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R-9275

REGENERATIVELY COOLED ROCKET ENGINE
FOR SPACE STORABLE PROPELLANTS

FINAL REPORT

NAS7-765

July 1973

Prepared for

National Aeronautics and Space Administration
Jet Propulsion Laboratory
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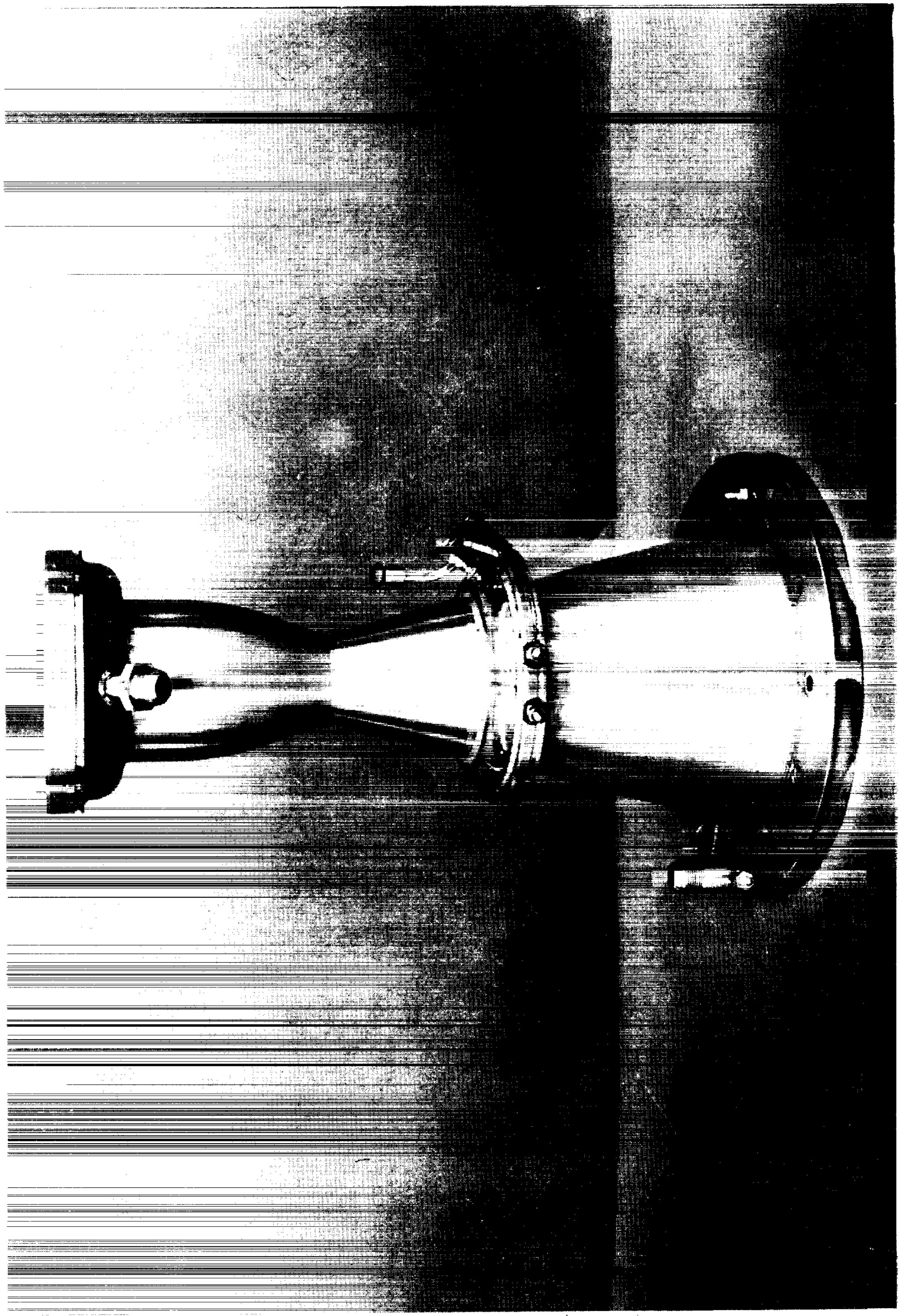

Frontispiece. Completed OF_2-B_2H_6 Double Coolant Jacketed Regenerative Thrust Chamber

ACKNOWLEDGMENTS

The contributions of the following personnel are gratefully acknowledged for the current task effort: Mr. R. Kiningham for the design and fabrication effort, Mr. G. Osugi for the cooling and data analysis, Mr. J. Marus for development support, and Mr. R. Knight for the test effort.

Special thanks go to the Yoke stand crew and all the other supporting fabrication, computing, and data personnel who benefited the program greatly throughout its entirety.

FOREWORD

The results of the analytical and experimental studies conducted by Rocketdyne, a Division of North American Rockwell Corporation under Contract NAS7-765 are presented in this report for the effort expended from 1 May 1972 to 30 December 1972. Previous work on this contract effort conducted from May 1970 through December 1971 has been reported in Rocketdyne report R-8866 published February 1973.

Technical direction for this program was supplied by W. B. Powell of the NASA Jet Propulsion Laboratory during this period. The JPL Program Manager was Mr. R. W. Riebling, and the NASA Program Manager was Mr. W. Cohen.

ABSTRACT

Analysis, design, fabrication, and test efforts were performed for the existing OF_2/B_2H_6 regeneratively cooled 1K (4448 N) thrust chamber to illustrate simultaneous B_2H_6 fuel and OF_2 oxidizer cooling and to provide results for a gaseous propellant condition injected into the combustion chamber.

The regeneratively cooled mode for the OF_2/B_2H_6 propellant combination had been explored on previous work with fuel cooling and for the current work the combined cooling mode had been selected for demonstration in an advanced fabrication milled channel construction thrust chamber.

Design, analysis, and fabrication efforts were completed satisfactorily for the thrust chamber with an integral OF_2 cooling jacket and manifolding provided together with the B_2H_6 cooling circuit. Various start and operating performance projections were made for both the demonstrator hardware and flight design configurations.

Test stand buildup for the thrust chamber hardware was accomplished including buildup for LN_2 and Freon propellant conditioning systems and propellant supply systems. In addition altitude diffuser hardware and cooling systems were reinstalled.

Thrust chamber regenerative test operation was accomplished in a series of eight tests at varying mixture ratio and run durations. A 50-second final duration test was terminated prematurely at 22 seconds by an OF_2 feed line failure. Values of 90.7 to 99.8 percent c* efficiency were noted for the longer duration tests. Minimal combustion deposits were observed at MR $\geq$ 3.0.

Data derived from performance, thermal and flow measurements confirmed predictions derived from previous test work and from concurrent analytical study. Development data derived from the experimental study were indicated to be sufficient to develop a preflight thrust chamber demonstrator prototype for future space mission objectives.

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INTRODUCTION AND SUMMARY

Previous investigations established the performance and regenerative cooling capabilities of B_2H_6 fuel with FLOX and OF_2 mixtures for space storable propulsion applications involving low chamber pressures (100 psia, 6.894×10^5 N/m^2) and relatively low thrust levels (1000 pounds, 4448 N) with a potential of 406 second impulse. The current program had the objective of extending the technology of regenerative thrust chamber cooling to the space storable propellants oxygen difluoride/diborane. The effort was undertaken because of the expanded interest in application of these propellants to establish workable hardware for future application to space propulsion systems. The overall goal of the previous investigation has been to provide analytical data, with experimental verification, to define the regenerative cooling capabilities of B_2H_6 when used with FLOX mixtures or OF_2.

The previous NASA contracted program work, conducted at Rocketdyne, was directed to provide these data over a range of variables. To obtain valid experimental heat transfer data in the combustion chamber and throat regions, it was necessary to conduct the tests with a high performance injector. Accordingly, a primary goal of this program was also to provide an injector capable of delivering a high characteristic exhaust velocity (c*) (93-96 percent of the theoretical value) for the conditions tested. A final goal was to provide an injector capable of stable operation at the design point. A summary of nominal engine parameters is shown in Table 1.

The completed project work had a duration of 20 months and was initiated on 1 May 1970. The interim summary report (Ref. 1) provided to NASA contains a description of the five previous technical effort tasks.

The project had a planned duration of 9 months and was initiated in April 1972 and concluded December 1972. This report contains a description of program work including analytical and test technical efforts. A summary of the three technical tasks is described as follows:

TABLE 1. NOMINAL DESIGN ENGINE FLIGHT SPECIFICATIONS

Cooling Propellant	Fuel and Oxidizer
Coolant Type	Regenerative-Double Jacketed
Thrust, pounds (N)	1000 (4448)
Specific Impulse (seconds)	405
Propellants (o/f)	OF_2/B_2H_6
Propellant Flow, lb/sec (Kg/sec)	2.47 (1.12)
Characteristic Velocity, ft/sec (m/sec)	6730 (2052)
Mixture Ratio	3.0
Area Ratio	60
Chamber Pressure, psia (N/m^2)	100 (6.89×10^5)
Throat Area, in^2 (cm^2)	5.305 (34.22)
Engine Fuel Inlet Pressure, psia (N/m^2)	190 (1.31×10^6)
Engine Oxidizer Inlet Pressure, psia (N/m^2)	180 (1.24×10^6)
Engine Fuel Inlet Temperature, R (K)	210 (117)
Engine Oxidizer Inlet Temperature, R (K)	230 (128)
Engine Fuel Injection Pressure, psia (N/m^2)	120 (8.27×10^5)
Engine Oxidizer Injection Pressure, psia (N/m^2)	125 (8.60×10^5)
Engine Fuel Injection Temperature, R (K)	735 (408)
Engine Oxidizer Injection Temperature, R (K)	550 (305)
Thrust Chamber Construction	Milled Channel/Electroformed Closeout
Thrust Chamber Material	Copper/Nickel
Dry Thrust Chamber Assembly Weight, pounds (Kg)	22 (10)
Dry Engine Weight, pounds (Kg)	33 (15)

Task VI: Thrust Chamber Modification

Based on analysis of data obtained in Ref. 1, detailed thermal analyses of the oxidizer coolant panel was conducted and one of the existing two thrust chambers was modified to incorporate integral OF_2 lengthwise coolant passages. The modified thrust chamber incorporated provisions for mounting JPL flight type propellant valves. Table 1 illustrates the nominal engine conditions.

Task VII: Demonstration of Dual Panel Regenerative Cooling With OF_2 and B_2H_6

Following test stand buildup, a series of short duration firings was conducted for the evaluation of startup and shutdown, performance, and heat transfer. During this test series, off-nominal test series including variations in propellant inlet temperatures and thrust chamber initial start temperatures were conducted and these effects on performance and heat transfer were demonstrated. Coincident with these tests, startup and shutdown transient performance was evaluated. Final tests of 10 and 22 seconds duration were accomplished. Characteristic velocity efficiencies ranging from 90.7-99.8 percent were observed with minimal boride combustion deposit conditions at MR values ≥ 3.0.

Task VIII: Reporting

In this task, monthly, quarterly, and summary reports were submitted for approval by the NASA JPL Technical Manager.

TECHNICAL DISCUSSION

TASK VI - THRUST CHAMBER MODIFICATION

During Task VI accomplished work included heat transfer and fluid flow analysis study performed preparatory to the design of the OF_2 cooling jacket to be incorporated for OF_2 flow gasification. Design studies were performed which developed the best approaches to incorporation of the cooling passages into the existing electroformed nickel layer on the No. 1 thrust chamber and for the adaptation of the OF_2 inlet and outlet manifolds to the existing flange points. Design, release of the drawings, and fabrication of the hardware were also accomplished during this Task VI effort.

Evaluations of both the existing modified hardware design and the proposed demonstrator prototype configuration were made to establish priming, start and cutoff impulse levels and the thermal transients associated with the thrust chamber hardware. In this study, determination of feed system capacitance and responses were evaluated.

The following discussion summarizes the fluid flow and thermal design analysis, thrust chamber fabrication and the analytical studies related to the start, run and shutdown transient aspects.

OXIDIZER FLUID FLOW AND HEAT TRANSFER DESIGN STUDY

A detailed thermal review of the experimental data obtained under Ref. 1 study indicated that both the fuel and oxidizer could be vaporized prior to injection with the existing thrust chamber heat input. The vaporization of B_2H_6 would occur in the low heat flux nozzle section and B_2H_6 would cool the throat and combustor as a gas. The secondary oxidizer coolant (OF_2), introduced at the existing common nozzle inlet location for the demonstrator, was proposed to supplement the primary B_2H_6 cooling and inject as a gas.

Completed studies showed the oxidizer cooling jacket to consist of 90 channels located behind the B_2H_6 channels. The channels were designed with a non-varying width of 0.060 inch and tailored lengthwise channel heights varying between 0.040 and 0.063 inch (1.0 to 1.6 mm). OF_2 channel widths of 0.050 to 0.070 inch (1.27 to 1.78 mm) were examined to provide a range of coolant mass velocities. Figure 1 illustrates the design range of coolant mass velocity. A channel width of 0.060 inch (1.53 mm) was based on the requirement of a minimum land with (0.046 inch) (1.17 mm) at the throat location. Channel height was varied with the inlet to throat point constant at 0.040 inch (1.0 mm), (G = 9.15 lb/in^2-sec or 6.37 x 10^3 kg/m^2-sec). A minimum coolant mass velocity of 5.83 lb/in^2-sec (4.1 x 10^3 kg/m^2-sec) was chosen to minimize coolant jacket discharge pressure loss and to employ the existing layer of electroformed nickel on the No. 1 OF_2/B_2H_6 regenerative chamber.

Figure 2 illustrates the inlet and outlet temperature levels and corresponding enthalpy levels. It is calculated that a 135 Btu/lb (3.13 x 10^5 j/kg) enthalpy rise would occur through the cooling passage resulting in an OF_2 outlet temperature of 90 F (32 C). Heat transfer rates for the OF_2 was based on available Rocketdyne supercritical and subcritical O_2, F_2, and OF_2 tube cooling data corrected for the design conditions. Figure 3 and 4 illustrate heat flux data for LO_2 with phase change as a function of mass velocity. A 10 percent reduction of the OF_2 heat transfer coefficients below this data was expected due to a lowered OF_2 heat capacity value. Based on the design mass velocity conditions an OF_2 heat flux input range of 0.64 to 0.90 Btu/in^2-sec (1.05 x 10^6 to 1.47 x 10^6 watt/m^2) was anticipated.

THRUST CHAMBER DESIGN THERMAL PARAMETERS

Prediction of the coolant total heat load for the combined double jacketed thrust chamber was based on the measured water and B_2H_6 heat input data derived from the previous Task IV regenerative testing. As shown in Fig. 5 , a total heat load of 600 Btu/sec (633 x 10^3 j/sec) was projected, to be shared 54 percent

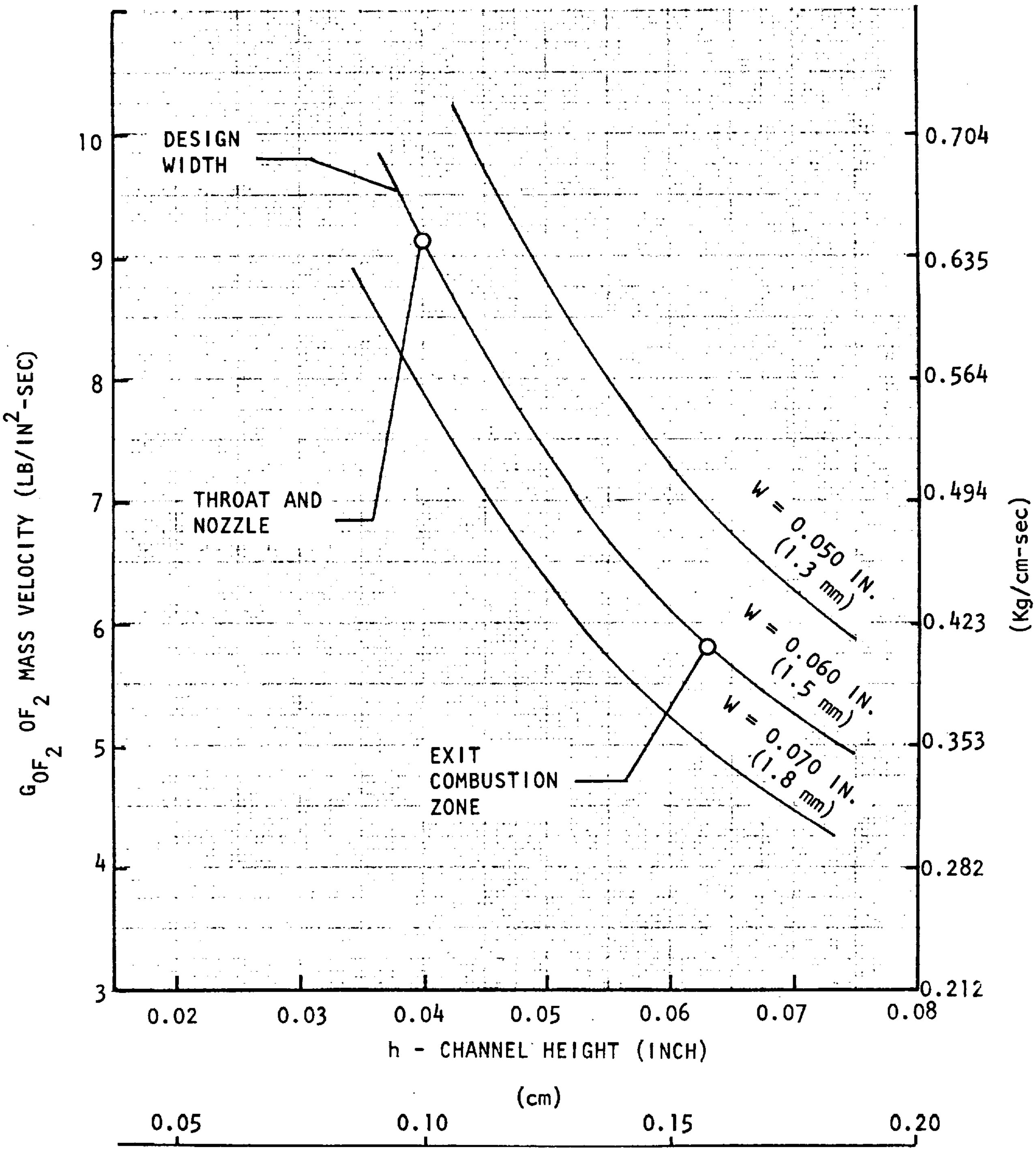


Figure 1. OF_2 Coolant Mass Velocity Versus Channel Height

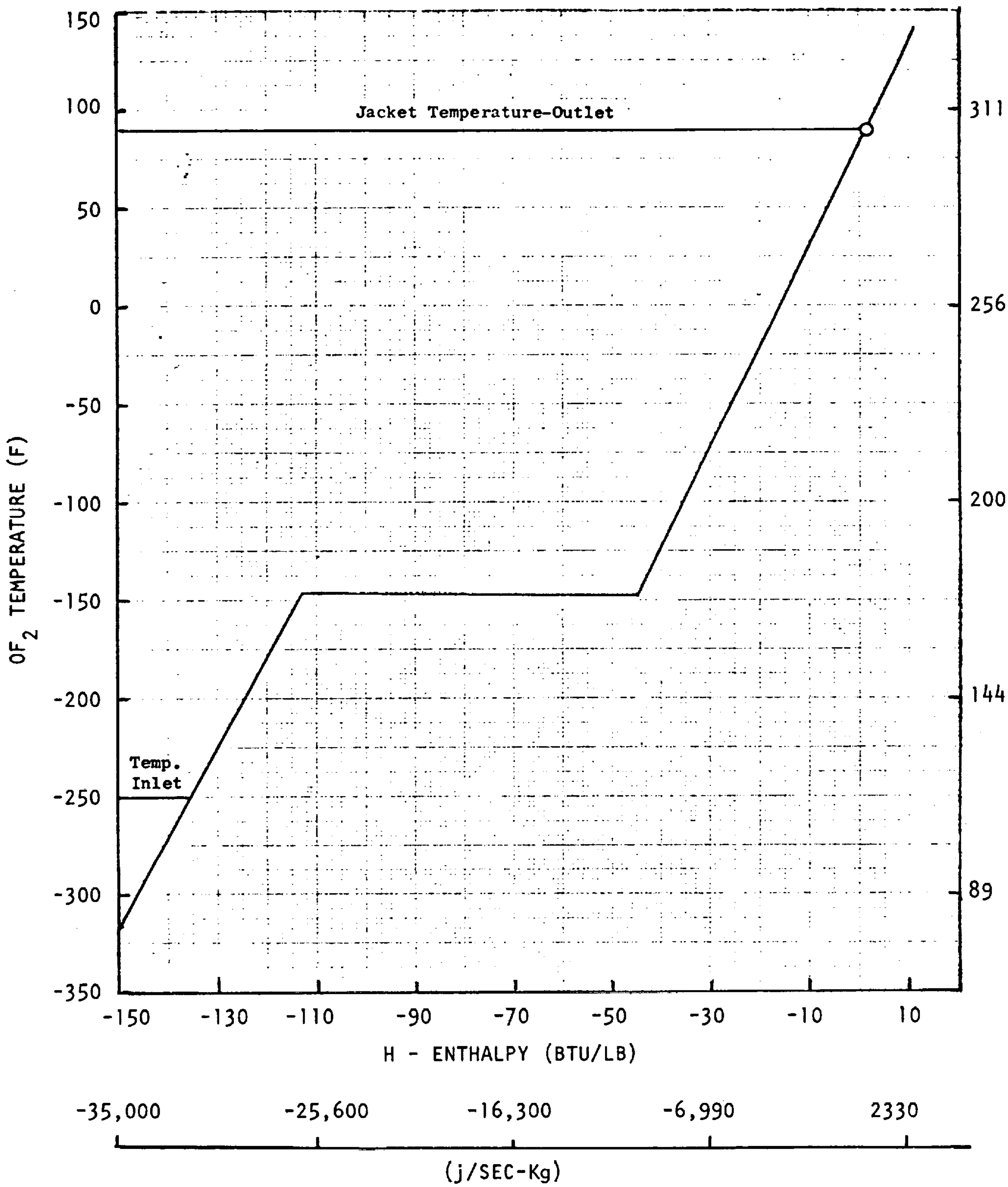


Figure 2. OF_2 Temperature Enthalpy Diagram (P = 175 psia, 1.21×10^6 N/m^2)

