-A Cover Sheet, Furnaced Brazed in Argon (No O_2-H_2 Reaction Present; Centerline Porosity in Braze Joint) (100X)

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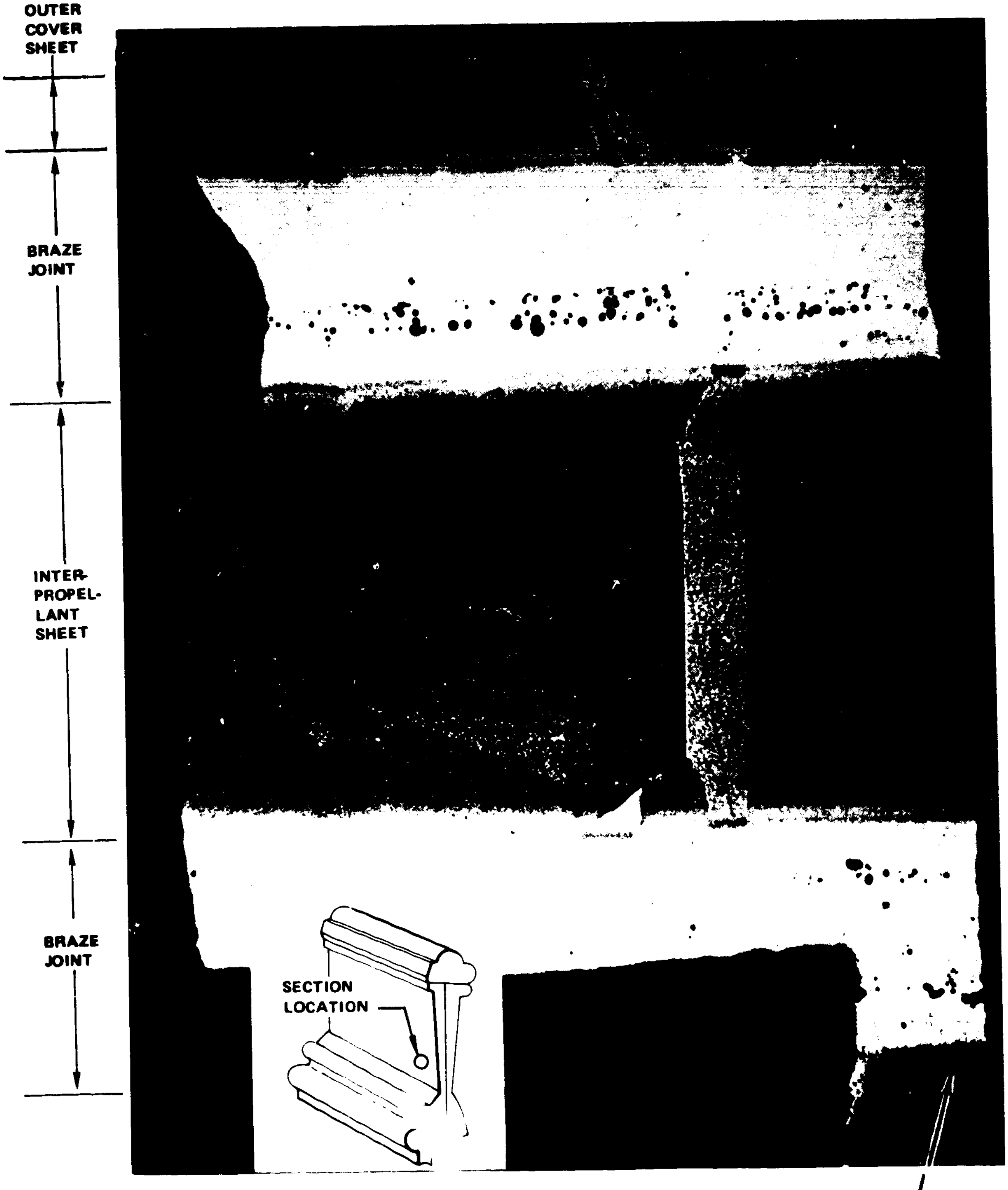


Figure 45. Section From Inner Half of Segment 510 (No O_2-H_2 Reaction Present) (100X)

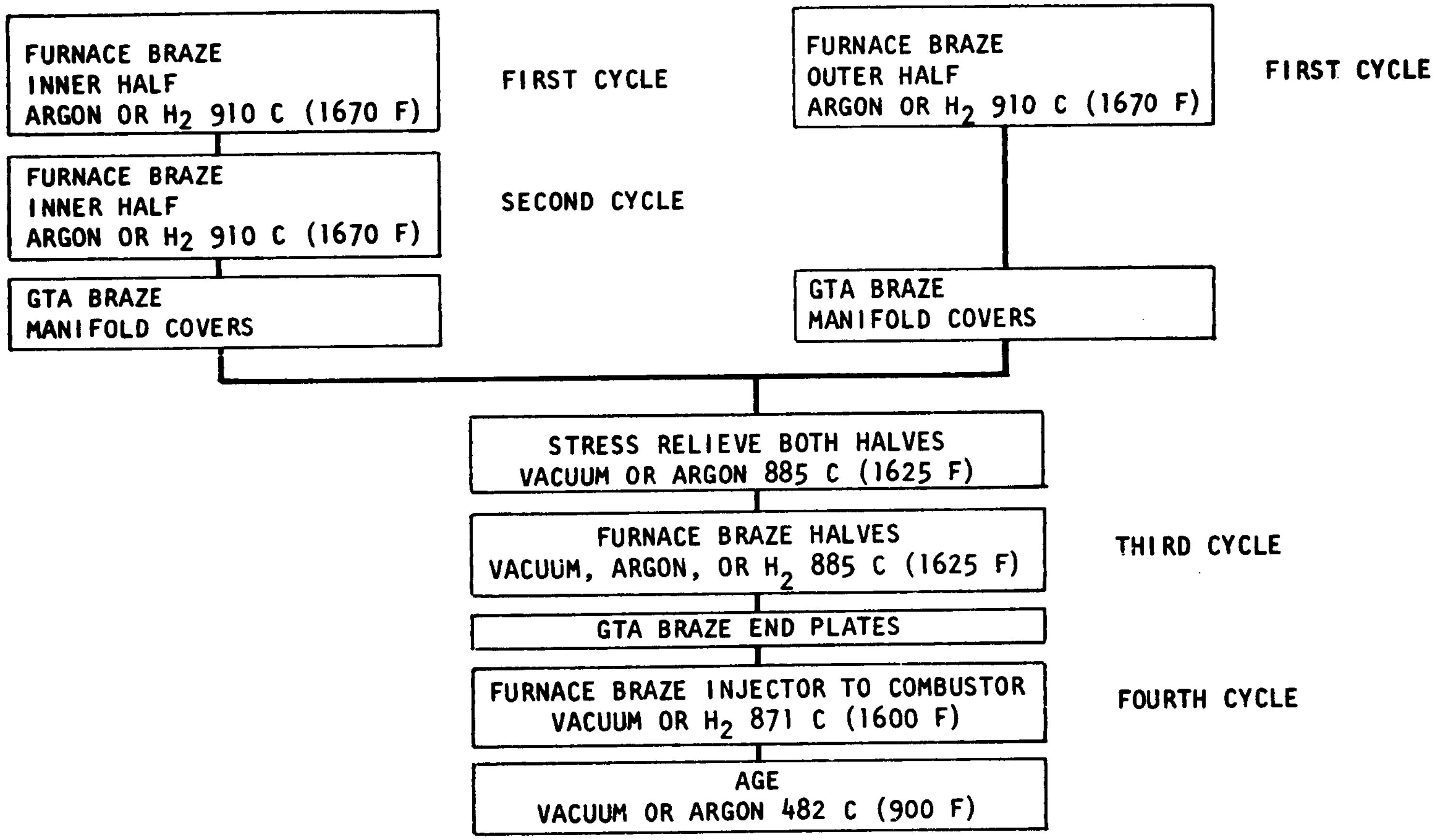


Figure 46. Segment Assembly Sequence

External surface oxides formed during GTA brazing were removed by abrasive cleaning prior to furnace brazing operations. The internal surfaces, i.e., cooling channels, were carefully flushed with inert gas during GTA brazing to minimize oxidation. Use of inert cover gases is normally adequate protection against oxidation and was considered a reasonable precaution in this case. In retrospect, however, scavenging of oxygen was probably incomplete. The geometry, with square-ended channels and many leak paths during manifold attachments, is difficult to purge completely.

All NARloy-A was chemically cleaned prior to the first braze cycle. On subsequent cycles, early in the program, cleaning between braze cycles was accomplished by degreasing. These cleaning steps had precedent in other programs involving the brazing of copper alloys, such as brazing of OFHC copper on F-1 injectors. During aerospike combustor fabrication, however, channel contamination problems were experienced, specifically on segments 512, 514, 516, and 518. Starting with segment 520, therefore, chemical cleaning operations were added between braze cycles. The segments with the added cleaning may have had less oxidation and correspondingly less H_2/O_2 reaction, but this point cannot be verified nondestructively.

There were several possible sources of surface oxidation in addition to GTA brazing. After furnace operations, assemblies were still warm when removed from the inert furnace atmosphere. Rocketdyne process controls required that NARloy assemblies remain in an inert atmosphere on cooling until the temperature was below 121 C (250 F). However, a NARloy-A surface oxidizes to some degree at ambient temperature and at a more rapid rate above 121 C (250 F), though the oxide layer is a thin, not a heavy scale. Thus, the repeated furnace operations characteristic of the aerospike fabrication history may have contributed significant amounts of oxygen. Perchloroethylene degreasing was used extensively to remove waxes from combustor assemblies after machining operations, and the temperature on removal from the degreaser was above 93 C (200 F). Hydraulic pressure testing required vacuum oven drying to remove water from the segments, and assemblies were normally above 93 C (200 F) when removed from the oven.

It is a fact that channel surface oxidation did occur, because channel discoloration was observed in the specimens removed from segments 514 and 518, which contained complete sections of channels.

Experiments were then run to demonstrate that oxygen diffusion from an oxide-coated surface can occur in normal furnace operations. Figures 47 and 48 show the results. The section in Fig. 47 and 48 was taken from a specimen which was furnace brazed in argon for 30 minutes at 910 C (1670 F) and then held in argon for two hours at 871 C (1600 F). It was removed from the furnace and the surfaces were oxidized by heating in air with an oxyacetylene torch until the surfaces were black and slightly scaled. The specimen was then returned to the furnace, and held at 871 C (1600 F) in argon for 120 minutes followed by 30 minutes in hydrogen at 871 C (1600 F). The long hold time in argon approximated the multiple furnace cycles on combustors which were furnace repaired several times. Severe

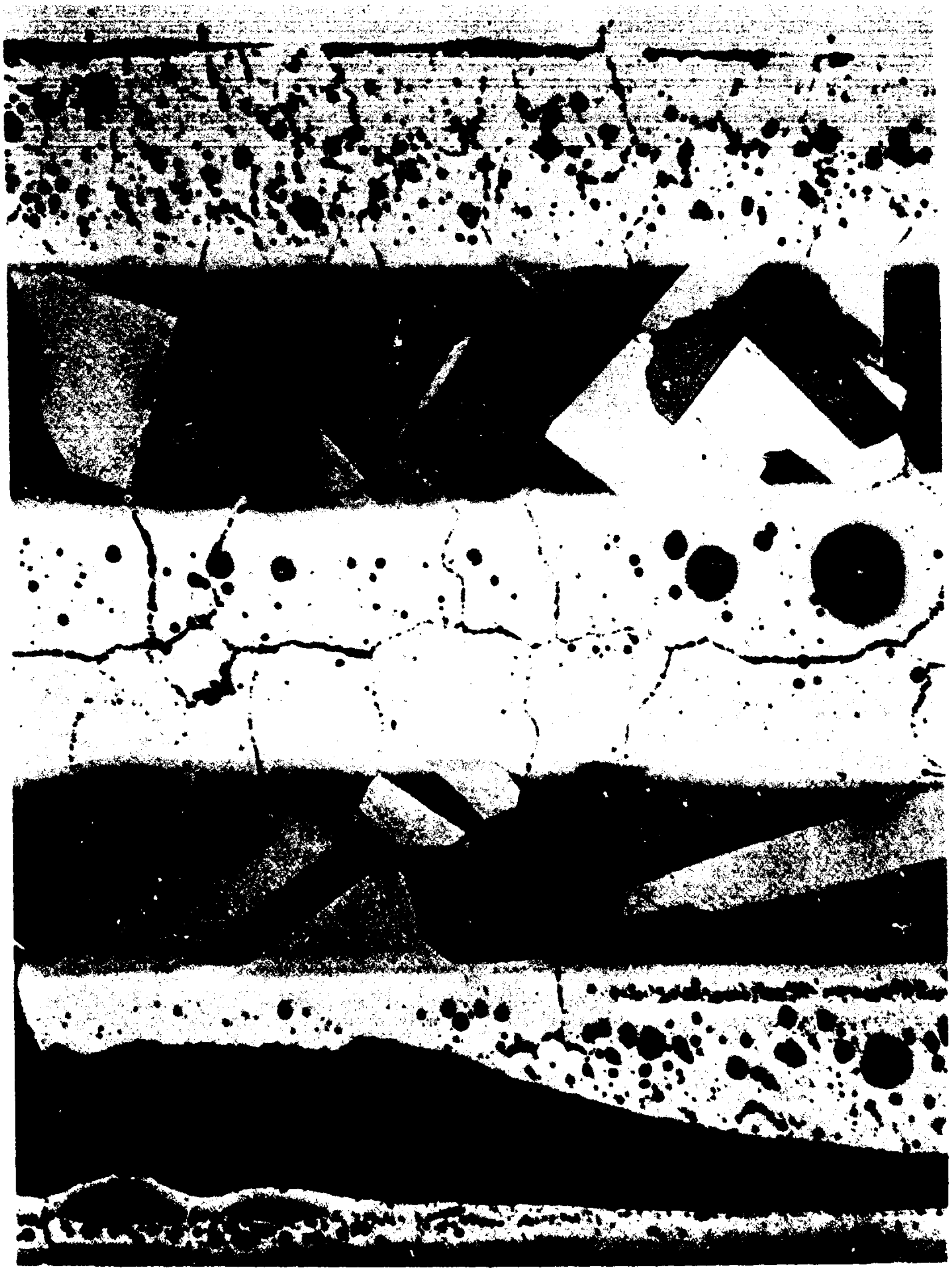


Figure 47. Test Specimen From NARloy-A Cover Sheet, Furnace Brazed in Argon, Surface Oxidized With Torch, Reheated in Argon Furnace to 871 C (1600 F), Then H_2 at 871 C (1600 F) (Shows Severe O_2-H_2 Reaction) (100X)

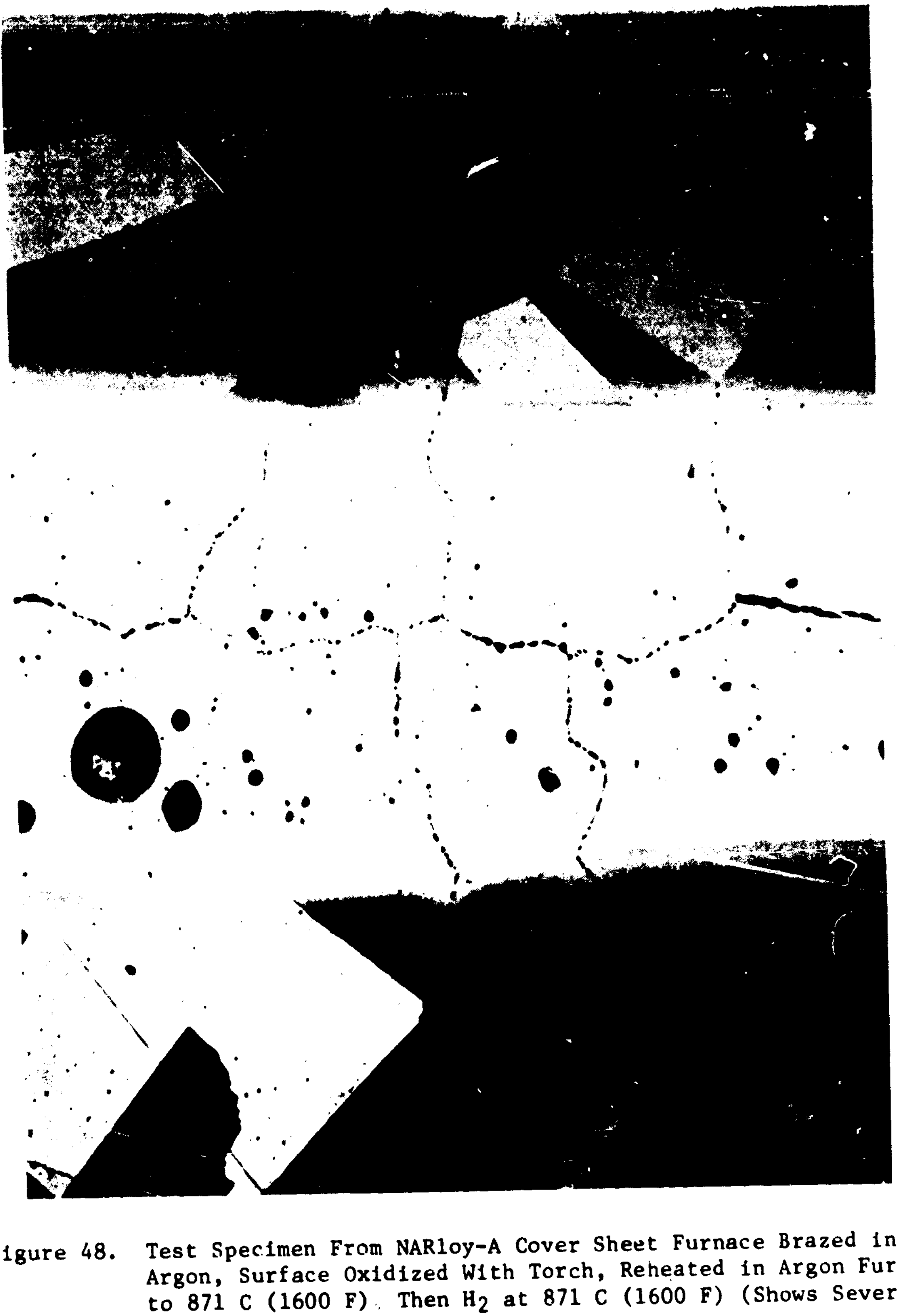


Figure 48. Test Specimen From NARloy-A Cover Sheet Furnace Brazed in Argon, Surface Oxidized With Torch, Reheated in Argon Furnace to 871 C (1600 F). Then H_2 at 871 C (1600 F) (Shows Severe O_2-H_2 Reaction) (200X)

H_2/O_2 reaction occurred, clearly indicating that surface oxides can be the source of oxygen which diffuses into NARloy and then reacts with H_2 when it is later introduced.

