Oxygen/Hydrogen Thrusters For Space Station Auxiliary Propulsion Systems

JPL Contract 956457
Final Report 956457-F-1
August 1984

Prepared By:
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(NASA-CR-175691) OXYGEN-HYDROGEN THRUSTERS FOR SPACE STATION AUXILIARY PROPULSION SYSTEMS Final Report (Aerojet Techsystems Co.) 109 p HC A06/MF A01 CSCL 21H

N85-25383

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G3/20 20752

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This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration.

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ABSTRACT

A program to determine the feasibility and technology requirements of a low-thrust, high-performance, long-life, gaseous oxygen (GO_2)/gaseous hydrogen (GH_2) thruster was initiated at the Jet Propulsion Laboratory (JPL) in the fall of 1982. Candidate engine concepts for auxiliary propulsion systems for space station applications were identified. The low-thrust engine (5-100 lb_f) requires significant departure from current applications of oxygen/hydrogen propulsion technology.

Selection of the thrust chamber material and cooling method needed for long life poses a major challenge. The use of a chamber material requiring a minimum amount of cooling or the incorporation of regenerative cooling were the only choices available with the potential of achieving very high performance. This report documents the design selection for the injector/igniter, the design and fabrication of a regeneratively cooled copper chamber, and the design of a high-temperature rhenium chamber, and presents the performance and heat transfer results obtained from the test program conducted at JPL using the above engine components. Approximately 115 engine firings were conducted in the JPL vacuum test facility, using 100:1 expansion ratio nozzles. Engine mixture ratio and fuel-film cooling percentages were parametrically investigated for each test configuration. The nominal chamber pressure was 30 psia.

The acceptability of rhenium as a chamber material was demonstrated for over 2800 seconds of thruster operation at temperatures up to 3300°F.

The regeneratively cooled copper chamber was designed for operation at higher pressures and coolant flow rates; actual testing at low pressures and low flow rates limited run duration due to high seal temperatures at the head end.

FOREWORD

In February 1983, the Aerojet TechSystems Company (ATC) and the California Institute of Technology, Jet Propulsion Laboratory (JPL) entered into a cooperative effort to evaluate and demonstrate technology issues applicable to space station auxiliary propulsion. The activity combined Aerojet's extensive experience in propellant injector/igniter design and cooling analysis with recent JPL experience in the design, fabrication, and testing of advanced combustion chamber materials.

The injector/igniter and several thrust chamber components were made available to JPL on a no-cost loan basis for use in the test program.

The individual tasks of the total program were divided between both JPL and ATC. Aerojet's responsibilities included supplying an injector/igniter, conducting design analyses on two chamber concepts, providing recommendations for each approach along with sketches and critical dimensions, reviewing JPL detailed drawings of both chambers, and evaluating data obtained during the JPL test program. A modification to the original program allowed Aerojet to fabricate one of the chambers.

JPL's tasks included preparation of fabrication drawings based on Aerojet sketches, fabrication of the rhenium chamber, providing the test facility, the conduct of all testing, and the test data processing and reduction. Analysis and interpretation of the results were joint activities.

Foreword (cont.)

Individuals participating in this program are as follows:

Marshall Appel - JPL Project Manager
Roy Bjorklund - JPL Test Engineer
Len Schoenman - ATC Project Manager
Deena Berkman - ATC Project Engineer
Don Rousar - ATC Program Manager

NOTE

The hot-fire test results presented in this report include only GH_2/GO_2 testing at low chamber pressures (30 psia). Additional testing with the same hardware was conducted by JPL at higher pressures (30-150 psia) and also with GO_2/methane propellants. A summary and some relevant plots are available in the appendix. JPL should be consulted for additional information.

NOMENCLATURE

BL	Boundary Layer Losses
C*	Characteristic Velocity
Cd-A	Discharge Coefficient Times Frontal Area
CVD	Chemical Vapor Deposition
DIV	Divergent Losses
ERE	Energy Release Efficiency
F	Thrust
Isp	Specific Impulse
KIN	Kinetic Losses
MR	Mixture Ratio
ODE	One-Dimensional Equilibrium Performance Based on Chemical Reaction Rates
ODK	One-Dimensional Kinetic Vacuum Performance Based on Chemical Reaction Rates
Pc	Chamber Pressure
$\dot{W}_F$	Fuel Flow Rate
$\dot{W}_O$	Oxidizer Flow Rate
$\dot{W}_T$	Total Flow Rate

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1.0 INTRODUCTION

A program to determine the feasibility and technology requirements of a low-thrust, high-performance, long-life, gaseous oxygen (GO_2)/gaseous hydrogen (GH_2) thruster was initiated at the Jet Propulsion Laboratory (JPL) in the fall of 1982. The thruster program could identify viable candidates for auxiliary propulsion systems for space station applications. The low thrust (i.e., 30 to 100 lb_f) for application on the space station requires a significant departure from current applications of oxygen/hydrogen propulsion technology. Although every effort was made to incorporate state-of-the-art technology wherever possible, significant technical questions that required resolution were raised prior to this program.

Table 1.1, from Reference 1, identifies a number of operational scenarios which would make H_2 and O_2 available as propellants for space station attitude control at no additional launch cost. The figure also shows the advantages of commonality of the H_2/O_2 propellant combination with other required on-board fluid-consuming systems.

Selection of the thrust chamber material and cooling method needed long life poses a major challenge. The use of a chamber material requiring a minimum amount of cooling or the incorporation of regenerative cooling were the only choices available with the potential of achieving very high performance.

Because of the small thruster size, the choice of the method for injection and ignition of the propellants was very limited and extensive use was made of the existing proven data base.

This report documents the design selection for the injector/igniter, the design and fabrication of a regeneratively cooled copper chamber, and the design of a high-temperature rhenium chamber, and presents the performance and heat transfer results obtained from the test program conducted at the NASA Jet Propulsion Laboratory utilizing the above engine components.

POSSIBLE SCENARIOS	RESUPPLY FLUIDS	PROPELLANT AND PROPULSION SYSTEMS
STS EXTERNAL TANK PROPELLANT SCAVENGING	LH_2, LO_2	H_2 RESISTOJET O_2/H_2 CHEMICAL
OTV PROPELLANT "TANK FARM" BOILOFF	LH_2, LO_2	H_2 RESISTOJET O_2/H_2 CHEMICAL
DEDICATED WATER RESUPPLY WITH WATER ELECTROLYSIS	[illegible]O (1)	O_2/H_2 CHEMICAL
INTEGRATION WITH ELECTRIC POWER SYSTEM FUEL CELLS	H_2O, LH_2, LO_2	O_2/H_2 CHEMICAL
INTEGRATION WITH ENVIRONMENTAL CONTROL/LIFE-SUPPORT SYSTEM INPUTS/OUTPUTS	FOOD (C), H_2O, H_2, O_2, N_2, N_2H_4	BIOWASTE RESISTOJET CH_4 + H_2/O_2 CHEMICAL

TABLE 1.1

COMMON FLUID SYSTEMS OPTIONS

2.0 SUMMARY AND CONCLUSIONS

Approximately 150 engine firings were conducted with three thrust chamber configurations and several propellant injection flow balances for a fixed injector design. All testing was conducted in the JPL vacuum test facility using 100:1 expansion ratio conical and RAO contoured nozzles. High-temperature chamber designs utilizing a hydrogen film as an oxidation barrier in conjunction with uncoated rhenium and H_2 regenerative cooling using copper and nickel as materials of construction were evaluated during the test program. Engine mixture ratio and fuel-film cooling percentage were parametrically investigated for each test configuration. The nominal chamber pressure was 30 psia.

The major conclusions from these tests were as follows:

- Reliable propellant ignition was attained over a wide range of mixture ratios at a energy level of 0.098 J. Engine overall mixture ratio varied from 2:1 to 3.8:1. Igniter mixture ratio varied from 6:1 to 90:1.

- The igniter-injector previously used for high-pressure (300 to 500 psia) liquid, two-phase, and gaseous oxygen-hydrogen functioned satisfactorily at low pressure (30 to 40 psia) using gaseous propellants.

- The rhenium chamber was tested with several insert/core flow balances to quantify the relation between performance and thermal design margin. Specific impulse levels between 360 and 438 lb_f-s/lb_m were demonstrated at the ODK optimum mixture ratio of ~2.5:1 and 30 to 40 psia chamber pressure.

2.0, Summary and Conclusions (cont.)

- The acceptability of rhenium as a chamber material for the oxygen/hydrogen propellant combination was demonstrated for over 2800 s of thruster operation at temperatures between 2000 and 3300°F*.

- Acceptable throat and chamber temperatures were demonstrated with the highest performing thruster configurations: 3300°F* for the rhenium chamber and under 1000°F for the regeneratively cooled chamber.

- Operating limitations at the highest performance levels were dictated by the capabilities of the chamber-injector seals (600°F) selected for the test program.

- The high seal temperatures experienced with the regeneratively cooled chamber were caused by excessive coolant bulk temperatures leaving the coolant jacket during operation.

- The high seal temperatures experienced with the rhenium chamber occurred during post-fire heat soak. This was resolved by the addition of a nitrogen purge following each test.

- The advantage of the theoretically higher performing bell-shaped, contoured nozzle vs. the conical nozzle was not realized for the operating conditions of this test program.

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* Subsequent testing with the rhenium chamber beyond the scope of this program demonstrated 4200°F rhenium wall temperature.

3.0 RECOMMENDATIONS

- An evaluation should be performed to determine the compatibility limits of rhenium in a hydrogen/water vapor environment.

- An evaluation should be performed of thermally resistant inner wall coatings to reduce the regeneratively cooled chamber coolant temperature rise.

- As an alternative method of reducing high coolant temperatures, an evaluation should also be performed of a combination regenerative/radiation cooled thruster design.

- Methods of joining the rhenium chamber to the stainless steel injector should be evaluated to eliminate the need for soft seals.

- Additional testing, including pulsing and thermal life cycling, should be performed to evaluate thruster performance under mission simulation.

- The chamber nozzle contour should be re-optimized and retested for the operating conditions of low Reynolds Number and low chamber pressure.

- A more efficient method of determining fuel flow split and core mixture ratios must be found. Temperature measurements at the tip of the film coolant sleeve should be obtained.

- A flow visualization experiment should be conducted to enhance the understanding of the present propellant combustion and mixing dynamics.

- A new regeneratively cooled chamber incorporating optimized cooling (to reduce total heat load) and a nozzle contour based on present test data should be designed, fabricated, and tested.

3.0, Recommendations (cont.)

- A new rhenium chamber should be designed and fabricated that would incorporate an optimum nozzle contour, integrated valves, and an improved chamber/injector attachment to eliminate the heat-soak condition on long-duration tests. Life cycle limit evaluation should be included in the test matrix.

4.0 TECHNICAL DISCUSSION

4.1 IGNITER-INJECTOR

The igniter-injector was designed and fabricated by the Aerojet TechSystems Company. Its functional operation is shown in Figure 4.1. This component was designed and fabricated in 1972 as a small thruster that could accept liquid, two-phase, or gaseous propellants and ignite them using a very low-energy spark (0.01 J). At the time, approximately 250 hot-fire tests were conducted to verify the original design goals.

The selection of the Aerojet platelet design for use in the present program was based on the previous test history, which demonstrated reliable and rapid (0.010 s) ignition and trouble-free operation under the following range of test conditions.

Propellant supply pressure	300 to 900 psia
Fuel supply temperature	-416 to 58°F
Oxygen supply temperature	-326 to 60°F
Chamber pressure	140 to 410 psia
Mixture ratio	2:1 to 5:1

The igniter-injector assembly is comprised of a stainless steel body containing two ports for screw-in poppet valves, a centrally mounted spark plug, and a bonded nickel faceplate containing the propellant manifolding, twelve radial in-flow fuel injection elements, and six like-on-like doublet oxygen injection elements, which produce six axial fans that flow radially inward to the center electrode.

All of the oxygen flows through the annular gap formed by the spark plug and the platelet stack containing the injection elements. The oxygen provides the required cooling for the electrode and the injector face. The hydrogen flow is split into two parts. A smaller amount is injected

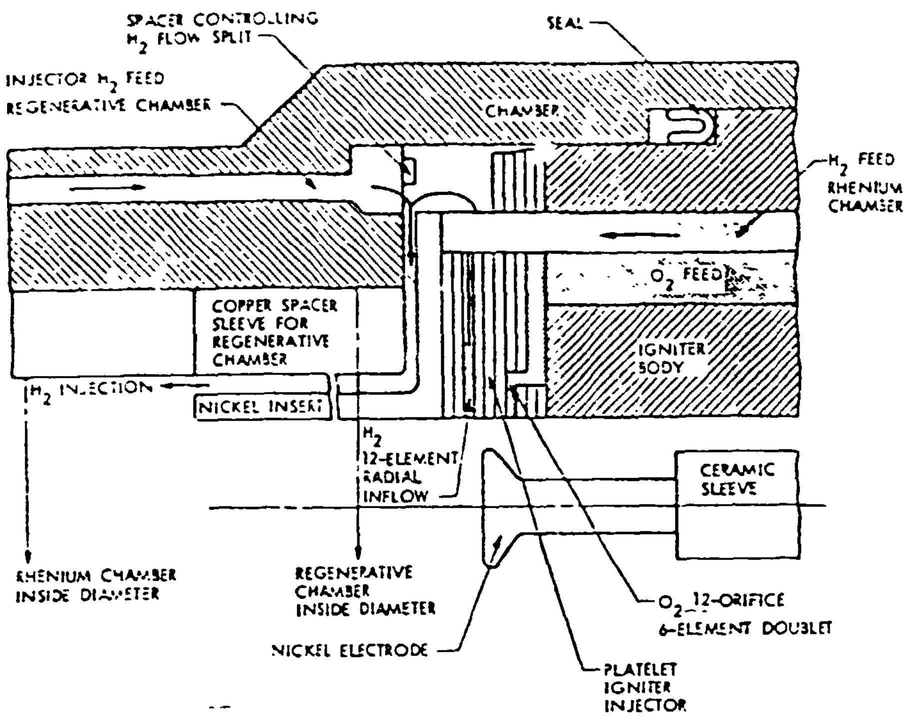

Figure 4.1 Igniter-Injector Flow Schematic

around the electrode, as shown in Figure 4.1, to provide a highly ignitable mixture. The remainder of the fuel is ducted behind a chamber insert, which is fabricated from Nickel 200 and contains twelve cooling channels 0.048 in. wide by 0.030 in. deep. The fuel is then injected 1.0 in. downstream of the electrode to mix with the oxygen-rich core flow. The ducted fuel provides cooling for the chamber head-end seals and the chamber insert. The fuel flow split is controlled by a spacer containing twelve slots located between the chamber housing and the insert. The fuel split is controlled by the frontal area of the slots. Previous testing utilized a 90/10 fuel flow split, whereby 90% of the fuel flowed through the ducted nickel insert and 10% entered the core to provide mixture ratios of 20:1 to 50:1 (with overall mixture ratios of 2:1 to 5:1) in the spark gap area.

The same injector, spacers, and chamber insert designs were used during testing of the regeneratively cooled and rhenium chambers described in the next section.

4.2 THRUST CHAMBERS

Three thrust chambers, a stainless steel checkout chamber, a high-temperature rhenium chamber, and a regeneratively cooled copper chamber, were designed and fabricated for use in the program. Because only one igniter-injector configuration was available for use, the chamber-to-injector interfaces were made identical. The initial goal of the program was to reach the highest performance achievable concomitant with available test facilities and test conditions. The thrust chambers were, therefore, designed for operation with a pressure of 500 psia at a mixture ratio of 4:1 to 5:1 and incorporated an 80% bell nozzle having an exit area ratio of 100:1. This would have provided a nominal thrust level of 45 lb_f. Additional design parameters and goals are provided in Tables 4.1 and 4.2. As a result of Space Station propulsion studies at JPL, the thruster program was subsequently changed to emphasize operation at a very low chamber pressure of 30 psia. The operating mixture ratio was shifted to 2.5:1, which is the approximate optimum theoretical one-dimensional kinetic (ODK) vacuum performance

TABLE 4.1

ORIGINAL DESIGN PARAMETERS

Chamber Type	Regenerative		High-Temperature	
			Cool Wall	Hot Wall
MR	5	4	4	4
Pc Nominal (psia)	500	500	500	500
W_T (lb_m/sec) (@ C* = 100%, Pc = 500 psia)	0.1012	0.0993	0.0993	0.0993
Pc Expected (psia)	475	475	393	460
Isp (sec)/ERE (%)	440/95	440/95	370/78.5	432/92
Throat Temperature (°F)	1,200	1,200	2,400	3,500
Thrust (lb_f)	45	44	38	43
W_O (lb_m/sec)	0.0844	0.0795	0.0795	0.0795
W_F (lb_m/sec)	0.0169	0.0199	0.0199	0.0199
Nozzle Area Ratio & Type	= 100:1 80% Bell - - - - - - - - - - - - -			
Supply Pressures* (psia)				
Ox	1,191	1,122	1,122	1,122
Fuel	750	826	625	625
Core MR*	69	55	55	55

Based on cold-flow test with 0.018 flow-control channel depth.

TABLE 4.2

APPROXIMATE PERFORMANCE GOALS

MR				5		4	
ODE NBP LH_2/LO_2	= 100:1			469		465	
I_{sp} 530°R Prop.			+4%	488	+5%	488	
Losses, %							
Div				0.4		0.4	
Kin				2.0		0.8	
BL				2.0		2.0	
Total				4.4		3.2	
Perfect Injector Isp				466		472	
Isp Goal				440		440	
ERE Loss, Sec				26		32	
Loss, %				5.3		6.6	
ERE, %				95		93	Inj. Eff. Required
E_m Required, %				60		60	

for a chamber pressure of 30 psi. The resulting thrust level was 2.73 lb_f. Because fabrication of the chambers was nearing completion at the time the program emphasis was changed, no design changes were incorporated to account for the new operating conditions.

- Rhenium Thrust Chamber

Based on the successful use of a rhenium chamber by JPL during a previous fluorine/hydrazine thruster program, rhenium material was chosen for use in this program. The high melting temperature (5760°F) and high-temperature strength properties of rhenium results in minimum cooling requirements of the chamber wall even when operating with an overall mixture ratio up to stoichiometric, which is approximately 5250°F, for the oxygen/hydrogen propellants. Unfortunately, rhenium oxidizes readily; therefore, an oxidation barrier must be incorporated. The propellant injection configuration provides a film of hydrogen as the oxidation barrier.

The rhenium chamber was fabricated (at the Ultramet Company, Pacoima, CA) utilizing a chemical vapor deposition (CVD) process. CVD is a method of plating that relies on the condensation of elements or compounds from the vapor state to form solid structural deposits. Because this is done on an atom-by-atom basis, impurity levels are typically less than 0.2%. The CVD process relies on utilizing a gaseous compound of the element that is flowed over a heated substrate; this results in the thermal decomposition and subsequent deposition of the metal onto the substrate. The substrate is then removed, leaving the desired part. Figure 4.2 shows a cross-section of the thrust chamber, and Figure 4.3 is a photograph of the completed part post-test. The design analysis defining the nozzle contour and chamber wall thickness for the 500 psia design point is provided in Appendix C.

- Regeneratively Cooled Thrust Chamber

The fuel regeneratively cooled chamber is a single-pass, counter-flow-type designed and fabricated by Aerojet. All the hydrogen enters via a

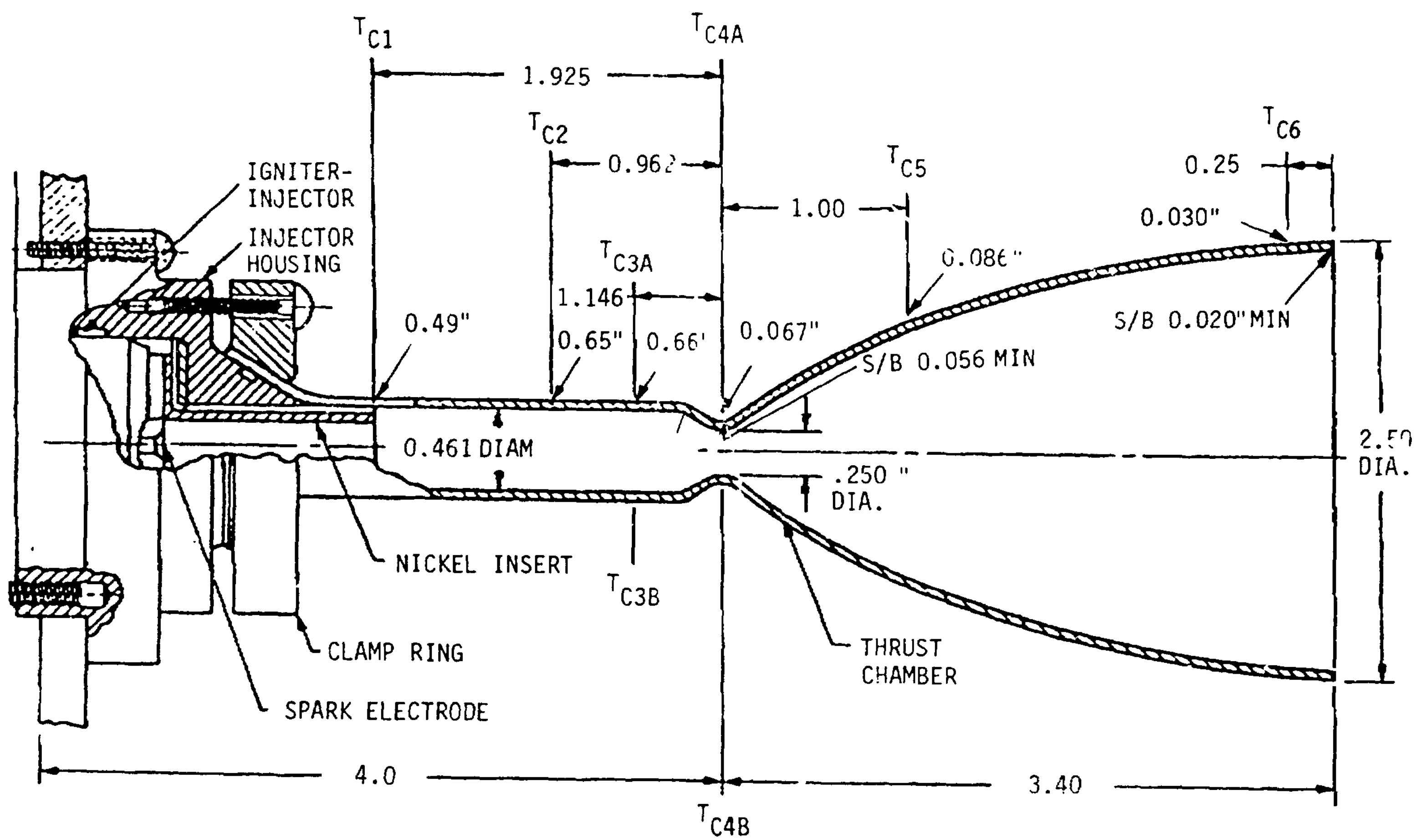

Figure 4.2. Cross-Section of Rhenium Chamber Showing Test Thermocouple Locations and Wall Thicknesses

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Figure 4.3. Completed Rhenium Chamber

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1/4-in.-diameter feed line located near the nozzle exit. The fuel distribution manifold is integral with a liner fabricated from an alloy of copper and 0.1% zirconium, and feeds sixty 0.015-in.-wide coolant channels. The channel depth varies along the length of the chamber to provide the required coolant velocity and wall temperature with a minimum of coolant pressure drop (10% of chamber pressure). The coolant discharges directly into the injector fuel manifold which, in turn, feeds fuel to both injection paths. The coolant channels are closed out with a thin layer of electrodeposited copper and a thick layer of electrodeposited nickel. This unique chamber design approach requires only one weld at the 1/4-in. feed line. The predicted temperatures at the design point of 5:1 mixture ratio and 500 psia chamber pressure, assuming 100% combustion efficiency, are as follows:

Throat temperature, maximum	1170°F
Head-end temperature, maximum	1180°F
Coolant bulk temperature, maximum	760°F
Nickel insert temperature, maximum	1387°F
Coolant ΔP	50 psid

Additional data related to the design of this chamber are provided in Appendix B.

Figure 4.4 shows a cross-section of the thrust chamber. As can be seen, the regeneratively cooled chamber assembly has a larger contraction ratio than the rhenium chamber, and therefore allows incorporation of an additional copper sleeve around the nickel insert. This larger contraction ratio was selected to allow rapid expansion of the exiting core gases, causing recirculation and enhanced mixing with the exiting ducted fuel. This would tend to increase performance. Figure 4.5 is a photograph of the completed part.

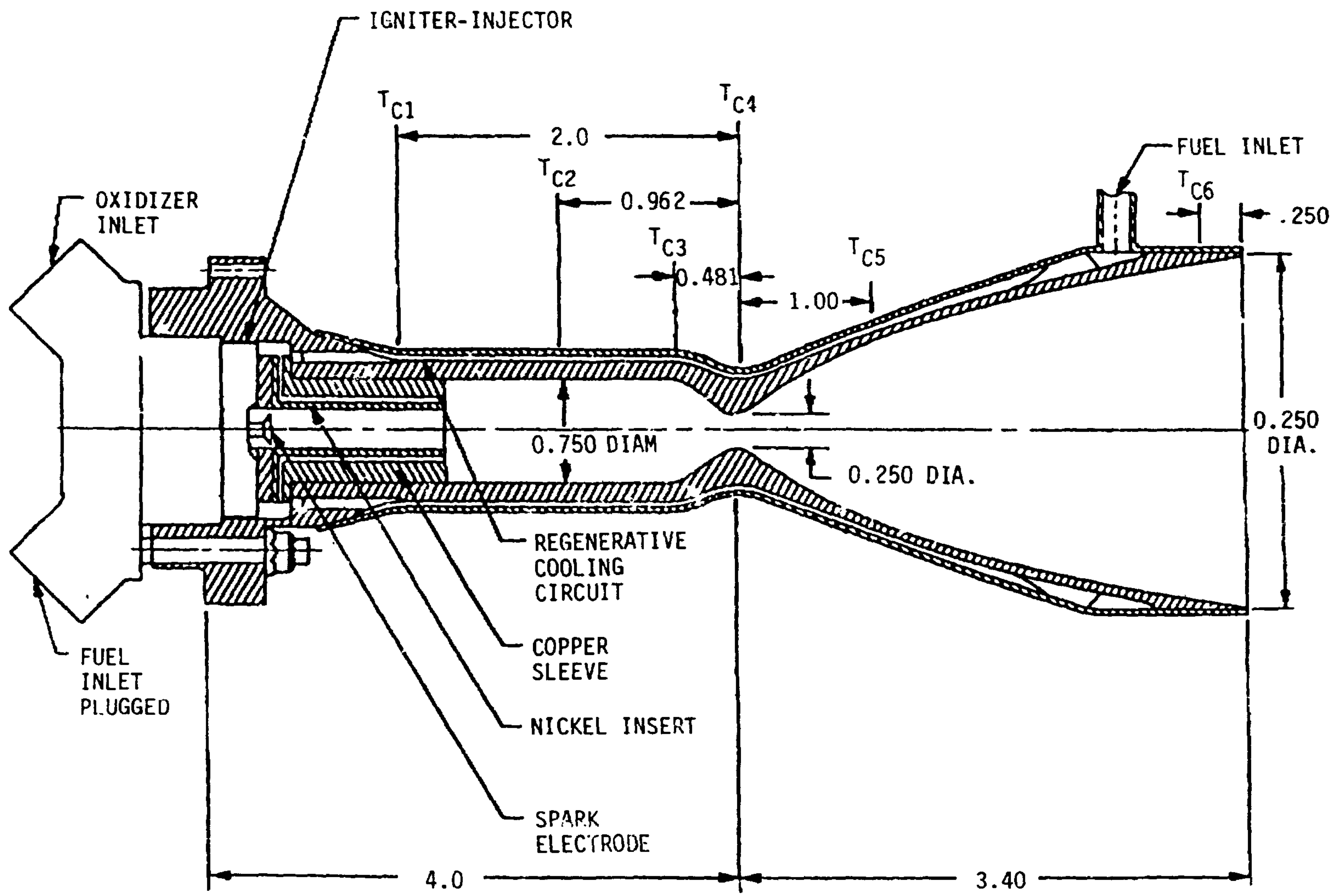

Figure 4.4. Cross-Section of Regeneratively-Cooled Chamber Showing Test Thermocouple Locations

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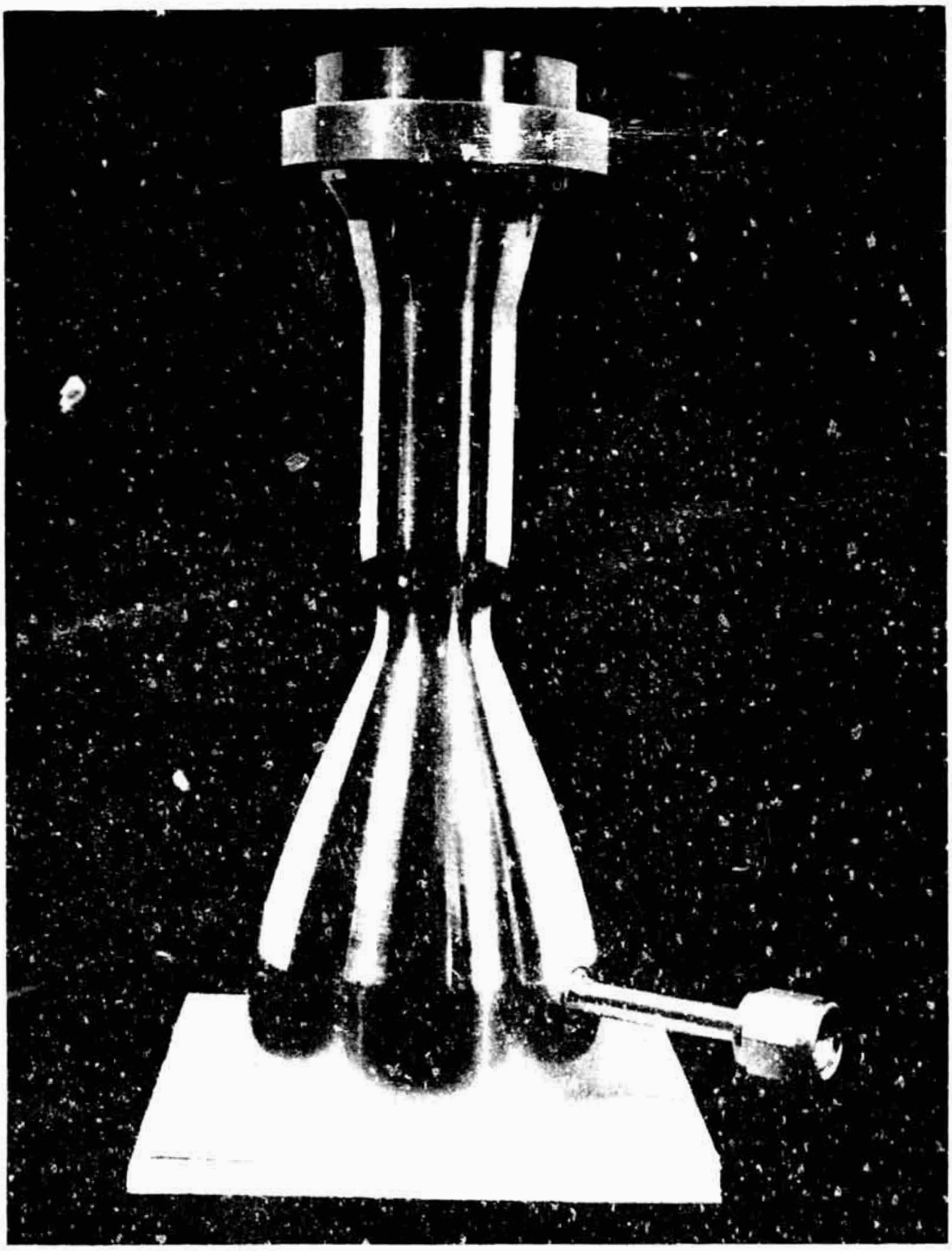

Figure 4.5. Completed Regeneratively-Cooled Thrust Chamber

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4.2, Thrust Chambers (cont.)

o <u>Stainless Steel Thrust Chamber</u>

A stainless steel thrust chamber was fabricated utilizing the same design as the rhenium thrust chamber except that an 18° half-angle conical nozzle, having the same exit area and length, was incorporated in place of the 80% bell nozzle for ease of fabrication. Figure 4.6 shows a cross-section of the stainless steel chamber. The stainless steel chamber was used during test-stand checkout and for initial propellant ignition tests and, later, for comparison of the performance of the two nozzle contours.

4.3 TEST FACILITY

All tests were conducted in a vacuum facility located at JPL. The facility is equipped with two parallel pumping systems. Each pumping system consists of a rotary-piston-type backing pump and a lobe-type booster pump in series. An exhaust diffuser and an exhaust gas intercooler were installed after early hot-fire checkout tests with the stainless steel chamber indicated that the cell pressure could not be maintained at a level that would produce a fully flowing nozzle with the chamber 100:1 expansion area ratio and chamber pressure of 30 psia. These modifications resulted in acceptable cell pressures of 0.005 psia.

