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30 September 1981



DESIGN, FABRICATION, TEST, AND DELIVERY OF
A HIGH-PRESSURE OXYGEN/RP-1 INJECTOR

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Final Report

By

L. Schoenman
R. S. Gross
Aerojet Liquid Rocket Company



Prepared For

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

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16. Abstract <p>This final report presents a summary of the design analyses for a liquid rocket injector using oxygen and RP-1 propellants at high chamber pressures of 20,682 kPa (3000 psia). This analytical investigation includes combustion efficiency versus injector element type, combustion stability, and combustor cooling requirements. The design and fabrication of a subscale injector/acoustic resonator assembly capable of providing a nominal thrust of 222K N (50,000 lbf) is presented.</p> <p style="text-align: center;">PRECEDING PAGE BLANK NOT FILMED</p>			
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FOREWORD

This is the final report submitted for the "Design, Fabrication, Test, and Delivery of a High-Pressure/RP-1 Injector" program as per the requirements of Contract NAS 8-33651. The work is being performed by the Aerojet Liquid Rocket Company (ALRC) for the NASA-George C. Marshall Space Flight Center (MSFC). The contract period of performance is 1 January 1980 through 15 July 1981.

The program goal is to provide combustion device technology required for the development of high-pressure liquid oxygen/hydrocarbon (LOX/HC) booster engines. The specific end product of this contract is a stable, high-performing, and compatible injector for 3000 psia chamber pressure operation, using liquid oxygen and liquid RP-1 as the propellants.

The NASA/MSFC project manager is Mr. Curtis R. Bailey. The ALRC program manager is Mr. J. W. Salmon, and the project engineers are Mr. R. S. Gross and, as of April 1981, Mr. L. Schoenman. The program lead analyst and mechanical designer are Mr. J. I. Ito and Mr. K. Y. Wong, respectively.

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LIST OF PRINCIPAL SYMBOLS

EB	=	Electron Beam Welding
ED	=	Electrical Discharge Machining
ERE	=	Energy Release Efficiency
HC	=	Hydrocarbon
HDF	=	High-Density Fuel
LOL	=	Like-on-Like
LOX	=	Liquid Oxygen
MMH	=	Monomethylhydrazine
MR	=	Mixture Ratio
OMS	=	Orbital Maneuvering System
PAT	=	Preatomized Triplet
PN	=	Part Number
RP-1	=	Rocket Propellant No. 1
SI	=	System International
STS	=	Space Transportation System
TCE	=	1,1,1-trichloroethane
TLOL	=	Transverse Like-on-Like
XDT	=	X-Doublet
C*	=	Characteristic velocity
Cd	=	Discharge coefficient
CSM	=	Combustion Stability Monitor
D	=	Diameter
$\Delta P/\rho a$	=	Pressure drop
E_m	=	Mixing efficiency
ϵ_{sl}	=	Sea-level area ratio
F	=	Thrust
fps	=	Feet per second
lbf	=	Pounds thrust
Isp	=	Specific impulse
Isp _{ODE}	=	Specific impulse, one-dimensional equilibrium
K	=	Thousand
°K	=	°Kelvin
kPa	=	Kilo pascals

LIST OF PRINCIPAL SYMBOLS (cont.)

K_w	=	Flow coefficient, (K_w) = $\left(\frac{\dot{w} \text{ (kg/sec)}}{\sqrt{\Delta P \text{ (kPa)}} S_g} \right)$ or $\left(\frac{\dot{w} \text{ (lb/sec)}}{\sqrt{\Delta P \text{ (psi)}} S_g} \right)$
L'	=	Length (prime)
$1L$	=	First longitudinal mode of instability
$1T$	=	First tangential mode of instability
λ_{atom}	=	Droplet atomization length
M	=	Million
μ	=	Micro
mps	=	Meter per second
N/m^2	=	Newton per square meter
N	=	Newtons
ρ	=	Density
P	=	Pressure
P_c	=	Chamber pressure
psia	=	Pounds per square inch absolute
$^{\circ}R$	=	$^{\circ}$ Rankine
r_{III}	=	Mass median droplet radius
σ_g	=	Geometric distribution of drop sizes
S_g	=	Specific gravity
T	=	Temperature
τ_g	=	Gas resonance time
τ_f	=	Fuel sensitive time lag for stability analysis
τ_{ox}	=	Oxidizer sensitive time lag for stability analysis
θ_f	=	Fuel impingement angle
V	=	Velocity
\dot{w}	=	Flowrate lb/sec

Subscript:

ox	=	Oxidizer
f	=	Fuel

I. INTRODUCTION

A. BACKGROUND

Over the past several years, increasing priority has been given to the development of an economical and practical Space Transportation System (STS). Numerous NASA-sponsored and ALRC in-house studies have identified high-pressure LOX/hydrocarbon booster engine stages to have significant envelope, weight, and payload advantages over current booster systems. High-pressure combustion is a critical technology to the development of a LOX/hydrocarbon booster engine. In these studies, various hydrocarbon and amine fuels have been considered, including RP-1, RJ-5, propane, hydrazine, monomethylhydrazine (MMH), and methane. On a comparative basis, RP-1 offers density, cost, and availability advantages over some of the other fuels. Unfortunately, no combustion and heat transfer data for the LOX/RP-1 combination at chamber pressures approaching 20,682 to 27,576 kPa (3000 to 4000 psia) has resulted from these study efforts.

This contracted effort supports the previous NASA/MSFC in-house booster technology programs by providing an injector for use with liquid oxygen and RP-1 propellants at chamber pressures to 20,682 kPa (3000 psia). The injector will subsequently be tested at MSFC, using a water-cooled calorimeter chamber over a chamber pressure range of 13,788 to 16,546 kPa (2000 to 2400 psia) and a hydrogen-cooled axial milled-slot chamber at pressures up to 20,682 kPa (3000 psia). Data from this test program will be an important step toward extending the existing predictive capabilities and hardware technology relevant to the LOX/RP-1 booster application.

B. OBJECTIVES

To meet the program objectives, demonstration of the following technical tasks was required:

I, B, Objectives

- ° Delivery to MSFC of a high-performance, stable injector for use with LOX/RP-1 propellants.
- ° Interfacing of the injector assembly with the calorimetric chamber for operation at 13,788 to 16,546 kPa (2000 to 2400 psia).
- ° Interfacing of the injector assembly with the hydrogen-cooled axial milled-slot chamber for operation at 20,682 kPa (3000 psia).
- ° Demonstrated C* efficiency >97%.
- ° Stable combustion; allowable chamber pressure oscillations <+ 5% P_c.

In order to accomplish these objectives, the program was divided into the following four major tasks:

- Task I - Analysis and Preliminary Design
- Task II - Detailed Design and Fabrication, Assembly, and Flow Check
- Task III - Delivery
- Task IV - Reviews and Reports

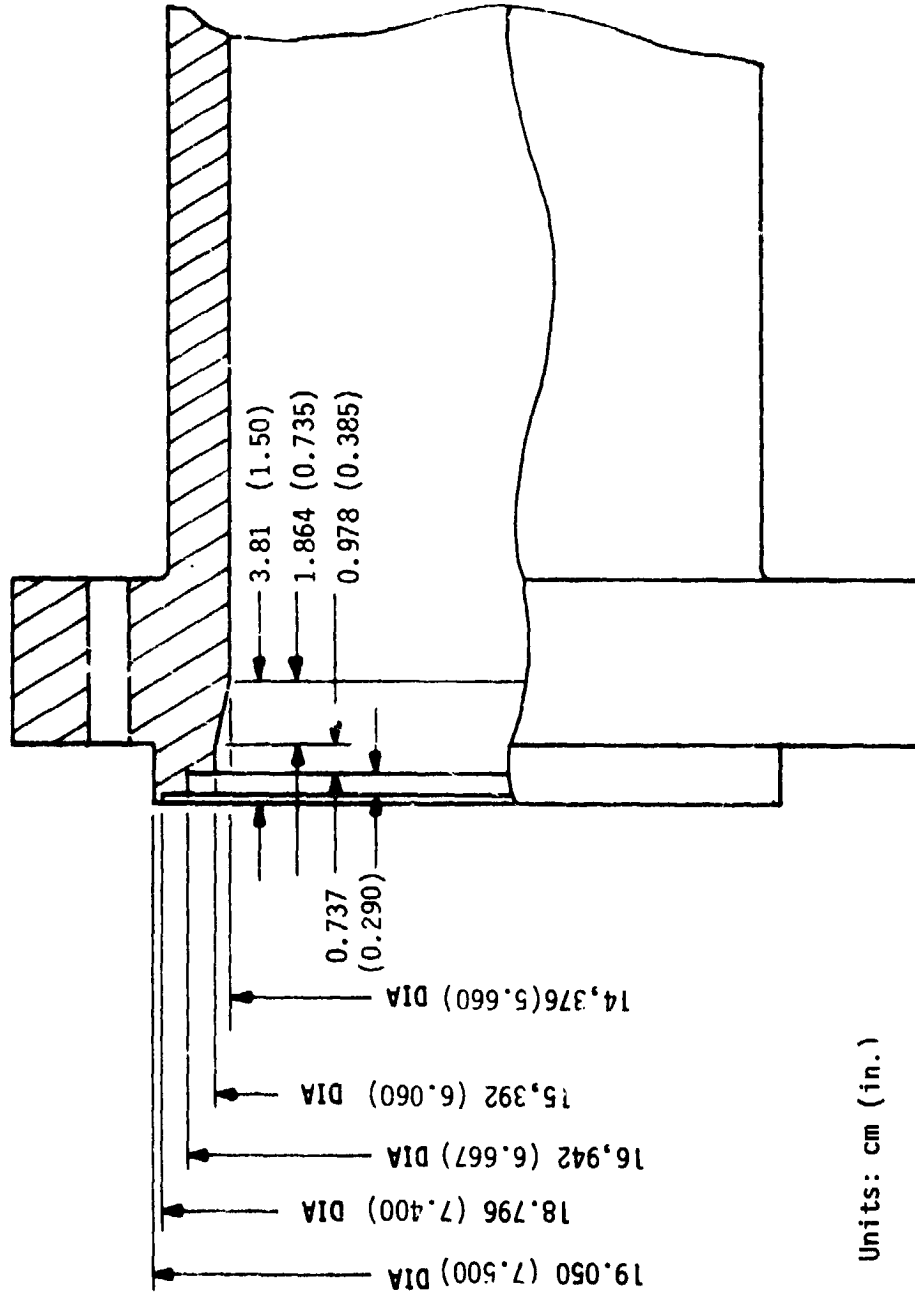
The objective of Task I, Analysis and Preliminary Design, was to identify those injector concepts capable of meeting the design requirements defined in Table I-1 while maintaining compatibility with the NASA chamber interface shown in Figure I-1.

The objective of Task II, Detailed Design and Fabrication, was to accomplish the detailed analysis, design, fabrication, and cold-flow verification of the selected injector concept.

TABLE I-I

LOX/RP-1 INJECTOR DESIGN REQUIREMENTS

Chamber Pressure	13,788 to 20,682 kPa (2000 to 3000 psia)	
Fuel:	RP-1	
Temperature	Ambient	
Max. Interface Pressure	27,576 kPa	(4000 psia)
Oxidizer:	Oxygen	
Temperature	103°K	(185°R)
Max. Interface Pressure	27,576 kPa	(4000 psia)
Propellant Mixture Ratio	2.8	
Characteristic Velocity Efficiency	>97%	
Allowable Chamber Pressure Oscillations	<+5% P _c	
Combustion Chamber:		
Throat Diameter	8.41 cm	(3.31 in.)
Chamber Diameter	14.38 cm	(5.66 in.)
Length (Injector to Throat)	35.48 cm	(13.97 in.)



Units: cm (in.)

Figure I-1. NASA Combustion Chamber Interface

I, B, Objectives

The objective of Task III, Delivery, was to accomplish the delivery of the completed injector assembly to MSFC. This included a minimum of six sets of seals and four sets of working drawings.

The above tasks were to be supported and documented by the review and reporting requirements of Task IV.

II. SUMMARY

A. DESIGN DESCRIPTION

The recommended injector design, shown in Figures II-1 and II-2, consists of a preatomized triplet (PAT) injector core pattern, together with a tangential fan X-doublet (XDT) barrier compatibility element. This design was based upon the results of the Task I (Analysis and Preliminary Design) effort, calibrated with hot-fire test data derived from the High-Density Fuel (HDF) Program (NAS 3-21030) during which both PAT and transverse like-on-like (TLOL) patterns were evaluated at chamber pressures of 8,272 and 13,788 kPa (1200 and 2000 psia), respectively (see Ref. 1).

The subscale injector design incorporates the two outer rows of XDT-type elements to protect the uncooled resonator and head end of the cooled chamber.

The acoustic resonator cavity is designed to attenuate the expected radial and tangential modes of high-frequency instability. The cavity is formed by the assembly of the injector subassembly (PN 1193158) and the resonator ring assembly (PN 1193155) and has variable tune capability. This fine-tuning feature allows the cavities to be reset to match the actual frequency ranges and cavity sound speeds, measured in the early test, in the event they differ from the predicted design values.

The resonator ring contains provision for sufficient high-frequency pressure measurement instrumentation to allow the optimum cavity settings to be calculated from the early tests.

The small central tube is provided within the injector body to introduce an ignition fluid comprised of a 15/85 blend of TEA/TEB.

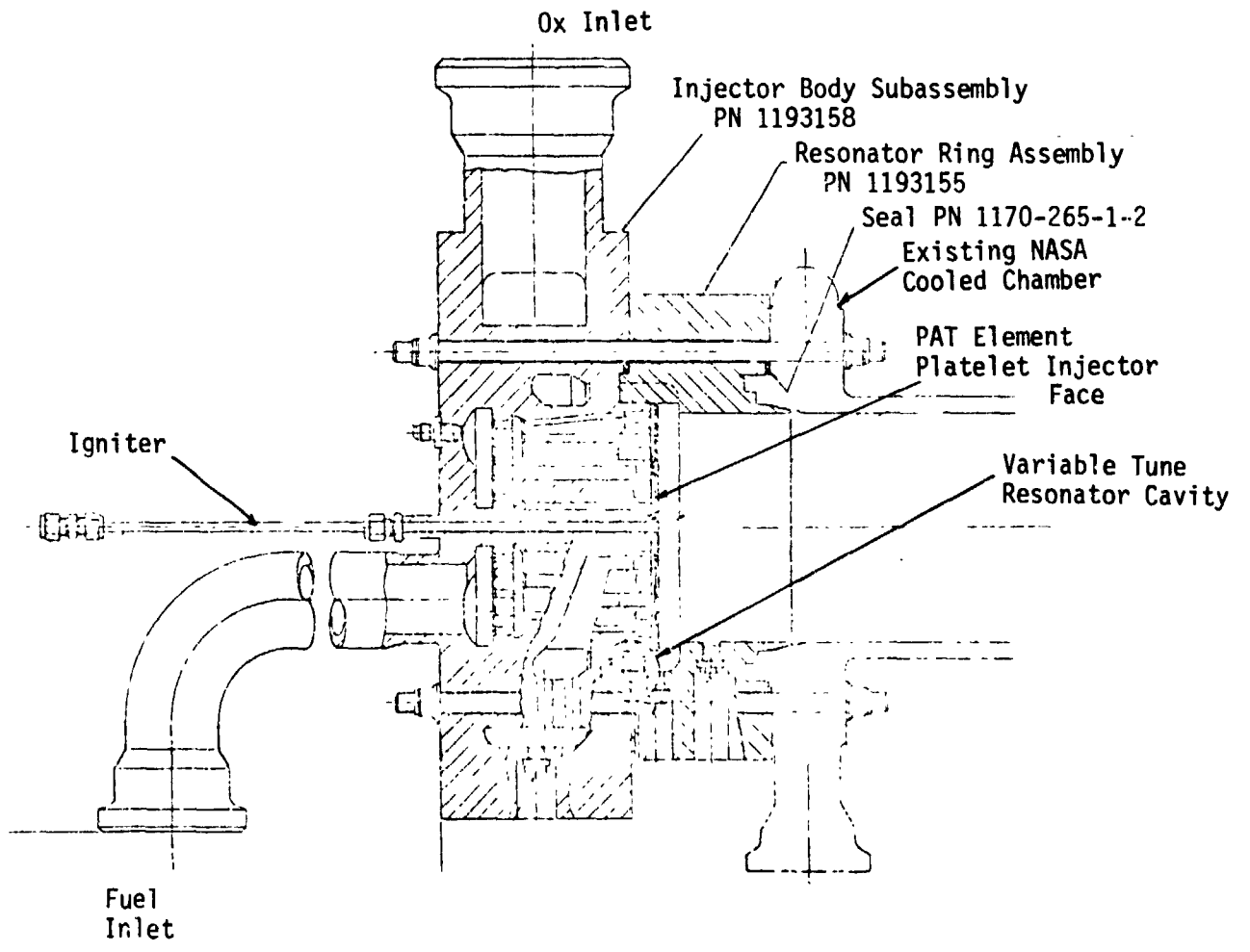
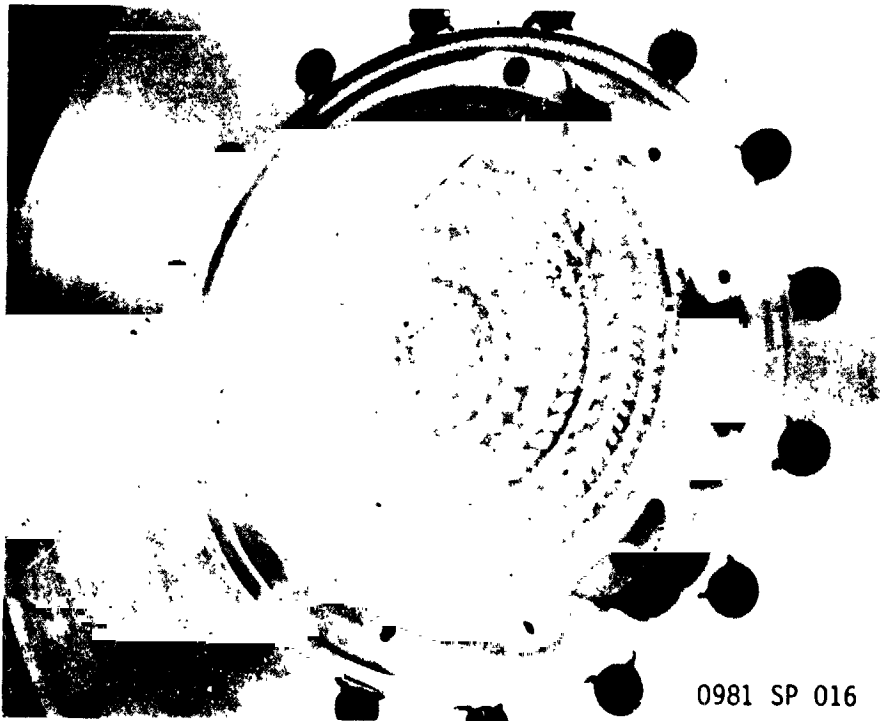


Figure II-1. LOX/RP-1 Injector Assembly PN 1193106

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Figure II-2. Photographs of Injector and Resonator

II, Summary (cont.)

B. DESIGN PHILOSOPHY

The primary areas of technical concern to the high-pressure LOX/RP-1 injector program are summarized in order of decreasing priorities in Table II-I. First and foremost is the fact that the acquisition of data is essential for the development of new technology. This requires that the test hardware be sufficiently durable to withstand a minimum test program and that adequate instrumentation for acquiring the necessary data be provided.

In order to select the optimum design recommendation from among many possible parallel approaches, the decision-making process must assess the REWARD/RISK payoff. Technological advancement is the desired benefit from this type of program. Hopefully, the setbacks and disappointments are acceptable, identifiable, and solvable and do not detract from the demonstrated accomplishments.

The prevention of combustion instability is unquestionably the greatest technical challenge and can be a significant cost driver in future LOX/HC engine development programs. Thus, stability must be demonstrated on this technology program. Furthermore, as demonstrated by the transverse platelet like-on-like element (TLOL) injector test results from the recent High-Density Fuel (HDF) Program (NAS 3-21030), even a marginally unstable injector will summarily and prematurely terminate the test program.

It can be shown analytically that, for a given injector atomization characteristic, operating at higher P_c increases droplet vaporization rate and diminishes high-frequency combustion stability margin. The TLOL-2000* injector (NAS 3-21030) was definitely less stable than the TLOL-1200*, which verifies this prediction. Increasing the total element quantity or

*1200 and 2000 designate operating pressure in psia

TABLE II-1

SUMMARIZED TECHNICAL RISK/REWARD ASSESSMENT

TECHNICAL CONCERNS	SHORT TERM RISK	LONG TERM RISK	DESIGN APPROACH TO SOLVE	DESIGN CONSEQUENCE	BACKUP TEST EXPERIENCE	DESIRED LONG-TERM BENEFIT
High frequency combustion instability	High frequency instability @ 40k will fail injector before test data acquisition is complete	Higher performance element may be stable @ 40k but is not available to 2.0m to 6.0m (to 100% RPM) (b) booster	Select injection element with proven high frequency stable combustion characteristics	Select Preatonized triplet (PAT)	PAT 2000 Stable combustion injector retrievable after 7 tests and 61 sec duration	Early technology identification of stable, face-compatible injection element could save \$-10 years and \$ billions from NASA LO ₂ /HC Booster Development Program
High Density Fuel Analysis, prediction and test data verified 100% (100% RP-1 engine will be unstable without damping)	40k-50k engines will also be unstable without damping	Baffles require cooling, degrade performance, improve cycle life for STS reuse requirements	Place primary emphasis upon element with potential application to prototype booster	PAT is viable candidate for booster stability	T100-2000 Unstable face, non-retrievable after 5 tests, 6 sec duration	
Injector face instability	Injector failure before testing completed	Selected element may not allow for 2.0m requirement	Select elements with demonstrated injector face compatibility	Select PAT	T100-1000 Marginal instability after 9 tests, 64 sec duration	
Existing chamber data chamber interface does not have provision for nozzle interface			Change face of PAT and design nozzle interface	Select until later		
Region cooled cavities cannot use uncooled variable tuning blocks and limit instrumentation capability	Uncooled blocks will melt. Non-tunable		Incorporate nozzle cavity measurement techniques into chamber interface	Acquire cavity cavity data to provide better compatibility for uncooled cavity	HDI Heat sink cavity limited to 3 sec duration	Verify hypothesis. Demonstrate higher booster ISP can be delivered by increasing chamber heat flux, operating at higher P _c , higher ISPQW in spite of 3-5% lower IC*
0% Success. Degrades performance	0% @ 40k effect, contrast 50k requirement		Use unselected cavity and unselected block	Provide HDI barrier compatibility low	PAT calorimeter data indicates low forward heat flux but requires some additional cooling	Redirect system optimization studies, redefine TPA technology requirements, allow Base Time 100 HC Booster penetration.
		LONG TERM RISK 0% @ 40k 6.0m (to 100% RPM) (b) booster ISPQW + 5% due to higher allowable P _c for same throat heat flux			PAT calorimeter data indicates low forward heat flux but requires some additional cooling	
Low 90% performance	Chamber heat flux not representative of high efficiency LO ₂ /RP-1 injector		See updated 100% prediction on PAT 6000 (table 13)	Substrate a design	PAT calorimeter heat flux data indicate strong dependence on test mixture ratio and verify PAT mixing ratio data	Verify combustion stability @ P _c 20,686 kPa (3000 psia). Thermal compatibility of injector chamber
		Degraded high performance injector is not tunable	Low cost PAT 100	Future cold flow instrumentation required	OMS & T100 sub-cavity element available for experiments	Identify performance improvement required for 100% not achieved
			Manufacture injector element with cavity instrumentation only	Use proven elements, manufacturing pattern on substrate	OMS & T100 injector indicate strong dependence on test mixture ratio degrades high frequency instability, buffer mixing has only second order effect on high frequency	Identify next step of LO ₂ /RP-1 injector technology program to improve cold flow, instrumentation
			Test with OSM tuned to include 100	Verify PAT time delay data, 100% Model 100 and 100% P _c 100% injected to ensure 100% ability at desired nominal operating point in 2nd generation injector		Provide calibrated tab data models for all models for future LO ₂ /HC Booster injector development program
0% Success. High frequency instability. High density fuel analysis, prediction and test data verified 100% (100% RP-1 engine will be unstable without damping). Since HDI PAT did not go as predicted, cannot verify 15,856 kPa (2,300 psia)	0% @ 40k effect, contrast 50k requirement. Failure not predicted					

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II, B, Design Philosophy (cont.)

reducing the orifice diameter results in finer atomization distributions which vaporize faster and degrade stability. There is much historical data supporting the prediction that "higher performance injectors" are less stable. LOX/RP-1 technology data from the 1960's have indicated that unlike impinging triplets and unlike doublets were less stable than like-on-like doublets. Recent analytical insight has attributed this stability difference to their drop size distributions. Triplets and unlike doublets produce more fine and more coarse droplets ($\sigma_g = 3.6$) compared to their mass median than like doublets ($\sigma_g = 2.3$). The preatomized triplet (PAT) element indicates more uniform distribution than the like doublet, based on experimental $d(\text{ERE}^*)/dx$ and $d(\%RP-1 \text{ Vap.})/dx$ data obtained for the TLOL-1200 and PAT-2000 injectors between 27.94-cm (11-in.) and 38.1-cm (15-in.) chamber L'. The fact that the PAT injector was considerably more stable than the doublet also supports this performance-derived conclusion.

When it becomes necessary to extrapolate this subscale combustion technology data obtained with ~12.7-cm (5-in.) diameter injectors to prototype boosters (~50.8-cm (20-in.) injector diameter), the transverse mode acoustic response frequencies will approximately decrease by a factor of 4:1. Thus, injectors which require extensive acoustic cavity tuning effort to stabilize at these subscale technology thrust levels are assured of being dynamically unstable without extensive injector baffling in full-scale booster applications. As shown in Table II-I, baffles degrade performance. The low performance (93.8% C*) of the LOX/RP-1 F-1 engine is proof of the above. Thus, for booster applications, it is best to select elements producing the most uniform atomization distribution. These injectors will be most stable, which not only minimizes the short-term risk of premature injector failure due to combustion instability, but also provides greatest promise for full-scale application. These injectors are least likely to suffer from later

*ERE = Energy Release Efficiency

II, B, Design Philosophy (cont.)

performance degradation as the result of either de-optimizations required to achieve stability in larger-diameter engines or due to baffle cooling losses. On the basis of the PAT Injector element was selected over all other candidates.

III. TECHNICAL DISCUSSION

A. DESIGN ANALYSES

1. Design Requirements

The contractual design and interface requirements for the injector to be delivered are documented in Table I-1 and Figure I-1. The imposed geometric and pressure parameters result in an assembly that delivers $\approx 222,400$ N ($\approx 50,000$ lb) of thrust at a chamber pressure of 20,682 kPa (3000 psia). The propellant flowrates at these conditions are as follows:

RP-1	17.10 kg/sec	(37.7 lb/sec)
LOX	47.90 kg/sec	(105.6 lb/sec)

The design analyses which follow translate these requirements into specific geometric configurations and define the resulting required inlet pressures and stabilizing devices for maintaining stable combustion.

2. Pattern Selection

The injector pattern selection plays a critical role in meeting both the 97% C^* efficiency and combustion stability goals. Section II,B, Design Philosophy, provides a discussion of the interaction of these parameters based on a broad range of test experience and data.

Figure III-1 depicts the injection element screening process for arriving at the recommended designs. This process requires that, as a minimum, uni-element cold-flow data and some hot-fire data be available for an element concept before it can qualify as a candidate. Untested minor modifications to proven elements are considered acceptable if they can be analytically shown to result in an improvement over previous experience.

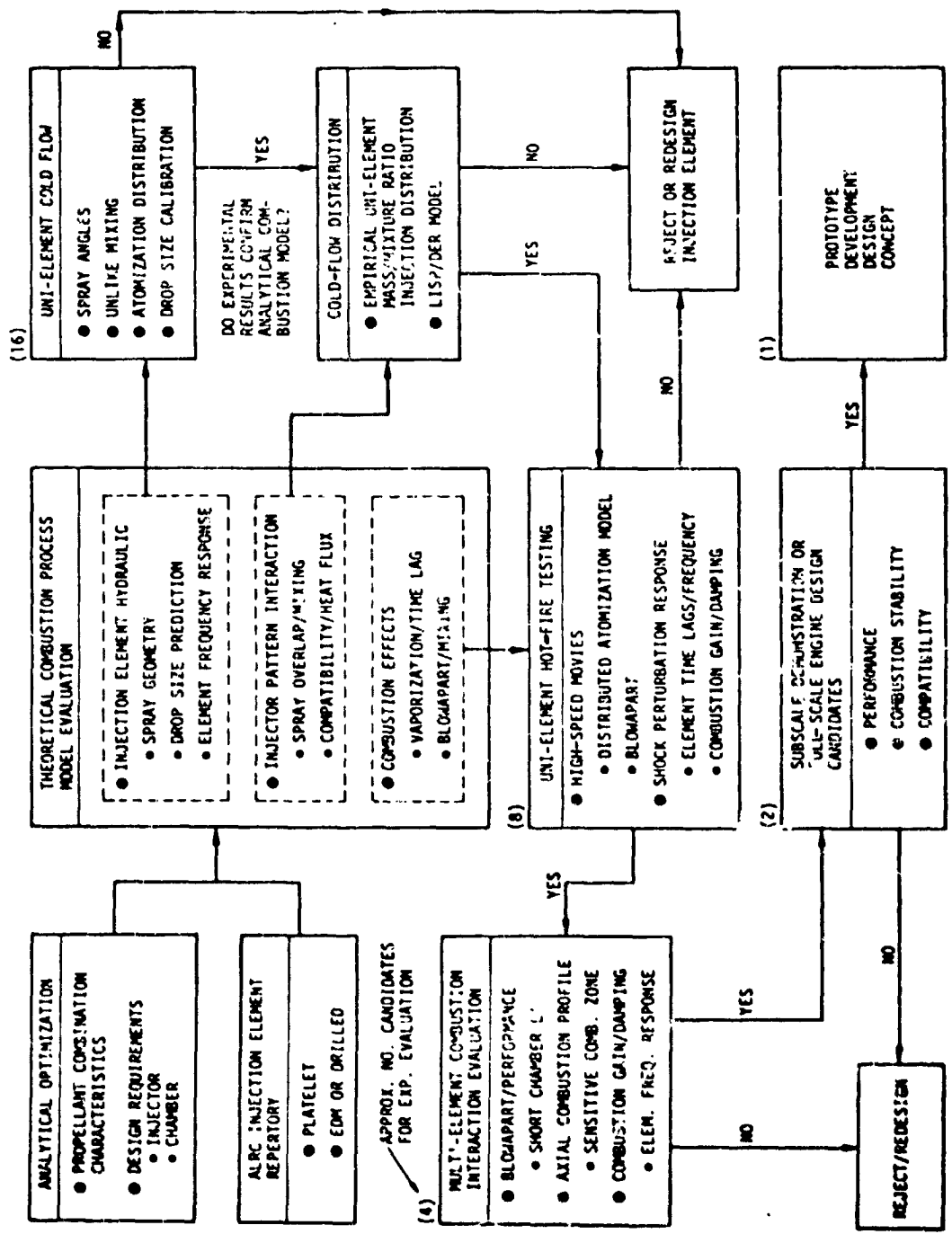


Figure III-1. ALRC Injection Element Screening Process - Summary

III, A, Design Analyses (cont.)