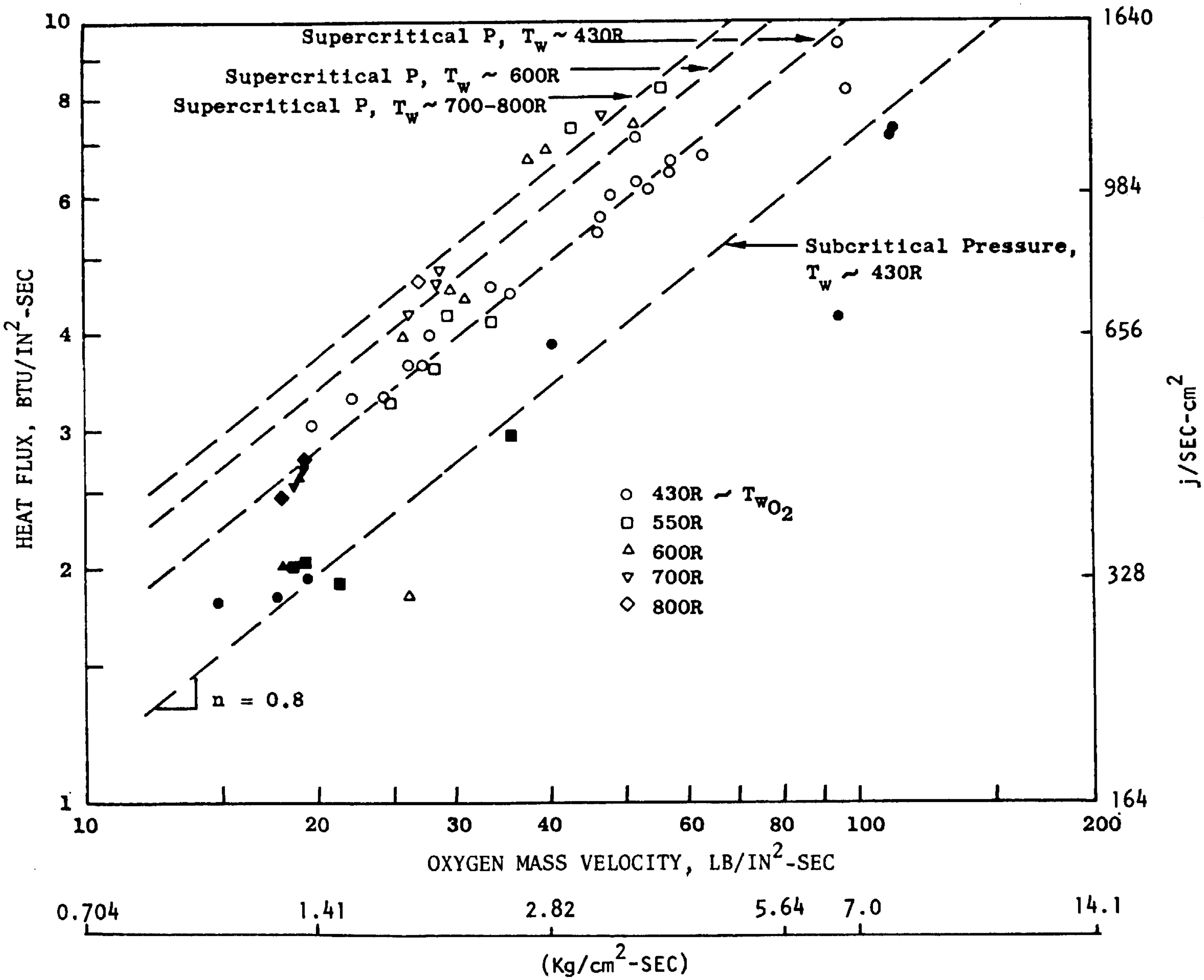


Figure 3. Concentric Tube Oxygen Heat Transfer Data - Models 1 and 3

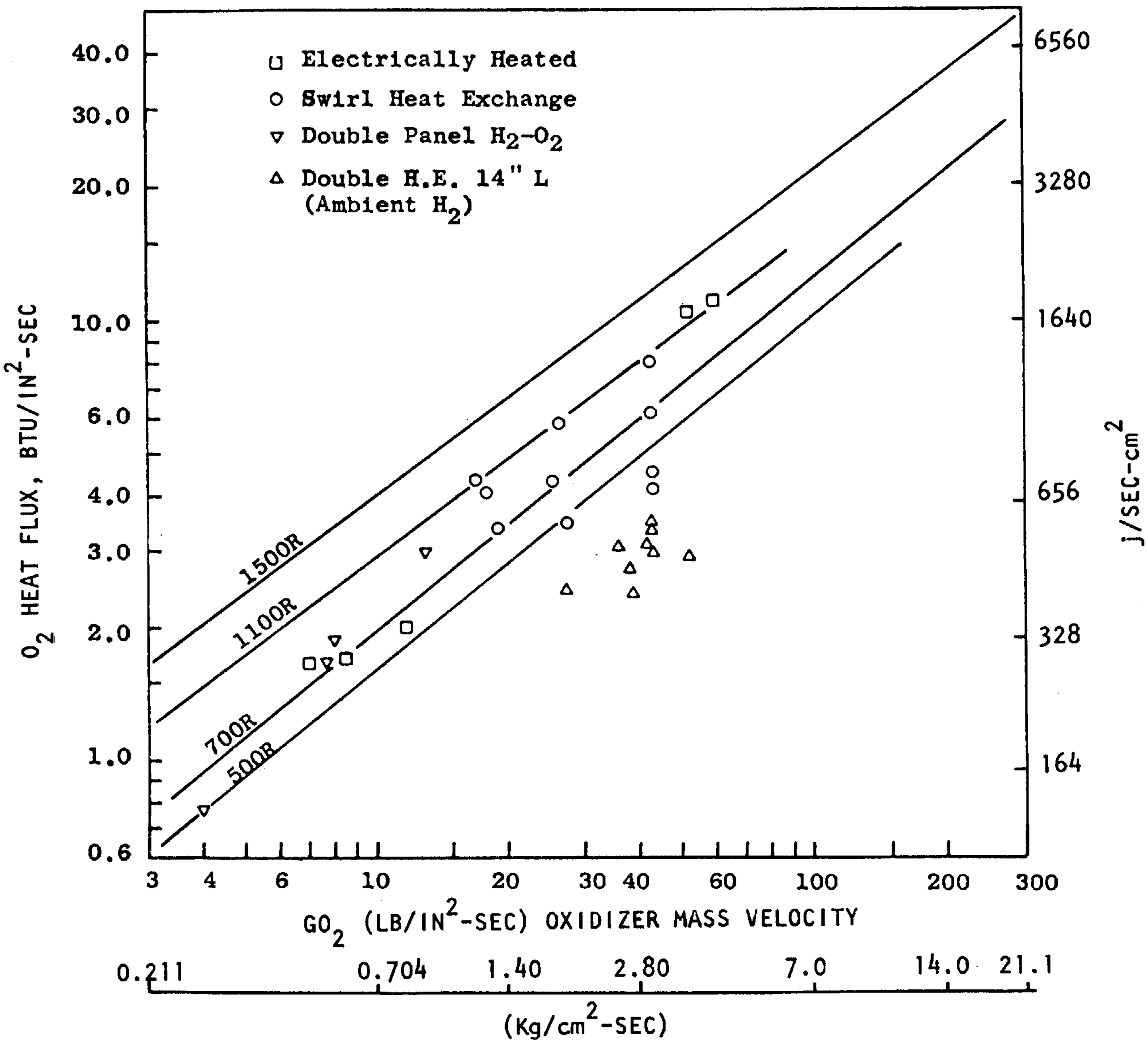


Figure 4. Liquid Oxygen Cooling Experimental Heat Flux vs Mass Velocity Data

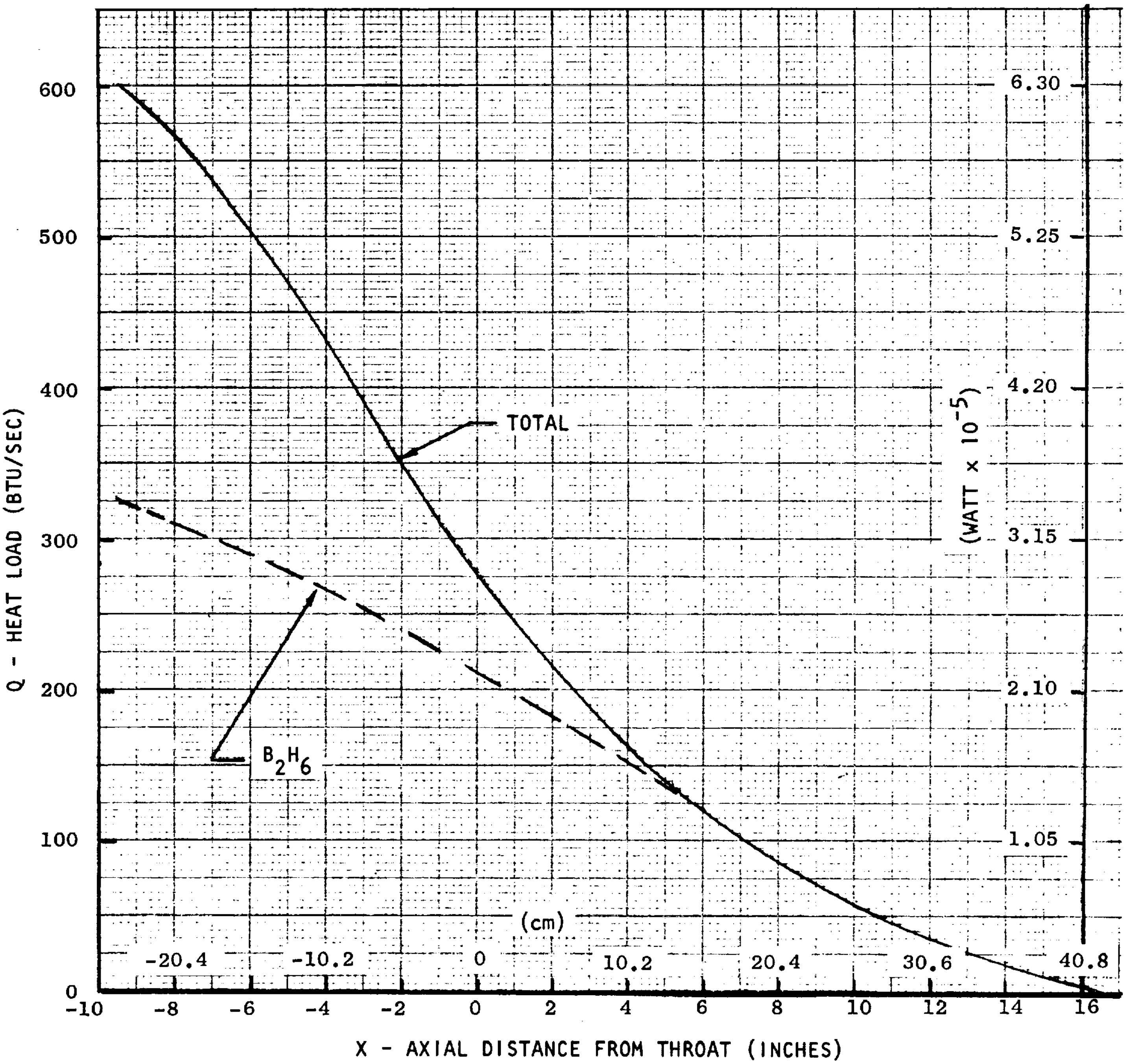


Figure 5. OF_2/B_2H_6 Total Chamber Heat Load vs Axial Distance (P_c = 100 psia, MR = 3.0)

to the B_2H_6 and 46 percent to the OF_2 oxidizer. Distribution of the heat load was based on the calorimeter heat flux profile measured during Task IV testing.

Figure 6 illustrates the design heat flux profile representative of the Task IV test results with the calorimeter. A peak heat flux of 4.15 Btu/in^2-sec (6.78 x 10^6 watt/m^2) occurs in the throat region and diminishes to 1.0 Btu/in^2-sec (1.63 to 10^6 watt/m^2) in the cylindrical portion of the combustor.

Figure 7 illustrates the OF_2 and B_2H_6 predicted coolant temperature profiles through the axial length of the chamber. Vaporization is completed for B_2H_6 propellant by 1 inch (2.54 cm) downstream of the throat with the OF_2 propellant vaporized at 4 inches (10.2 cm) upstream of the throat. An inlet condition of -250 F (117 K) was assumed). Discharge temperatures of 310 F (427 K) for the B_2H_6 fuel and 90 F (305 K) for the OF_2 oxidizer were predicted.

Final prediction comparison with test data was to be based on OF_2 and B_2H_6 jacket inlet temperatures obtained during the Task VII test series.

A two-dimensional computer model was developed for the throat, combustion zone, and area ratio of 6.0 points to establish the wall temperatures at these points. A nodal network of 377 nodes was set up on the Rocketdyne DEAP (Differential Equation Analyzer Program) to develop the steady state temperature distribution around the cooling passages.

Figure 8 illustrates the throat wall temperature distribution. A peak gas wall temperature of 493 F (530 K) and back wall of 251 F (395 K) is shown. A small thermal gradient exists due to the low heat flux level imposed, combined with the high conductivity copper and nickel materials.

Figure 9 illustrates the combustor region wall temperature distribution for a heat flux of 1 Btu/in^2-sec (1.63 x 10^6 watt/m^2). A peak gas side wall temperature of 442 F (502 K) and back wall temperature of 372 F (462 K) is illustrated. A lesser thermal gradient exists from the wall front to back side as a result of a lowered heat flux level.

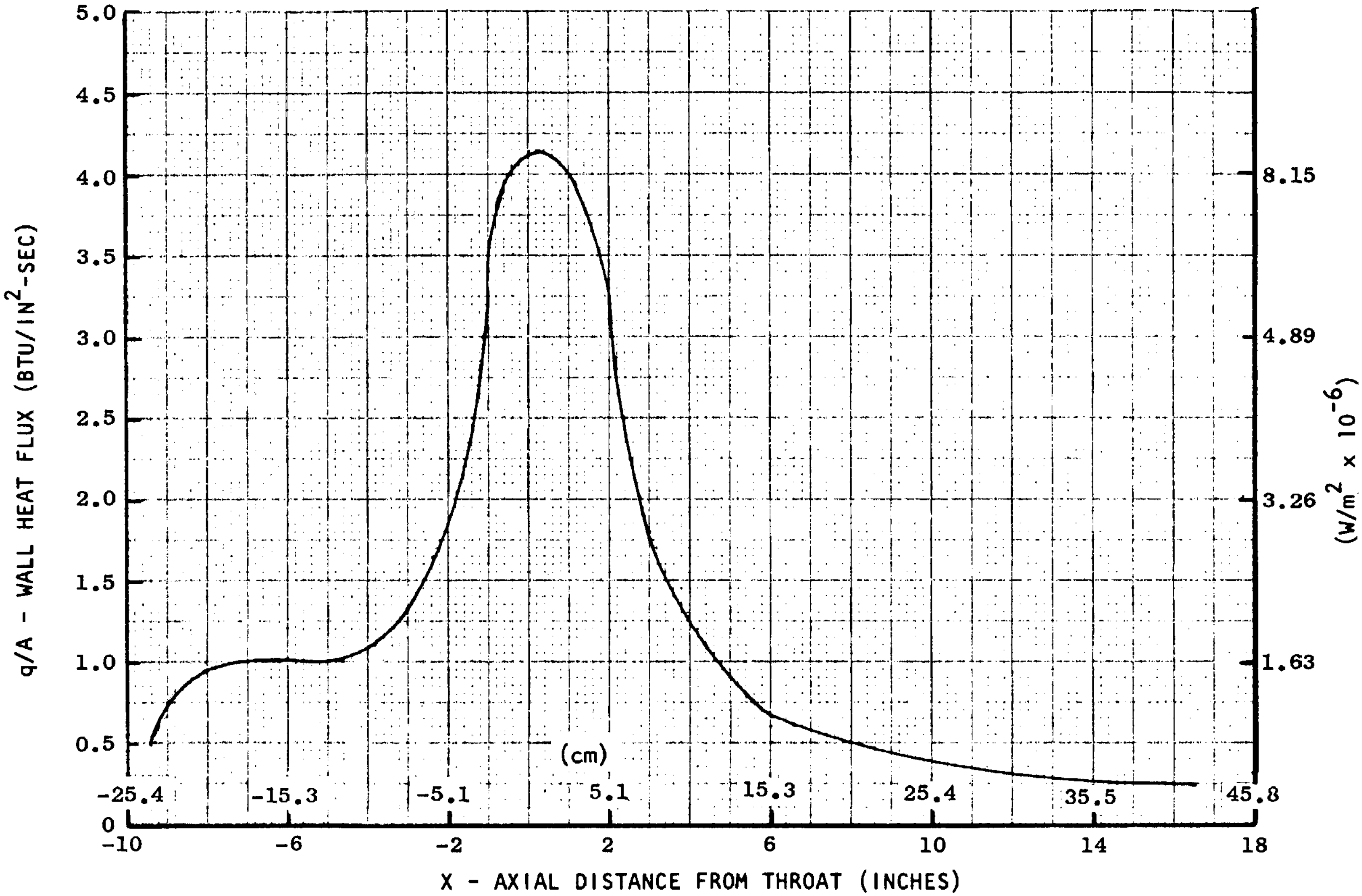


Figure 6. OF_2/B_2H_6 Regeneratively Cooled Chamber Design Heat Flux Profile

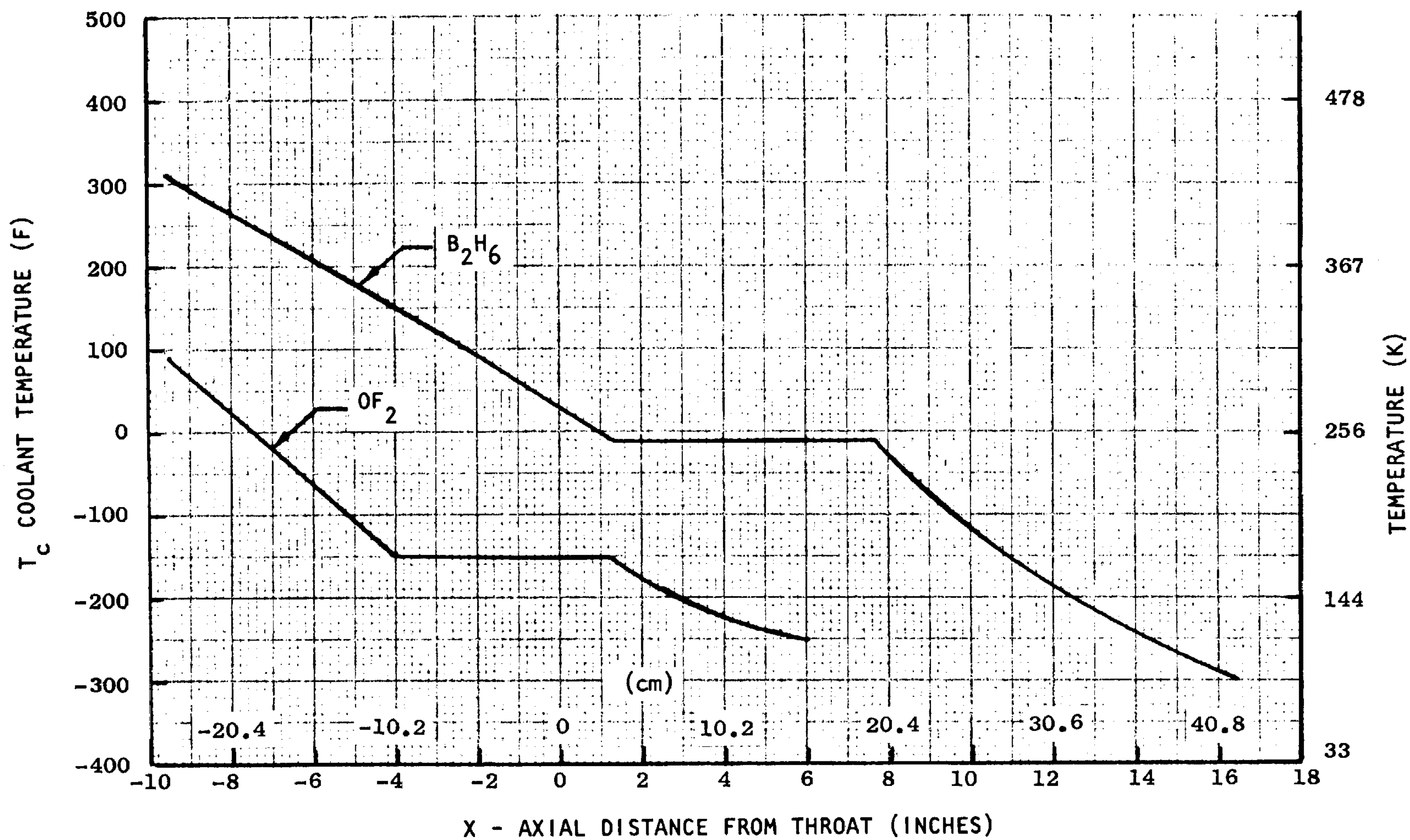
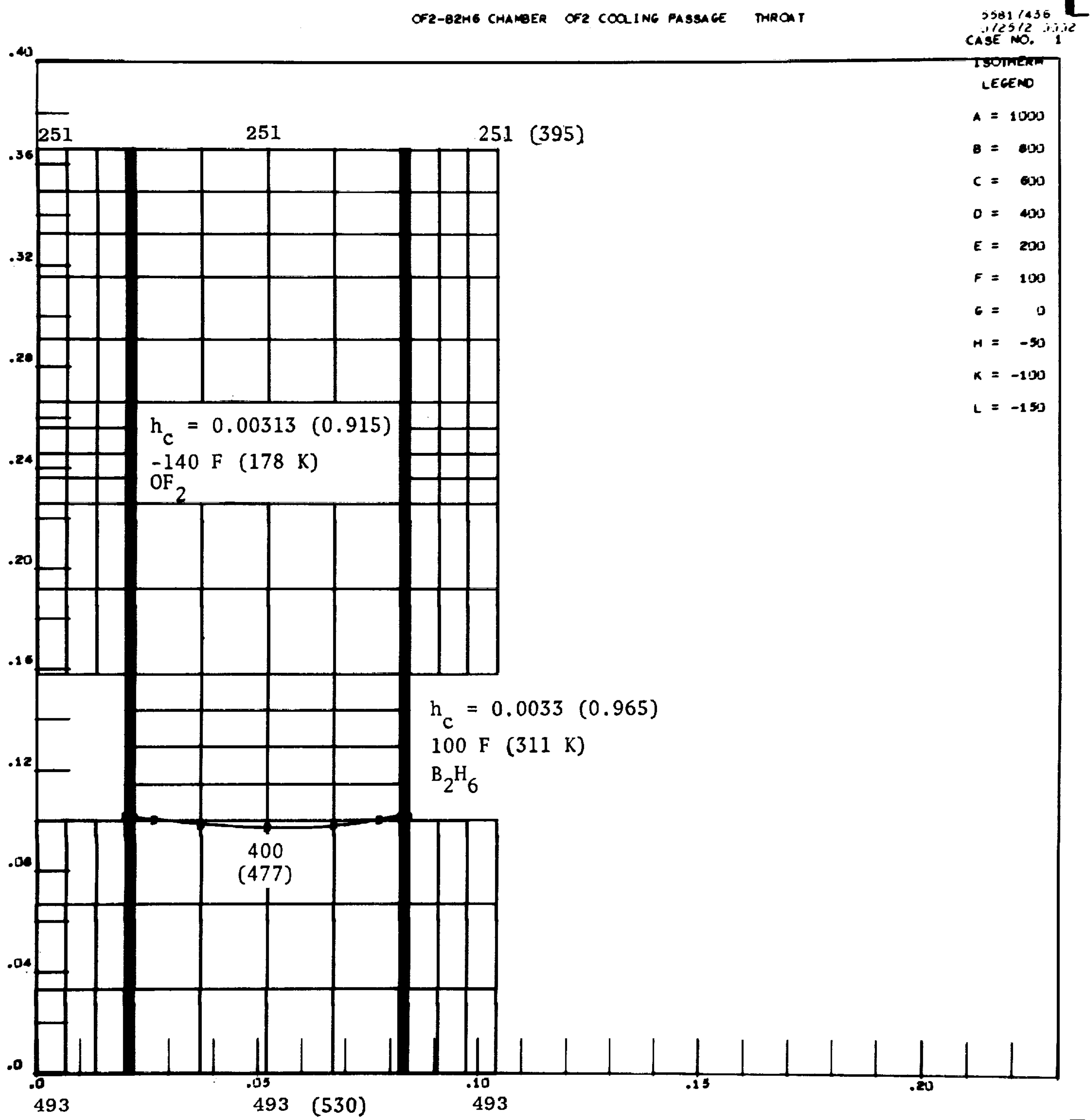
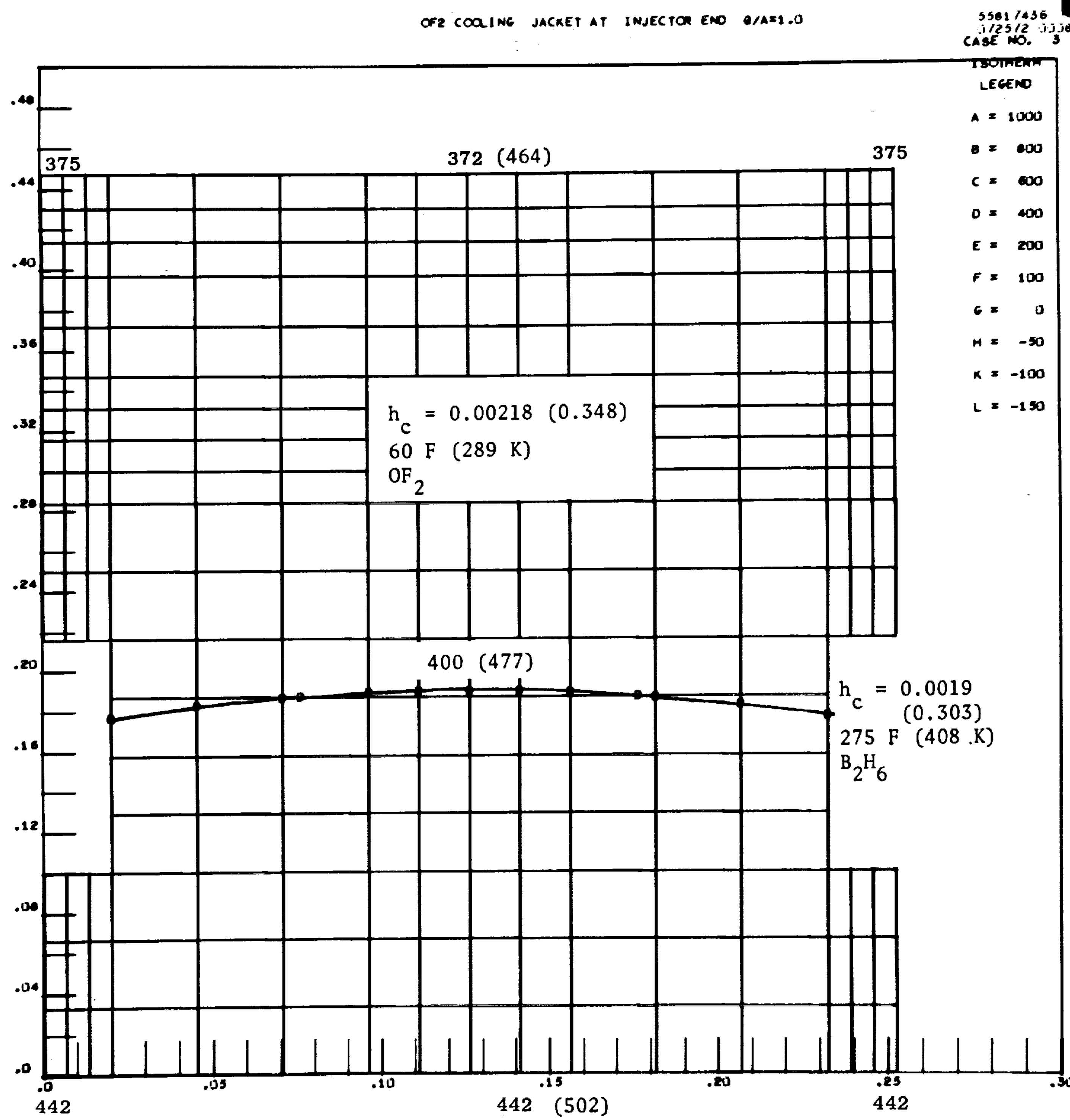


Figure 7. OF_2/B_2H_6 Regenerative Chamber Coolant Temperature Profiles



h_g = 0.000625 Btu/in^2-sec-R (0.183 j/cm^2-sec-K), T_{AW} ≐ 7000 F (4150 K)

Figure 8. Two-Dimensional Thermal Analysis of Throat Section



h_g = 0.000149 Btu/in^2-sec-R (0.0238 j/cm^2-sec-K), T_{AW} = 7000 F (4140 K)

Figure 9. Two-Dimensional Thermal Analysis of Injector End Section

Figure 10 illustrates the OF_2 entry point temperature distribution for a heat flux of 0.685 Btu/in^2-sec (1.12×10^6 watt/m^2). A peak gas wall temperature of 51 F and back wall of -2 F (284 K and 255 K, respectively) were determined.