The vacuum test cell is fully instrumented for recording temperatures, pressures, and thrust. Measurements are recorded and stored in a computerized instrumentation system. The thrust measuring system is dynamically calibrated immediately before and after each test through the use of a remotely controlled deadweight system.

4.4 TEST SUMMARY AND RESULTS

A total of 115 tests were conducted during the present program utilizing the Aerojet igniter-injector, as defined in Table 4.3. These included 51 tests with the stainless steel chamber during test-stand checkout and

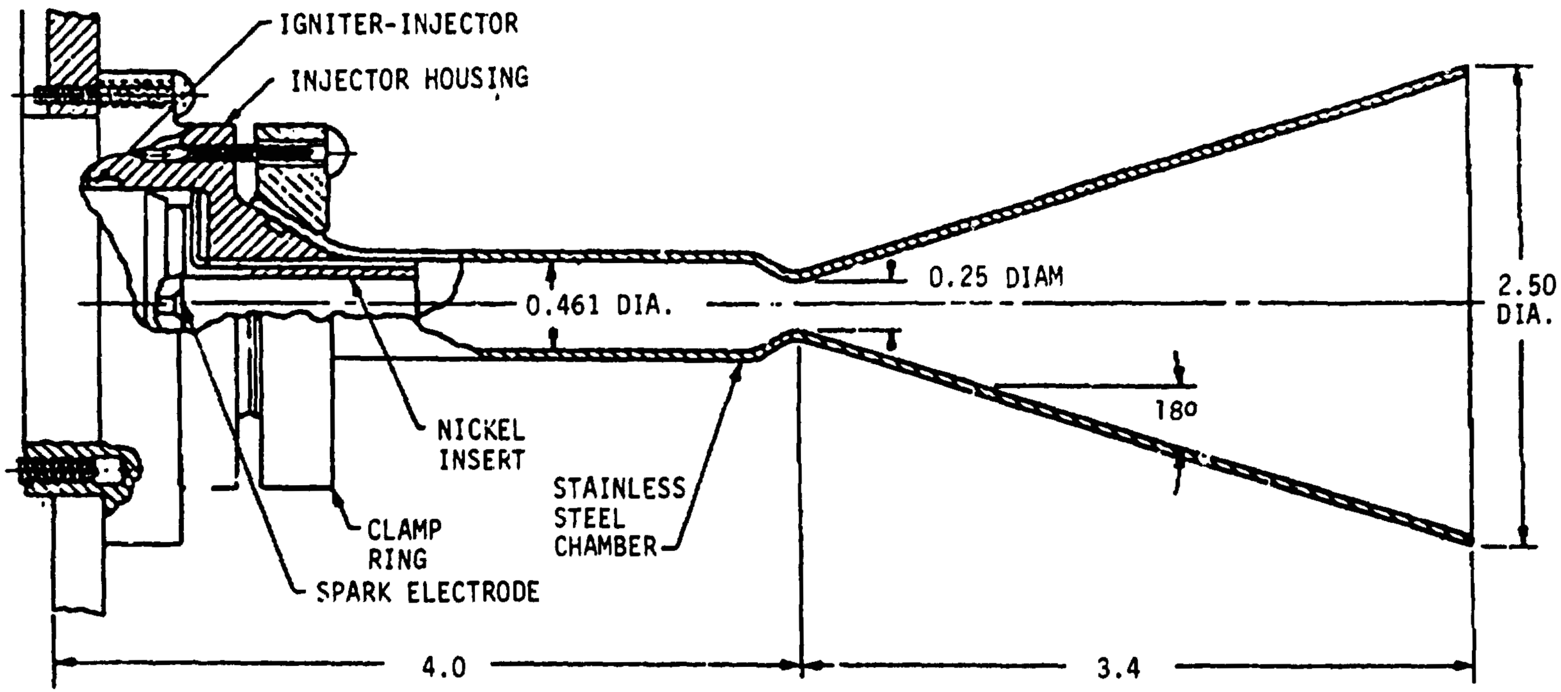

Figure 4.6. Cross-Section of Stainless Steel Chamber

TABLE 4.3
TEST PROGRAM SUMMARY

TEST NO.	CHAMBER	OBJECTIVE/COMMENTS
1-51	STEEL	0.018 - 0.010 IN. SPACER DEPTH - CHECKOUT OF FACILITY, IGNITION AND PRELIMINARY DATA
57-65	RHENIUM	0.010 IN. SPACER DEPTH - PERFORMANCE, HEAT TRANSFER, DURABILITY
66-73	REGENERATIVE	0.010 IN. SPACER DEPTH - PERFORMANCE, HEAT TRANSFER, DURABILITY
74-83	RHENIUM	0.010 - 0.008 IN. SPACER DEPTH - IMPROVED PERFORMANCE, MR SURVEY
84-88	STEEL	PERFORMANCE COMPARISON OF 80% BELL AND 18° CONICAL NOZZLE
89-104	RHENIUM	0.005 IN. SPACER DEPTH - IMPROVED PERFORMANCE - FRONT END TOO HOT, SUSPECT PLUGGING AND FLOW CONTROL PROBLEM
105-115	RHENIUM	0.005 IN. SPACER DEPTH - SPACER SLOTS MODIFIED TO CONTROL FUEL FEED- I_{SP} AND PA DATA NOT VALID

calibration. The balance of the tests were conducted during the thrust chamber evaluations. A Bendix Company Model 10-397230-1 exciter supplied the spark energy (0.098 J). No instances of nonignition occurred during any of the tests because of igniter failure.

- Regeneratively Cooled Thrust Chamber Tests

A total of eight tests were conducted utilizing the regeneratively cooled chamber. Figure 4.7 shows the chamber mounted in the test stand. Although the chamber was designed for operation at much higher pressures and, thus, flow rates, it was decided to run it with the lower pressure even though adequate cooling may not have been achieved. As was expected, run duration was limited by the head-end seal temperature. The tests were terminated when the head-end temperature reached 600°F. A maximum test duration of 50 s was accomplished.

Figure 4.8 shows the effect of varying overall mixture ratio on performance. At the ODK optimum overall mixture ratio of 2.5:1, a vacuum performance value of 393 lb_f-s/lb_m was achieved for the conditions tested.

Figure 4.9 shows the chamber outer wall temperature versus time during one of the tests. The thermocouple locations are shown in Figure 4.4. As can be seen, except for the head-end, steady-state temperatures were approached at all locations. The low temperature of 530°F reached at the throat would indicate that long chamber life could be expected.

The regeneratively cooled chamber temperature rise rates for both the head-end and the throat are shown in Figure 4.10 for various mixture ratios. Although the chamber was not allowed to cool completely following each test, it still appears from the figure that a lower mixture ratio provides more coolant and, therefore, lower wall temperatures at the throat.

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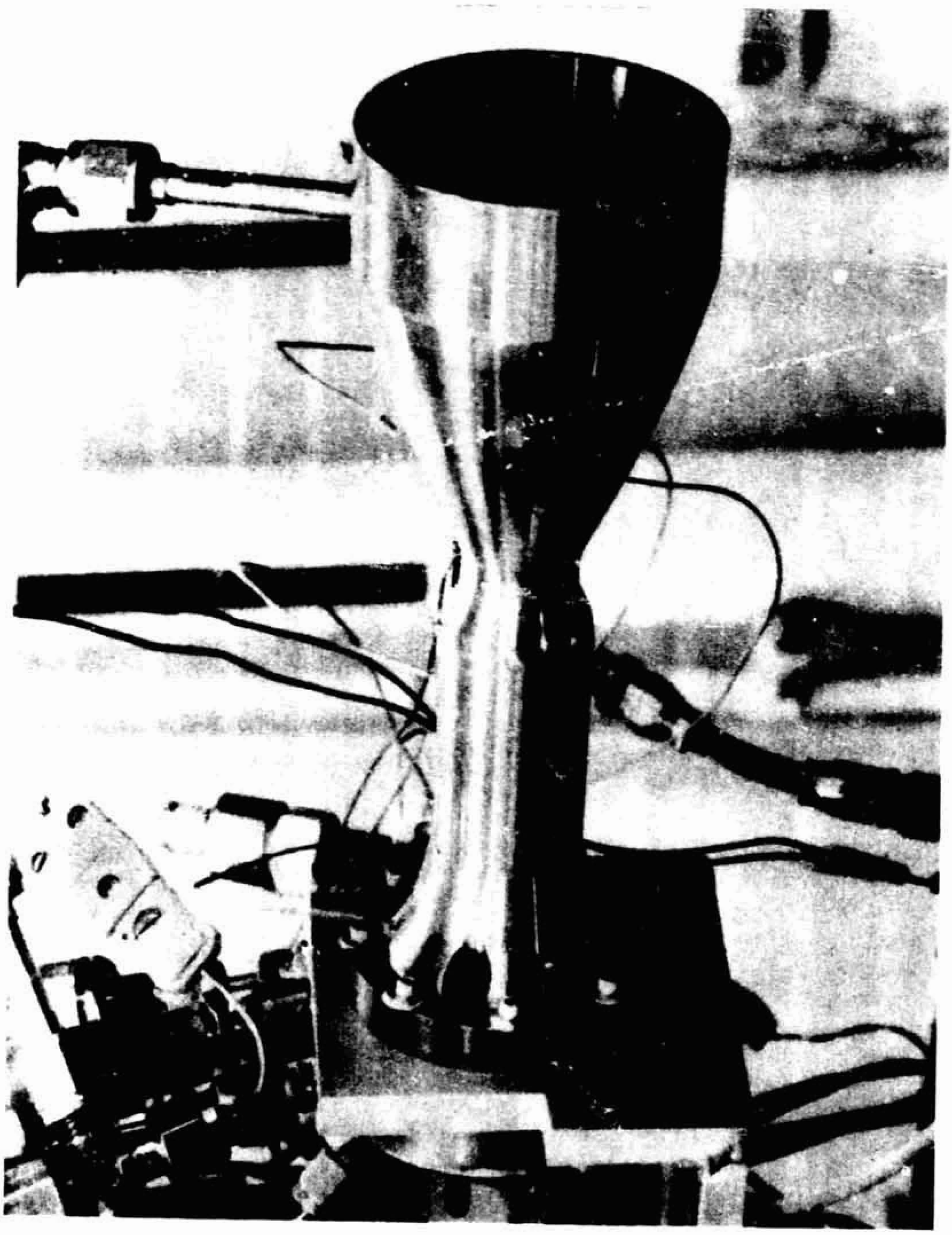

Figure 4.7. Regenerative Chamber Mounted in Test Stand

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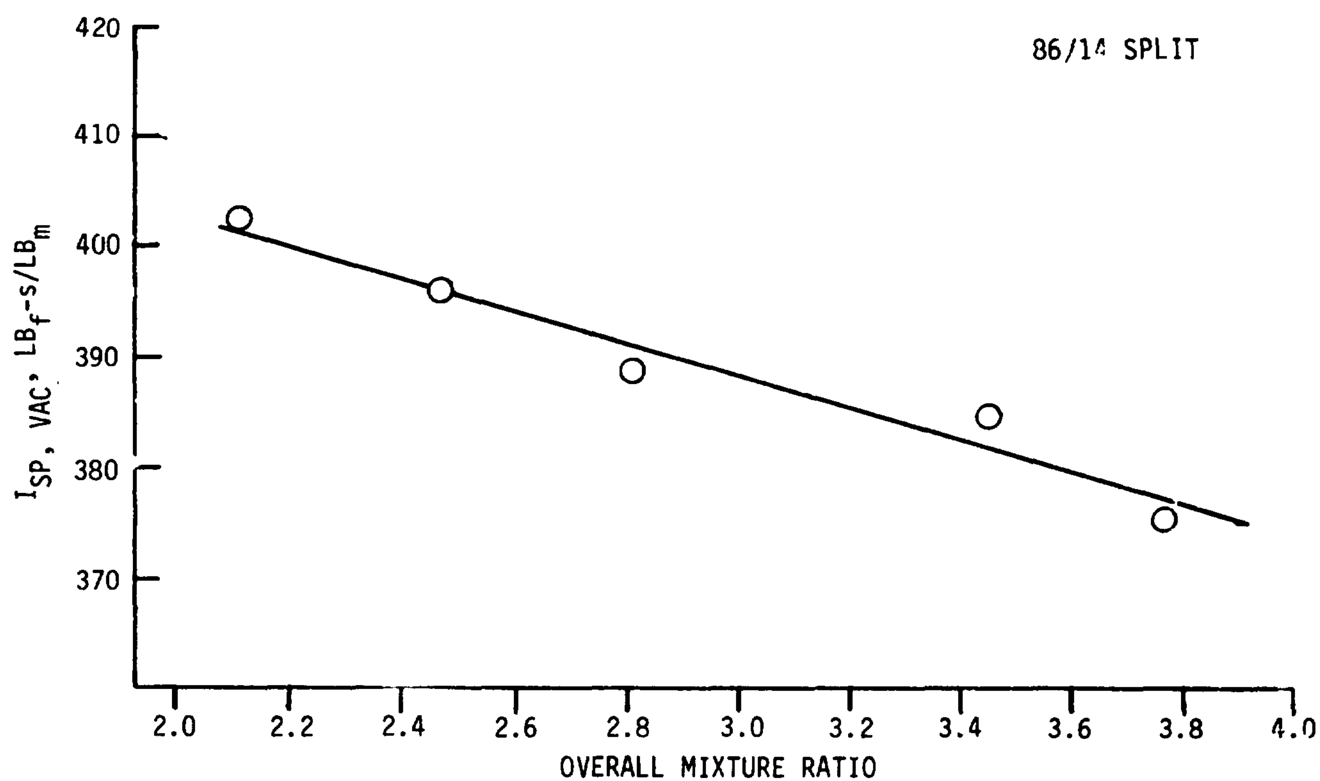

Figure 4.8. Regenerative Chamber Performance vs. Overall Mixture Ratio

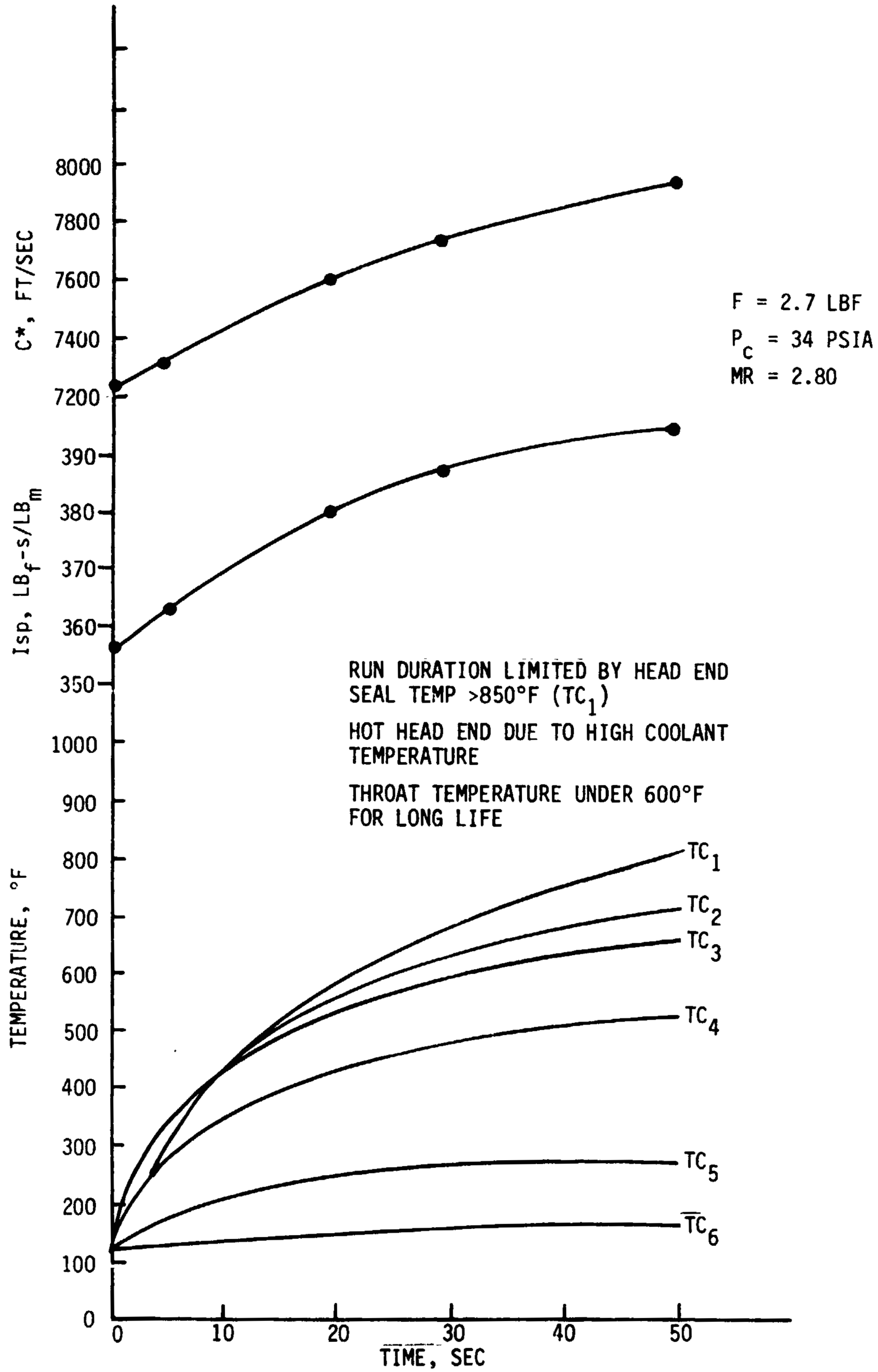

Figure 4.9. Regenerative Chamber - Temperatures and Performance Transients

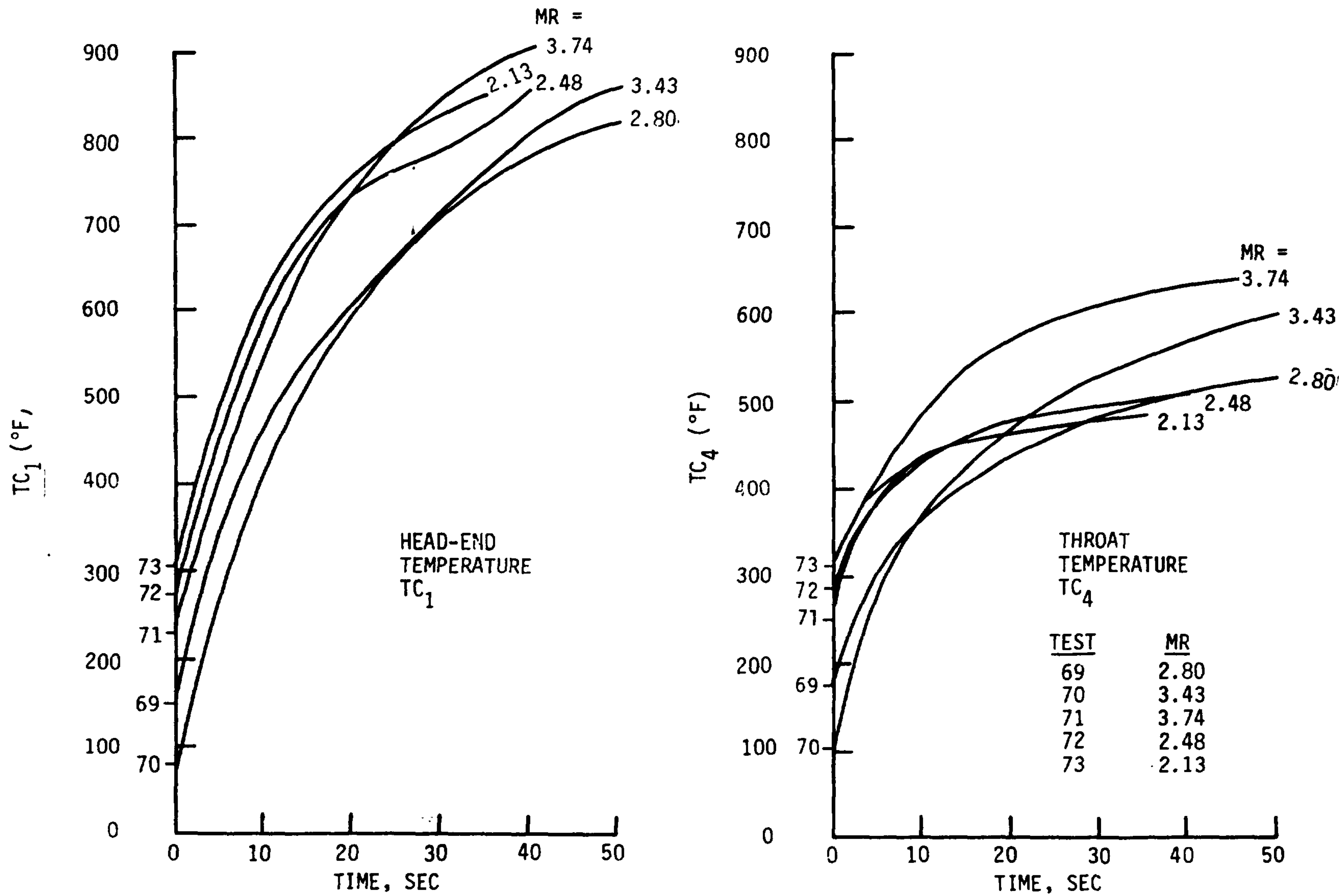

Figure 4.10. Regenerative Chamber Rise Rates

Figure 4.11 shows the thermocouple temperatures as a function of axial distance along the length of the chamber. A plot of two tests at two different MR's shows the consistency of the cooling pattern. Steady-state was obtained in the nozzle section during both tests.

Based on the results of the tests, it is felt that a regeneratively cooled chamber could be designed that would provide adequate cooling for long durations with a chamber pressure of 30 psia. This could be accomplished by eliminating the regenerative cooling of the nozzle to lower the coolant bulk temperature rise and, thus, the head-end temperature.

o Rhenium Chamber Tests

A total of 41 tests were conducted utilizing the rhenium chamber. Figure 4.12 shows the chamber mounted in the vacuum test facility. A total run duration of 2852 s was accumulated during the tests. Four of the tests were conducted for durations of 300 s. Figure 4.13 overlaps test data from 4 tests at the same conditions. The data are highly repeatable and indicate that steady-state conditions were attained after approximately 40-60 s of operation. Most subsequent performance and mapping tests were for durations of 60 s. The main concern during the rhenium chamber tests was the possibility of oxidation causing severe corrosion of the walls, shortening the life of the chamber. No degradation of the chamber walls was observed during any of the tests at temperatures up to 3300°F.

One of the primary objectives of the tests was to determine the effect of insert/core fuel flow split on performance. As explained previously, the amount of fuel allowed to flow in the chamber insert supplying the hydrogen oxidation barrier is controlled by a copper spacer with 12 flow passages. Figures 4.14 and 4.15 show the effect of varying the area of the spacer flow passages on performance during several 60-s tests. As can be seen, lowering the flow area, and thus the barrier flow, results in an increase in performance. The increase is caused by the lowering of the core gas mixture ratio,

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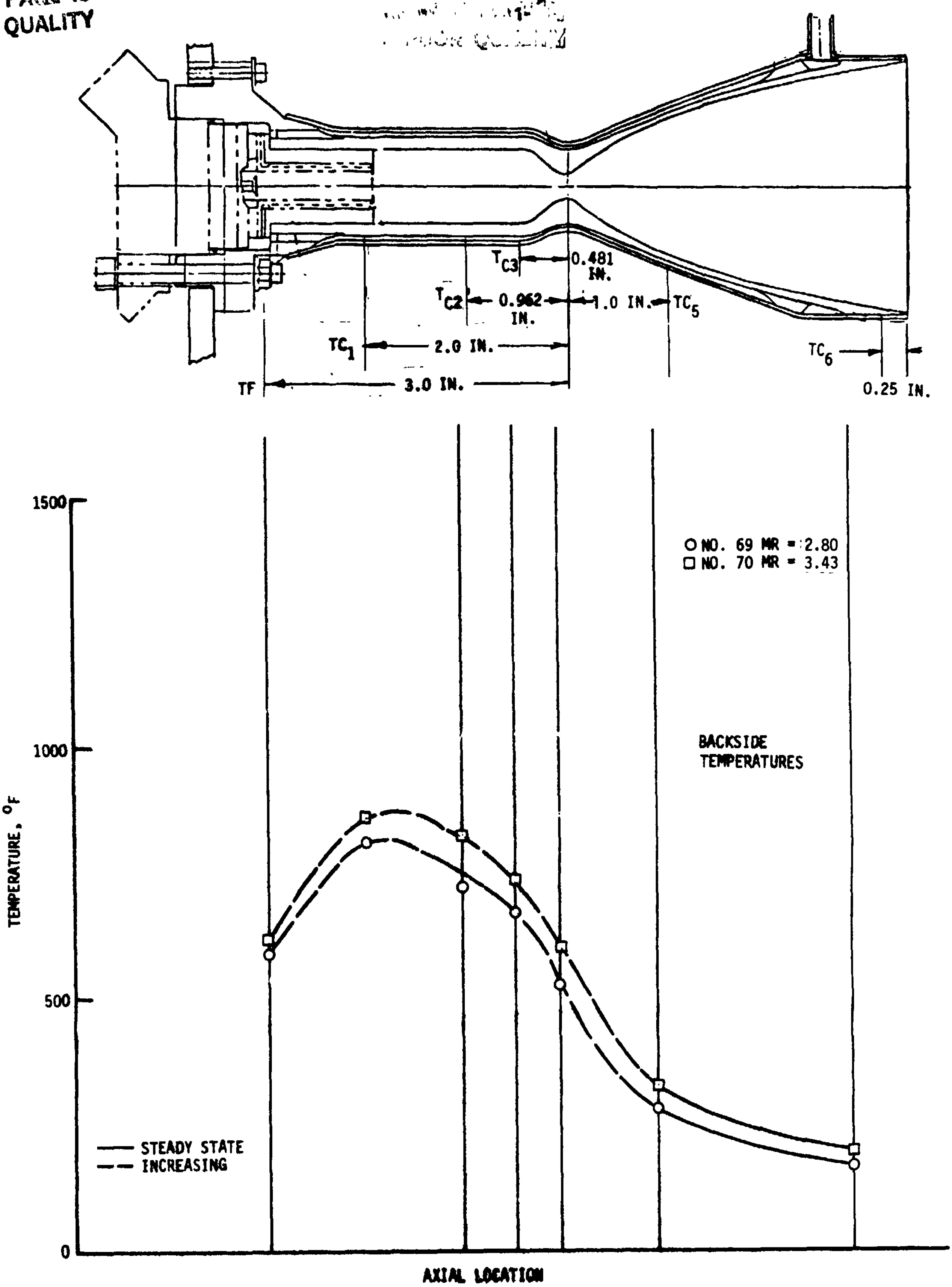

Figure 4.11. Regenerative Chamber Axial Temperature Distribution

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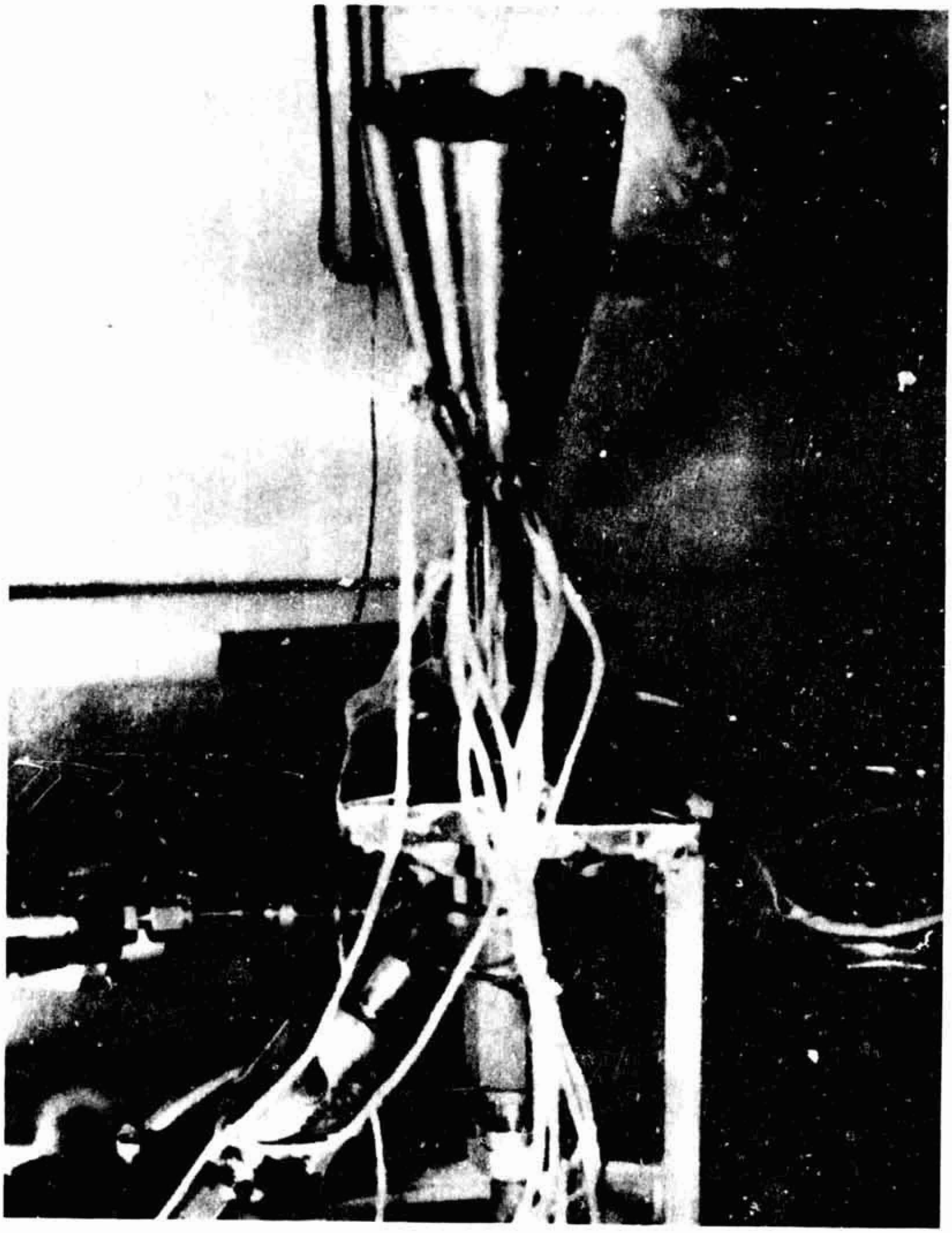

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Figure 4.12. Rhenium Chamber Mounted in Test Stand