Figure III-2 defines the categories of element concepts considered applicable to the LOX/RP-1 booster engine, along with comments on their features.

Figure III-3 illustrates the various injection element configurations and their resulting spray patterns. Figures III-4 and III-5 further define the geometric characteristics of the TLOL and PAT elements which are prime candidates for the high-performance core elements. Figure III-5 also defines the characteristics of the recommended XDT barrier compatibility elements.

HIGH-PERFORMANCE CORE ELEMENTS

The NAS 3-21030 data are the best current analytical/experimental correlations for both the TLOL-1200 and PAT-2000 injectors. Ambient and heated fuel temperature and both 27.94-cm (11-in.) and 38.10-cm (15-in.) length chambers were tested. These data are documented in Reference 1. By testing these injectors over a range of mixture ratios from approximately 2 to 4, it was possible to separate mixing and vaporization losses, yielding both % E_{m} and % RP-1 vaporization efficiency. Due to its volatility, the LOX vaporization efficiency was assumed to be 100% at all conditions. Excellent correlations were evident between Pc-based % C^* and thrust-based % ERE at the sea level nozzle area ratio (ϵ_{51}) of 5.8:1. The exception was the $L' = 27.94$ -cm (11-in.) TLOL-1200 data, where the C^* data became progressively more invalid late in the test program due to suspected throat delamination of the NASA-supplied slotted/electroformed chambers.

Due to the large mixing losses associated with these first-generation injectors, % C^* and % ERE are not exactly equal, nor will % ERE be

ELEMENT TYPE

- Preatomized Triplet
 - High Performance. Good Injector Face Compatibility and Good Stability Characteristics.
- X-Doublet (XDT)
 - Excellent Chamber Wall Compatibility. Low Performance.
- Platelet Aerobee Mixed-Element Pattern-See Figure III-3
 - Excellent Theoretical Stability Potential; High Performance; Face Compatibility Unknown.
- V-Doublet
 - Excellent Theoretical High-Frequency Stability Demonstrated with Storables (OMS); Good Performance; Face Compatibility Unknown.
- TLOL/EDM-LOL
 - Thus Far Limited < 8272 kPa (1200 psia) Chamber Pressure by Stability and Injector Face Incompatibility. Was Baseline 1960 Technology Standard.

Figure III-2. Candidate LO₂/HC Injection Element Concepts

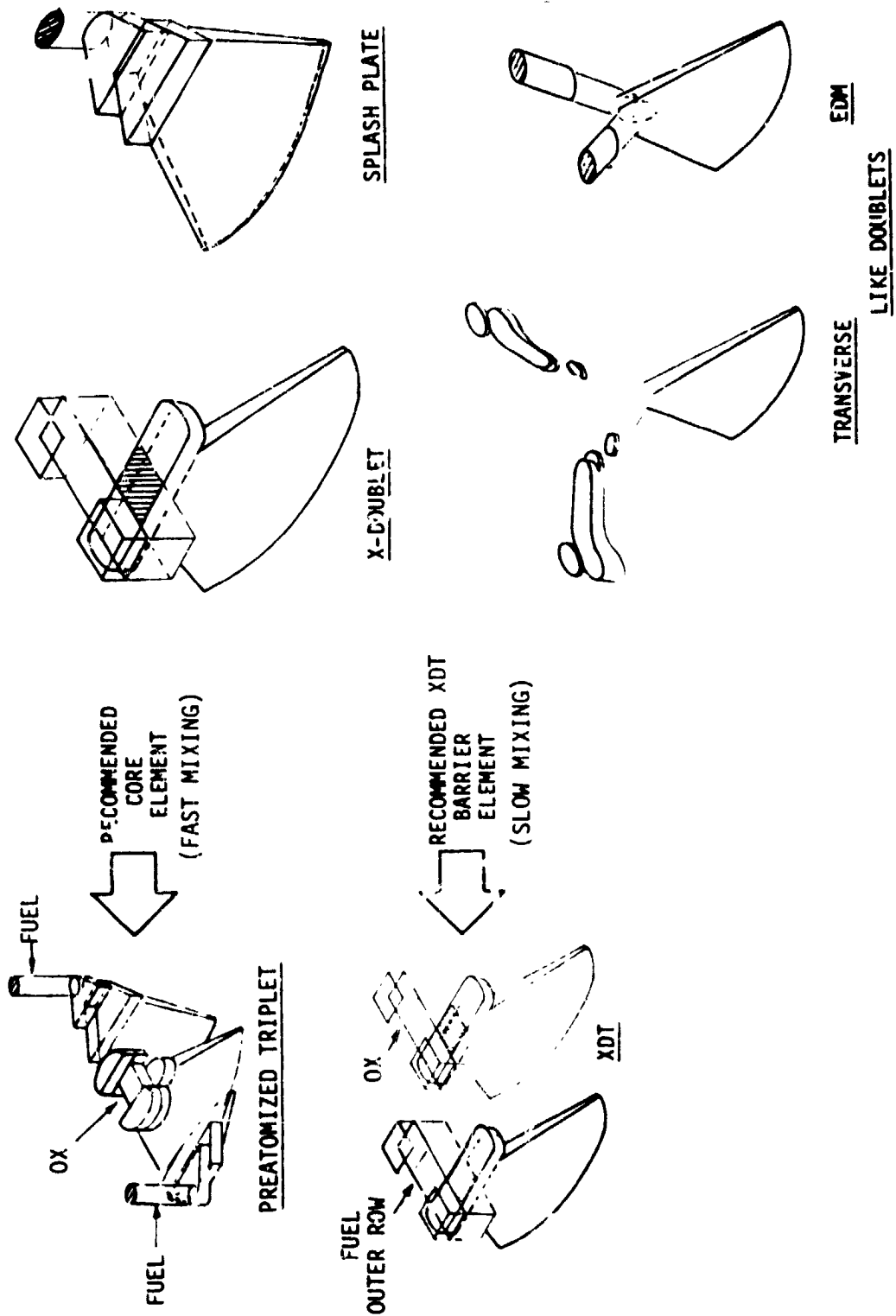


Figure III-3. Proposed Injection Element Concepts

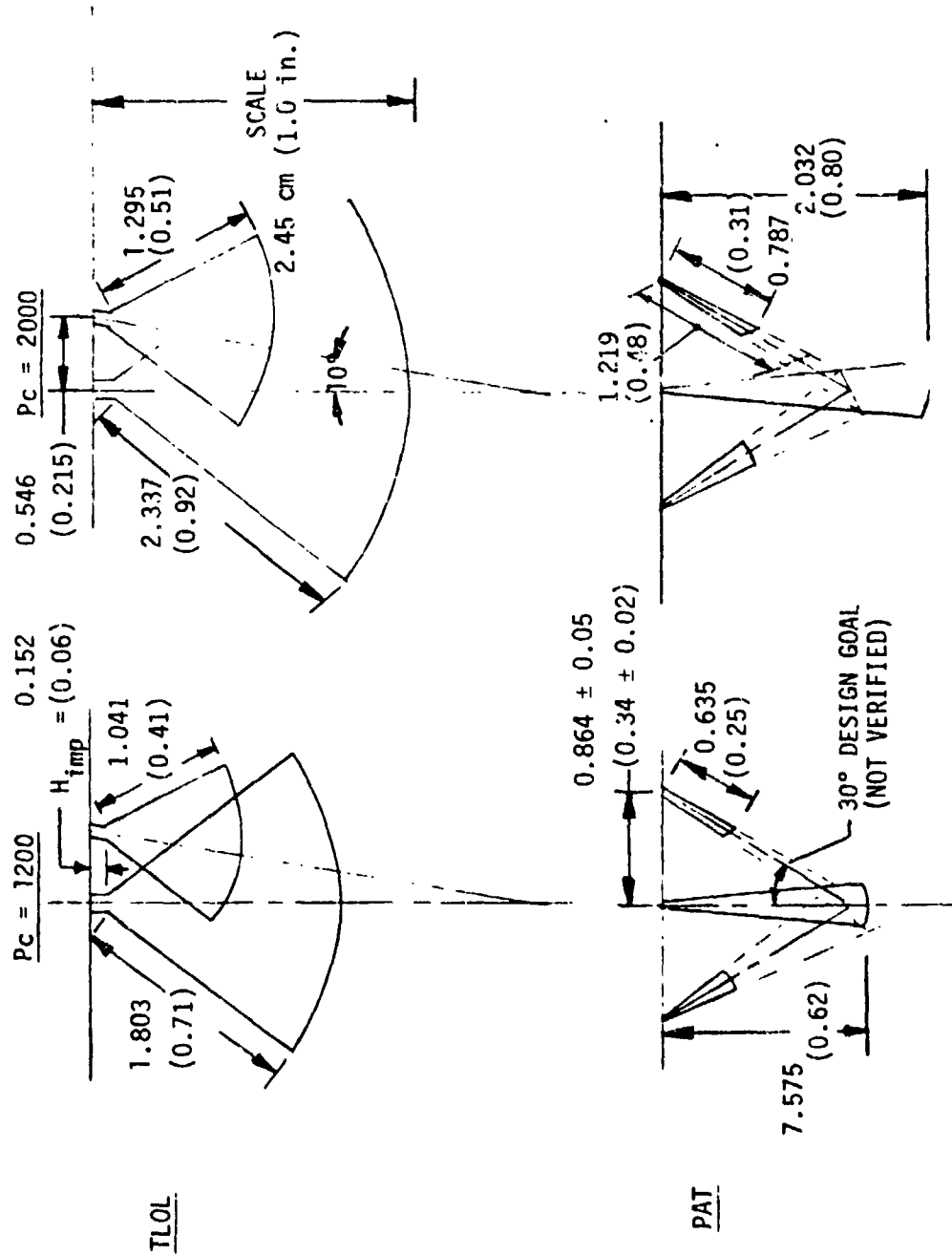


Figure III-4. Spray Atomization Pattern Schematic

PATTERN:	PREATOMIZED TRIPLET			TLOL EDM-L0L			PLATELET AEROBEE			BARRIER COMPATIBILITY	
	OXID	FUEL		OXID	FUEL		OXID	FUEL		OXID	FUEL
CIRCUIT:											
<u>BARRIER</u>											
ELEMENT	XDT									XDT	XDT
QUANTITY	96									96	96
% MASS	20									20	20
<u>CORE</u>											
ELEMENT	XDT	S/P	L0L	L0L	TLOL	TLOL	S/P*				
QUANTITY	72	144	72	72	48	48	48				
% MASS	80	80	80	80	40	40	40				
<u>Pc = 3000 kPa</u>											
\dot{W}_j (kg/sec)	38.3	13.7	38.3	13.7	6.85	38.3	6.85			9.57	3.40
ΔP (kPa)	6204	4481	6204	4481	4481	6204	4481			6204	4481
V_j (mps)	106.7	106.7	85.3	85.3	85.3	85.3	106.7			106.7	106.7
D_{orif} (cm)	0.274	0.142	0.231	0.157	0.137	0.282	0.175			0.119	0.084
r_{atom} (cm)	3.56	1.68	5.03	1.98	2.82	6.71	1.55			1.40	0.79
r_m ($\times 10^{-3}$ cm)	5.08	3.56	6.86	5.59	3.56	8.64	3.56			2.44	2.16

*Splash plate

Figure III-5. Injector Characteristics of Proposed Pattern Options (SI Units)
(Sheet 1 of 2)

PATTERN:	PREATOMIZED TRIPLET		TLOL EDM-LOL		PLATELET AEROBEE		BARRIER COMPATIBILITY	
	OXID	FUEL	OXID	FUEL	OXID	FUEL	OXID	FUEL
CIRCUIT:								
BARRIER								
ELEMENT	XDT				XDT		XDT	XDT
QUANTITY	96				96		96	96
% MASS	20				20		20	20
CORE								
ELEMENT	XDT	S/P	LOL	LLOL	TLOL	TLLOL	S/P*	
QUANTITY	72	144	72	72	48	48	48	
% MASS	80	80	80	80	40	40	40	
$P_c = 3000 \text{ psia}$								
$\dot{W}_i \text{ (lbm/sec)}$	85.4	30.2	85.4	30.2	15.1	84.5	15.1	7.5
$\Delta P \text{ (psid)}$	900	650	900	650	650	900	650	650
$V_j \text{ (fps)}$	350	350	280	280	280	280	350	350
$D_{\text{orif}} \text{ (in.)}$	0.108	0.056	0.091	0.062	0.054	0.111	0.069	0.033
$\lambda_{\text{atom}} \text{ (in.)}$	1.40	0.66	1.98	0.78	1.11	2.64	0.61	0.31
$r_m \text{ (x10}^{-3} \text{ in.)}$	2.0	1.4	2.7	2.2	1.4	3.4	1.4	0.96

*Splash plate

Figure III-5. Injector Characteristics of Proposed Pattern Options (English Units)
(Sheet 2 of 2)

III, A, Design Analyses (cont.)

a unique function of test mixture ratio alone. Mixing losses for any $E_m < 100\%$ will always maximize at the peak performance mixture ratio since performance drops off on both the fuel-rich and oxidizer-rich stream tubes. Thus, delivered C^* efficiency minimizes at $O/F = 2.3$ since that is where C^* optimizes. Specific impulse peaked at $O/F \sim 2.5$ for the nozzle expansion ratio ($\epsilon_{S1} = 5.8$) tested, and, hence, the ERE mixing efficiency minimizes near this mixture ratio.

Flight configuration boosters will probably utilize $\epsilon \sim 40$ nozzle expansion ratios whose I_{sp} peaks around $O/F = 2.8$. Hence, the delivered $\% C^*$ at $O/F = 2.3$ or the present $\% ERE$ at $O/F = 2.5$ with the 5.8 sea-level nozzle will be representative of the flight nozzle $\% ERE$ to be expected at $O/F = 2.8$ rather than the current $\% ERE$ at $O/F = 2.8$ with the $\epsilon = 5.8$ nozzle or the $\% C^*$ at $O/F = 2.8$. The expected operating efficiencies are documented in Table III-I. The PAT-3000 (Core) column, entitled "Old E_m ," shown in the table, is based on the HDF (NAS 3-21030) calibrated RP-1 vaporization model and uses the HDF-PAT E_m value of 73%. Note, however, that the values previously quoted for $\% C^*$ were actually for $\% ERE$ at $O/F = 2.8$ with the prototype booster flight expansion ratio nozzle. This represented the absolute minimum ERE combustion efficiency, not $\% C^*$ at $O/F = 2.8$ as previously reported. Even with the old prediction model, the PAT-3000 Core C^* efficiency at $O/F = 2.8$ was predicted to be $97.0\% \pm 0.2\%$, depending upon whether ambient or heated RP-1 was tested.

The second point of difference between the HDF PAT-2000 and the MSFC PAT-3000 is that two design modifications were incorporated. First, the unlike fuel impingement angle was increased from a 60° total included angle to 90° . Uni-element LOX/HC hot-fire photographic data (NAS 9-15724) with PAT elements show that the combustion gases between the LOX and HC sprays retard fuel penetration into the LOX spray; thus, increasing the fuel impingement angle will most probably improve inter-element E_m . The second

TABLE III-1
 UPDATED LO₂/RP-1 PERFORMANCE PREDICTION SUMMARY

PROGRAM: CONTRACT NO:	High-Density Fuel Comb. & Cooling NAS 3-21030			Hi Pc LO ₂ /RP-1 Injector Prediction NAS 8-33551		
	TL0L - 1200	PAT - 2000	PAT - 3000 (CORE) ELEMENTS (80% Mass)	OLD E _m	XDT (BARRIER, ELEMENT (20% Mass))	
INJECTOR						
Fuel Imp. Ang., 2θ _f	N/A	60	90	90	0	
Cant Angle, θ _{cant}	0	29±5	37±30	37±30	30	
Mix. Eff., % E _m	82	73	80±7	73	60	
$T_{RP-1} = 70^{\circ}F$						
L' chem., Cm (in.)	27.94 (11)	38.10 (15)	27.94 (11)	38.10 (15)	44.20 (17.4)	
RP-1 Vap.	93.5	96	92	98	98	
% C*	Invalid	57.7	94.8	96.7	96.2	
% ERE (ε ₅₁ -5.8)	96.0	97.2	94.5	96.5	95.9	
% ERE (ε _{flight} -40)	95.9	97.0	94.0	95.6	95.5	
$T_{RP-1} = 240^{\circ}F$						
RP-1 Vap.	95	97	99+	99+	99+	
% C*	Invalid	96.0	97.4	98.5 ± 1.3	97.2	
% ERE (ε ₅₁ -5.8)	96.4	95.8	97.0	97.9 ± 1.6	96.3	
% ERE (ε ₄₀)	96.2	95.1	96.5	97.7 ± 1.7	96.0	

III, A, Design Analyses (cont.)

design modification was that the new pattern rotated the PAT element to increase a spray fan alignment relative to the chamber wall. Smaller angles result in better chamber wall compatibility but minimize inter-element spray overlap between fuel-rich and oxidizer-rich zones from adjacent elements. The HDF PAT-2000 injector has a uniform core without special compatibility elements. The MSFC PAT-3000 injector pattern rotated the element $37^{\circ}30'$ to the chamber wall to further improve the spray overlap, as compared to the 24° and 34° rotation used on the PAT-2000. While these modifications seem to improve E_m , in the absence of mathematical models for quantitatively predicting the magnitude of improvement, it was initially decided to use the same 73% E_m prediction for all PAT injectors and to retain these values until a uni-element cold-flow optimization program could quantify the E_m improvement magnitude or until it could be replaced by a better experimental hot-fire E_m value with the new injector.

An attempt has since been made to try and estimate the E_m improvement. It was assumed that the mixing deficiency, $1-E_m$, is proportional to $180^{\circ}-20_f$. Using this analogy, E_m was calculated to increase from 73% to 80%. The "tolerance" on this improvement was assumed to be $\pm 100\%$ of the change, or $E_m = 80\% \pm 7\%$. The % C* and % ERE's at both $\epsilon_s \sim 5.8$ and $\epsilon_{flight} \sim 40$ are shown in Table III-1 for this revised analytical assumption. The resultant core performance efficiency predictions range from $>98\%$ C* to between 97-98% ERE efficiencies. However, the core efficiency must be reduced by 1% in the subscale version due to the interaction with the XDT barrier compatibility row. This 1% reduction may not be present in the full-scale design. As noted in Table II-1, the prototype booster cooling loss due to an XDT barrier compatibility row is significantly reduced due to the larger chamber diameter and reduced barrier mass fractions.

III, A, Design Analyses (cont.)

OUTER ROW COMPATIBILITY ELEMENTS

A compatibility barrier would not only permit testing with the existing marginally cooled combustion chamber head end but could also provide performance advantages for real engine applications. The compatibility row around a hot core permits operation up to 27,576 kPa (4000 psia) chamber pressure while maintaining heat fluxes comparable to 13,788 kPa (2000 Pc). The higher booster nozzle area ratio for a given envelope delivers 4-5% higher Isp at the higher chamber pressure and more than offsets the barrier cooling losses. Furthermore, in a 2.224 to 4.448 M N (500K to 1 M lbf) thrust booster engine, the barrier mass fraction required to achieve chamber compatibility is considerably reduced. Therefore, by incorporating chamber compatibility elements with significantly reduced barrier mass fraction due to the larger booster chamber diameter, the cooling performance penalty is only on the order of 1/2% Isp. This indicates that the improvement possible at higher Pc (from the standpoint of higher theoretical performance attributable to the higher area ratio nozzle) more than offsets the loss from the use of barrier cooling. Additional analyses conducted during Task II have further refined the estimated barrier cooling performance loss attributable to the XDT element to approximately a 1% performance penalty.

3. Stability Analyses

This section summarizes the results of the stability analyses conducted for the LOX/RP-1 combustor design selected. Stability margins for the chug, longitudinal (1L), and high-frequency modes were predicted using the standardized computer models, calibrated to the existing high-pressure LO₂/RP-1 test results documented in Reference 1. Table III-II defines the injector element design data employed in these analyses.

TABLE III-II

SI Units

LOX/RP-1 INJECTOR DATA
PAT CORE ELEMENTS - 80% Mass Flow

Pc = 20682 kPa		Pc = 13788 kPa	
T_{ox} = 102°K	T_f = 294°K	T_{ox} = 102°K	T_f = 294°K
ρ_{ox} = 1128 kg/m ³	ρ_f = 801 kg/m ³	ρ_{ox} = 1122	ρ_f = 801
Sg_{ox} = 1.07	Sg_f = 0.80	Sg_{ox} = 1.122	Sg_f = 0.80
ΔP_{ox} = 4136 kPa	ΔP_f = 3102 kPa	ΔP_{ox} = 1841	ΔP_f = 1379
V_{ox} = 88.4 mps	V_f = 88.4 mps	V_{ox} = 58.7	V_f = 58.8
D_{ox} = 0.2819 cm	D_f = 0.145 cm	D_{ox} = 0.2819	D_f = 0.145
Cd_{ox} = 0.60 cm	Cd_f = 0.69 cm	Cd_{ox} = 0.60	Cd_f = 0.69
$\lambda_{ox, atom}$ = 3.52 cm	$\lambda_{f, atom}$ = 1.684 cm	$\lambda_{ox, atom}$ = 3.366*	$\lambda_{f, atom}$ = 1.610*
$r_{m,ox}$ = 0.0053 cm	$r_{m,f}$ = 0.0076 cm	$r_{m,ox}$ = 0.0056*	$r_{m,f}$ = 0.0079
	θ_f = 45°		θ_f = 45°

XDT BARRIER ELEMENTS - 20% Mass Flow

Pc = 20682 kPa		Pc = 13788 kPa	
T_{ox} = 102°K	T_f = 294°K	T_{ox} = 102°K	T_f = 294°K
ρ_{ox} = 1128 kg/m ³	ρ_f = 801 kg/m ³	ρ_{ox} = 1122	ρ_f = 801
Sg_{ox} = 1.128	Sg_f = 0.80	Sg_{ox} = 1.122	Sg_f = 0.80
ΔP_{ox} = 2922 kPa	ΔP_f = 3102 kPa	ΔP_{ox} = 1746	ΔP_f = 1379
V_{ox} = 83.8 mps	V_f = 88.4 mps	V_{ox} = 55.8	V_f = 58.8
D_{ox} = 0.130 cm	D_f = 0.089 cm	D_{ox} = 0.130	D_f = 0.089
Cd_{ox} = 0.60 cm	Cd_f = 0.60 cm	Cd_{ox} = 0.60	Cd_f = 0.60
$\lambda_{ox, atom}$ = 1.494 cm	$\lambda_{f, atom}$ = 0.729 cm	$\lambda_{ox, atom}$ = 1.427	$\lambda_{f, atom}$ = 0.699
$r_{m,ox}$ = 0.0027 cm	$r_{m,f}$ = 0.0038 cm	$r_{m,ox}$ = 0.0028	$r_{m,f}$ = 0.0041

*For Pc < 13788 kPa assume λ_{atom} and r_m are essentially constant.

TABLE III-II (cont.)

English Units

LOX/RP-1 INJECTOR DATA
PAT CORE ELEMENTS - 80% Mass Flow

Pc = 3000 psia		Pc = 2000 psia	
T_{ox} = -275°F	T_f = 70°F	T_{ox} = -275°F	T_f = 70°F
ρ_{ox} = 70.4 lbm/ft ³	ρ_f = 50 lbm/ft ³	ρ_{ox} = 69.4	ρ_f = 50
Sg_{ox} = 1.128	Sg_f = 0.80	Sg_{ox} = 1.112	Sg_f = 0.80
ΔP_{ox} = 569 psi	ΔP_f = 450 psi	ΔP_{ox} = 257	ΔP_f = 200
V_{ox} = 275 fps	V_f = 290 fps	V_{ox} = 186	V_f = 193
D_{ox} = 0.110 in.	D_f = 0.057 in.	D_{ox} = 0.110	D_f = 0.057
Cd_{ox} = 0.60 in.	Cd_f = 0.69 in.	Cd_{ox} = 0.60	Cd_f = 0.69
$\lambda_{ox, atom}$ = 1.386 in.	$\lambda_{f, atom}$ = 0.663 in.	$\lambda_{ox, atom}$ = 1.325*	$\lambda_{f, atom}$ = 0.634*
$r_{m,ox}$ = 0.0021 in.	$r_{m,f}$ = 0.0030 in.	$r_{m,ox}$ = 0.0022*	$r_{m,f}$ = 0.0031*
	θ_f = 45°		θ_f = 45°

XDT BARRIER ELEMENTS - 20% Mass Flow

Pc = 3000 psia		Pc = 2000 psia	
T_{ox} = -275°F	T_f = 70°F	T_{ox} = -275°F	T_f = 70°F
ρ_{ox} = 70.4 lbm/ft ³	ρ_f = 50	ρ_{ox} = 69.4	ρ_f = 50
Sg_{ox} = 1.128	Sg_f = 0.80	Sg_{ox} = 1.112	Sg_f = 0.80
ΔP_{ox} = 569 psi	ΔP_f = 450	ΔP_{ox} = 257	ΔP_f = 200
V_{ox} = 275 fps	V_f = 290	V_{ox} = 186	V_f = 193
D_{ox} = 0.051 in.	D_f = .035	D_{ox} = 0.051	D_f = 0.035
Cd_{ox} = 0.60 in.	Cd_f = 0.60	Cd_{ox} = 0.60	Cd_f = 0.60
$\lambda_{ox, atom}$ = 0.588 in.	$\lambda_{f, atom}$ = 0.287	$\lambda_{ox, atom}$ = 0.562	$\lambda_{f, atom}$ = 0.275
$r_{m,ox}$ = 0.00105 in.	$r_{m,f}$ = .0015	$r_{m,ox}$ = 0.0011	$r_{m,f}$ = 0.0016

*For Pc < 2000 psia assume λ_{atom} and r_m are essentially constant.

III, A, Design Analyses (cont.)

CHUG MODES

Correlation of the High-Density Fuel (HDF) test results (Ref. 1) with chug predictions revealed the need to modify the standard combustion time lag calculation to account for LOX/RP-1 propellants. The fuel atomization length and droplet radius calculated by the methods of Reference 2 were multiplied by a factor of 1.5, an empirical correction based on HDF performance results. In addition, the total time lags were evaluated at 20% of propellant vaporization plus a "mixing" time lag of 0.1 ms instead of at just the conventional 20% vaporization time.

The injector is predicted to be chug-stable at its operating points of $P_c = 20,682$ kPa (3000 psia), $MR = 2.8$ and $P_c = 13,788$ kPa (2000 psia), $MR = 2.8$. Eight other operating points were examined to determine the lower chamber pressure limit. A minimum chug-stable chamber pressure limit of 12,340 kPa (1790 psia) is predicted for a mixture ratio of 2.8. A 420 Hz instability mode is predicted for lower pressures.

LONGITUDINAL (1L) MODES

The atomization time lags used to make the 1L predictions were arrived at by correlating the HDF 1L test data with analytical predictions. Correlation could be obtained only with the use of distributed atomization time lags. The time lags were distributed according to a logarithmic-normal distribution, with the concentrated atomization time lag as the median. The standard deviation used was 2.3. This is the same standard deviation used by Priem and Heidmann for drop-size distribution as discussed in Reference 2.

III, A, Design Analyses (cont.)

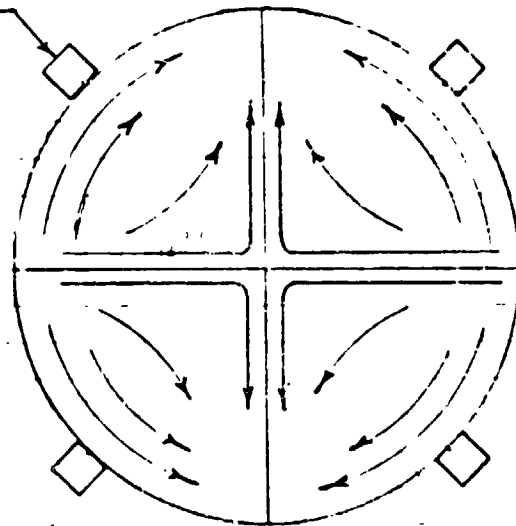
When the selected distributed atomization time lags are used, the PAT injector is predicted to experience 1L instability problems at the low P_c operating point of $P_c = 13,788$ kPa (2000 psia) and $MR = 2.8$. The expected 1L frequency mode is 1400 ± 100 Hz. The nominal operating point of $P_c = 20,682$ kPa (3000 psia) and $MR = 2.8$ is predicted to be 1L stable. The lower limit for stable operation is predicted to be about 15,856 kPa (2300 psia) at $MR = 2.8$. Therefore, initial tests should be at pressures greater than 17,235 kPa (2500 psia).

HIGH-FREQUENCY MODES

The high-frequency modes are predicted to be 1T at 4700 Hz, 2T at 7800 Hz, and 2T + 1L at 7800 Hz.