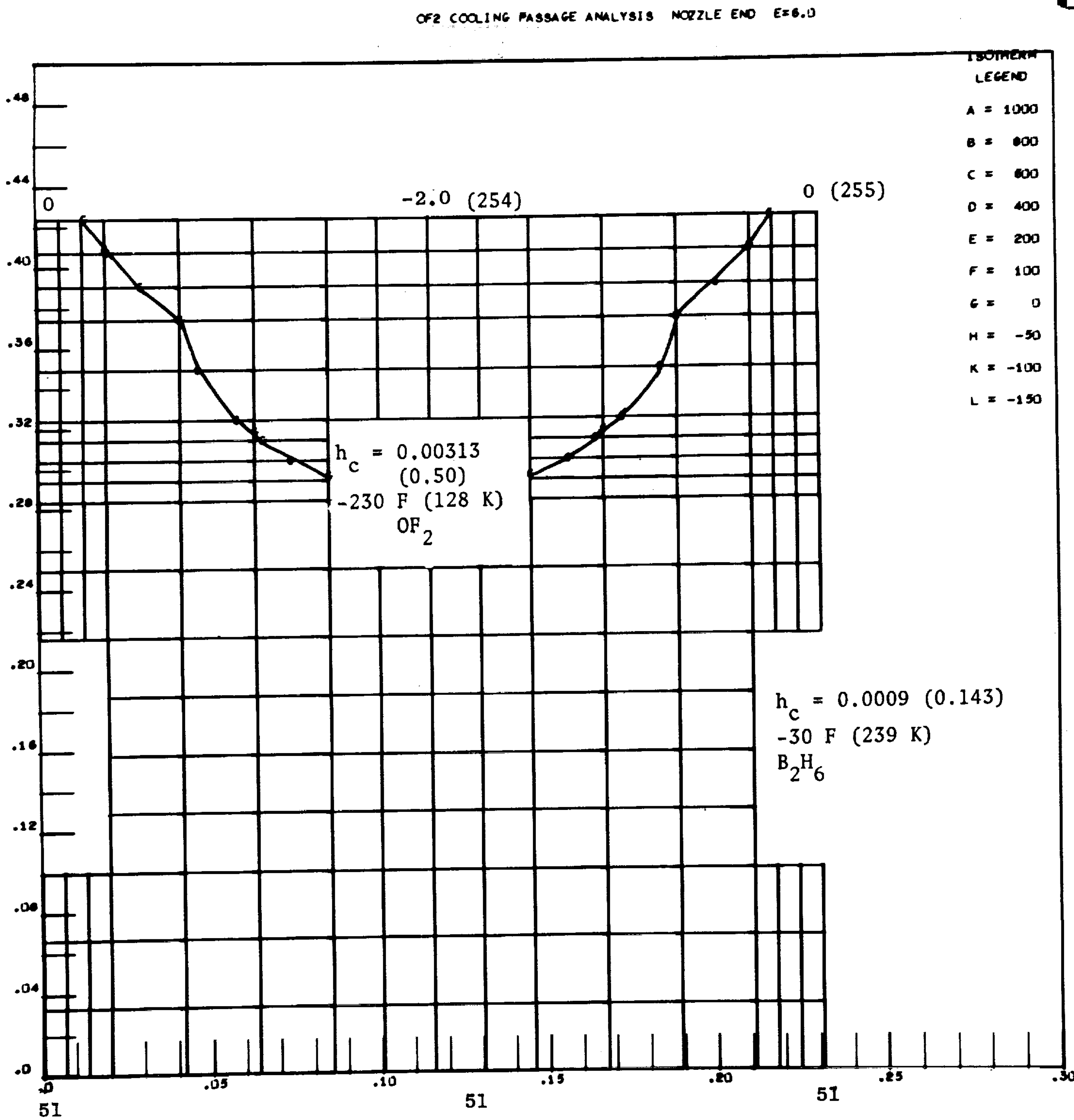
OF_2 COOLING JACKET DESIGN CONFIGURATION

Figure 11 illustrates a drawing of the chamber assembly design including manifolding. A single inlet manifold externally supported to the presently existing water inlet flange was provided. Adaptation to the JPL furnished valve assembly (Ref. 4) with close coupling to minimize start and shutoff volume was also provided.

Discharge from the OF_2 cooling channels was directed through an expansion turn into the discharge manifold volume in order to reduce the discharge head losses. Minimum discharge manifold volume, with two discharge points located 180 degrees apart to feed the injector inlet, was provided. TIG welding of the OF_2 discharge manifold to the existing injector flange was proposed.

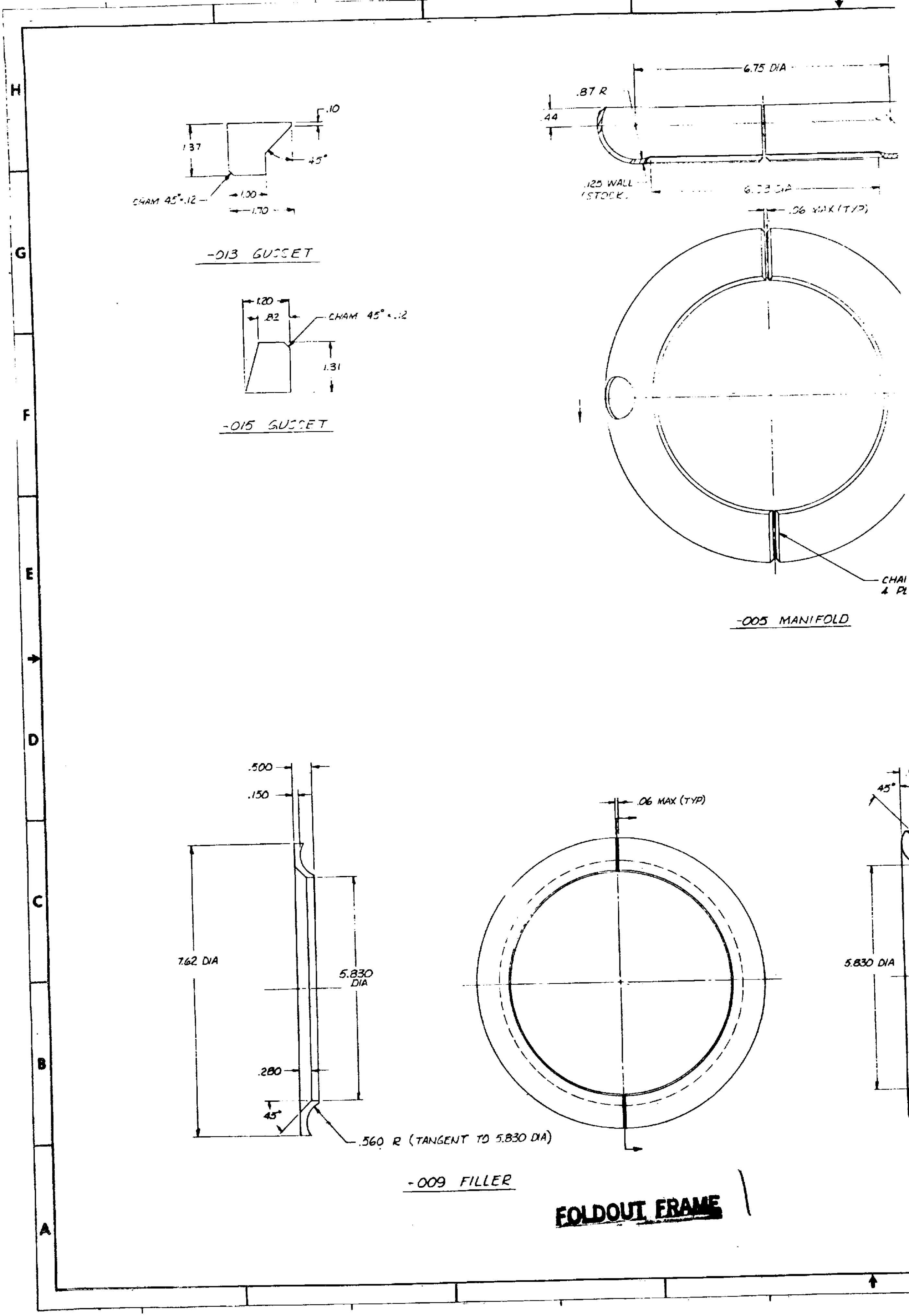
The design shown utilizes the existing electroformed nickel jacket covering the B_2H_6 channels to provide the material for OF_2 channel machining. The decision to employ the existing nickel layer without an added small layer at the forward end (to provide a greater depth for OF_2 coolant passage discharge) was made. This decision was based on cost, time, and risk estimates which favored the use of the existing unmodified nickel layer.

Manifold shell design pressures were set at 375 psia (2.58×10^6 N/m^2) to ensure an adequate safety factor for manifold pressure surges and possible ignition pressure spikes.

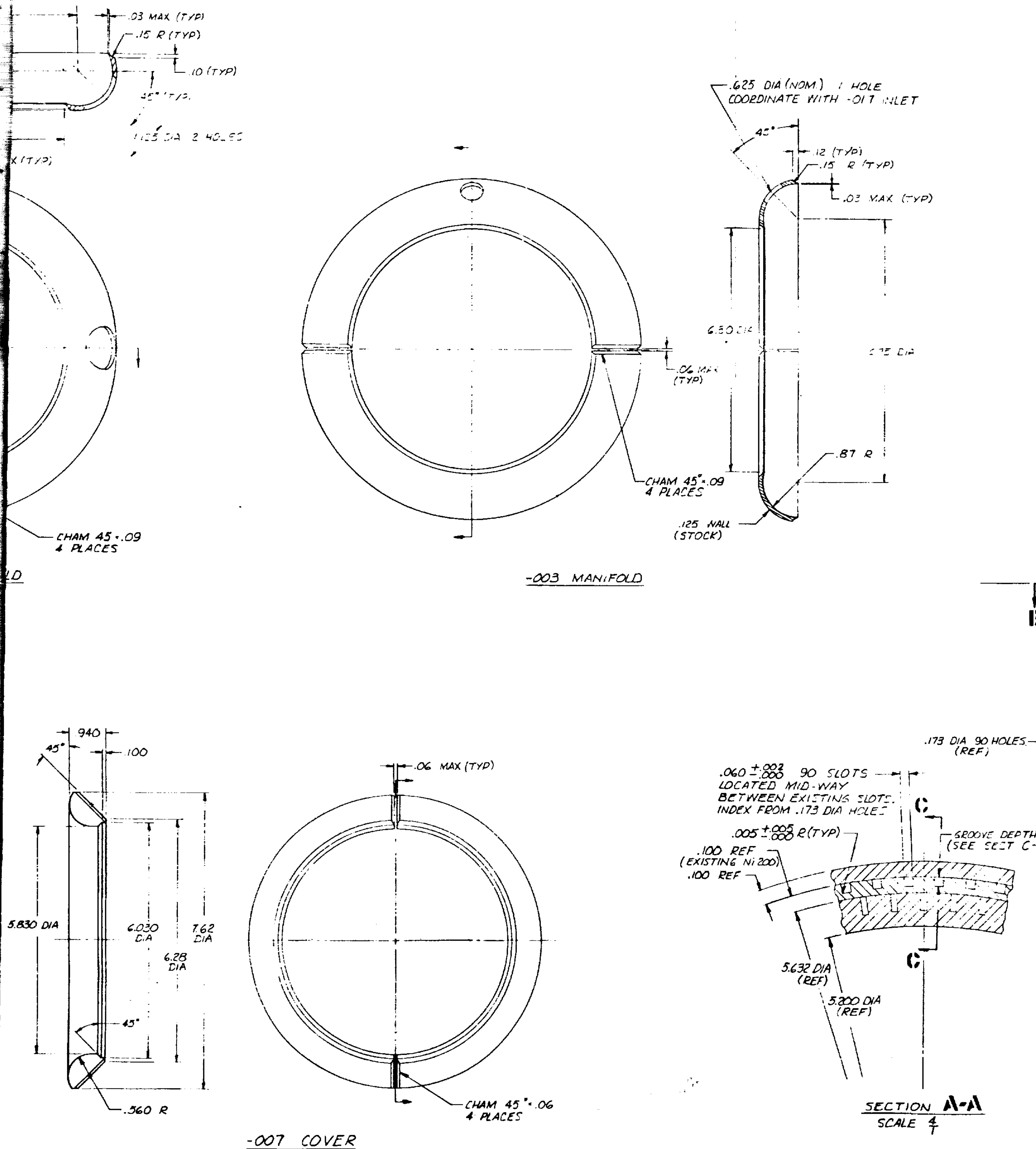


h_g = 9.85 x 10^{-5} Btu/in^2-sec-R (0.0157 j/cm^2-sec-K), T_{AW} = 7000 F (4140 K)

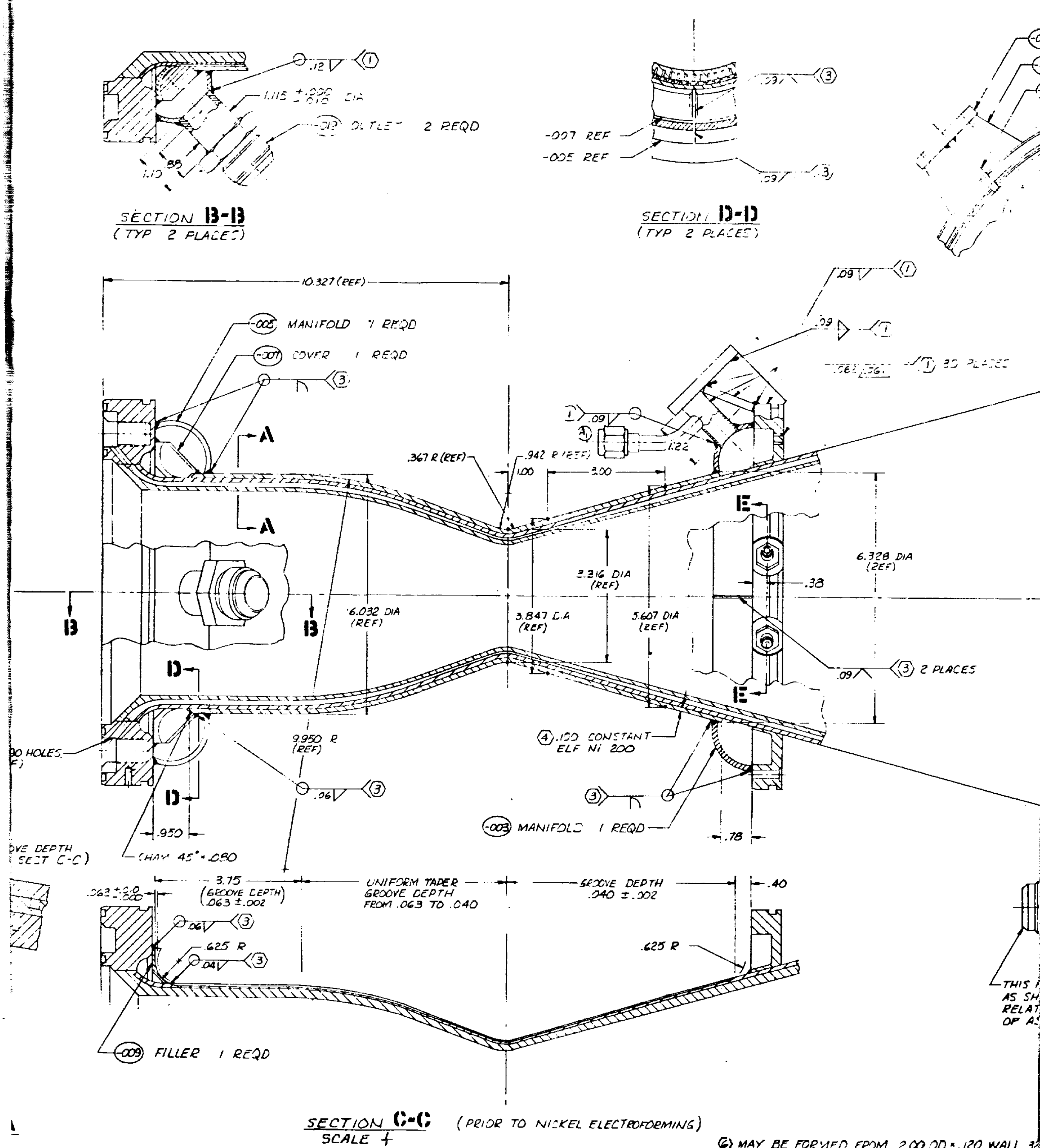
Figure 10. Two-Dimensional Thermal Analysis of Nozzle End Section



FOLDOUT FRAME

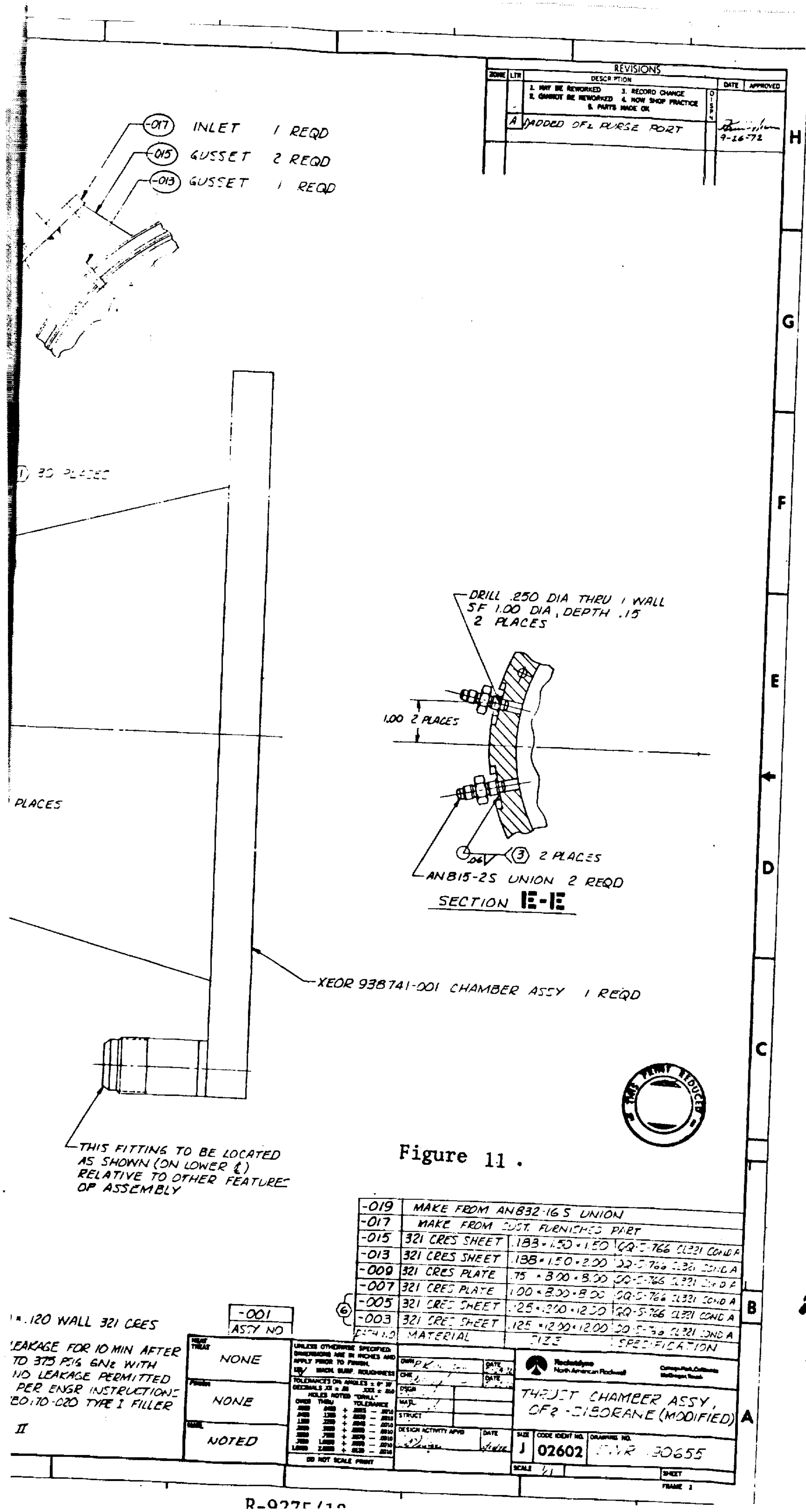


FOLDOUT FRAME 2



FOLDOUT FRAME 3

6 MAY BE FORMED FROM 2.00 OD × .120 WALL 3… TUBING
5. TEST FOR EXTERNAL & INTERNAL LEAKAGE FOR 10… PRESSURIZING OUTER MANIFOLD TO 375 PSIG GN… ASSEMBLY SUBMERGED IN WATER. NO LEAKAGE P…
4 ELECTROFORM NICKEL CLOSURE PER ENGR INS…
3 GTA BRAZE PER RA0107-027, USE RB0170-020 TYP…
2 MACHINE PER RA0103-002
1 WELD PER RA0107-027 CLASS II
NOTES: UNLESS OTHERWISE SPECIFIED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-015 GUSSET 2 REQD
-013 GUSSET 1 REQD
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DRILL .250 DIA THRU 1 WALL
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SECTION E-E
XEOR 938741-001 CHAMBER ASSY 1 REQD
THIS FITTING TO BE LOCATED AS SHOWN (ON LOWER ℄) RELATIVE TO OTHER FEATURES OF ASSEMBLY
THIS PRINT REDUCED
-019 MAKE FROM AN832-16S UNION
-017 MAKE FROM CUST. FURNISHED PART
-015 321 CRES SHEET .188 × 1.50 × 1.50 QQ-S-766 CL321 COND A
-013 321 CRES SHEET .188 × 1.50 × 2.00 QQ-S-766 CL321 COND A
-009 321 CRES PLATE .75 × 3.00 × 3.00 QQ-S-766 CL321 COND A
-007 321 CRES PLATE 1.00 × 8.00 × 8.00 QQ-S-766 CL321 COND A
-005 321 CRES SHEET .125 × 12.00 × 12.00 QQ-S-766 CL321 COND A
-003 321 CRES SHEET .125 × 12.00 × 12.00 QQ-S-766 CL321 COND A
DASH NO. MATERIAL SIZE SPECIFICATION
6
.120 WALL 321 CRES
LEAKAGE FOR 10 MIN AFTER TO 375 PSIG GN2 WITH NO LEAKAGE PERMITTED PER ENGR INSTRUCTIONS 80170-020 TYPE I FILLER
II
-001
ASSY NO
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FINISH NONE
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UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES AND APPLY PRIOR TO FINISH.
DO NOT SCALE PRINT
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Rocketdyne
North American Rockwell
THRUST CHAMBER ASSY, OF2 - DIBORANE (MODIFIED)
SIZE J
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30655
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A

Figure 11.