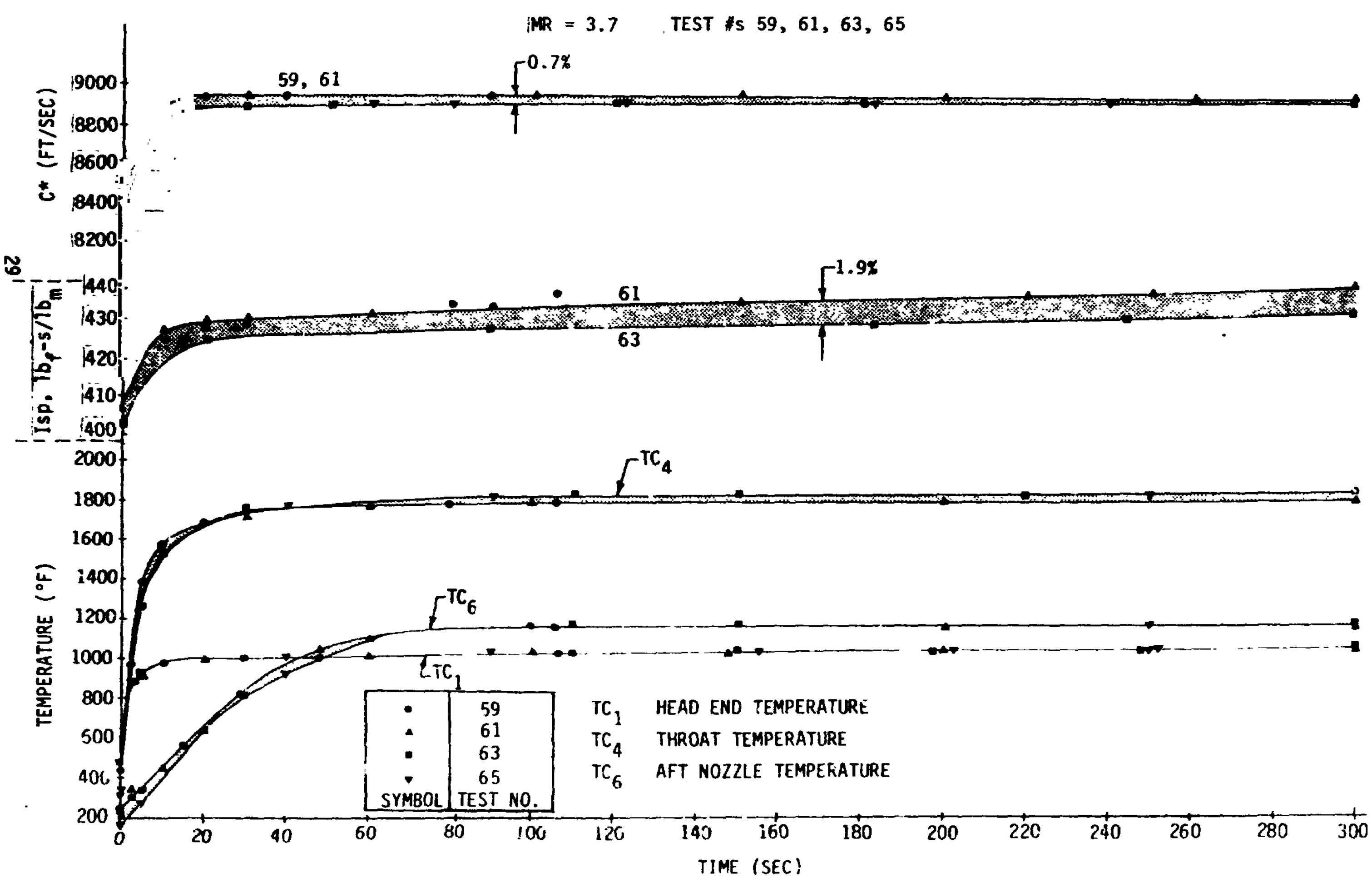

Figure 4.13. Rhenium Chamber Repeatability

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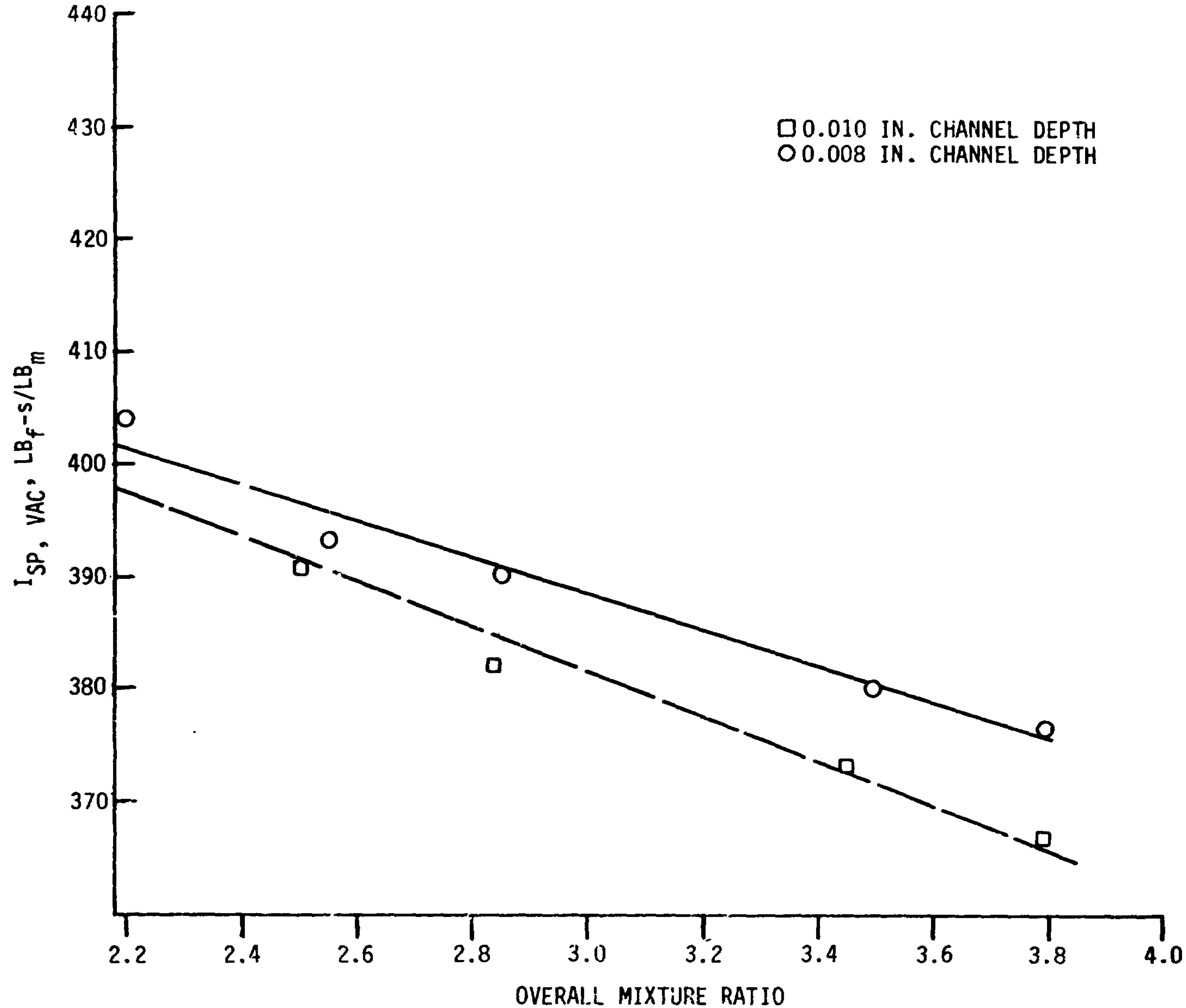

Figure 4.14. Rhenium Chamber Performance vs. Mixture Ratio

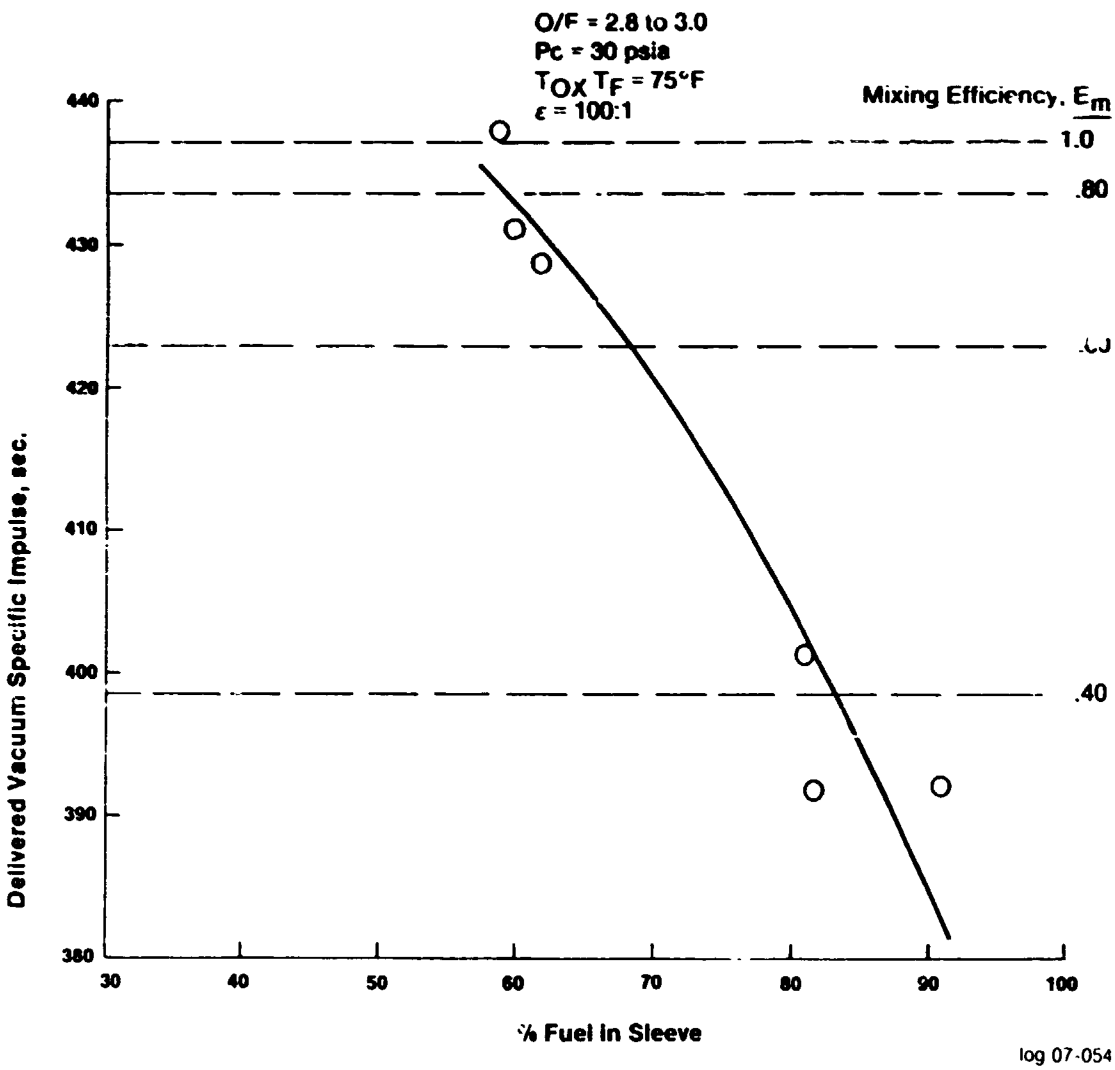

Figure 4.15 Rhenium Chamber Performance Vs. % Fuel In Sleeve

Use or disclosure of data contained on this sheet is subject to the restriction on the title page of this proposal or quotation

which is significantly above stoichiometric. As the mixture ratio is lowered, the temperature and energy of the gases are raised. Lowering the overall mixture ratio results in a performance increase for the same reason. At the ODK optimum overall mixture ratio of 2.5:1, a performance value of 394 lb_f-s/lb_m was achieved with an insert/core flow split of 89%/11%. With a flow split of 86%/14%, a value of 397 lb_f-s/lb_m was achieved.

Figure 4.16 indicates the same basic performance trend; at low chamber pressures, the maximum Isp is obtained at low core mixture ratios (between 5-10), where the ignition/nonignition limit is being approached. The maximum performance achieved throughout the tests was 438 lb_f-s/lb_m at a core mixture ratio of approximately 6:1.

During the first 60-s test with a spacer incorporating 0.005-in. by 0.047-in. passages, more fuel entered the core than was intended. The actual cause for the additional fuel entering the core has n been determined. Instead of the core operating with a mixture ratio of 12.3:1, as intended, it apparently operated with a mixture ratio of 5.9:1. Vacuum performance of the thruster for this condition was 438 lb_f-s/lb_m with an overall mixture ratio of 2.86:1.

Theoretically, with a constant spacer channel frontal area and a constant overall MR, the core MR should also remain constant. The actual core MR for each test was determined as follows: the overall Cd-A (discharge coefficient times frontal area) was calculated (based on measured temperatures, pressures, and flow rates), from which a constant spacer Cd-A (corresponding to the passage frontal area used on the particular test) was subtracted. The result is a core Cd-A which is translated into a core MR. The calculated core MR's varied significantly from the theoretical values in Tests No 96 through No. 103. This was possibly due to plugging of the fuel orifices leading to the core. Subsequent cleaning of the injector fuel orifices resolved the high core MR values.

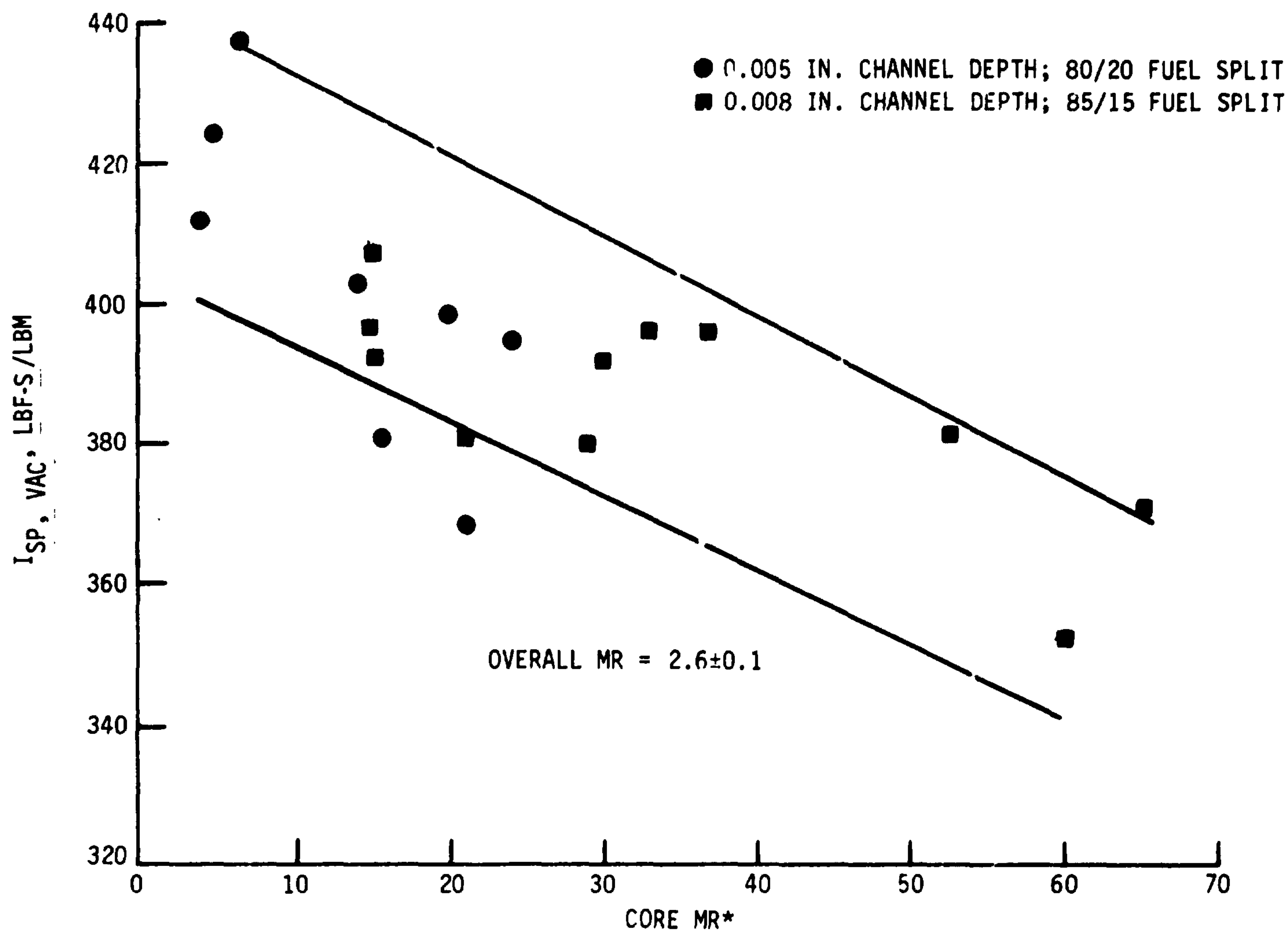

Figure 4.16. Rhenium Chamber Performance vs. Core Mixture Ratio

Typical wall temperature rise rates are shown in Figure 4.17 at the locations shown in Figure 4.2. The axial temperature distribution is shown in Figure 4.18. The maximum wall temperature measured during the rhenium chamber tests was 3359°F.

Steady-state temperature as a function of the overall mixture ratio is shown in Figures 4.19 and 4.20 for various flow splits. The head-end cools with increasing MR due to the cooler core gases, while the throat temperature rises due to the decrease in fuel barrier flow. Maximum steady-state wall temperature measured in the barrel section was 3050°F.

Wall temperatures as a function of the core mixture ratio are shown in Figures 4.21 and 4.22. The throat does not appear to be dependent on core MR as was the case with overall MR. Again, the high core MR values are calculated based on the assumption that each spacer has a constant flow coefficient.

Nozzle thermocouples TC_5 and TC_6 both approached steady-state during Test No. 91, a 60-sec-duration test. A thermodynamic analysis was performed (see Appendix F) using the transient thermocouple data from this test to define the heat transfer coefficients and thus infer the nature of the boundary layer at low pressures. The analysis concluded that the experimental heat transfer coefficients were 3 to 4 times higher than analytical techniques would predict based on a turbulent boundary layer. It is generally expected that small engines establish laminar boundary layers at the throat, and that these are maintained throughout the nozzle to provide lower-than-turbulent coefficients. However, at the extremely low Reynolds Numbers of this test (1000 to 1600), laminar coefficients can exceed turbulent values by a factor of 2. No explanation for the high experimental values can be made at this time.

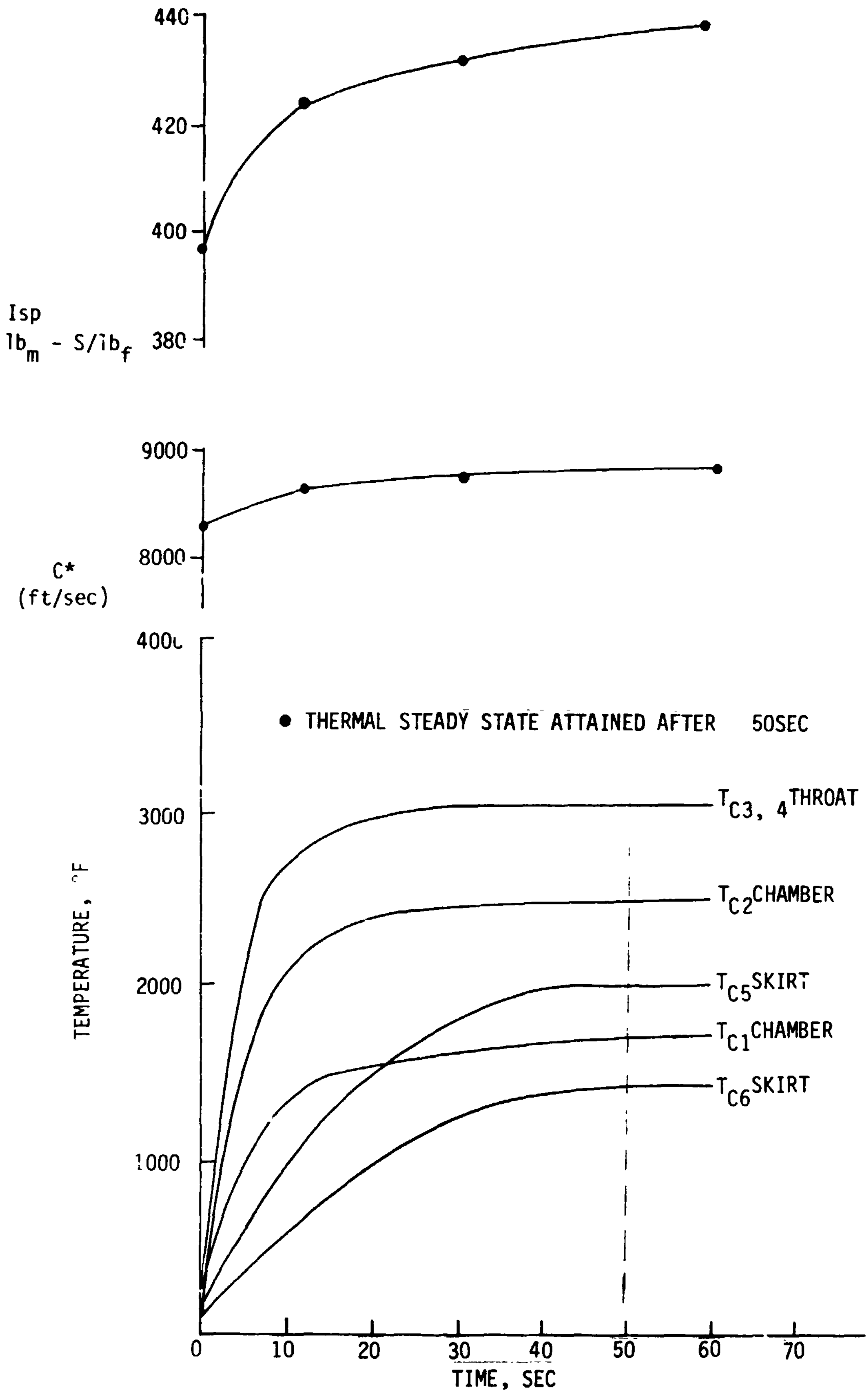

Figure 4.17. Rhenium Chamber Temperatures and Performance Transients

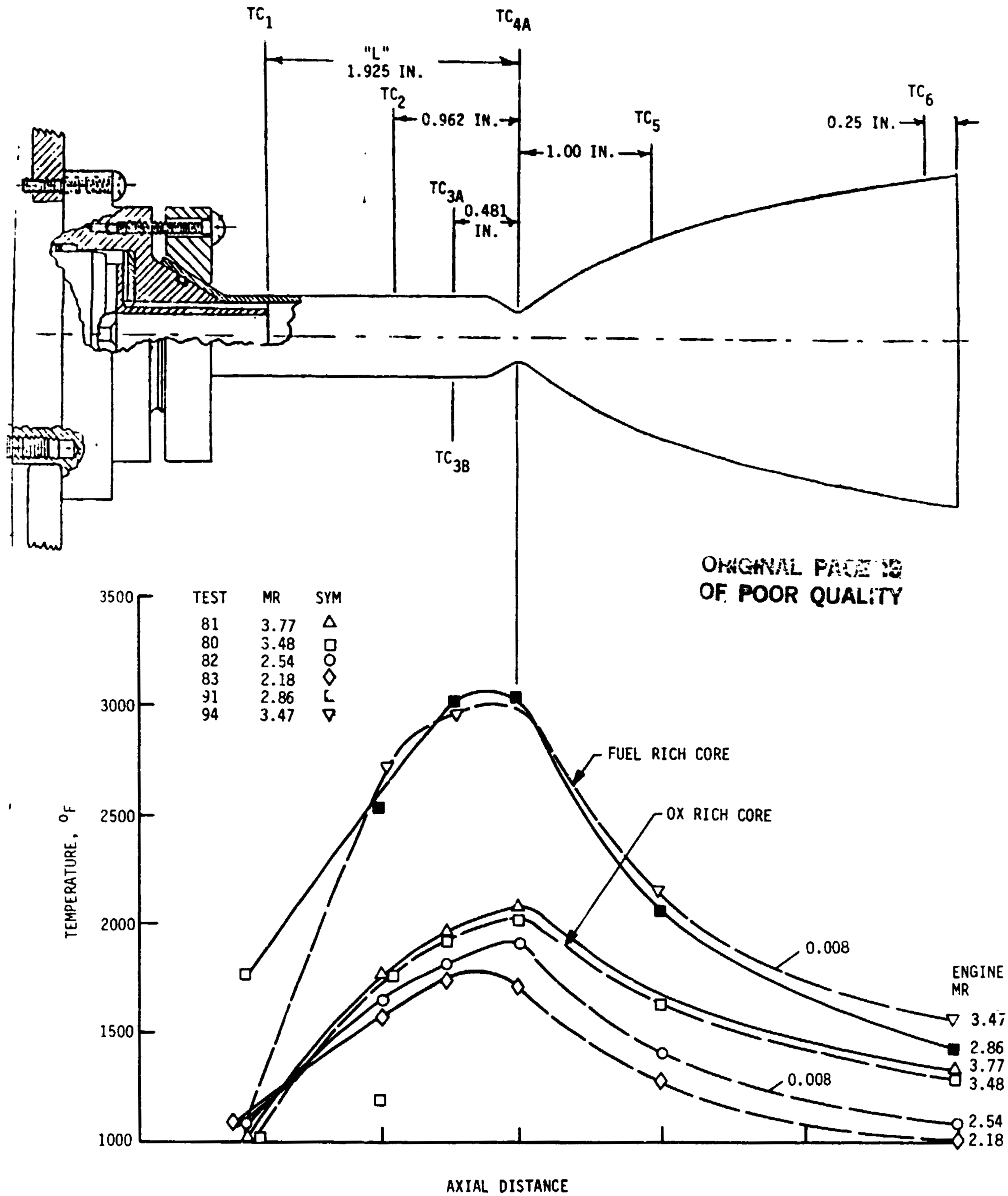

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Figure 4.18. Rhenium Chamber Axial Temperature Distribution vs. MR

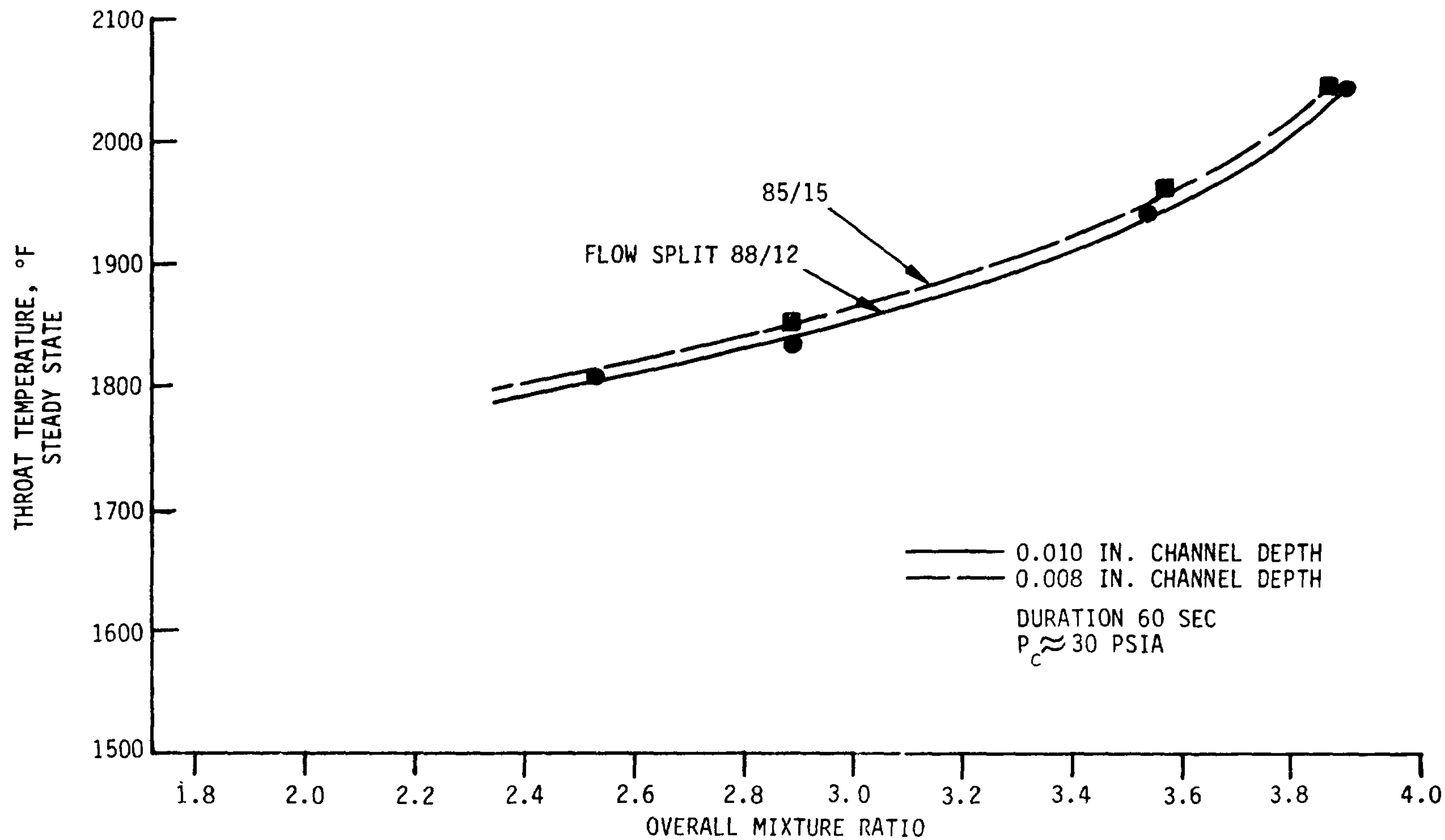

Figure 4.19. Rhenium Chamber Steady State Throat Temperature vs. Overall Mixture Ratio

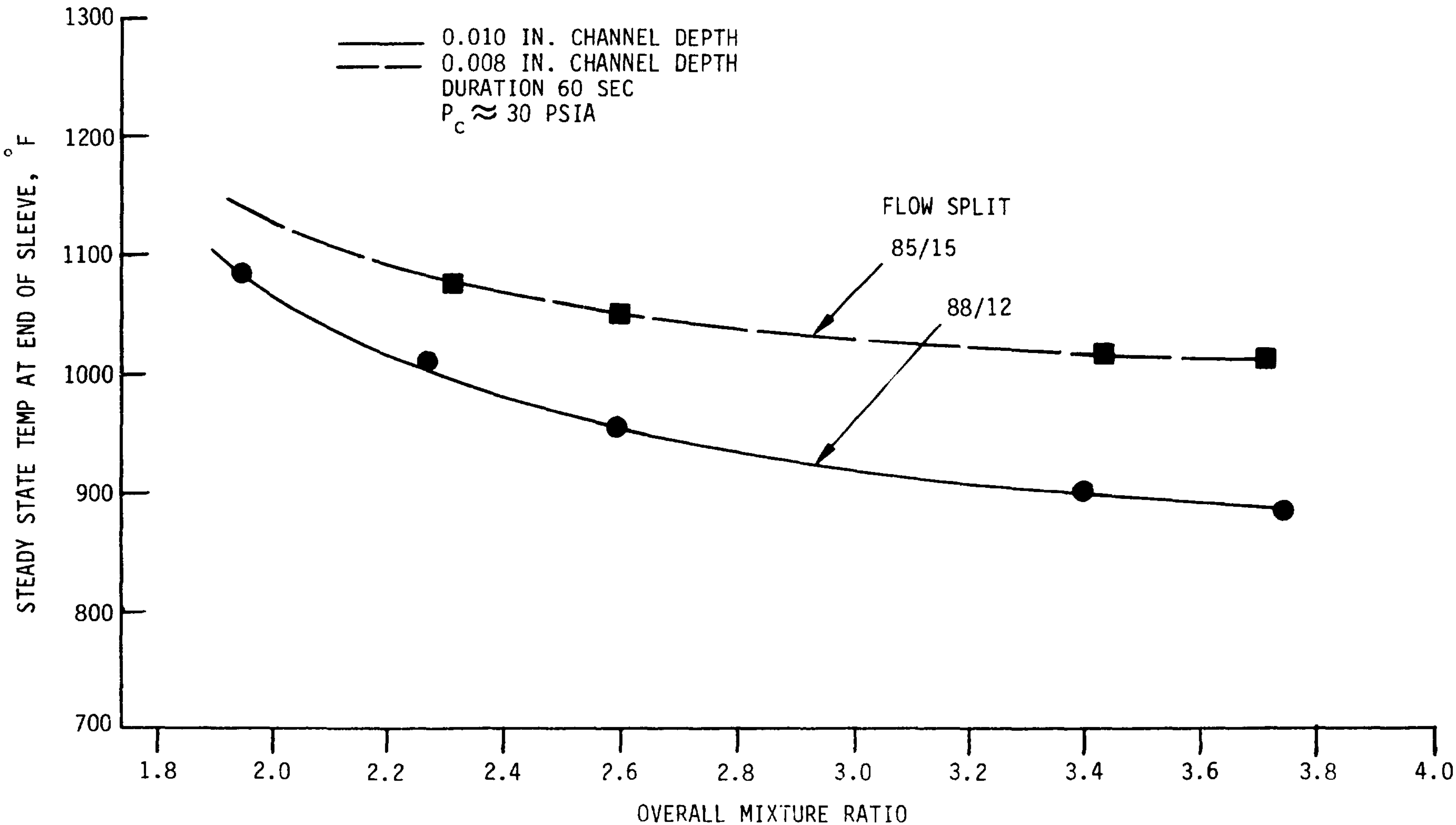

Figure 4.20. Rhenium Chamber Steady State Sleeve Temperature vs. Overall Mixture Ratio