The injector pressure interaction index (n) used in this analysis is based on the correlation of HDF test results with analytical predictions and has a value of 0.7. Based on HDF test results (Ref. 1), the sensitive time lag (τ) is taken to be the vaporization time of 20% propellant vaporized. The sensitive time lags are $\tau_f = 0.166$ ms and $\tau_{ox} = 0.0168$ ms at 13,788 kPa (2000 psia) and $\tau_f = 0.115$ ms and $\tau_{ox} = 0.0116$ ms at 20,682 kPa (3000 psia). The analysis predicts that a monotone cavity configuration would not be sufficient to damp a 2T + 1L mode. A bitone configuration with a 1T depth of 3.81 cm (1.5 in.) and a 2T depth of 1.728 cm (0.7 in.) is required to damp all the anticipated modes. These depths are based on an estimated cavity sound speed of 610 mps (2000 fps). The cavity width is 1.016 cm (0.4 in.). The analysis indicates that cavity splits of either eight at 1T and four at 2T or nine at 1T and three at 2T will stabilize the injector. The cavity configuration with nine at 1T and three at 2T was selected to avoid 2T mode orientation effects which could occur with the 8-1T and 4-2T configuration (see Figure III-6). Figure III-7 illustrates the geometry of the cavities tuned for 1 and 2T instability modes.

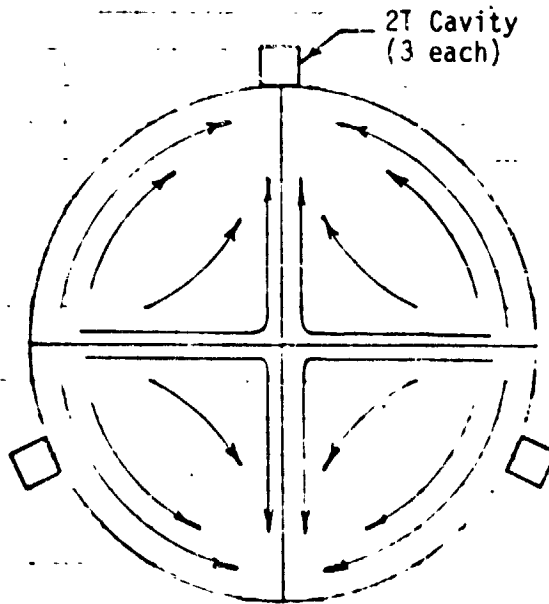
2T Cavity
(4 each)



Worst-case
orientation

Cavities located
at points of
minimum pressure
and maximum velocity

2T Cavity
(3 each)



Better
orientation

At least one
2T cavity is
near point of
pressure maximum
and velocity minimum

Figure III-6. 2T Mode Orientation

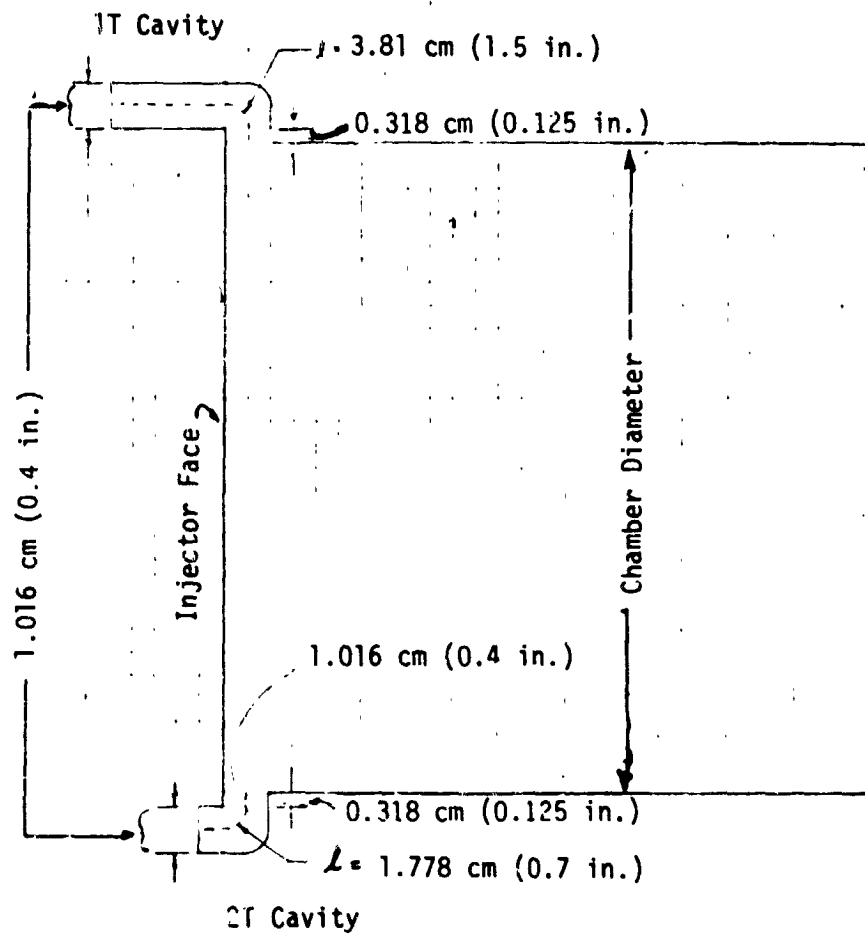


Figure III-7. Acoustic Cavity Detail

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III, A, Design Analyses (cont.)

STABILITY ANALYSIS CONCLUSIONS AND RECOMMENDATIONS

1. The LOX/RP-1 PAT injector is predicted to be chug-stable at the nominal operating conditions ($P_c = 13,788$ and $20,682$ kPa (2000 and 3000 psia) at $MR = 2.8$).

2. A chamber pressure chug limit of $12,340$ kPa (1790 psia) is predicted for the LOX/RP-1 injector at $MR = 2.8$. Chugging at 420 Hz is predicted to occur at chamber pressures below this.

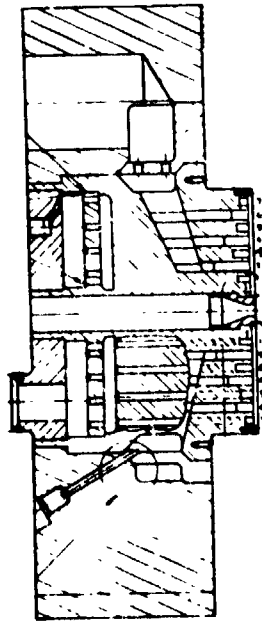
3. The injector is predicted unstable in the 1L mode at $P_c = 13,788$ kPa (2000 psia) and $MR = 2.8$ and is predicted to be 1L stable at $P_c = 20,682$ kPa (3000 psia) and $MR = 2.8$. The 1L instability will be recognized by a 1400 ± 100 Hz frequency. Initial testing should be at $17,235$ kPa (2500 psia) or higher to avoid the 1L mode.

4. The injector is predicted to be stable in all high-frequency modes with the use of nine 1T ($L = 3.81$ cm (1.5 in.), $W = 1.016$ cm (0.4 in.) and three 2T ($L = 1.778$ cm (0.7 in.), $W = 1.016$ cm (0.4 in.) cavities based on an estimated 610 mps (2000 fps) cavity sound speed. The actual cavity sound speed must be determined in the early testing by using the pressure wave relative time of arrival at Kistler transducers located at different positions in the resonator cavity ring.

5. The LOX/RP-1 injector should be tested at the conditions analyzed herein to verify model predictions, deferring the low-pressure tests where potential 1L modes exist until the end.

4. Injector Manifold Hydraulics

The MSFC LOX/RP-1 injector manifold design is conceptually identical to the design used and developed on the HDF program. A comparison of the two injectors is shown in Figure III-8. A detailed description of the manifold flow paths is provided in Section III,B,3.

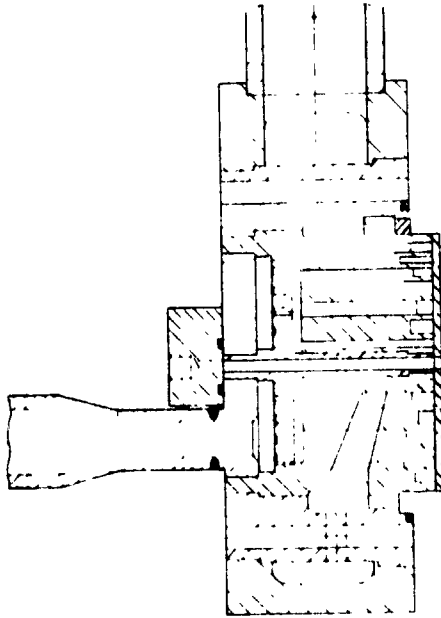


NAS 3-21030
PN 1191403

Pc, kPa (psia)	13,788 (2K)		
F, N (lbf)	89,600 (20K)		
<u>CIRCUIT</u>	<u>OXID</u>	<u>FUEL</u>	
W _i kg/sec (lbm/sec)	17.65 (38.9)	6.31 (13.9)	
Inlet Dia., cm (in.)	5.08 (2)	3.81 (1.5)	
Channel Width, cm (in.)	0.51 (0.20)	0.38 (0.15)	
Land Width, cm (in.)	0.254 (0.10)	0.254 (0.10)	

Manifold Distribution Orifice

Quantity	90	84
Dia., cm (in.)	0.475 (0.187)	0.318 (0.125)



NAS 8-33651

	20,682 (3K)		
	222,400 (~50K)		
<u>CIRCUIT</u>	<u>OXID</u>	<u>FUEL</u>	
W _i kg/sec (lbm/sec)	47.90 (105.6)	17.10 (37.7)	
Inlet Dia., cm (in.)	7.62 (3)	5.08 (2)	
Channel Width, cm (in.)	0.851 (0.335)*	0.51 (0.20)	
Land Width, cm (in.)	0.318 (0.125)	0.318 (0.125)	

Quantity	32*	60
Dia., cm (in.)	1.031 (0.046)*	0.51 (0.20)

(*Task II Update)

Figure III-8. Comparison of High-Density Fuel and LOX/RP-1 Injector Manifolds

III, A, Design Analyses (cont.)

A detailed hydraulic analysis of the injector manifold was conducted for ALRC PN 1191403, the high-density fuel injector. Changes from this earlier design consist of enlarged inlet lines in order to accommodate the higher engine flowrates. Furthermore, the hydraulic resistance of the injector manifold distribution orifices was reduced to accommodate the higher flowrate. The predicted velocity distribution and pressure drops in both the fuel and oxidizer circuits of this design are shown in Table III-III at the maximum $P_c = 20,682$ kPa (3000 psia) operating point. The overall injector manifold resistance is predicted to result in 393 kPa (57 psid) fuel manifold and 607 kPa (88 psid) oxidizer manifold pressure drop at maximum thrust.

B. DETAILED DESIGN DESCRIPTION

This section provides a detailed description of the injector designed to meet the objectives and goals of the program. The design details were developed from the Task I analytical activities covered in Section III,A. A description of the design is accomplished by use of engineering drawings and photographs of the components in various stages of assembly.

1. Assembly Description

The injector assembly, shown in Figures III-9 and III-10, is fabricated completely from 300 series stainless steel, with the exception of the platelet pattern plate and a portion of ring manifolding to which the pattern plate is welded. The latter material is a high-purity nickel. Nickel was selected for the faceplate assembly because it provides the higher thermal conductivity required to provide additional face cooling margin. The nickel-clad rings were required to allow proper welding of the faceplate to the body.

TABLE III-III

INJECTOR MANIFOLD HYDRAULIC SUMMARY

Ref: B/P # 1191403

	FUEL			OXID		
	V_f mps (fps)	ΔP_f kPa (psid)	V_{ox} mps (fps)	ΔP_{ox} kPa (psid)	V_{ox} mps (fps)	ΔP_{ox} kPa (psid)
Inlet Line (Round)	11.3 (37)	137.9 (20)	12.8 (42)	41.4 (6)		
(Squashed)	18.6 (61)					
Upper Fuel Dome	14.0-18.3 (46.60)					
Outer Oxidizer Torus	-	-	(In) 12.8 (42) (Stagnation) 3.66 (12)	27.6 (4)		
Distribution Plate	19.8 (65)	137.9 (20)	17.7 (58)	165.5 (24)		
Inner Oxidizer Ring	-	-	10.4 (34)	27.6 (4)		
Radial Oxidizer Manifold	-	-	13.7 (45)	103.4 (15)		
Downcomer	14.6 (48)	82.7 (12)	18.9 (62)	186.1 (27)		
Channel	7.6-10.7 (25-35)	34.5 (5)	9.1-13.1 (30-43)	55.2 (8)		
Total Manifold ΔP kPa (psid)		393 (57)		607 (88)		

1 INTERPRET DRAWING PER ALUC-STD-0026.

2 MAKE PER AS470-7A WITH 1103100 AND APPLICABLE DASH NUMBER.

3 BRAZE TO IN DIMS PER COGNIZANT PROJECT ENGINEER.

4 GUNITE TUBE ASSY AND BODY ASSY TO BE FUSED WITH .010.

5 APPLY TO ALL BOLT TORQUES PER ALUC-STD-0026 AT BARELY EXCEPT AND AND.

6 INSTALL FITTINGS PER AS0900.

7 ALL DIAMETERS ON A COMMON AXIS TO BE .010 CIRCULAR UNLESS OTHERWISE NOTED.

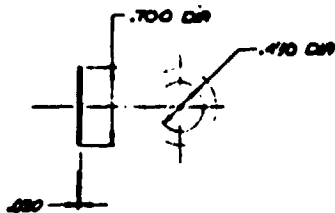
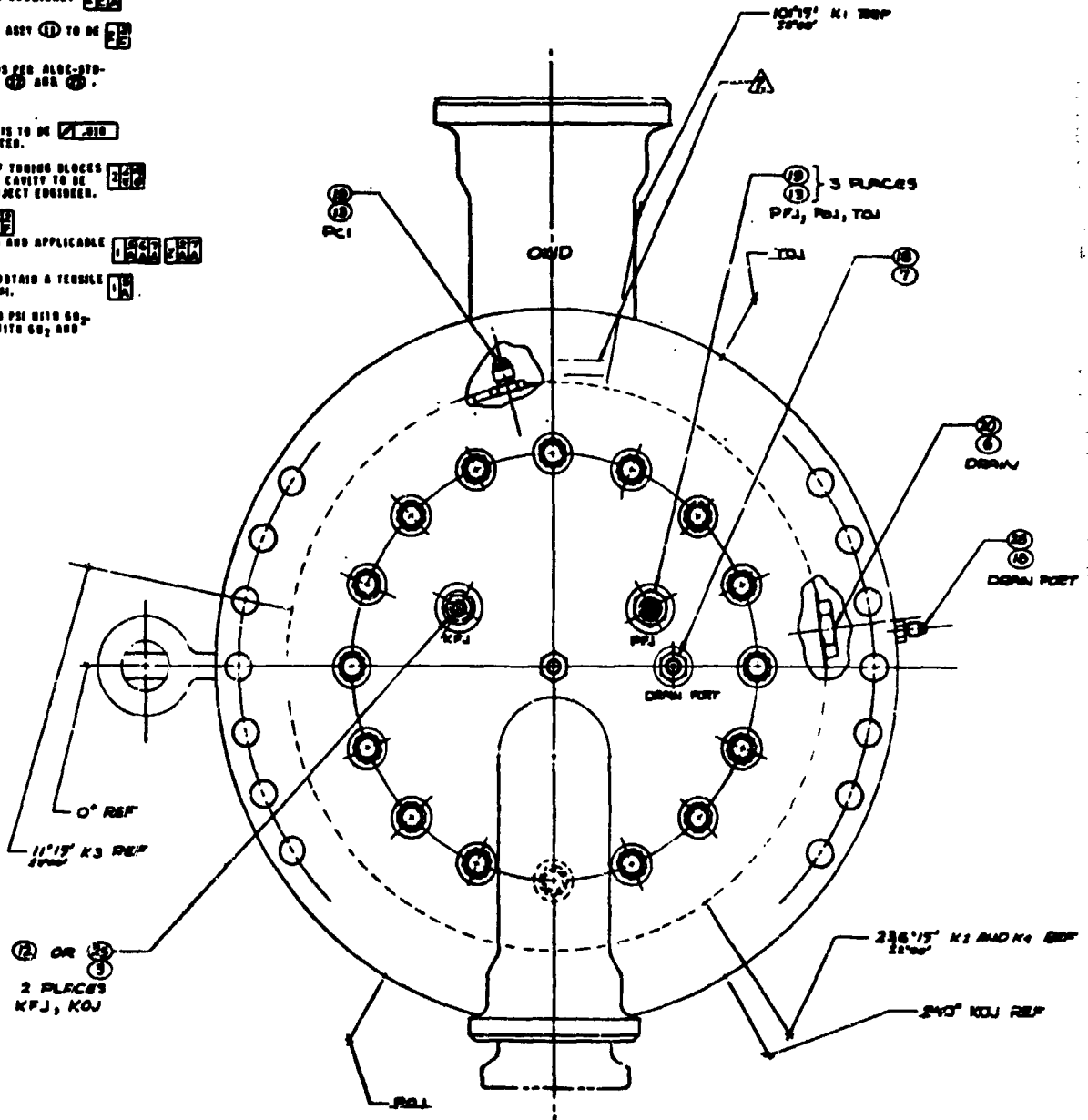
8 THE QUANTITY AND SELECTION OF TURNING BLOCS OR TO BE ASSIGNED PER CAVITY TO BE DETERMINED PER COGNIZANT PROJECT ENGINEER.

9 TO BE SUPPLIED BY CUSTOMER.

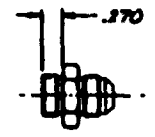
10 MAKE PER AS470-29 WITH 1103100 AND APPLICABLE DASH NUMBER.

11 HEAT TREAT PER MIL-R-6075 TO OBTAIN A TENSILE STRENGTH BETWEEN 155 TO 165 KSI.

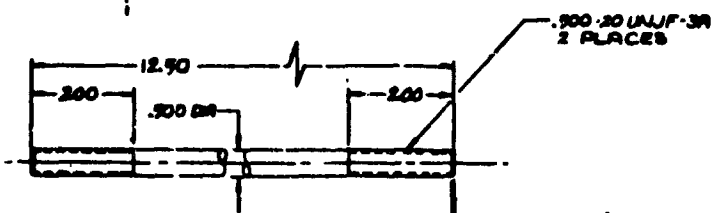
12 7000 PSI TEST ASSY TO 4000 PSI; 50 PSI WITH GUNITE TEST AT 3000 PSI; 50 PSI WITH GUNITE AND GUNITE FOR 5 MINUTES MINIMUM.



1 DETAIL SCALE = 2/1

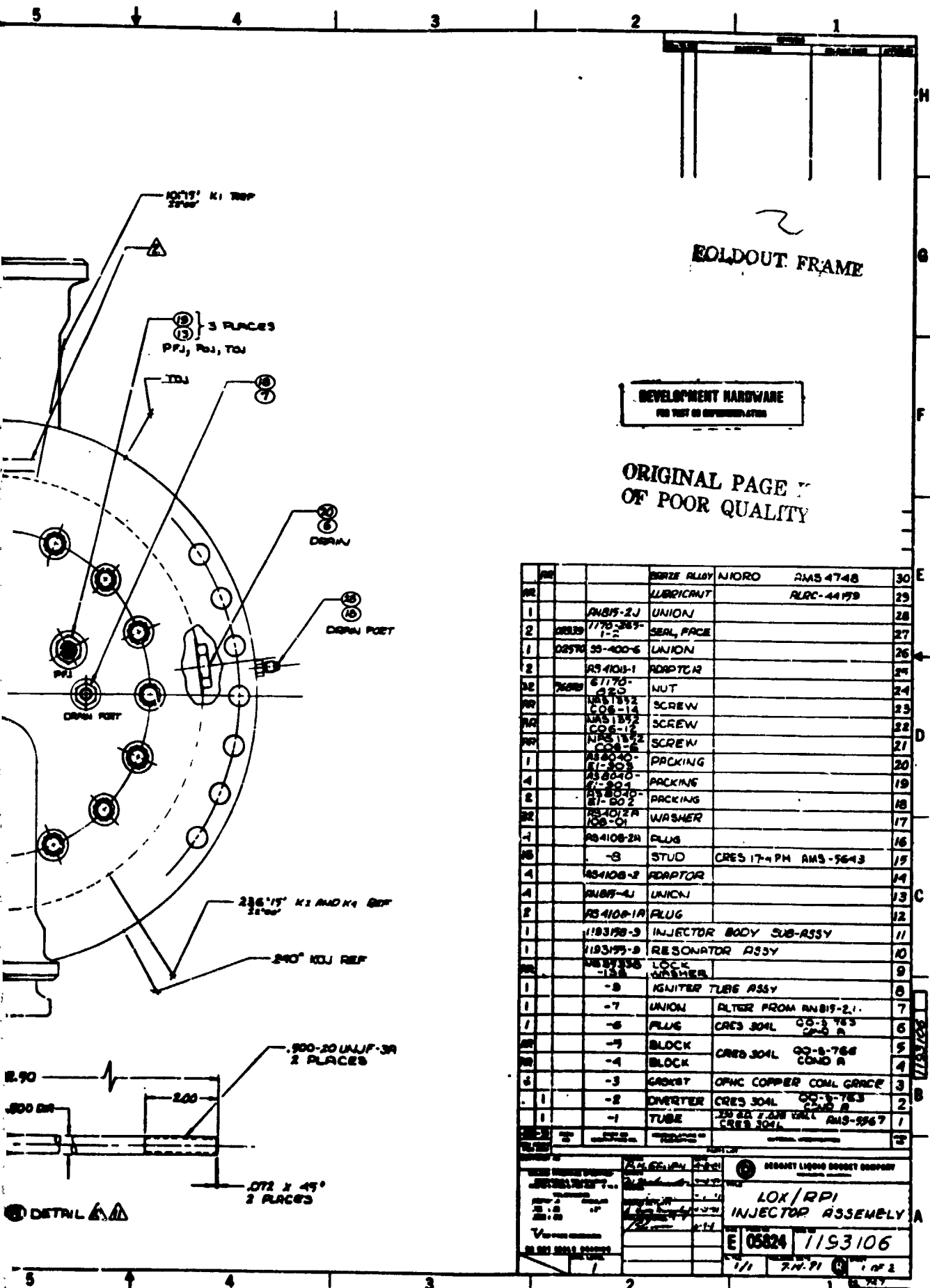


2 DETAIL SCALE = NONE



3 DETAIL

MOLDOUT FRAME



DEVELOPMENT HARDWARE
FOR TEST OF REPRESENTATION

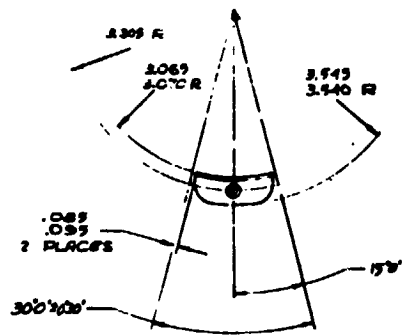
ORIGINAL PAGE
OF POOR QUALITY

QTY	PART NO	SIZE	ALLY	N/O	AMS	
					AMS 4748	30
			LUBRICANT		RLRC-44179	29
1	AN819-2J		UNION			28
2	CRS39 7778-349-1-2		SEAL, FACE			27
1	CRS70 33-400-6		UNION			26
2	AS4108-1		ADAPTOR			25
2	AS1770-2		NUT			24
2	AS1552 CO8-14		SCREW			23
2	AS1552 CO8-12		SCREW			22
2	AS1552 CO8-8		SCREW			21
1	AS8040-21-202		PACKING			20
4	AS8040-21-202		PACKING			19
2	AS8040-21-202		PACKING			18
2	AS4028 CO8-01		WASHER			17
1	AS4108-2A		PLUG			16
16	-8		STUD	CRES 17-4 PH	AMS-5643	15
4	AS4108-2		ADAPTOR			14
4	AN819-4J		UNION			13
2	AS4108-1A		PLUG			12
1	1193108-3		INJECTOR BODY SUB-ASSY			11
1	1193109-3		RESONATOR ASSY			10
2	AS87335-128		LOCK WASHERS			9
1	-8		IGNITER TUBE ASSY			8
1	-7		UNION	ALTER FROM AN819-2.1		7
1	-6		PLUG	CRES 304L CO-3-783 COND A		6
2	-7		BLOCK	CRES 304L CO-5-788 COND A		5
2	-4		BLOCK	CRES 304L CO-5-783 COND A		4
6	-3		GASKET	OFHC COPPER COML GRACE		3
1	-2		OVERTER	CRES 304L CO-3-783 COND A		2
1	-1		TUBE	316 SS 2.00 WALL	AMS-5567	1

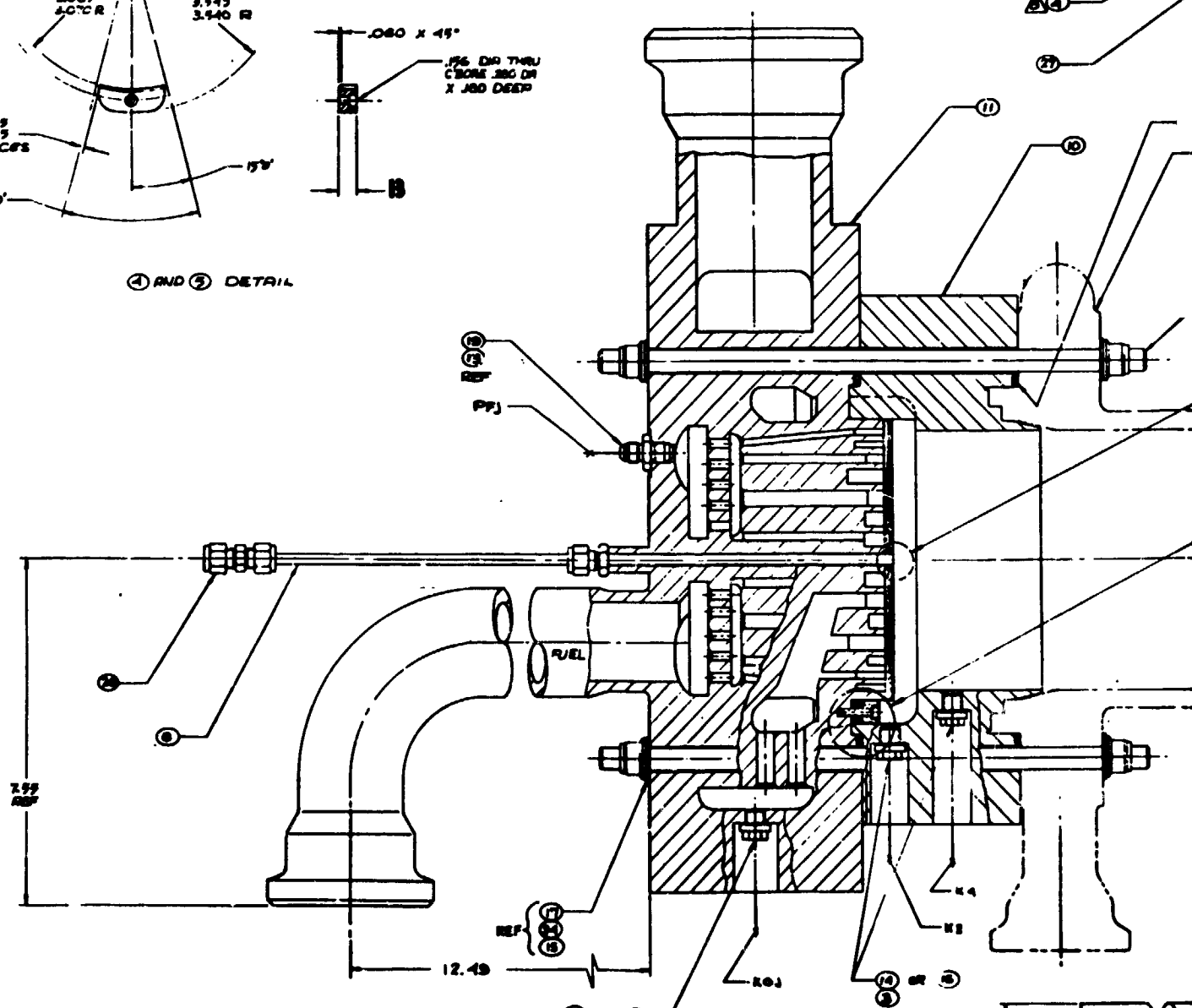
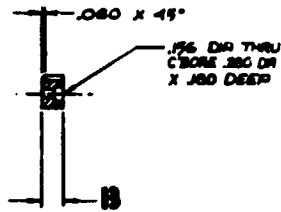
Figure III-9. Injector Assembly (Sheet 1 of 2) 35