A second specimen was run without the long exposure to high temperature in argon prior to hydrogen exposure. As oxygen diffusion rates are relatively slow, there was some question about the capability to move oxygen into the NARloy in one hydrogen furnace operation. Safety requirements at Rocketdyne dictate that all hydrogen furnace operations employ an argon atmosphere during heating. Hydrogen is introduced only above 760 C (1400 F) furnace temperature. Because the braze tooling used for the combustor segments was massive, the heating rates were slow; a typical brazing cycle required 2-1/2 hours in argon from ambient temperature to 760 C (1400 F) and another 1-1/2 hours in hydrogen to the brazing temperature of 871 to 910 C (1600 to 1670 F). The heating interval in argon might provide the time necessary for oxygen diffusion, while the H_2/O_2 reaction could take place in the subsequent H_2 portion of the cycle. The test specimen was first brazed in hydrogen at 910 C (1670 F) in the normal manner. It was then surface oxidized in air with an oxyacetlene torch until it was discolored but not scaled. The furnace cycle following oxidation was a typical hydrogen braze cycle, duplicating the times in the preceding text. The H_2/O_2 reaction occurred, proving that there is sufficient O_2 diffusion during heating in argon up to 760 C (1400 F) to provide the damaging oxygen in one hydrogen furnace cycle. The results are shown in Fig. 49.

With the mechanism established, it was now possible to reconstruct the fabrication situations which caused the NARloy cracking. Looking at the sequence in Fig. 46, it can be seen that there was no source of surface oxidation in the first two braze cycles, as all NARloy parts were chemically cleaned before the first braze cycle, and the operations between the first and second braze cycle consisted only of mechanical assembly in a clean area. There were no elevated temperature operations and thus no foreign materials introduced at that time. The first opportunity for surface oxidation and diffusion of oxygen into the NARloy-A was the GTA brazing of manifold covers, followed by a stress relief in vacuum or argon, which occurred immediately before the third braze cycle (the joining of the two combustor halves). The stress relief at 885 C (1625 F) provided ample opportunity to drive oxygen into the NARloy.

Either hydrogen or vacuum brazing was used for the third and fourth cycle depending on equipment availability. Subsequent repair cycles also used various atmospheres (hydrogen, argon, or vacuum) so the sequence of atmospheres was not the same for all segments. Regardless of the exact sequence; however, exposure to hydrogen on the third braze cycle or any cycle thereafter appears likely to have caused an H_2/O_2 reaction in the NARloy-A. A review of the furnace records showed that all combustors except six were brazed in hydrogen at some time after the second braze cycle. Table 9 lists the furnace information by combustor segment number, together with an estimate of the probability of the presence of the H_2/O_2 reaction.

PROCESS CYCLE:
1. FURNACE BRAZE H_2 910 C (1670 F) 1 HOUR
2. OXIDIZE BY OXYACETLYENE TORCH
3. REHEAT TO SIMULATE H_2 FURNACE BRAZE CYCLE AT 885 C (1625 F). ARGON USED TO 760 C (1400 F)

Figure 49. Oxidation/Diffusion, H_2-0_2 Reaction Experiment (Shows Severe H_2-0_2 Reaction at Grain Boundaries)

TABLE 9. AEROSPIKE THRUST CHAMBER REPAIR SUMMARY OF FURNACE CYCLE HISTORY ON SEGMENTS

	Segment No.	Number of Cycles in H_2	H_2 on 3rd Cycle or After	Likely to be Free of H_2 Embrittlement?
	507	5	Yes	No
	508	4	Yes	No
	9	2	Yes	No
	10	3	Yes	No
Segments on 25K Assembly	11Δ	2	No	Probably Good
	12	4	Yes	No
	13	4	Yes	No
	14Δ	4	Yes	No
	15Δ	5	Yes	No
	16	4	Yes	No
	17	3	Yes	No
	18Δ	1	Yes	No
	19	2	No	Probably Good
	20	1	No	Probably Good
	21	2	Yes	No
	22	1	No	Probably Good
	23	1	No	Probably Good
	24	1	Yes	No
	25	0	No	Definitely Good
	26	1	Yes	No
	27Δ	1	Yes	No
	28	1	Yes	No
	29	1	Yes	No
	30	1	Yes	No
	31	1	Yes	No
	32	1	Yes	No
	33	2	Yes	No
	34	1	Yes	No

ΔRemoved from assembly after fire

It was important for program reasons to determine how many of the segments exposed to hydrogen were affected by the hydrogen/oxygen reaction. A metallographic sampling plan was devised for this purpose. Segments 507 and 510, with known cracks, were sampled in multiple locations, and several other segments were sampled in one location each from the outer coversheet and liner. The results are listed in Table 7 and photomicrographs not already displayed are presented in Fig. 50 through 59. Segment 507 had extensive cracking on the inner liner's oxidizer coversheet, yet samples from the outer liner showed no O_2/H_2 reaction. The reverse was true of segment 510; cracks were found near both aft end edges of the outer coversheet, but a sample from the inner coversheet and liner showed no H_2/O_2 reaction. This evidence indicated that the varying fabrication histories of individual segments resulted in unpredictable local H_2/O_2 reaction areas which cannot be detected by any simple sampling technique. However, the sampling results of Table 7 agree fairly well with the furnace records of Table 9, i.e., the segments exposed to a hydrogen brazing atmosphere after the second cycle all showed some evidence of H_2/O_2 reaction (segment 518 may be an exception), and the segments not exposed to hydrogen had no reaction. The overall conclusion with regard to usability of segments was that no reliable metallographic sampling plan is possible to prove that no H_2/O_2 reaction has occurred. All segments exposed to hydrogen after the second braze cycle must be assumed to have some areas of reduced ductility due to the H_2/O_2 reaction.

The NARloy-A cracking investigation resulted in the termination of the program. Of the 19 remaining combustors on the thrust chamber assembly, only 5 could be counted upon to be free of the reduced strength and ductility caused by the presence of the H_2/O_2 reaction. Of the five combustors in work for replacements, only one was sure to be free of the reaction. Experience during the repair effort on 507R and 510R had demonstrated that the presence of the chains of voids caused by the O_2/H_2 reaction could result in cracking during cryogenic cycling. Such cycling was an inescapable part of the planned test program, so the risk of cracks and test stand fires if the existing combustors were used was too great to permit program continuation.

Figure 50. Section From outer Half of Segment 504 (No O_2-H_2 Reaction Present) (200X)

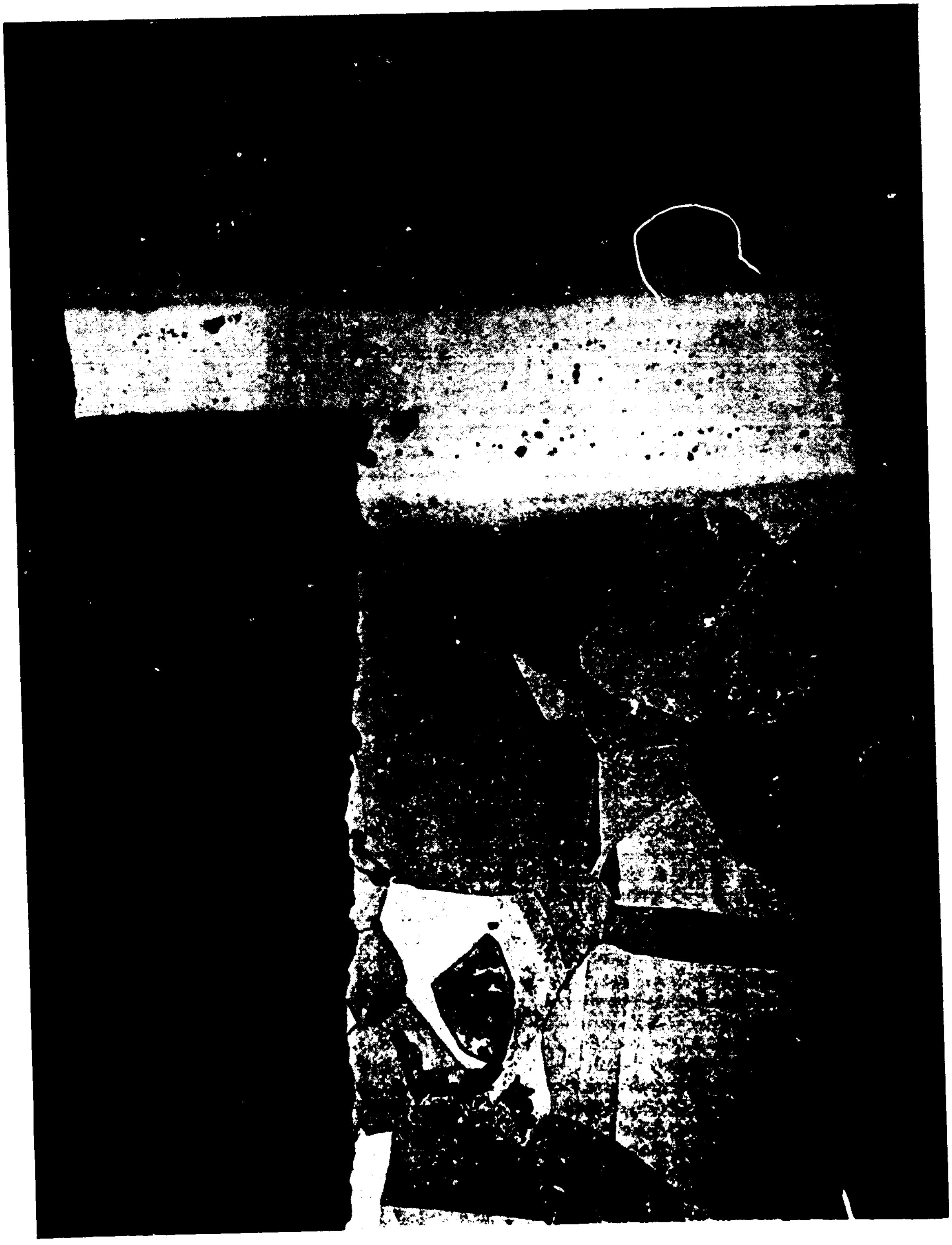


Figure 51. Section From Outer Half of Segment 507 (No O_2-H_2 Reaction Present) (100X)

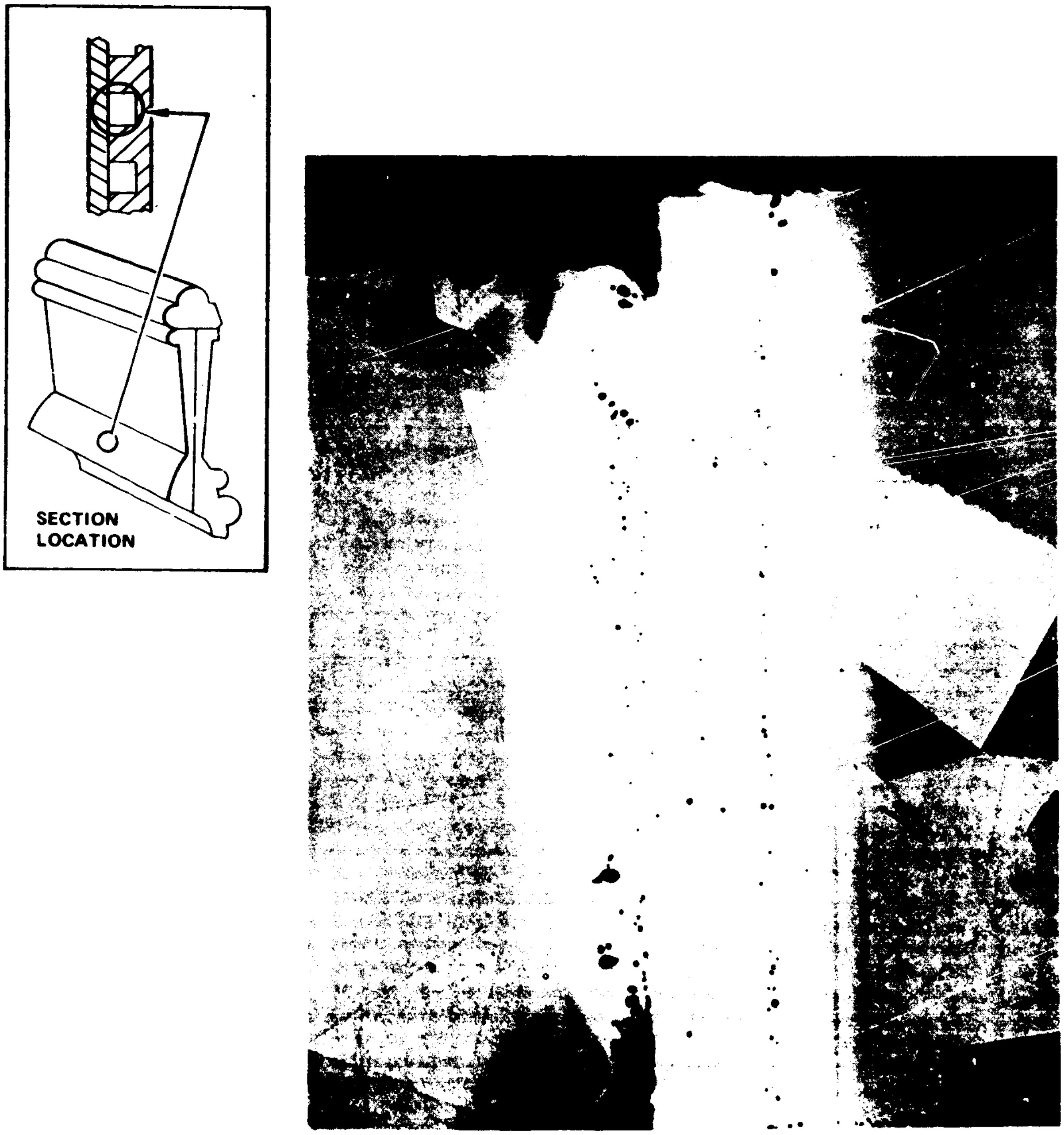


Figure 52. Section From Center of Outer Half of Segment 510 (No O_2-H_2 Reaction Present) (200X)

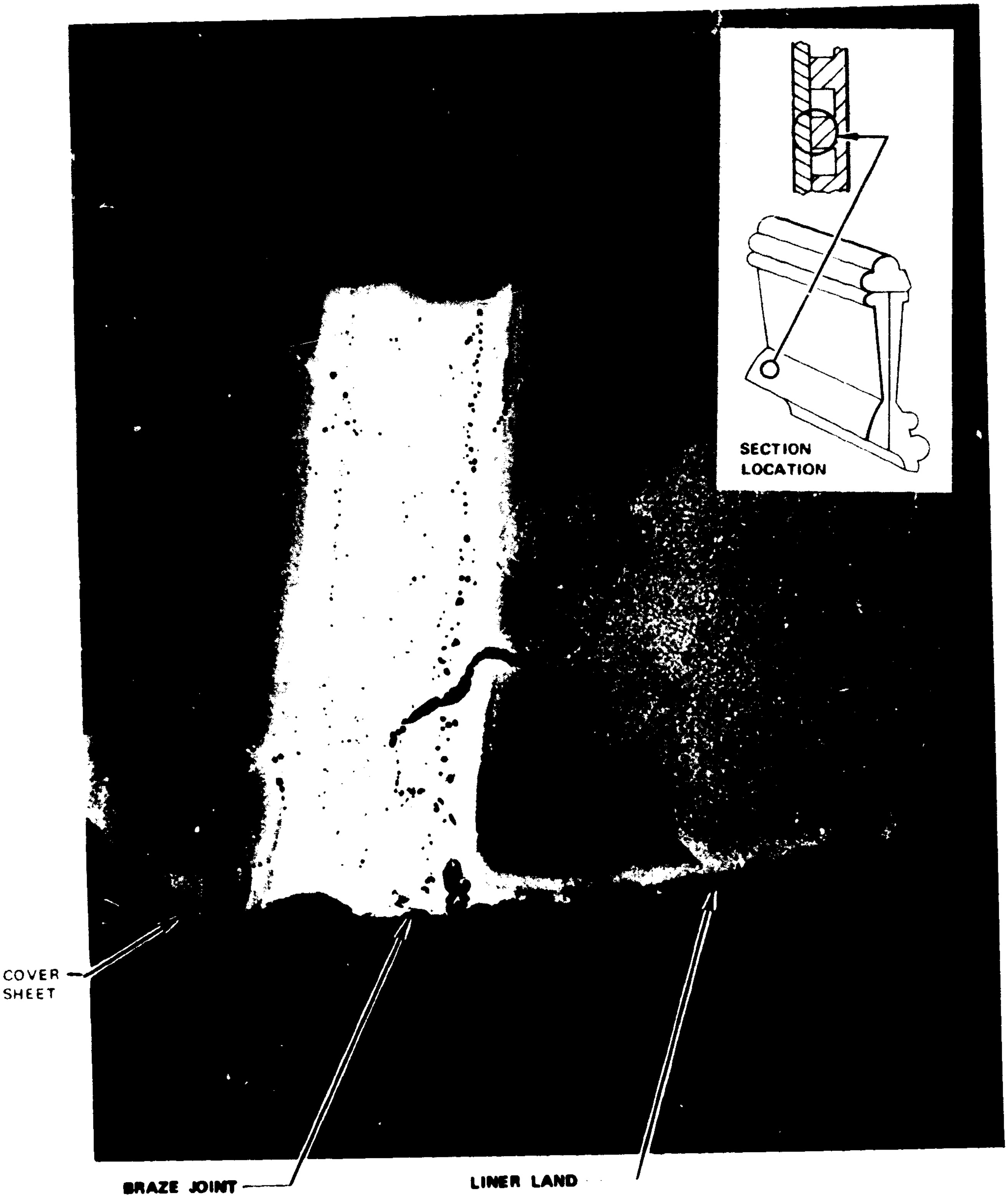


Figure 53. Section From Outer Half of Segment 512, Showing Severe O_2-H_2 Reaction (100X)