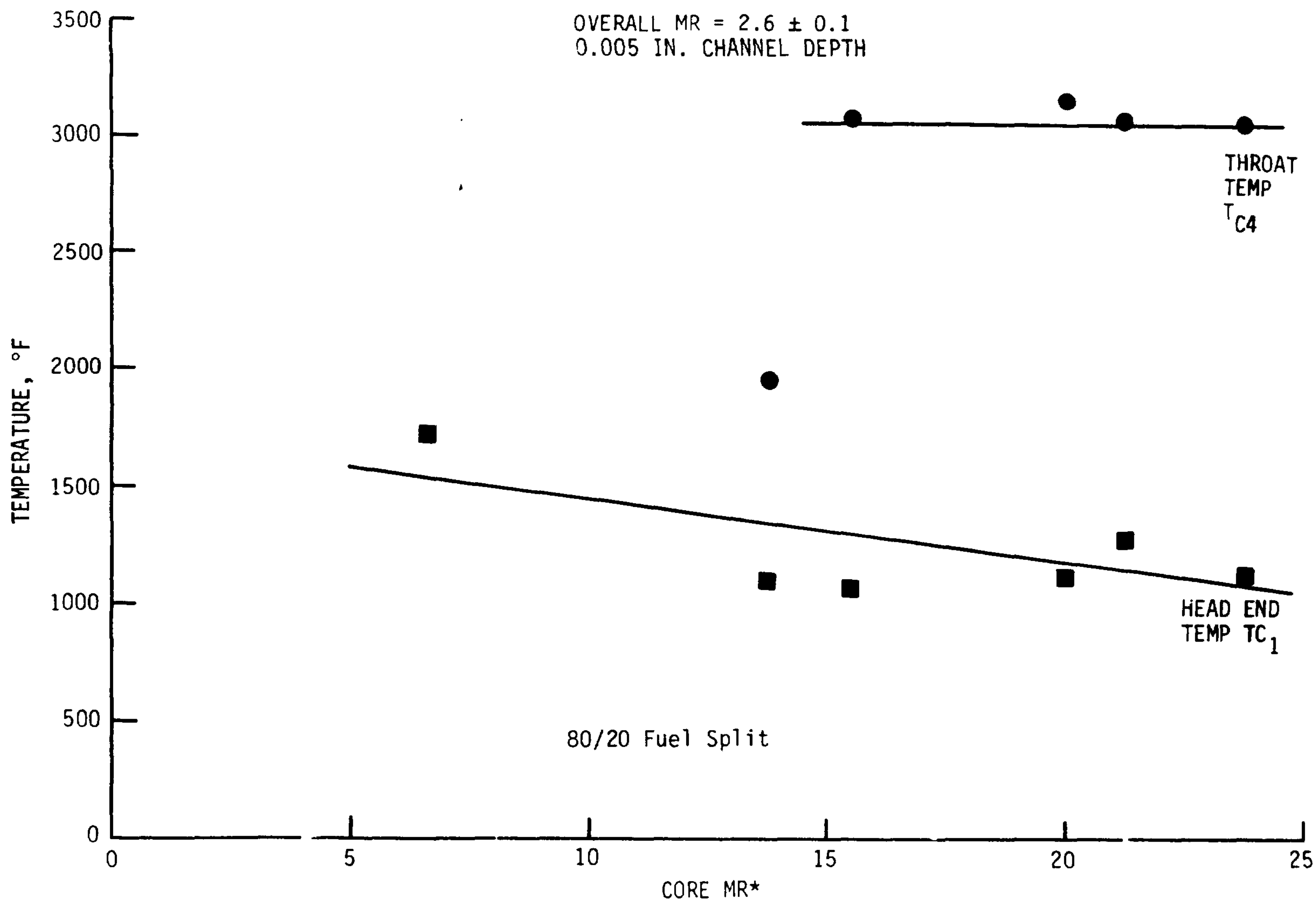

Figure 4.21. Rhenium Chamber Temperatures vs. Core Mixture Ratio

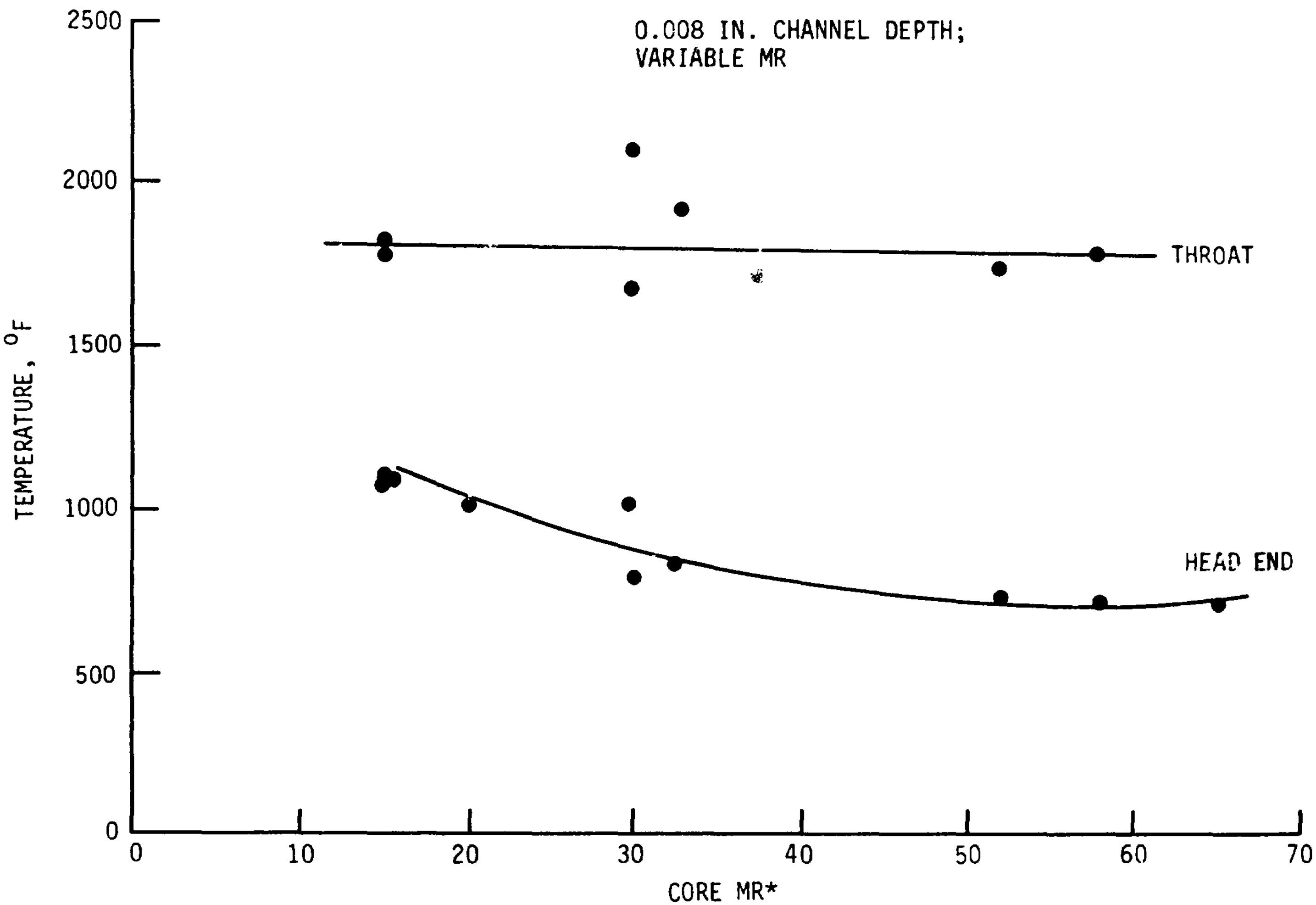

Figure 4.22. Rhenium Chamber Temperatures vs. Core Mixture Ratio - 85/14 Fuel Split

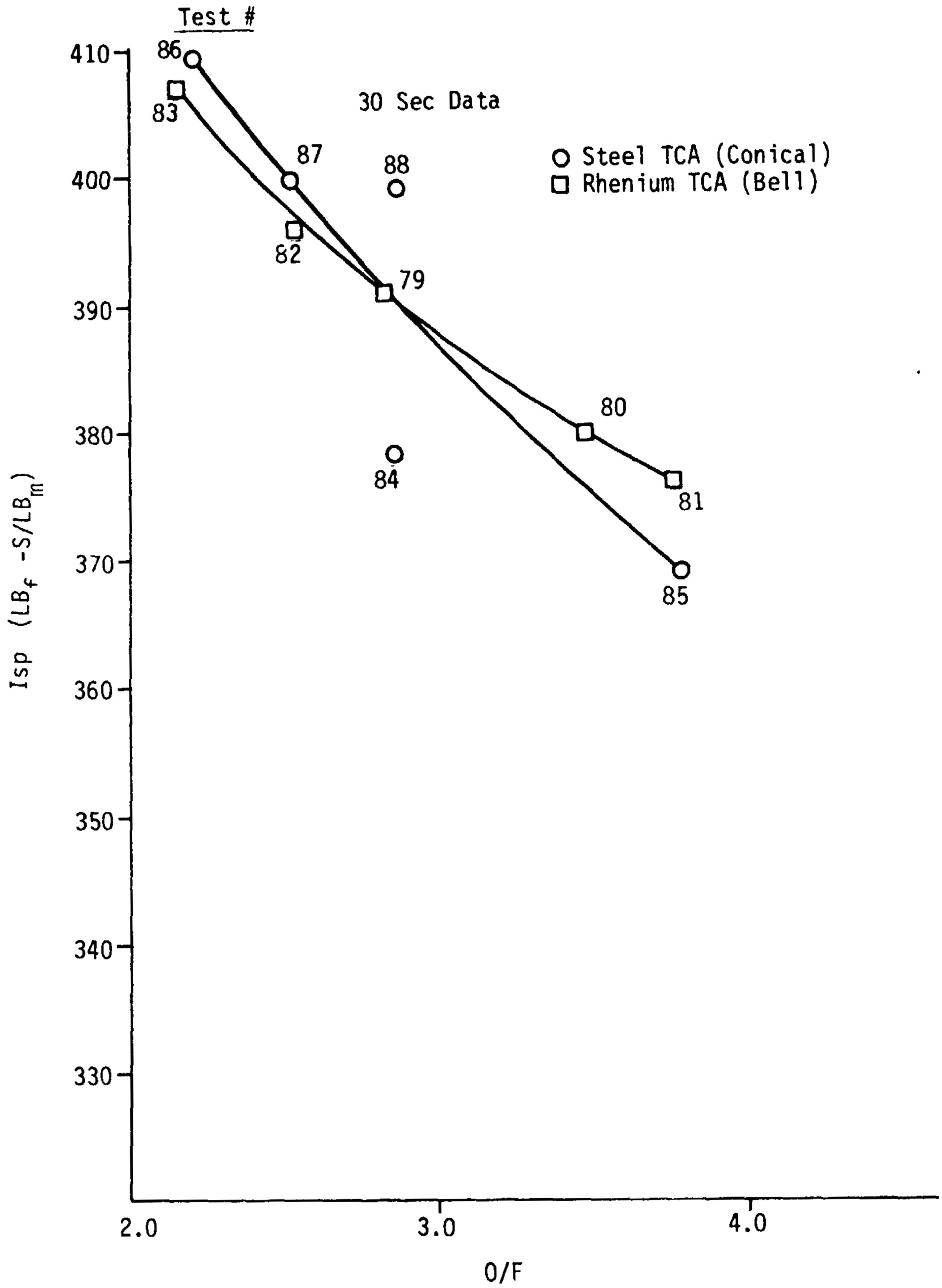

Figure 4.23. Comparison of Bell And Conical Nozzle Performance

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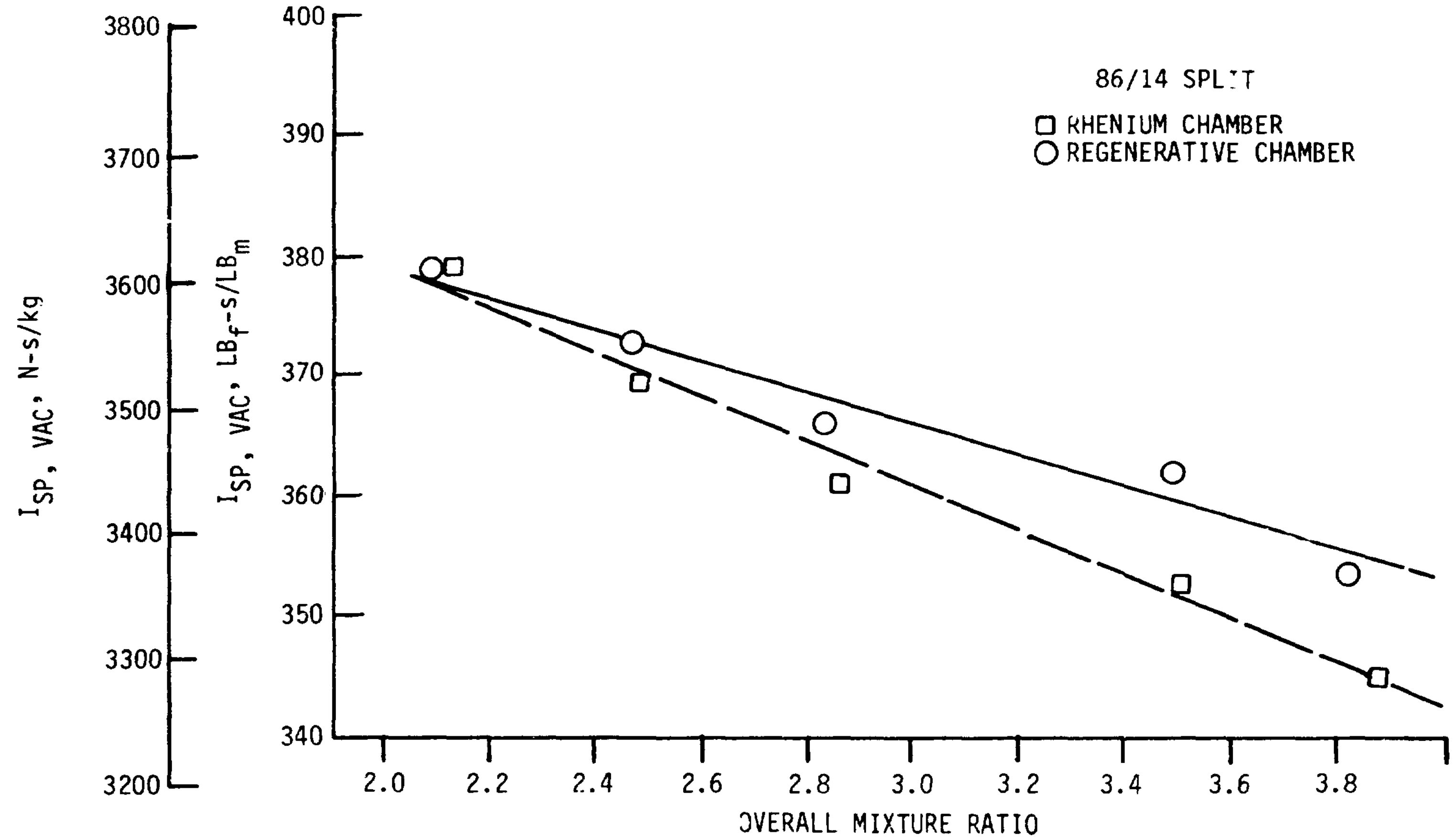


Figure 4.24. Comparison of Rhenium and Regenerative Chamber Performance

5.0 REFERENCES

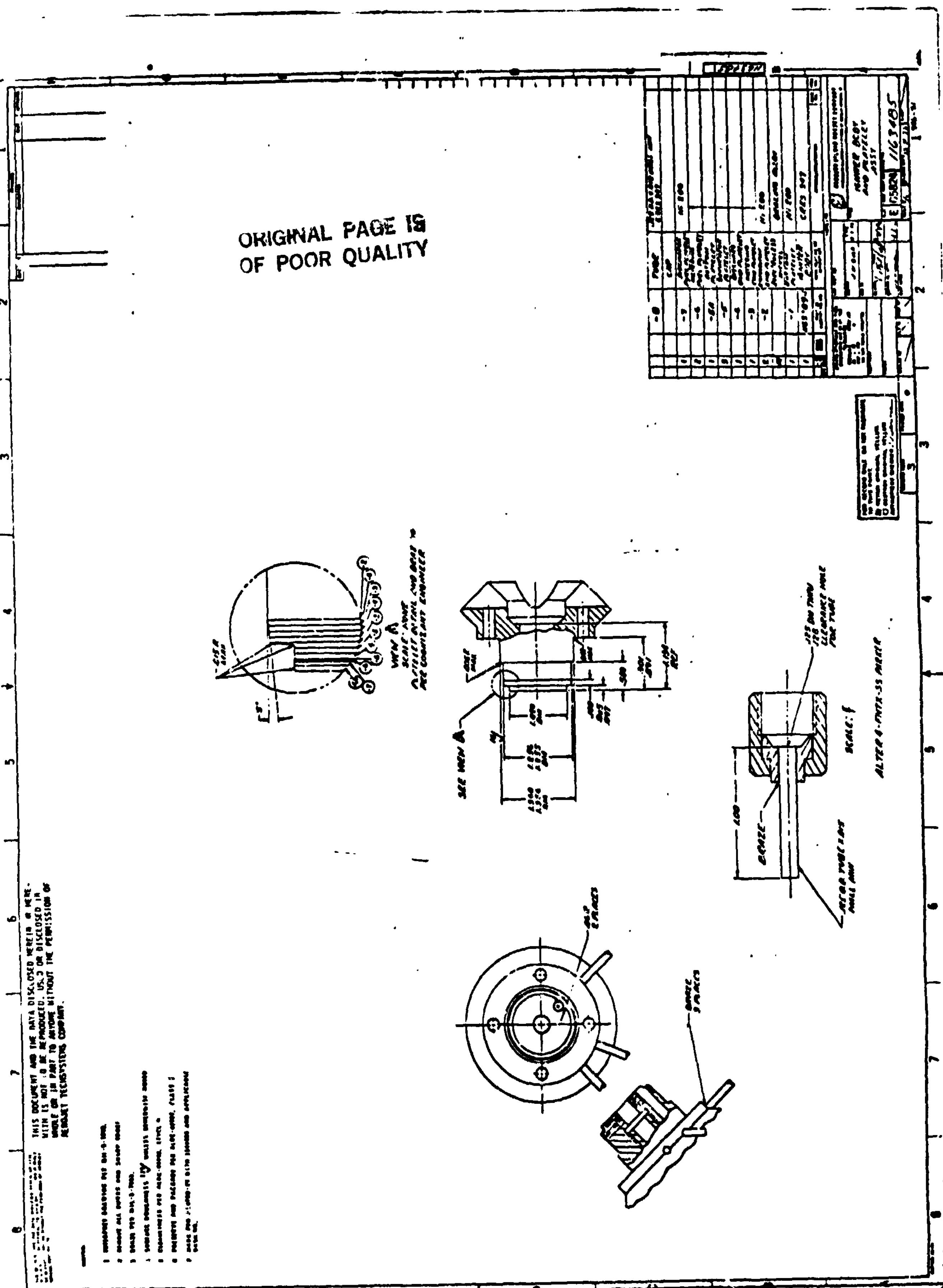
1. Rosenberg, S. D., and Garrison, P. W., "An Integrated Space Station Propulsion System," 1984 Joint Army/Navy/NASA/Air Force (JANNAF) Propulsion Meeting, New Orleans, LA.

2. Blubaugh, A. L., and Schoenman, L., "Extended Temperature Range ACPS Thruster Investigation," NAS CR-134655, August 1974.

3. Appel, M. A., Kaplan, R. E., and Tuffias, R. H., "Liquid Fluorine/Hydrazine Rhenium Thruster Update," 1983 Joint Army/Navy/NASA/Air Force (JANNAF) Propulsion Meeting, Monterey, CA.

APPENDIX A

INJECTOR/IGNITER DESIGN DATA



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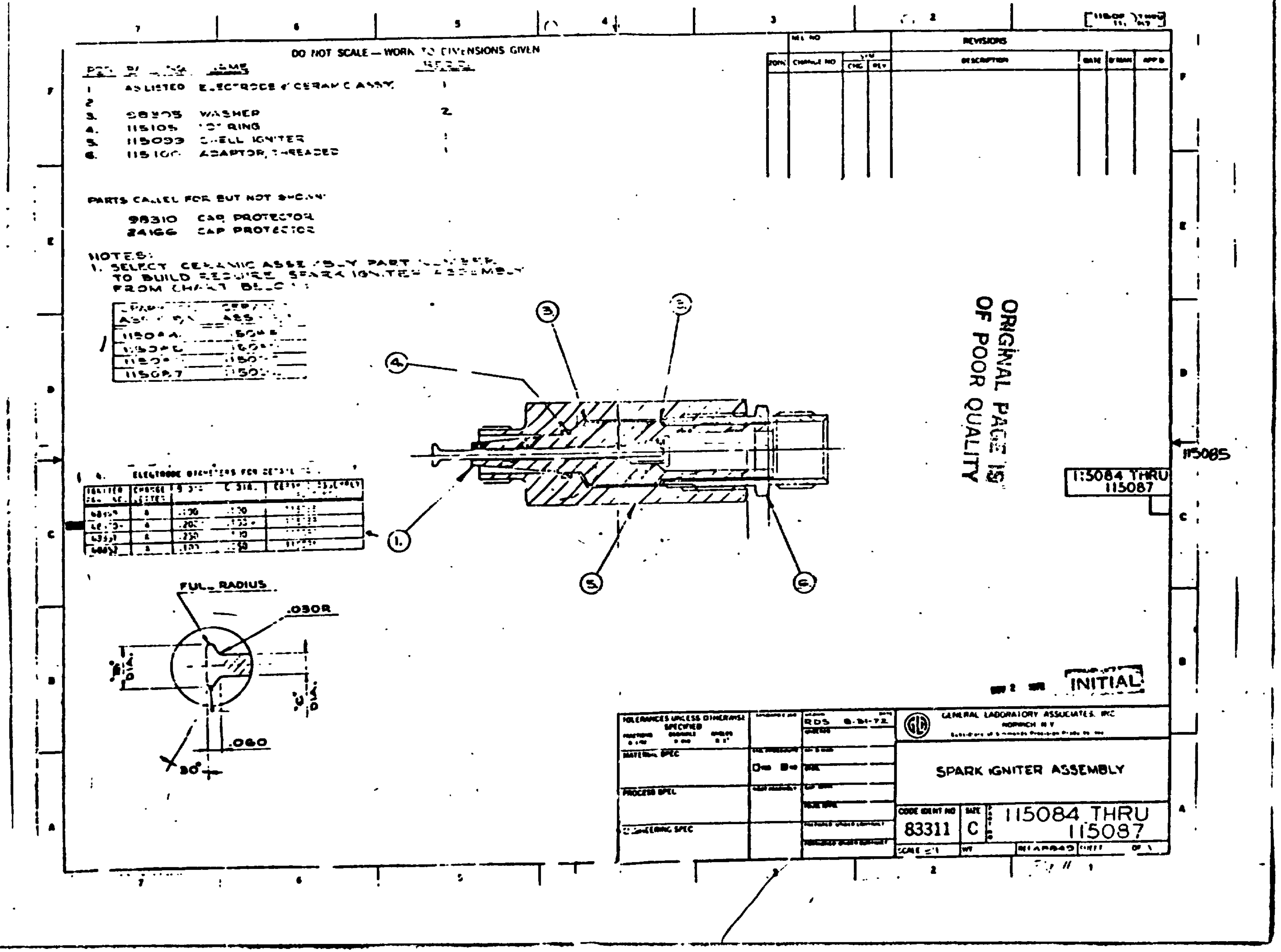
DO NOT SCALE — WORK TO DIMENSIONS GIVEN
1 AS LISTED ELECTRODE & CERAMIC ASSY. 1
3. 98205 WASHER 2
4. 115105 "O" RING
5. 115093 SHELL IGNITER
6. 115100 ADAPTOR, THREADED
PARTS CALLED FOR BUT NOT SHOWN
98310 CAP PROTECTOR
24166 CAP PROTECTOR
NOTES:
1. SELECT CERAMIC ASSEMBLY PART NUMBER TO BUILD REQUIRED SPARK IGNITER ASSEMBLY FROM CHART BELOW
FULL RADIUS
.050R
.060
30°
REVISIONS
DESCRIPTION
115085
115084 THRU 115087
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INITIAL
TOLERANCES UNLESS OTHERWISE SPECIFIED
MATERIAL SPEC
PROCESS SPEC
ENGINEERING SPEC
RDS 8-31-72
GENERAL LABORATORY ASSOCIATES, INC
NORWICH N.Y.
SPARK IGNITER ASSEMBLY
CODE IDENT NO
83311
C
115084 THRU 115087

APPENDIX B

REGENERATIVE CHAMBER DESIGN DATA

REGENERATIVE CHAMBER DESIGN

THERMAL ANALYSIS

The thermal analysis for the regenerative chamber was performed for the nominal operating parameters listed below:

	F	=	45 lbF
	MR	=	5
	Pc	=	500 psia
	Tc	=	6060°F/5600°F
H_2 Coolant	P_{in}	=	900 psia
	T_{in}	=	530°R
Oxygen	P_{in}	=	1200 psia
	T_{in}	=	530°R

The flow rate of the coolant for the analysis is approximately 0.02 lb_m/sec. A coolant temperature rise of 690°F is expected, with a corresponding pressure drop of 50 psi. The analysis optimized (within budgetary limits) the geometry of the channels using improved channel manufacturing capabilities developed under the 1983 IR&D Advanced Regenerative Chamber Technology Program. A diagram of temperature predictions for the regenerative chamber is shown in Figure B.1. The thermal analysis output from the HEAT program is available in Table B.1. The actual channel geometries in the high-area-ratio nozzle have been slightly modified to simplify fabrication, reduce weight, and add a screen within the inlet manifold.

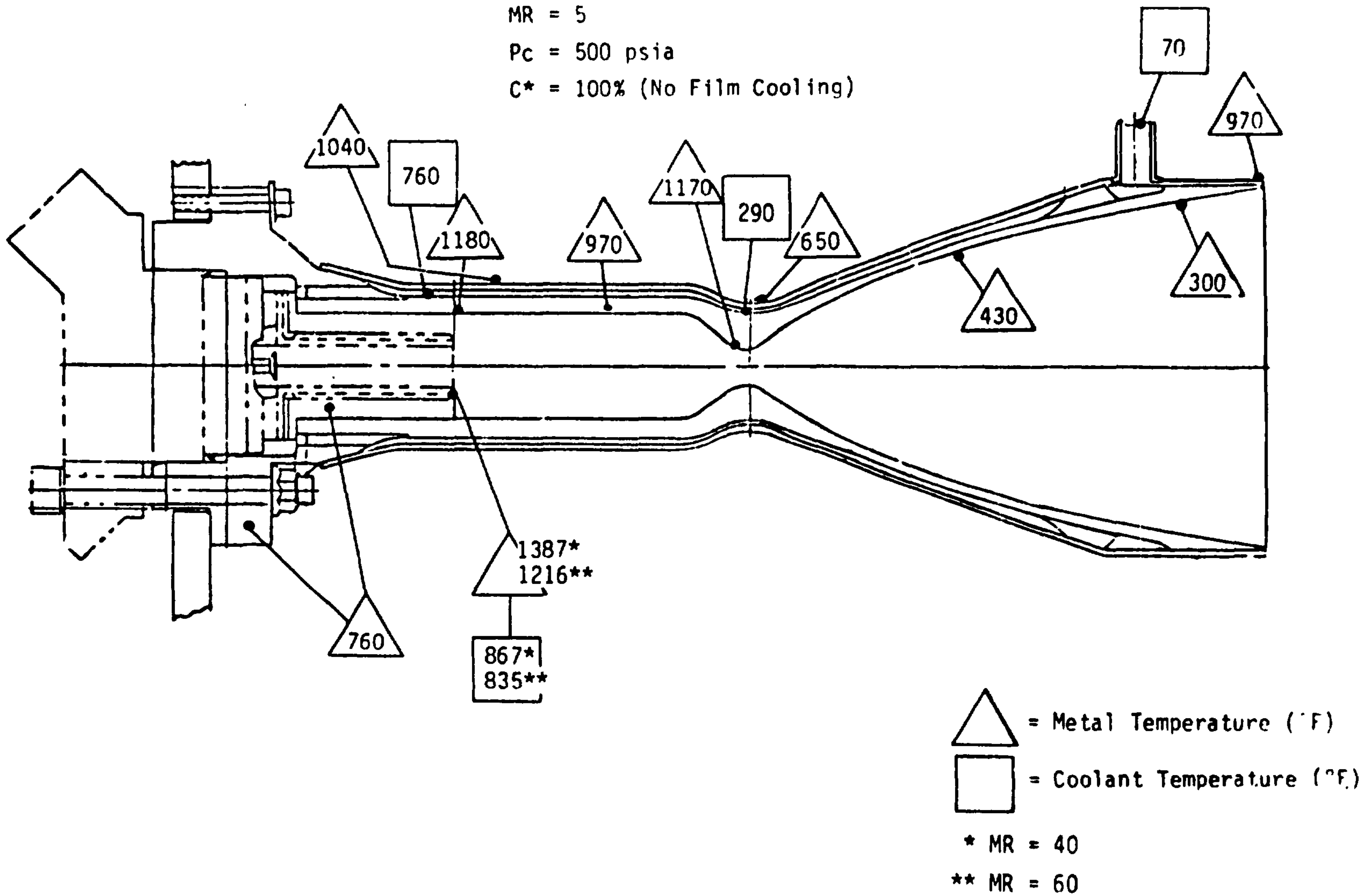
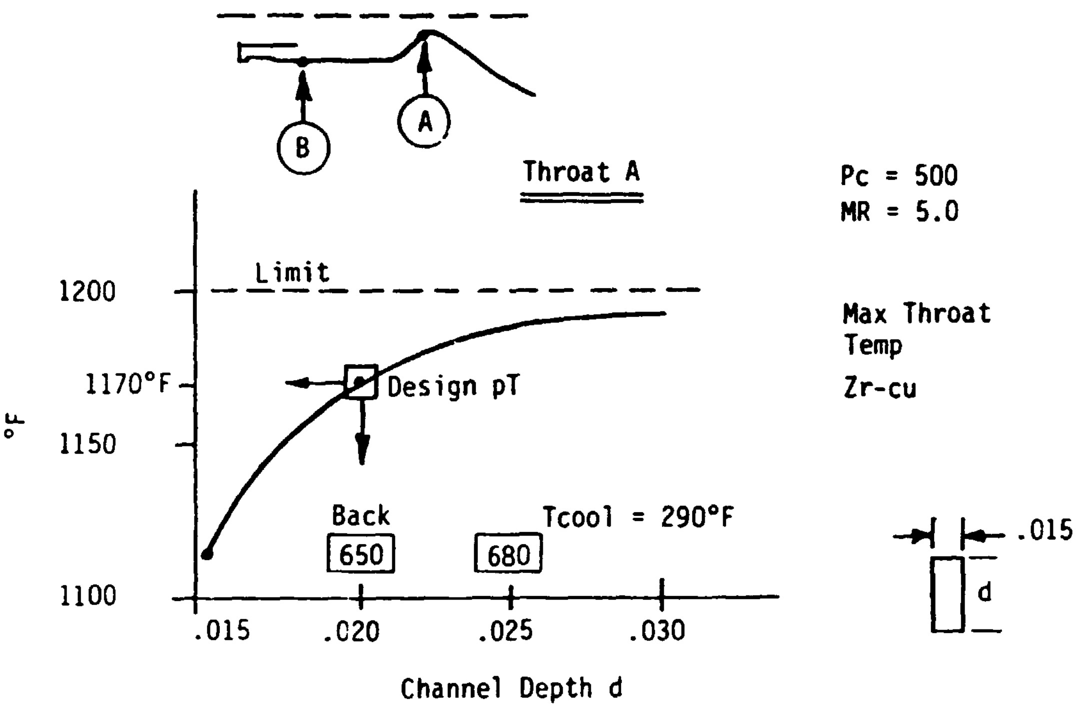