8 7 6 5 4

ITEM NO.	B
④	.390
⑤	.400

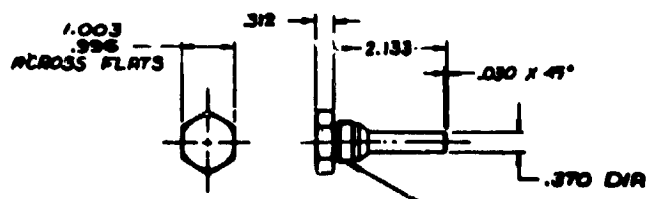


④ AND ⑤ DETAIL



7.77 REF

12.49



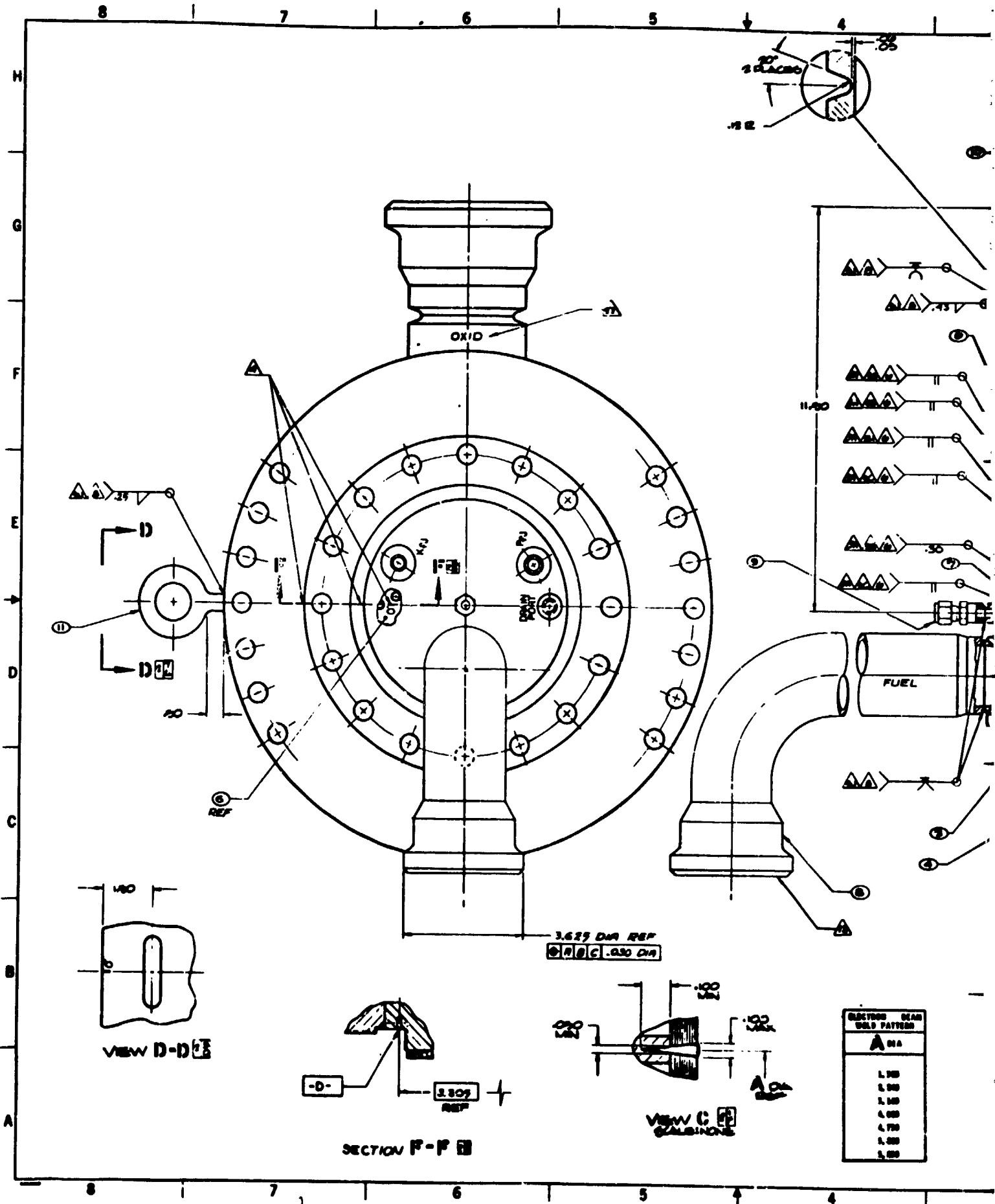
⑥ DETAIL MACHINING PER MS 35676 EC

-19 ASSY

.374 .390 DIA STOCK

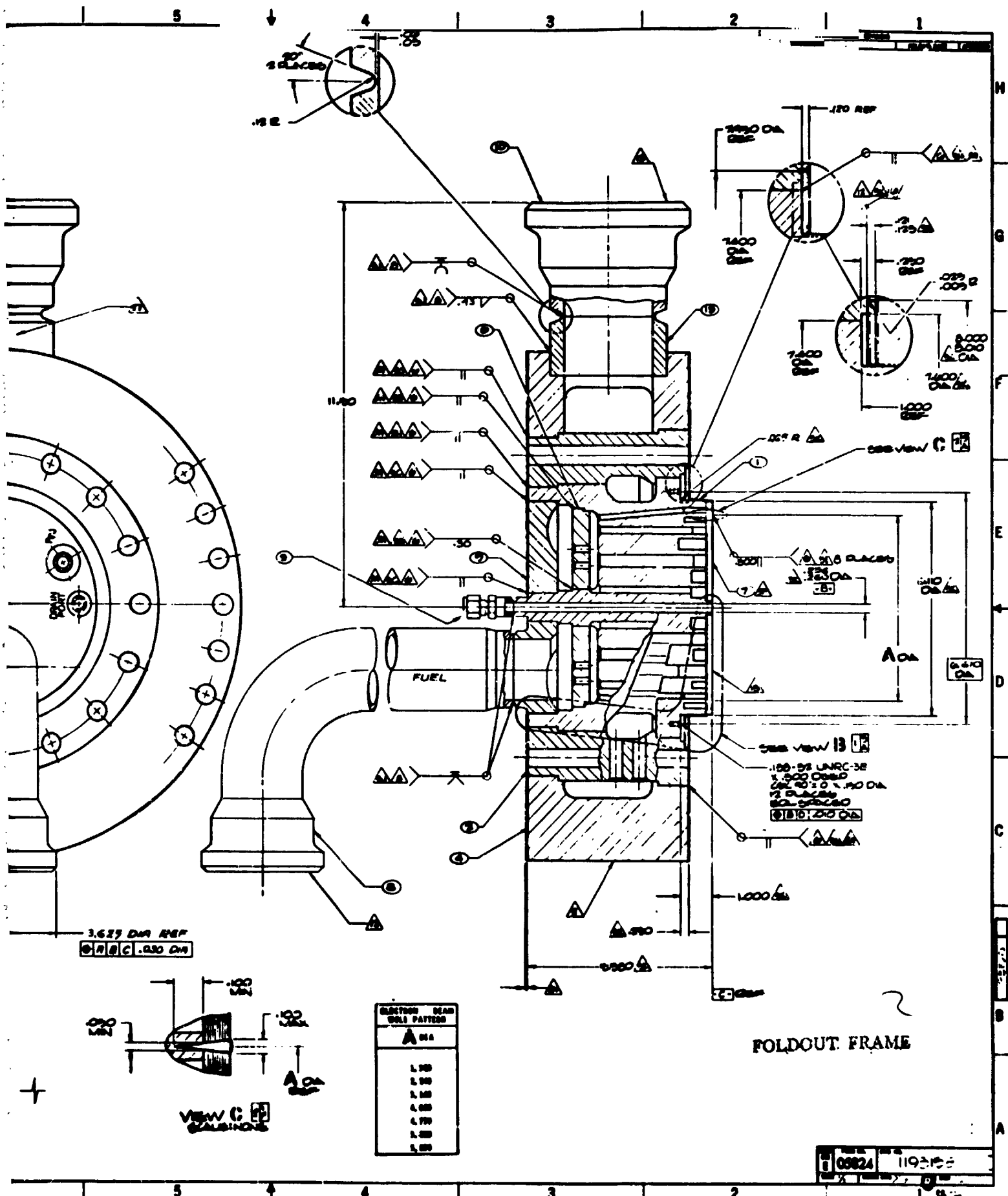
.090 R

REMOVE FRAME



POINT POINT BEALME

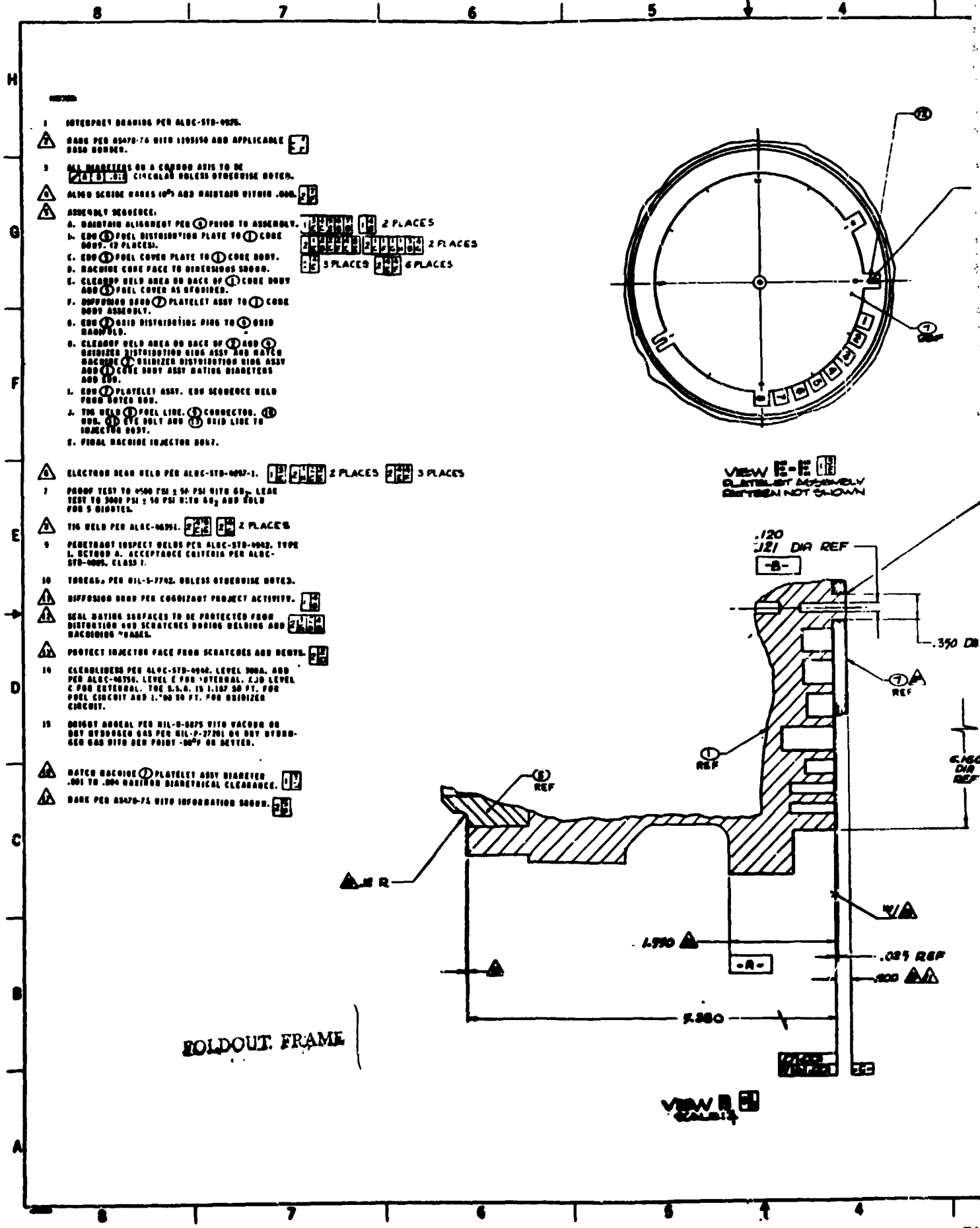
Figure 1



SECTION DASH	
DASH PATTERNS	
▲	614
1.	1.00
2.	1.50
3.	1.50
4.	4.00
5.	4.75
6.	1.00
7.	1.00

05824 11/23/66

Figure III-10. Injector Body Subassembly (Sheet 1 of 2)



1 INTERPRET DRAWING PER ALUC-STD-002.

▲ HAZE PER AS470-70 WITH INFORMATION AND APPLICABLE DATA BORDER.

3 ALL MARKETERS ON A COMMON AXIS TO BE CENTERED UNLESS OTHERWISE NOTED.

▲ ALSO SCRIBE MARKS (Ø) AND MAINTAIN WITHIN .000.

▲ ASSEMBLY SEQUENCE:

A. MAINTAIN ALIGNMENT PER (Ø) PRIOR TO ASSEMBLY.

B. EDGE (Ø) POOL DISTRIBUTION PLATE TO (Ø) CORE BODY. 2 PLACES

C. EDGE (Ø) POOL COVER PLATE TO (Ø) CORE BODY. 2 PLACES

D. BACKSIDE CORE FACE TO DIMENSIONS 3000.

E. CLEARWELD WELD AREA ON BACK OF (Ø) CORE BODY AND (Ø) POOL COVER AS REQUIRED.

F. SUPPORTING BODY (Ø) PLATELET ASSY TO (Ø) CORE BODY ASSEMBLY.

G. EDGE (Ø) OXID DISTRIBUTION RING TO (Ø) OXID BODY WELD.

H. CLEARWELD WELD AREA ON BACK OF (Ø) AND (Ø) OXIDIZER DISTRIBUTION RING ASSY AND WATCH BACKSIDE OXIDIZER DISTRIBUTION RING ASSY AND (Ø) CORE BODY ASSY HAVING DIAMETERS AND TGD.

I. EDGE (Ø) PLATELET ASSY. EDU SEQUENCE WELD FROM NOTES 200.

J. THE WELD (Ø) POOL LINE, (Ø) CONNECTOR, (Ø) RING, (Ø) FIVE DOLT AND (Ø) OXID LINE TO INJECTOR BODY.

K. FINAL MACHINE INJECTOR BOLT.

▲ ELECTRON BEAM WELD PER ALUC-STD-007-1. 2 PLACES 3 PLACES

7 PROOF TEST TO 4500 PSI 2.50 PSI WITH 60. LEAK TEST TO 3000 PSI 2.50 PSI 0:10 60, AND HOLD FOR 5 MINUTES.

▲ TIG WELD PER ALUC-00351. 2 PLACES

9 PENETRANT INSPECT WELDS PER ALUC-STD-0002, TYPE L METHOD A. ACCEPTANCE CRITERIA PER ALUC-STD-0005, CLASS I.

10 TORQUES PER MIL-S-7742, UNLESS OTHERWISE NOTED.

▲ DIFFUSION BOND PER COGNIZANT PROJECT ACTIVITY.

▲ SEAL MATING SURFACES TO BE PROTECTED FROM DISTORTION AND SCRATCHES DURING WELDING AND MACHINING "GAMES".

▲ PROTECT INJECTOR FACE FROM SCRATCHES AND DENTS.

10 CLEARANCES PER ALUC-STD-0002, LEVEL 300A, AND PER ALUC-00350, LEVEL E FOR INTERNAL, 2.0 LEVEL C FOR EXTERNAL, THE D.S.G. IS 1.107 50 FT. FOR POOL CIRCUIT AND 1.100 50 FT. FOR OXIDIZER CIRCUIT.

15 BRIGHT APPEAR PER MIL-S-8075 WITH VACUUM OR GET WITHIN 605 PER MIL-P-27201 OR GET WITHIN 605 WITHIN 605 POINT -004 OR BETTER.

▲ WATCH MACHINE (Ø) PLATELET ASSY DIAMETER .001 TO .004 MAXIMUM DIA METRICAL CLEARANCE. 12

▲ HAZE PER AS470-75 WITH INFORMATION BOARD. 20

VIEW E-E
CATALYST ASSEMBLY
DETAILS BETWEEN NOT SHOWN

.120 DIA REF
-B-

.350 DIA

Ø 170 REF
Ø 170 REF

Ø REF

Ø REF

1.970

-R-

Ø 170 REF

.025 REF

.000

BOLDOUT FRAME

VIEW B-B
SCALE 1/8"

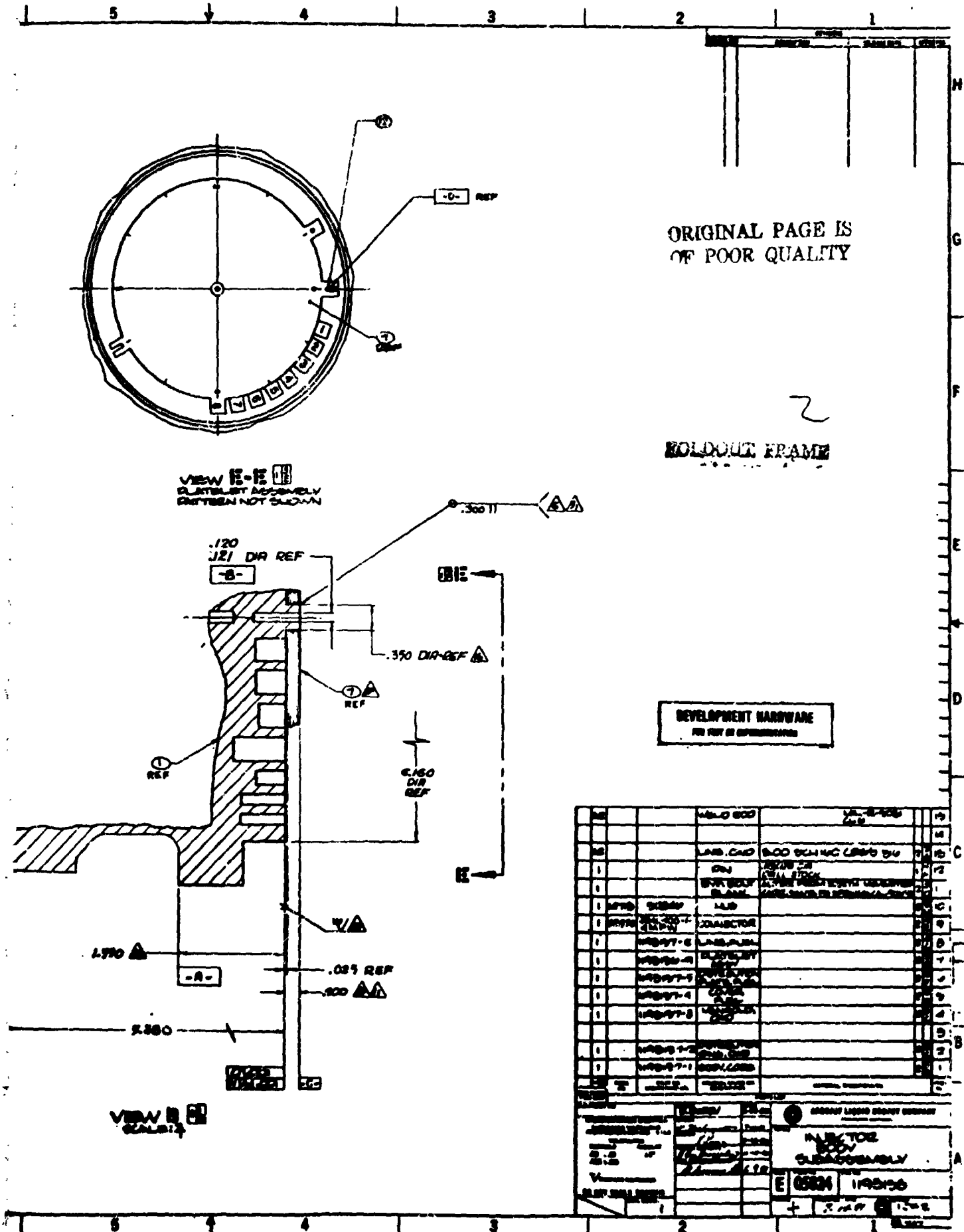


Figure III-10. Injector Body Subassembly (Sheet 2 of 2)

III, B, Detailed Design Description (cont.)

Mating of the injector subassembly (PN 1193158) and the resonator assembly (PN 1193155) produces an L-shaped annular cavity at the periphery of the injector face. The annular cavity is divided into 12 compartments, each containing a removable arc-shaped tuning block which is held in place by a socket head screw. These can be seen in Figure II-2. The segmented cavity prevents tangential modes of combustion instability from developing within the cavity. The removable blocks allow the cavity to be easily retuned if required.

The injector assembly contains ports for measurement of manifold pressures and chamber pressures. Drain ports are provided for removing cleaning solvents from the manifold while the assembly is mounted in a horizontal position, with the lifting eyebolt in the vertically upward orientation. These features can be seen in Figure III-9.

Assembly of the all-welded injector and the resonator ring requires the use of a single spring-activated Teflon face seal. The recommended part (PN 1170-265-1-2) is a RACO brand seal, manufactured by the Fluorocarbon Company. This type of oxygen-compatible seal is specifically designed for use at cryogenic temperatures. The same seal is also used at the interface of the resonator ring and the NASA-supplied cooled chambers.

The injector, resonator, and NASA-supplied cooled chamber flanges are held by sixteen 1.27-cm (0.5-in.) diameter studs which are 31.75 cm (12.5 in.) long. The stud material is 17-4 stainless alloy, heat-treated per MIL H 6875 to condition H-900 to H-1025 in order to provide a tensile stress capability of 1.1×10^6 kPa (160K psi). The actual stress is 0.83×10^6 kPa (120K psi) at the recommended torque value of 149 ± 27 m-N (110 ± 20 ft-lbF). The recommended torque value assumes the use of Fel-Pro C5A lubricant on the studs. The required torque may be different for other lubricants.

III, B. Detailed Design Description (cont.)

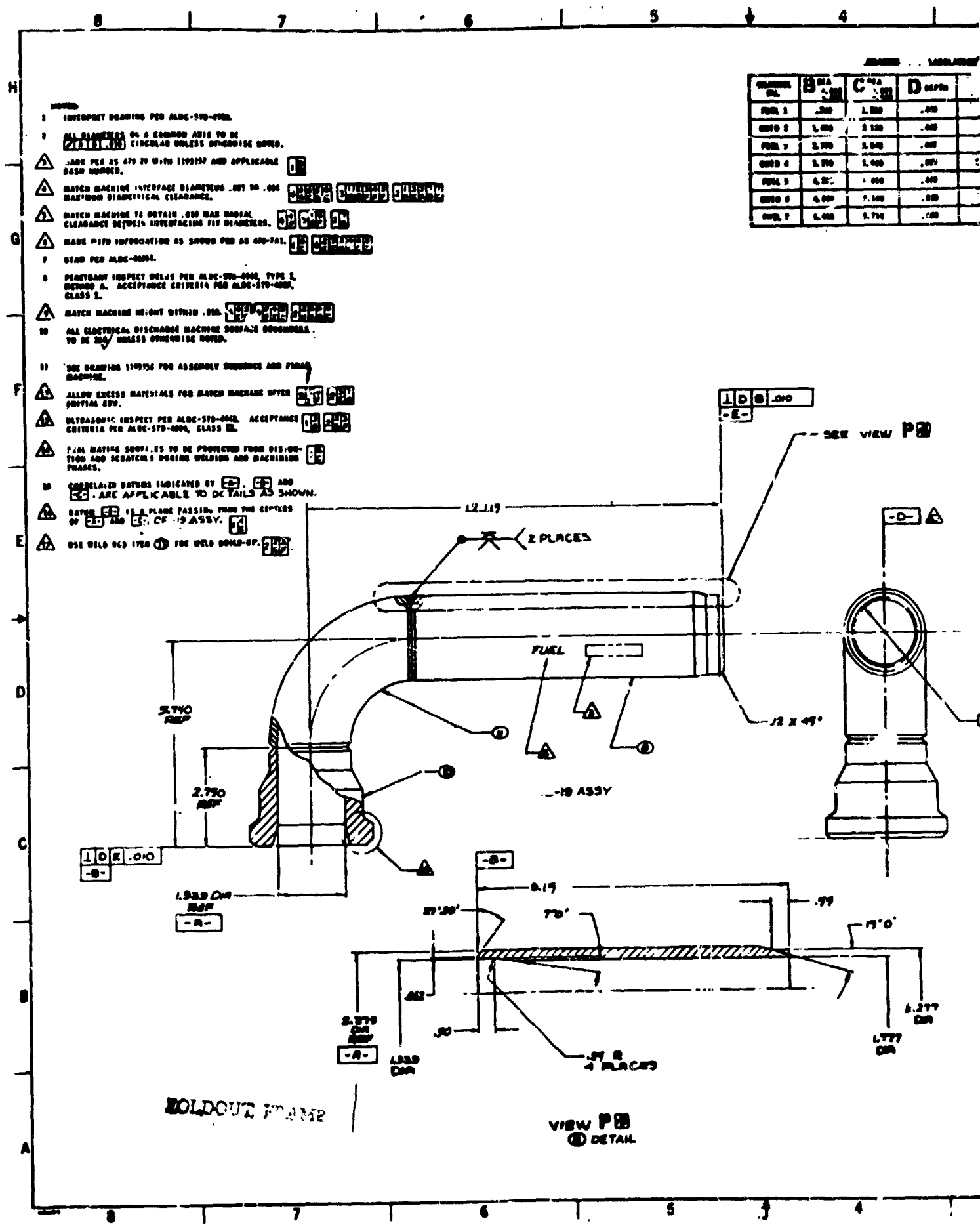
2. Propellant Interfaces

The test stand propellant delivery system interfaces with the injector inlet lines through weld-on Greyloc hubs. The fuel enters the back of the injector through a 5.08-cm (2-in.) Schedule 80 pipe/elbow having a 5.08-cm (2-in.) Greyloc hub (PN 52822). The oxygen enters the side-mounted 7.62-cm (3-in.) pipe via a 7.62-cm (3-in.) Greyloc hub (PN 52846). The Greyloc clamps (not supplied) for the 5.08-cm (2-in.) size (2GR20) are PN's 48502 and 48503 for the 7.62-cm (3-in.) pipe size (3GR25) oxygen line. The seal rings, which should be replaced when the lines are opened, require Greyloc PN's 51236 and 51237 for the fuel and oxygen circuits, respectively.

3. Manifolding

The components which form the manifolding system are shown in Figures III-11 through III-20. The fuel flows from the 5.08-cm (2 in.) inlet line through the back coverplate into an annular distribution manifold (Figures III-12 and III-9). A primary flow distribution plate (PN 1193157), shown in Figure III-13, redistributes the incoming fuel before it enters the injector manifold downcomers. The downcomers, shown in Figures III-14 and III-15, transport the fuel from the plenum located downstream of the primary flow distribution plate to the face rings also shown in Figure III-15. The outermost ring and each alternate face ring moving inward is supplied with fuel. The injector elements are fed directly from the face rings.

The oxygen, entering through a single side-mounted 7.62-cm (3-in.) line (Figure 18), splits into two equal streams and flows circumferentially around the injector core through an annular passage which continuously decreases in the cross-sectioned area. This flow path can be seen in the drawing of Figure II-1.

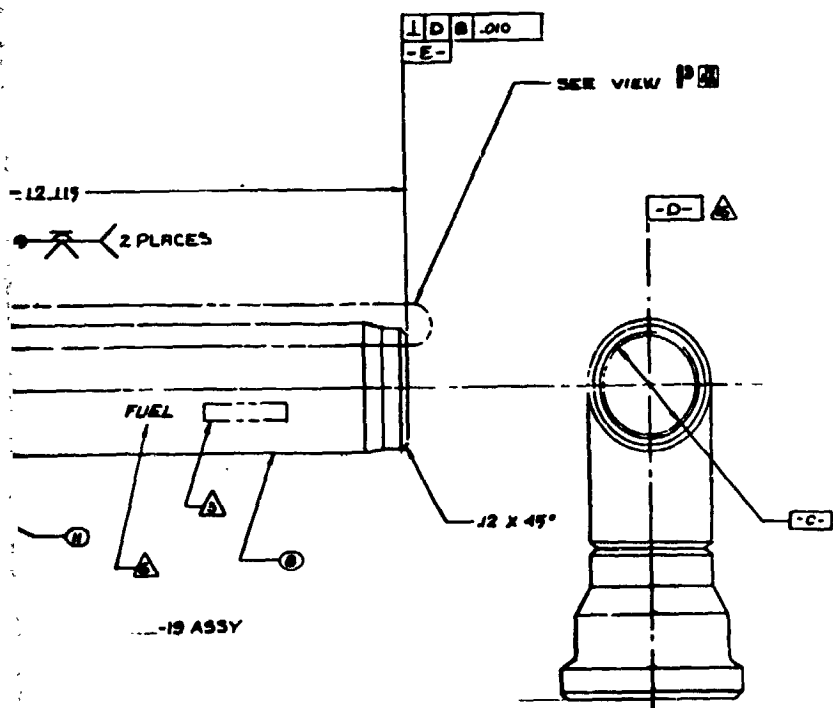


CHAMFER DIA	B DIA	C DIA	D DIA
POH 1	.500	1.200	.600
POH 2	1.400	2.100	.600
POH 3	1.700	2.400	.600
POH 4	1.700	2.400	.600
POH 5	1.800	2.500	.600
POH 6	1.800	2.500	.600
POH 7	1.800	2.500	.600

Figure

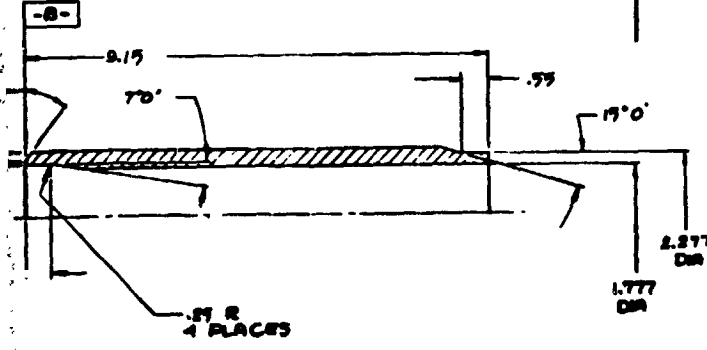
INJECTOR - LABORATORY

CHANNEL NO.	B DIA	C DIA	D DEPN	E LENGTH	CHANNEL WIDTH DEG	LAND WIDTH DEG
CHNL 1	.300	1.300	.040	.700		.120
CHNL 2	1.400	2.120	.040	.700	1	.120
CHNL 3	2.100	3.000	.040	.600		.120
CHNL 4	3.700	3.900	.025	1.200	2	.120
CHNL 5	4.300	4.610	.040	.700	3	.120
CHNL 6	4.000	3.100	.025	1.000	4	.120
CHNL 7	5.000	5.700	.040	.700	5	.120
					6	.120
					7	.120
					8	.120



BOLDOUT FRAME

DEVELOPMENT HARDWARE
FOR TEST OR EXPERIMENTATION



AR	QTY	DESCRIPTION	REF	QTY	DESCRIPTION	REF	QTY	DESCRIPTION	REF	QTY	DESCRIPTION	REF
		WELD ROD	ML-8-7037	14	CLASS 6							
		WELD ROD	NI 61	13	ML-8-21962							
		7884 #2	ELBOW	12	2.00 SEN 80 CRFS 316							
		HW3 92822	MUD	11								
				10								
				9								
				8								
				7								
		DISTRIBUTION PLATE, FUEL	PERALCO	6	2MS 2297							
		CO VALV, FUEL	31-8-8	5	OO-8-788							
			CRFS	4	CL 304L COND A							
		MANIFOLD ORIF	CRFS	3	OO-8-763							
		DISTRIBUTION BOARD, FUEL		2	CL 304L COND A							
		BODY, CASE		1								