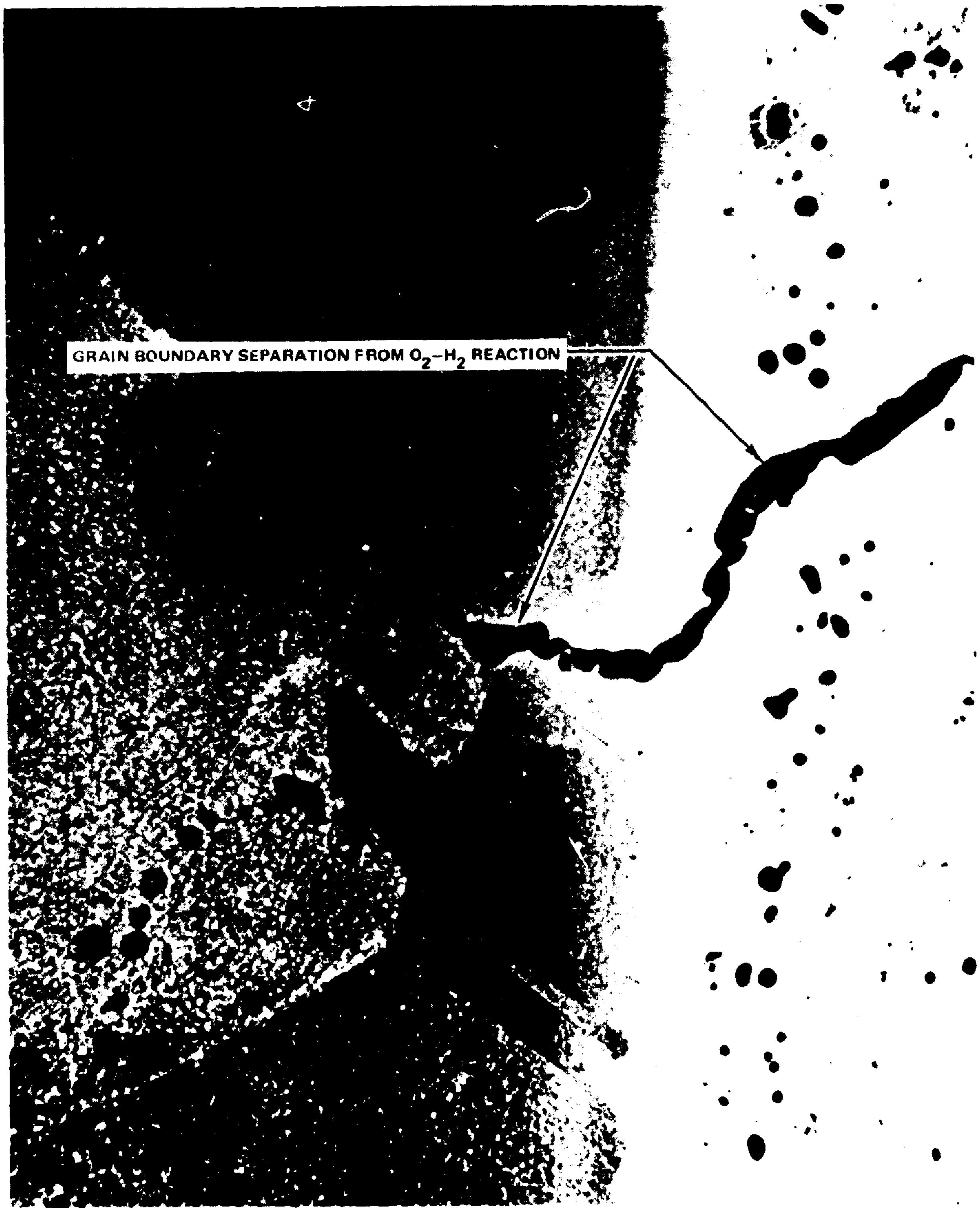


Figure 54. Section From Outer Half of Segment 512, Showing Severe O_2-H_2 Reaction (400X) (Blowup of Fig. 53)

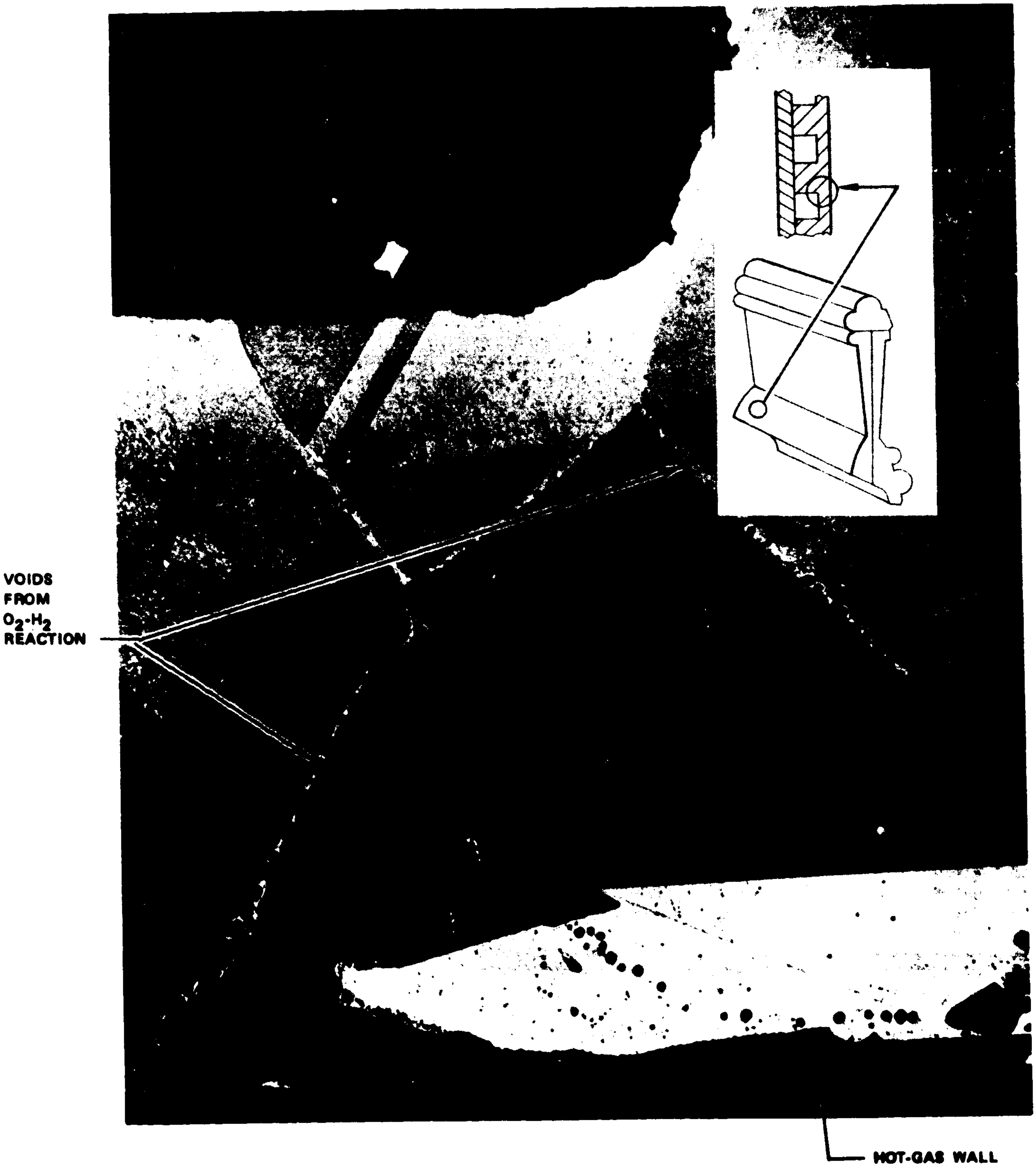


Figure 55. Section From Outer Half of Segment 514 Showing Severe O_2-H_2 Reaction (200X)

Figure 56. Section From Outer Half of Segment 518 (100X)

Figure 57. Section From Outer Half of Segment 522 [No O_2-H_2 Reaction Present; Same Location on Combustor as Fig. 42 (100X). The Large Section to the Right of the Braze Joint is From the Liner Land.]

Figure 58. Sections From Aft Edge of Outer Cover Sheet on Segment 523 (No O_2-H_2 Reaction Present) (100X)

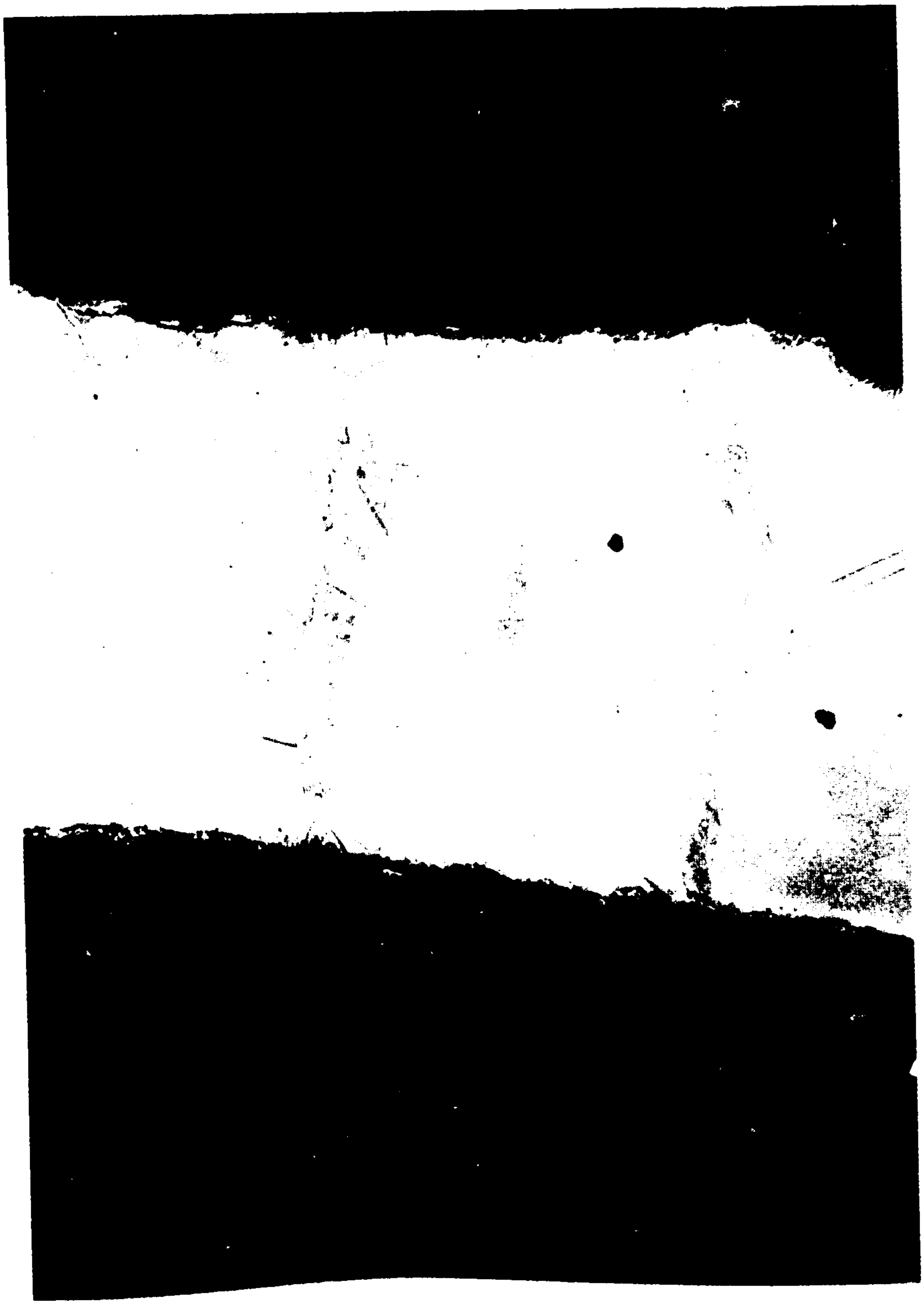


Figure 59. Section From Outer Half of Segment 525 (No O_2-H_2 Reaction Present; Section Shown is Part of a Liner Land) (100X)

NOZZLE REPAIR

BACKGROUND

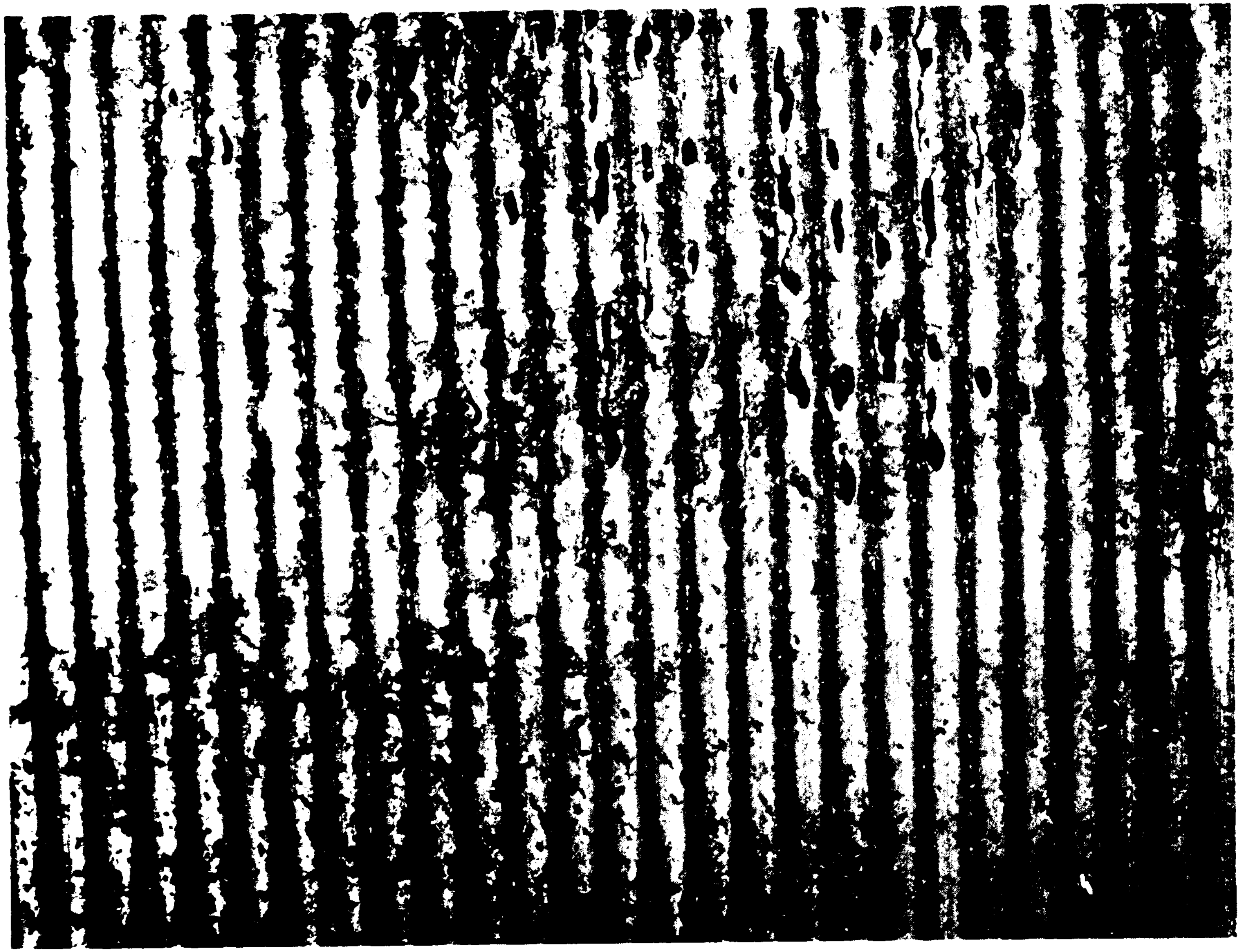
The aerospike thrust chamber assembly is furnished with a tubular truncated spike nozzle which serves to expand the gases leaving the 24 combustor segments. The nozzle is described in the Thrust Chamber Assembly Description section of this report.

During the test stand incident, the nozzle suffered localized heating on its interior portions (i.e., the "cold side"), because it was sprayed with molten titanium from the burning inner combustor support ring. Repairs to this type of tubular nozzle represent a technical challenge, in that the tubes are only 0.13-mm (0.005 inches) wall thickness and have a constant taper from 1.78 to 2.79-mm (0.080 to 0.110 inches) in diameter.