Figure B.1. Regen Chamber Temperature Predictions



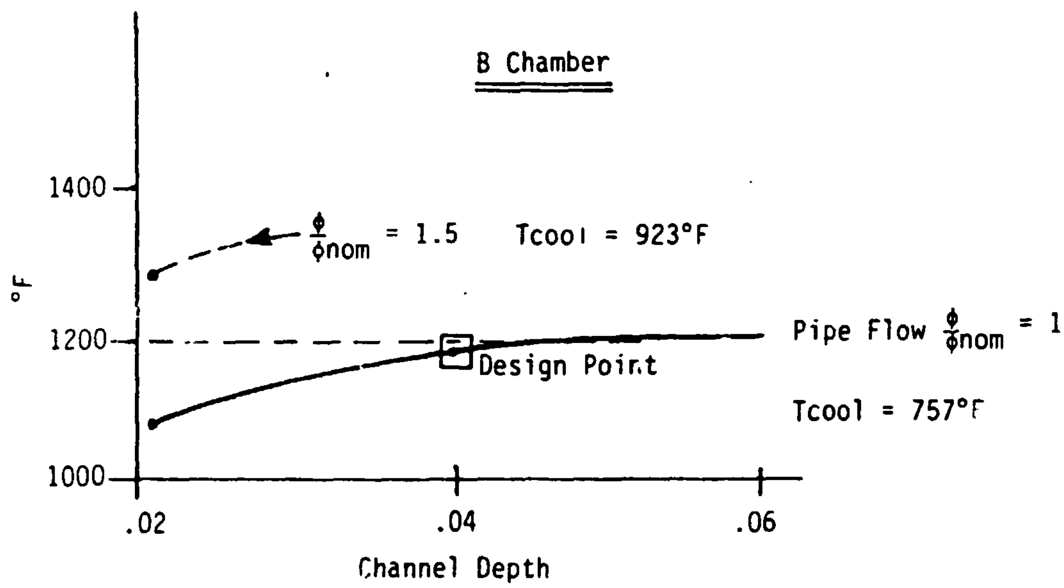


Figure B.2. Chamber Cooling Limits

AEROJET LIQUID ROCKET COMPANY

HEAT

A HEAT TRANSFER ANALYSIS OF REGENERATIVE COOLING

THE STUDY IS FOR

JPL GH2/GO2 THRUSTER

THE COOLANT IS HYDROGEN (AES)   FLOWING IN RECTANGULAR SLOTS

MR= 5.00   PC= 500. PSIA   TC=6060. R   WCTAR= .10 LB/SEC   PIN= 900. PSIA   TIN= 530. R

FLOW SUMMARY TABLE

STATION NO	POS	FLOW RATE	• • • LIQUID • • • PRESSURE	TEMP	VELOCITY	MACH NO.	FILM COEFFICIENTS CLOSURE	GAS	LIQUID	WALL TEMPERATURES LIQUID	METAL	GAS	• • HEAT TRANSFER • • Q/A1	Q/A0	QSUM	QOST
	IN.	LBM/SEC	PSIA	DEG F	FT/SEC		BTU/IN2-SEC-R			DEGREE F			BTU/IN2-SEC		BTU/S	
								HG	HLB	TWLC	TW	TWGS	QA1C	QAC2		
-	INLET	-	900.0	70.3	0.0											
1	3.40	.02	899.7	70.3	73.0	.017	.235-02	.551-04	.234-02	127.7	128.5	130.0	.13	.25	.0000	.000
2	2.36	.02	899.4	108.2	78.0	.017	.233-02	.819-04	.232-02	182.1	183.2	185.4	.17	.37	.2307+01	.000
3	1.65	.02	899.2	138.7	82.6	.018	.235-02	.116-03	.234-02	227.4	228.7	231.7	.21	.51	.4151+01	.000
4	1.19	.02	899.0	166.8	86.1	.018	.234-02	.166-03	.232-02	273.9	275.4	275.7	.25	.72	.5824+01	.000
5	.99	.02	899.0	179.9	87.8	.018	.233-02	.201-03	.230-02	297.8	299.5	304.5	.27	.87	.6620+01	.000
6	.81	.02	898.7	192.6	116.9	.024	.290-02	.244-03	.287-02	322.6	326.2	339.5	.37	.93	.7379+01	.000
7	.65	.02	898.2	205.3	161.7	.033	.374-02	.302-03	.370-02	345.8	358.5	376.1	.52	1.01	.8137+01	.000
8	.50	.02	896.9	218.3	255.9	.051	.541-02	.382-03	.537-02	360.9	387.0	410.3	.77	1.10	.8911+01	.000
9	.34	.02	888.1	233.9	577.1	.115	.109-01	.532-03	.108-01	356.1	403.0	430.9	1.32	1.39	.9838+01	.000
10	.29	.02	886.6	239.6	589.1	.117	.108-01	.608-03	.108-01	367.8	416.1	447.8	1.38	1.52	.1018+02	.000
11	.22	.02	884.8	247.5	596.2	.117	.108-01	.747-03	.108-01	385.1	440.7	472.9	1.48	1.72	.1065+02	.000
12	.17	.02	883.5	252.6	601.6	.118	.102-01	.851-03	.107-01	359.6	460.3	494.4	1.57	1.50	.1101+02	.000
13	.12	.02	882.2	255.5	606.8	.119	.108-01	.108-02	.107-01	414.6	481.6	517.3	1.66	2.10	.1136+02	.000
14	.08	.02	881.2	264.1	611.1	.119	.108-01	.128-02	.106-01	428.2	501.1	538.0	1.75	2.29	.1164+02	.000
15	.05	.02	880.2	268.5	615.1	.119	.108-01	.153-02	.106-01	441.6	521.6	555.1	1.84	2.47	.1150+02	.000
16	.24	.02	879.9	270.0	616.2	.120	.108-01	.164-02	.106-01	446.3	529.1	566.8	1.68	2.54	.1198+02	.000
17	.02	.02	879.5	272.5	618.7	.120	.105-01	.277-02	.102-01	557.2	687.6	745.3	2.90	4.30	.1213+02	.000
18	.00	.02	879.0	275.9	621.7	.120	.103-01	.229-02	.100-01	614.0	767.0	834.1	3.29	4.65	.1233+02	.000
19	-.09	.02	876.8	298.3	635.1	.122	.101-01	.386-02	.974-02	731.0	916.8	1303.8	4.24	5.61	.1348+02	.000
20	-.16	.02	874.2	322.7	664.7	.125	.967-02	.431-02	.941-02	912.8	1139.4	1259.3	5.55	7.26	.1511+02	.000
21	-.19	.02	872.9	337.4	679.1	.126	.985-02	.342-02	.966-02	863.6	1064.1	1174.6	5.08	6.41	.1598+02	.000
22	-.22	.02	871.7	350.8	685.4	.127	.957-02	.280-02	.981-02	832.5	1005.2	1107.0	4.73	5.86	.1677+02	.000
23	-.26	.02	870.6	362.2	696.5	.128	.100-01	.235-02	.989-02	814.9	955.3	1047.6	4.47	5.55	.1750+02	.000
24	-.29	.02	869.5	374.8	703.1	.128	.101-01	.199-02	.997-02	798.6	911.6	993.7	4.22	5.28	.1819+02	.000
25	-.32	.02	868.4	385.6	709.3	.129	.101-01	.170-02	.100-01	781.1	870.5	941.6	3.97	4.55	.1883+02	.000
26	-.35	.02	870.9	394.2	593.1	.107	.863-02	.152-02	.852-02	798.1	865.2	927.8	3.44	4.76	.1933+02	.000

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27	-.38	.02	872.3	422.3	510.5	.052	.755-02	.129-02	.744-02	810.6	862.7	918.6	3.04	4.60	.1982+02	.000
28	-.41	.02	873.2	410.3	445.6	.061	.673-02	.131-02	.662-02	821.6	864.1	915.1	2.72	4.48	.2025+02	.000
29	-.45	.02	873.8	418.0	402.8	.072	.609-02	.127-02	.599-02	833.4	869.7	917.7	2.49	4.41	.2075+02	.000
30	-.48	.02	874.2	425.7	365.5	.065	.557-02	.125-02	.547-02	847.1	880.1	927.0	2.30	4.38	.2120+02	.000
31	-.73	.02	872.7	461.0	388.1	.067	.567-02	.125-02	.558-02	891.4	924.1	970.7	2.29	4.34	.2447+02	.000
32	-.98	.02	871.2	536.2	411.9	.070	.578-02	.125-02	.569-02	935.7	966.2	1014.3	2.27	4.30	.2775+02	.000
33	-1.24	.02	869.6	591.5	434.3	.072	.587-02	.125-02	.578-02	981.6	1013.9	1059.6	2.26	4.25	.3102+02	.000
34	-1.49	.02	867.9	646.7	458.4	.074	.596-02	.125-02	.588-02	1027.3	1059.3	1104.6	2.24	4.21	.3430+02	.000
35	-1.74	.02	866.2	701.8	480.9	.075	.604-02	.125-02	.597-02	1073.6	1105.5	1150.3	2.22	4.17	.3757+02	.000
36	-1.99	.02	864.4	756.9	504.8	.077	.614-02	.125-02	.607-02	1119.8	1151.4	1195.8	2.20	4.13	.4085+02	.000
37	-2.24	.02	862.5	811.5	528.2	.079	.622-02	.125-02	.614-02	1167.1	1156.4	1242.4	2.18	4.06	.4412+02	.000
38	-2.50	.02	860.5	866.9	551.5	.081	.628-02	.125-02	.620-02	1215.3	1246.3	1289.9	2.16	4.04	.4739+02	.000
39	-2.75	.02	858.4	921.9	573.9	.082	.634-02	.125-02	.628-02	1262.8	1293.6	1336.7	2.14	3.59	.5067+02	.000
40	-3.00	.02	856.3	976.8	598.2	.084	.643-02	.125-02	.637-02	1309.8	1340.3	1383.0	2.12	3.55	.5394+02	.000
-	EXIT	-	856.3	976.8	0.0											

STATION NO	POS	AREA RATIO	• • • •TEMPERATURES• • • • GAS RECOVERY	GAS FILM	COOLANT FILM	• • •PRESSURE LOSSES• • • FRICT DROP	DYNAM DROP	TURN LOSS	•••• WALL = 5 •••• T3	TINT	TBS	TWL2	TWG2	QAO2	QAI2
	IN		DEGREE F			PSI			-•	DEGREE F				••• • BTU/IN2-SEC ••	
1	3.40	100.00	4903.2	2516.6	59.0	.00	.18	.00	127.0	123.6	123.5	127.7	130.1	.26	.13
2	2.36	73.27	4928.0	2556.8	145.2	.28	.02	.00	180.9	175.9	175.8	182.1	185.5	.39	.17
3	1.69	52.27	4954.9	2593.4	183.1	.19	.02	.00	225.4	218.2	218.1	227.4	231.5	.55	.21
4	1.19	35.52	4984.7	2632.4	220.3	.16	.02	.00	270.7	260.3	260.1	273.9	280.0	.78	.25
5	.99	28.62	5001.6	2652.3	236.5	.07	.01	.00	293.7	281.0	280.9	297.8	305.0	.94	.27
6	.81	22.56	5019.5	2680.7	257.7	.08	.16	.00	314.1	303.5	303.3	322.8	342.0	1.14	.37
7	.65	17.22	5040.4	2711.8	275.6	.14	.34	.00	333.8	325.4	325.1	345.8	383.1	1.41	.52
8	.50	12.46	5065.3	2744.9	289.6	.32	1.04	.00	350.6	344.6	344.2	360.9	424.5	1.78	.77
9	.34	7.78	5102.1	2777.3	257.4	1.92	6.87	.00	357.6	354.0	353.2	356.1	452.6	2.47	1.32
10	.29	6.35	5116.0	2795.6	303.7	1.17	.25	.00	366.5	362.0	362.1	367.8	473.3	2.83	1.38
11	.22	4.58	5143.6	2824.6	316.3	1.56	.21	.00	375.5	375.0	374.1	385.1	505.4	3.46	1.48
12	.17	3.42	5166.7	2850.4	326.6	1.20	.16	.00	389.2	384.1	383.2	399.6	534.1	4.13	1.57
13	.12	2.50	5192.6	2875.3	337.3	1.12	.15	.00	398.4	392.6	391.7	414.8	566.1	4.58	1.66
14	.08	1.85	5216.4	2906.5	346.2	.89	.13	.00	405.5	399.2	398.3	428.2	596.5	5.52	1.75
15	.05	1.35	5244.3	2936.7	355.1	.83	.12	.00	411.8	404.8	403.9	441.6	629.0	7.08	1.84
16	.04	1.19	5254.2	2947.9	355.8	.28	.03	.00	413.6	406.3	405.4	446.3	641.5	7.58	1.88
17	.02	1.04	5325.6	3116.5	414.8	.27	.07	.00	500.8	485.4	487.8	557.2	867.4	12.47	2.98
18	.00	1.00	5472.0	3230.5	441.5	.27	.05	.00	546.1	532.5	530.8	614.0	975.0	14.83	3.39
19	-.09	1.26	5560.3	3375.9	533.2	1.73	.51	.00	654.5	638.0	635.5	731.0	1171.5	17.02	4.24
20	-.16	2.15	5594.7	3515.2	617.7	1.79	.75	.00	842.9	823.8	820.5	912.9	1435.6	17.94	5.55
21	-.19	2.82	5556.0	3456.4	666.5	.88	.43	.00	816.7	795.3	796.2	863.6	1316.8	14.64	5.08
22	-.22	3.59	5597.5	3408.1	591.6	.89	.35	.00	758.1	787.4	779.4	832.5	1216.6	12.25	4.73
23	-.26	4.44	5599.2	3364.4	589.1	.90	.21	.00	785.8	770.9	768.0	814.9	1129.6	10.48	4.47
24	-.29	5.36	5600.3	3326.5	586.7	.50	.19	.00	774.2	759.9	757.1	798.6	1052.7	9.06	4.22
25	-.32	6.41	5600.3	3291.5	583.3	.50	.18	.00	761.0	747.5	744.9	781.1	982.8	7.85	3.97
26	-.35	7.27	5600.3	3275.1	596.1	.62	-2.08	.00	772.1	756.6	754.3	798.1	957.5	7.05	3.44
27	-.38	7.99	5600.3	3271.0	606.5	.41	-1.83	.00	781.7	764.2	762.2	810.6	941.6	6.59	3.04
28	-.41	8.54	5600.3	3267.1	616.0	.29	-1.17	.00	791.1	771.5	769.7	821.7	933.9	6.13	2.73
29	-.45	8.88	5600.3	3267.3	625.7	.22	-.80	.00	801.1	779.5	777.9	833.4	934.2	5.92	2.49
30	-.48	9.00	5600.3	3271.6	636.4	.17	-.50	.00	812.6	788.8	787.2	847.2	942.8	5.84	2.31
31	-.73	9.00	5600.3	3292.3	666.3	1.12	.32	.00	857.3	833.7	832.2	891.4	986.3	5.76	2.29
32	-.98	9.00	5600.3	3315.1	726.0	1.19	.34	.00	902.0	878.6	877.1	935.8	1025.6	5.73	2.27
33	-1.24	9.00	5600.3	3337.6	786.6	1.26	.32	.00	948.3	925.1	923.7	981.6	1074.9	5.67	2.26

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34	-1.49	9.00	5600.3	3360.1	637.0	1.34	.34	.00	994.4	971.4	975.0	1027.3	1119.8	5.62	2.24
35	-1.74	9.00	5600.3	3382.0	807.8	1.41	.22	.00	1041.2	1016.5	1017.1	1073.7	1165.4	5.56	2.22
36	-1.99	9.00	5600.3	3405.5	528.4	1.49	.24	.00	1087.8	1065.2	1063.9	1119.5	1210.7	5.50	2.20
37	-2.24	9.00	5600.3	3426.7	589.5	1.57	.24	.00	1135.4	1113.1	1111.0	1167.1	1257.1	5.44	2.18
38	-2.50	9.00	5600.3	3452.4	1041.1	1.64	.23	.00	1164.0	1161.9	1160.6	1215.4	1304.5	5.38	2.16
39	-2.75	9.00	5600.3	3475.7	1092.4	1.72	.32	.00	1231.9	1210.1	1208.9	1262.9	1351.2	5.33	2.14
40	-3.00	9.00	5600.3	3456.6	1142.2	1.80	.25	.00	1279.3	1257.7	1256.4	1309.8	1397.2	5.27	2.12

GEOMETRY SUMMARY TABLE

ALL INCHES

STATION NO	POS	NUMBER CHANNELS	DEPTH	WIDTH	EQ DIA	EFF SLR AREA	LEG SPREAD	HEIGHT (L.WDTH)	RG	RA	WALL THICKNESS	COATING THICKNESS	SPACE	UNCEF DIA	FLOW AREA	AREA RATIO	DEV LENGTH
			. . . . . .	. . .	. . CHANNEL	GEOMETRY	. . .				. . . .	. . . .	. . . . . .				
1	3.40	60	.120	.015	.0268	.000	.000	.122	.000	.000	.0600	.0000	.0000	.0000	.001812	100.00	3.62
2	2.36	60	.120	.015	.0268	.000	.000	.102	.000	.000	.0600	.0000	.0000	.0000	.001812	73.27	2.56
3	1.69	60	.120	.015	.0268	.000	.000	.086	.000	.000	.0600	.0000	.0000	.0000	.001812	52.27	1.87
4	1.19	60	.120	.015	.0268	.000	.000	.065	.000	.000	.0600	.0000	.0000	.0000	.001812	35.52	1.35
5	.99	60	.120	.015	.0268	.000	.000	.061	.000	.000	.0600	.0000	.0000	.0000	.001812	28.62	1.13
6	.81	60	.052	.015	.0255	.000	.000	.061	.000	.000	.1321	.0000	.0000	.0000	.001326	22.56	.94
7	.65	60	.048	.015	.0246	.000	.000	.061	.000	.000	.2667	.0000	.0000	.0000	.001022	17.22	.76
8	.50	60	.044	.015	.0224	.000	.000	.060	.000	.000	.2700	.0000	.0000	.0000	.000660	12.46	.60
9	.34	60	.020	.015	.0171	.000	.000	.050	.000	.000	.2700	.0000	.0000	.0000	.000300	7.78	.41
10	.29	60	.020	.015	.0171	.000	.000	.046	.000	.000	.2700	.0000	.0000	.0000	.000300	6.35	.35
11	.22	60	.020	.015	.0171	.000	.000	.041	.000	.000	.2700	.0000	.0000	.0000	.000300	4.58	.26
12	.17	60	.020	.015	.0171	.000	.000	.038	.000	.000	.2700	.0000	.0000	.0000	.000300	3.42	.20
13	.12	60	.020	.015	.0171	.000	.000	.034	.000	.000	.2700	.0000	.0000	.0000	.000300	2.50	.14
14	.08	60	.020	.015	.0171	.000	.000	.031	.000	.000	.2700	.0000	.0000	.0000	.000300	1.85	.10
15	.05	60	.020	.015	.0171	.000	.000	.028	.000	.000	.2700	.0000	.0000	.0000	.000300	1.35	.05
16	.04	60	.020	.015	.0171	.000	.000	.028	.000	.000	.2700	.0000	.0000	.0000	.000300	1.19	.04
17	.02	60	.020	.015	.0171	.000	.000	.027	.000	.000	.2700	.0000	.0000	.0000	.000300	1.04	.02
18	.00	60	.020	.015	.0171	.000	.000	.026	.000	.000	.2700	.0000	.0000	.0000	.000300	1.00	.00
19	-.09	60	.020	.015	.0171	.000	.000	.028	.000	.000	.2700	.0000	.0000	.0000	.000300	1.26	-.09
20	-.16	60	.020	.015	.0171	.000	.000	.033	.000	.000	.2700	.0000	.0000	.0000	.000300	2.15	-.17
21	-.19	60	.020	.015	.0171	.000	.000	.035	.000	.000	.2700	.0000	.0000	.0000	.000300	2.82	-.22
22	-.22	60	.020	.015	.0172	.000	.000	.037	.000	.000	.2597	.0000	.0000	.0000	.000301	3.59	-.26
23	-.26	60	.020	.015	.0172	.000	.000	.037	.000	.000	.2328	.0000	.0000	.0000	.000302	4.44	-.30
24	-.29	60	.020	.015	.0173	.000	.000	.037	.000	.000	.2075	.0000	.0000	.0000	.000303	5.39	-.34
25	-.32	60	.020	.015	.0173	.000	.000	.037	.000	.000	.1820	.0000	.0000	.0000	.000305	6.41	-.38
26	-.35	60	.024	.015	.0187	.000	.000	.037	.000	.000	.1620	.0000	.0000	.0000	.000367	7.27	-.42
27	-.38	60	.028	.015	.0198	.000	.000	.037	.000	.000	.1461	.0000	.0000	.0000	.000430	7.99	-.45
28	-.41	60	.032	.015	.0208	.000	.000	.037	.000	.000	.1344	.0000	.0000	.0000	.000492	8.54	-.49
29	-.45	60	.036	.015	.0216	.000	.000	.037	.000	.000	.1274	.0000	.0000	.0000	.000554	8.88	-.52
30	-.48	60	.040	.015	.0222	.000	.000	.037	.000	.000	.1250	.0000	.0000	.0000	.000616	9.00	-.56
31	-.73	60	.040	.015	.0222	.000	.000	.037	.000	.000	.1250	.0000	.0000	.0000	.000616	9.00	-.81
32	-.98	60	.040	.015	.0222	.000	.000	.037	.000	.000	.1250	.0000	.0000	.0000	.000616	9.00	-1.06
33	-1.24	60	.040	.015	.0222	.000	.000	.037	.000	.000	.1250	.0000	.0000	.0000	.000616	9.00	-1.31
34	-1.49	60	.040	.015	.0222	.000	.000	.037	.000	.000	.1250	.0000	.0000	.0000	.000616	9.00	-1.56
35	-1.74	60	.040	.015	.0222	.000	.000	.037	.000	.000	.1250	.0000	.0000	.0000	.000616	9.00	-1.82

03/02 JELOPU 04/7AA/E3 ALFC 3 3. DATE 030283

37	-2.24	60	.040	.015	.0222	.000	.000	.037	.000	.000	.1250	.0000	.0000	.0000	.000616	5.00 -2.32
38	-2.50	60	.040	.015	.0222	.000	.000	.037	.000	.000	.1250	.0000	.0000	.0000	.000616	5.00 -2.57
39	-2.75	60	.040	.015	.0222	.000	.000	.037	.000	.000	.1250	.0000	.0000	.0000	.000616	5.00 -2.82
40	-3.00	60	.040	.015	.0222	.000	.000	.037	.000	.000	.1250	.0000	.0000	.0000	.000616	5.00 -3.08

PROPERTY SUMMARY TABLE

RHO=LBM/FT3 MU=LBM/IN-SEC K=BTU/IN-SEC-R CP=BTU/LBM-R TEMP=F

STATION NO	POS	RHOR	RHOF	RHOW	MUP	MUF	MUW	KR	KF	CFB	CPF	TSAT	CAS CBF	CPF	RHCF MUF	KF	WALL KP KC	RADIATION F	FEFV
1	3.40	.309	.294	.279	.49-06	.51-06	.52-06	.26-05	.27-05	3.60	3.57	-399.8	.00000	.0	-0.00	.00	.49-02.00	....	.00
2	2.36	.285	.270	.256	.51-06	.53-06	.55-06	.27-05	.28-05	3.56	3.53	-399.8	.00000	.0	-0.00	.00	.45-02.00	....	.00
3	1.69	.273	.256	.239	.53-06	.55-06	.57-06	.28-05	.29-05	3.53	3.52	-399.8	.00000	.0	-0.00	.00	.45-02.00	....	.00
4	1.19	.262	.242	.225	.54-06	.57-06	.60-06	.28-05	.30-05	3.52	3.50	-399.8	.00000	.0	-0.00	.00	.49-02.00	....	.00
5	.99	.257	.235	.218	.55-06	.58-06	.61-06	.29-05	.30-05	3.52	3.49	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
6	.81	.252	.229	.211	.56-06	.59-06	.62-06	.29-05	.31-05	3.51	3.49	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
7	.65	.247	.224	.204	.56-06	.60-06	.64-06	.29-05	.31-05	3.51	3.49	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.09
8	.53	.242	.220	.201	.57-06	.61-06	.64-06	.30-05	.32-05	3.50	3.49	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
9	.34	.236	.217	.201	.58-06	.61-06	.64-06	.30-05	.32-05	3.50	3.48	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
10	.29	.231	.213	.197	.58-06	.61-06	.65-06	.30-05	.32-05	3.45	3.48	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
11	.22	.228	.205	.193	.58-06	.62-06	.66-06	.31-05	.32-05	3.49	3.48	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
12	.17	.226	.206	.185	.59-06	.63-06	.66-06	.31-05	.33-05	3.45	3.48	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
13	.12	.224	.202	.185	.59-06	.63-06	.67-06	.31-05	.33-05	3.45	3.48	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
14	.06	.223	.200	.182	.59-06	.64-06	.68-06	.31-05	.33-05	3.49	3.48	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.09
15	.05	.221	.198	.179	.59-06	.64-06	.69-06	.31-05	.33-05	3.49	3.48	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
16	.04	.221	.158	.179	.60-06	.64-06	.69-06	.31-05	.34-05	3.45	3.48	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.09
17	.02	.220	.185	.155	.60-06	.67-06	.74-06	.31-05	.35-05	3.45	3.48	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
18	.00	.219	.179	.152	.60-06	.65-06	.77-06	.31-05	.36-05	3.45	3.46	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
19	-.09	.213	.166	.136	.61-06	.72-06	.82-06	.32-05	.38-05	3.48	3.48	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
20	-.16	.205	.150	.118	.62-06	.77-06	.90-06	.33-05	.40-05	3.48	3.49	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
21	-.19	.201	.152	.122	.63-06	.76-06	.88-06	.33-05	.40-05	3.48	3.49	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
22	-.22	.197	.152	.125	.64-06	.76-06	.87-06	.33-05	.40-05	3.48	3.49	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
23	-.26	.194	.153	.126	.64-06	.76-06	.86-06	.34-05	.40-05	3.48	3.49	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
24	-.29	.191	.153	.128	.65-06	.76-06	.85-06	.34-05	.40-05	3.48	3.49	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
25	-.32	.189	.154	.130	.66-06	.76-06	.85-06	.34-05	.40-05	3.48	3.49	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
26	-.35	.188	.152	.128	.66-06	.76-06	.85-06	.35-05	.40-05	3.48	3.49	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.09
27	-.38	.186	.151	.127	.66-06	.77-06	.86-06	.35-05	.40-05	3.48	3.49	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.09
28	-.41	.185	.150	.126	.67-06	.77-06	.86-06	.35-05	.40-05	3.48	3.49	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
29	-.45	.183	.149	.125	.67-06	.78-06	.87-06	.35-05	.41-05	3.48	3.49	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
30	-.48	.181	.147	.124	.68-06	.78-06	.87-06	.35-05	.41-05	3.48	3.49	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
31	-.73	.171	.141	.123	.71-06	.80-06	.85-06	.37-05	.42-05	3.48	3.49	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.09
32	-.96	.161	.135	.116	.72-06	.83-06	.91-06	.38-05	.44-05	3.45	3.49	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.09
33	-1.24	.153	.129	.112	.76-06	.85-06	.94-06	.40-05	.45-05	3.49	3.50	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
34	-1.49	.145	.124	.108	.78-06	.87-06	.96-06	.41-05	.46-05	3.45	3.50	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
35	-1.74	.138	.115	.105	.81-06	.85-06	.98-06	.43-05	.47-05	3.49	3.50	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
36	-1.99	.131	.115	.102	.82-06	.92-06	.95-06	.44-05	.49-05	3.50	3.50	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
37	-2.24	.126	.111	.099	.86-06	.94-06	.10-05	.45-05	.50-05	3.50	3.51	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
38	-2.50	.120	.106	.096	.88-06	.96-06	.10-05	.47-05	.51-05	3.50	3.52	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
39	-2.75	.116	.103	.093	.91-06	.98-06	.11-05	.48-05	.53-05	3.50	3.53	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00
40	-3.00	.111	.099	.090	.93-06	.10-05	.11-05	.50-05	.54-05	3.51	3.54	-399.8	.00000	.0	-0.00	.00	.50-02.00	....	.00

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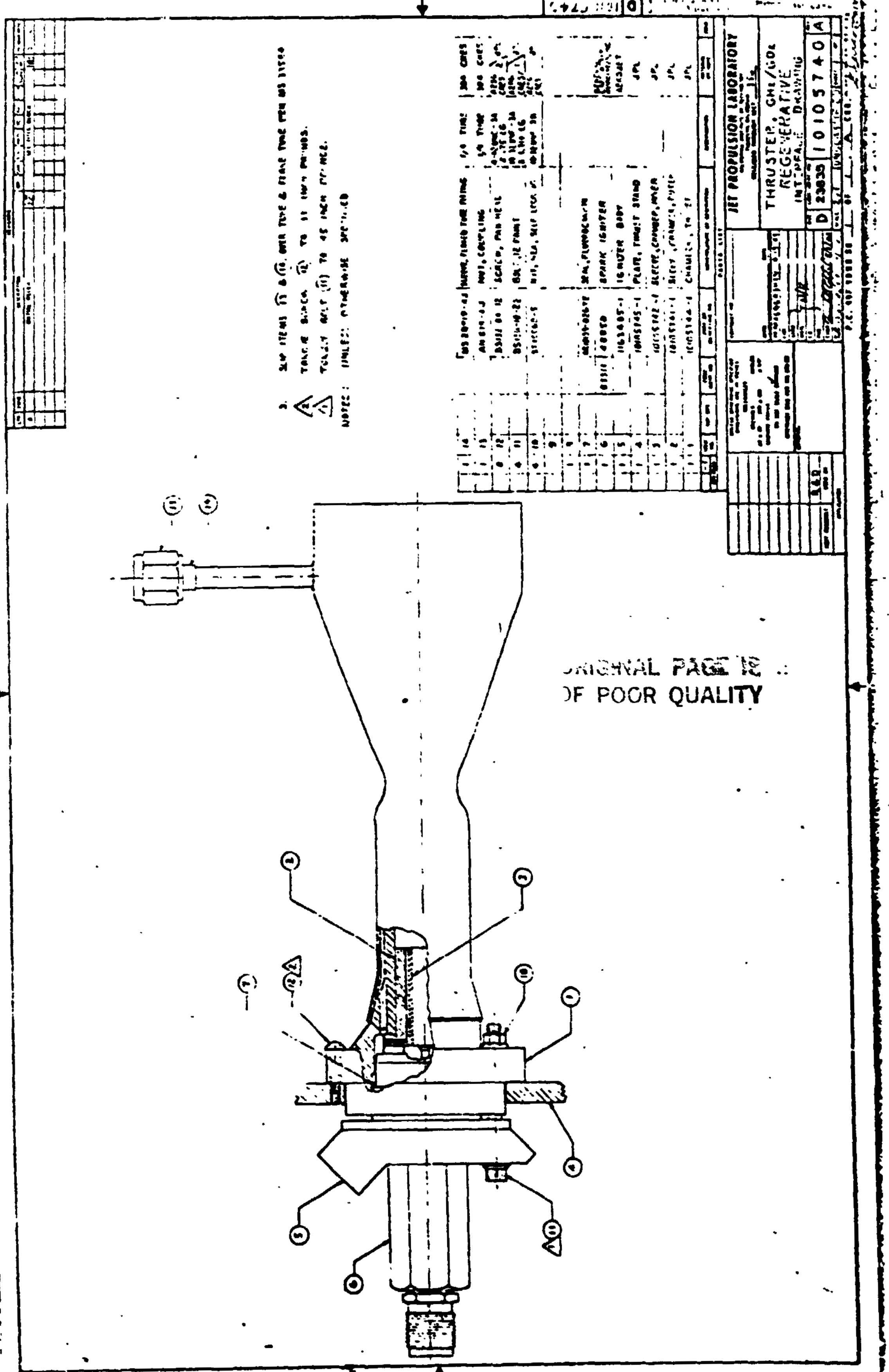

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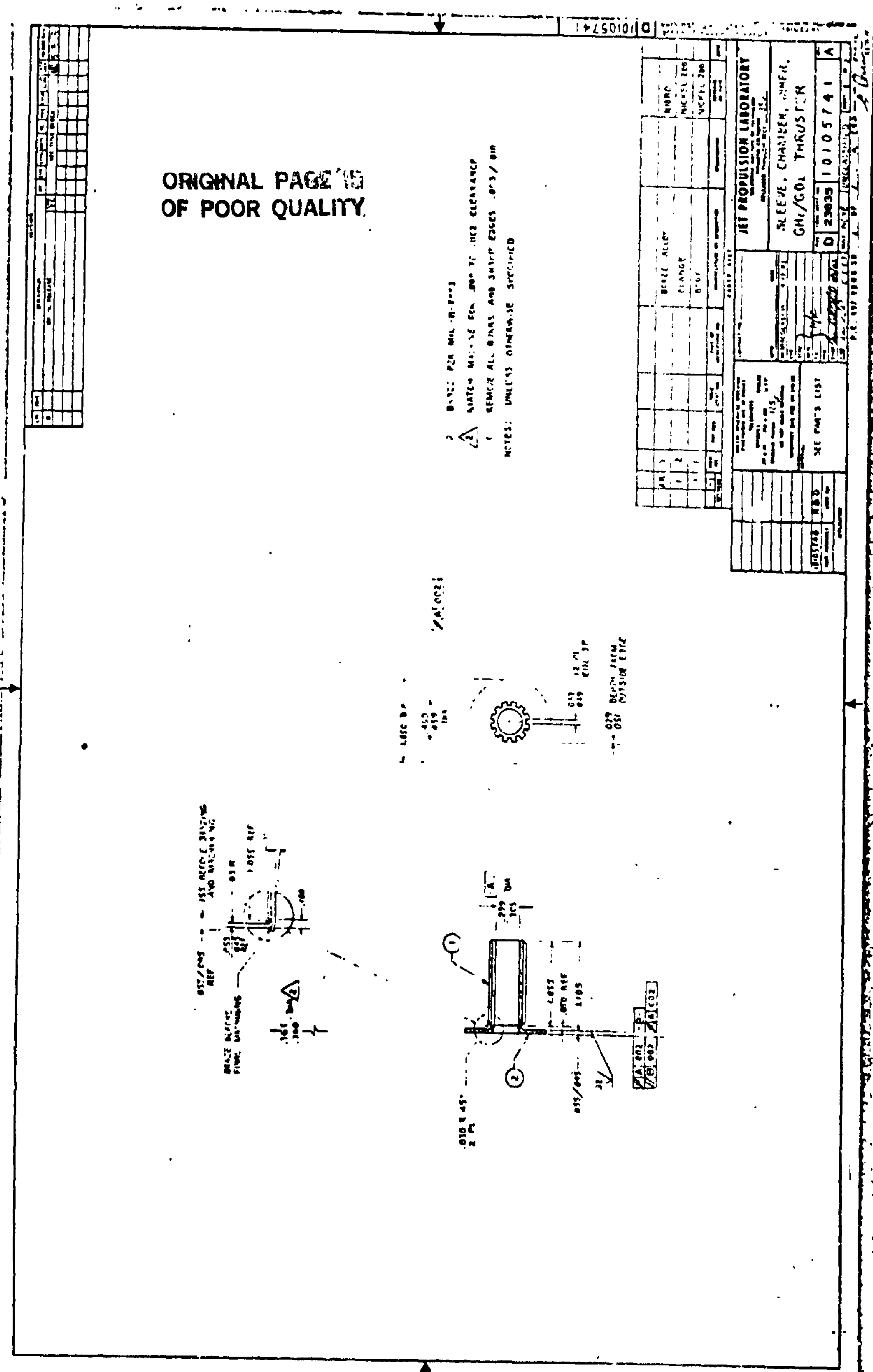