VIEW P B
DETAIL

APPROVED FOR DATE: 7/2/68 BY: [Signature] TITLE: [Title]	APPROVED FOR DATE: 7/2/68 BY: [Signature] TITLE: [Title]	APPROVED FOR DATE: 7/2/68 BY: [Signature] TITLE: [Title]	DETAILS - COMPONENT, INJECTOR E 05824 1193157 VI 2/4/68
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Figure III-11. Injector Components Details (Sheet 1 of 4)

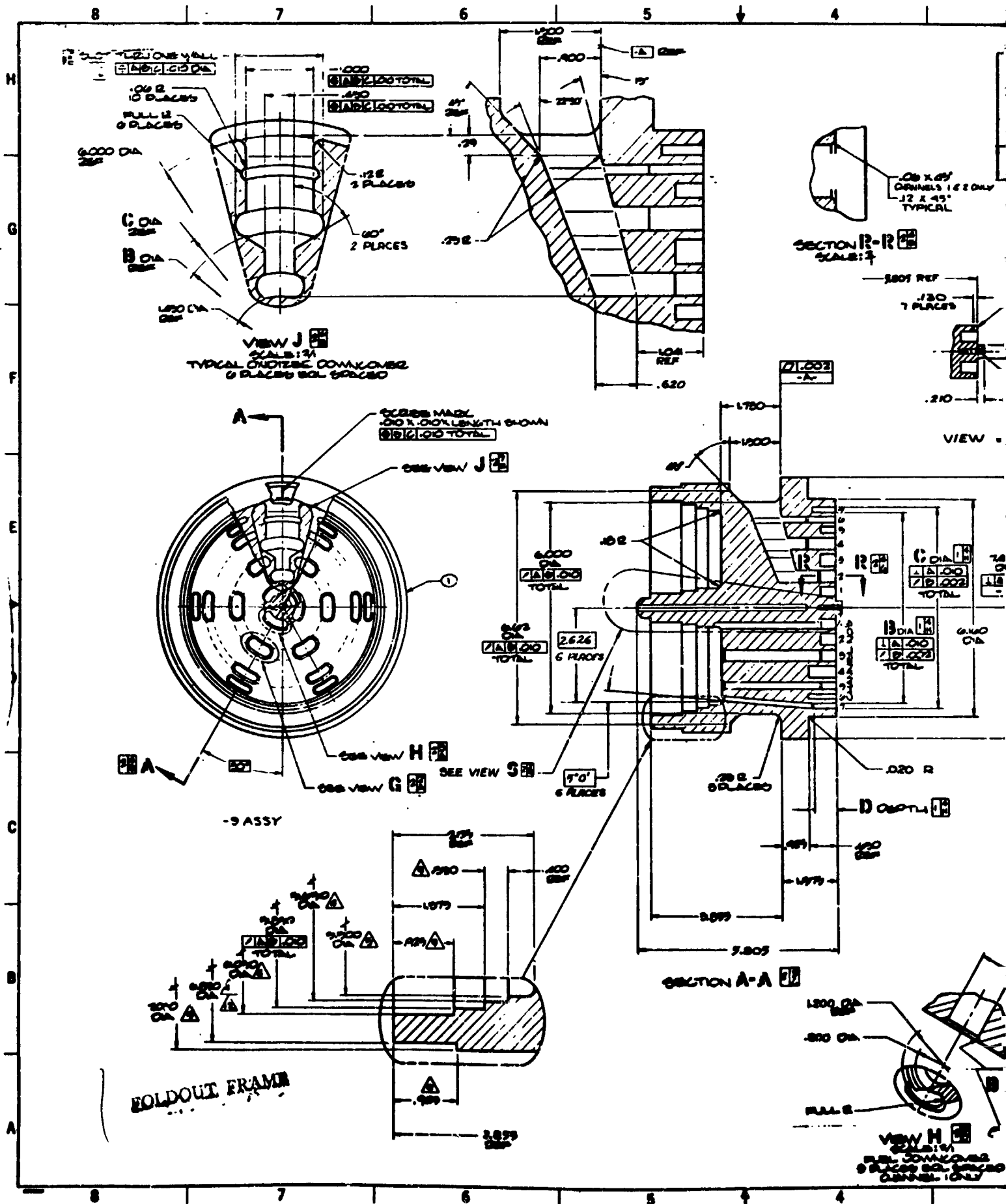


Figure III-

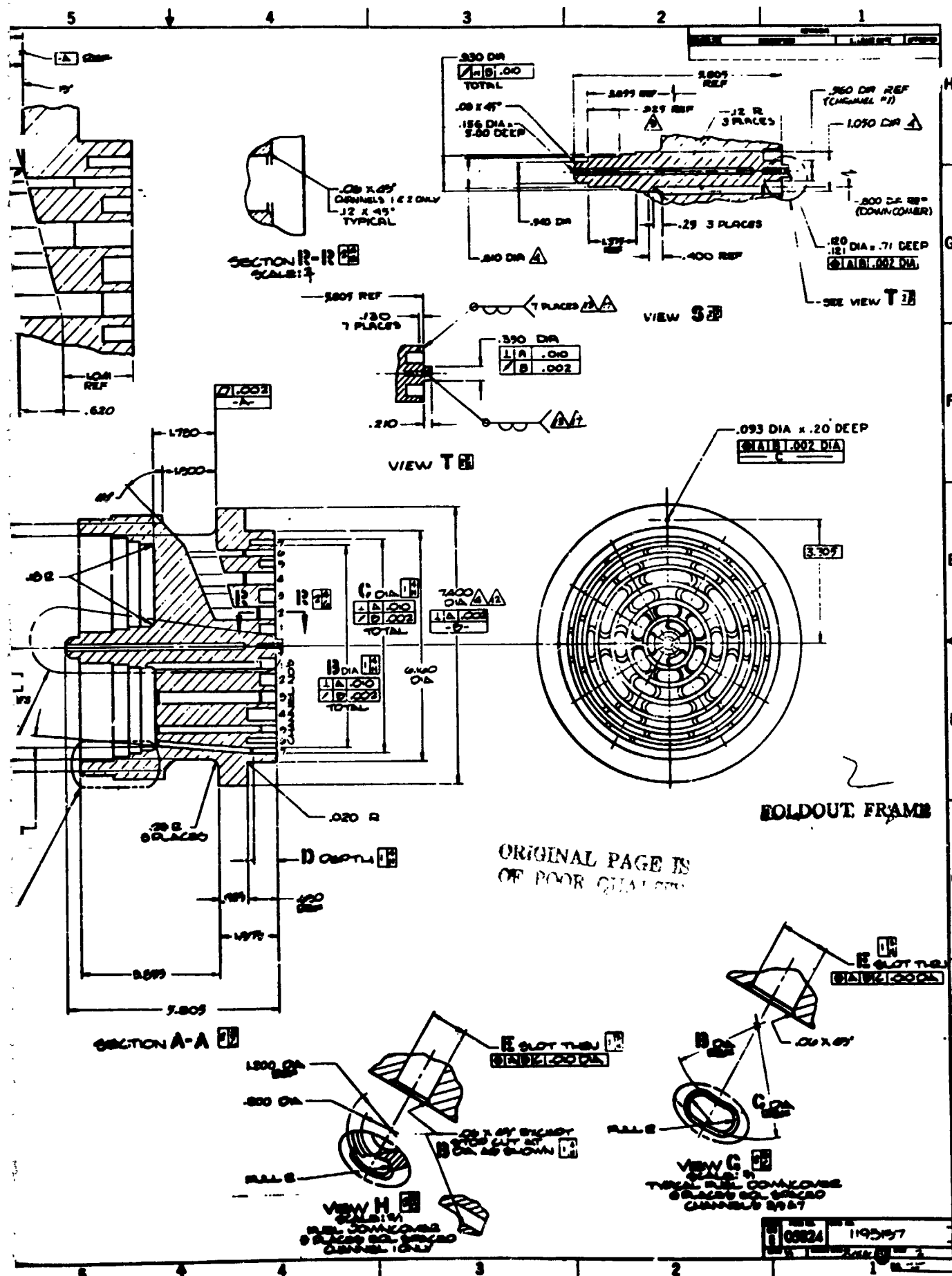


Figure III-11. Injector Components Details (Sheet 2 of 4)

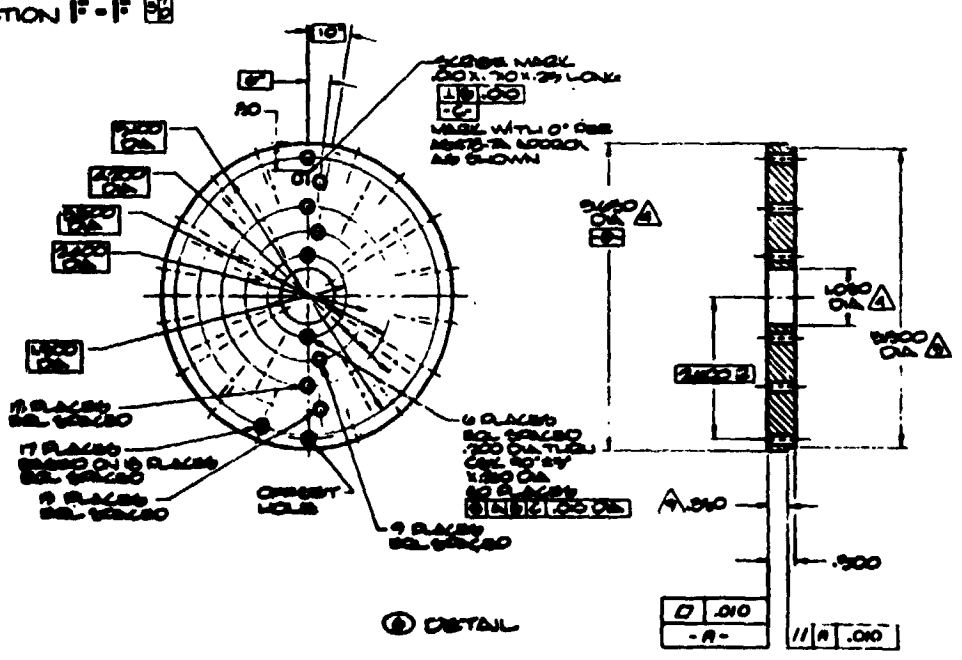
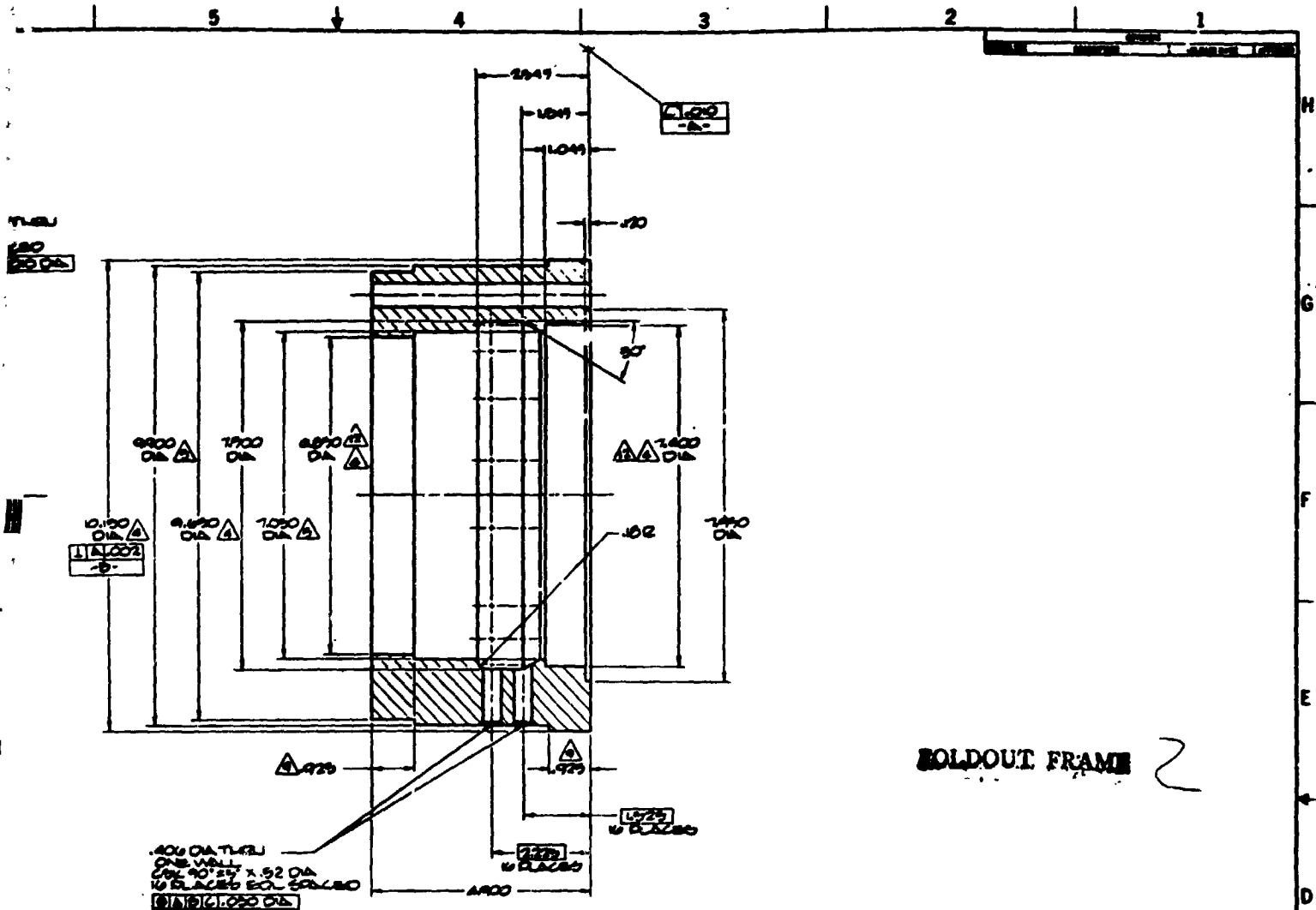


Figure III-11. Injector Components Details (Sheet 3 of 4)

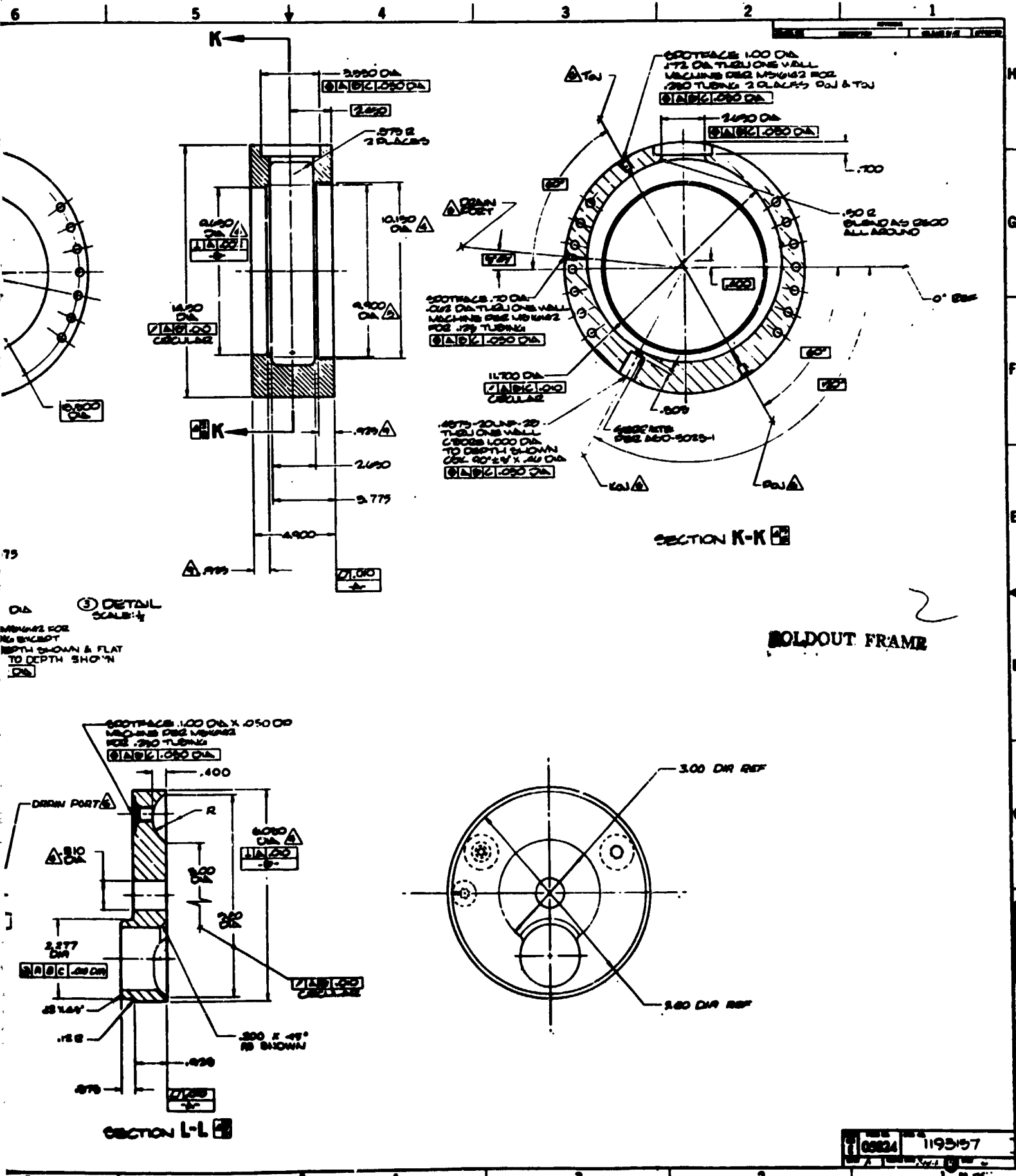


Figure III-11. Injector Components Details (Sheet 4 of 4)

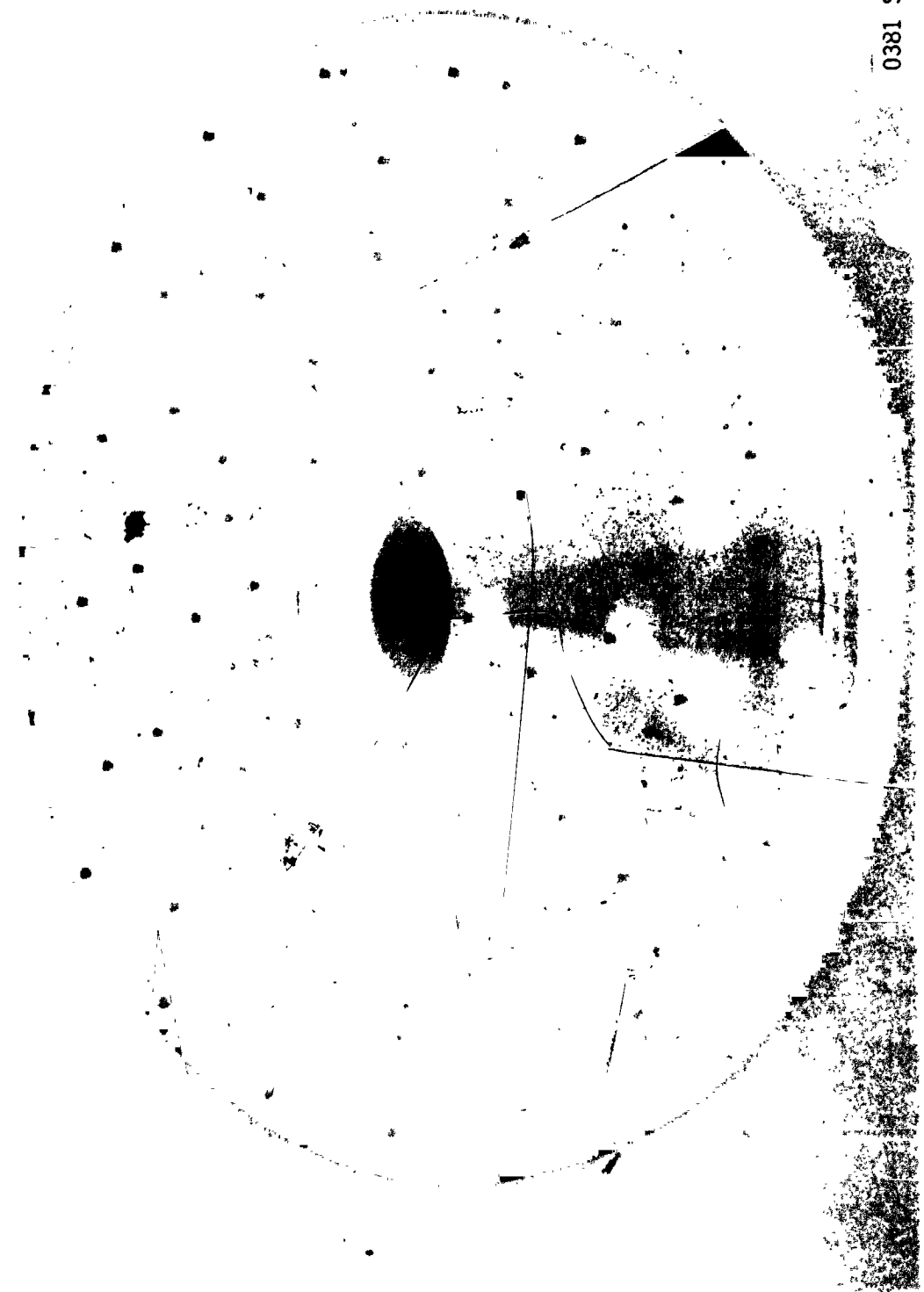
0924 119517

0381 SP 026



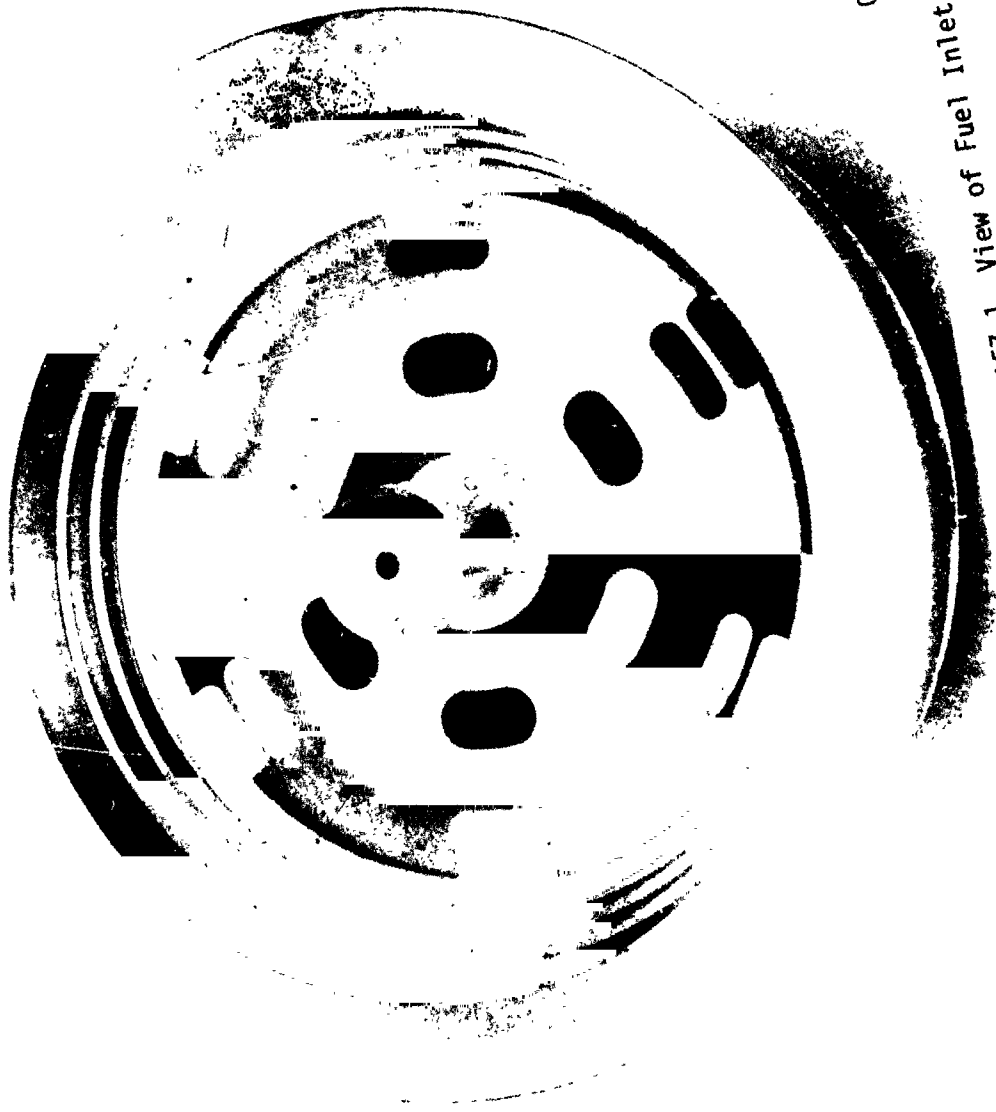
Figure III-12. Fuel Coverplate PN 1193157-5

UNCLASSIFIED
DATE 11/19/2013



0381 SP 028

Figure III-13. Fuel Distribution Plate PN 1193157-6

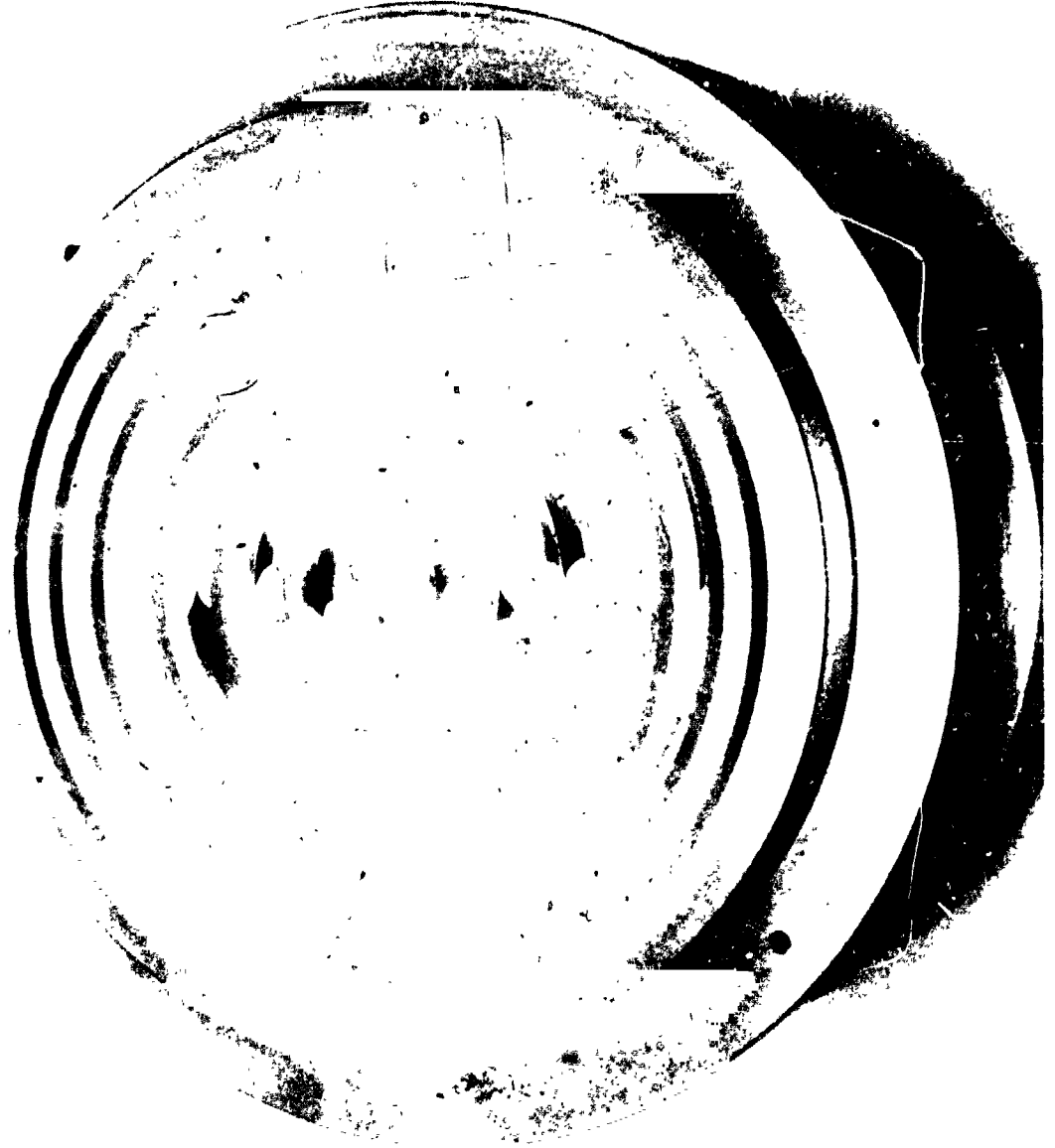


0381 SP 031

Injector Body Core PN 1193157-1, View of Fuel Inlet Side

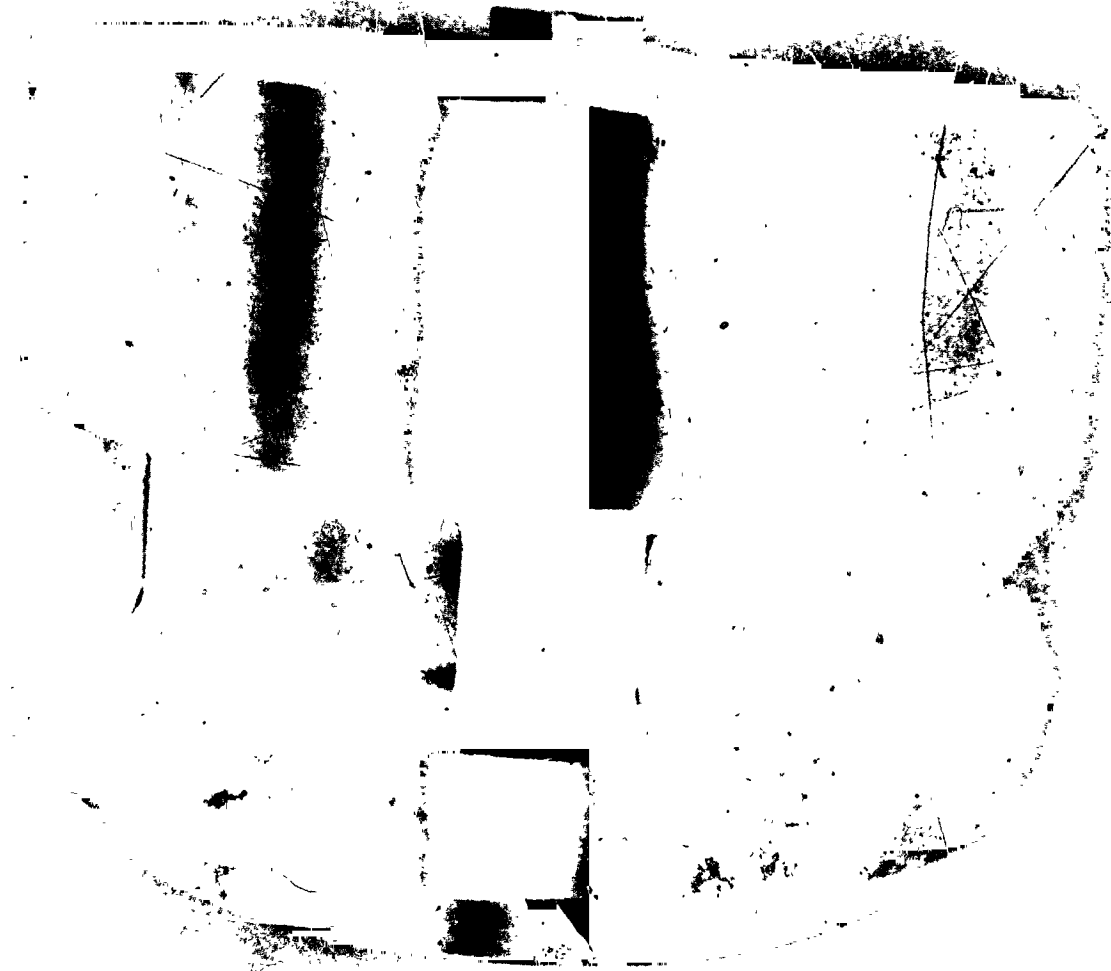
Figure III-14.