Because of the general need for developing the technology for effecting repairs to complex lightweight tubular nozzles, a company-sponsored technology program was undertaken during CFY 75. Repair techniques were developed first by evaluating candidate methods on sample tubes. When the techniques had been brought to the stage that they appeared reasonably reliable, they were applied to the aerospike thrust chamber nozzle. By the time the current contract began, the major portion of the work of physically repairing the nozzle tubes of the aerospike chamber had been completed. The nozzle repairs continued to be conducted under company sponsorship during the present contract. The activities and results on nozzle repair are reported here for information purposes.

An illustration of the general damage suffered by the thrust chamber during this incident is shown in Fig. 25 and a closeup of the typical tube damage suffered by the nozzle tubes is shown in Fig. 60. The pattern of tube damage is catalogued and shown in Fig. 61. Basic tube repair techniques were partially developed during CFY 75. Two methods of repair were applied, the saddle-patch repair and the inserted tube repair. Figure 62 describes the two methods in sketch form. For the saddle-patch approach, a nickel sheet of 0.2 to 0.25-mm (0.008 to 0.010 inch) thickness is used. Each saddle-patch is formed to the contour of the tube and is brazed to the tube with an oxyacetlylene minitorch, using EASY-FLO No. 3 braze alloy. The tube insertion repair method requires grit blasting to clear the oxides from the inner surface of the tubes and also to clear the zirconium oxide from the outer hot gas surface of the tubes. The damaged area is then cut out (like a window), and the tube ends are cleaned and deburred. New tapered tubes are inserted in place with a 1.02 to 1.52-mm (0.040 to 0.060 inch) overlap at each end. Nickel shims are wedged between each tube to fill the gaps, then flux is applied and the tubes are brazed in place, again using the oxyacetyline minitorch and the EASY-FLO No. 3 braze alloy.

Experience early in the repair development activities brought out one of the limits of the **saddle-patch repair technique.** From this series of tests,



1EH35-3/13/75-C1C

Figure 60. Typical Nozzle Tube Damage

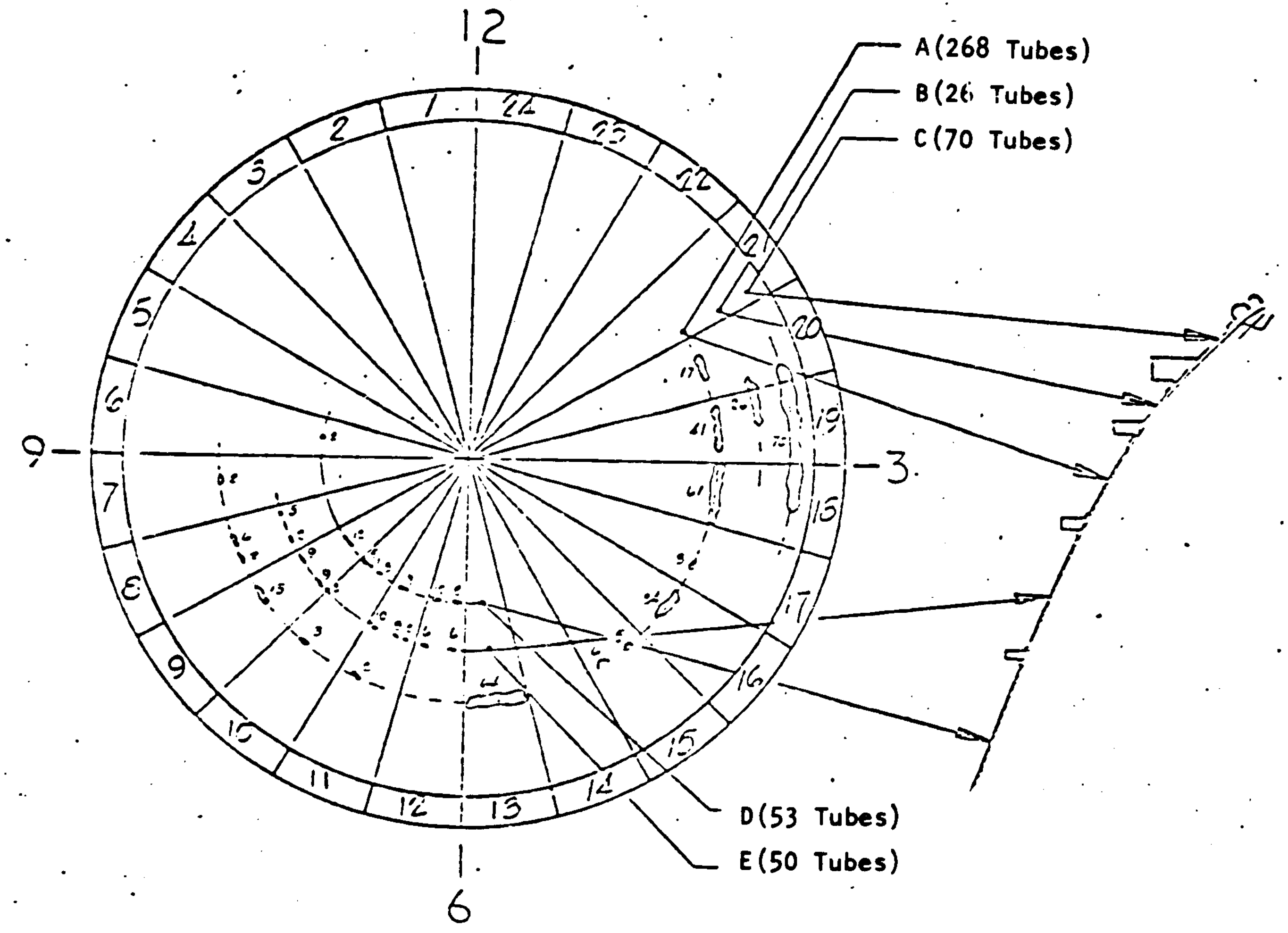


Figure 61. Location of Tube Damage

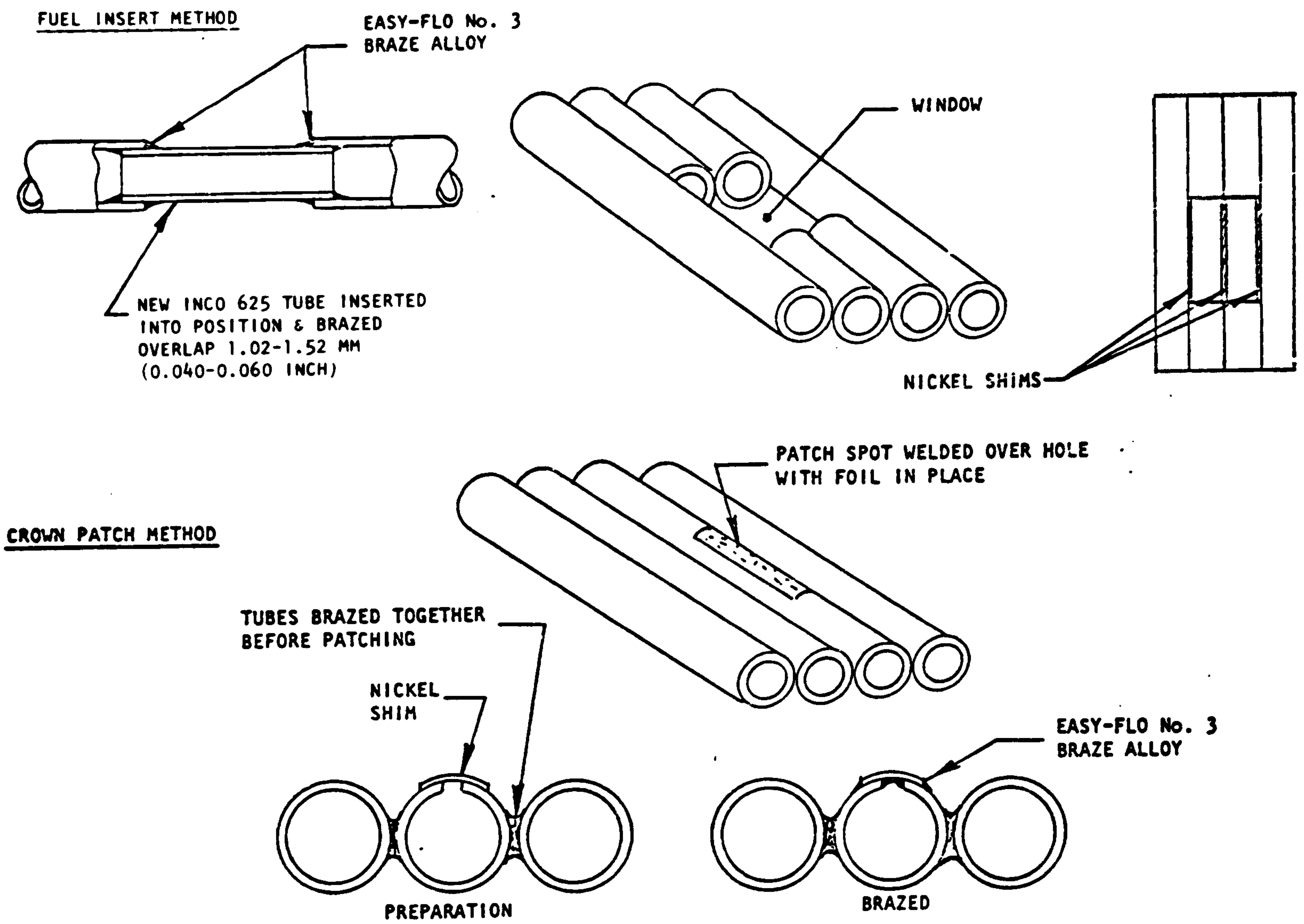


Figure 62. Tube Repair Methods

it was concluded that the size of the saddle-patch should be limited to 12.70 mm (1/2 inch) in length, and that each patch must fit so as to be accessible to the flow of braze alloy on all the four edges, i.e., to avoid the overlap indicated in Fig. 63.

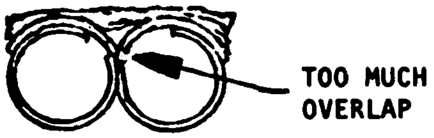


Figure 63. Improper Saddle Patch Condition

During the current contract, repairs to all tubes in which leaks could be identified were completed. A total of 1053 saddle-patches were applied along with 155 tube inserts. The tube inserts were applied in 18 different window locations. Repairs were also made to the burned-out section of the Inconel 718 hatbands.

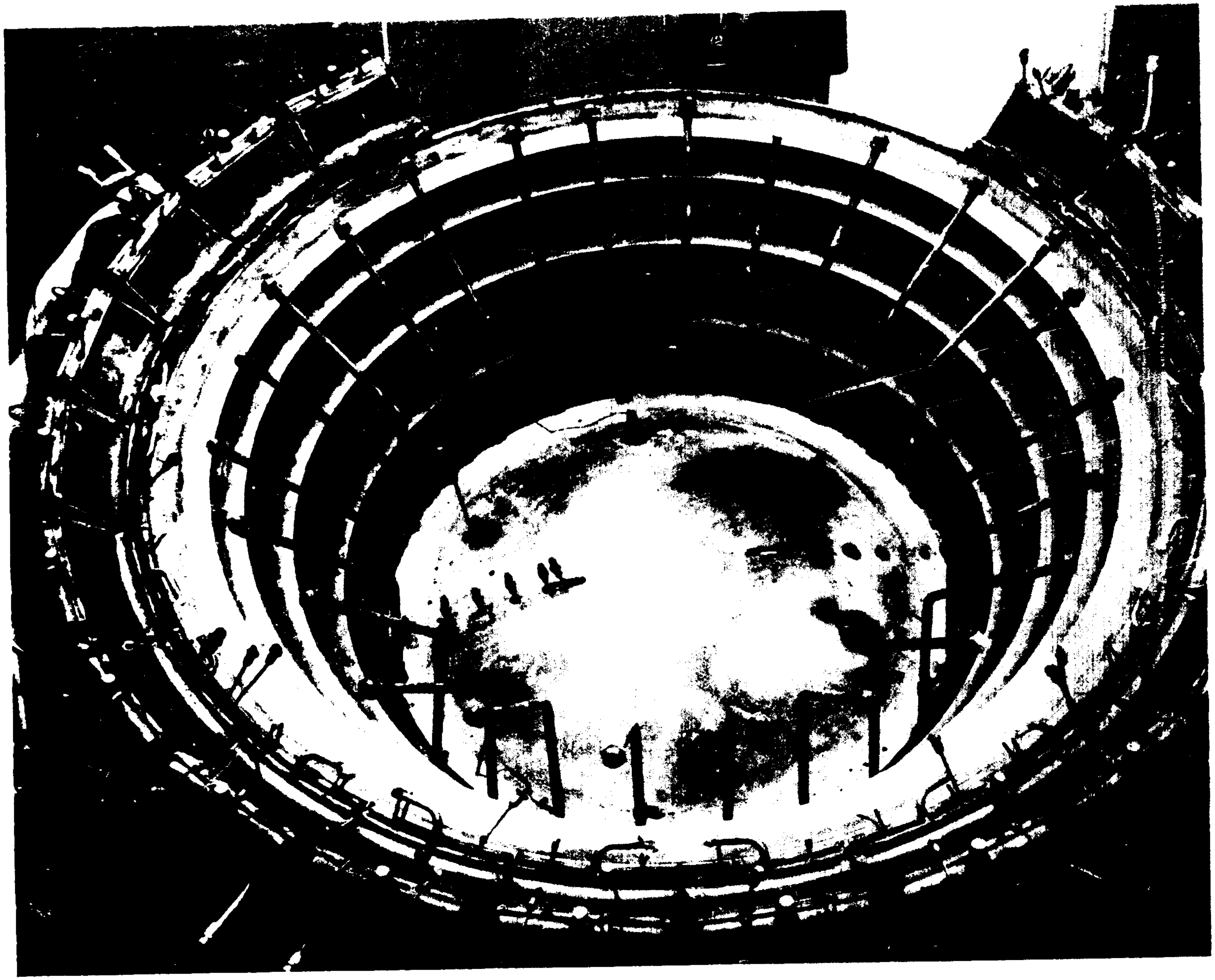
As a finish to the repair, and to pick up minute leaks and reinforce areas that had been thinned but not actually holed through, the repaired nozzle surface was grit blasted to prepare it for adhesion and then plasma sprayed with an approximately 0.10-mm (0.004-inch) thick layer of nickel/chromium alloy. A photo of the repaired nozzle is shown in Fig. 64.

Several techniques were developed to assess the quality of the repairs and their suitability for withstanding the severe conditions encountered during hot firing. Each of these quality assessment techniques is described separately below.

Leak testing appeared to be most practically conducted with relatively low pressure shop air, on the order of 689 kPa (100 psig), and leak detect solution. Higher pneumatic pressures were considered unsafe for close access and, while higher hydrostatic pressures were available, leaks were very difficult to pin-point under hydrostatic pressure alone.

Hydrostatic pressure testing was utilized to determine the ultimate structural capability of the repairs. All of the tube repairs on the nozzle were subjected to 6 895 kPa (1000 psi) hydrostatic proof test. Additionally, a test segment was isolated and subjected to a 20 684 kPa (3000 psig) hydrostatic test. It had been intended that the entire assembly received a 24 821 kPa (3600 psi) hydrostatic test, but the accompanying aerospike thrust chamber repair and firing program was terminated before the assembly was brought to the condition where the 24 821 kPa (3600 psi) pressure test could be conducted.

When a nozzle is fired as a portion of a cryogenic thrust chamber assembly, it is subjected to some rather severe temperature excursions. The liquid hydrogen fuel lead will first subject the nozzle tubes to cryogenic temperatures and, after this condition is sustained for a few seconds, the



1XE22-4/19/76-C1A

Figure 64. Completed Nozzle Repair

oxygen will be admitted to the combustor and will rapidly bring the hydrogen coolant to well above ambient temperature. During cutoff, there will be a fuel lag which will again subject the nozzle to cryogenic temperatures. This duty cycle raises a question as to whether the type of nozzle repairs being developed here would be degraded by rapid temperature excursions. Checkout tests were therefore conducted to evaluate this effect. Liquid nitrogen was flowed through the nozzle inlet manifold for sufficient time so that liquid nitrogen was seen to leave the nozzle aft collection manifold. When liquid flow had been established, the feed was cut off and the nozzle permitted to warm up to ambient temperature. This procedure was repeated three times. Leak testing was then conducted after the cryogenic shock excursion and indicated that all repairs had come through the procedure without damage, except for one of the locations where the tube insert type of repair had been utilized. For this tube insert patched area, there had apparently been insufficient braze penetration between the inserted tube and the parent tube so that the inserted tubes pulled loose, and small leaks ensued. Additional braze was applied to this area and the defect corrected. Cryogenic shock testing is thus established as a useful technique for evaluation of tubular nozzle repairs.