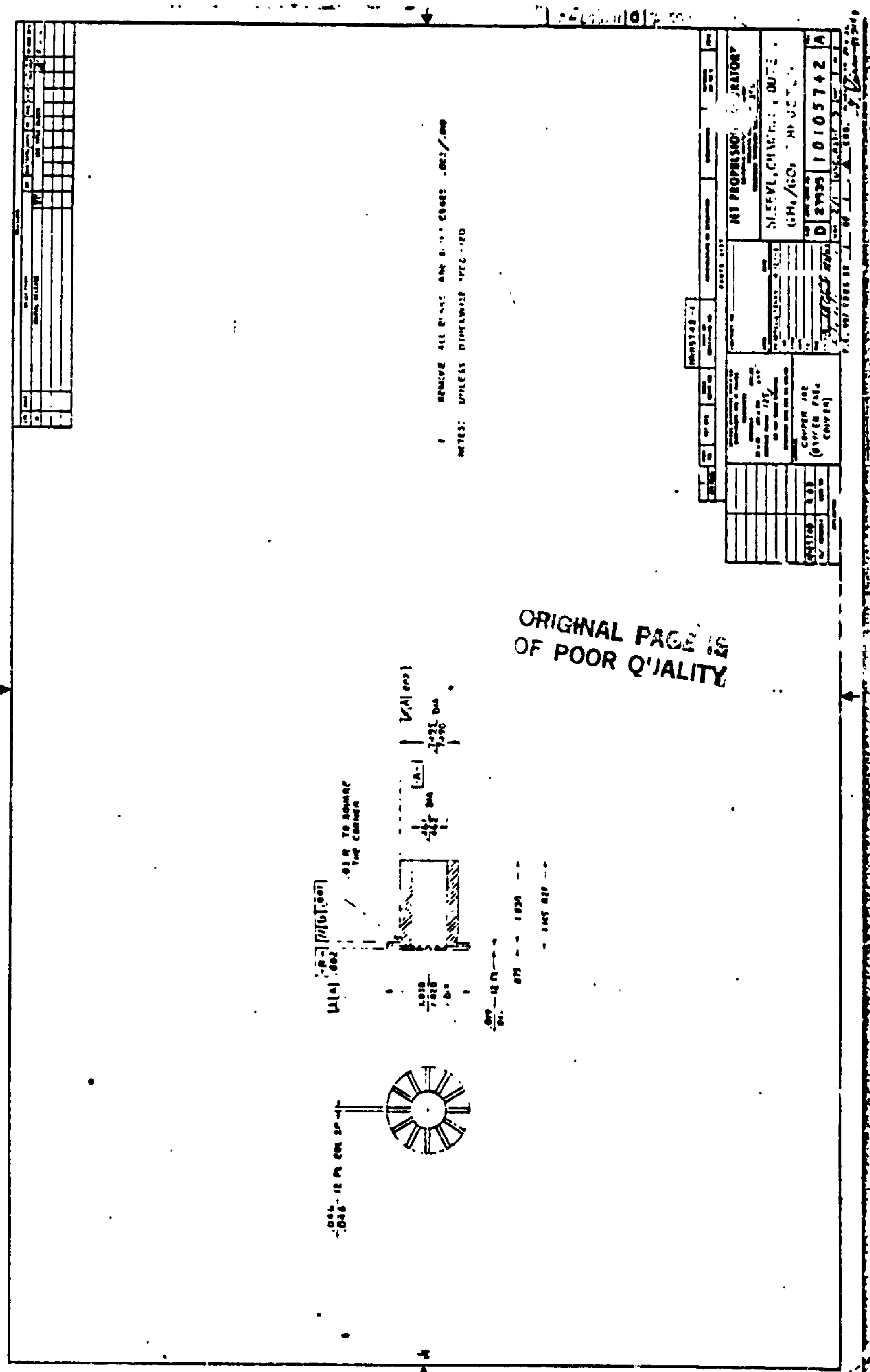

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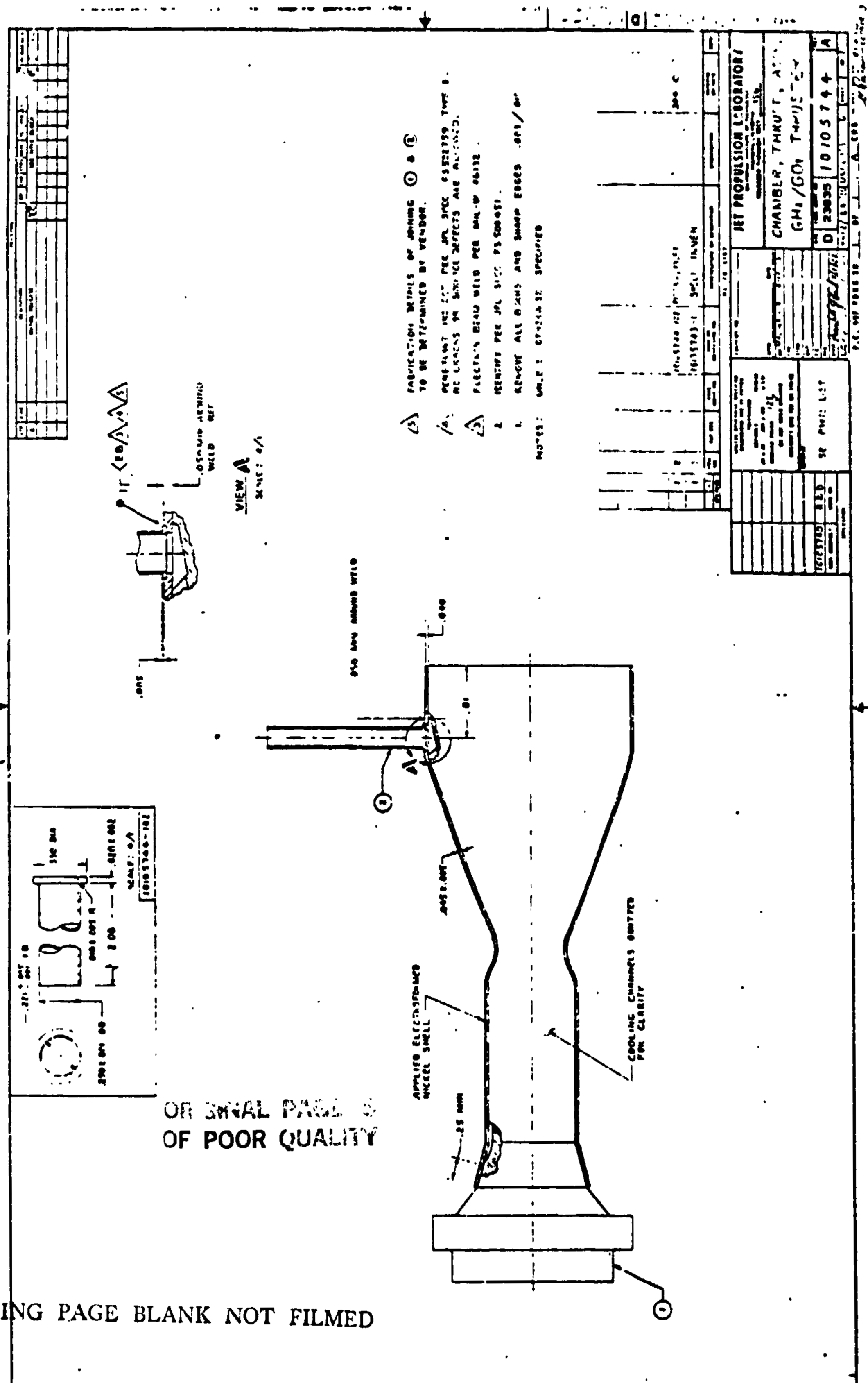

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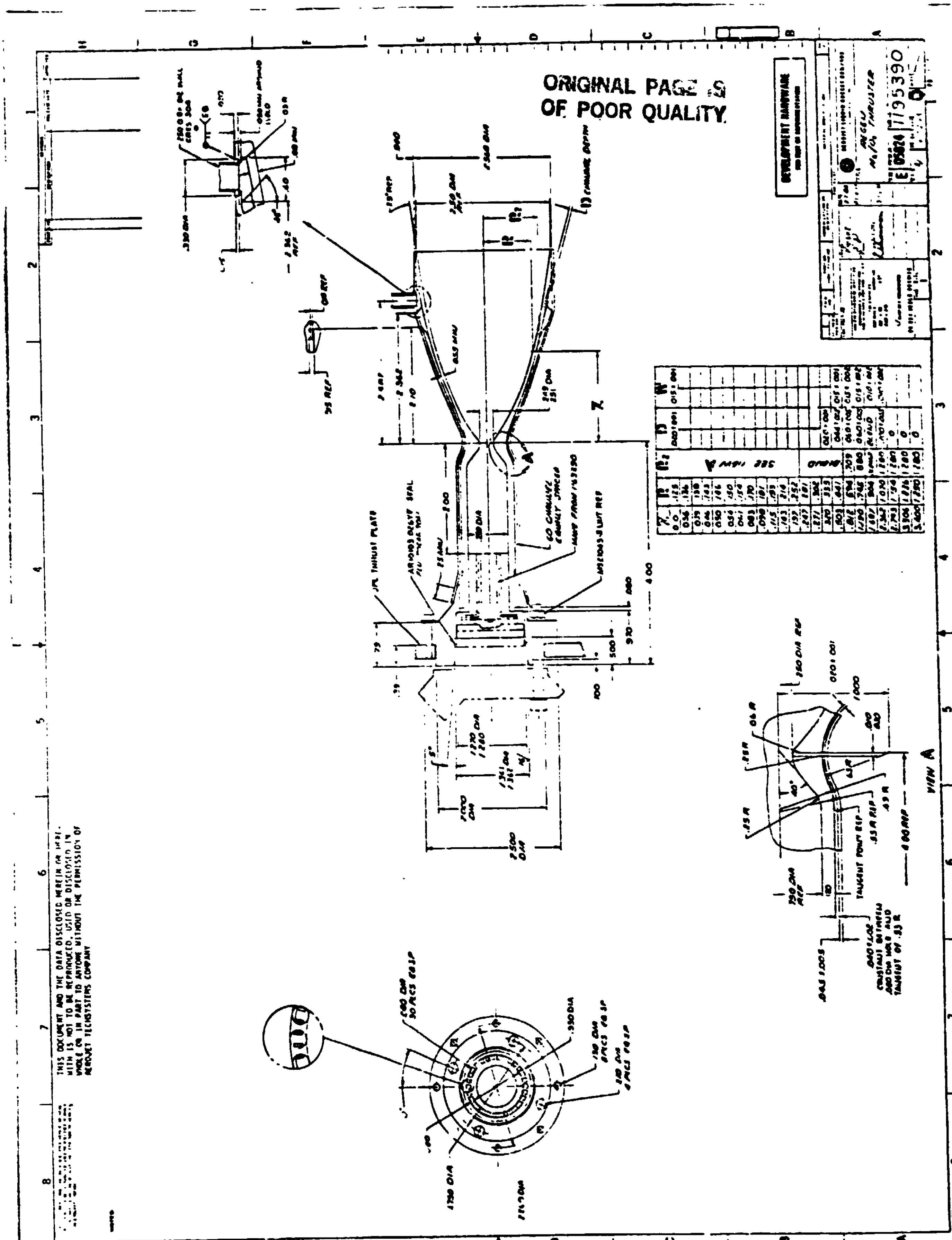


APPENDIX C

RHENIUM CHAMBER DESIGN DATA

GH_2/GO_2 THRUSTER

THICKNESS OF RHENIUM CHAMBER

Life = 20 hr

Max Creep = 1% in 20 hr

Temperature: Throat = ≈4,000°F) Design Limit
Chamber = 2,900°F)

		Nominal	1.5X
Pressure:	Throat	300	450 psia
	Chamber	500	750

Linear Creep Rate: $0.01/20 \times 60 = 8.3 \times 10^{-6}$/min

Design Properties for Rh in H_2, Ref. 3:

at 2,900°F, Stress = 4,000 psi
at 4,000°F, Stress = 1,000 psi

Throat Thickness:

$$T = \frac{PD}{2\ S} \quad \frac{450 \times 0.25}{2 \times 1,000} = 0.056 \text{ in.}$$

Chamber Thickness@2,900°F:

$$\frac{750 \times 0.75}{2 \times 4,000} = 0.070 \text{ in.}$$

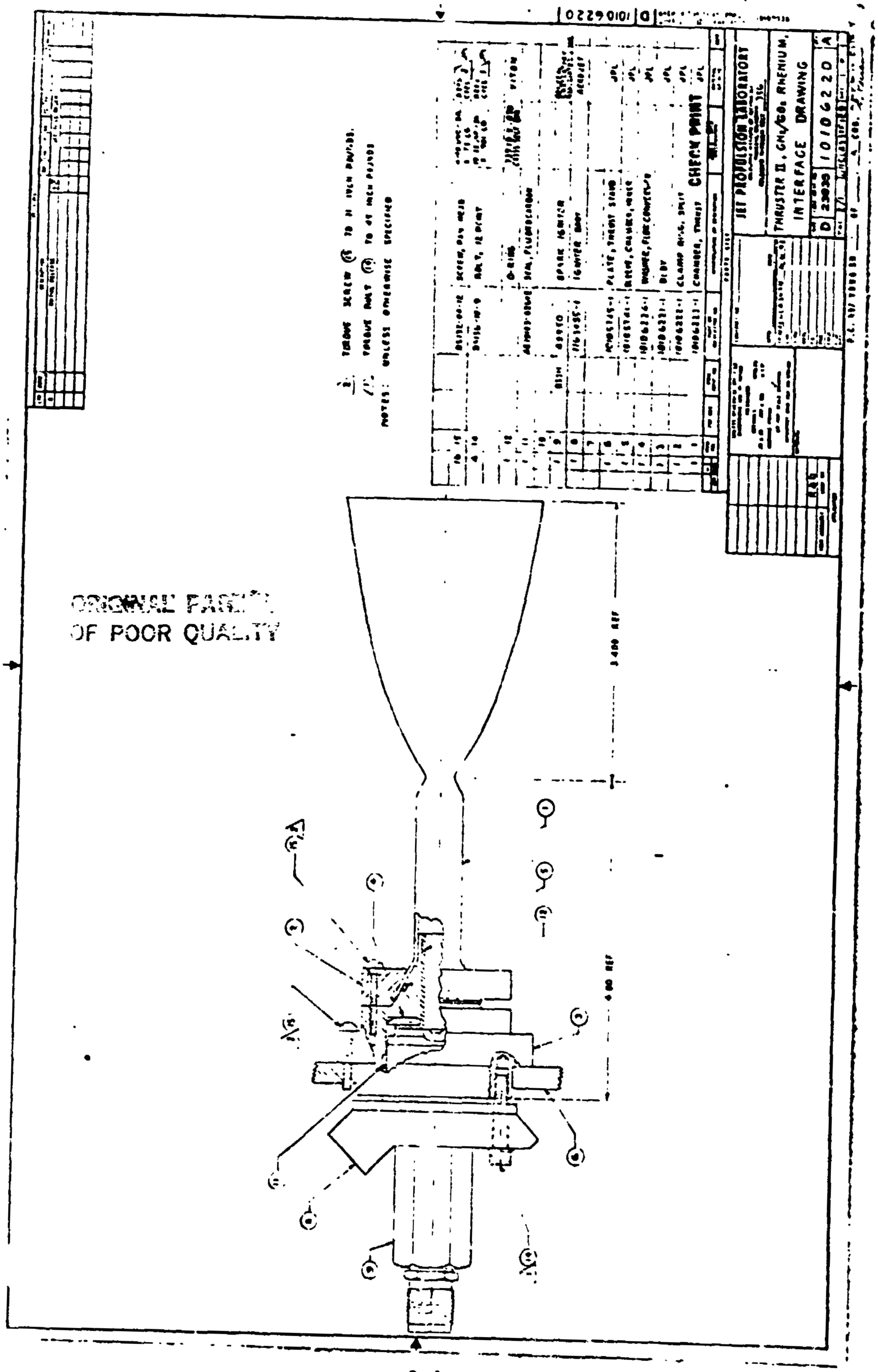
Recommendation

Rhenium thickness should be 0.070 in. in cylindrical chamber region, and 0.056 in. at the throat. Exit nozzle 0.02 to 0.070 acceptable.

NOZZLE CONTOUR

100:1 Expansion Ratio
99.65 % η_{div}
$\gamma = 1.216$

R	Z
0.125	0.0
0.136	0.036
0.138	0.039
0.143	0.046
0.146	0.050
0.150	0.054
0.154	0.061
0.170	0.083
0.181	0.098
0.193	0.115
0.214	0.143
0.252	0.197
0.281	0.247
0.302	0.271
0.333	0.320
0.441	0.503
0.594	0.812
0.745	1.190
0.904	1.687
1.070	2.362
1.154	2.793
1.236	3.306
1.250	3.400



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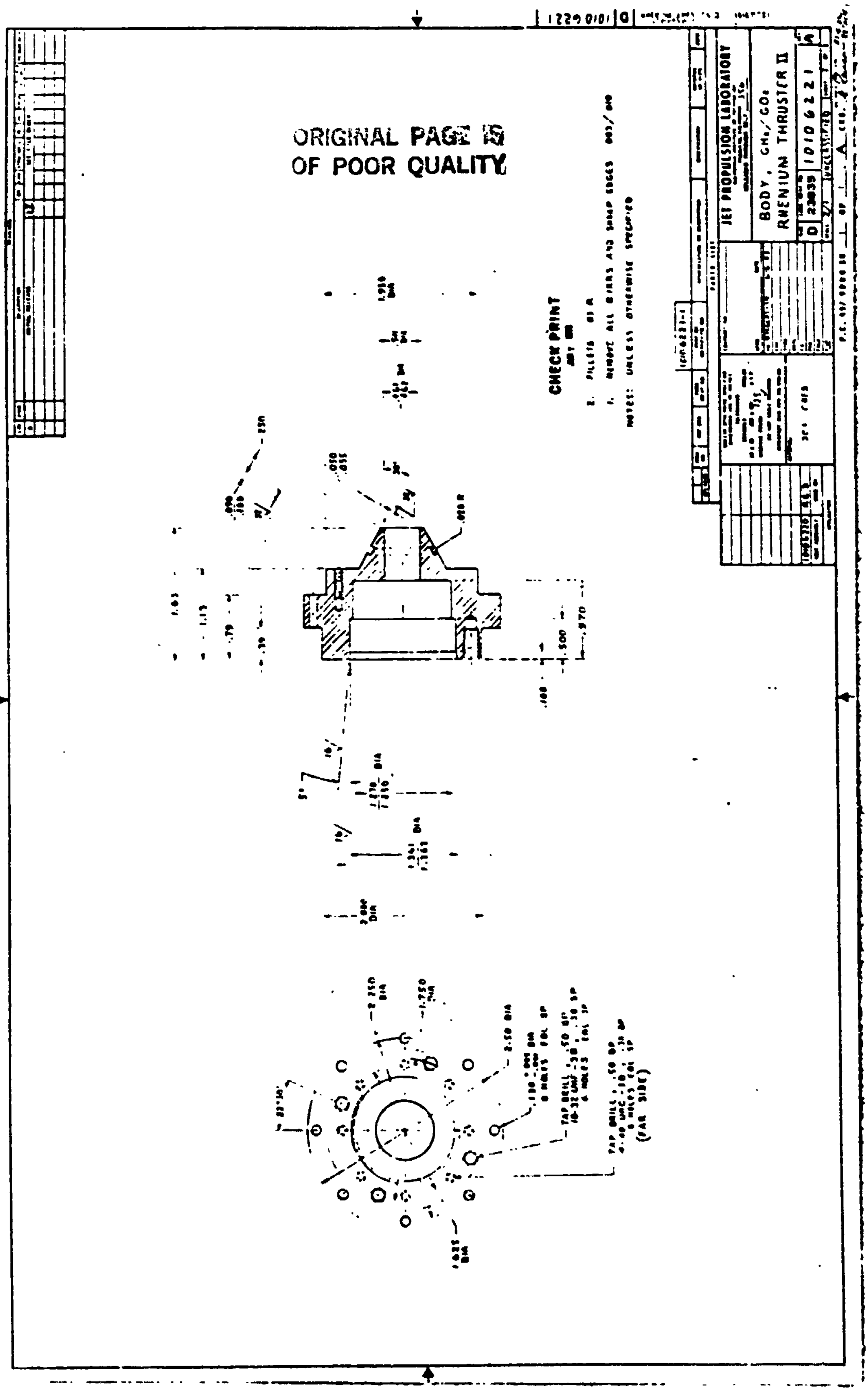

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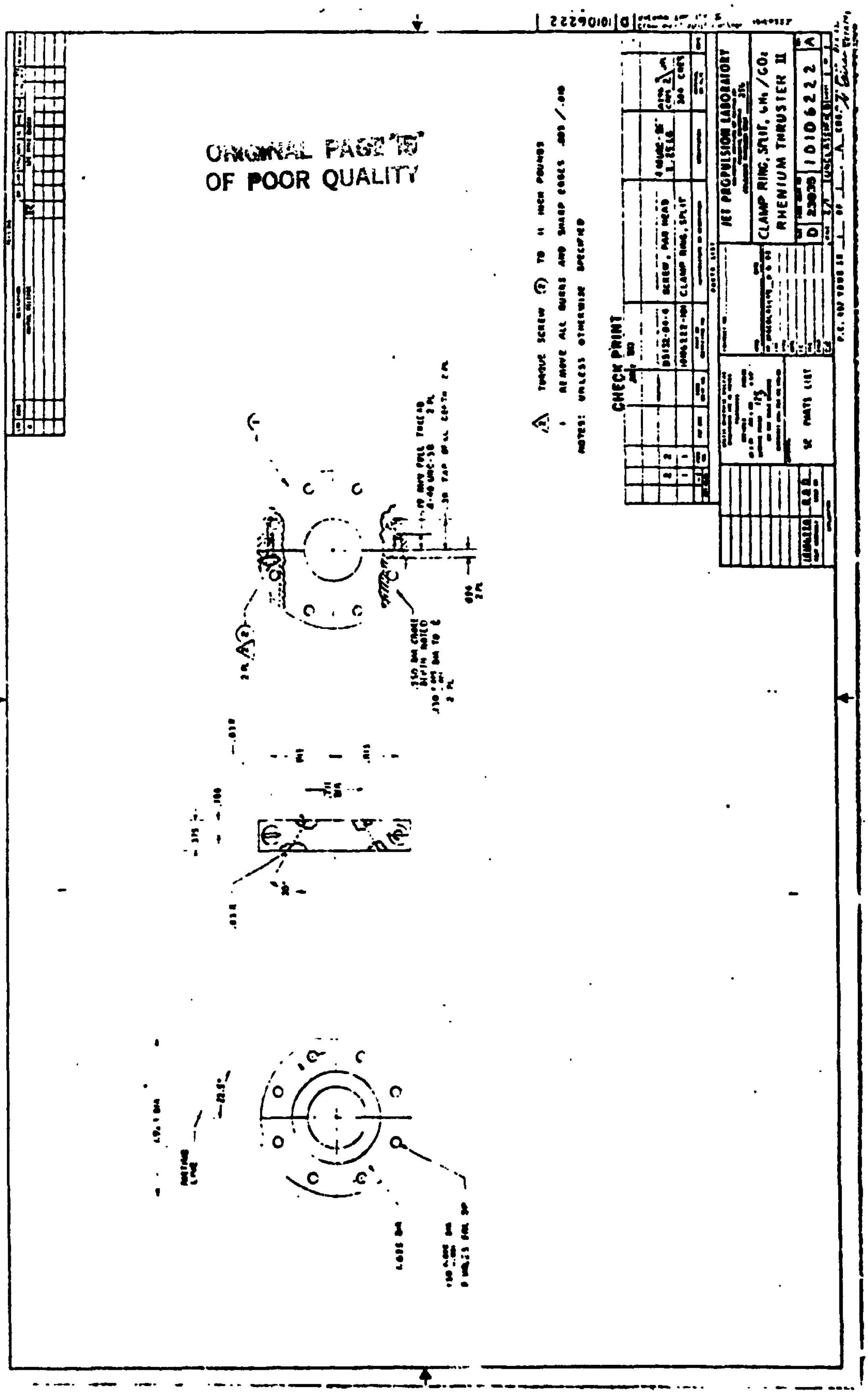

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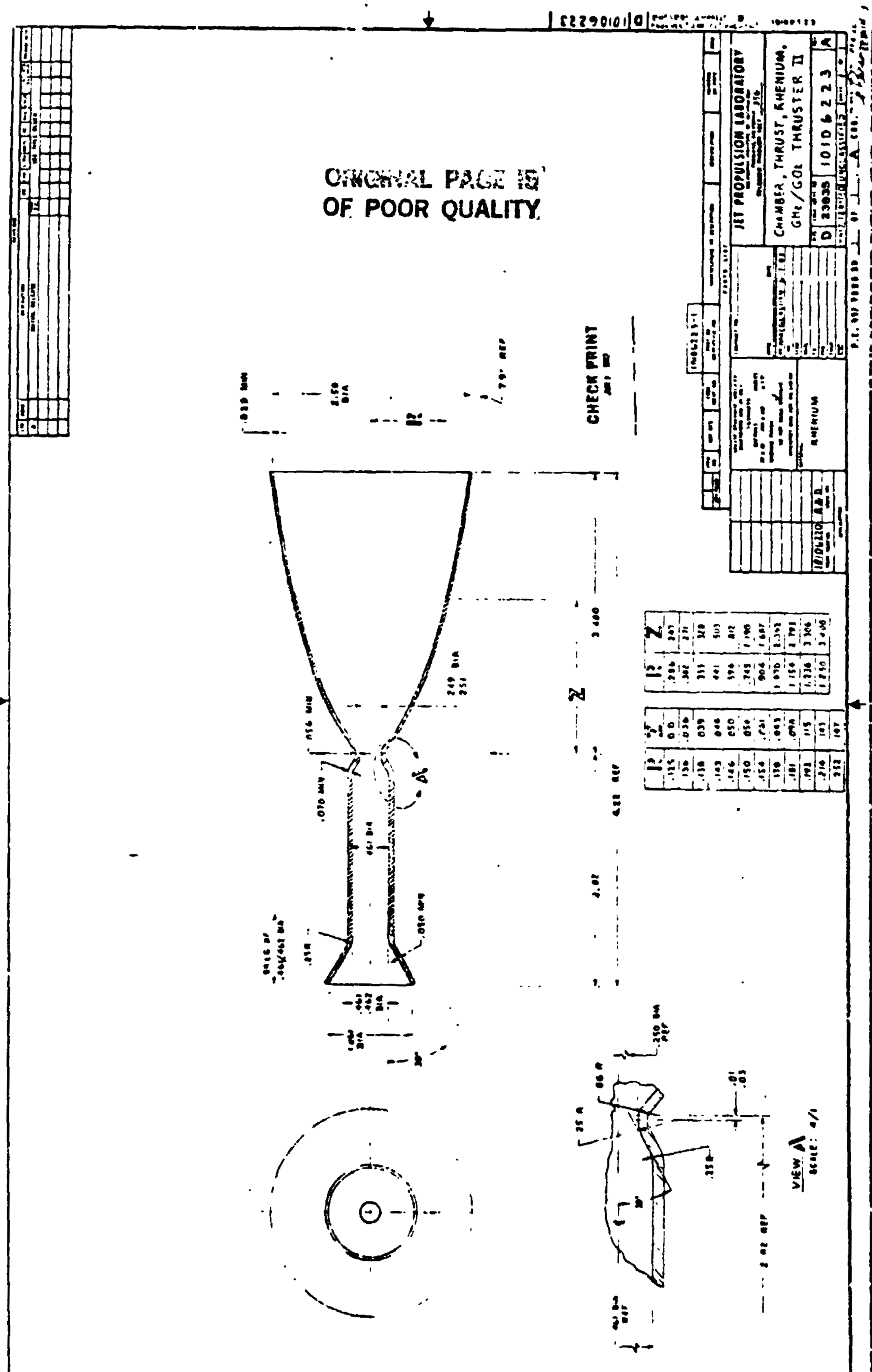