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0381 SP 030

Figure III-15. Injector Body Core PN 1193157-1, View of Ring Manifold



0381 SP 029

Figure III-16. Injector Body Core PN 1193157-1, Side View of Oxygen Inlet

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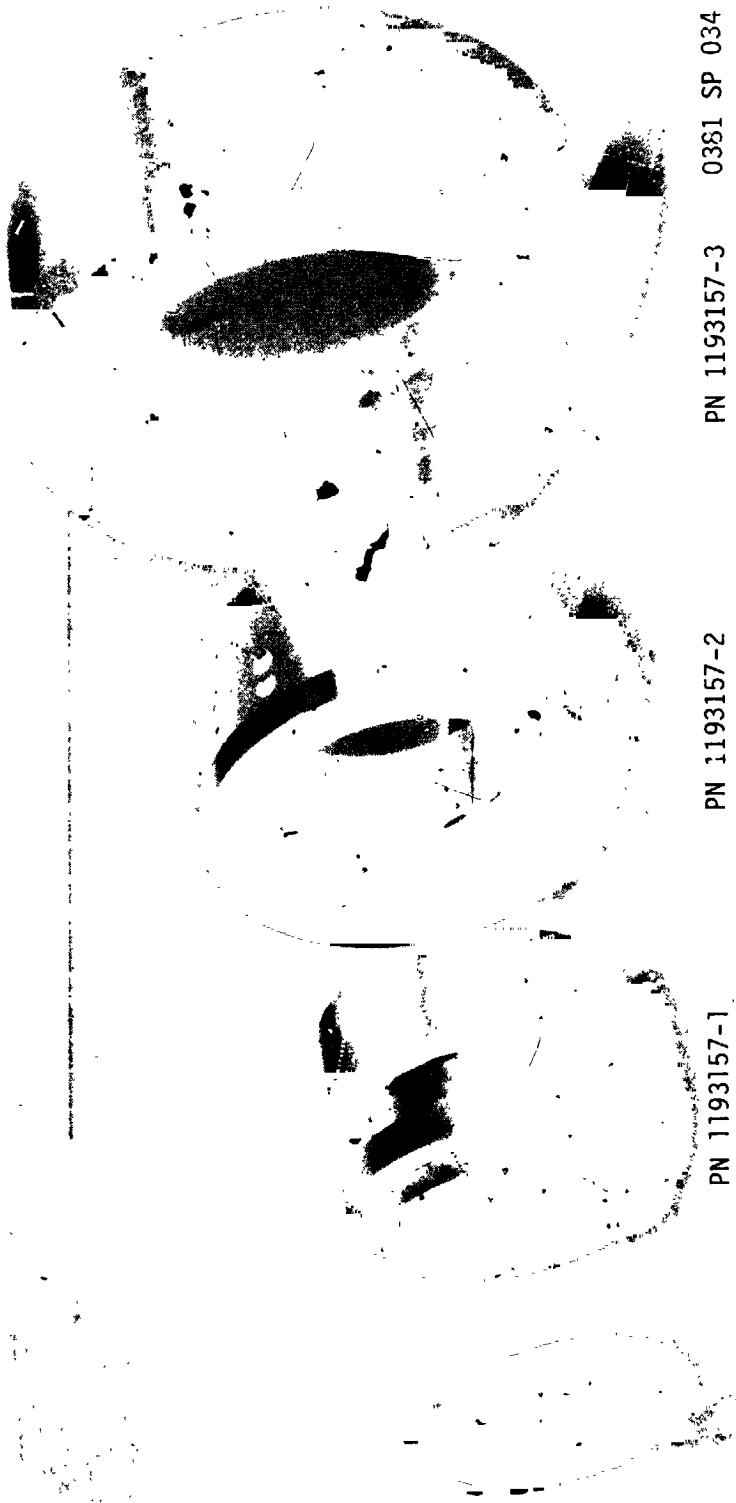


0781 SP 127
Figure III-17. Subassembly of Core, Fuel Distribution Plate, and Fuel Cover



0381 SP 027

Figure III-18. Oxidizer Manifold PN 1193157-3



PN 1193157-1 PN 1193157-2 PN 1193157-3 0361 SP 034

Figure III-19. Oxidizer Distribution Manifolding

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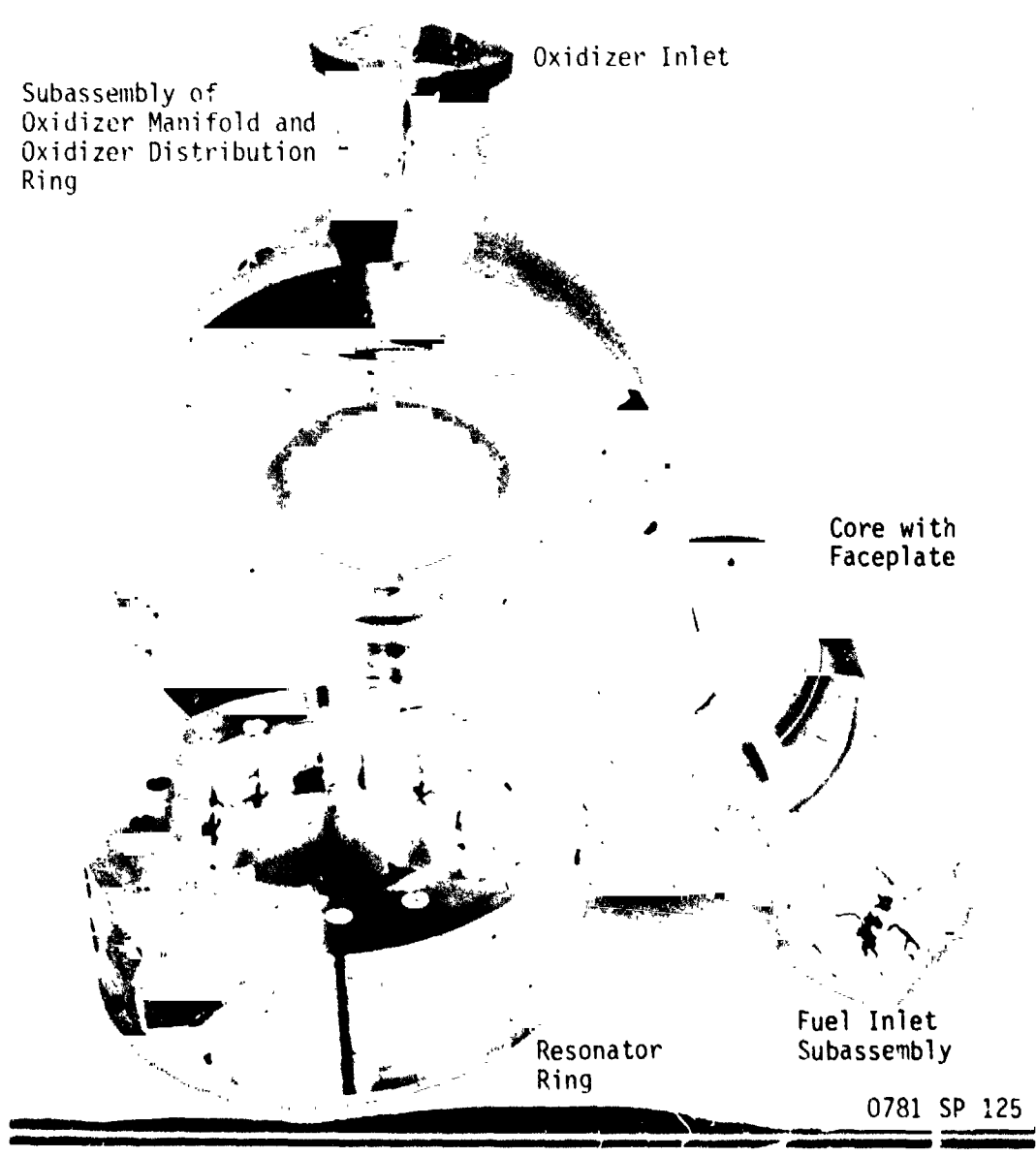


Figure III-20. Injector Subassemblies and Resonator Ring

III, B, Detailed Design Description (cont.)

The oxygen then flows radially inward through a primary flow distribution ring which can be seen in Figure III-19. The secondary plenum, located on the downstream side of the distribution ring, supplies a series of six cross-flow passages which intersect downcomers EDM-machined into the bottom of the face rings. These can be seen in Figures III-15 and III-16. The second, fourth, and sixth ring supply oxygen to the injection elements.

The flow distribution uniformity expected to result from this manifolding design is shown in Figure III-21, which provides data obtained from other contracts utilizing similar manifolding and flow distribution plates and rings.

4. Acoustic Resonator

The acoustic resonator design (PN 1193155) is shown in figure III-22. A photograph of the flange portion of the resonator is provided in Figure III-20.

5. Selected Injector Element Pattern

Detailed drawings of the selected injector mixed-element pattern are shown in Figure III-23. A photograph of the finished faceplate following welding to the body is provided in Figure III-24.

C. FABRICATION

The fabrication methods employed in the manufacture of the injector body and resonator ring involved conventional machining and electrical-discharge machining (EDM) of the non-circular manifold and downcomer passages seen in Figures III-14 -15, and -16. Electron-beam (EB) welding was

(Mass Distribution Measured Without Faceplate)

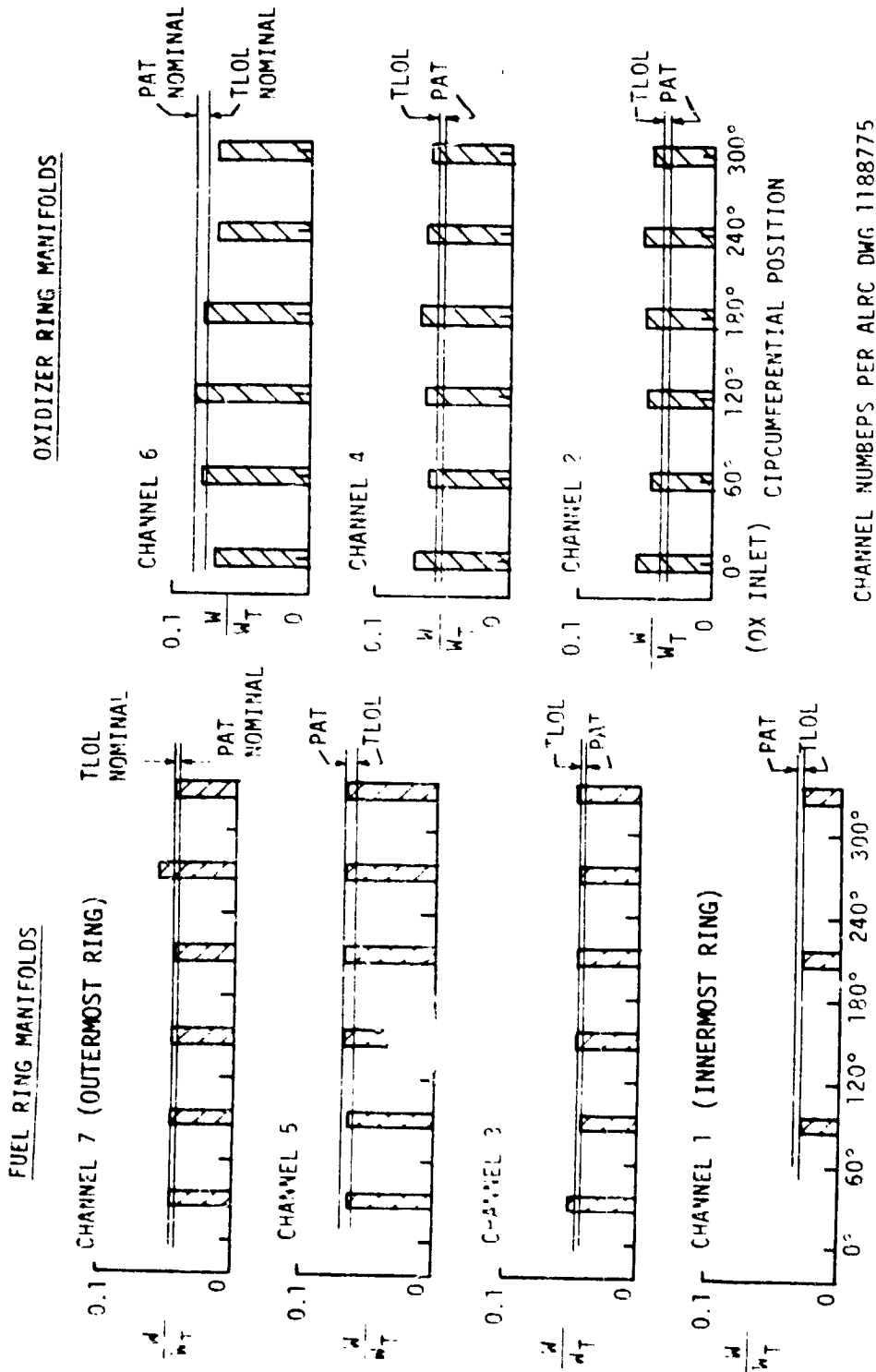


Figure III-21. Expected Injector Manifold Hydraulic Distribution

SPREY BRASSING PER ALRC-STD-0036.

DIAMETERS ON A COMMON AXIS TO BE $\pm .015$ CIRCULAR UNLESS OTHERWISE NOTED.

FINISH PER AS470-20 WITH 110BSS AND APPLICABLE SYMBOLS.

ALL INSTRUMENTATION REFERENCE DESIGNATIONS BEAR PART PER AS470-7A. DO NOT MARK ON SEAL SURFACE.

WELDING SURFACES TO BE PROTECTED FROM OXIDATION AND SCRATCHES DURING WELDING AND FINISHING PHASES.

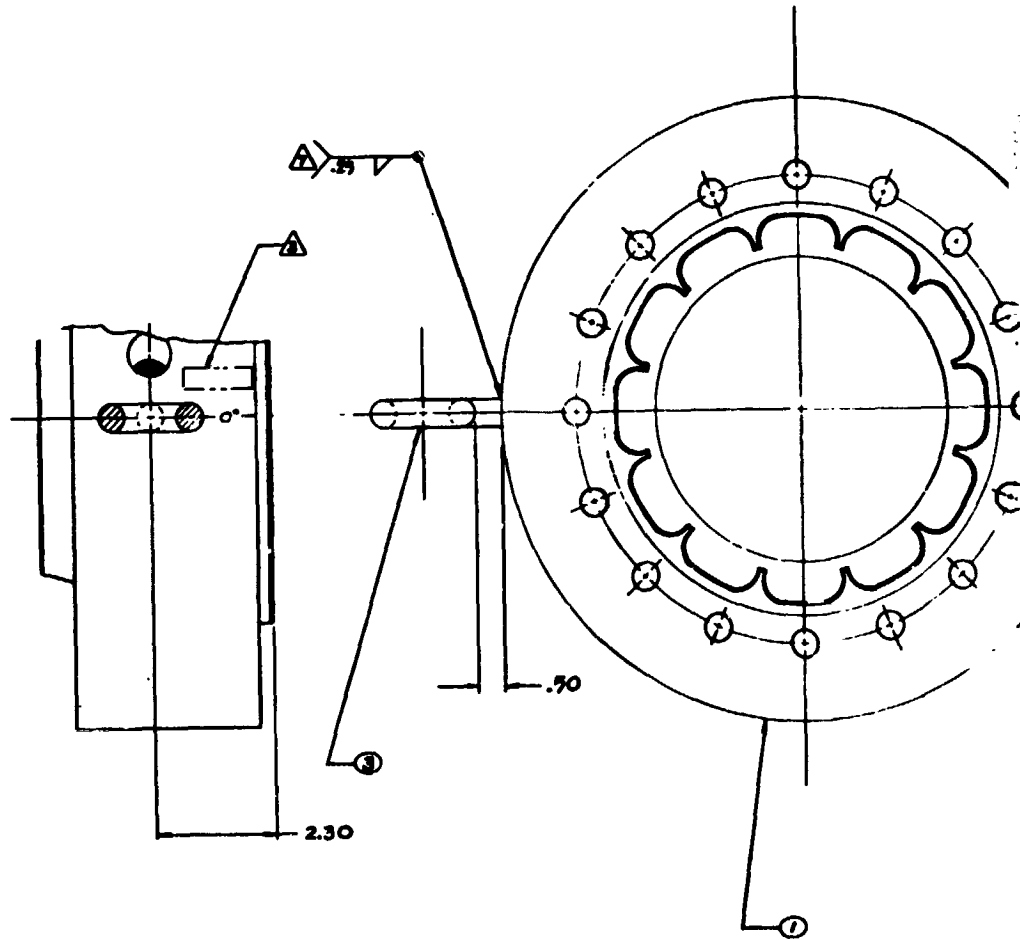
HOLE LOCATIONS ARE BASIC AND UNLESS OTHERWISE NOTED.

FINISH PER ALRC-0030.

ULTRASONIC INSPECT WELDS PER ALRC-STD-0002. PER S. BEHND A. ACCEPTANCE CRITERIA PER RC-STD-0005, CLASS I.

LEAK CHECK PER MIL-R-6075 WITH VACUUM OR HYDROGEN GAS PER MIL-P-27201 OR DRY HYDROGEN GAS WITH Dew POINT -80°F OR BETTER.

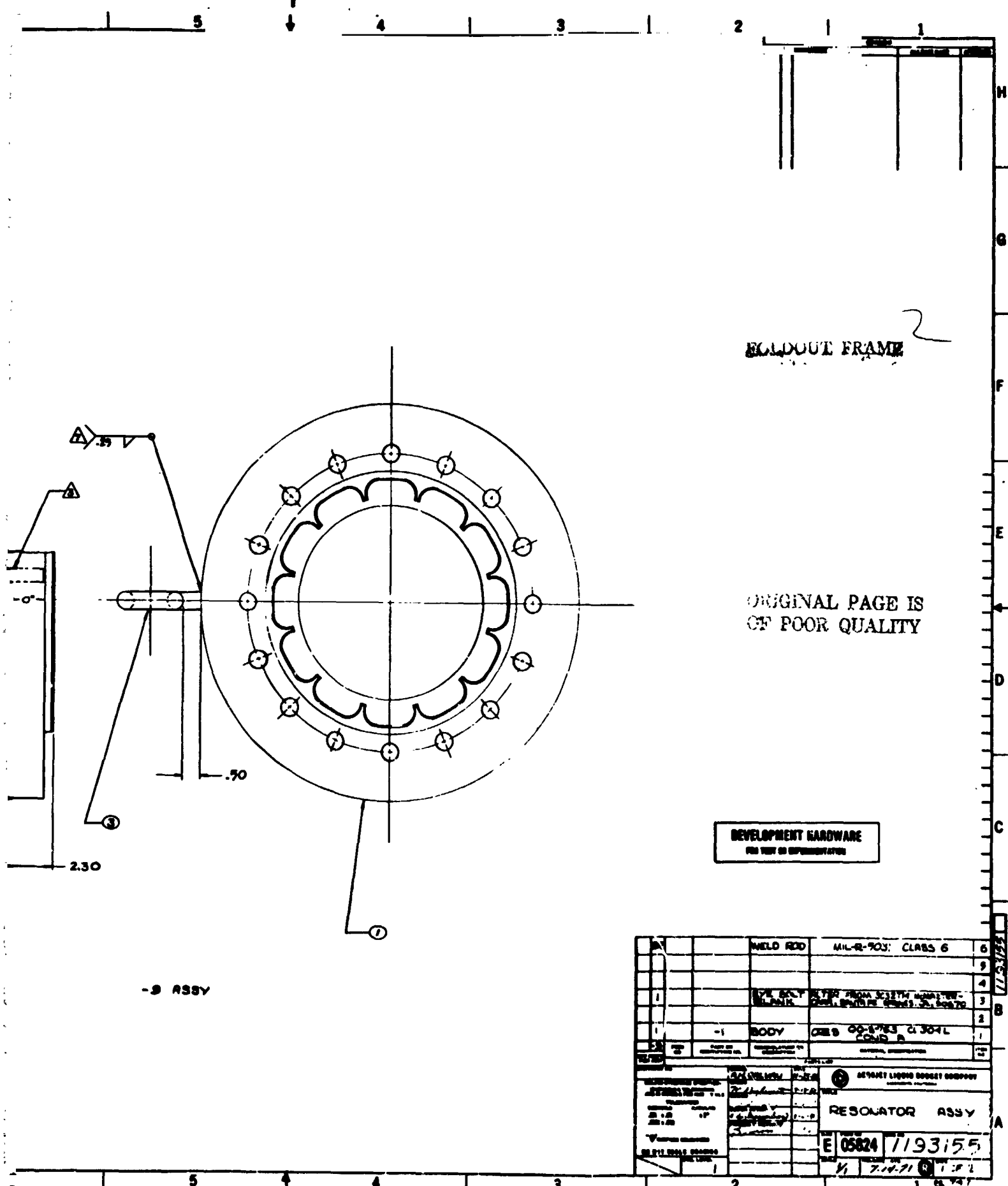
D
C
B
A



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FOLDOUT FRAME

-9 ASSY



WELD BEAD

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DEVELOPMENT HARDWARE FOR TEST OF DISPERATION

-9 ASSY

1		WELD BEAD	MIL-R-903: CLASS 6	6
2				9
3				4
4		WELD BEAD	FROM 3527H RESONATOR	3
5				2
6				1
7				1
8				1
9				1
10				1
11				1
12				1
13				1
14				1
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99				1
100				1

Figure III-22. Resonator Assembly (Sheet 1 of 2)

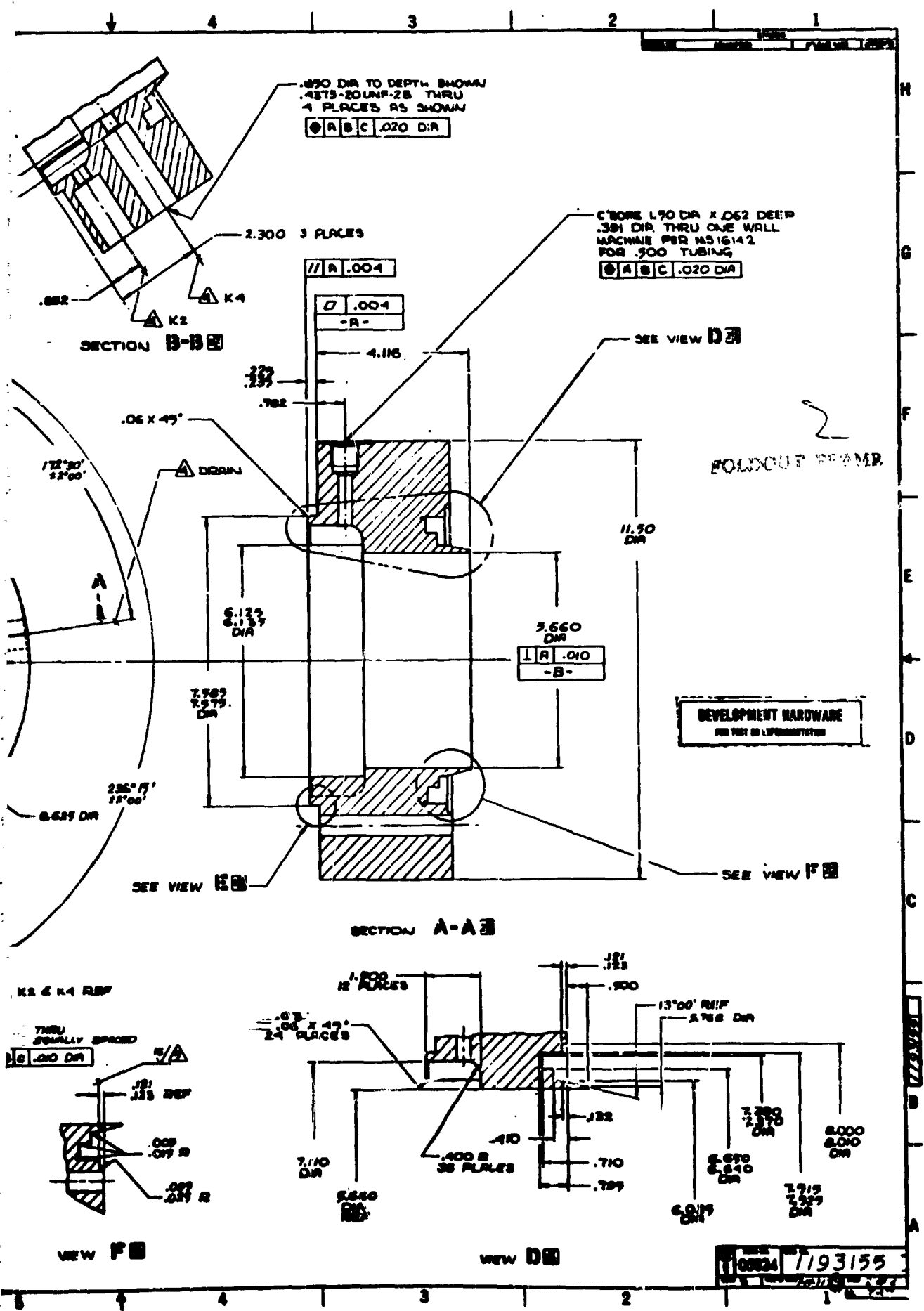
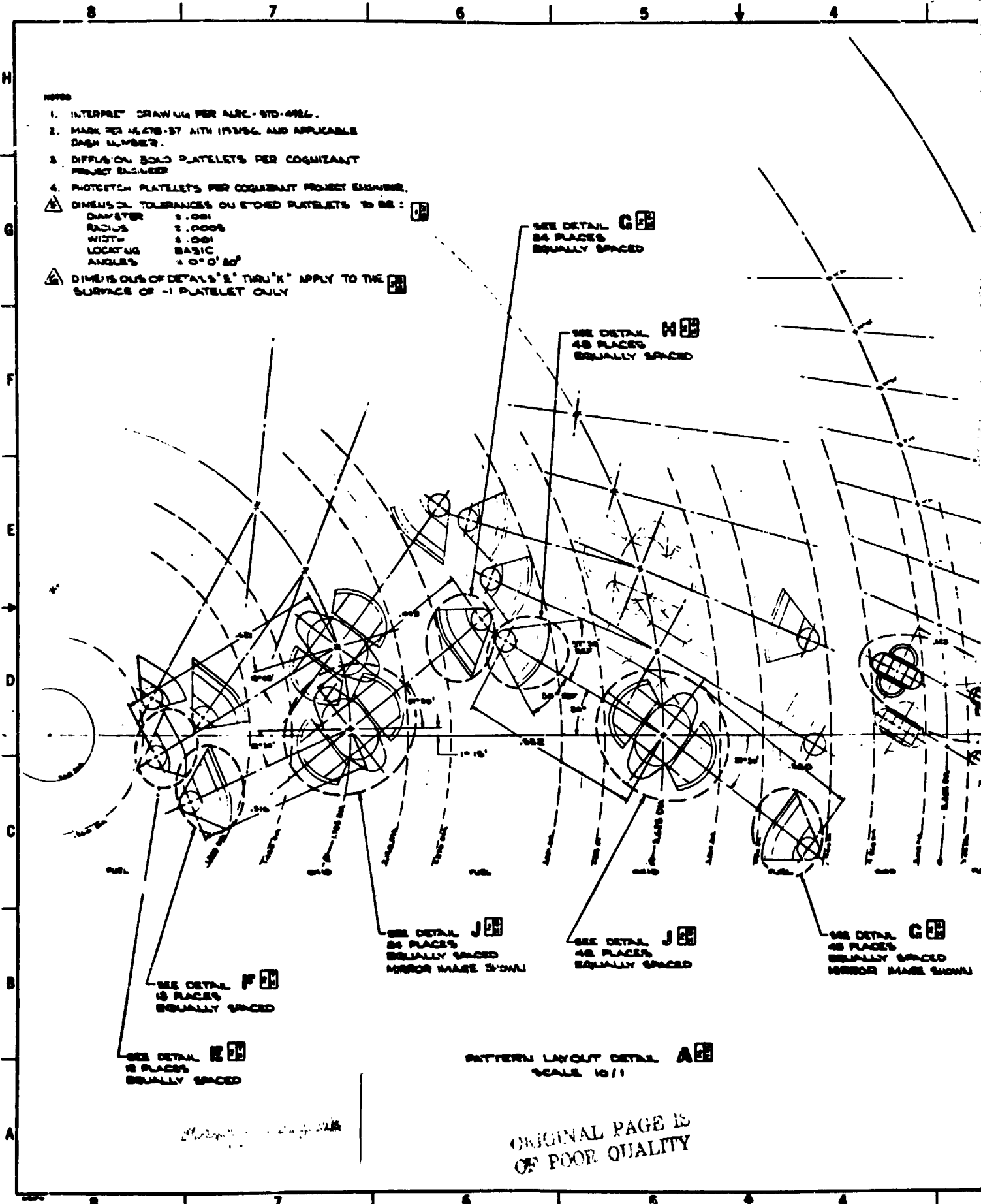


Figure III-22. Resonator Assembly (Sheet 2 of 2)



- NOTES
1. INTERPRET DRAWING PER AISC-STD-498G.
 2. MARK PER AISC-37 WITH 175/86, AND APPLICABLE DASH NUMBER.
 3. DIFFUSION BOND PLATELETS PER COGNIZANT PROJECT ENGINEER.
 4. PHOTOETCH PLATELETS PER COGNIZANT PROJECT ENGINEER.