Both of the repair techniques under development involved the application of braze alloy to the tube and patch and, therefore, they present some risk that "dropthrough" of the alloy will significantly increase the resistance of the tube to the cooling hydrogen flow. Because of this possible hazard, each of the repaired tubes was flow checked utilizing the technique illustrated in Fig. 65. Additionally, a representative sample of tubes that had not required repair were flow checked to establish a base condition. In utilizing this technique, one relies upon the condition that the static pressure at each tube exit is very close to atmospheric, and that all the tube exit areas are nearly equal. The square root of the total pressure measurement detected by the impact tube is therefore an indicator of the relative weight rate flow of air through the tube being probed. The air pressures throughout the nozzle system are all low, on the order of 14 kPa (2 psig), so that there is no possibility of choking in any location. In this respect, the flow conditions are consistent with those existing in a hydrogen-cooled nozzle, and the flow distribution in the test setup will closely simulate the firing condition. By the method described, it was possible to estimate the average flow through all the tubes in the nozzle and then, by comparison, to evaluate the reduction in the flow of those repaired tubes whose resistance had been affected by the repair activity. The results of this air flow check indicated that the tube repair techniques did not result generally in a gross reduction of flow in the repaired tubes as compared to the unrepaired tubes. This can be seen in the plot of Fig. 66 for the nozzle tubes in line with one of the 24 aerospike combustors. The unrepaired tubes are identified with a black dot. However, a number of repaired tubes did show a significant flow reduction so that it was necessary to establish a criterion for acceptability and to rework those tubes whose flow fell below this criterion. For this particular nozzle, it was possible to establish the criterion that no tube would be

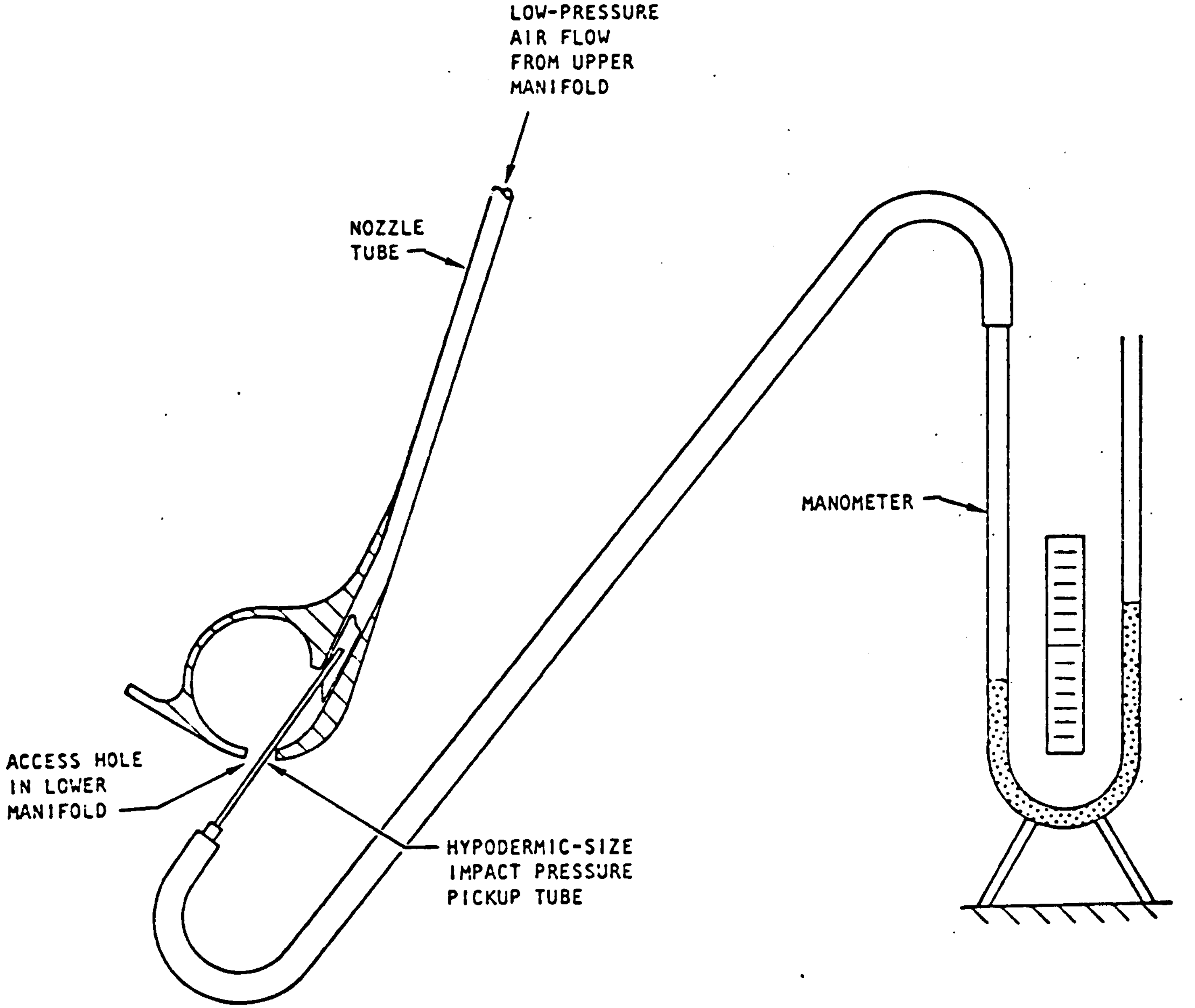


Figure 65. Air Flow Measurement to Detect Nozzle Tube Flow Restrictions

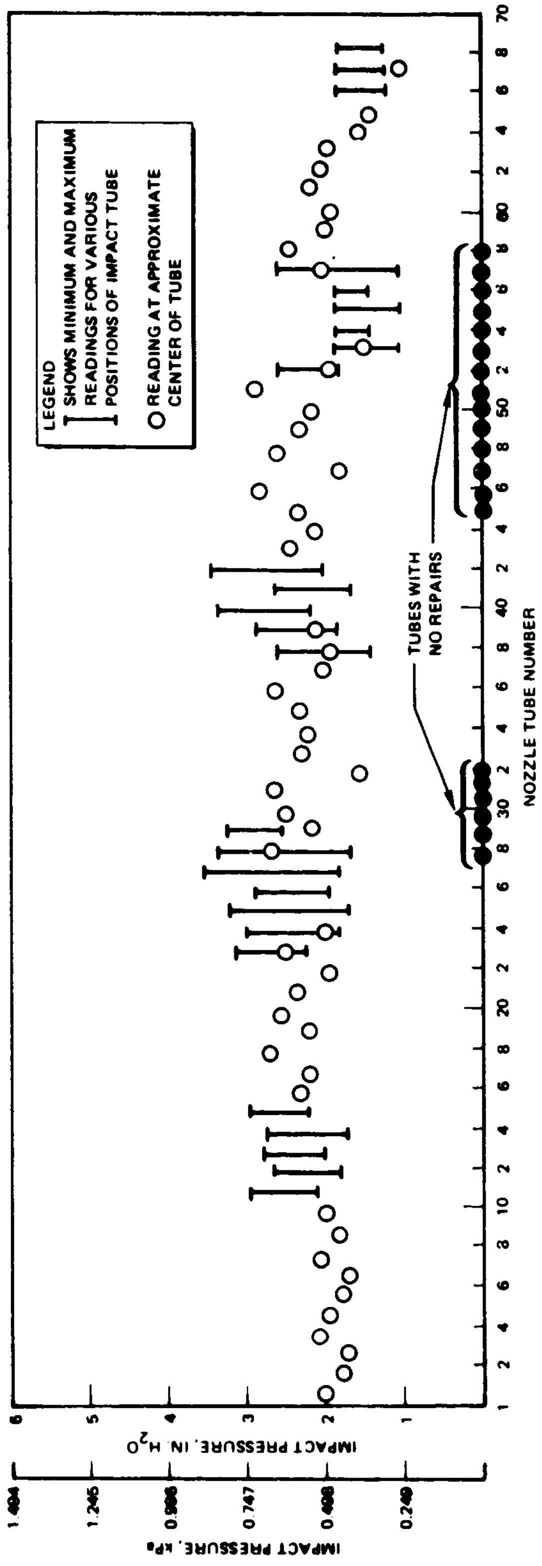


Figure 66. Typical Results -- Flow Check of Repaired Nozzle Tubes, Unit 526

accepted whose flow was less than 65% of the average flow in all the tubes. The acceptable flowrate was based on the calculated heat transfer conditions and stresses projected for operation. Twelve of the repaired tubes were reworked to meet the criterion.

Quality evaluation via X-ray was also found to provide useful information. The braze alloy placement is readily determined in that the braze alloy is seen on the X-rays as a light area. X-rays permit evaluation of the adhesion of saddle-patches and the degree of overlap, and braze penetration into the joints of tube insert repairs.

CHAMBER SUPPORT STRUCTURE

BACKUP RINGS

The 24 combustors, and the aerospike nozzle to which they are attached, are supported by being sandwiched between titanium rings that serve to position the combustors correctly on the nozzle. The rings accept the thrust generated by the combustors and the nozzle and transmit that thrust to a central gimbal bearing. The inner ring of this two-ring assembly was so seriously damaged during the fire that had terminated the previous test program that the ring had to be replaced rather than repaired. It had already been demonstrated on the previous contract that a sufficiently lightweight construction for this ring could be designed and fabricated, so it was decided on this contract that the replacement ring would not exactly duplicate the previous design. It omitted some of the intricate but weight-saving machining that tends to add materially to cost and schedule time. A new design, No. RS003737X, was made to define the configuration of the new inner backup ring. A copy of the drawing is incorporated in Fig. 67 of this report. A titanium forging from which this ring could be machined was available from the previous program. A five-axis, numerically controlled milling machine was utilized for machining the lightening holes, and a VTL tracer lathe was used for the external contour. A photo of the completed ring is shown in Fig. 68.

The outer backup ring was to be repaired by weld buildup of the location showing minor burn damage and by welding in a segment to replace the one area that suffered major burn damage. Photos of the outer backup ring showing the areas that sustained damage during the test stand fire are presented in Fig. 69 and 70. A fabrication experiment was conducted in which samples of titanium backup rings obtained from existing ring segments were welded in a controlled atmosphere box (argon), under conditions duplicating as closely as possible the physical conditions that would exist when repairs were made to the actual backup ring. The weld samples were then sectioned and subjected to tensile testing. Section examination and tensile tests showed that the weld properties were well above the minimums required for adequate strength in the locations to be welded on the actual backup ring. Drawing RS005333X, which is presented in this report as Fig. 71, was then released to define the backup ring repair procedure. Repair effort on the actual outer backup ring was never carried out because fabrication effort was stopped by the combustor problem.

THRUST CONE AND SUPPORT STRUTS

The structure that carries the thrust from the inner backup ring to the gimbal bearing is illustrated in Fig. 27. As can be seen, a number of titanium struts carry the load in tension from the backup ring to the base of the thrust cone, and the cone carries the thrust in compression up to the gimbal bearing. All of these parts were somewhat affected by the fire that had occurred on the previous test. All parts were carefully cleaned and examined. Decisions were made on which parts could be refurbished and

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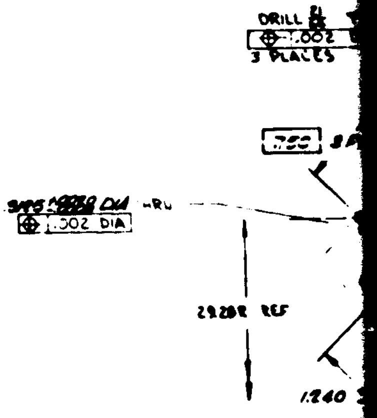
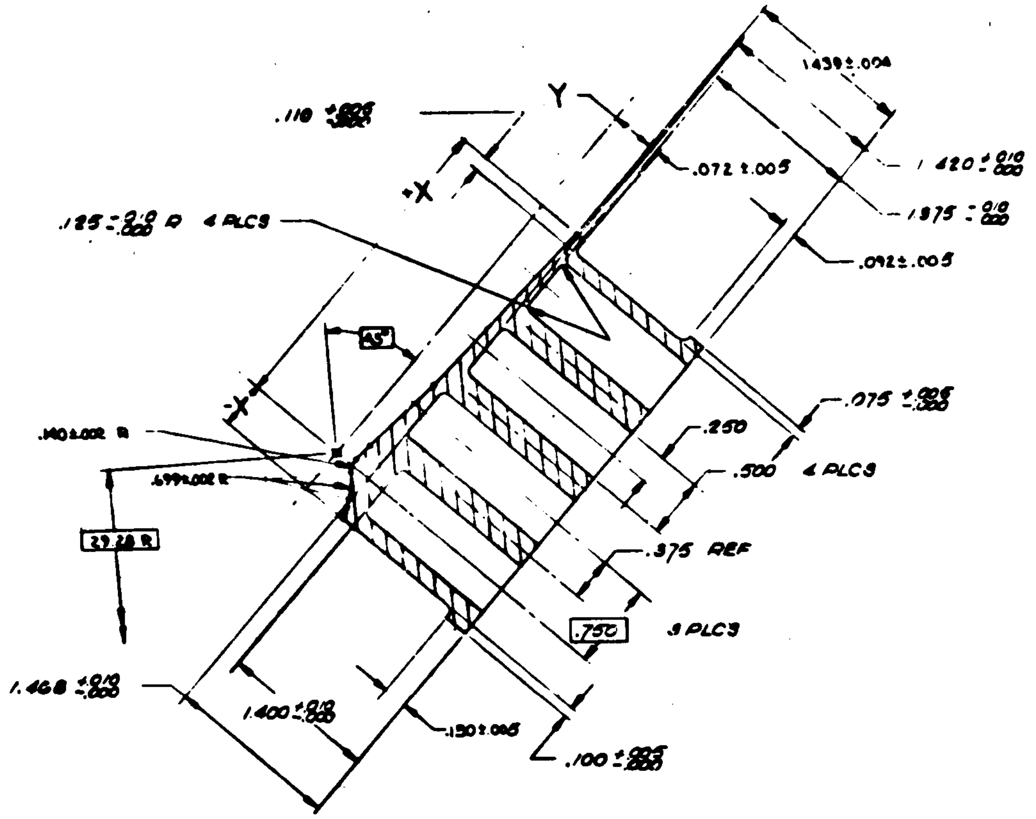
X ±.002	Y ±.002
2.760	.381
.990	.262
.240	.178
.064	.166
-.040	.203
-.245	.334
-.300	.358
-.400	[illegible]





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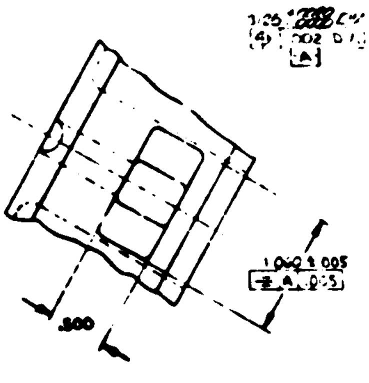
TYP 48 PLACES



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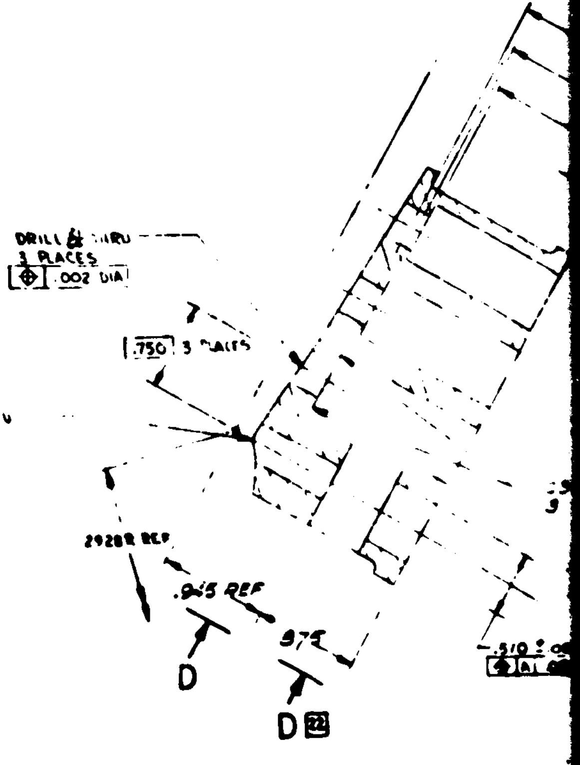

SECTION B-B 13
SCALE 4
TYP 12 PLACES

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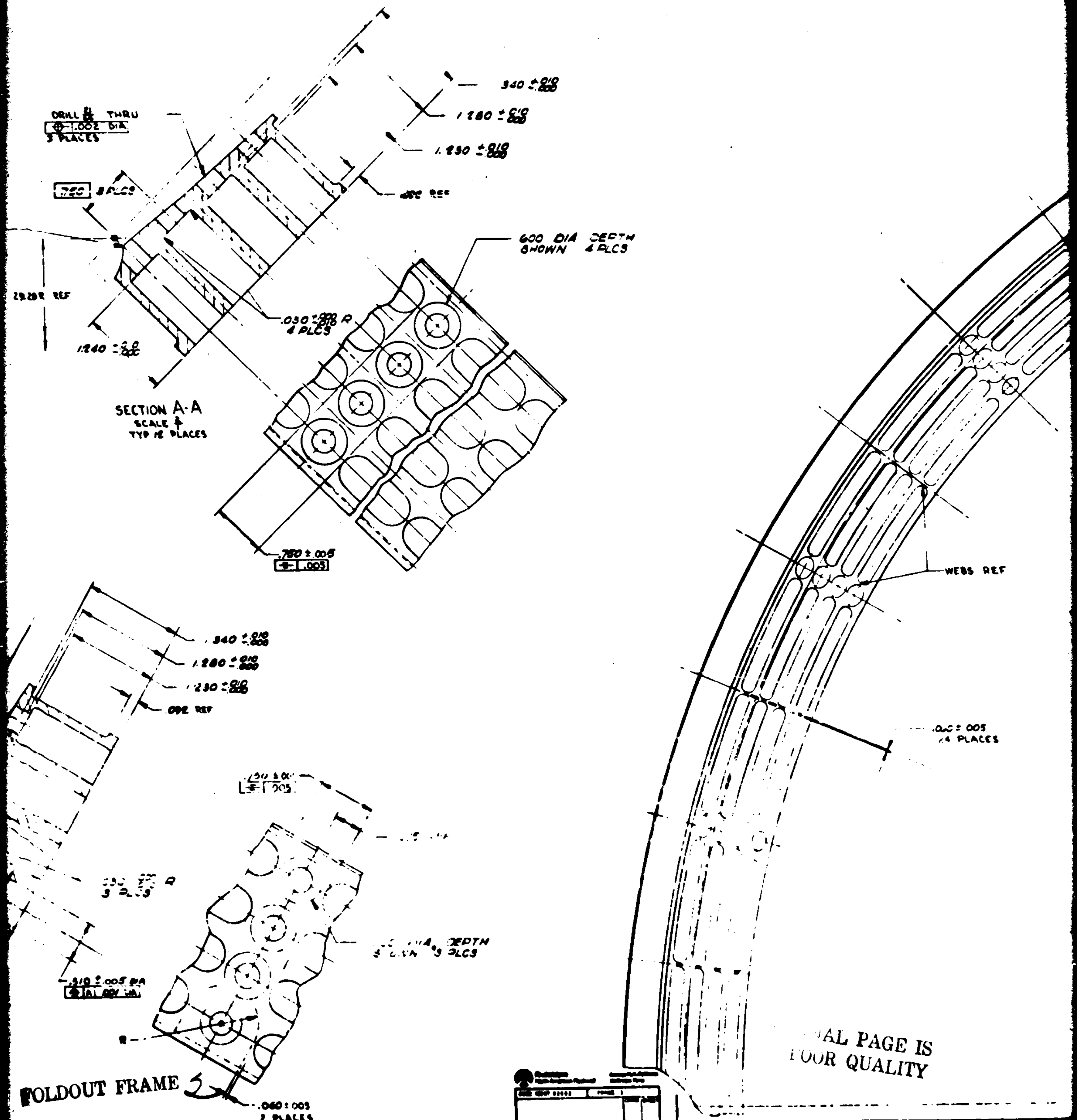