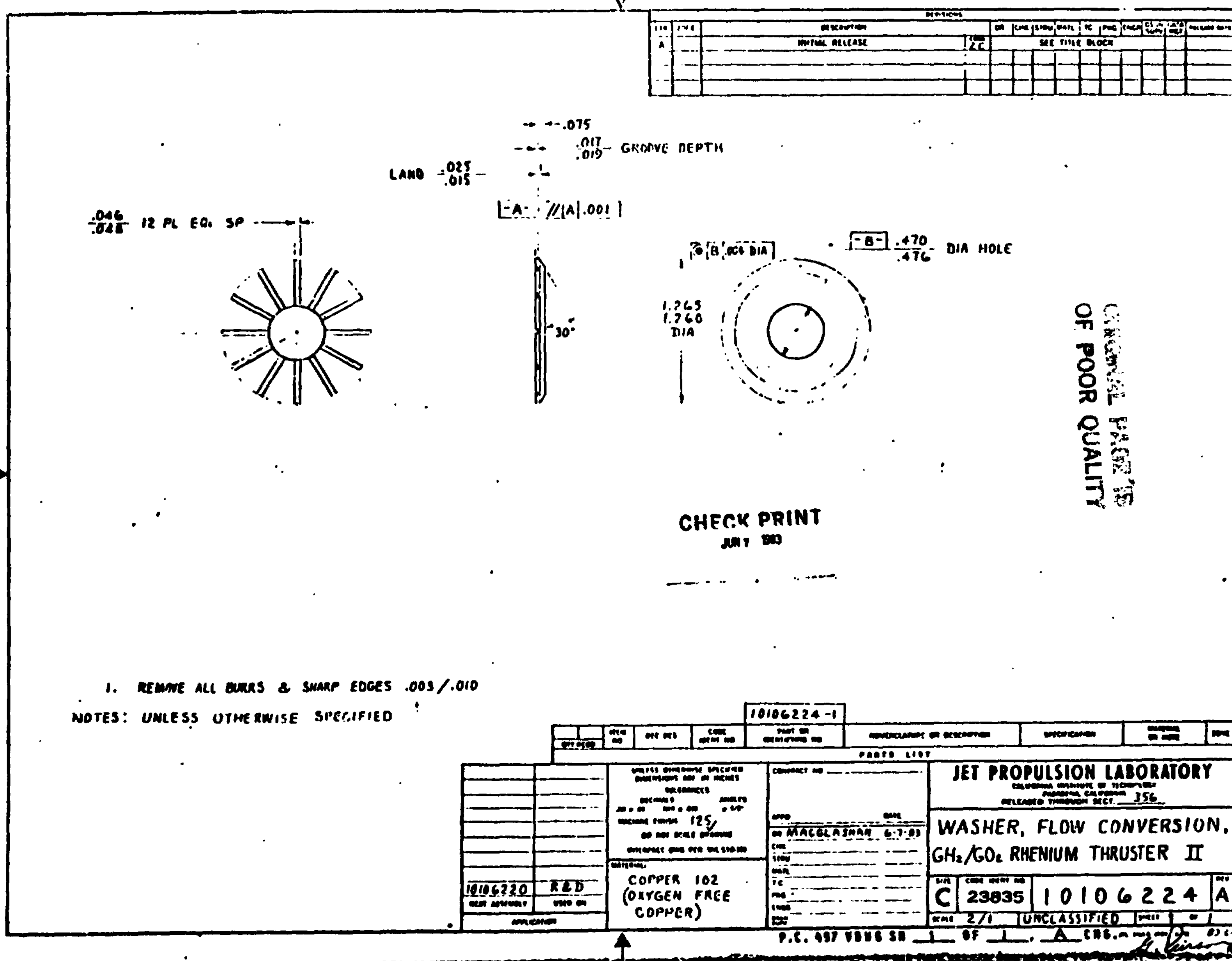

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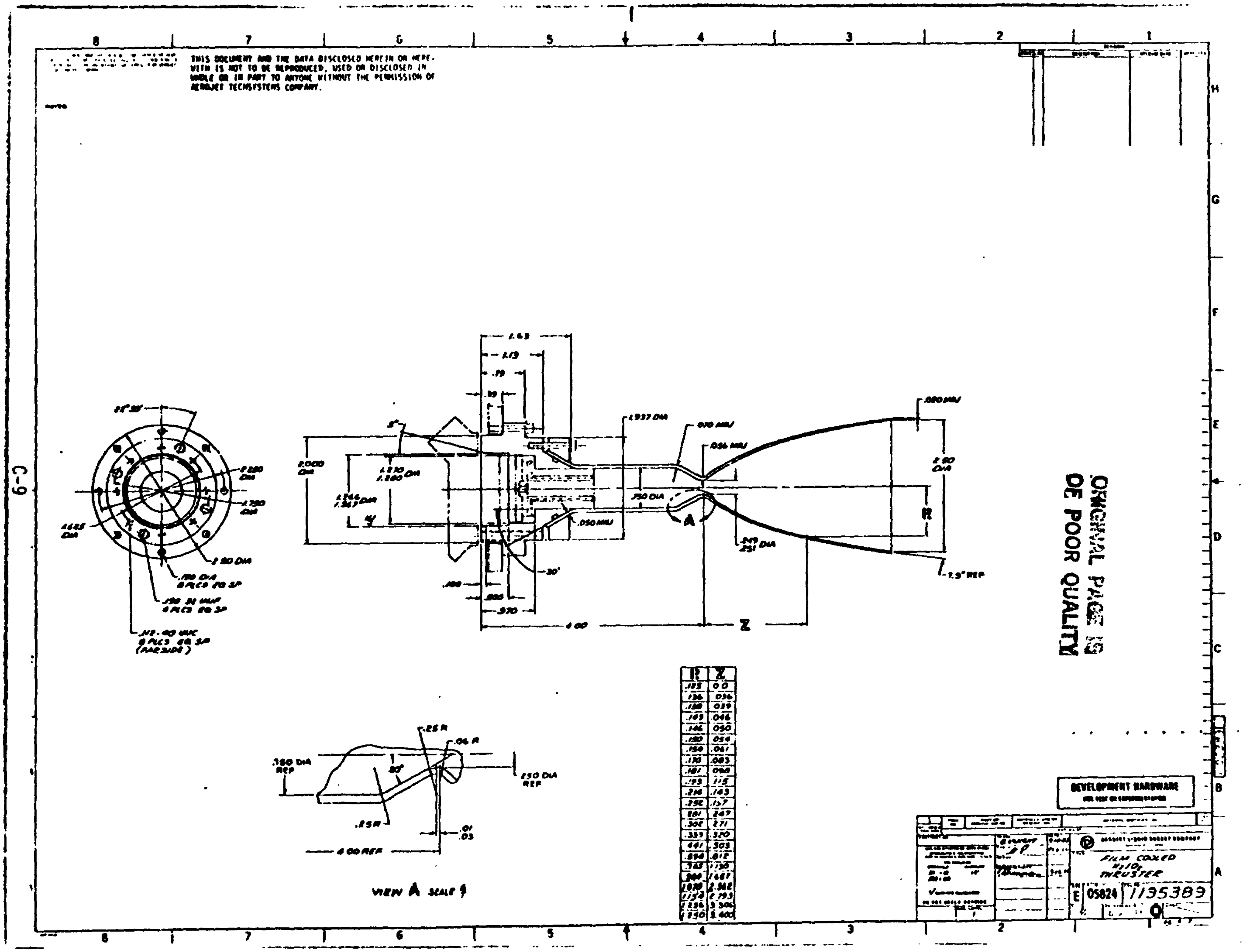


R	Z
.125	0.0
.136	.036
.138	.039
.143	.046
.146	.050
.150	.054
.158	.061
.170	.083
.181	.098
.193	.115
.216	.143
.252	.157
.281	.247
.308	.271
.333	.320
.441	.503
.594	.812
.743	1.130
.900	1.687
1.010	2.362
1.152	2.793
1.236	3.306
1.250	3.400

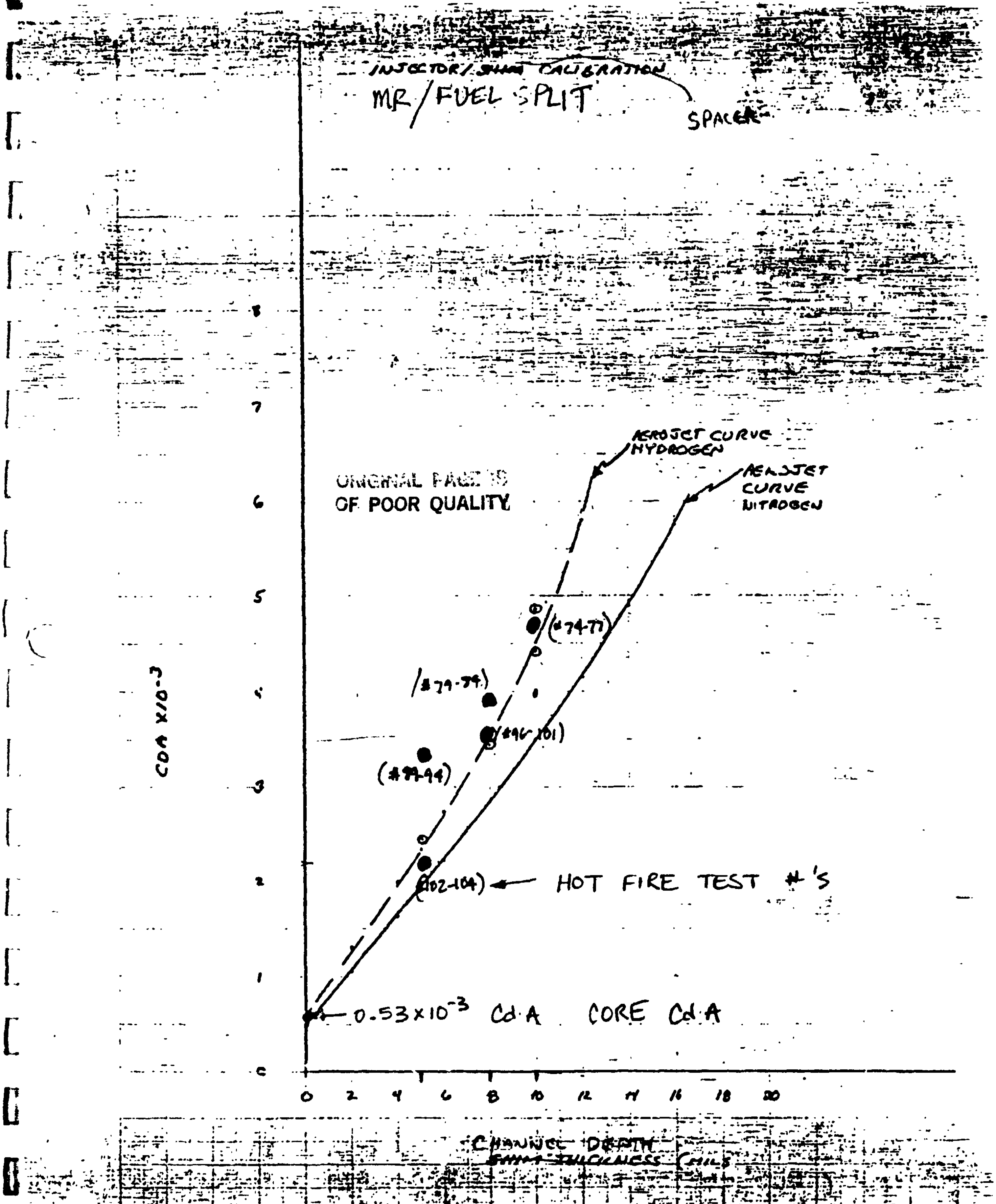
APPENDIX D

COLD-FLOW AND HOT-FIRE Cd-A DATA

THEORETICAL CORE MIXTURE RATIOS

CHANNEL DEPTH

SHIM SIZE	FUEL SPLIT	Cd·A RATIO CORE/TOTAL	OVERALL MR 2.0	OVERALL MR 2.5	OVERALL MR 3.0
			CORE MR		
.005	80/20	$\frac{.53}{2.7}$	10	12.5	15
.008	85/15	$\frac{.53}{3.5}$	13.3	16.7	20
.010	89/11	$\frac{.53}{4.5}$	16.7	20.8	25



INJECTOR/SHIM CALIBRATION
MR/FUEL SPLIT
SPACER
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AEROJET CURVE
HYDROGEN
AEROJET
CURVE
NITROGEN
(#74-77)
(#79-89)
(#96-101)
(#89-94)
(102-104)
HOT FIRE TEST #'s
0.53×10⁻³ Cd·A CORE Cd·A
CDA X10⁻³
CHANNEL DEPTH
SHIM THICKNESS (MILS
0
1
2
3
4
5
6
7
8
10
12
14
16
18
20

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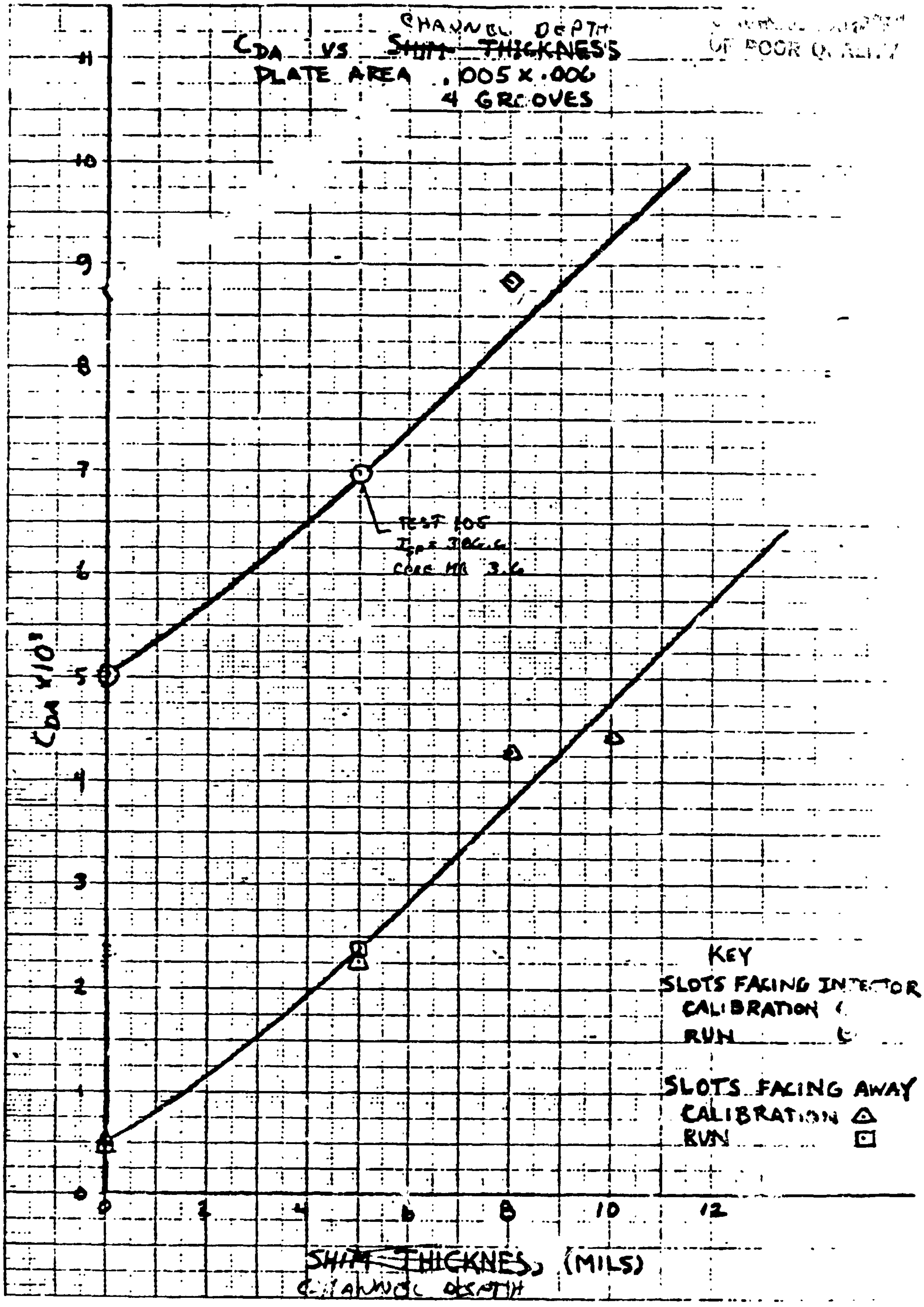

D-4 SEE OTHER PLOTS ALSO

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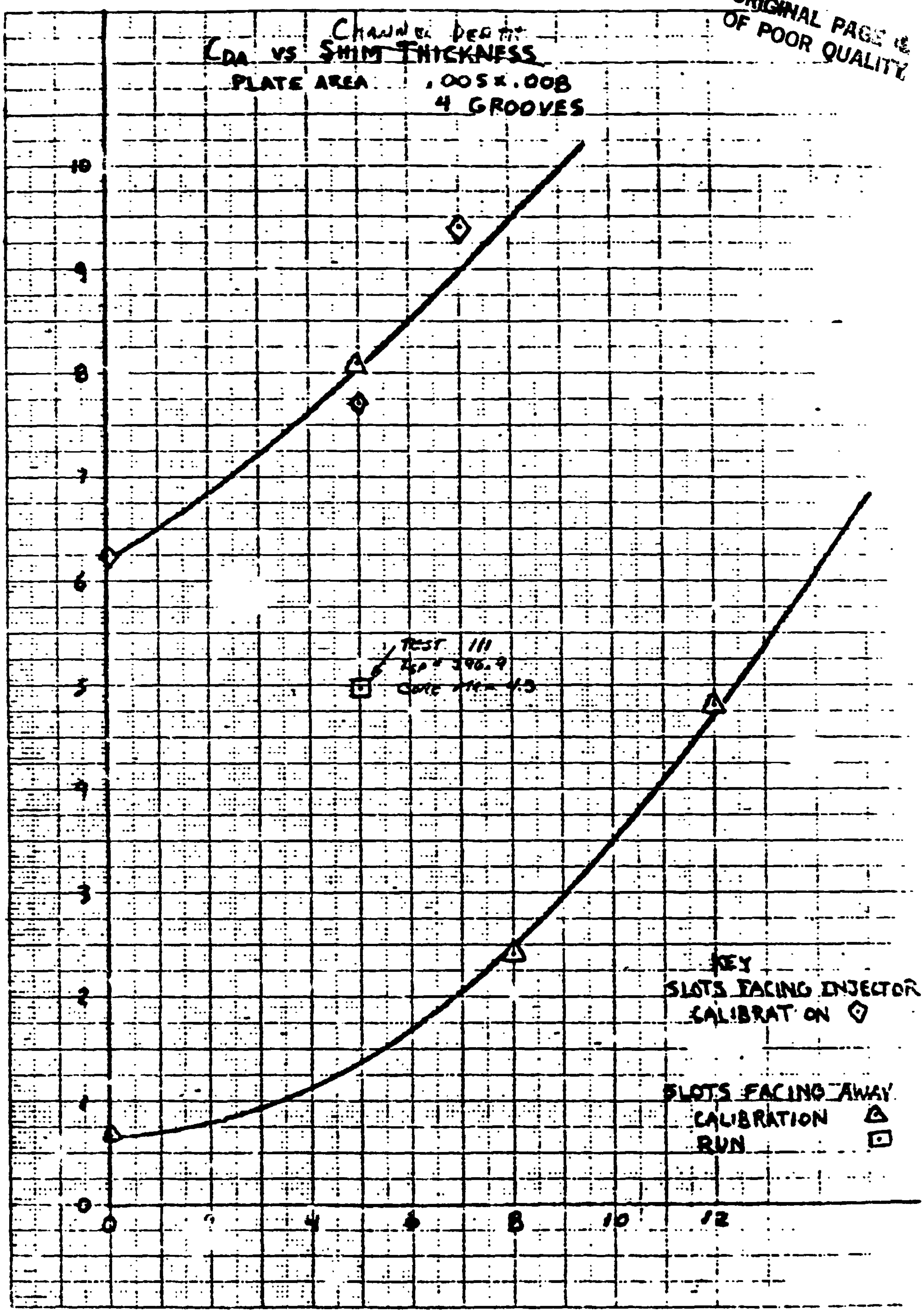

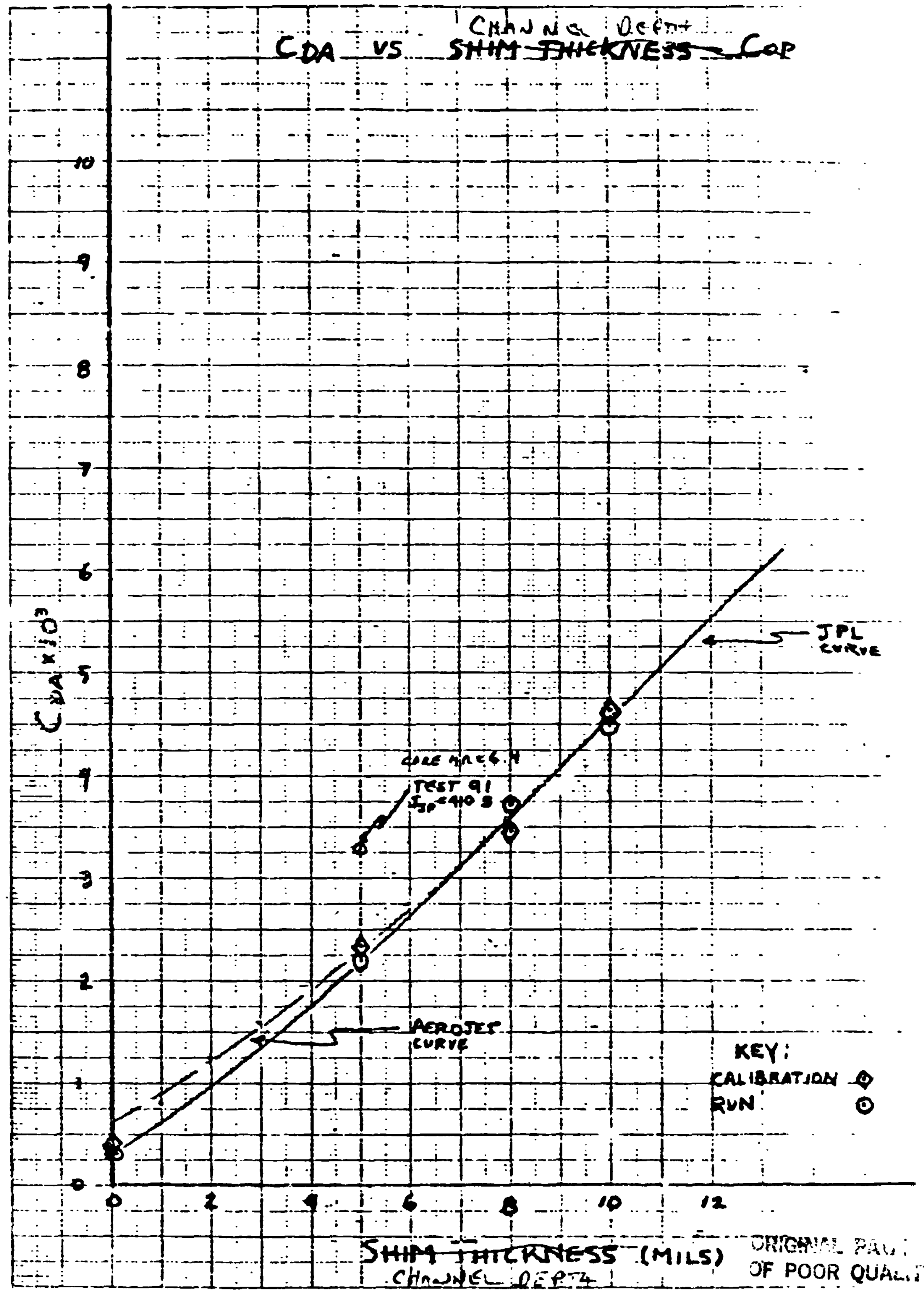

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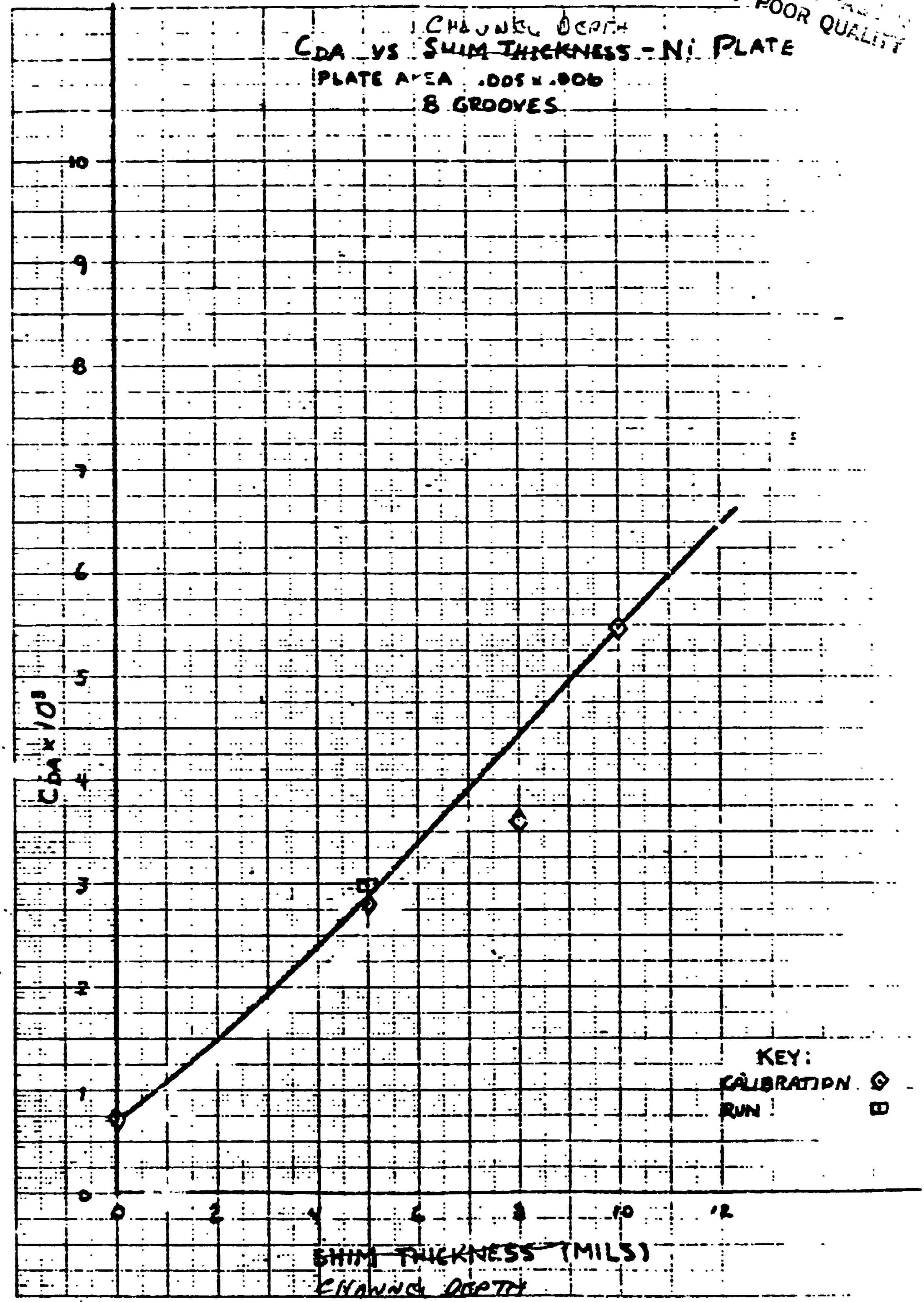

APPENDIX E

HOT-FIRE TEST DATA SUMMARY

HOT FIRE DATA
RHENIUM CHAMBER TESTS

TEST NO.	SHIM IN.	CALC SPLIT	DUR (SEC)	F_{VAC} (LBF)	$I_{SP_{VAC}}$ (LBF-S/LBM)	C* (FT/SEC)	MR	W_O (LBM/SEC) $\times 10^{-3}$	W_F (LBM/SEC) $\times 10^{-3}$	POV (PSIA)	TOV (°F)	PFV (PSI)	TFV (°F)	TC_1 (°F)	TC_2 (°F)	TC_3 (°F)	TC_4 (°F)	TC_5 (°F)	TC_6 (°F)	P_C (PSIA)	COMMENTS	TEST NO
55	.010	--	5	2.562	431	8896	3.78	4.704	1.244	198.6	74.8	202.0	75.1	[illegible]98	1295	1299	1231	216	159	33.5		55
57	.010	96/4	50	2.678	446	9000	3.72	4.725	1.271	199.7	75.9	206.6	76.2	1022	1644	178[illegible]	1756	1308	986	34.2		57
59	.010	97/3	107	2.685	443	9052	3.69	4.765	1.290	201.2	75.1	209.7	75.5	1022	1640	1777	1779	1457	1158	34.7		59
61	.010	97/3	300	2.694	446	9026	3.62	4.729	1.308	199.7	75.1	213.5	79.9	1045	1651	1777	1787	1454	1151	34.5		61
63	.010	97/3	300	2.694	446	8906	3.75	4.720	1.258	200.8	83.1	207.3	91.0	1054	1684	1810	1825	1459	1172	34.0		63
65		97/3	300	2.530	424	8981	3.75	4.707	1.254	200	81.7	205	81.7							33.9	PA TRANSDUCER NOT WORKING	65
74	.010	82/18	60	2.609	385		2.83	5.000	1.768	211.3	75.9	288.1	78.4	956	1651	1751	1891	1466	1152			74
75	.010	88/12	60	2.984	378		3.44	6.154	1.787	260.4	77.3	291.2	78.4	901	1675	1808	2015	1612	1271			75
76	.010	90/10	60	3.171	368	7329	3.78	6.801	1.797	287.7	77.0	292.6	77.7	887	1713	1860	2133	1737	1354	39.9		76
77	.010	87/13	60	2.457	394	7837	2.50	4.448	1.780	188.1	76.6	289.8	77.7	1012	1661	1758	1858	1411	1104	30.9		77
78	.010	87/13	300	2326	407	7856	2.16	3.902	1.808	165.2	78.0	2939	75.9	1085	1665	1751	1813	1404	1133	28.4		78
79	.008	85/15	60	2.668	392	7938	2.83	5.028	1.777	212.4	75.5	289.1	76.6	1050	1729	1896	1915	1484	1198	34.2		79
80	.008	85/15	60	3.070	382	7665	3.48	6.242	1.794	263.8	75.9	291.5	75.5	1019	1772	1861	2040	1617	1313	39.0		80
81	.008	88/12	60	3.259	378	7563	3.77	6.801	1.803	287.4	75.9	292.9	75.1	1013	1796	1998	2108	1677	1356	41.2		81
82	.008	85/15	60	2.503	397	7969	2.54	4.525	1.778	191.1	75.1	288.8	75.1	1078	1651	1810	1825	1399	1102	31.8		82

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APPENDIX E

HOT FIRE DATA
RHENIUM CHAMBER TESTS

TEST NO.	SHIM IN.	CALC SPLIT	DUR (SEC)	F_{VAC} (LBF)	Isp_{VAC} (LBF-s/LBM)	C* (FT/SEC)	MR	W_O (LBM/SEC) $\times 10^{-3}$	W_F (LBM/SEC) $\times 10^{-3}$	POV (PSIA)	TOV (°F)	PFV (PSI)	TFV (°F)	TC_1 (°F)	TC_2 (°F)	TC_3 (°F)	TC_4 (°F)	TC_5 (°F)	TC_6 (°F)	Pc (PSIA)	COMMENTS	TEST NO
83	.008	86/14	60	2.325	408	8104	2.18	[illegible]	1.791	164.9	76.6	290.8	74.8	107	1725	1725	1720	1304	1010	29.2		83
89	.005	60/40	5	2.848	412	8509	2.87	5.119	1.786	214.7	67.8	288.8	70.0	975	1689	2076	2205	484	304	37.2		89
90	.005	59/41	5	2.856	412	8549	2.82	5.114	1.814	214.7	68.9	293.3	70.0	1033	1734	2113	2242	543	365	37.5		90
91	.005	59/41	60	3.014	438	8845	2.86	5.095	1.780	214.3	70.8	288.4	72.2	1725	2549	3038	3050	2057	1443	38.5	CHAMBER 'O' RING SEAL FAILED DURING SOAK BACK	91
92	.005	60/40	60	2.941	431	8495	2.82	5.036	1.788	212.1	72.2	289.8	72.6	1224	1812	2444	2521	1827	1331	36.7	RUN WITH FAILED 'O' RING	92
93	.005	62/38	60	2.920	428	8534	2.84	5.036	1.775	212.4	73.7	287.7	72.9	1367	1837	2630	3312	1906	1389	36.8	RUN WITH FAILED 'O' RING	93
94	.005	83/17	60	2.638	400	8100	3.47	5.115	1.476	215.4	72.2	239.1	72.2	1070	2715	2972	3029	2185	1574	33.8	APPEARS THE CORE PART OF INJECTOR PLUGGED, NO ACTUAL PLUGGING FOUND	94
95																					NO TEST	95
96	.008	91/9	60	2.690	392	7712	2.84	5.073	1.788	213.2	70.0	289.8	72.6	790	1547	1772	1829	1418	1164	33.5		96
97	.008	94/6	60	3.056	378	7479	3.48	6.265	1.802	263.4	80.4	291.9	72.2	745	1551	1803	1889	1512	1251	38.2		97
98	.008	94/6	60	3.002	345	7352	3.80	6.872	1.808	288.9	70.4	297.6	71.1	722	1561	1827	1927	1554	1297	40.4	QUESTIONABLE INSTRUMENTATION	98
99	.008	94/6	60	2.478	396	7726	2.54	4.491	1.765	188.8	70.4	285.7	71.1	810	1547	1763	1798	1374	1135	30.6	INJECTOR OR SOMETHING PLUGGED	99
100	.008	94/6	60	2.251	397	7699	2.20	3.891	1.771	163.7	71.1	286.7	71.5	827	1739	2018	2057	1535	1254	27.6	INJECTOR OR SOMETHING PLUGGED	100
101	.008	95/5	60	3.173	369	7283	3.84	6.813	1.775	286.6	71.1	287.4	71.5	722	1561	1829	1922	1542	1296	39.6		
102	.005	87/13	60	2.674	390	7800	2.87	5.092	1.773	214.3	71.5	287.4	72.9	1117	3130	3359	3300	2347	1635	33.9		

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HOT FIRE DATA
RHENIUM CHAMBER TESTS

APPENDIX E

TEST NO.	SHIM IN.	CALC SPLIT	DUR (SEC)	F_{VAC} (LBF)	$I_{SP_{VAC}}$ (LBF-S/LBM)	C* (FT/SEC)	MR	W_O (LBM/SEC) $\times 10^{-3}$	W_F (LBM/SEC) $\times 10^{-3}$	POV (PSIA)	TOV (°F)	PFV (PSI)	(°F)	TC_1 (°F)	TC_2 (°F)	TC_3 (°F)	TC_4 (°F)	TC_5 (°F)	TC_6 (°F)	Pc (PSIA)	COMMENTS	TEST NO
103	.005	89/11	60	2.677	392	7645	2.89	5.064	1.754	213.2	71.9	284.3	72.6	1126	3125	3305	3210	2358	1648	33.0		103
104	.005	88/12	50	2.439	356	7794	2.96	5.075	1.775	214.3	75.1	288.4	75.5	12[illegible]4	2963	3143	3156	2316	1607	3[illegible].8		104
105	.005	28/72	5	2.766	403	8690	2.84	5.069	1.783	213.2	70.8	288.1	69.3	1425	2687	2738	2318	435	293	37.7	(MAIN FUEL PASSAGE WAS PARTIALLY OPEN TO ALLOW FLOW TO CORE) ADDED A PLATE WITH (4) .005 x .006 SLOTS FACING INJECTOR	105
108	.005	81/19	5	2.675	392	7836	2.83	5.035	1.777	212.1	72.6	289.1	76.6	854	1473	1540	1524	320	220	33.8	.005 x .006 PLATE REVERSED TO BLOCK OFF FLOW FROM FUEL PASSAGE TO CORE	108
109	.005	81/19	60	2.651	389	7921	2.85	5.036	1.764	212.1	73.3	286.0	72.9	1096	1760	1976	2064	1614	1210	34.1		109
110	.005	38/62	5	2.698	395	7948	2.82	5.030	1.786	211.7	71.5	289.8	74.0	750			1351	273	200	34.3	CHANGED PLATE TO (4) .005 x .008 SLOTS	110
111	.005	40/60	60	2.755	406	8521	2.80	5.000	1.764	210.9	74.0	289.8	74.8	1297		2646	2594	1934	1516	36.6		111
114	.005	[illegible]	5	2.640	400	8072	2.81	4.862	1.732	205.7	72.9	287.4	74.8	872	2695	2245	1964	270	214	33.7		114
115	.005	65/35	60	[illegible]453	372	8216	2.81	4.862	1.732	204.9	72.9	281.2	74.4	1037	1401	2158	2240	1732	1300	34.3		115