△ DIMENSIONAL TOLERANCES ON ETCHED PLATELETS TO BE: 0.02

DIAMETER	± 0.01
RADIUS	± 0.005
WIDTH	± 0.01
LOCATING BASIC	
ANGLES	± 0° 0' 30"

△ DIMENSIONS OF DETAILS "E" THRU "K" APPLY TO THE SURFACE OF -1 PLATELET ONLY 0.02

SEE DETAIL **G** 0.02
24 PLACES
EQUALLY SPACED

SEE DETAIL **H** 0.02
48 PLACES
EQUALLY SPACED

SEE DETAIL **J** 0.02
24 PLACES
EQUALLY SPACED
MIRROR IMAGE SHOWN

SEE DETAIL **J** 0.02
48 PLACES
EQUALLY SPACED

SEE DETAIL **G** 0.02
48 PLACES
EQUALLY SPACED
MIRROR IMAGE SHOWN

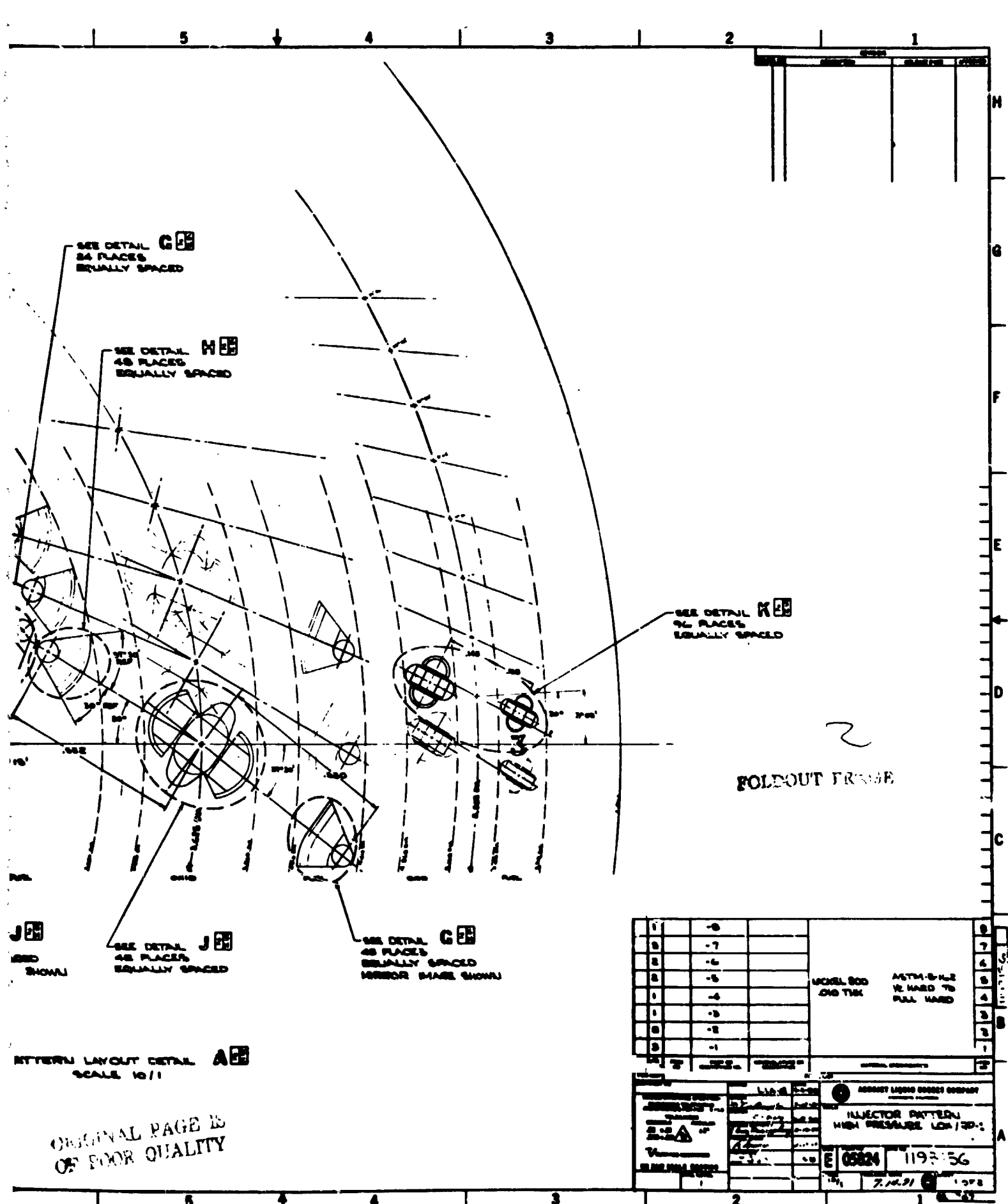
SEE DETAIL **F** 0.02
18 PLACES
EQUALLY SPACED

SEE DETAIL **E** 0.02
18 PLACES
EQUALLY SPACED

PATTERN LAYOUT DETAIL **A** 0.02
SCALE 10/11

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Figure III-23. Inj



SEE DETAIL G
24 PLACES
EQUALLY SPACED

SEE DETAIL H
48 PLACES
EQUALLY SPACED

SEE DETAIL K
96 PLACES
EQUALLY SPACED

SEE DETAIL J
48 PLACES
EQUALLY SPACED

SEE DETAIL G
48 PLACES
EQUALLY SPACED
MIRROR IMAGE SHOWN

FOLDOUT FRINGE

PATTERN LAYOUT DETAIL A
SCALE 10/11

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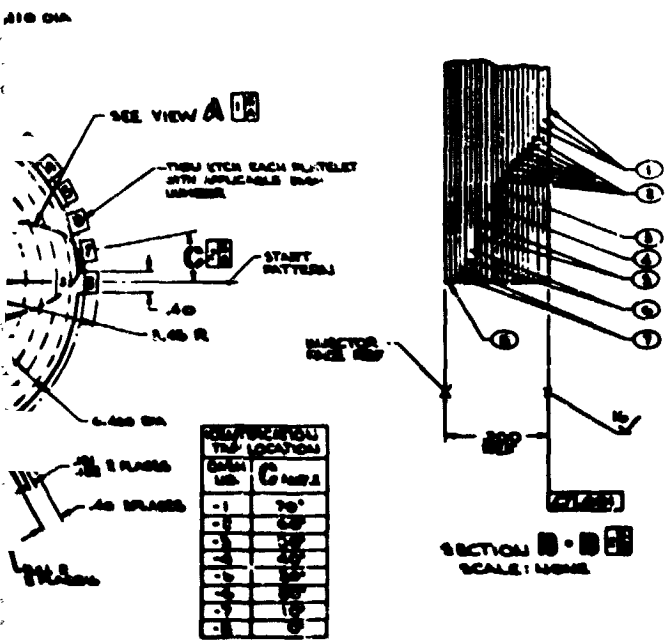
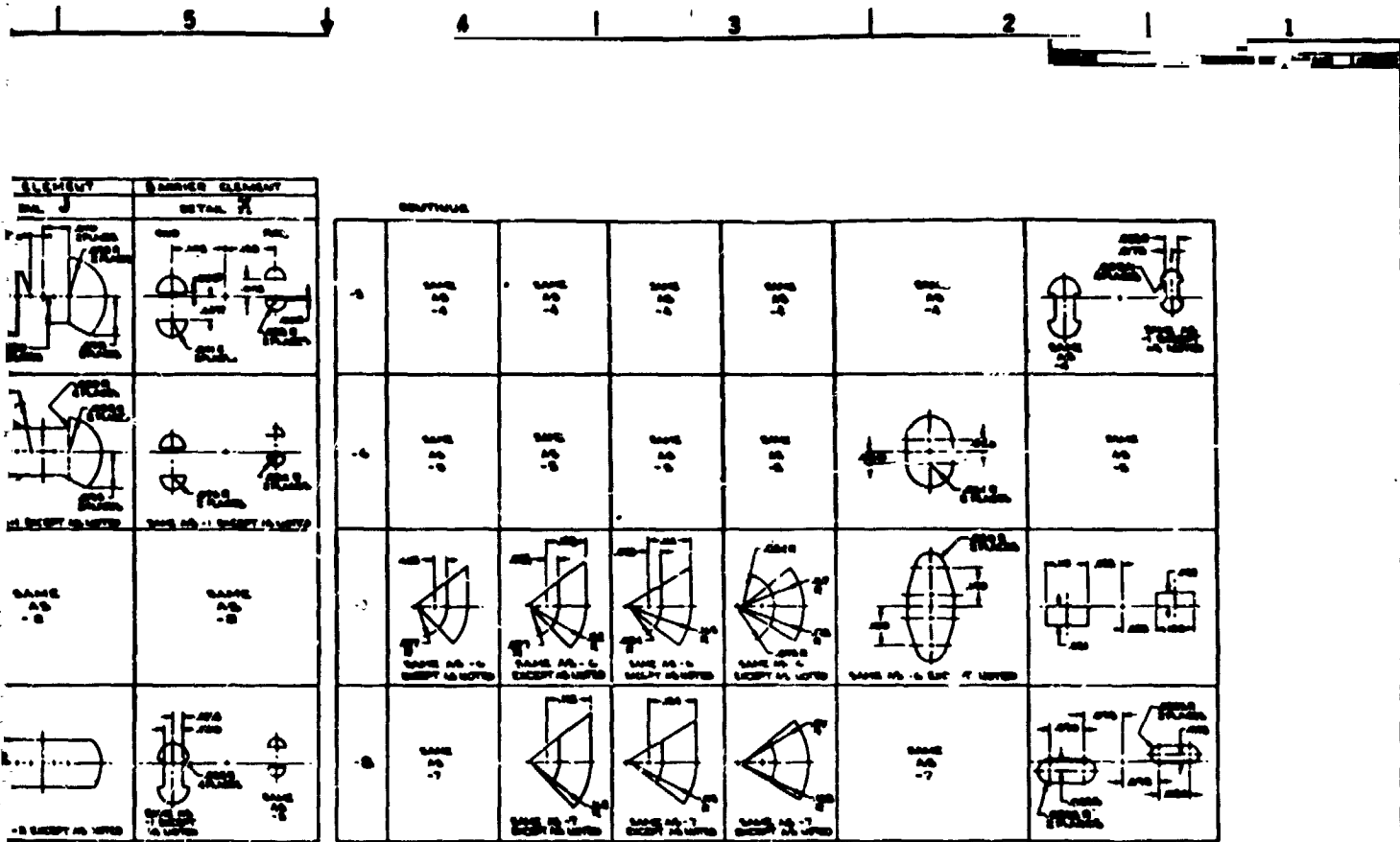
1	-6		8
2	-7		7
3	-6		6
4	-5		5
5	-4		4
6	-3		3
7	-2		2
8	-1		1

UNCL. 800
OAS TIK

ASTM-B-112
1/2 HARD TO
FULL HARD

APPROVED FOR RELEASE AUTHORITY DATE BY	L.L.G.	APPROVED FOR RELEASE AUTHORITY DATE BY	APPROVED FOR RELEASE AUTHORITY DATE BY
INJECTOR PATTERN HIGH PRESSURE LOX/RP-1		E 05824 1198-56	
7/24/51		1958	

Figure III-23. Injector Pattern, High-Pressure LOX/RP-1 (Sheet 1 of 2)
58



BOLDOUT FRAME

0024 93156

Figure III-23. Injector Pattern, High-Pressure LOX/RP-1 (Sheet 2 of 2)
59

0781 SP 128

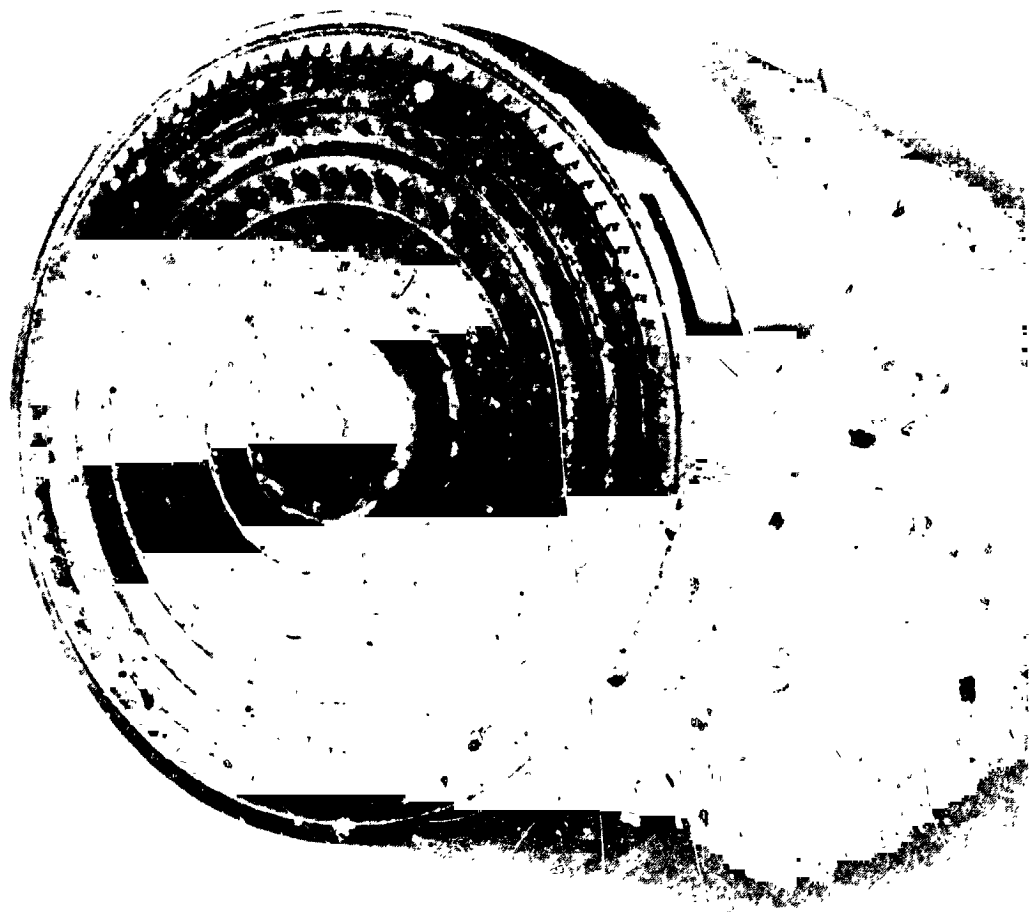


Figure III-24. Faceplate Following Welding to Body

III, C, Fabrication (cont.)

employed to join the major flange and core subassemblies. These welds can be seen in Figures III-17 and III-20.

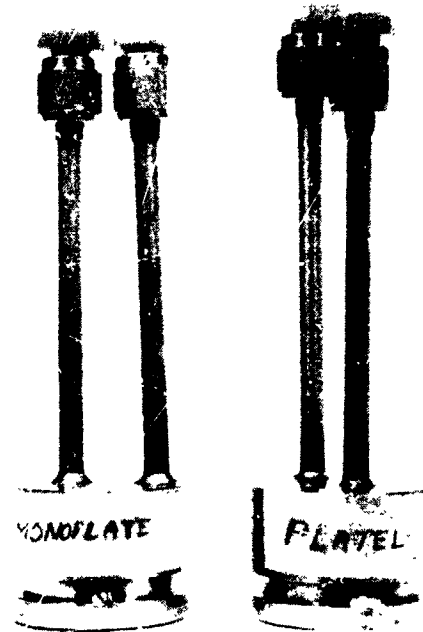
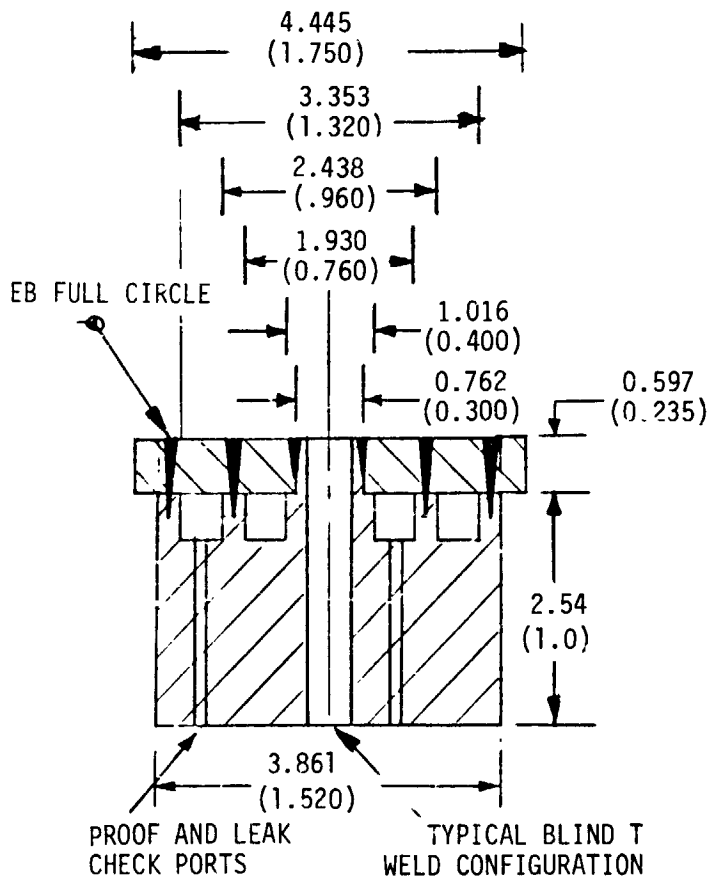
The nickel faceplates were etched and bonded according to proprietary ALRC processes. The stack of fine platelets was prebonded, and the unitized assembly was then electron-beam-welded to the face rings as shown in Figure III-24. The initial EB-weld specimens employed to check out the Ni-200 to Cres 304L blind T welding parameters (see Figure III-25) indicated that this joint could not be satisfactorily completed because of the excessive thickness of the Ni stack (0.508 cm (0.2 in.)) relative to the 304L ring manifold (0.318 cm (0.125 in.)). The energy levels required to penetrate the nickel resulted in overheating the stainless steel and produced voids at the interface.

Contractual fabrication activities were temporarily stopped while ALRC explored various options to overcome these limitations. Satisfactory results were obtained by the addition of an intermediate material at the interface between the Ni-200 platelet stack and the Cres 304L body.

Photographs and photomicrographs of the test sections containing an intermediate filler are shown in Figure III-26. Additional full-scale simulated manifold fabrication weld verification testing was conducted prior to welding the deliverable injector. A full-scale manifold used for these tests is shown in Figure III-27. The resulting assembly was pressure-tested to provide a 20,682 kPa (3000 psi) pressure across the face

D. COLD-FLOW CHARACTERIZATION AND CHECKOUT

To ensure that the injector would perform as predicted hydraulically, several cold-flow tests with water were performed.



2 SPECIMENS - 20682 kPa (3000 psia)
 PROOF "0" LEAKAGE GN₂ @ 1034 kPa
 (150 psia)

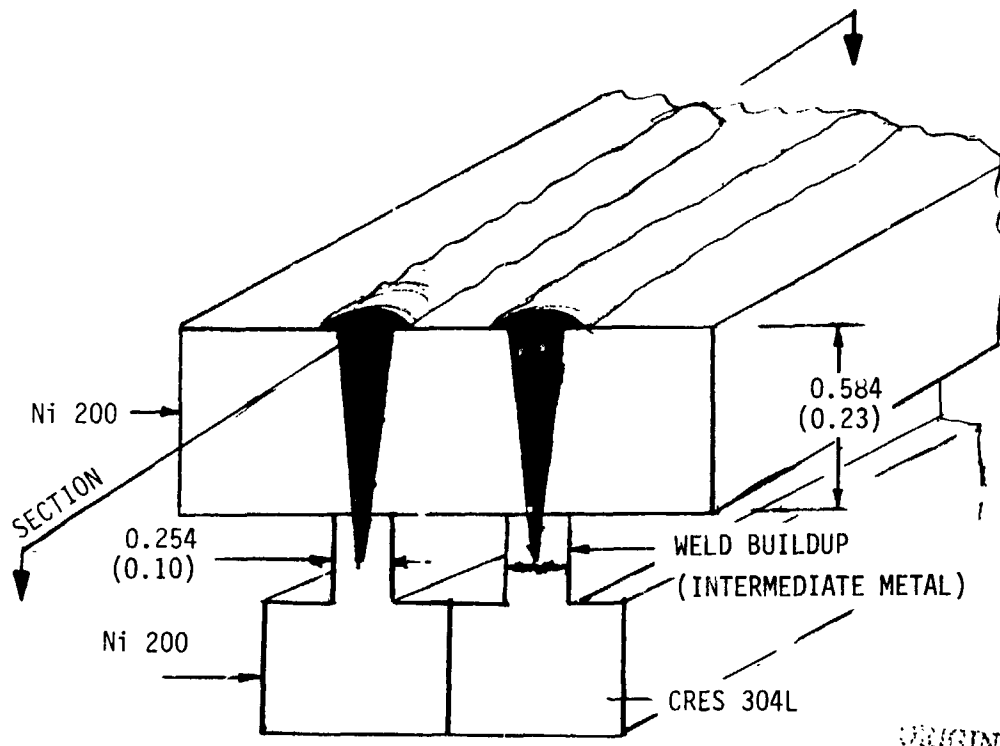


Ni-200 FACE
 TO
 Ni-200 LAND



NICKEL-200/PLATELET FACE
 TO
 Ni-61 OVER CRES 304L

Figure III-25. Experimental Evaluation of Circular Weld Specimens



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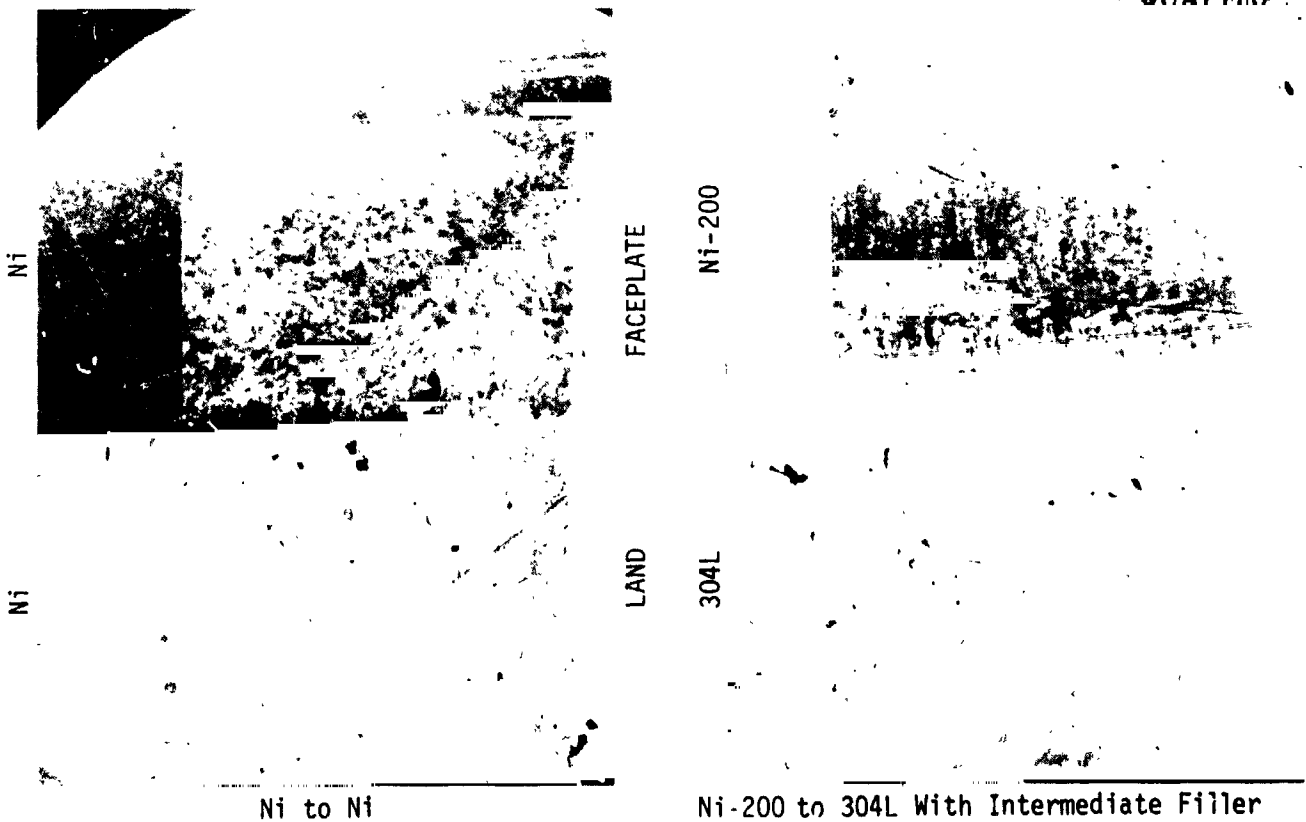
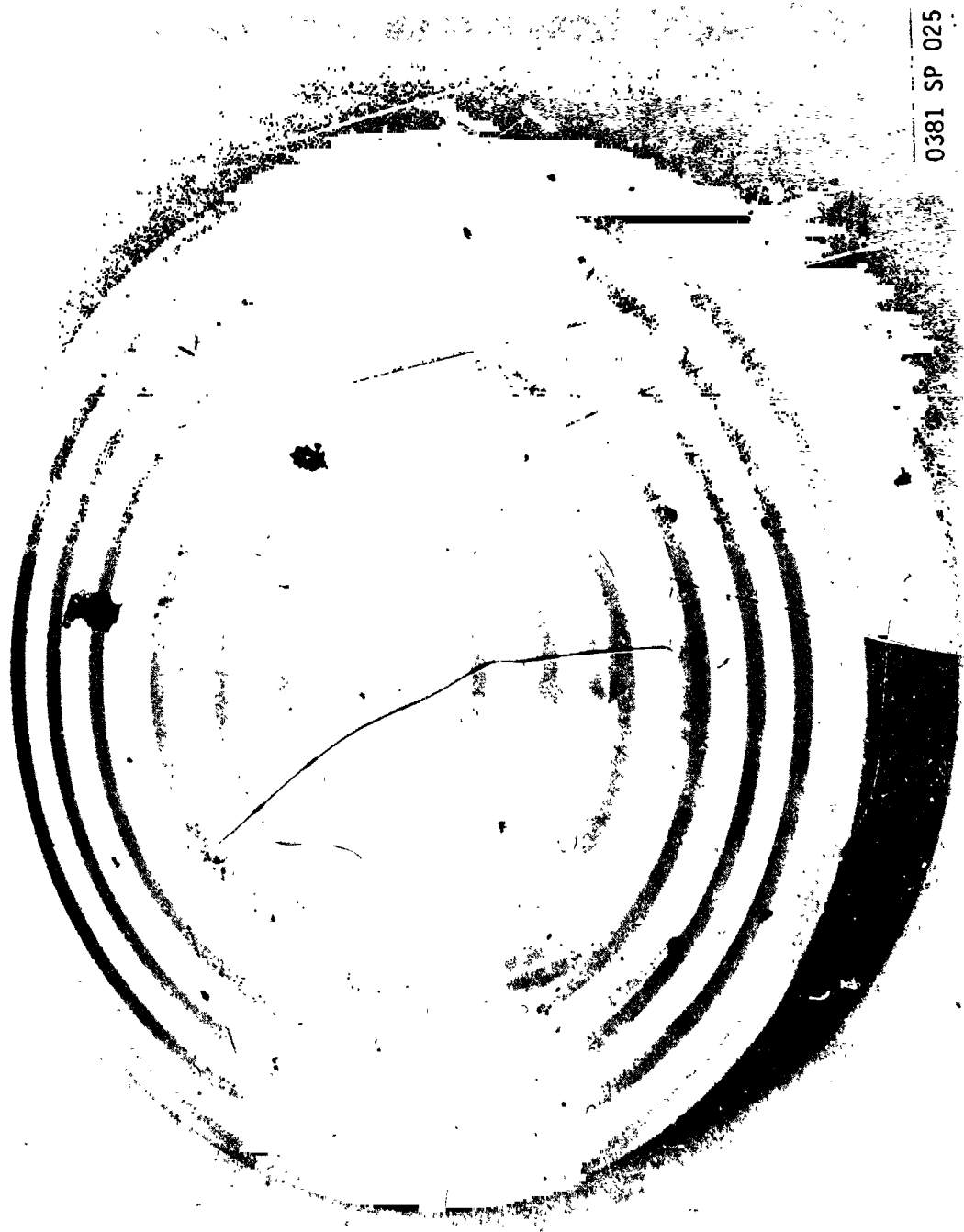


Figure III-26. T Bar Linear Weld Samples



0381 SP 025

Figure III-27. Full-Scale Manifold Used for Weld Verification Tests

III, D, Cold-Flow Characterization and Checkout (cont.)