Chamber Wall Thermocouple Instrumentation

Testing employed chromel-alumel thermocouples on the jacket periphery located at axial intervals along the chamber. Measurements of the chamber external back side temperature provided an axial temperature distribution for indirectly determining the coolant temperatures and gas surface heat inputs. These test data were compared to the two-dimensional nodal network setup to assess the wall temperature distribution on the gas side surface.

START-SHUTDOWN ANALYSIS

Two engines were considered for the start/shutdown transient evaluation conducted. The first was the OF_2/B_2H_6 double jacketed demonstrator undergoing fabrication; the second, a reduced volume "flight" design with improvements in reduced line, manifold and injector volumes. Further volume reductions were projected with additional detailed design study in the area of chamber and manifold integration.

The determination of these transient periods is necessary in order to more fully develop an exact total impulse or mission ΔV effect. For long operating durations ($\geq$ 100 seconds) a reasonable error prediction ($\pm$0.2 second) is not of significance. For pulsing engines or shorter duration thrust times ($\leq$ 5 seconds burn time) a repeatable and short transient definition becomes of greater significance. For the proposed OF_2/B_2H_6 engine design, necessary operational applications are more similar to the first category.

In the determination of the time taken for a steady state chamber pressure from buildup or time decay from a main fuel valve open signal or main oxidizer valve close signal, the critical time was considered to be affected by;

- Valve opening (closing) period
- Prechill period required
- System fluid volume
- Initial feed system wall temperature
- Feed system thermal capacitance

For the OF_2/B_2H_6 dual regeneratively cooled chamber design test hardware, both fuel and oxidizer side factors were considered in order to assess the operating start/shutdown time periods.

Start/Cutoff Transient-Test Data Review

A review of the start and cutoff transients of the previous Task IV calorimeter and B_2H_6 fuel regeneratively cooled chamber was made. As typically shown in Fig. 12 with a 1 second B_2H_6 jacket chill prior to MOVO (main oxidizer valve opening) a flow transient of approximately 200 ms is noted to the 90 percent P_c point, followed by a thermal transient affected 1 second period to 100 percent P_c. Shutdown was seen to occur in a 110 ms period. The flow system was governed by a sonic venturi (constant gaseous flow) on the oxidizer side and a cavitating venturi on the fuel side (constant liquid flow). The time measured included both valve travel time, ignition time (hypergolic propellants) and feed system volume fill time. An overshoot in pressure is seen during the start transient as a result of ignition delay, accumulated propellants in the combustor and an increased propellant flowrate over nominal during the start period. Shutdown is shown to occur in a shorter time period both due to valve travel time and a reduced total flow in the transient period.

Table 2 illustrates a summary of start and cutoff times for the Task IV testing previously concluded. (Data shown omitted were deleted due to reduced time slice data being unavailable for these test runs.) An average start time of 310 ms and shutdown time of 118 ms are shown. The valve operating time (presently $\approx$ 60 ms) with incorporation of the JPL flight valve would approximate these total time periods (valve operating time $\approx$ 75 ms). Further reductions can be achieved for this gaseous system with reduced oxidizer manifold and line volumes.

Fuel Lead Period

A review of the B_2H_6 jacket flow and temperature stabilization time from previous Task IV testing was made. A 2.0 second fuel lead sequence studied is shown in Fig. 13 . As illustrated a near steady flow is shown at 0.6 second from fuel lead introduction, with a "steady" outlet temperature of 1.7 seconds. Recognizing the thermal lag of the chamber wall, after the initial testing with a 2.0 second fuel lead, a 1.0 second fuel lead was provided to assure a

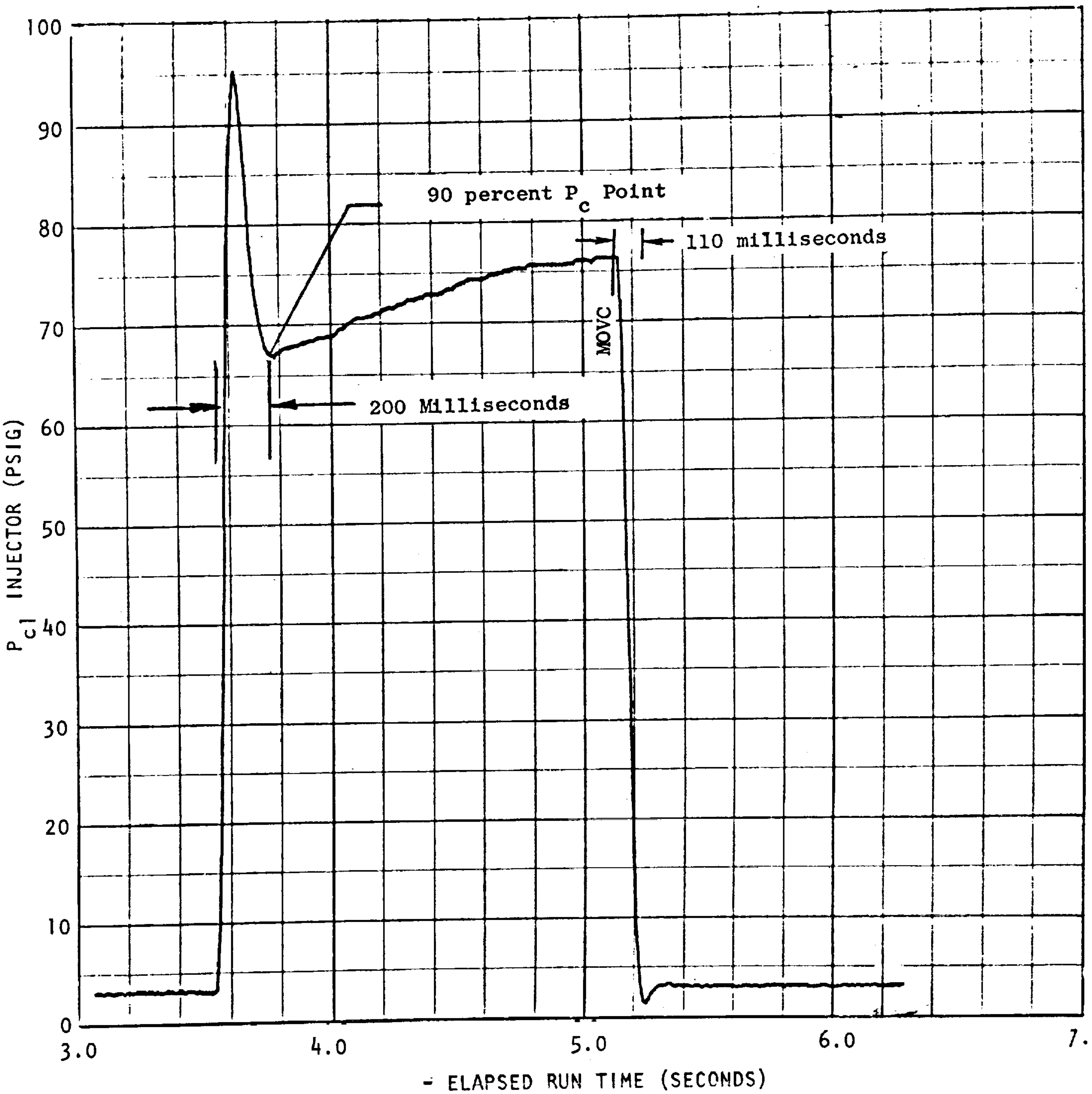


Figure 12. Chamber Pressure Rise vs Elapsed Time (Test 010)

TABLE 2. START AND CUTOFF TRANSIENTS ON OF_2/B_2H_6 CHAMBER TESTING (90 PERCENT RISE AND FALL TIMES)

Run No.	Start τ (milliseconds)	Cutoff τ (milliseconds)
6*	250	120
7*	330	130
8*	300	100
9	220	100
10	270	110
11	470	120
12	---	120
13	---	---
14	320	140
15	---	---
16	---	---
17	---	---
Average	$\bar{\tau}_{ST} = 310$	$\bar{\tau}_{SD} = 118$

Experimental chamber values do not include 1.0 second fuel lead time.

* Calorimeter chamber, all others B_2H_6 fuel cooled chamber.

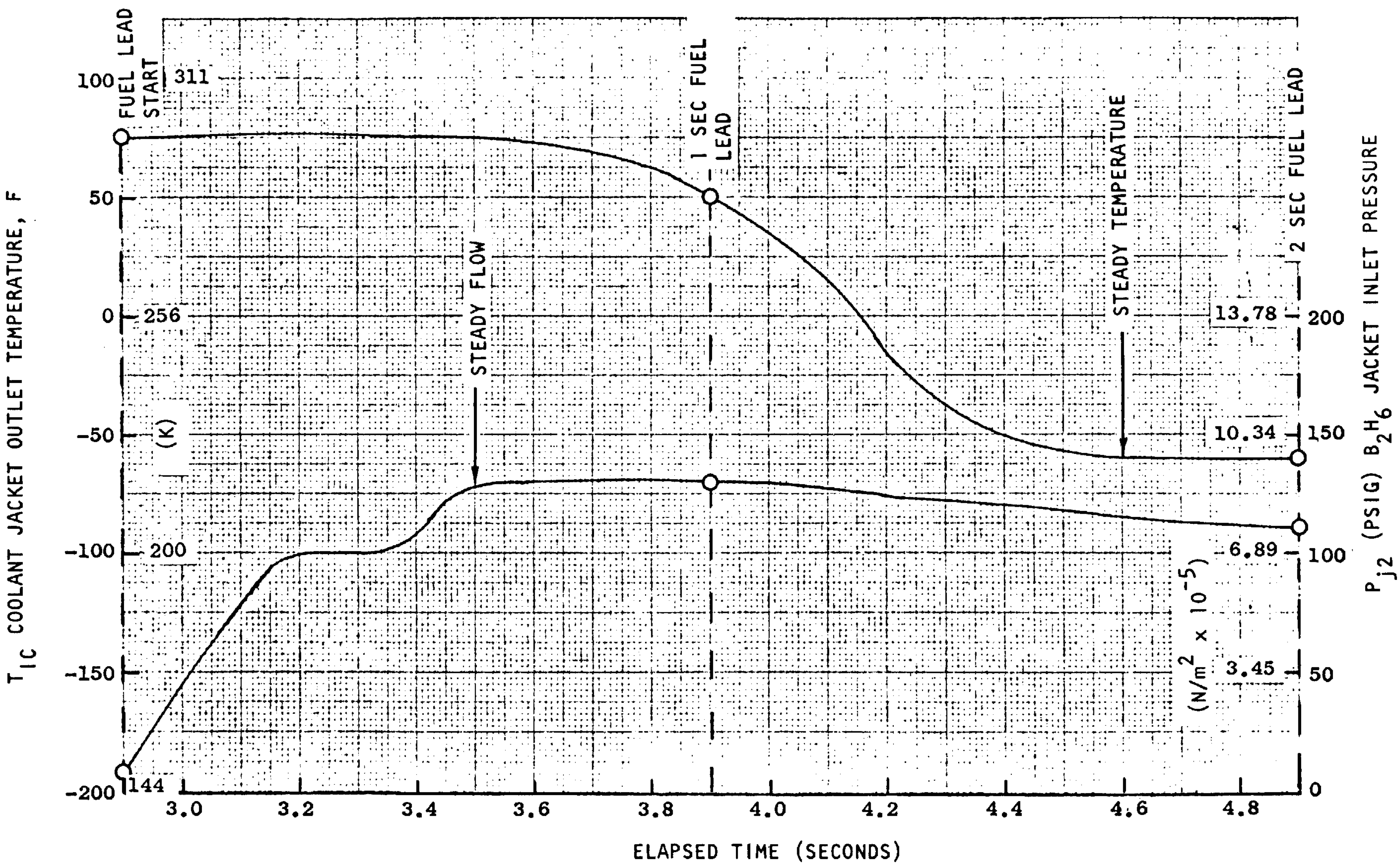


Figure 13. F_2/O_2-B_2H_6 Thrust Chamber Jacket Inlet Pressure and Discharge Temperature During Fuel Lead Sequence ($\dot{W}_f$ = 0.63 lb/sec, 0.29 Kg/sec)

higher fuel injection temperature at ignition. This shorter lead was used with good success on all subsequent testing. A shorter fuel lead ($\approx$0.5 second) before MOV open signal was recognized as possible but not undertaken due to risk, cost, and time factors. During the test program effort conducted during Task VII, this aspect was further studied.

Figure 14 illustrates the fuel injection temperature behavior from the previous Task IV regenerative test series. As shown a 1 second fuel lead (2 seconds on test 009) results in a further temperature decay post ignition. This is caused by the chamber wall thermal capacitance which delays the heat transfer to the B_2H_6 coolant. A shortening of the fuel lead time to $\leq$ 0.5 second, as indicated, would result in a diminishment of the temperature "sag" prior to injection temperature buildup. Moreover a shorter fuel lead will result in a more rapid chamber pressure rise to the steady state level and consequently the allowance of a more simultaneous main oxidizer valve opening. Further experimental study of oxidizer valve sequencing relative to the MFV was planned for the Task VII test program.

Feed System Capacitance Determination

Evaluation of the volumes of the fuel and oxidizer flow system was performed from the JPL valve discharge point to the injector orifice discharge plane. During previous study it was determined that the feed system capacitance or flow time during the start or chill period directly limits the minimum start time.

Table 3 illustrates the computed B_2H_6 feed system volume distribution and Table 4 the OF_2 feed system volume distribution for the double jacketed demonstrator test chamber. In addition a review of the high capacitance portions of the feed system was made to develop potential reductions in chamber volume since it was recognized that a projected flight engine should be more sophisticated design version compared to the demonstrator.

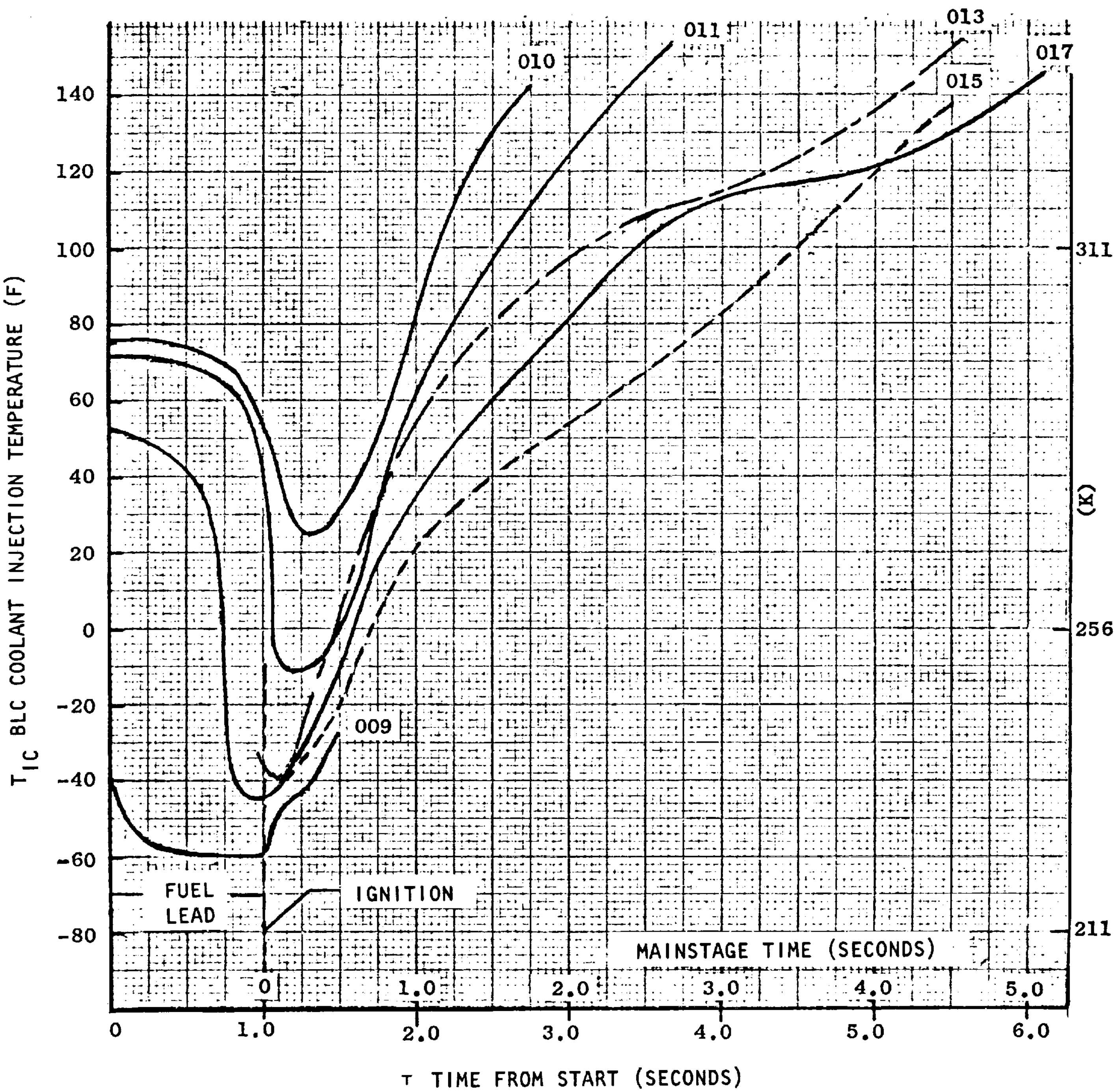


Figure 14. Comparison of Regenerative Chamber BLC Injection Temperature Transients During Ignition and Early Mainstage (Tests 009-017)

TABLE 3. SUMMARY OF B_2H_6 FEED SYSTEM VOLUMES FOR DEMONSTRATOR AND FLIGHT DESIGNS

Location	Demonstrator Engine in^3 (cm^3)	Projected Flight Engine in^3 (cm^3)
Inlet Valve Discharge	2.0 (32.8)	1.0 (16.4)
Inlet Port	1.3 (21.3)	1.0 (16.4)
Inlet Manifold	18.6 (305.0)	9.0 (148.0)
Cooling Passages	8.1 (132.0)	6.1 (100.0)
Discharge Manifold	5.9 (96.7)	4.0 (65.6)
Injector Feed Ports	0.5 (8.2)	0.5 (8.2)
Injector Ring Volume	3.3 (54.1)	2.5 (40.9)
Total Volume	39.7 (650.0)	24.1 (395.0)
Volume Averaged Density	$\bar{\rho}_f$ = 20.0 lb/ft^3 (320 kg/m^3)	$\bar{\rho}_f$ = 17.5 lb/ft^3 (280 kg/m^3)

TABLE 4. SUMMARY OF OF_2 FEED SYSTEM VOLUMES FOR DEMONSTRATOR AND PROJECTED FLIGHT DESIGNS

Location	Demonstrator Engine in^3 (cm^3)	Projected Flight Engine in^3 (cm^3)
Inlet Valve Discharge	1.0 (16.4)	1.0 (16.4)
Inlet Port	0.3 (0.49)	0.3 (0.49)
Inlet Manifold	25.1 (411.0)	11.0 (180.0)
Cooling Passages	4.0 (65.6)	4.0 (65.6)
Discharge Manifold	21.8 (358.0)	15.0 (246.0)
Discharge Tube Fittings	2.3 (37.7)	0.0 (0.0)
Transfer Tubes	14.4 (236.2)	8.0 (131.2)
Injector Dome Inlet	3.5 (57.4)	2.0 (32.8)
Dome Volume	28.0 (459.2)	14.0 (229.6)
Injector Orifices	2.0 (32.8)	2.0 (32.8)
Total Volume	102.4 (1679.0)	57.3 (939.0)
Volume Averaged Density	$\bar{\rho}_o$ = 27.5 lb/ft^3 (440 kg/m^3)	$\bar{\rho}_o$ = 23.7 lb/ft^3 (379 kg/m^3)

Substantial volume reductions for the flight engine can be foreseen in the inlet manifold on both the fuel and oxidizer sides. On the fuel side a single tapered manifold with a single entry point would replace the present heavy high capacitance demonstrator triple fuel manifold. For the oxidizer side the inlet manifold was sized to fit the existing water flange; for a flight design a smaller manifold ring diameter with a tapered geometry would be chosen.

Coolant passage volume would be unchanged for the OF_2 side with the demonstrator design close to optimum. For the B_2H_6 fuel side some reduction in the nozzle coolant flow area (ϵ = 6 to 20) is required in order to reduce wall surface temperatures for a flight design. This reduction would be accomplished with a channel height decrease which will be beneficial to the overall nozzle weight, thermal capacitance, and wall time response.

Small decreases in discharge manifold volume can be projected for the fuel manifold and more substantial changes in the oxidizer manifold, OF_2 transfer lines and injector body volume. For the flight design a substantial reduction could be obtained by routing the oxidizer flow internally through the injector periphery with an integrated flow transfer passage rather than external plumbing.

Table 3 and 4 also illustrate operational average flow densities during steady state conditions in the feed systems. A reduced average density present during regenerative operation prior to cutoff would lessen the trapped fuel or oxidizer weight in the feed system downstream of the valve.

Further reductions in feed system volume, especially in the high fluid density regions, (valve to vaporization points) can be seen as beneficial both to the start and cutoff transient times. Future detailed flight design studies will be necessary in order to arrive at a minimum flow volume condition.

Flow Priming Time

On the assumption of the fuel and oxidizer feed system priming time limiting the start transient, and the trapped fluid weight limiting the cutoff transient, an analysis was performed to establish the envelope of start times. Both the demonstrator and projected flight system were compared. As shown in Fig. 15, if a liquid fuel density is chosen, a priming time of 1.05 seconds is shown for the demonstrator chamber and 0.65 second on a reduced fuel volume flight design. For an average reduced fuel density characteristic of the steady state operating density conditions, time reductions to 0.65 second and 0.35 second, respectively, were calculated. During warm chamber fuel lead starts it is expected that the feed system volume will be at an average density substantially lower than the liquid and similar to the steady state operating density condition. With the time lag inherent for the wall heat sink capacitance, after chamber pressure initiation it appeared that a full liquid condition would not be necessary prior to start. This is also true of the oxidizer which is injected in a gaseous state.

Reductions in time between MFV open and MOV open, below a 0.5 second level can be allowed if the fuel lead is not allowed to proceed to a near steady flow condition but is at a sufficiently high level to assure a high injection orifice delta pressure during the chamber pressure transient and overshoot. A realistic minimum was expected in the range of 0.25 second.

Figure 16 illustrates the demonstrator chamber start time compared on the basis of (1) the demonstrated start transient with the B_2H_6 cooling passages only and a 1.0 second fuel lead, (2) a reduced lead to 0.5 second and its projected start transient, and (3) a double propellant cooled demonstrator (with its larger than necessary capacitance volume) with a 0.35 second fuel lead. A total time for the demonstrator chamber of 1.0 second appeared attainable. A demonstrator cutoff transient time is limited by the oxidizer system volume; 0.8 second would be anticipated for a near simultaneous valve closing time.