APPENDIX E

HOT FIRE DATA
REGEN CHAMBER TESTS

EST NO.	SHIM IN.	CALC SPLIT	DUR (SEC)	F_{VAC} (LBF)	Isp_{VAC} (LBF-s/LBM)	C* (FT/SEC)	MR	W_O (LBM/SEC) $\times 10^{-3}$	W_F (LBM/SEC) $\times 10^{-3}$	POV (PSIA)	TOV (°F)	PFV (PSI)	TFV (°F)	TC_1 (°F)	TC_2 (°F)	TC_3 (°F)	TC_4 (°F)	TC_5 (°F)	TC_6 (°F)	TF (°F)	P_C (PSIA)	COMMENTS	TEST NO
66	.010	--	5	2.312	357	[illegible]	2.66	4.706	1.767	199	76.6	288	78.4	264	265	266	233	117	89	119	30.4	TFJ NOT POSITIONED PROPERLY	66
67	.010	--	10	2.351	365	7556	2.69	4.692	1.746	199	79.9	285	80.2	428	408	397	336	172	119	214	30.8	TFJ NOT POSITIONED PROPERLY	67
68	.010	--	15	2.352	378	7657	2.56	4.463	1.746	188	72.6	287	74.8	473	451	428	341	184	116	238	30.1	TFJ NOT POSITIONED PROPERLY	68
69	.010	--	50	2.671	392	7907	2.80	5.020	1.792	212	75.1	291	74.8	923	726	676	529	284	175	591	34.1	TFJ NOT POSITIONED PROPERLY	69
70	.010	--	50	3.067	386	7734	3.43	6.151	1.793	260	76.2	292	77.7	867	830	747	601	325	200	617	38.9	TFJ NOT POSITIONED PROPERLY	70
71	.010	-	30	3.183	370	7512	3.74	6.787	1.813	287	76.6	295	77.0	912	881	791	640	347	210	661	40.9	TFJ NOT POSITIONED PROPERLY	71
72	.010	--	44	2.488	393	[illegible]	2.48	4.509	1.818	191	78.4	296	77.3	856	702	672	514	272	171	652	31.2	TFJ NOT POSITIONED PROPERLY	72
73	.010	--	39	2.294	401	[illegible]389	2.13	3.385	1.825	165	81.2	297	77.3	851	755	644	487	256	169	653	28.0	TFJ NOT POSITIONED PROPERLY	73

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HOT FIRE DATA
STAINLESS STEEL CHAMBER TESTS

TEST NO.	SHIM IN.	CALC SPLIT	DUR (SEC)	F_{VAC} (LBF)	$I_{SP_{VAC}}$ (LBF-S/LBM)	C* (FT/SEC)	MR	W_O (LBM/SEC) $\times 10^{-3}$	W_F (LBM/SEC) $\times 10^{-3}$	POV (PSIA)	TOV (°F)	PFV (PSI)	TFV (°F)	TC_1 (°F)	TC_2 (°F)	TC_3 (°F)	TC_4 (°F)	TC_5 (°F)	TC_6 (°F)	Pc (PSIA)	COMMENTS	TEST NO
84	.008	83/17	31	2.599	378.1	7627	2.86	5.094	1.780	215.1	75.1	289.8	77.[illegible]	--	--	--	1364	--	--	33.2		84
85	.008	87/13	23	3.168	368.9	730[illegible]	3.78	6.788	1.798	237.0	76.6	292.9	78.4	--	--	--	1512	--	--	39.7		85
86	.008	87/13	39	2.326	409.4	10845	2.22	3.916	1.763	165.6	76.6	287.0	77.3	--	--	--	1431	--	--	39.0		86
87	.008	88/12	32	2.485	399.6	7745	2.53	4.455	1.764	188.5	77.3	287.4	78.0	--	--	--	1506	--	--	30.5		87
88	.008	88/12	39	2.703	399.2	7620	2.87	5.071	1.768	188.5	78.0	288.1	78.4	--	--	--	1515	--	--	33.0		88

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APPENDIX F

THERMODYNAMIC ANALYSIS REPORT NO. 6983:1058

Aerojet TechSystems Company

DEVELOPMENT ENGINEERING

THERMODYNAMIC ANALYSIS REPORT

NUMBER: 6983:1058

DATE: 20 Feb. 1984

SUBJECT: THERMAL ANALYSIS OF JPL O_2/H_2 THRUSTER DATA

NO. OF ENCLOSURES

NO. OF APPENDICES

ADDITIONAL INFORMATION AND WORK NOTES INCLUDED IN MICROFILM FILE CDN

PREPARED FOR: L. Schoenman

INTRODUCTION

JPL recently tested a thin-wall rhenium thruster with a 100:1 expansion ratio at low chamber pressures using GH_2/GO_2 propellants. Massive film cooling was provided by introducing part of the fuel through a sleeve. Analysis of the nozzle thermocouple data was of interest to define heat transfer coefficients and thus infer the nature of the boundary layer at low pressures, i.e., to determine if the boundary layer was turbulent, laminarized or in a rarefied flow regime. The specific data of interest were TC5 and TC6 on Test 91, a 60 sec. test at a chamber pressure of 38 psia during which the two nozzle thermocouples approached steady state. Test conditions are summarized in Table I and nozzle thermocouple location parameters are identified in Table II.

KEYWORDS: Misc. - Rockets (21), Nozzle (53), Thermal (104), Gaseous (163), Test Results (202), 1984 (269), Ewen (304)

DISTRIBUTION:

W. R. Thompson, 6983 File, D. L. Kors

PREPARED BY: R. L. Ewen

REVIEWED BY: S. Buccella

APPROVED BY: J. L. PIEPER, MANAGER

The analysis reported herein consisted of defining the adiabatic wall temperature and heat transfer coefficient which provide an approximate fit of each thermocouple transient, defining the wall mixture ratios which correspond to these adiabatic wall temperatures and then interpreting the heat transfer coefficients using properties for the corresponding mixture ratio.

SUMMARY

Fitting the transient response of TC5 and TC6 resulted in very high heat transfer coefficients and relatively low adiabatic wall temperatures as shown in Table IV. The difference in adiabatic wall temperature between locations is greater than can be predicted, which resulted in lower wall mixture ratios at TC6. The high heat transfer coefficients can be explained in part by the extremely low Reynolds numbers, for which laminar boundary layer coefficients about double typical turbulent values can be expected.

TRANSIENT DATA ANALYSIS

Transient wall analyses using the 1DCOND program, Ref. 1, were run in order to infer adiabatic wall temperatures and heat transfer coefficients based on matching the thermocouple transients. These parametric studies were guided by energy balance calculations for two conditions: (1) early in the transient using the slope of the measured temperature vs time curves, Figure 1, and (2) steady state using wall temperatures slightly higher than the data at 60 sec. Wall temperatures have not quite reached steady state at the latter time. Both the constant and wall temperature dependent heat transfer coefficient options of 1DCOND were used, but the latter did not improve the data fit. Rhenium properties were obtained from Ref. 2; the specific heats and thermal conductivities of Table III were added to 1DCOND as IMATL = 13. Figure 2 shows the emissivity data; a combination of curves 2 and 3 was used herein, with the 1DCOND input value based on a temperature late in the transient.

As shown in Figure 1, it was not possible to obtain a precise fit of the measured transients. The predictions shown are typical of the parametric study results. Table IV gives the ranges of adiabatic wall temperatures and heat transfer coefficients which appear to provide the best data fit. It is apparent from the low adiabatic wall temperatures that the film cooling is having a significant effect.

WALL MIXTURE RATIO

TRAN72 was used to generate the adiabatic wall temperature vs mixture ratio curves shown in Figure 3. The H-P option was utilized with the adiabatic wall enthalpy defined as

$$H_{aw} = (1 - Pr_w^{0.5}) H_e$$

and the free-stream enthalpy based on the one-dimensional values given in Table II. Note that the laminar rather than turbulent recovery factor was assumed since laminarization of the boundary layer was expected.

Table IV includes the wall mixture ratio ranges defined by Figure 3 from the adiabatic wall temperatures inferred above. Since the difference in the latter between thermocouple locations is greater than that indicated by Figure 3, lower mixture ratios are obtained at TC6. Such a result is inconsistent with all film cooling theory. Use of a turbulent recovery factor would increase the mixture ratio discrepancy.

HEAT TRANSFER COEFFICIENT CORRELATION

The heat transfer coefficients of Table IV were compared to the following non-reactive turbulent pipe flow correlation:

$$h_g = C_g \quad DBFC\ (MR_w, T_f) \left(\frac{W_T}{MW_e} \cdot \frac{T_e}{T_f} \cdot F_{2D} \right)^{0.8} D^{-1.8}$$

with the property parameter DBFC evaluated at a wall mixture ratio of 1.70*. Table IV includes the resultant correlation coefficients, Cg, which range from 2.3-3.7 compared to typical turbulent coefficients of 0.8-0.9. Note that these values are normalized to the Bartz coefficient of 0.026 which is included in DBFC. These results may seem surprising in view of the anticipated boundary layer laminarization. Using film properties at a wall mixture ratio of 2.0, the following Reynolds numbers are calculated:

Location	Re_D
Throat	8030
TC5	1630
TC6	1010

With such a low throat Reynolds number, laminarization definitely should have occurred in the convergent section. If a laminar boundary layer is maintained in the nozzle, heat transfer coefficients below typical turbulent values would usually be expected. However, at the extremely low Reynolds numbers associated with this test, the laminar coefficients can exceed the turbulent values. This results from the $Re_x^{-0.5}$ dependency of the laminar Stanton number compared to $Re_D^{-0.2}$ for the turbulent. Approximate calculations at TC6 indicate the laminar coefficient could be twice the turbulent value, while the experimental coefficients of Table IV are about three times the typical turbulent value. The higher experimental coefficients cannot be explained by combustion product radiation or chemical reactions in the boundary layer; a reactive model at the wall mixture ratios inferred herein is almost identical to the non-reactive model of Table IV.

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*The variation of DBFC with MR_w is small for the range of interest herein.

REFERENCES

1. Memo 9751:0318, R. L. Ewen to J. L. Pieper, 16 July 1979, Subject: One-Dimensional Conduction Program

2. Y. S. Touloukian, et. al., Thermophysical Properties of Matter, TPRC Data Series, Vols. 1, 4 and 7, 1970

C - 2

TABLE I. TEST 91 SUMMARY

Duration, sec.	60
Pc, psia	38
Core O/F	6.0
Overall O/F	2.64
Vacuum Thrust, lbf	3.0
Total Flow Rate, lb/sec	.00735
Ambient Pressure, psia	.037

TABLE II. NOZZLE THERMOCOUPLE LOCATION PARAMETERS

	TC5	TC6
Area Ratio	28.9	93.7
Inside Radius, in.	0.672	1.21
Wall Thickness, in.	0.086	0.030
Wall Pressure, psia	0.21	0.047
Exit Plane View Factor	0.112	0.485
Temperature at FS2, °F	2057	1443
Free-Stream Static Enthalpy, Btu/lb	-3715	-4341

TABLE III. RHENIUM PROPERTIES

Temperature °F	Specific Heat Btu/lb-°F	Conductivity 10^{-3} Btu/in-sec-°F
0	.0327	0.655
75	.0332	0.641
200	.0336	.625
400	.0342	.602
600	.0348	.590
800	.0353	.588
1000	.0358	.590
1200	.0364	.593
1400	.0369	.600
1600	.0374	.607
1800	.0379	.616
2000	.0383	.627
2200	.0387	.637

Density = 0.760 lb/in^3

TABLE IV. ANALYSIS SUMMARY

	TC5	TC6
Adiabatic Wall Temperature, °F	2310-2430	1830-2030
Heat Transfer Coefficient, 10^{-4} Btu/in^2 -sec-°F	1.0 - 1.35	.260-.305
Mixture Ratio at the Wall	1.74-1.85	1.44-1.61
Normalized Correlation Coefficient Cg	2.7 - 3.7	2.3 - 2.7
Free-Stream Static Temperature (2D),°R	2270	1738
Free-Stream Molecular Weight	14.09	14.11
Mass Velocity Ratio F_{2D}	1.61	1.62
Film Temperature, °R	2680	2150
DBFC	.0206	.0190

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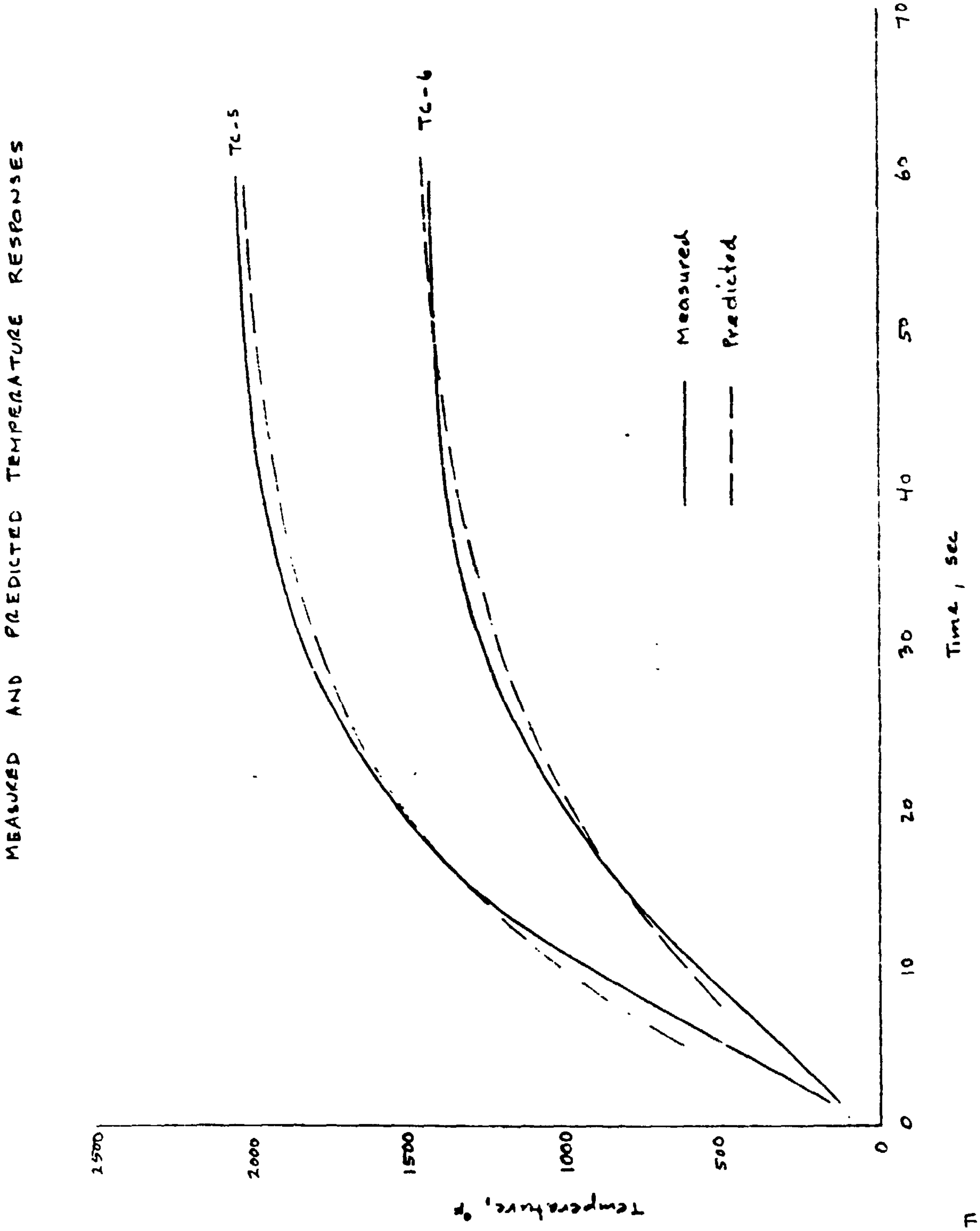

Figure 1

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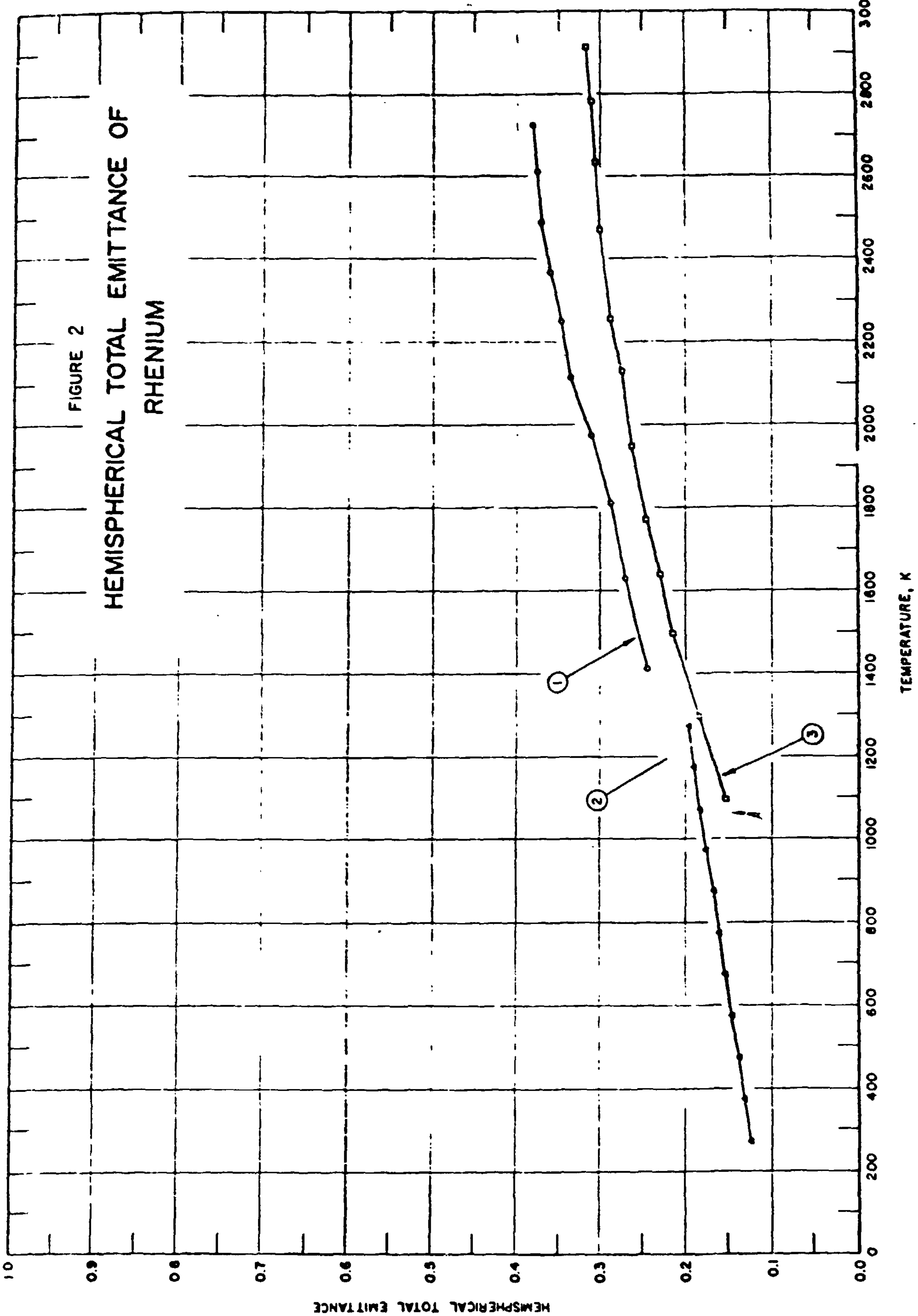


FIGURE 2
HEMISPHERICAL TOTAL EMITTANCE OF RHENIUM

ADIABATIC WALL TEMPERATURES

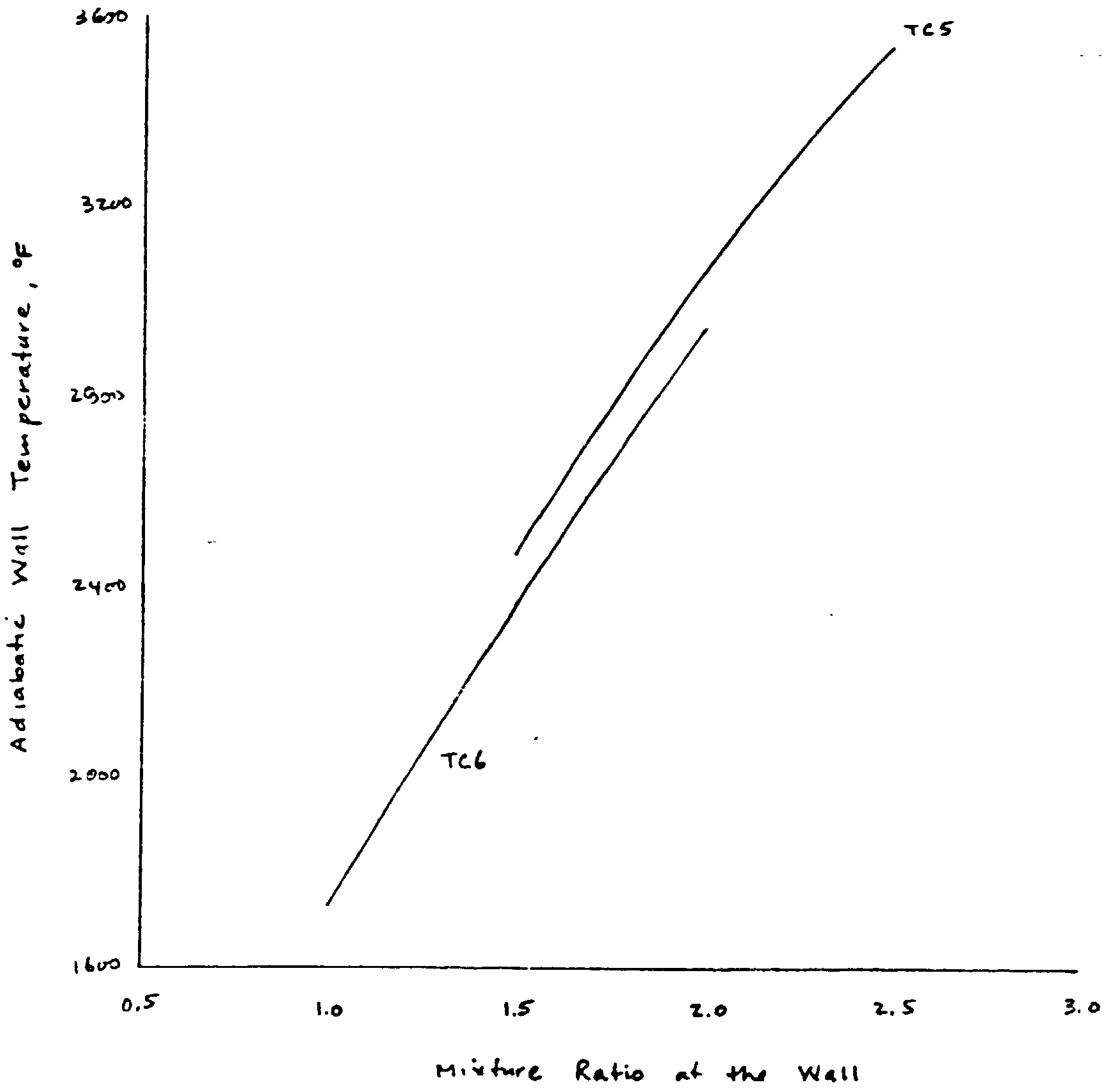


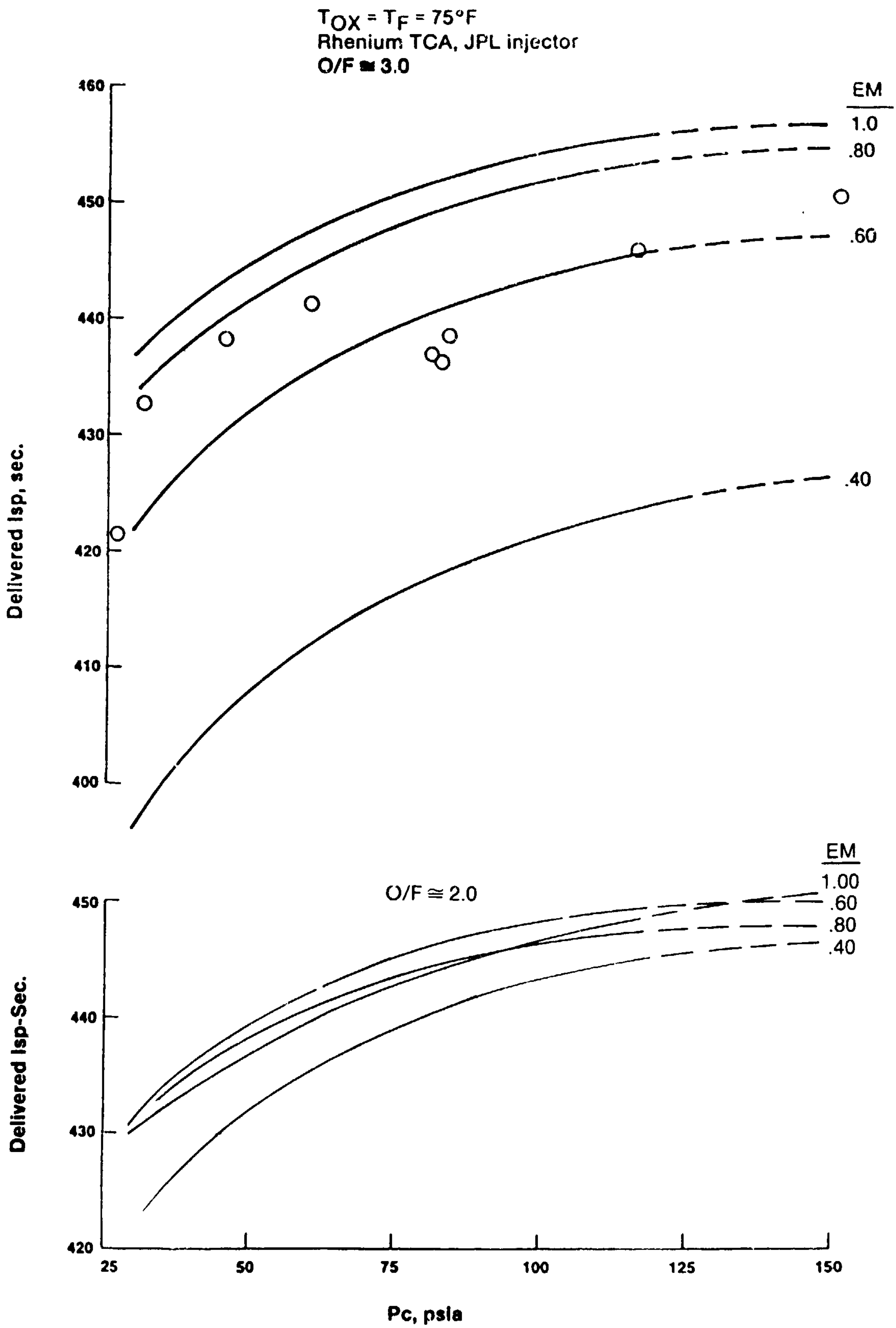
Figure 3

APPENDIX G

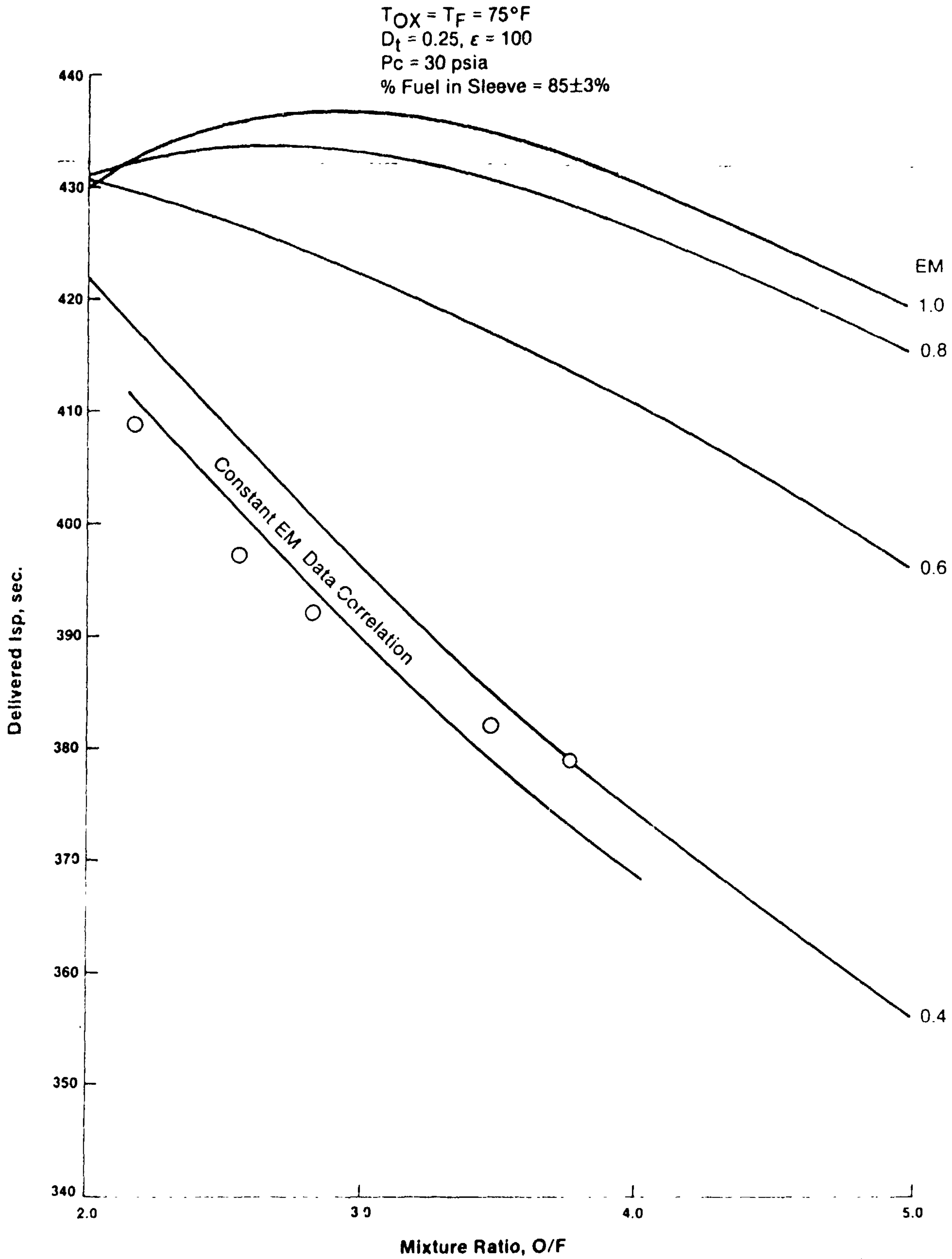
HIGH-PRESSURE TEST SUMMARY

EXTENDED TEST SUMMARY

Test No.	Chamber	Pressure	Propellants	Objective/Comments
123-152	Stainless Steel	30-40 psia	GO_2/GH_2	Installed JPL Injector
153-178	Rhenium	30-40 psia	GO_2/GH_2	-
179-183	Stainless Steel	50-75 psia	GO_2/Methane	-
184-189	Rhenium	30-40 psia	GO_2/GH_2	Data No Good #187
190-195	Rhenium	30-40 psia	GO_2/Methane	Throat Dia Increased $\sim$0.007 in.
196-224	Rhenium	50-150 psia	GO_2/GH_2	>3800°F Rhenium Chamber Temperature



$T_{OX} = T_F = 75°F$
Rhenium TCA, JPL injector
O/F ≅ 3.0
EM
1.0
.80
.60
.40
Delivered Isp, sec.
460
450
440
430
420
410
400
O/F ≅ 2.0
EM
1.00
.60
.80
.40
Delivered Isp-Sec.
450
440
430
420
25
50
75
100
125
150
Pc, psia



$T_{OX} = T_F = 75°F$
$D_t = 0.25, \varepsilon = 100$
Pc = 30 psia
% Fuel in Sleeve = 85±3%
440
430
420
410
400
390
380
370
360
350
340
Delivered Isp, sec.
2.0
3.0
4.0
5.0
Mixture Ratio, O/F
EM
1.0
0.8
0.6
0.4
Constant EM Data Correlation

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