1. Pressure Drop and Pattern Check

Early in the fabrication process, prior to bonding the platelet stack, a mechanically clamped loose stack (Figure III-28) was flow-tested with a simulated manifold body. The purpose of the test was to verify the spray pattern and predicted pressure drop.

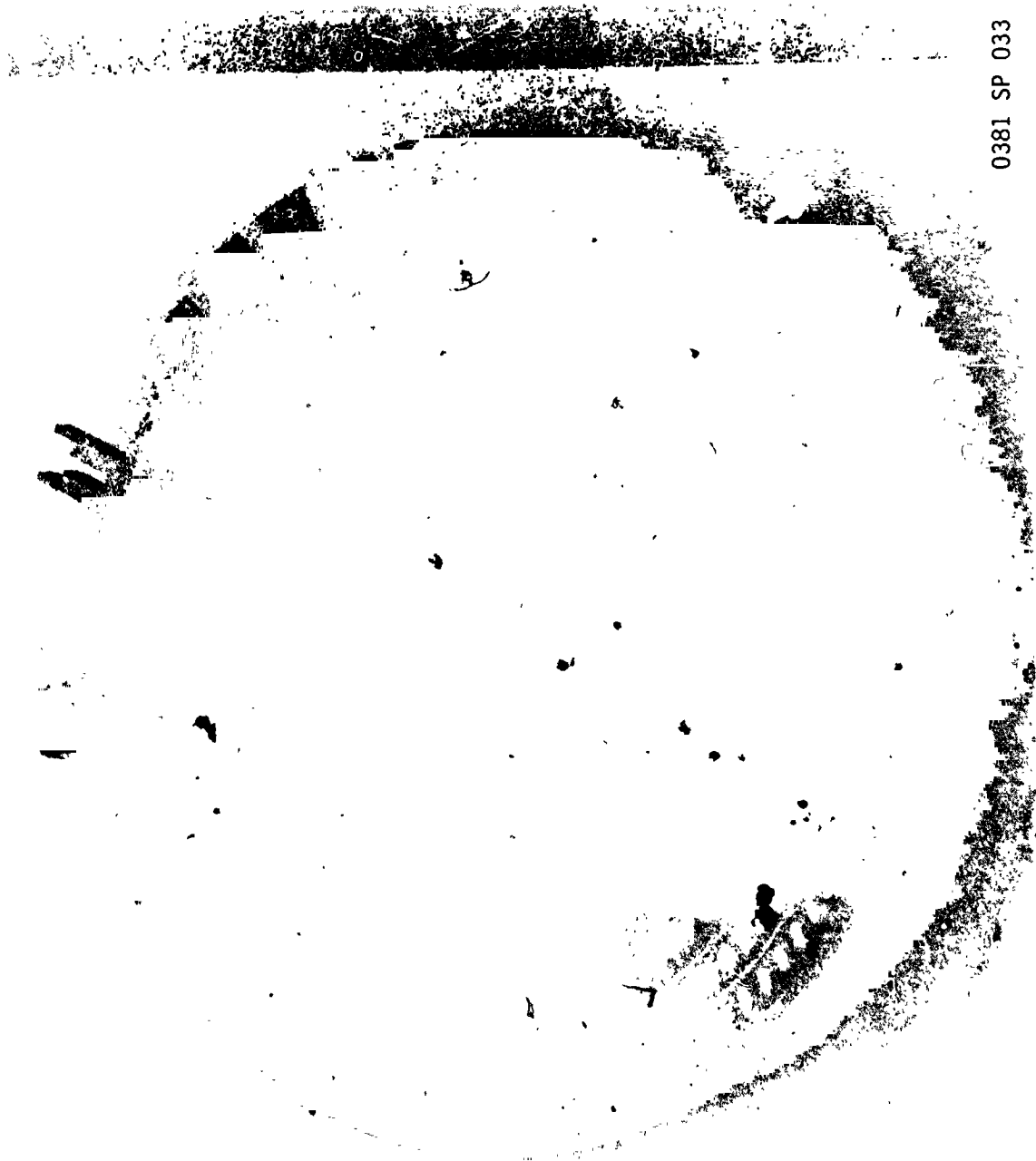
Initial flow tests indicated that the operational pressure drop was less than the expected 4,136 kPa (600 psi) target (see Table III-IV). A new flow metering platelet (PN 1193156-1) was etched, using a modified procedure to obtain a sharp-edged rather than a chamfered inlet. Reflow of the assembly with the replacement part provided the desired results, as indicated in Table III-V.

2. Injector Assembly Cold-Flow Testing

After final weld assembly and following a successful proof test of 31,023 kPa (4500 psia) and leak checks of 13,788 kPa (2000 psia) with GN_2 , the oxidizer and fuel circuits were independently flow-tested with water. These data are provided in Table III-VI. Based on the test results, it is predicted that, at the lower operating point of $P_c = 13,788$ kPa (2000 psia), the fuel inlet line pressure will be 15,234 kPa (2210 psia) and the oxidizer inlet line pressure will be 15,427 kPa (2237 psia). At the maximum operating pressure of 20,682 kPa (3000 psia) P_c , the fuel inlet line pressure is estimated to be 23,935 kPa (3472 psia) and the oxidizer inlet line pressure is estimated to be 24,371 kPa (3535 psia).

3. Mixture Ratio Distribution

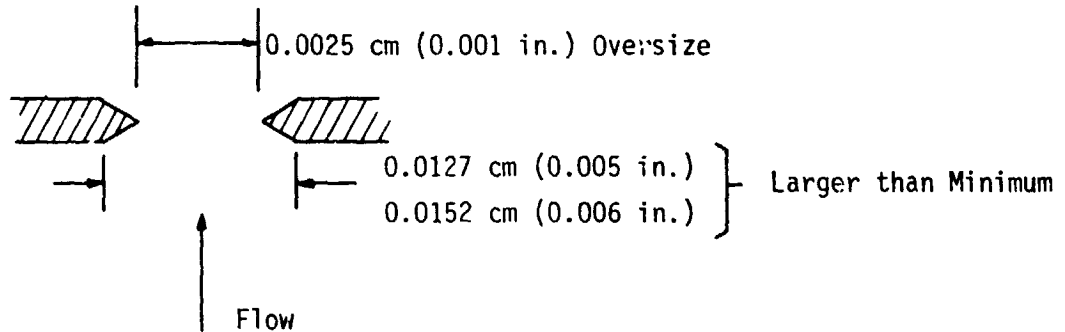
The cold-flow data indicated that 80% of the mass flow would be in the injector core and that the core MR is 2.83. The remaining 20% mass flow is in the barrier, at a MR of 2.76.



0381 SP 033

Figure III-28. Assembly of Loose Platelets Prior to Cold-Flow Testing

TABLE III-IV
 LOOSE-STACK COLD-FLOW
 TEST #1 - LARGE CHEVRON



Single-Element Flow

Location	ΔP , kPa (psi)	\dot{w} , kg/sec (lb/sec)	K_w^*
Outer Fuel	68.9 (10)*	0.0068 (0.0149)	0.00081 (0.00471)
	172.4 (25)	0.0103 (0.0226)	0.00078 (0.00452)
	344.7 (50)	0.0143 (0.0315)	0.00077 (0.00445)
Outer Oxidizer	68.9 (10)	0.0133 (0.0293)	0.00160 (0.00926)
	172.4 (25)	0.0206 (0.0455)	0.00157 (0.00910)
	344.7 (50)	0.0293 (0.0645)	0.00158 (0.00912)
Oxidizer Main	68.9 (10)	0.0833 (0.1837)	0.01002 (0.0580)
	131.0 (19)	0.1075 (0.2369)	0.00940 (0.0544)
Fuel Main	68.9 (10)	0.0174 (0.0383)	0.00209 (0.0121)
	172.4 (25)	0.0271 (0.0597)	0.00206 (0.0119)

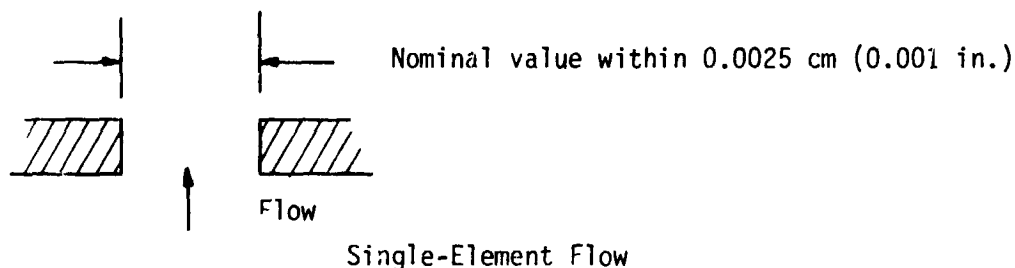
All Elements, Calculated

Kw Oxidizer	Core = 0.699 (4.046)	82%
	Barrier = <u>0.152 (0.879)</u>	18%
	Total = 0.851 (4.926)	O/F Barrier = 2.47
	ΔP_{ox} = 2875 kPa (417 psi)	O/F Core = 2.88
Kw Fuel	Core = 0.299 (1.728)	80%
	Barrier = <u>0.0756 (0.438)</u>	20%
	Total = 0.375 (2.166)	
	ΔP_{Fuel} = 2613 kPa (379 psi)	

$$*(K_w) = \left(\frac{\dot{w} \text{ (kg/sec)}}{\sqrt{\Delta P \text{ (kPa)} S_g}} \right) \text{ or } \left(\frac{\dot{w} \text{ (lb/sec)}}{\sqrt{\Delta P \text{ (psi)} S_g}} \right)$$

*SI Units (English Units)

TABLE III-V
 LOOSE STACK COLD-FLOW
 TEST #2 - SHARP-EDGED ORIFICE



Location	ΔP , kPa (psi)	\dot{W} , kg/sec (lb/sec)	K_w^*
Outer Fuel	68.9 (10)*	0.00638 (0.01407)	0.00077 (0.00445)
	172.4 (25)	0.00989 (0.0218)	0.00075 (0.004365)
	344.7 (50)	0.01374 (0.0303)	0.00074 (0.00429)
Outer Oxidizer	68.9 (10)	0.01330 (0.02932)	0.00160 (0.00927)
	172.4 (25)	0.02075 (0.04575)	0.00158 (0.00915)
	344.7 (50)	0.02975 (0.06559)	0.00160 (0.00928)
Oxidizer Main	68.9 (10)	0.07099 (0.1565)	0.00885 (0.0495)
	172.4 (25)	0.11249 (0.248)	0.00857 (0.0496)
	344.9 (50)	0.16198 (0.3571)	0.00872 (0.0505)
Fuel Main	68.9 (10)	0.01642 (0.0362)	0.00199 (0.0115)
	172.4 (25)	0.02567 (0.0566)	0.00195 (0.0113)
	344.7 (50)	0.03624 (0.0799)	0.00195 (0.0113)

All Elements Calculated

Kw Oxidizer	Core = 0.620 (3.586)	80%
	Barrier = <u>0.153 (0.886)</u>	20%
	Total = 0.773 (4.472)	O/F Barrier = 2.76
	$\Delta P_{ox} = 3485$ kPa (506 psi)	O/F Core = 2.83
Kw Fuel	Core = 0.281 (1.627)	80%
	Barrier = <u>0.072 (0.416)</u>	20%
	Total = 0.353 (2.043)	
	$\Delta P_{Fuel} = 2937$ kPa (426 psi)	

$$*(K_w) = \left(\frac{\dot{w} \text{ (kg/sec)}}{\sqrt{\Delta P \text{ (kPa)} S_g}} \right) \text{ or } \left(\frac{\dot{w} \text{ (lb/sec)}}{\sqrt{\Delta P \text{ (psi)} S_g}} \right) \quad *SI \text{ Units (English Units)}$$

TABLE III-VI

FINAL ASSEMBLY COLD-FLOW

OX CIRCUIT

H ₂ O Flow w kg/sec	H ₂ O Flow w lb/sec	ΔP kPa		ΔP (Pfg-Pback) psi		Kw (ΔP)(gage)	Kw (absolute gage)
		458.5	66.5	1082-600	157-87		
16.6	36.6	458.5	66.5	1082-600	157-87	4.49	4.38
19.4	42.8	654.9	95.0	1517-855	220-124	4.39	4.37
22.9	50.4	882.4	128.0	2103-1213	305-176	4.45	4.44
Expected Value = 4.4							
FUEL CIRCUIT							
Water Flow w kg/sec	Water Flow w lb/sec	ΔP kPa		ΔP (Poj-Pback) psi		Kw (ΔP)(gage)	Kw (absolute gage)
		710.1	103.0	951-241	138-35		
8.89	19.59	710.1	103.0	951-241	138-35	1.93	1.93
9.97	21.99	879.0	127.5	1193-296	173-43	1.95	1.93
10.72	23.63	1013.4	147.0	1379-345	200-50	1.95	1.93

Expected Value 2.043

IV. OPERATION

The LOX/RP-1 injector design requirements and predicted operating parameters are contained in Table IV-1. Also included are maximum allowable operating pressure values that should be incorporated into test operating procedures. It has been predicted that all of the design requirements will be satisfied. In addition, ALRC feels confident that other important factors such as chamber heat flux can also be met satisfactorily.

A. IGNITION SYSTEM AND START SEQUENCE

In order to achieve a smooth, reliable start, ALRC recommends the use of a 0.15/0.85 mixture of TEA/TEB. In the event of a TEB availability problem, TEA will achieve satisfactory ignition; however, TEA does leave heavy deposits that may have to be removed.

A suggested igniter plumbing schematic is shown in Figure IV-1. A low-flow oxygen supply line which parallels the main valve is shown as a typical method of limiting the pre-ignition pressure drop across the injector face during the start transient to a maximum of 13,788 kPa (2000 psia). Other methods, such as a preprogrammed valve opening rate, would also be acceptable. This suggested ignition system would provide the capability of loading a predetermined quantity of igniter fluid into an accumulator. A small purge flow should be maintained through the igniter, following its cut-off, to ensure proper cooling of the igniter port and the central portion of the injector face. The purge can be GN₂, as shown, or RP-1. This purge pressure should be sufficiently high to preclude backflow into the igniter in the event of an instability. A check valve is required to preclude backflow. Figure IV-2 shows the ignition sequence and start transient employed in the 13,788-kPa (2000-psia) High-Density Fuel Program. A 0.02-ms (minimum) ox lead start is recommended for a soft start. The valve opening rates should be controlled to prevent the ΔP across the injector face from exceeding 13,788 kPa (2000 psia).

TABLE IV-1

DESIGN REQUIREMENTS AND PREDICTED OPERATION (SI Units)

	<u>Requirement</u>	<u>Prediction</u>	<u>Maximum Operating Value</u>
Chamber Pressure(Pc), kPa	13788/20682	13788/20682	
Fuel:	RP-1		
Temperature, °K	Ambient		
Maximum Interface Pressure, kPa	15450/24129		27576 ²
Flowrate, kg/sec	11.39/17.10	11.39/17.10	
Oxidizer:	LOX		
Temperature, °K	358		
Maximum Interface Pressure, kPa	15856/25508		27576 ²
Flowrate, kg/sec	31.93/47.90	31.93/47.90	
Propellant Mixture Ratio	2.8		
Characteristic Velocity Efficiency	>97%		
Allowable Chamber Pressure Oscillations	<± 5% ¹		
Combustion Chamber:			
Throat Diameter, cm	8.407		
Chamber Diameter, cm	14.376		
Length(Injector to Throat), cm	35.484		
Ignition Fluid:		TEA/TEB	
Temperature, °K		Ambient	
Flowrate, kg/sec		TBD	
Pressure Drop:			
P _{FJ} - P _c , psia		1447/3254	17235
P _{OJ} - P _c , psia		1639/3688	17235

(1) <5% after tuning of resonator cavity with actual test data

(2) Proof pressure test(31023 kPa)

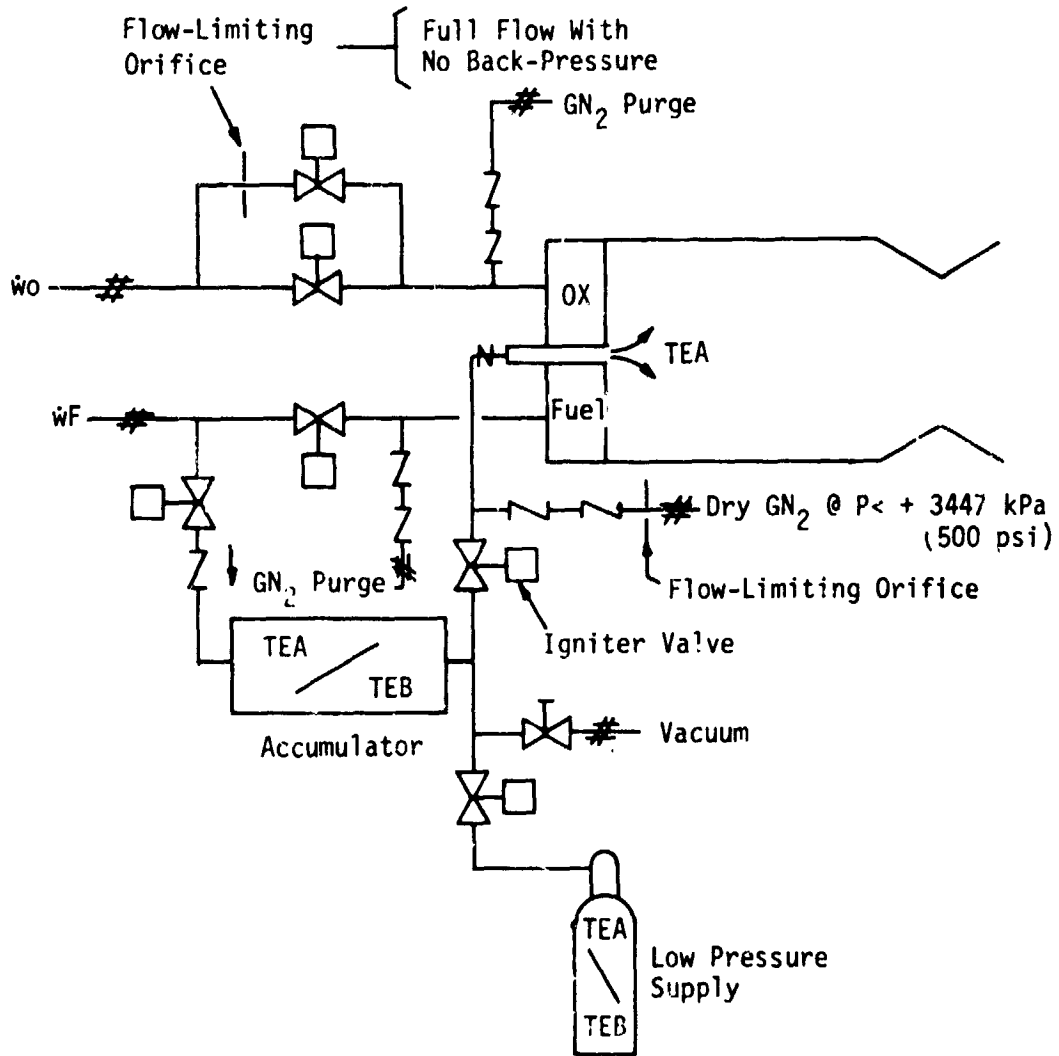
TABLE IV-1 (cont.)

DESIGN REQUIREMENTS AND PREDICTED OPERATION (English Units)

	<u>Requirement</u>	<u>Prediction</u>	<u>Maximum Operating Value</u>
Chamber Pressure(Pc), psia	2000/3000	2000/3000	
Fuel:	RP-1		
Temperature	Ambient		
Maximum Interface Pressure	2244/3500		4000 ²
Flowrate, lbm/sec	25.1/37.7	25.1/37.7	
Oxidizer:	LXX		
Temperature, °R	185		
Maximum Interface Pressure	2300/3700		4000 ²
Flowrate, lbm/sec	70.4/105.6	70.4/105.6	
Propellant Mixture Ratio	2.8		
Characteristic Velocity Efficiency	>97%		
Allowable Chamber Pressure Oscillations	<+ 5%*	1	
Combustion Chambers:			
Throat Diameter, in.	3.310		
Chamber Diameter, in.	5.660		
Length (Injector to Throat), in.	13.97		
Ignition Fluid:		TEA/TEB	
Temperature		Ambient	
Flowrate, lbm/sec		TBD	
Pressure Drop:			
P _{FJ} - P _c , kPa		210/472	2500
P _{OJ} - P _c , kPa		233/535	2500

(1) <5% after tuning of resonator cavity with actual test data

(2) Proof pressure test (4500 psia)






-  Check Valve
-  Remote Valve
-  Filter 100 μ Absolute

Figure IV-1. Suggested Propellant Supply for the Ignition System

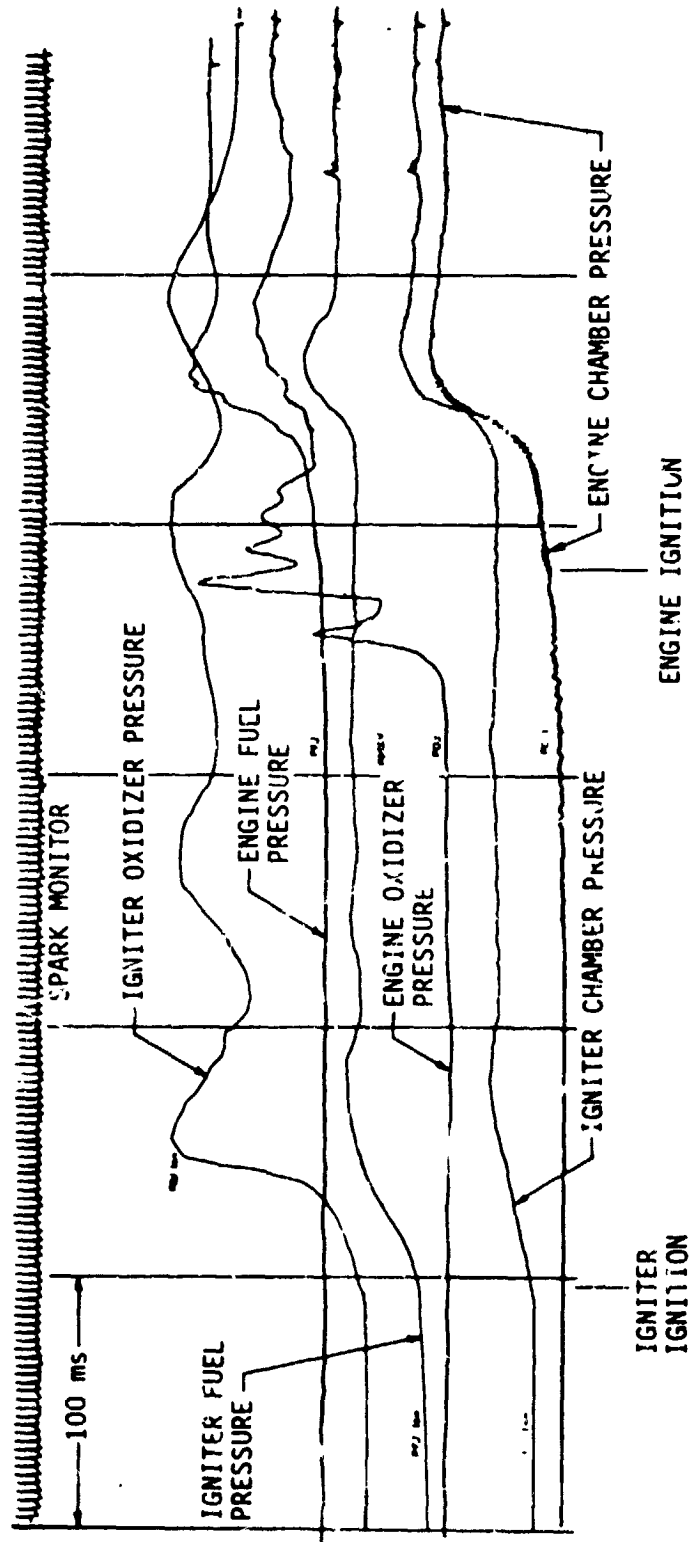


Figure IV-2. Ignition Transient of 2000 psia LOX/RP-1 Engine

IV, A, Ignition System and Start Sequence (cont.)

The recommended test sequence is as follows:

Start

- a. Make sure all valves are closed.
- b. Open igniter system vacuum valve to remove any air from system.
- c. Close vacuum valve.
- d. Open TEA/TEB low-pressure supply valve to fill accumulator to selected capacity.
- e. Close supply valve.
- f. Open fuel valve to accumulator. Accumulator should now be at fuel supply pressure.
- g. Perform facility sequencing.
- h. Start signal.
- i. Open secondary oxidizer valve. LOX flowrate should be 45.36 kg/sec (100 lb/sec) at full thrust.
- j. Open igniter valve.
- k. Sample chamber pressure for ignition. Shut down if ignition is not achieved prior to fuel valve initiation.
- l. Initiate fuel valve opening.
- m. Initiate main oxidizer valve opening.
- n. Sample for chamber pressure; shut down if full Pc is not achieved.
- o. If recommended GN₂ purge circuit is used, close igniter valve.*

*Damping of fuel through igniter port during test will reduce performance.

IV, A, Ignition System and Start Sequence (cont.)

Shutdown

- a. Close oxygen valve.
- b. Close fuel valve.

5. CARE AND HANDLING

The LOX/RP-1 injector assembly PN 1193106 comprises two major components:

Injector Body Subassembly PN 1193138
Resonator Ring Assembly PN 1193155

In addition, there are the small igniter components plus various seals, fasteners, and extra tuning blocks for the acoustic resonator.

The following suggestions and comments may be helpful during the handling operation of this unit. They are as follows:

1. The unit was shipped with a protective face cover. This cover should remain in place during all handling operations to protect the soft, fully annealed nickel face. In addition, LOX cleaning processes which are not compatible with nickel, such as picklings, should not be employed.

2. The injector assembly weighs approximately 160 kg (350 lb) and should be handled accordingly. A lifting eyebolt has been provided for this purpose. Drain ports have been placed to function properly when the eyebolt is in the vertically upward position.

IV, B, Care and Handling (cont.)

3. The high-strength nuts and bolts supplied with the unit are subject to galling and should be lubricated with a propellant-compatible lubricant such as Fel-Pro.

4. The unit should be LOX-cleaned prior to firing.

5. The propellant, RP-1, and the oxidizer should be filtered to 100 microns absolute or less.

6. The unit was delivered with the resonator cavity ring installed and tuned to dampen the most likely modes of combined 1T/2T instability. It may be necessary to resize the cavities if the actual gas sound speed in the cavities differs from the estimated values. The high-frequency pressure measuring ports provided allow the necessary data for resizing these ports to be obtained.

7. Once a stable cavity configuration has been obtained and verified by several short 1/2- to 1-sec tests, the tuning blocks should be tack-welded in place at the screw head and in the corners. Experience has shown that the screws (regardless of torque and locking compounds used) work themselves loose due to the thermal and vibration effects encountered in long-duration tests.

ALRC Post-Test LOX Cleaning Procedure

Normal high pressure post-test GN₂ purges are employed to remove excess propellant from the feed system following valve closure at the end of a test. Before each test, both the fuel and oxidizer circuits are degreased with GN₂-atomized 1,1,1-trichloroethane (TCL). Hot GN₂ at 353 to 367°K (175 to 200°F) is recommended. Before introducing the clearing

IV, B, Care and Handling (cont.)

solvent, the cryogenic oxidizer line is allowed to warm to ambient temperature. This warming prevents the cleaning solvent from freezing in the line. LOX and solid trichloroethane can detonate on contact, causing extensive damage.

Following verification that collected samples of the TCE are free of hydrocarbon, the LOX system is purged with hot GN₂-atomized Freon TF. The Freon will replace the TCE; the manifold drain ports and resonator cavity drain ports remain open during these cleaning operations. (California and ALRC environmental regulations require that liquid TCE be collected and disposed of in accordance with toxic waste standards for this material.) A hot GN₂ dry purge at 353 to 367°K (175 to 200°F) is maintained until it is evident that all residual cleaning solvents have been removed.

Dry GN₂ trickle purges are maintained during the LOX line chill-down operation to prevent contamination and potential frost deposits within the engine.

The trickle purges remain in effect until the prefire high-pressure purge sequence is initiated.

C. INSTRUMENTATION

The following instrumentation ports have been provided:

Injector

Fuel Manifold Pressure	PFJ
Oxidizer Manifold Pressure	POJ
Oxidizer Manifold Temperature	TOJ

IV, C, Instrumentation (cont.)

High-Frequency Manifold

Oxidizer	K _{OJ}
Fuel	K _{FJ}

Resonator Capacity and Ring

Chamber Pressure	Pc-1	} (Kistler Model 601)
High-Frequency Chamber Pressure	K-1	
High-Frequency Chamber Pressure	K-2	
High-Frequency Chamber Pressure	K-3	
High-Frequency Chamber Pressure	K-4	

The Kistler ports have been designed to utilize a 7-mm to 7/16-20 standard thread adapter fitting. This fitting (PN 1183588) is shown in Figure IV-3. PN 1183588-1 contains a 0.157-cm (0.062-in.) diameter restrictor to protect the Kistler diaphragm and is for use in the hot gas stream. PN 1183588-2 is recommended for use in the propellant lines.

D. PROPELLANT FILTRATION REQUIREMENTS

The minimum passage sizes in the injector are as follows:

Fuel Circuit	0.061 cm (0.024 in.)
Oxidizer Circuit	0.089 cm (0.035 in.)

These occur in the barrier elements (see Figure III-23). The recommended filtration sizes for the propellant are 100 microns absolute for both fuel and oxidizer.

REFERENCES

1. LaBotz, R.J., D.C. Rousar, and H.W. Valler. High-Density Fuel Combustion and Cooling Investigation. Final Report, ALRC, NAS 3-21030, NASA-CR 165177, 1981.
2. Priem, R.J. and Heidman, M.F. Propellant Vaporization as a Design Criterion for Rocket Engine Combustion Chambers, NASA TR-67, 1960.