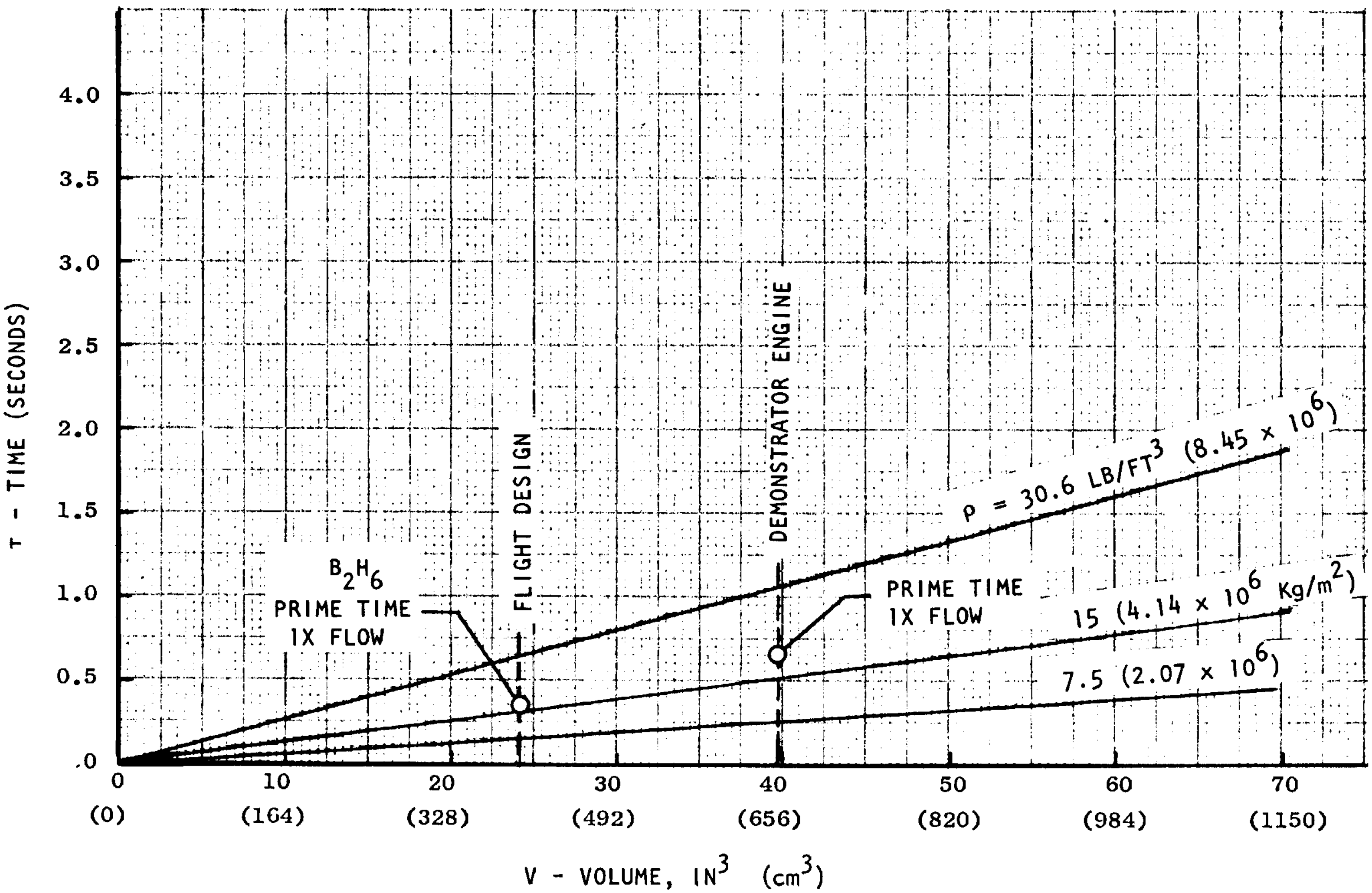


Figure 15. B_2H_6 Fuel Priming Time vs Feed System Volume

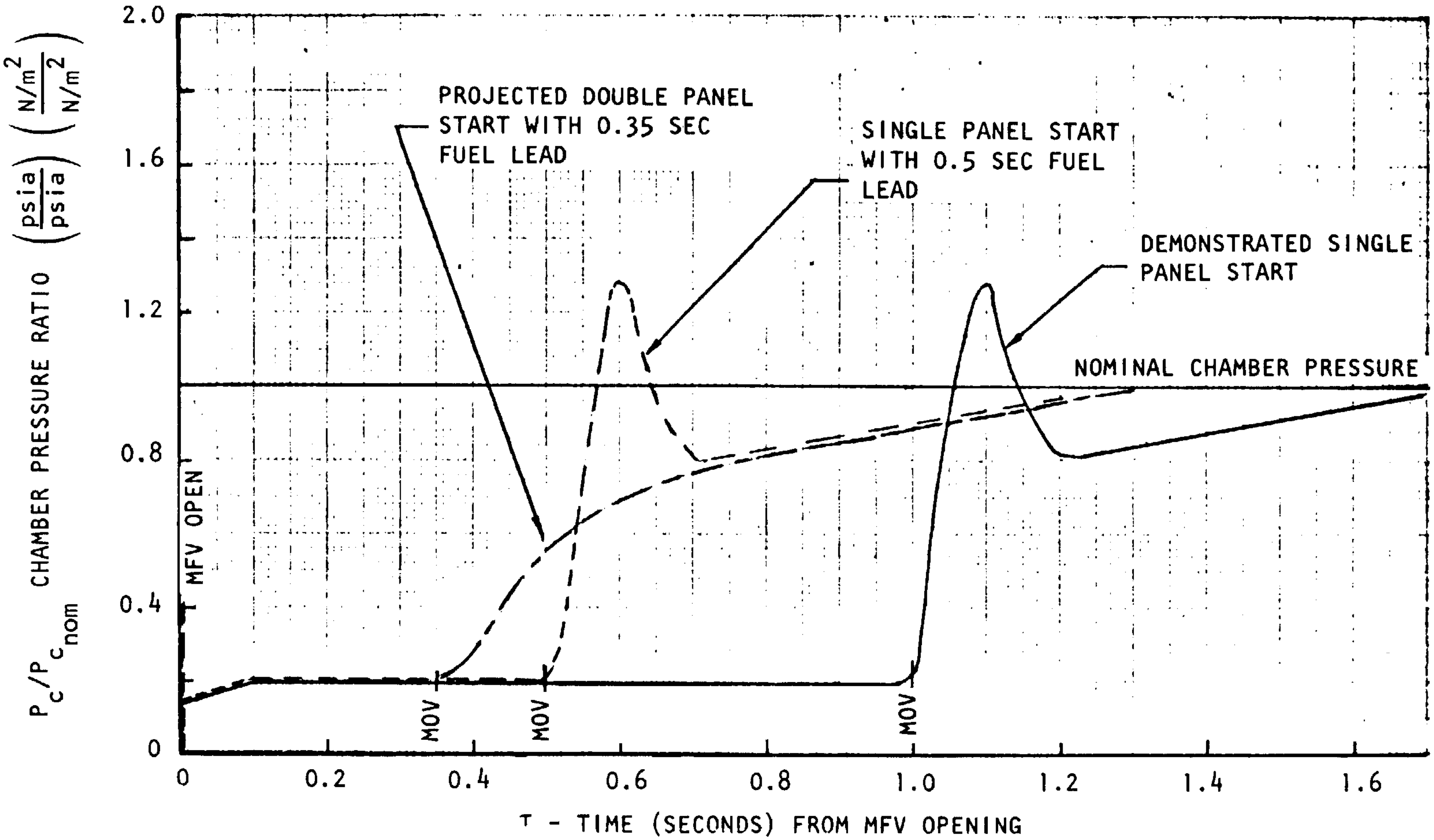


Figure 16. Comparative OF_2/B_2H_6 Demonstrator Start Transients With Single and Double Panel Cooling Passages

Further study is necessary to evaluate the effects of the strongly reduced mixture ratio at the low chamber pressure levels.

Figure 17 and 18 illustrate the choked flow operating lines for the demonstrator fuel and oxidizer sides over a range in chamber pressure. As a result of vaporization of the fuel and oxidizer during startup and shutdown conditions, the gaseous flow will be choked through the feed system and limited by the applied inlet pressure. As a result of low initial fuel injection temperature during the start period, a higher than rated flow will be expected (non-cavitating venturi system). For the oxidizer the initial warm jacket oxidizer discharge temperature will be near the design level (90 F, 305 K) resulting in an initial flow near rated. The use of control venturis at the engine valve discharges would allow a better flow stabilization condition during the start period at the expense of a total pressure loss (10 percent).

THERMAL TRANSIENT PERIOD

A determination of the actual transient period for the jacket coolant discharge temperature from Task IV regenerative testing indicated a steady state level was not achieved until approximately a 20 second time into the run. As a result the coolant jacket temperature somewhat affects the final asymptotic level of the chamber pressure after initial semi-stabilization. The thermal transient of the chamber is principally influenced by the following principal factors;

- Wall heat flux
- Thermal mass
- Heat transfer coefficient
- Channel geometry

The supersonic area ratio portion of the nozzle downstream of the throat dominates the thermal transient response due to a low wall heat flux, a low coolant heat transfer coefficient and the comparatively thick wall nozzle section. A data review indicates toward the nozzle exit (ϵ = 14.5)

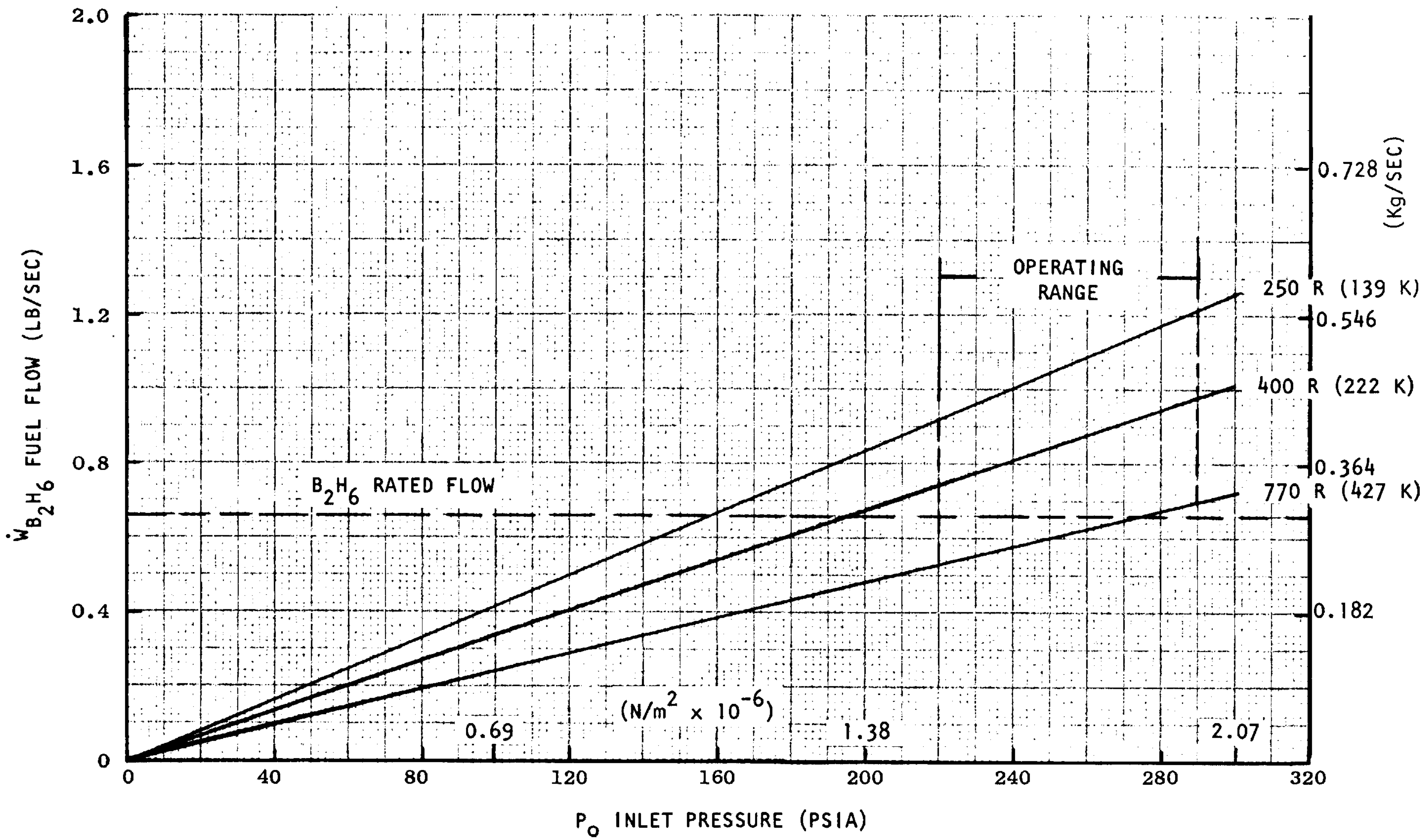


Figure 17. B_2H_6 Fuel Flow vs Inlet Pressure for Demonstrator Chamber (K = 0.068)

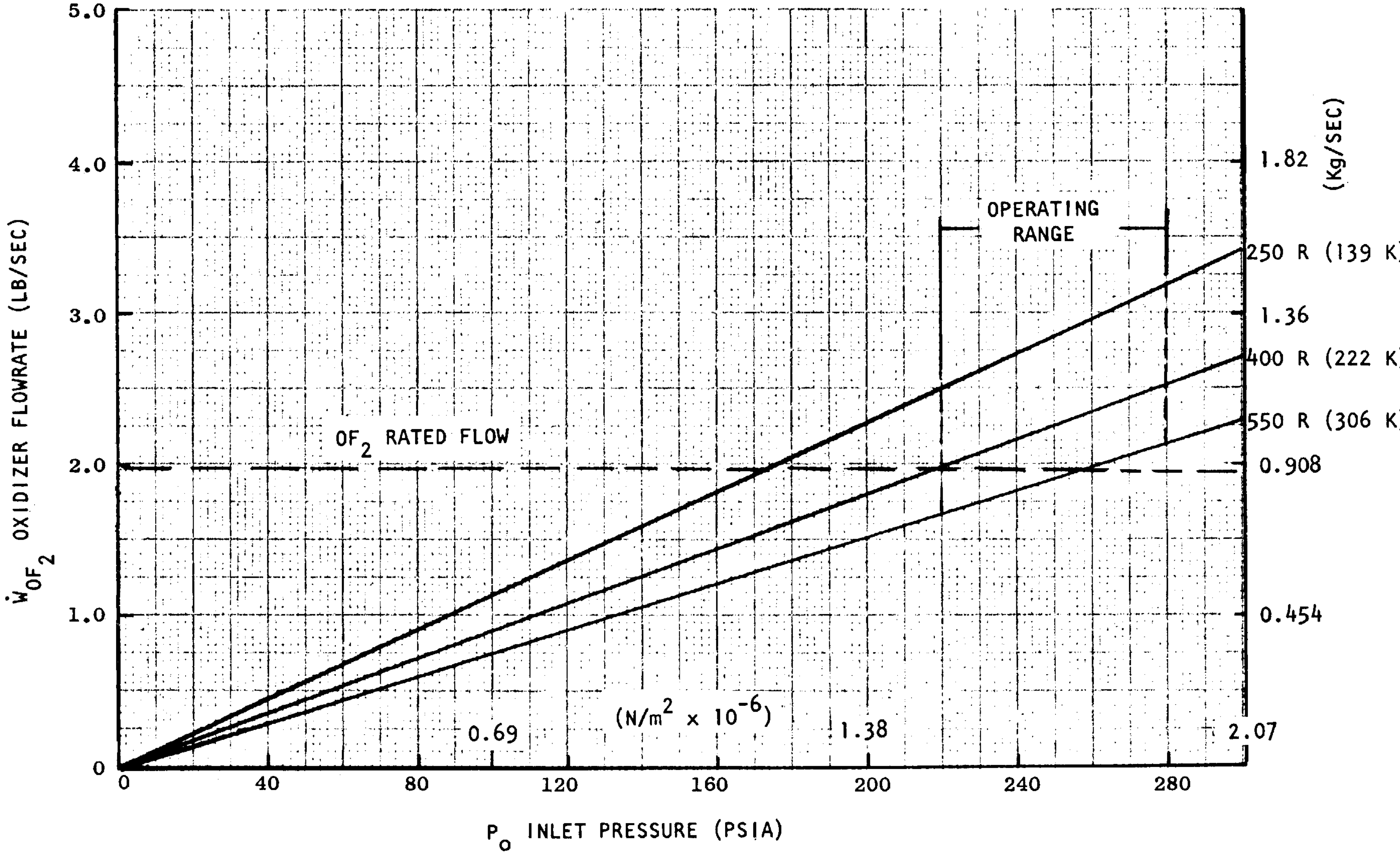


Figure 18. OF_2 Oxidizer Flow vs Inlet Pressure for Demonstrator Chamber (K = 0.180)

temperature stabilization occurs in 45 seconds and reduced nozzle area ratio points (ϵ = 7) in 10 seconds. Combustor and throat response times would be seen to be substantially less due to higher imposed heat flux levels. A balance of heat input to the wall and the stored plus convection heat loss becomes

$$Q_{in} = Q_{out} + Q_{stored}$$

The wall time response can be derived as

$$\tau = -A \ \ell n \ (1 - B \ (T_w - T_c))$$

$$A = \frac{\rho C_p}{2 h_c} \left[\frac{(b + t) \ (W + L) + hL}{(h + W)} \right]$$

$$B = \frac{2 h_c}{q/A} \left[\frac{(h + W)}{(L + W)} \right]$$

The time equation above can be rearranged to

$$B \ (T_w - T_c) = 1 - e^{-(\tau/A)}$$

To achieve to within a $(1/e^2)$ final wall temperature level

$$\tau = \frac{\rho C_p}{h_c} \left[\frac{(b + t) \ (W + L) + h \ L}{h + W} \right]$$

Figure 19 illustrates the wall thermal response for the following conditions

ρ = 0.323 lb/in^3 (0.00897 Kg/cm^3)

C_p = 0.099 Btu/lb-R (0.099 cal/gm-K)

$b + t$ = 0.200 inch (0.508 cm)

h = 0.116 inch (0.294 cm)

W = 0.040 inch (0.102 cm)

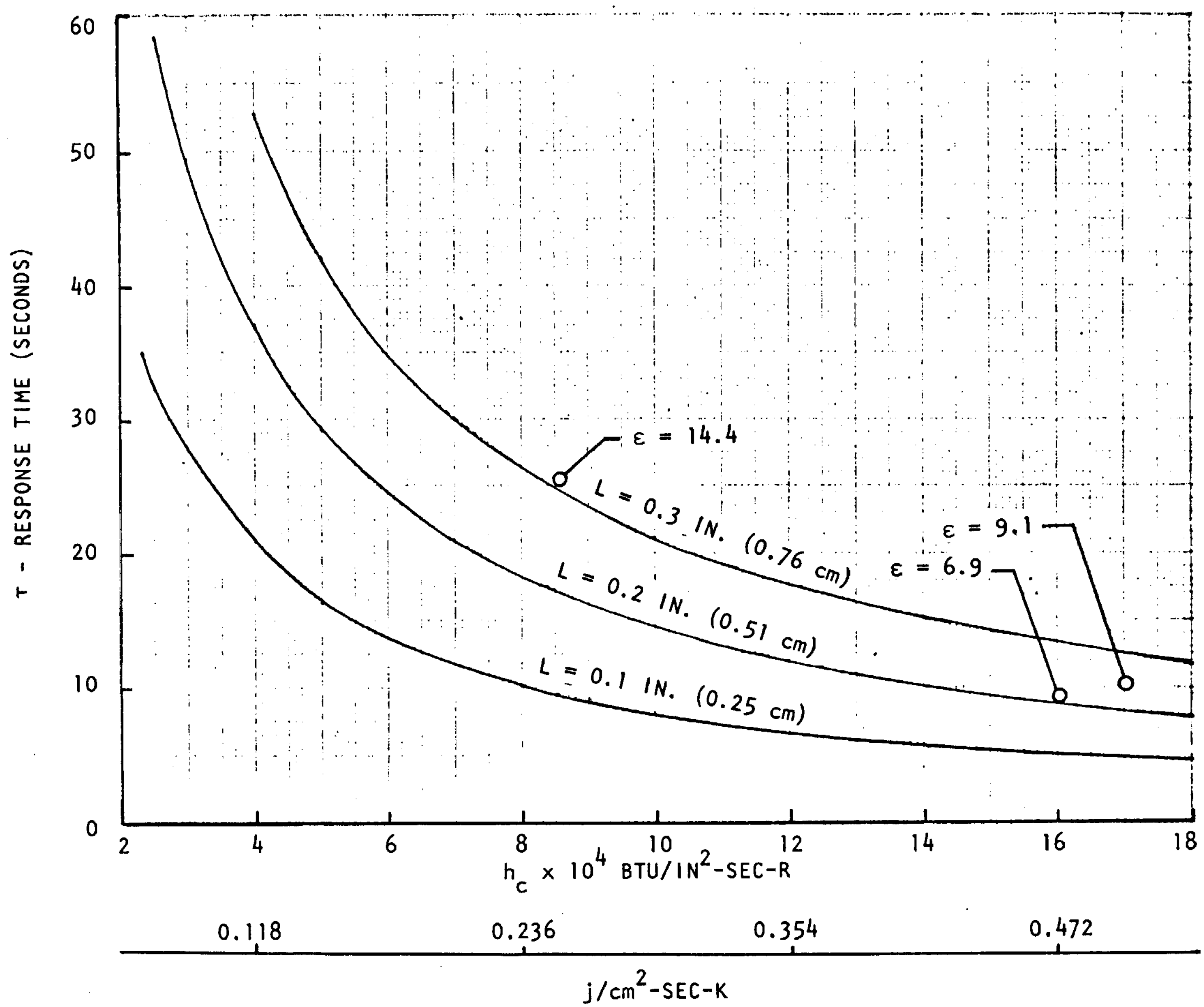


Figure 19. Demonstrator Nozzle Wall Temperature Response Time vs B_2H_6 Coolant Heat Transfer Coefficient

For reduced flight design volumes reductions in both trapped propellants should shorten both the start and cutoff period. On the basis of the projected flight design volumes, a 44 percent reduction in time could be projected with a 0.56 second start and a 0.45 second cutoff time.

Start and Cutoff Total Impulse Determination

The impulse in terms of integrated force x time for the start and cutoff becomes a function of the following variables:

- Total fuel and oxidizer trapped jacket flow
- Mixture ratio during start or cutoff transient
- Chamber pressure level during start or cutoff transient

The total impulse is primarily dictated by the first two factors with the chamber pressure affecting the combustion efficiency and nozzle C_F efficiency. On the basis of a reduced mixture ratio from nominal during fuel lead (start) or fuel lag (shutdown) conditions, a degradation in I_{SP} would be anticipated at chamber pressures lower than the nominal.

Based on the demonstrator start time shown in Fig. 16 and no specific impulse reduction due to mixture ratio, a time integration under the chamber pressure trace is necessary to define the start and cutoff values. Preliminary analysis of the demonstrator and projected flight designs resulted in the following values.

Chamber	Start Impulse* lb-sec (kg-sec)	Cutoff Impulse* lb/sec (kg-sec)
Demonstrator	480 (218)	384 (175)
Flight	270 (123)	216 (98)

* No impulse degradation assumed due to low MR period during transient

Substantial time reductions can be achieved by reducing the channel height together with the gas wall (t) back wall (b) and channel height (h). A decrease in the gas side wall thickness to 0.050 inch (1.3 mm), the back wall closure to 0.050 inch (1.3 mm) and the channel height to 0.058 inch (1.5 mm) will lessen the thermal response to 46 percent of the original value. Further study would be required in this area toward a flight design configuration.

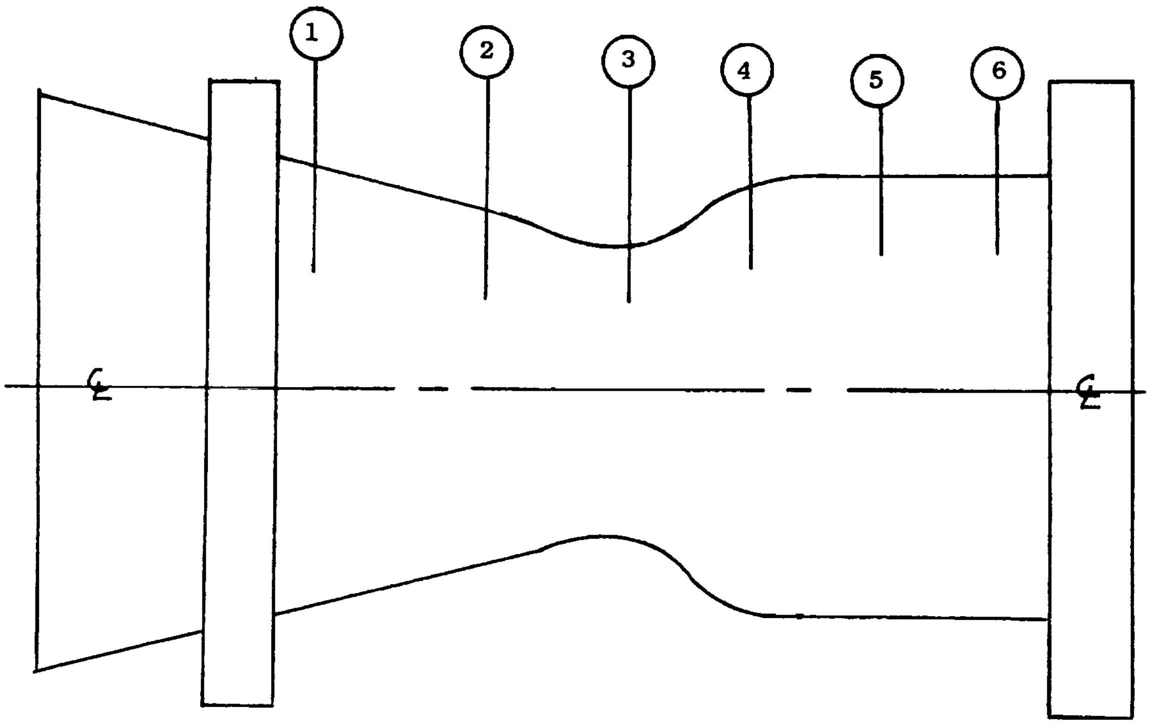
CHAMBER FABRICATION EFFORT

Upon completion of the initial design analysis study work, the OF_2/B_2H_6 thrust chamber was fabricated by slotting of the OF_2 cooling passages in the existing nickel electroformed structural jacket, nickel electroforming the jacket structural closure and finally welding the manifold and valve closures at the inlet and outlet OF_2 flow points. The following summary describes the work related to the chamber fabrication effort completed prior to the Task VII test series.