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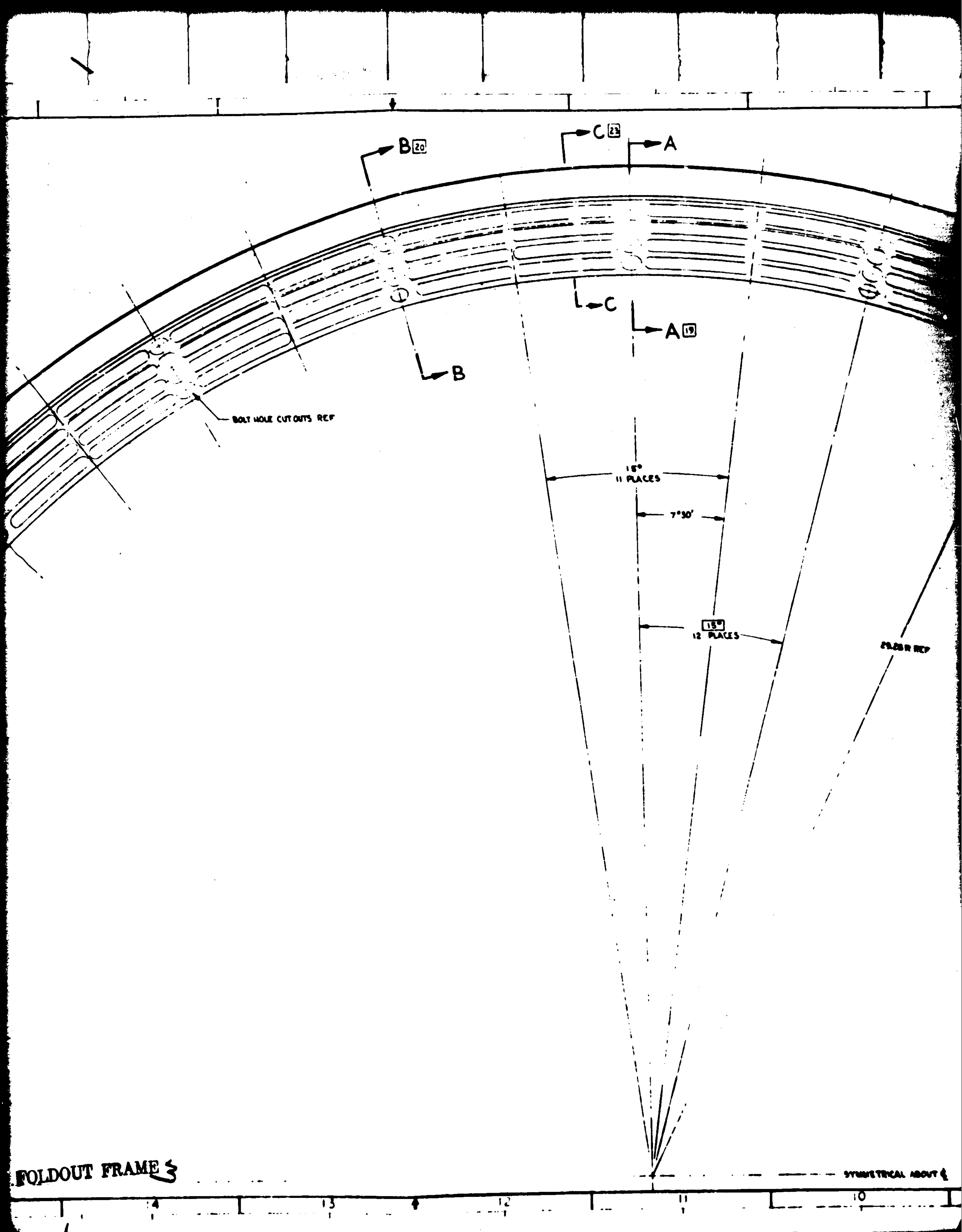

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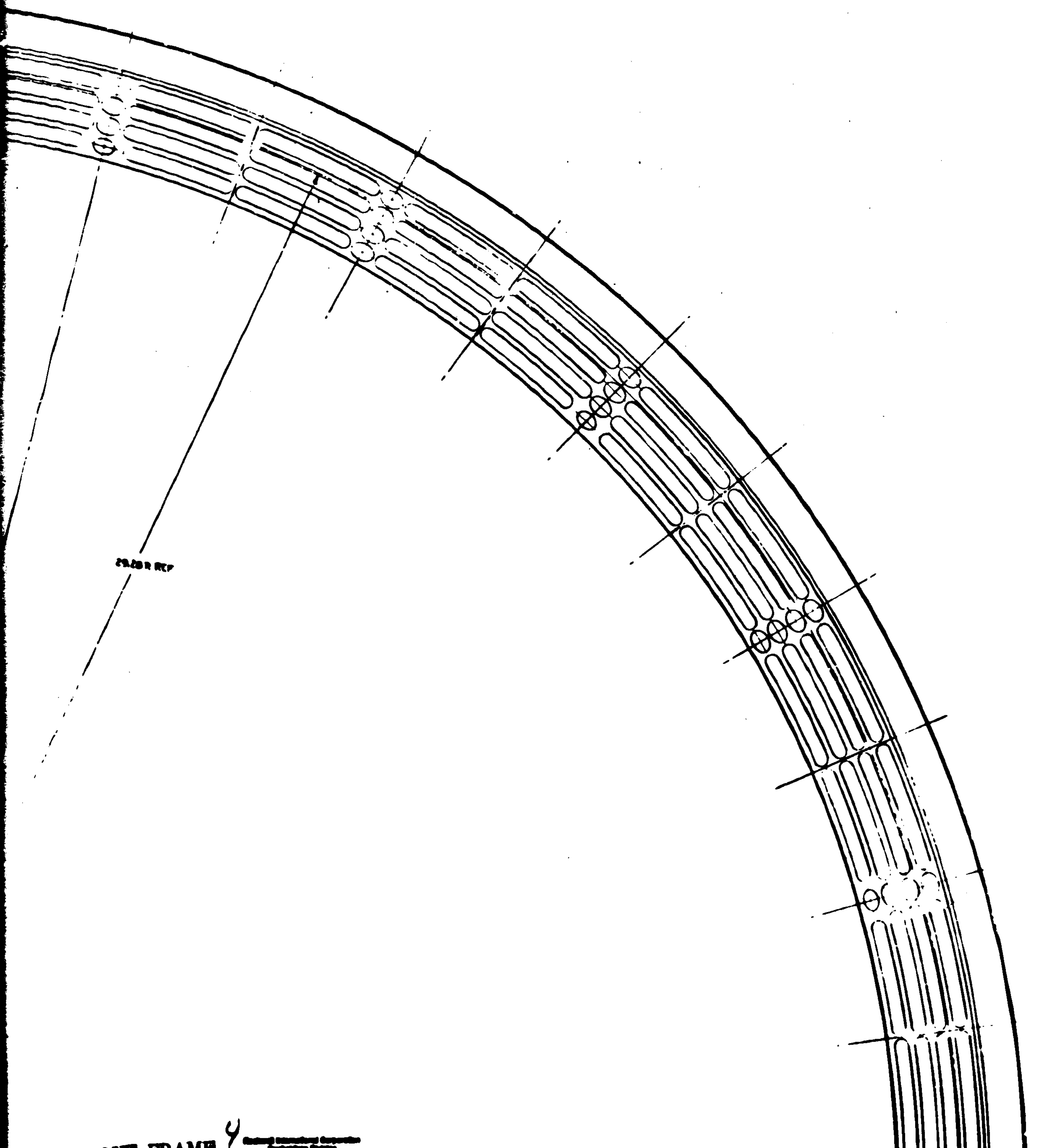

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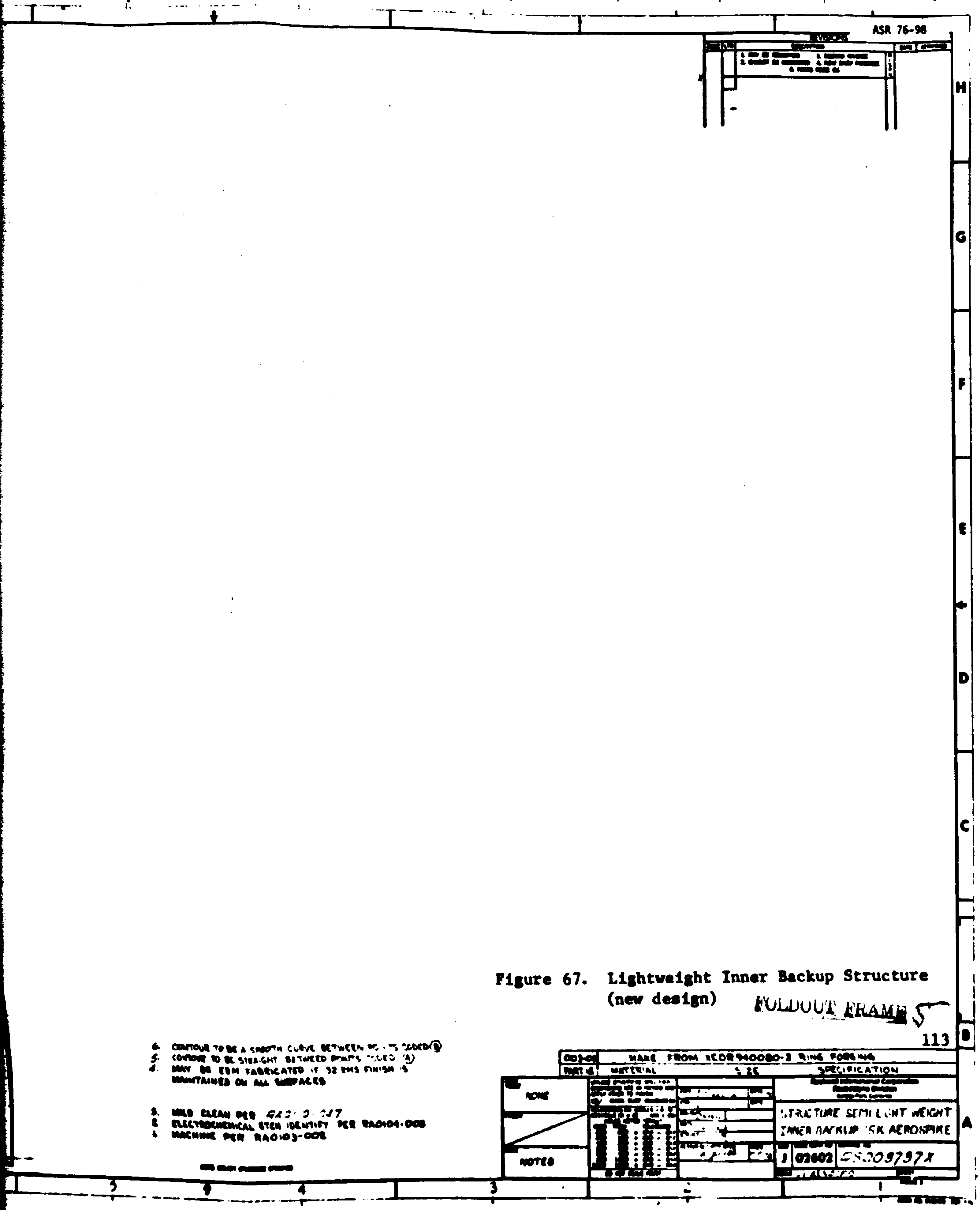

Figure 67. Lightweight Inner Backup Structure (new design)

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6. CONTOUR TO BE A SMOOTH CURVE BETWEEN POINTS CODED (B)
5. CONTOUR TO BE STRAIGHT BETWEEN POINTS CODED (A)
4. MAY BE EDM FABRICATED IF 32 RMS FINISH IS MAINTAINED ON ALL SURFACES

3. MILD CLEAN PER RA0[illegible]
2. ELECTROCHEMICAL ETCH IDENTIFY PER RA0104-008
1. MACHINE PER RA0103-002

003-01 MAKE FROM RCOR940080-3 RING FORGING
PART NO. MATERIAL SPECIFICATION

NONE

NOTES

STRUCTURE SEMI LIGHT WEIGHT INNER BACKUP [illegible]K AEROSPIKE

J 02602 [illegible]S209737X

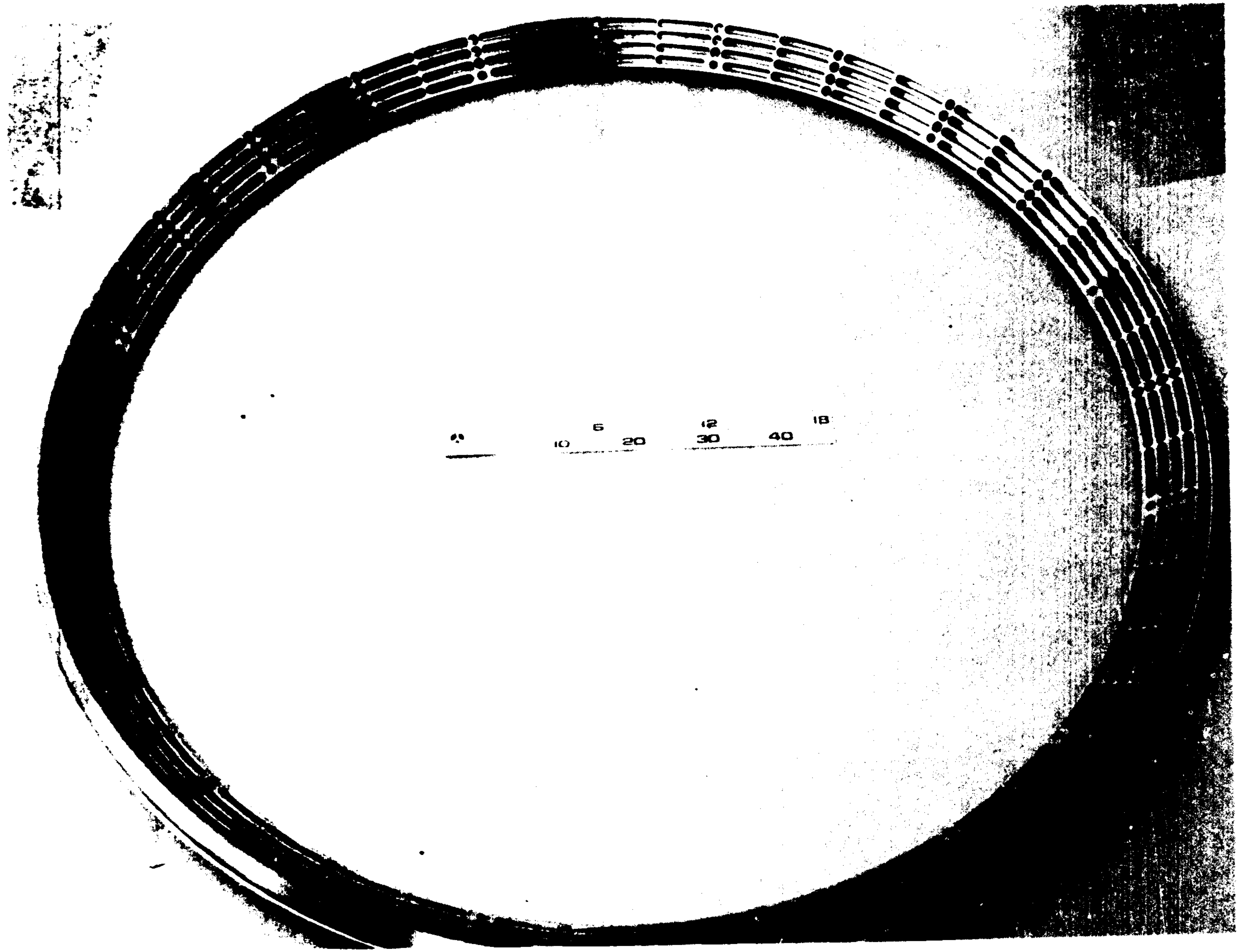

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Figure 68. Completed Inner Backup Structure Ring