Initial Fabrication Effort

During the initial fabrication period inspection of the overal chamber and nickel wall thickness closeout values on the existing previously fired OF_2/B_2H_6 regenerative chamber was accomplished. Due to some out of round warpage of the thrust chamber (up to 0.013 inch) in previous testing, a centering mandrel was made to true the chamber for the machine drilling of the OF_2 cooling passages. Insertion of the new mandrel resulted in reduction of the warpage to an acceptable level for coolant passage machining.

Measurement of the existing nickel layer was made to determine the minimum thickness of nickel which would result with slotting to the defined design drawing depth. Figure 20 illustrates the measured thickness levels. As shown a minimum thickness of 0.099 inch (2.52 mm) was measured at location 4 which had an OF_2 coolant passage height of 0.058 inch (1.48 mm) leaving an 0.041 inch (1.05 mm) nickel barrier to the backside of the B_2H_6 coolant channels. At the injector end the nominal OF_2 coolant passage depth was 0.063 inch (1.6 mm) leaving a minimum OF_2 to B_2H_6 barrier of 0.039 inch (1 mm). Conference with design personnel indicated this to be an acceptable thickness level between the fuel and oxidizer propellants.



	0°	90°	180°	270°	270° *
Bottom	0	+8	+15	+9	---
1	0.112	0.112	0.111	0.112	(0.284)
2	0.112	0.112	0.109	0.110	(0.279)
3	0.109	0.105	0.110	0.108	(0.274)
4	0.100	0.101	0.099	0.099	(0.226)
5	0.103	0.104	0.105	0.103	(0.262)
6	0.104	0.105	0.109	0.102	(0.259)
Top					

* cm

Figure 20. OF_2/B_2H_6 Thrust Chamber ELF Nickel Thickness Measurements by Ultrasonic Micrometer

Coolant Passage Machining

Figure 21 illustrates the overall setup of the mandrel and tracing template used for the OF_2 groove slotting. Careful indexing was provided in order to assure an accurate division of the chamber periphery for the 90 OF_2 coolant passages. Measurement and some template adjustment was necessary also to provide the best coolant passage depth uniformity with the slightly eccentric chamber.

Coolant passage machining for the OF_2 coolant was completed and the coolant channels measured to determine dimensional limits. Figure 22 illustrates the coolant passages in the machined thrust chamber. A detail of the upper chamber end OF_2 discharge machining is illustrated in Fig. 23 . An expansion following the passage turn was provided to reduce OF_2 gas discharge pressure losses.

Figure 24, 25, and 26 illustrate the channel height measurements made at a 1.0 inch downstream of the injector plane, the throat location, and the nozzle at 1.0 inch upstream of the nozzle flange. Median channel heights for these locations are shown at 0.063, 0.038, and 0.044 inch, respectively. The respective print nominals for these values were 0.063, 0.040, and 0.040. The table below lists for comparison the limits shown graphically.

Channel Location	Nominal in. (cm)	Minimum in. (cm)	Maximum in. (cm)
Injector (Print)	0.063 (0.160)	0.061 (0.155)	0.065 (0.155)
Injector (Actual)	0.063 (0.160)	0.058 (0.147)	0.069 (0.175)
Throat (Print)	0.040 (0.102)	0.038 (0.0966)	0.042 (0.107)
Throat (Actual)	0.038 (0.0966)	0.035 (0.0890)	0.047 (0.119)
Nozzle (Print)	0.040 (0.102)	0.038 (0.0965)	0.042 (0.107)
Nozzle (Actual)	0.044 (0.112)	0.039 (0.0990)	0.051 (0.129)

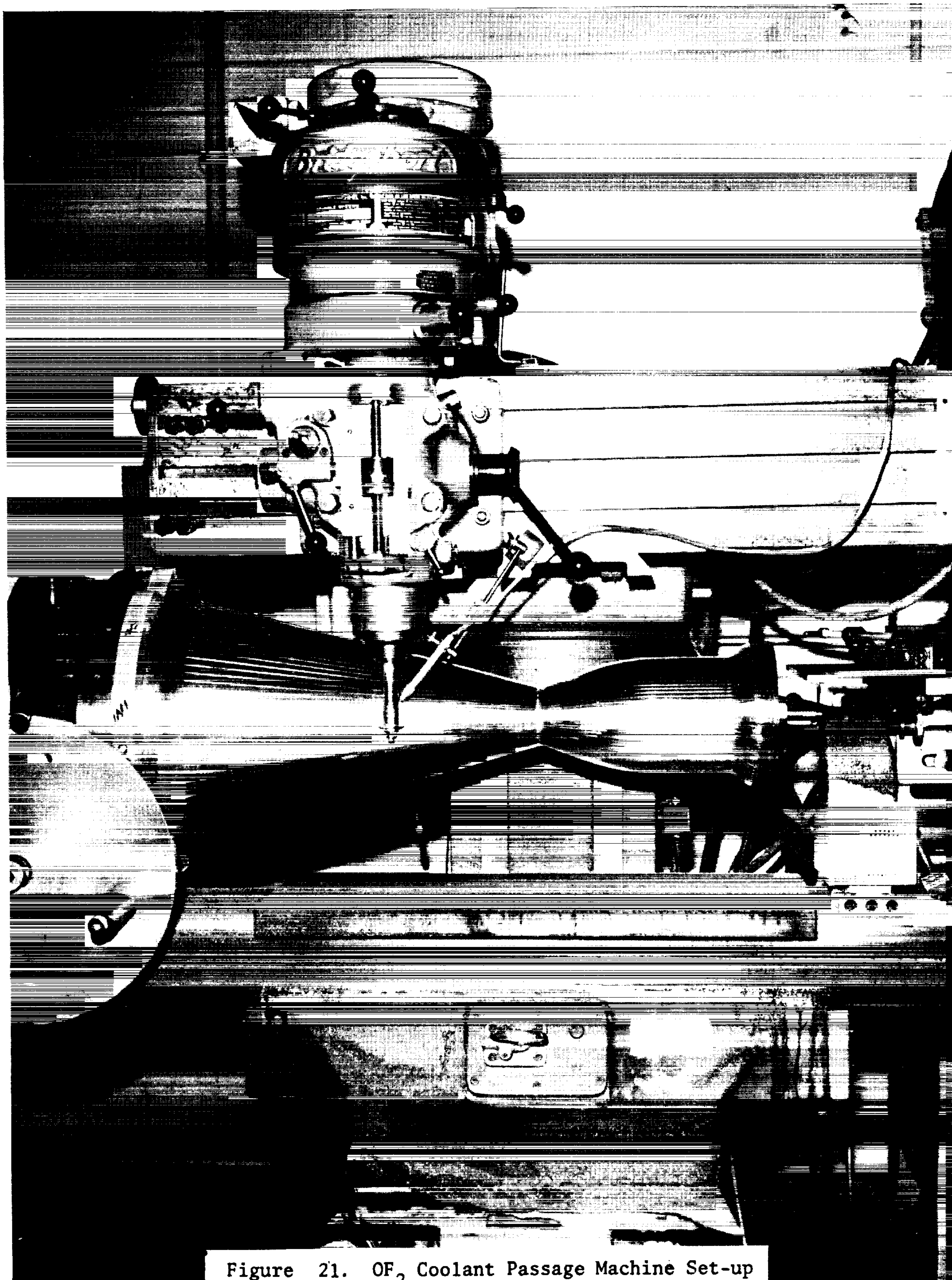


Figure 21. OF_2 Coolant Passage Machine Set-up

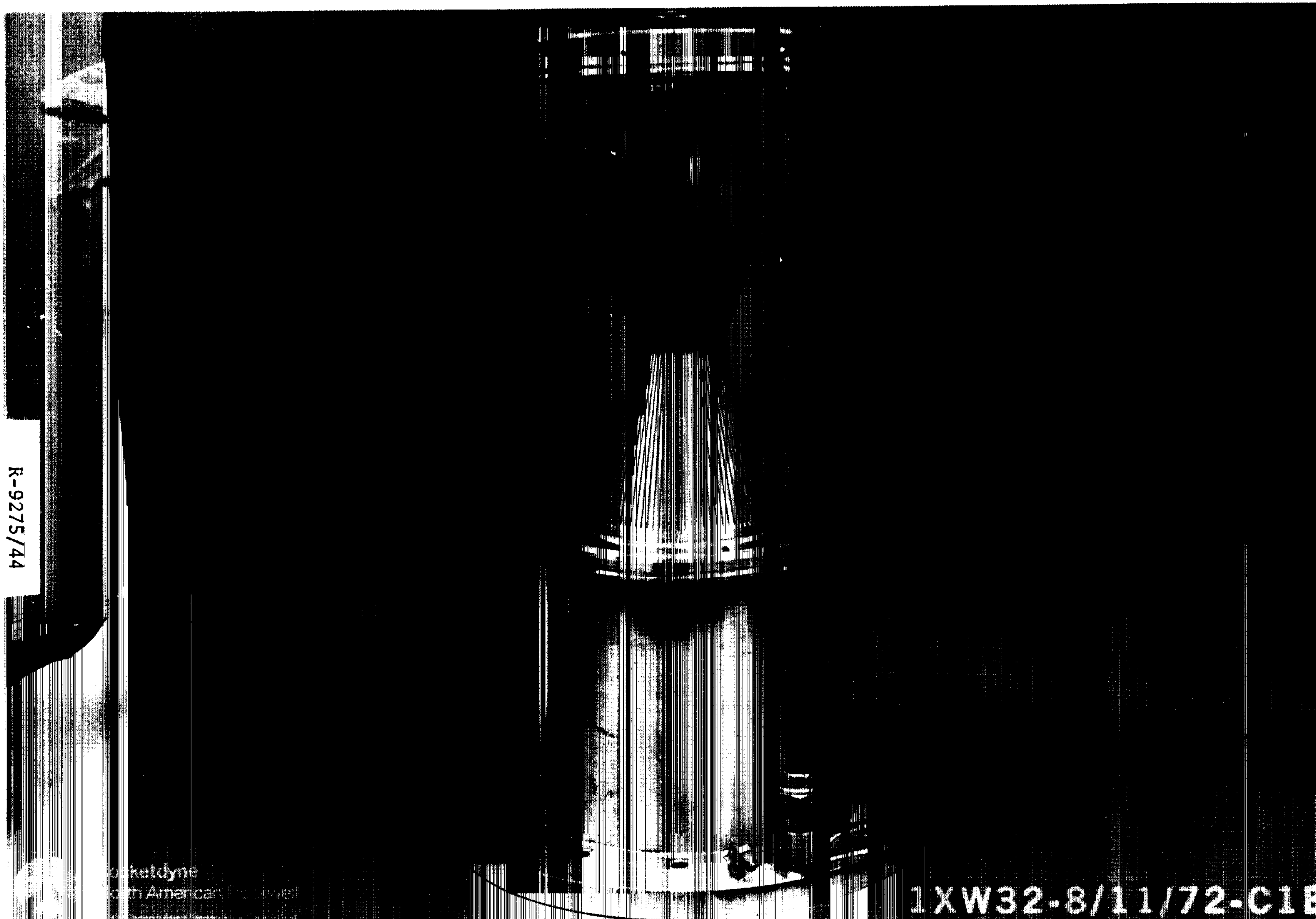


Figure 22. OF_2/B_2H_6 Chamber With Completed OF_2 Channel Machining

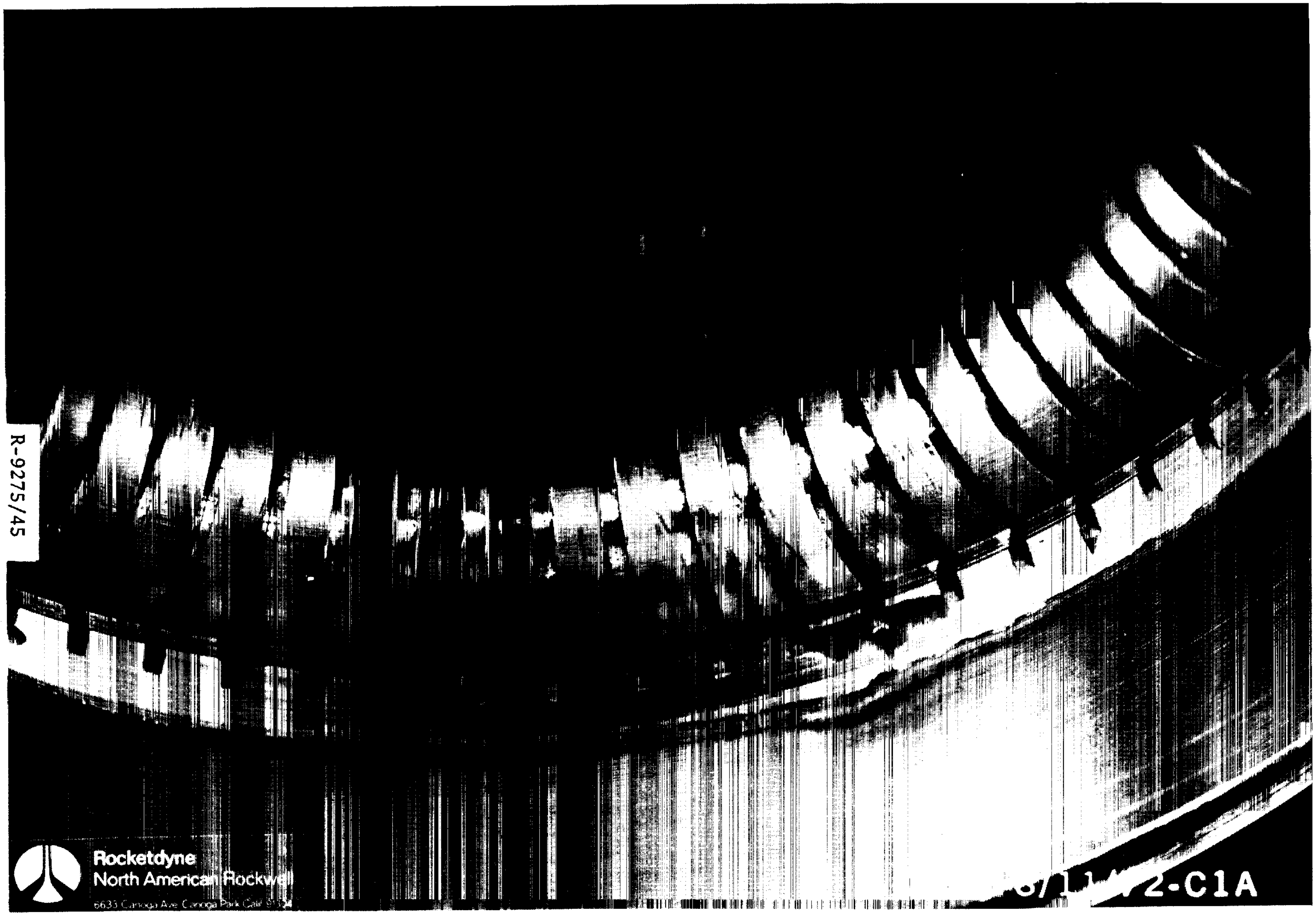


Figure 23. OF_2/B_2H_6 Chamber OF_2 Coolant Passage Discharge Detail

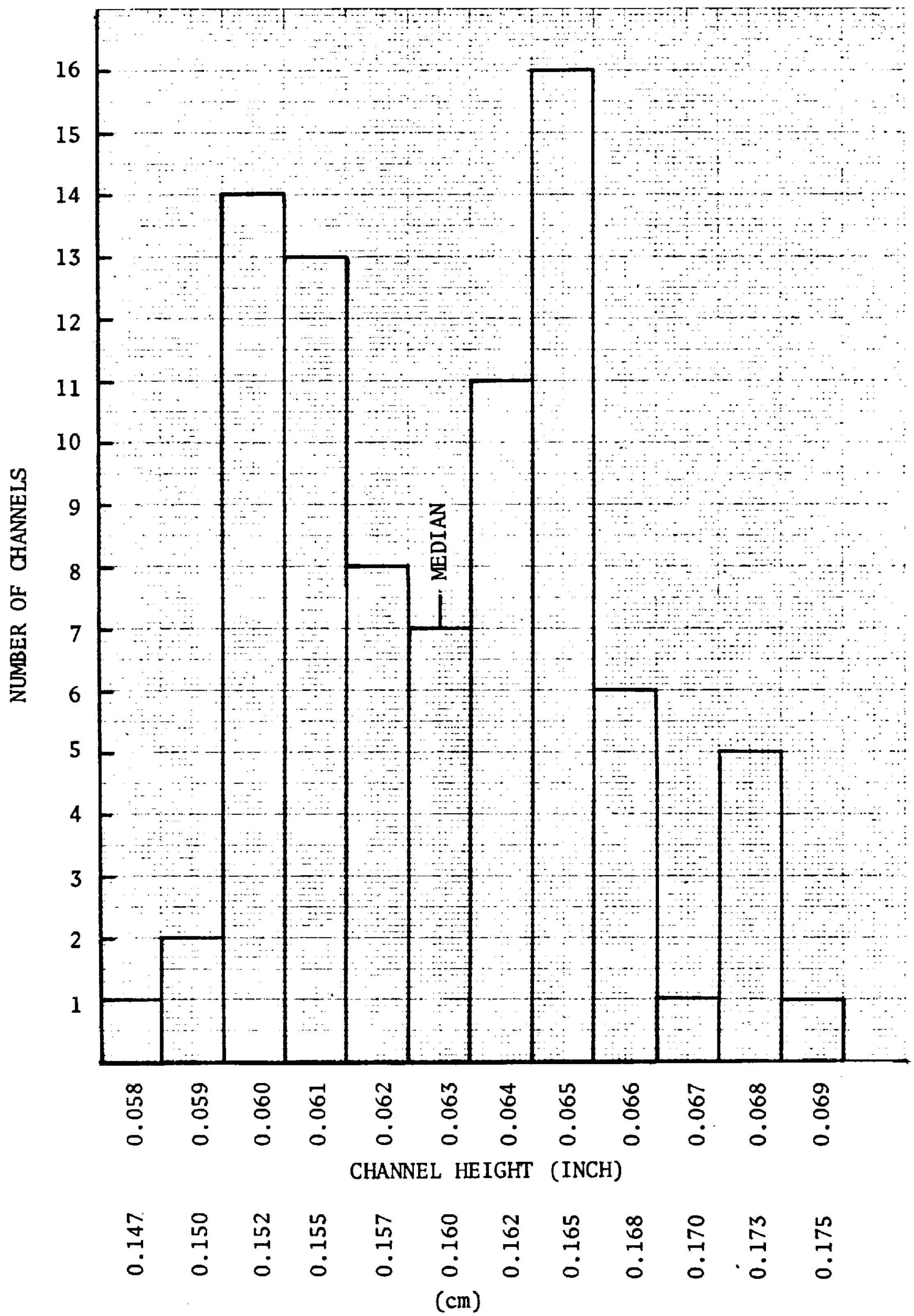


Figure 24. OF_2-B_2H_6 Regenerative Chamber No. 1 OF_2 Channel Height Distribution (Location 1 Inch D.S. of Injector)

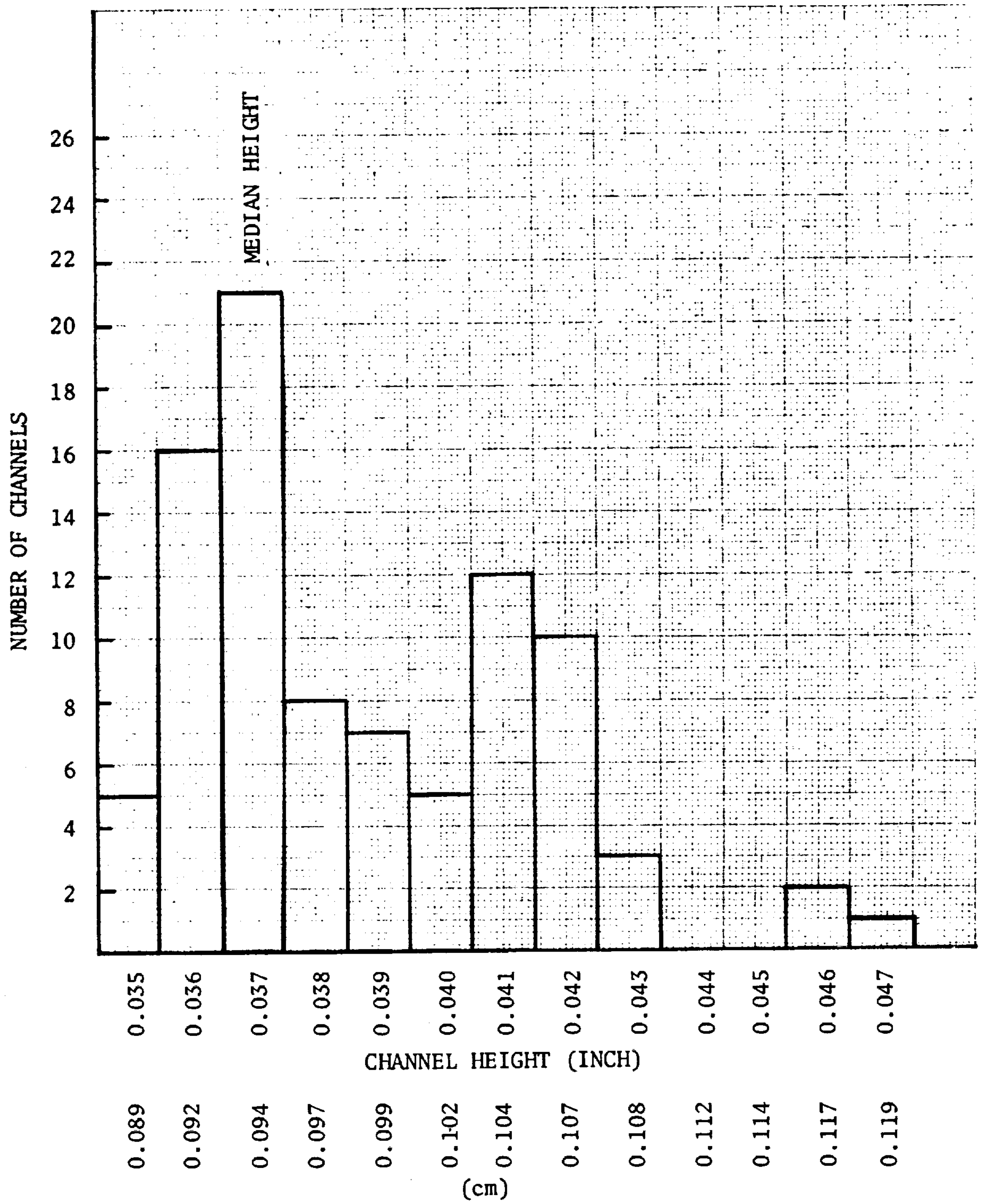


Figure 25. OF_2/B_2H_6 Regenerative Chamber No. 1 OF_2 Channel Height Distribution (Throat Location)

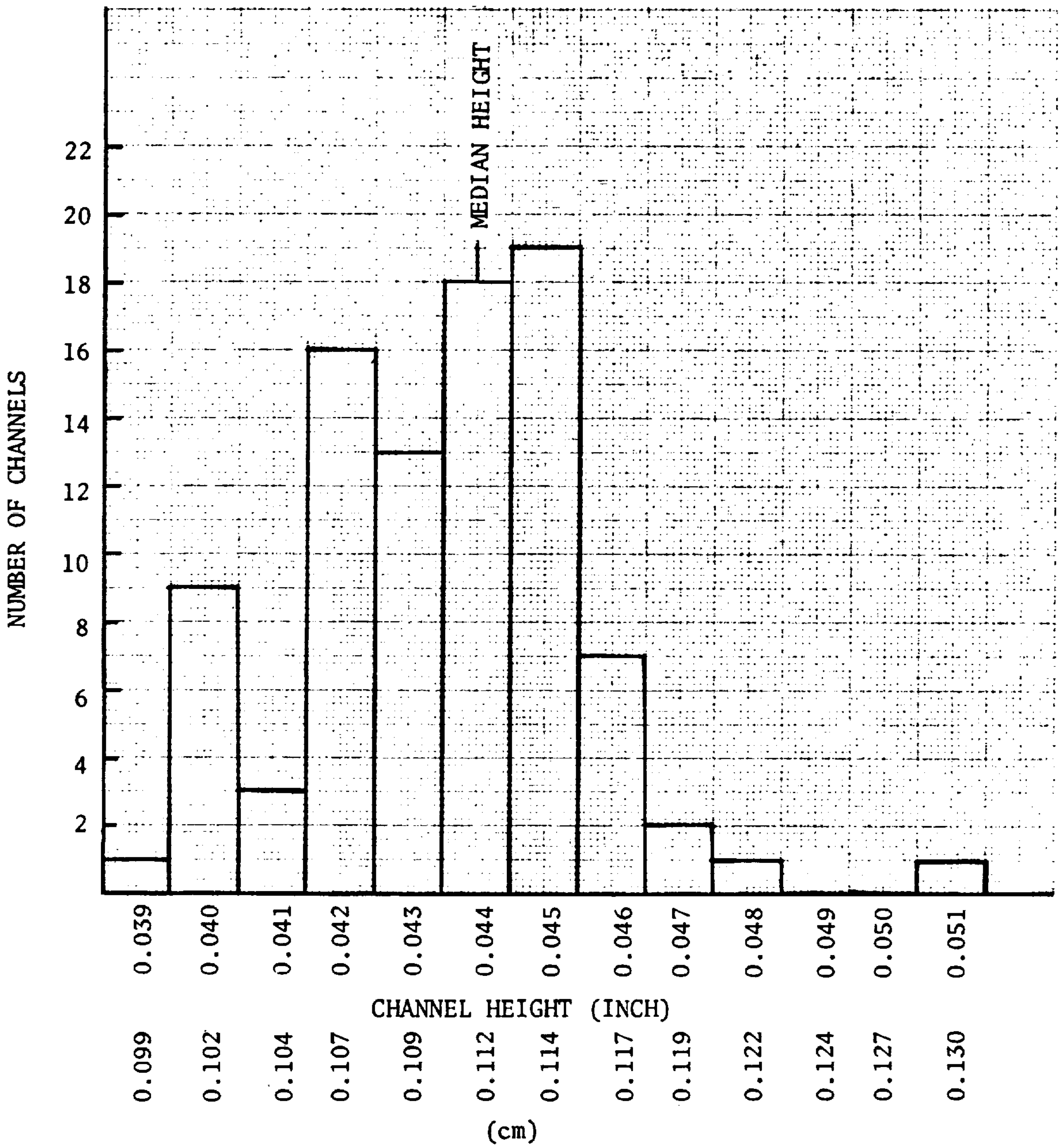


Figure 26. OF_2/B_2H_6 Regenerative Chamber No. 1 OF_2 Channel Height Distribution (1.0 Inch Upstream of Nozzle Flange)

Channel dimensions outside of the print tolerances were examined and shown to be acceptable from a cooling standpoint. The deviation of the channel outside of the print tolerance is due primarily to a slight eccentricity of the chamber which occurred during previous manifold welding and hot fire testing.

Coolant Passage Closeout and Electroforming

Fabrication of new tooling for an 0.100 inch (0.254 cm) nickel electroform deposition over the coolant passages to form a structural shell was accomplished. Nickel buildup was to be accomplished at approximately 0.001 inch (0.00254 cm) per hour to minimize nodule growth. Difficulty with the shielding design was initially incurred as a result of the existing lower inlet manifold which provided an obstruction to the shielding. Modifications were finally provided to ensure an adequate and uniform nickel coverage.

Figure 27 illustrates an overall view of the chamber with the shielding installed. Figure 28 illustrates a closeup view of the OF_2 channels and shielding design.

The chamber was electroformed with an initial 24 hour strike, inspected, and returned to the bath for the final buildup to 0.10 inch (0.254 cm).

Figure 29 illustrates the completed nickel electroformed layer closing out the OF_2 passages. Subsequent to removal of the tooling, the No. 1 thrust chamber was final machined for the acceptance of the lower and upper oxidizer manifolds.

At the completion of the machining of the nickel layer, the wax removal process from the channels was accomplished.

Manifold Installation and Assembly

Fabricated split inlet and outlet manifolds were welded to the thrust chamber with inert arc, aircraft quality welding.

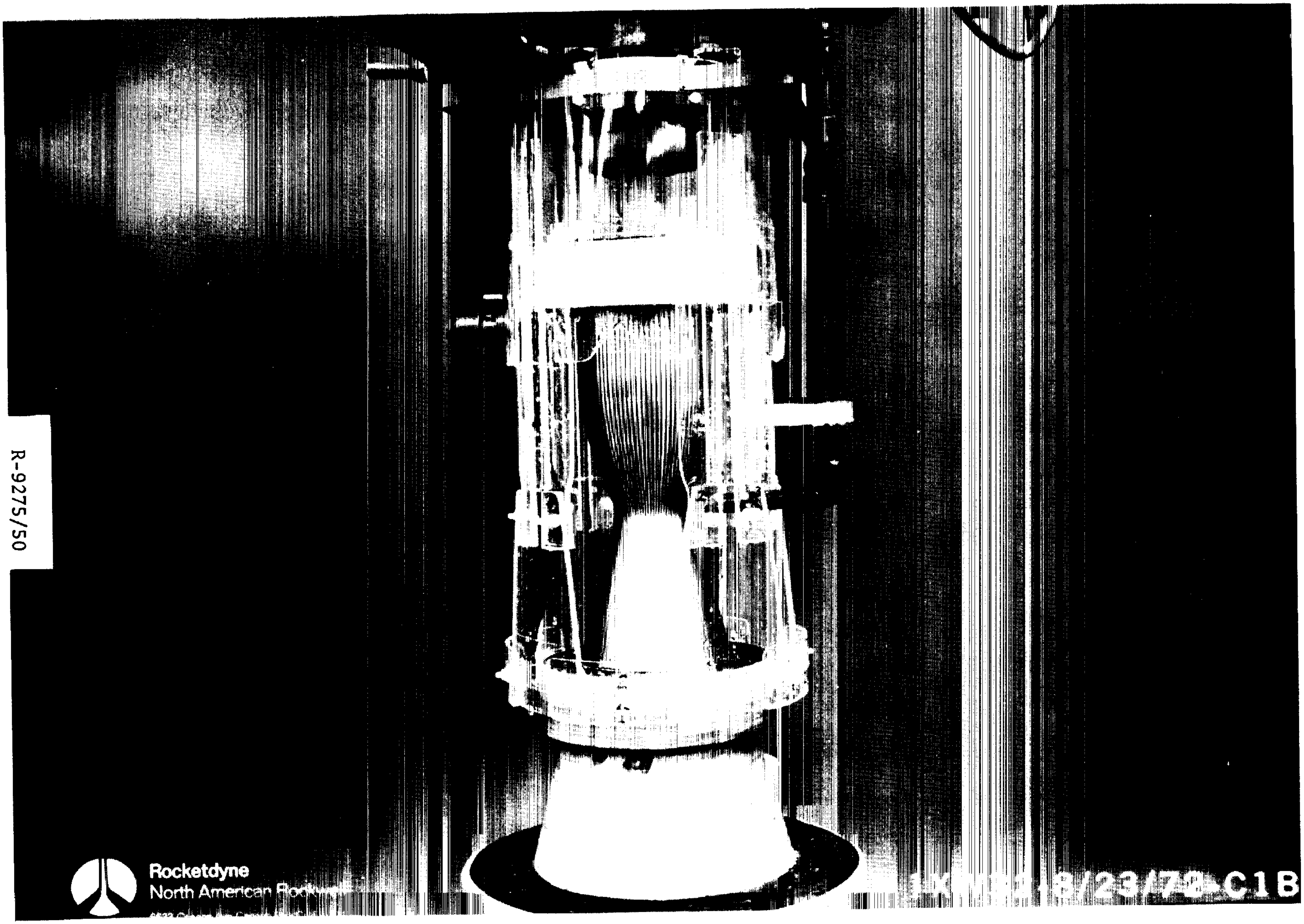


Figure 27. Overall View of OF_2/B_2H_6 Thrust Chamber No. 1 Illustrating Electroform Tooling

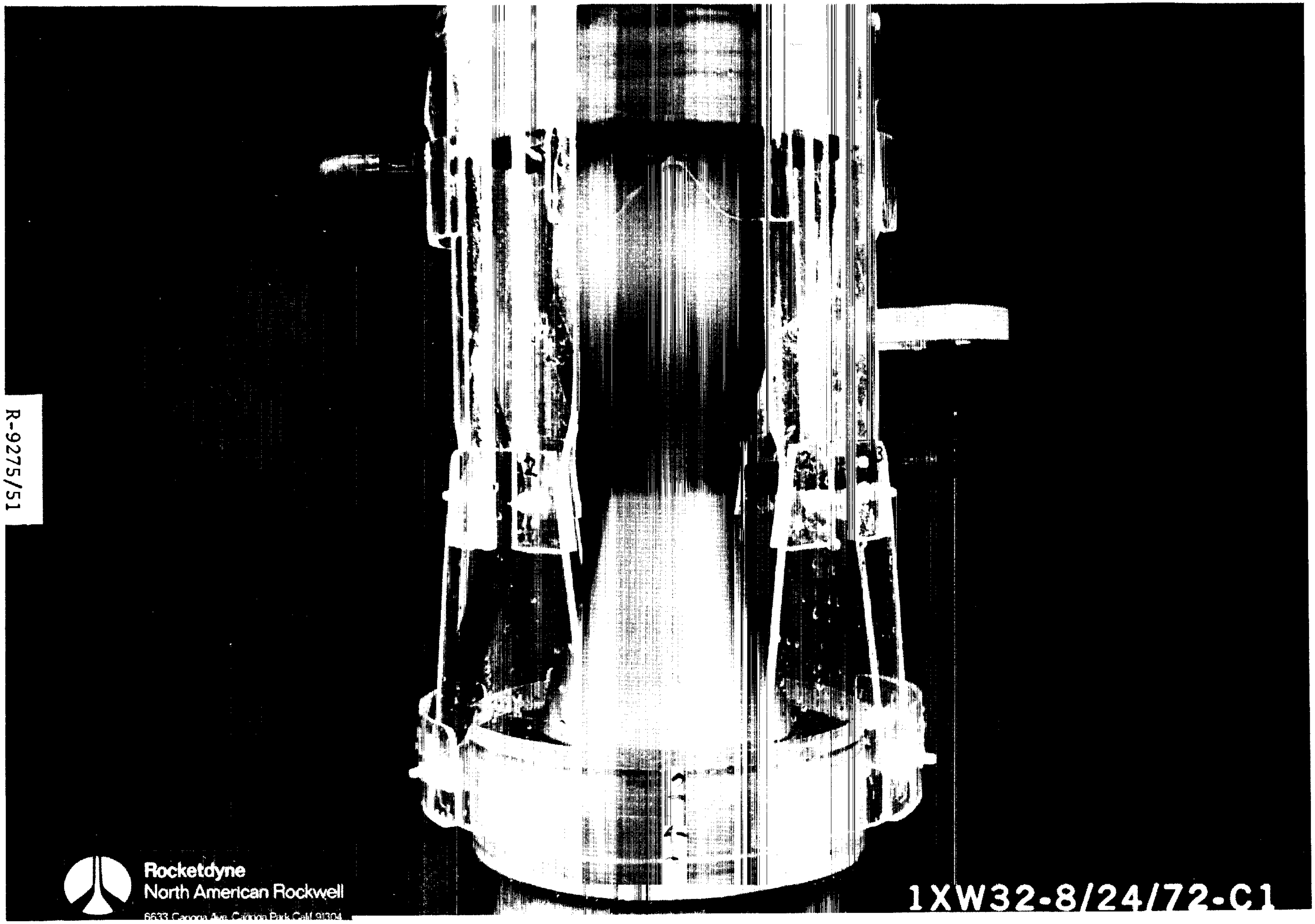
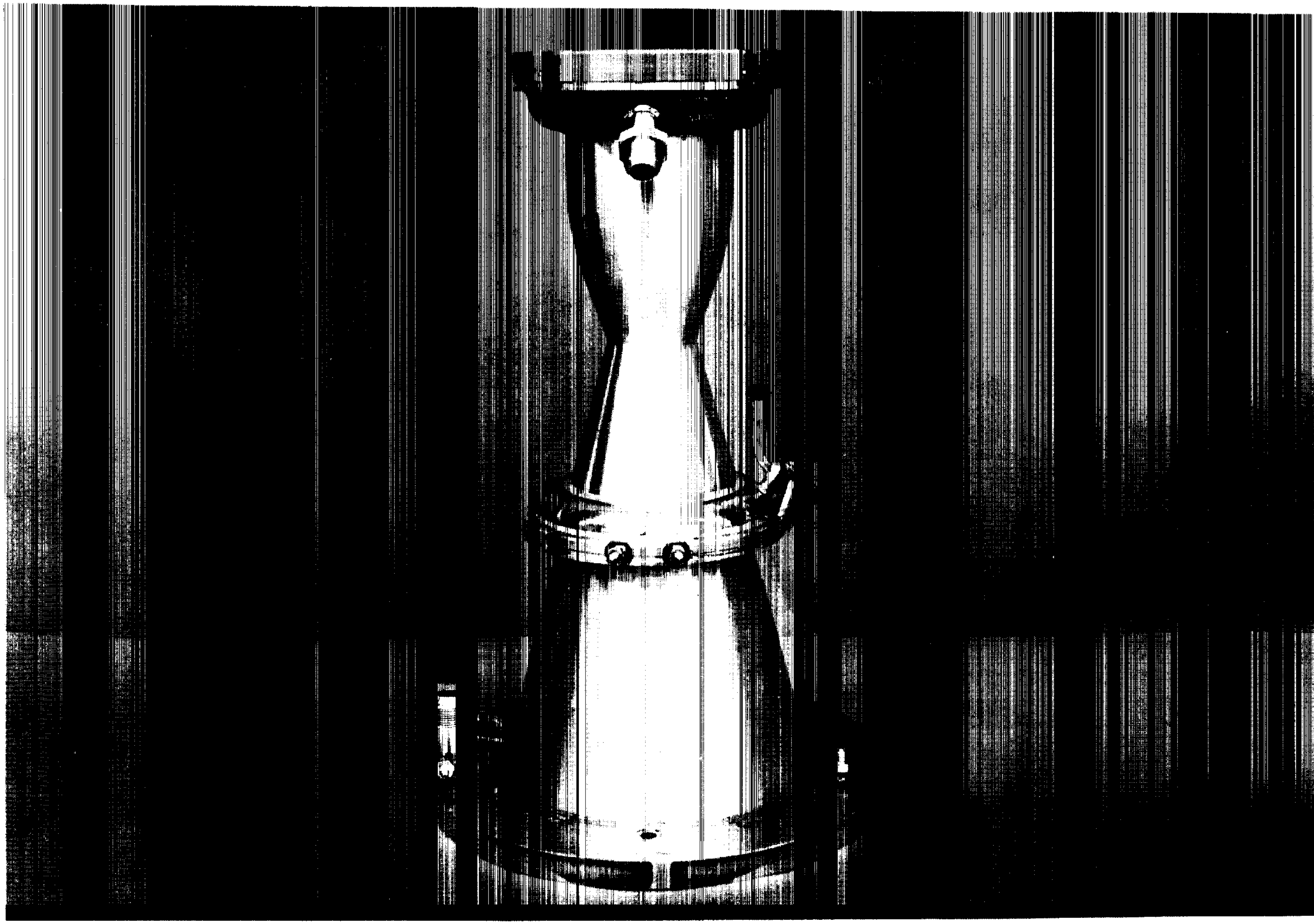


Figure 28. OF_2/B_2H_6 Electroformed Chamber No. 1 Removed From Nickel Plating Bath



1XW31-9/29/73-C1B

Figure 29. Completed OF_2/B_2H_6 Double-panel Regenerative Thrust Chamber Assembly

Welding of the valve mounting supports and the JPL furnished valve inlet/discharge fuel and oxidizer fittings were accomplished upon completion of welding of the manifold closures.

A detailed inspection, pressure check, and flow calibration was conducted upon completion of fabrication. The final assembly was shipped to the Rocketdyne Santa Suana facility for test installation in the available diffuser-ejector altitude system at Yoke stand.

TASK VII - DEMONSTRATION OF DUAL PANEL REGENERATIVE COOLING WITH OF_2 AND B_2H_6

Task VII work was concerned with the actual test operation and result evaluation. For the planned test series, modification of the stand to allow both liquid B_2H_6 and OF_2 to the chamber coolant manifold inlets was performed. This was accomplished on the OF_2 side by liquification of the stored OF_2 bottle bank gases in an LN_2 jacketed run tank.

TEST STAND MODIFICATION AND BUILDUP

Test stand modification and buildup at Yoke Stand in the Propulsion Research Area at Santa Susana, was initiated in parallel with the thrust chamber completion effort. Modification of the test stand to provide a simultaneous liquid OF_2 jacket flow, gaseous F_2/O_2 injector flow and liquid B_2H_6 fuel flow was accomplished for testing of the 20:1 area ratio nozzle at a nominal 100 psia (6.9×10^5 N/m^2) chamber pressure (MR = 3.0) with the previously existing altitude diffuser setup.

The NASA JPL furnished fuel and oxidizer propellant valves (Ref. 2) were to be employed during this test series. Direct mounting of the OF_2 valve at the chamber OF_2 inlet flange was accomplished. The B_2H_6 valve was connected to the existing B_2H_6 fuel inlet at the 20:1 area ratio flange point and supported from the nozzle flange.

B_2H_6 Feed System

Figure 30 illustrates the B_2H_6 feed system modified for a low temperature chill of the B_2H_6 feed system. Modification of the feed system over that previously used during Task IV study included a new pump recirculation unit and a new Freon-14 to LN_2 chill loop replacing the previous methylcyclohexane to LN_2 loop. With the new conditioning system the fuel and jacket temperature could be lowered to -250 F (117 K) compared to the -120 F (189 K) limit used during previous Task IV study.

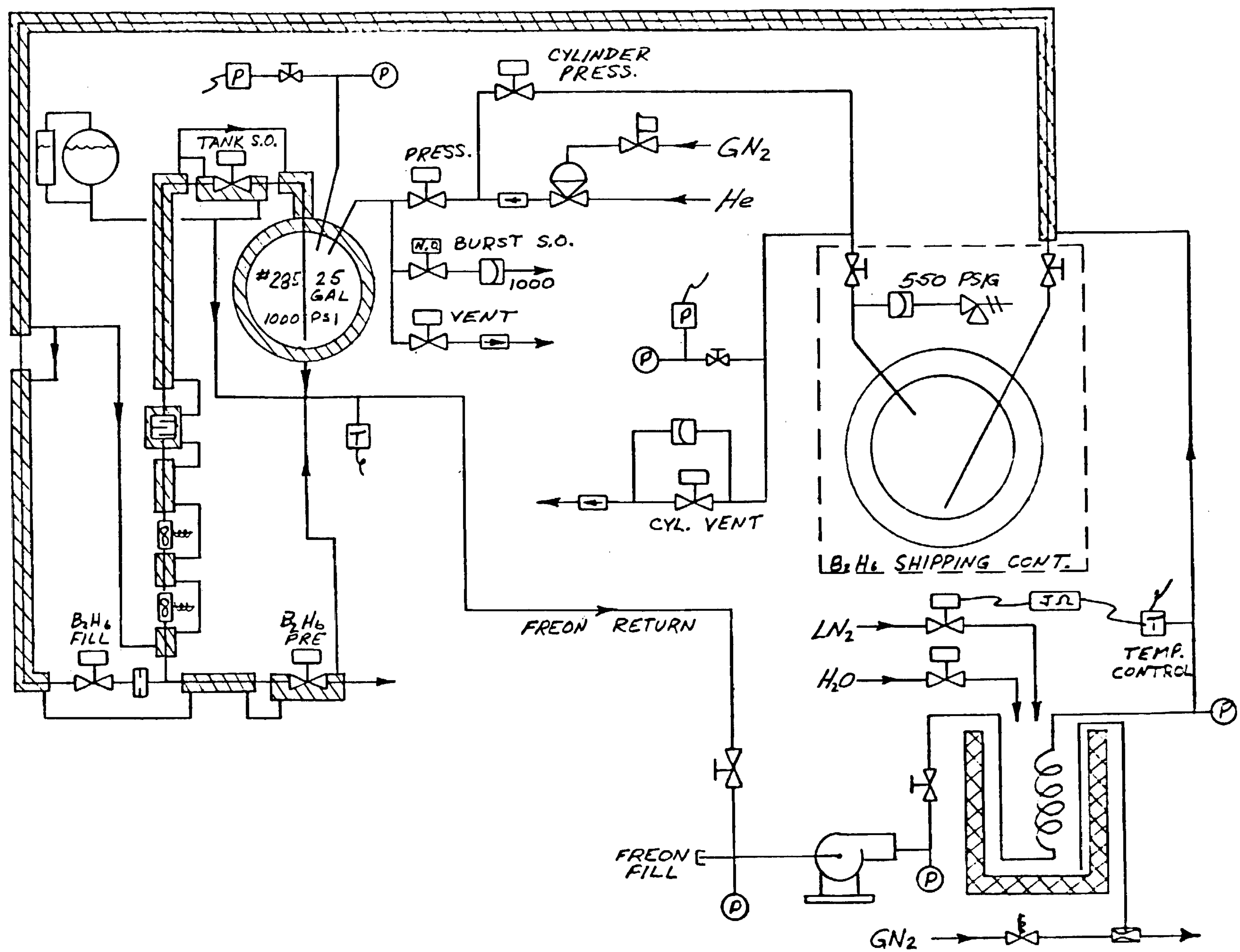


Figure 30. B_2H_6 System

Direct connection of the JPL furnished B_2H_6 shipping container (Ref. 5) to the feed system point used previously for the B_2H_6 40-pound Calary transport cylinders was made. This container tank supplied the 25 gallon run tank as shown in Fig. 30.

The B_2H_6 feed system used was similar to that successfully used during previous Task IV testing study. B_2H_6 valve sequencing was planned to be similar to that previously used with some fuel lead reduction with the colder propellants to ensure a moderately warm (0 F) fuel injection temperature at the main oxidizer valve opening signal point. Initial blowdown calibration testing of the B_2H_6 fuel side was planned with a 1.5 second fuel lead to establish the chilldown temperature versus time. Previous 1.0 second fuel lead times were planned to be reduced to approximately 0.75 second to assure adequate flow priming as well as a warm fuel injection temperature.

OF_2/FLOX Feed System

Figure 31 and 32 illustrate the OF_2 jacket and F_2/O_2 injector feed system configuration, respectively, planned for the initial test series with separate jacket and injector flows and propellant conditions. During initial testing the OF_2 was to be flowed overboard with measurement of the heat input and pressure drop conditions for the oxidizer jacket. A parallel supply of 15 OF_2 bottles (135 pounds OF_2) supplied the OF_2 jacket flow which was preconditioned by the LN_2/Freon chill loop in a 43 gallon tank (Fig. 33). The F_2/O_2 feed system was unchanged from Task IV testing.

Bypassing of the F_2/O_2 injector feed system was to be accomplished after testing established the heat load pressure and temperature conditions to the OF_2 jacket flow.