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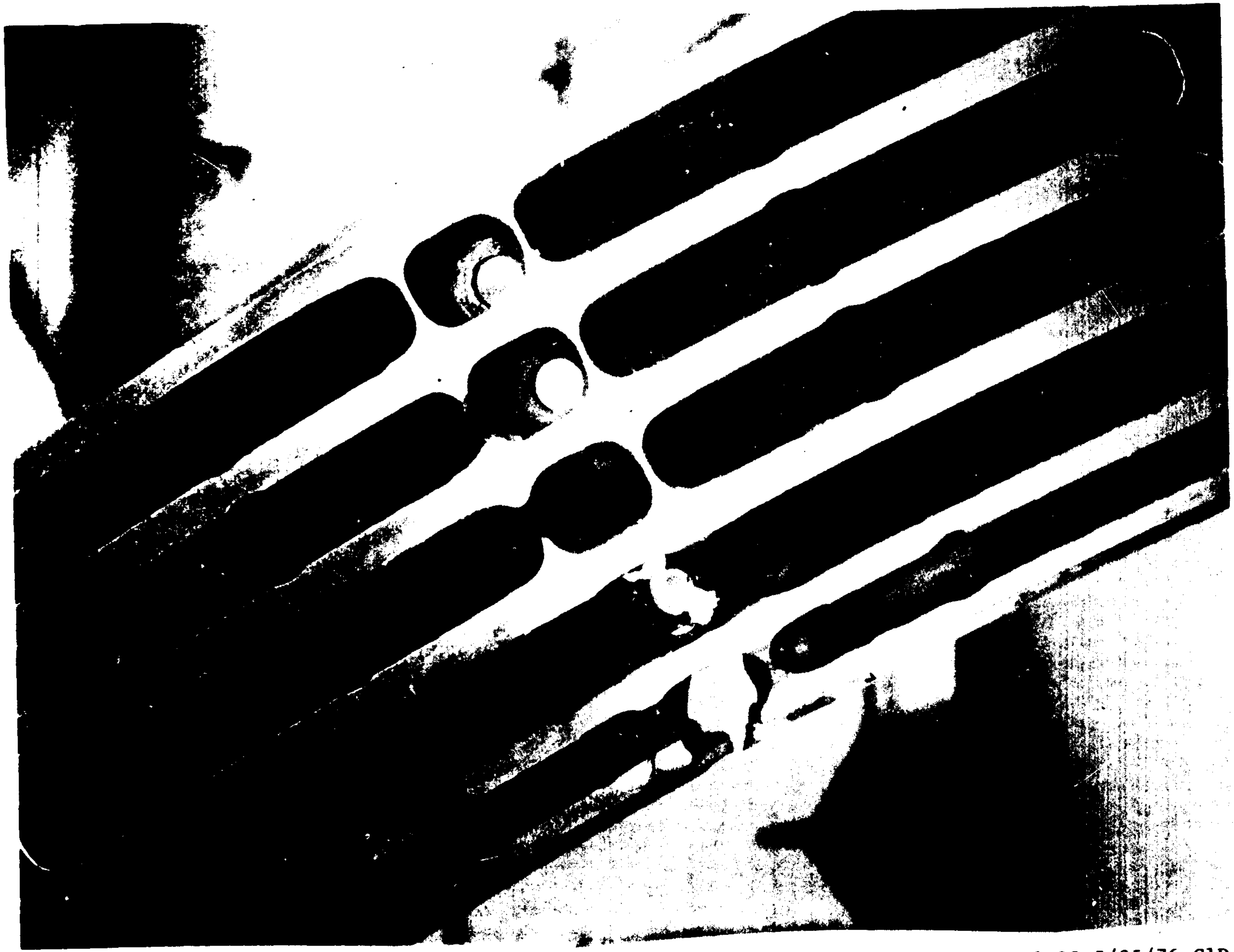
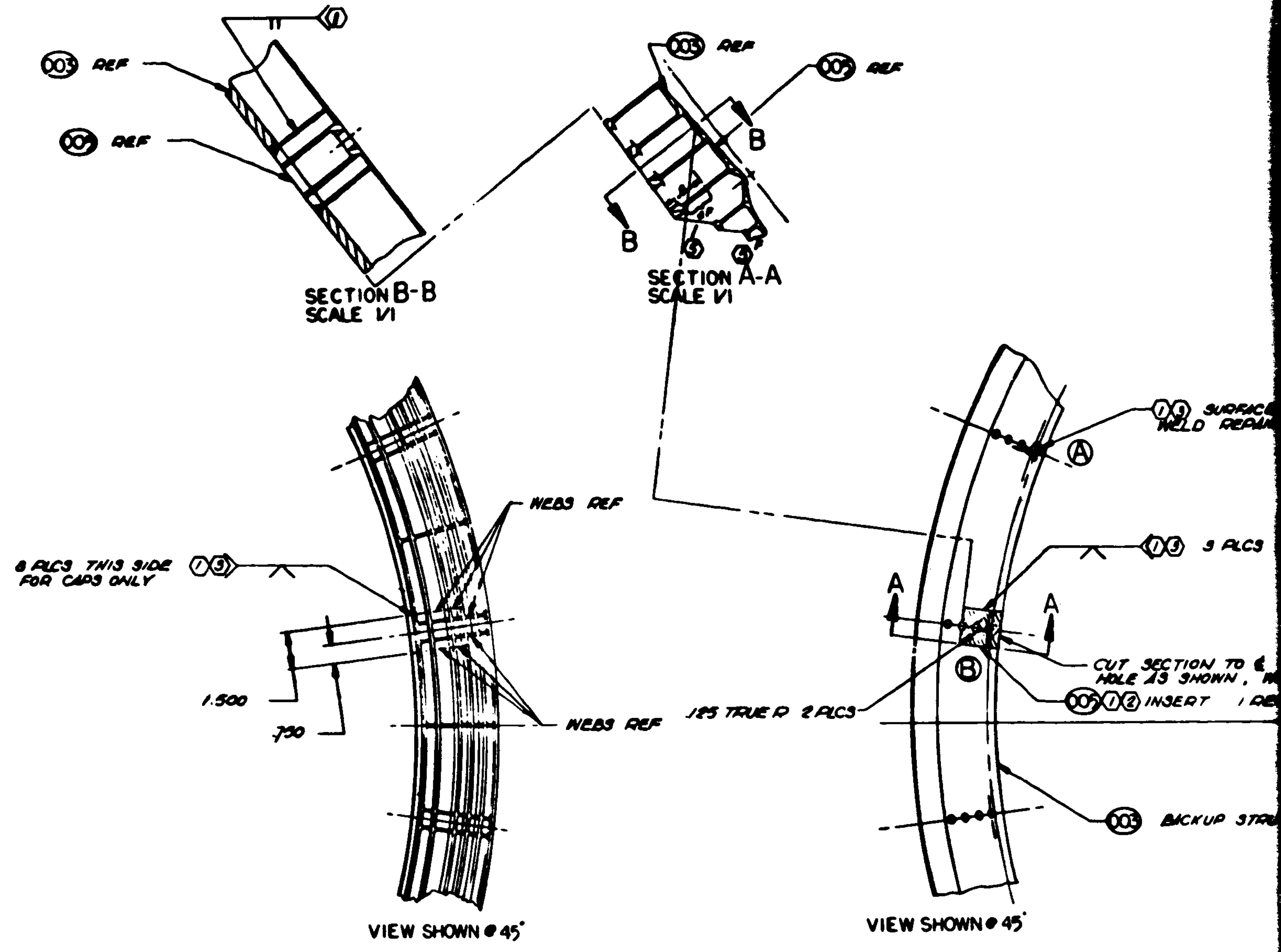
Figure 69. Inner Surface Damage -- Outer Backup Structure



1E22-5/25/76-C1D

Figure 70. Bolt Hole Damage -- Outer Backup Structure



ADD TITANIUM FILLER MATERIAL 6-2-4-2 TO WEB LENGTHS MAX 10 P AND CAPS,
4 MACHINE PER RA0108-002
AFTER WELDING ALL WELDS TO BE GROUND FLUSH WITH EXISTING
INSERT TO BE MADE FROM EXISTING SECTION THEN WELDED IN PLAC
WELD PER RA0107-026, CLASS I. USE ARGON ATM BOX, & WELD PER

ASR 76-169

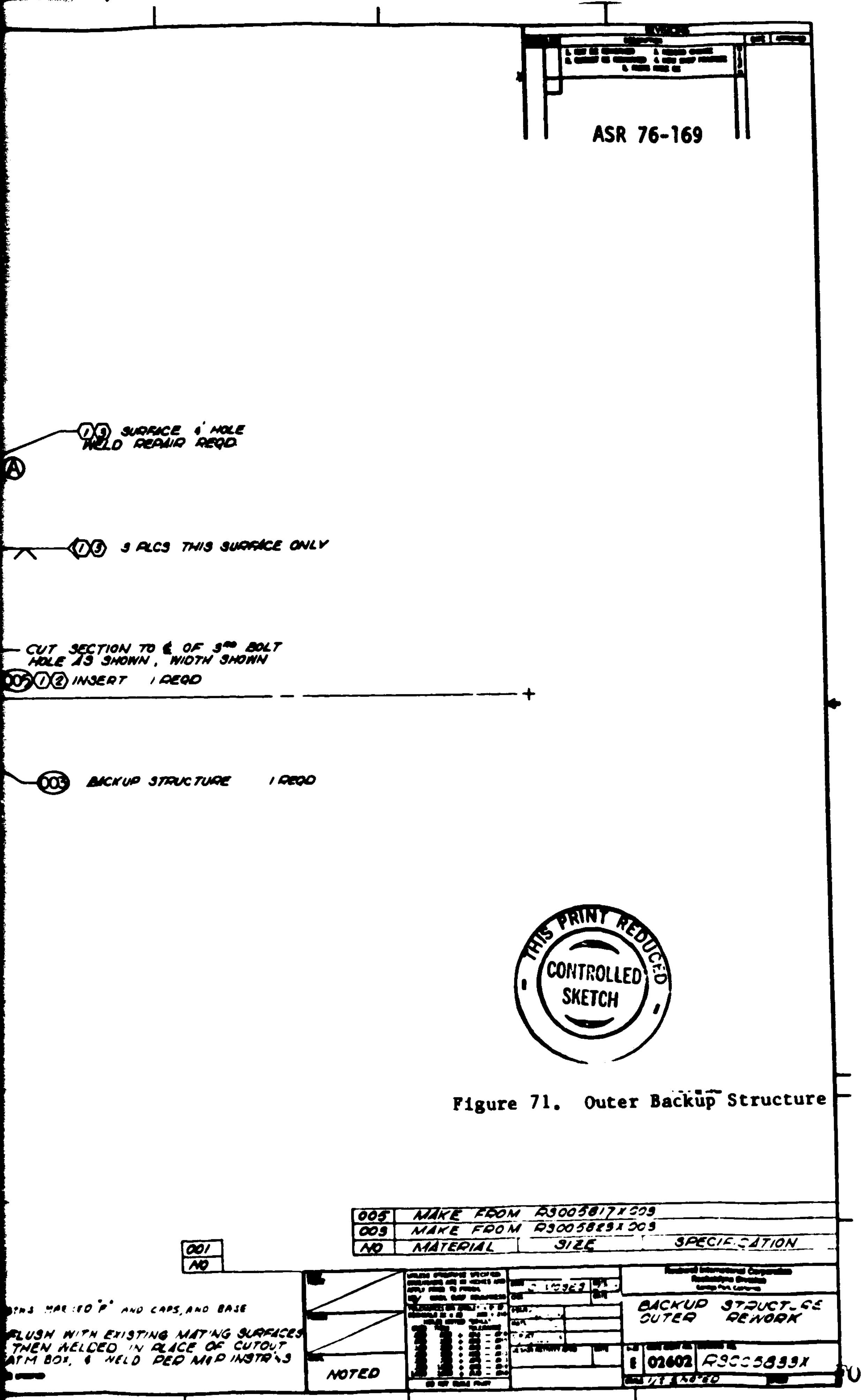


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Figure 71. Outer Backup Structure

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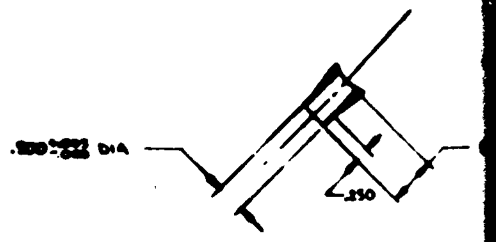
which needed replacement. Refurbishment of this structure was partially completed. The titanium thrust cone and its base were let to a vendor for remanufacture of the base, and its assembly by E-B welding to the existing cone. Work was completed on the thrust cone and it was accepted through inspection at Rocketdyne.

Several of the struts that carry the load from the inner backup ring to the base of the thrust cone were damaged sufficiently in the fire so as to require replacement. The tooling required for jigging during assembly by welding and during the subsequent heat treatment for stress relief was completed. Additionally, the detail parts, i.e., titanium clevises and titanium tubing, were completed. This material was ready for assembly by welding and heat treating when fabrication effort was halted in mid-June.

INTERCONNECT COMPONENTS

The major interconnect components, i.e., fuel and oxygen distribution manifolds, are illustrated in Fig. 27. These parts were severely damaged during the fire and required substantial replacement. Additionally, a design modification was made to provide better access than previously existed for completion of the assembly welds, there being a substantial probability that it was one of the assembly welds whose failure triggered the test stand fire incident of 19 November 1975. The redesign of the fuel and oxidizer interconnecting components was completed and drawings RS005835X and RS005836X, presented here as Fig. 72 and 73, were released to support fabrication and assembly effort. The usable portions of the previous manifolding were cleaned and refurbished and necessary replacement parts identified. Fabrication of new parts was never initiated.



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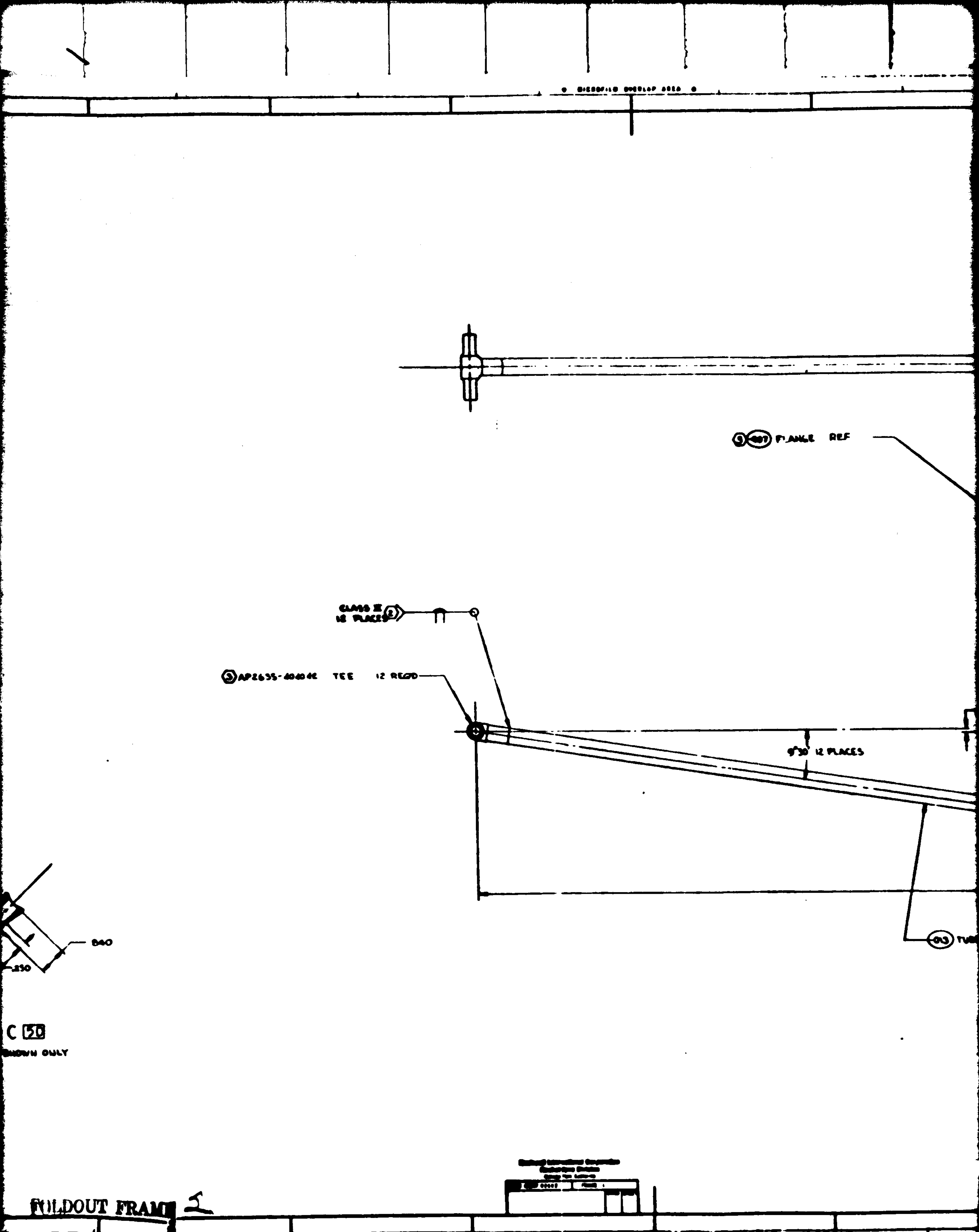

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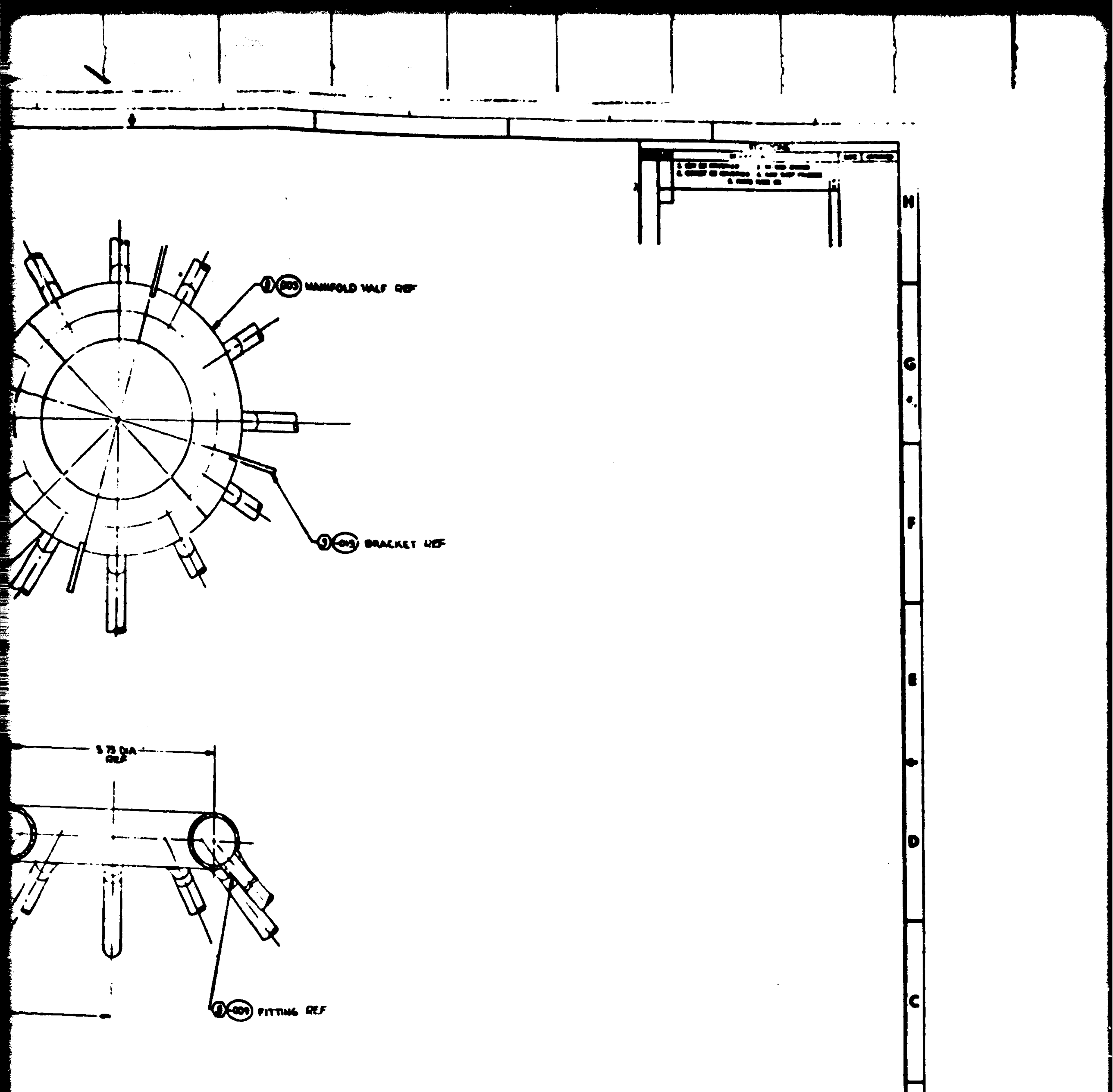

Figure 72. Oxidizer Manifold Inlet Assembly

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⑨	-015	347 CRES SHEET	.12 × .70 × 2.00	QQ-S-766 CL 347 COND A	3F
	-013	347 CRES TUBE	.250 OD × .035 WT	MIL-T-8808 TYPE I	7C
⑨	-009	347 CRES BAR	.75 DIA × .25	QQ-S-763 CL 347 COND A	4C
⑨	-007	347 CRES BAR	3.125 DIA × 2.50	QQ-S-763 CL 347 COND A	6F
⑨	-005	347 CRES TUBE	.375 OD × .035 WT	MIL-T-8808 TYPE I	6F
⑤	-003	347 CRES TUBE	.500 OD × .050 WT	MIL-T-8808 TYPE I	3G
	NO.	MATERIAL	SIZE	SPECIFICATION	ZONE

001
ASSY

LECTROCHEMICAL ETCH IDENTIFY PER RA0104-008
DE EX 37 [illegible] REWORKABLE TO REQD DIMS
ELD PER RA0107-027
ACHINE PER RA0103-008

NONE
NONE
NOTED

MANIFOLD - OXIDIZER INLET ASSY OF 25K AEROSPIKE

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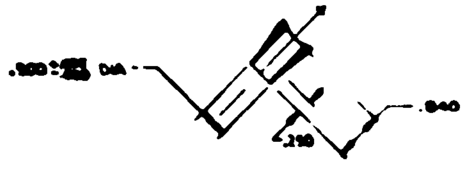

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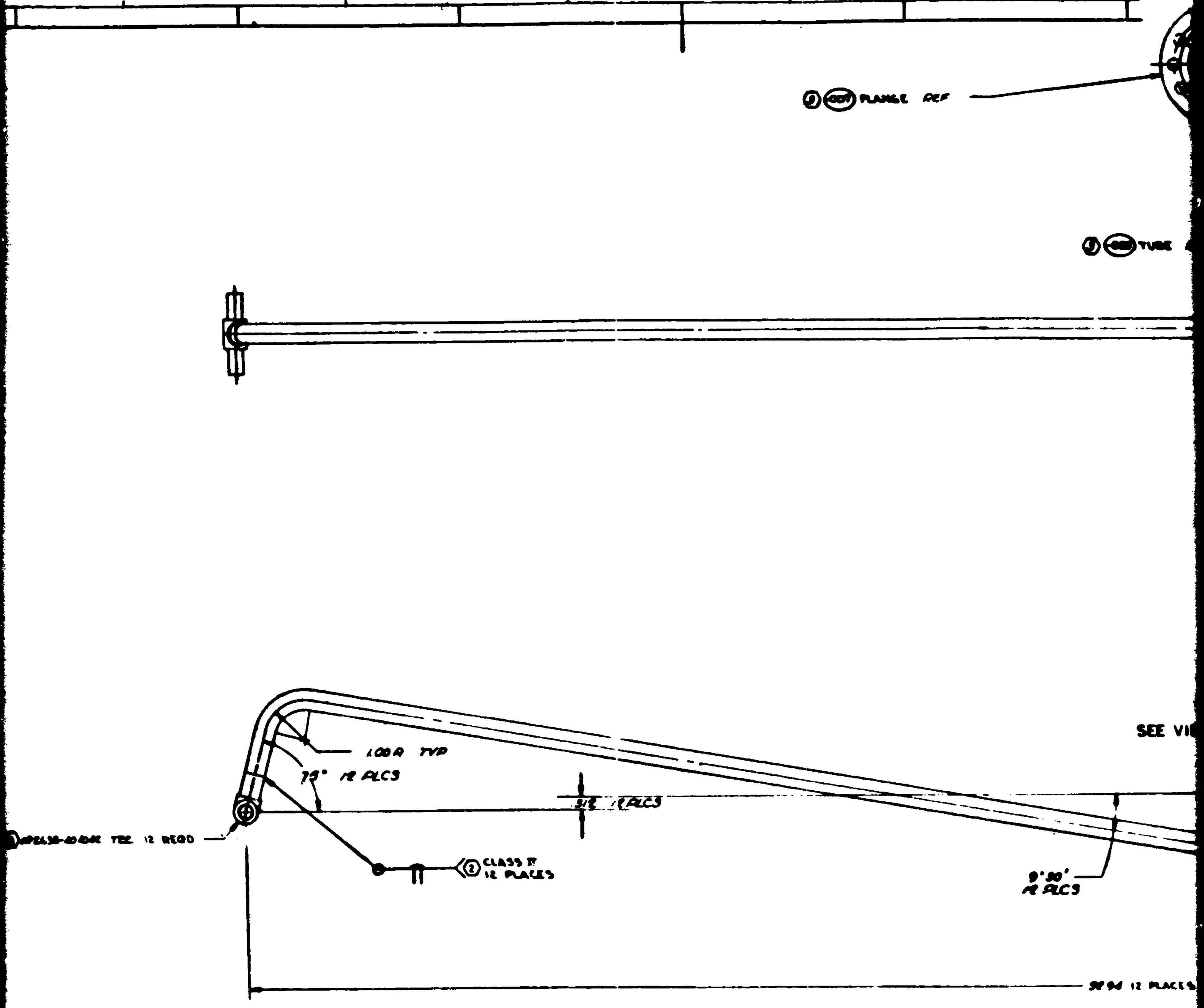

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● MICROFILM OVERLAP AREA ●

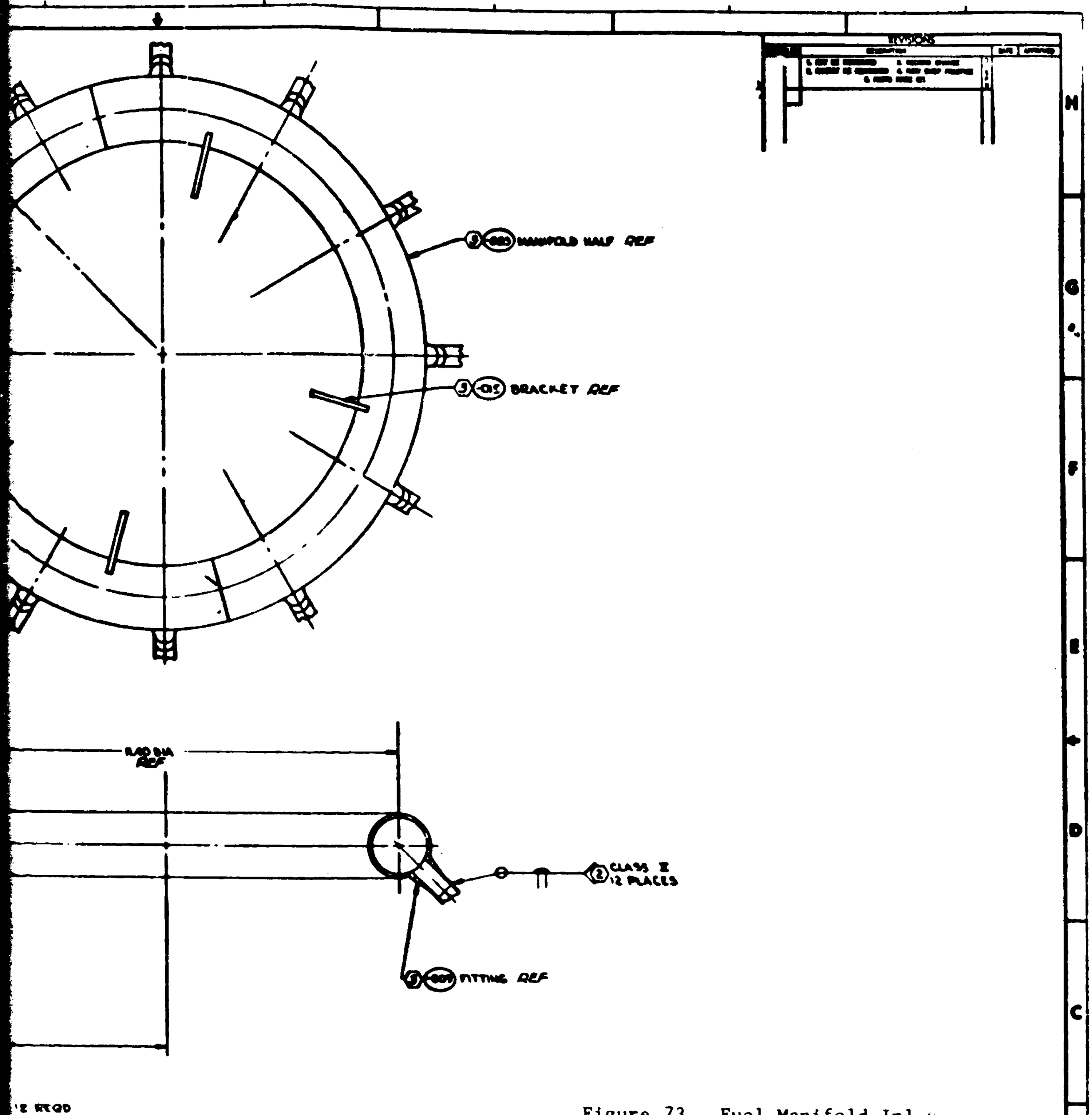

Figure 73. Fuel Manifold Inlet Assembly

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	NO.	MATERIAL	SIZE	SPECIFICATION	ZONE
(9)	-019	347 CRES SHEET	2 × .20 × 2.00	QQ-S-766 CL 347 COND A	[illegible]
	-013	321 CRES TUBE	[illegible]	MIL-T-8808 TYPE I	[illegible]
(9)	-009	347 CRES BAR	[illegible] DIA × .75	QQ-S-763 CL 347 COND A	3C
(9)	-007	347 CRES BAR	3.25 DIA × 2.50	QQ-S-763 CL 347 COND A	5H
(9)	-005	347 CRES TUBE	[illegible] OD × [illegible] WT	MIL-T-8808 TYPE I	6G
(9)	-003	347 CRES TUBE	1.500 OD × .156 WT	MIL-T-8808 TYPE I	3G

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OF POOR QUALITY

- ELECTROCHEMICAL ETCH IDENTIFY PER RA0104-008
- USE EXISTING PARTS REWORKABLE TO REQD DIM'S
- WELD PER RA0107-027
- MACHINE PER RA0103-002

NONE
NONE
NOTED

MANIFOLD - FUEL INLET, ASSEMBLY OF 25K AEROSPIKE

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DISCUSSION OF RESULTS

This program set out on a challenging task--the repair and refurbishment of a seriously damaged thrust chamber assembly, and its hot-firing evaluation for both performance and structural integrity. It was recognized at the start that there were some risks inherent in the objectives, i.e., it might prove to be impossible to effect the repairs satisfactorily, or apparently successful repairs might fail prematurely in service. The risks were justified by the possible gains. The previous Air Force program had successfully demonstrated that an aerospike chamber could be designed and fabricated to provide a very substantial reduction in engine length while attaining a competitive engine weight. The damaged chamber remaining on termination of the Air Force program presented an opportunity to obtain and hot-fire evaluate an aerospike thrust chamber of flight configuration for very much less than would be required to design, fabricate, and test such a chamber from the beginning.

Several positive results were obtained during the disassembly and repair procedures:

1. The tubular nozzle repair effort brought out that large-scale repairs on lightweight tubular nozzles are feasible, returning the nozzle to a fireable condition at a cost very much less than that required for complete replacement. The saddle-patch method developed is applicable in areas where heat fluxes are relatively modest, and has the advantage of low cost. The tube insert method is applicable where extensive damage has been done to the tube, or the heat flux conditions are too high to permit reliance on saddle-patches.

   Both of the tube repair techniques are very dependent for their success on the skill of the metal fitter and brazer. Before applying these techniques to an actual nozzle, the technique of the metal fitter and brazer should be checked by making a number of sample repairs.

   Quality assessment techniques have been developed to permit determination of the quality of the repaired nozzle areas short of actually firing the assembly and replacement of defective repairs. Cryogenic shock testing, air flow checking, pneumostatic testing, and hydrostatic pressure checking are recommended in each instance.
2. The aerospike structure repairs indicate that it is feasible to repair such complex structures as the outer titanium backup ring.
3. The work conducted with combustor dissection and reassembly bears out the basic validity of the concept of the repair of such complex copper channel cooling structures by the method of excising the damaged areas and brazing properly configured replacements in their place.

The basic success of these repair techniques must be considered a positive factor in future evaluations of the aerospike thrust chamber concept.

It is ironic that the NARloy-A material condition, which resulted in conclusion of the program, was present in the material immediately after the initial fabrication of the combustors, and was in no way caused by either the fire which terminated the previous Air Force program or by the repair efforts conducted under the NASA program. It is now also recognized that the test stand fire that terminated the Air Force program may have originated with coversheet cracking.

Rocketdyne had recognized during all of its procedures with NARloy-A that oxygen contamination of the NARloy and subsequent embrittlement by exposure to high temperature hydrogen represented a threat to the integrity of the NARloy-A. The embrittlement that did occur was the result of the failure of the precautions taken to cope adequately with the conditions of exposure. As is typical on any program, a sample combustor, No. 504, was first fabricated and extensively test fired as a precursor to the 24 combustors of the complete assembly. No. 504 performed admirably, suffered no cracking in service and, on examination of samples during the current investigation, displayed no evidence of hydrogen embrittlement. However, No. 504 was assembled entirely by the Materials and Processes laboratory personnel and it is presently realized that their procedures resulted in much less oxidation than subsequent operations in the manufacturing shop. It was further unfortunate that the constraints of time and money prevented the manufacture and dissection of one or more combustors expressly for the purpose of the evaluation of the soundness of the manufacturing techniques. That discipline is frequently given lip service but seldom observed.

It is believed that much more satisfactory results would have been obtained in the initial fabrication program had the NARloy-Z composition been utilized instead of NARloy-A. NARloy-Z contains 0.5% zirconium, which acts as a getter for oxygen, permitting a higher degree of oxygen exposure during fabrication than the NARloy-A composition.

In assessing the overall results of the program, one must keep in mind that the material cracking problem with the NARloy-A combustor material does not have any special significance for the aerospike thrust chamber concept. Aerospike thrust chambers are fabricated of the same materials as bell thrust chambers. The problem was a materials processing problem and not an aerospike problem.

The program did have several positive results for the aerospike concept, even though it was not possible to carry it through to the hot-firing phase. The aerospike must still be regarded as a contender for length-limited space propulsion application. The developmental programs previously conducted have demonstrated the concept's performance and length advantages. The previous Air Force program demonstrated that an aerospike thrust chamber roughly 20% of the length of an equivalent bell chamber could be designed and fabricated to a competitive weight. And the present NASA contract demonstrated that maintenance and repair procedures will be available for aerospike thrust chambers that will permit cost-effective repairs to their assemblies.