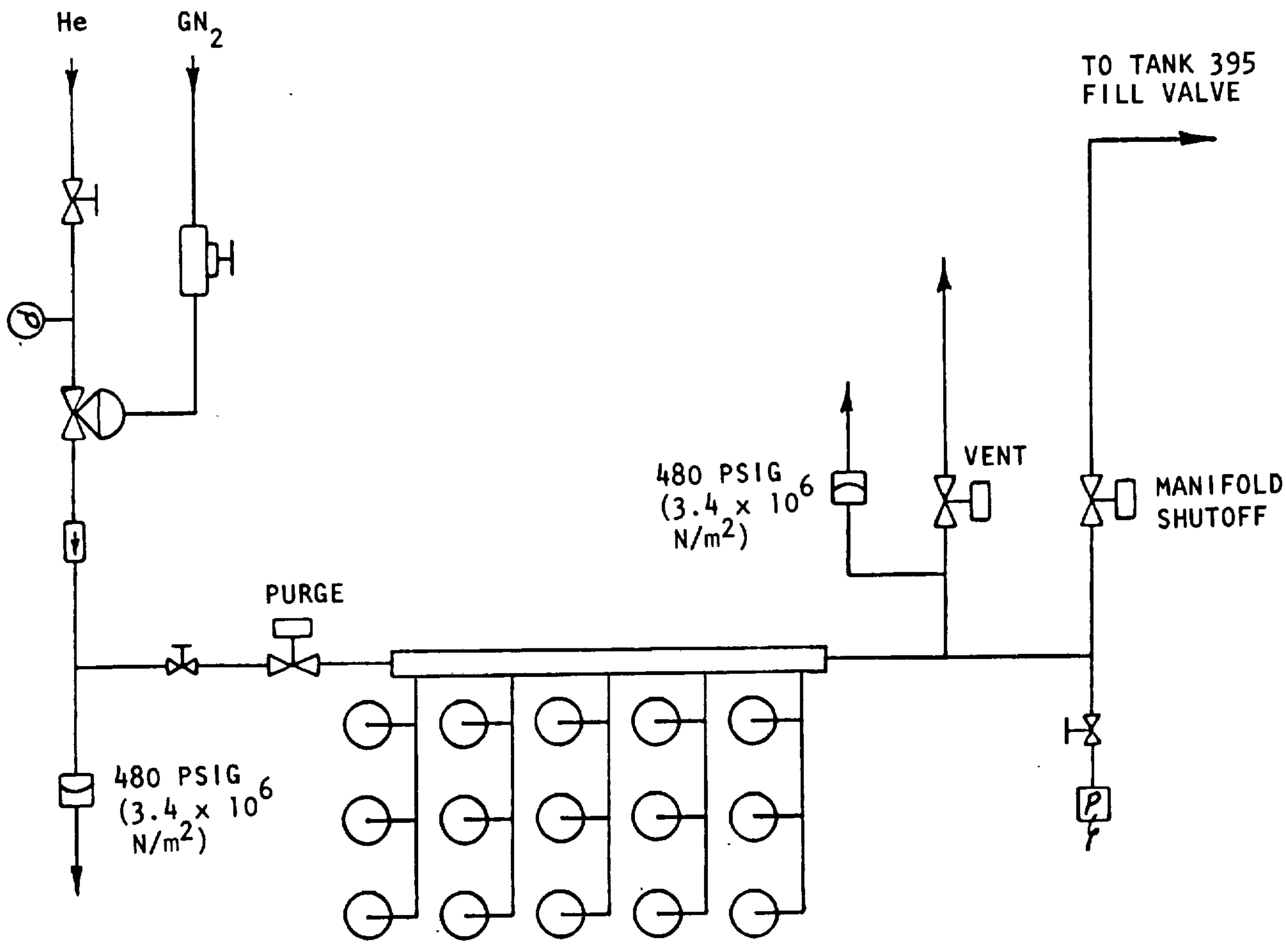


Figure 31. OF_2 Manifold - Pit 2

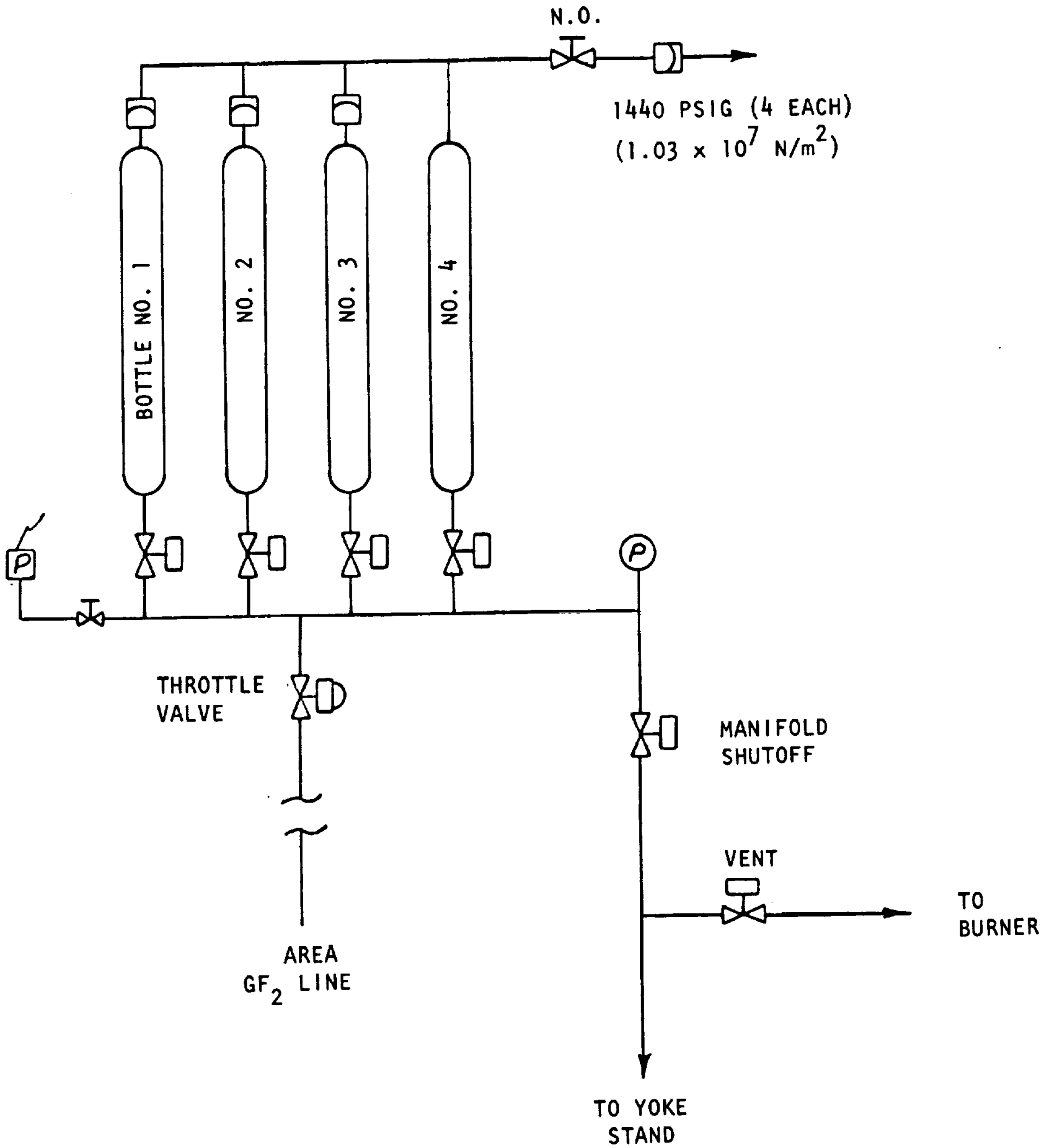


Figure 32. FLOX Bottle Bank

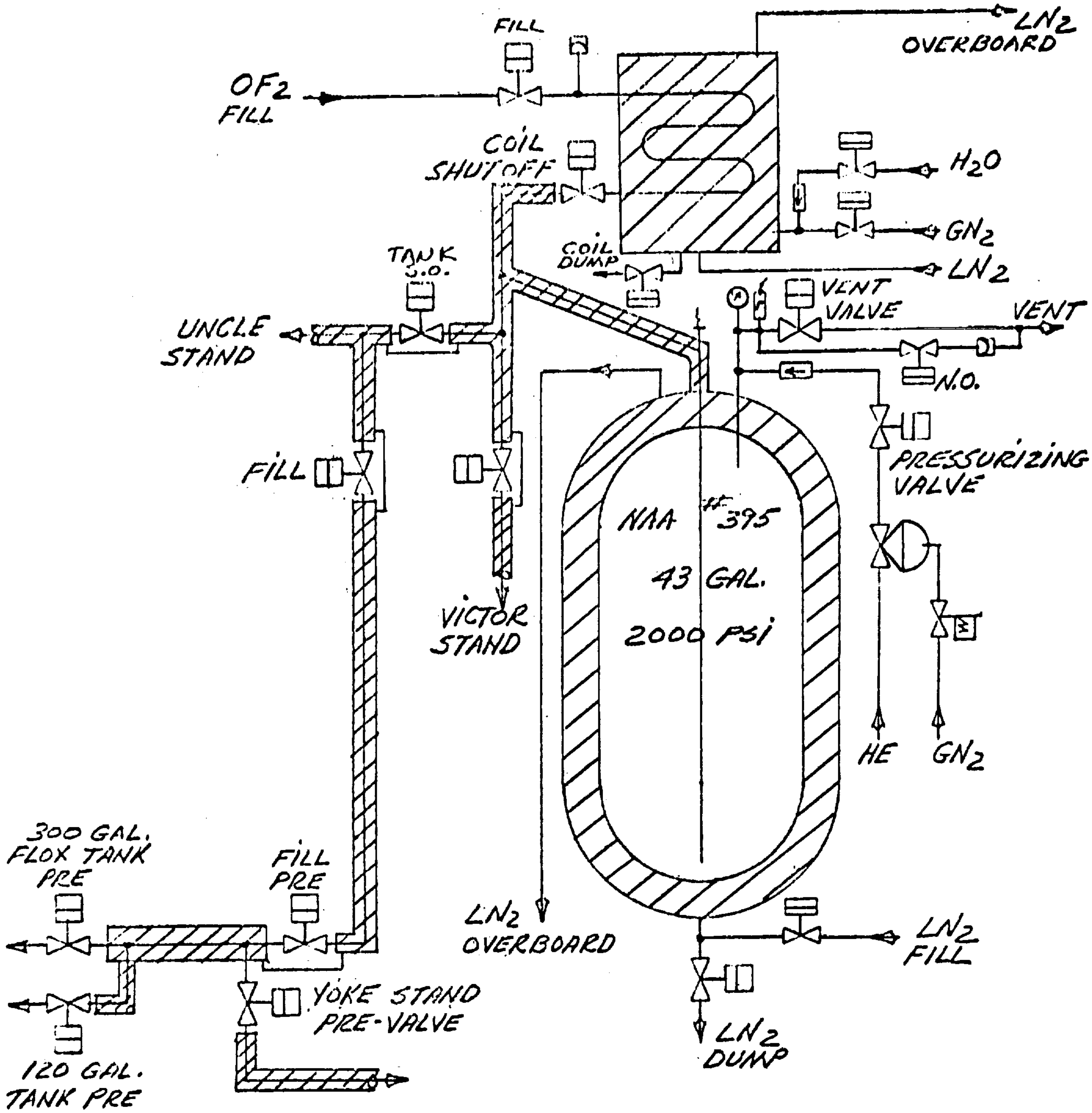


Figure 33. 43 Gallon OF_2 Pressure Vessel No. 395

Diffuser Ejector System

The diffuser ejector system capable of 1 psia operation as demonstrated during previous Task IV testing was employed during the test series. The GN_2 driver and water cooling system diagram are illustrated in Fig. 34.

Thrust Chamber Flow Schematic and Instrumentation

Added instrumentation to that used during previous Task IV testing included seven axially spaced thermocouples tack welded to the combustor jacket to provide local back wall temperature measurements. These were to be indicators of the local gas side wall temperature measurements by comparison to previous computer temperature solution. B_2H_6 and OF_2 jacket inlet/outlet pressure and temperatures were also monitored.

Figure 35 illustrates the thrust chamber flow and valve setup for the Task VII testing. Pre and post test purging was provided.

Chamber Installation

Completion of the Freon chill loop plumbing, OF_2 feed system plumbing, and chamber installation was accomplished. Figure 36 illustrates the Yoke Stand setup with installed fuel and oxidizer run valves. Chamber thermocouple instrumentation was spot welded to the nozzle and combustion chamber wall for back wall temperature measurement.

Initial stand pressure leak checks conducted with the JPL furnished gold plated metal O-ring seals on inlet and outlet port flanges indicated unacceptable leakage at all four points. Alternate K-seals with black teflon coated surfaces were installed. Initial testing indicated sealing on all except the OF_2 valve discharge port. Reworking of this flange seat surface was accomplished. Subsequent installation and leak checking of this surface indicated satisfactory results for the remainder of the test program.

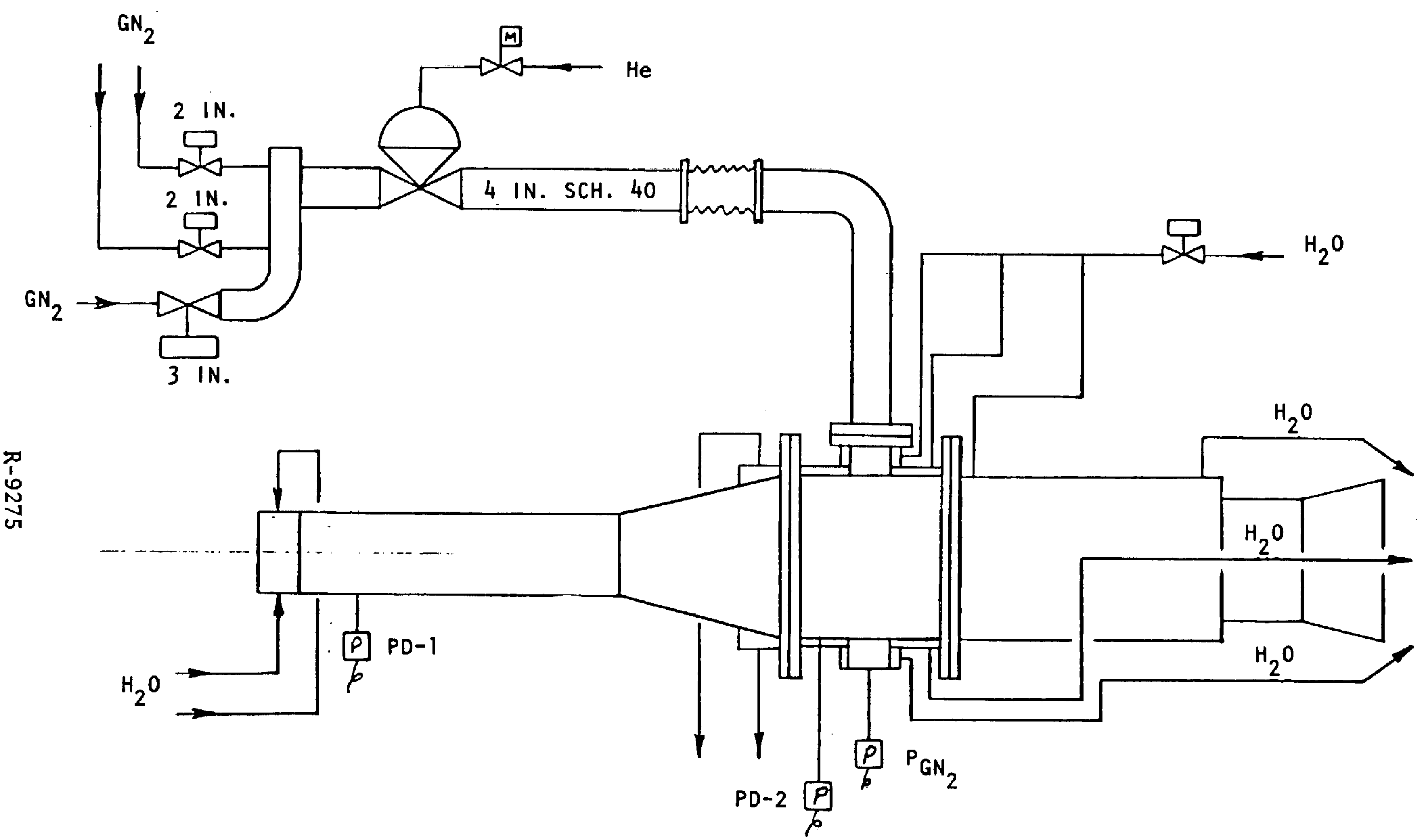


Figure 34. Diffuser-Ejector System-Yoke

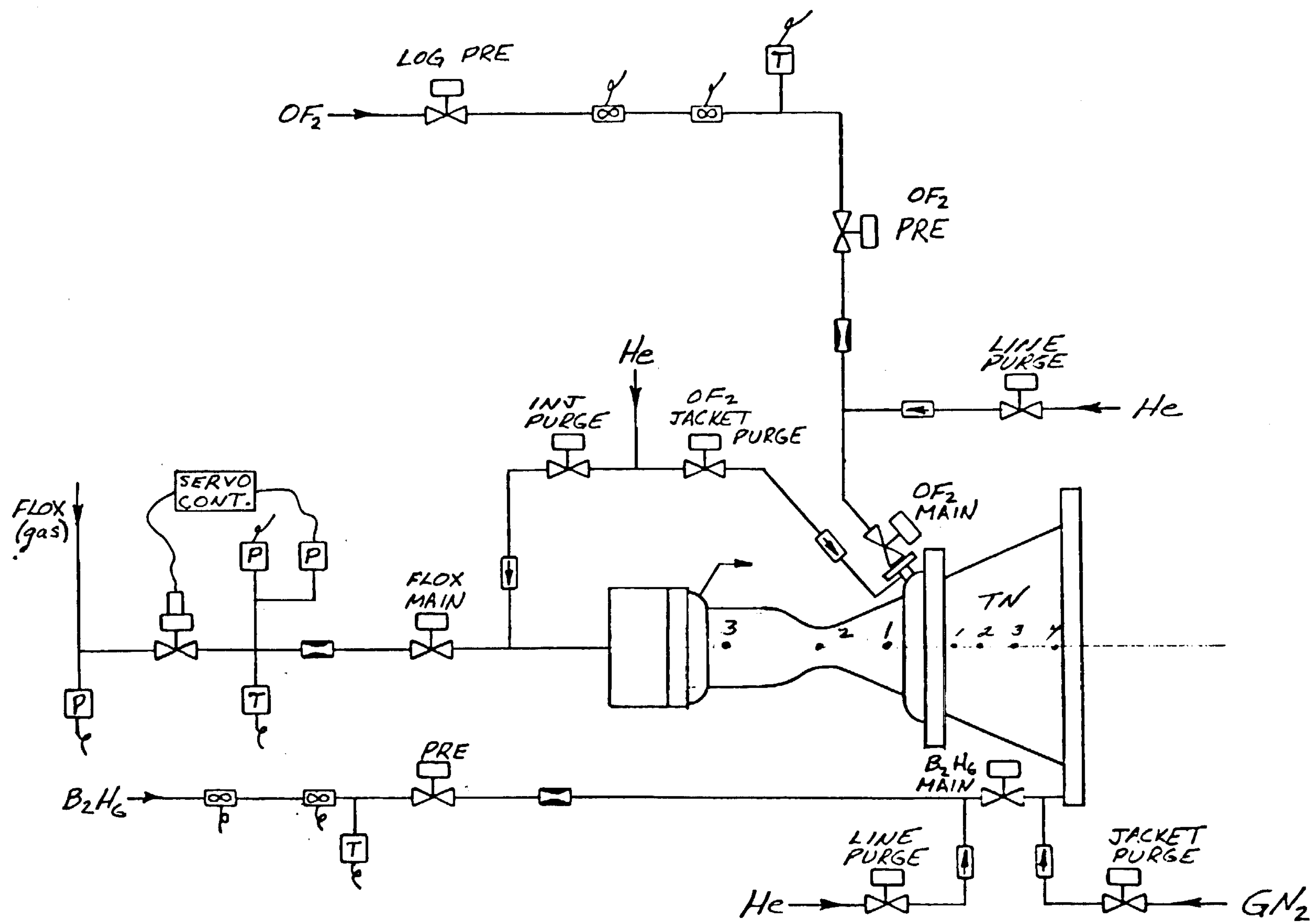
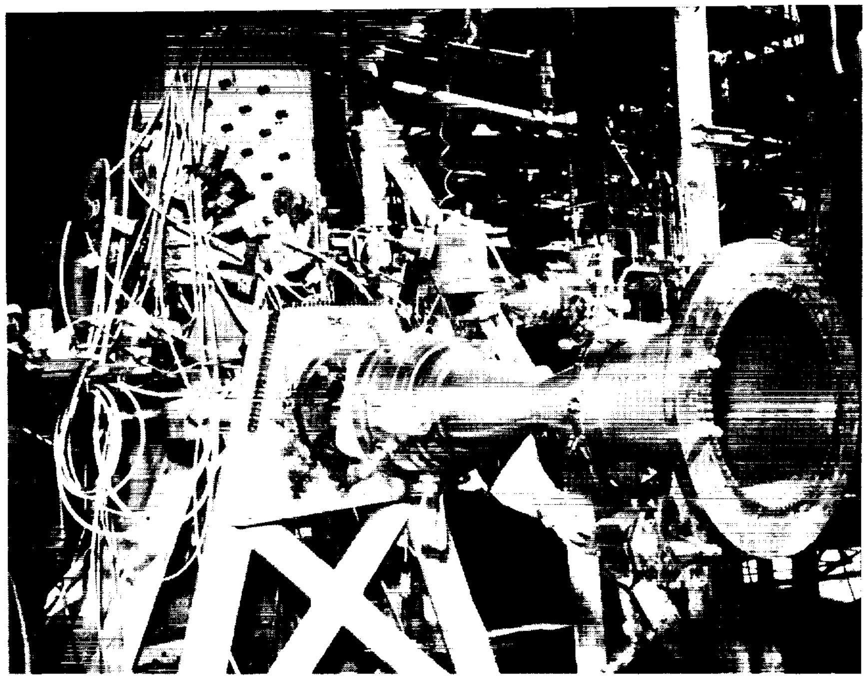
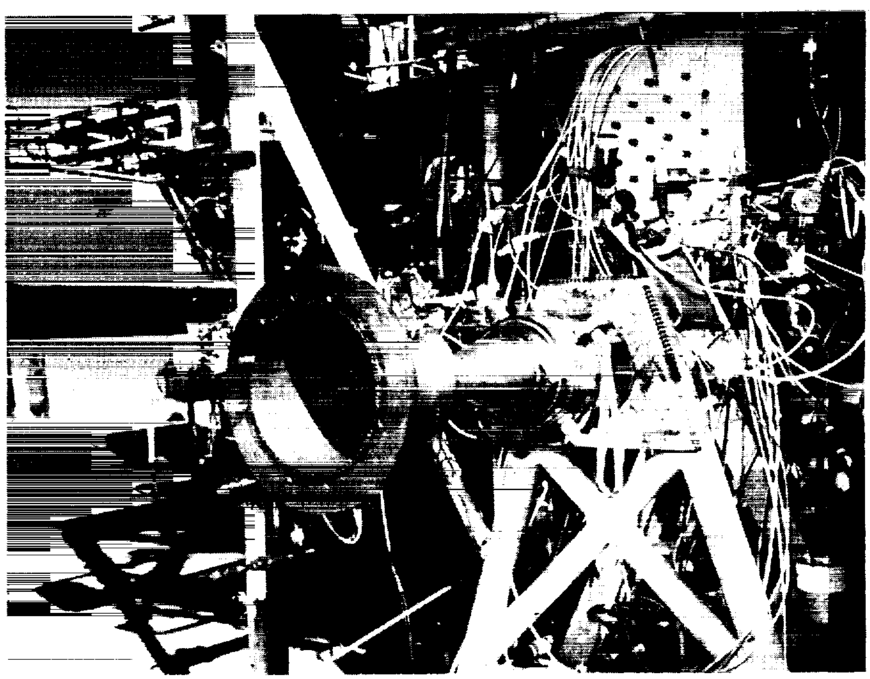


Figure 35. Thrust Chamber Flow Schematic



(a) Left View Illustrating Valve Supports and Thrust Mount



(b) Right Hand View

Figure 36. OF_2/B_2H_6 No. 1 Regenerative Thrust Chamber Installed on PRA Yoke Stand (10-23-72)

The JPL run valves used on the OF_2 and B_2H_6 cooling jackets performed entirely satisfactorily with a total of 12 on/off cycles accomplished of the OF_2 valve and 12 performed on the B_2H_6 valve.

TEST PROGRAM

The Task VII test program effort was conducted on the completed thrust chamber hardware installed at Yoke Stand PRA. The test series included initial blowdowns, short duration mixture ratio surveys, heat transfer surveys, and a longer duration final test series. The following discussion summarizes the test program objectives and the test program conducted. Figure 36 illustrated the test hardware installed on the Yoke Test Stand.

Test Program Plan

The proposed test plan considered initial checkout testing with a water simulant to establish a data point comparison with previous Task IV effort to provide heat load and pressure drop levels comparable to the OF_2 simulated coolant. Following the checkout testing, OF_2 coolant would be used in a bypass operation made to allow the combustion chamber to be overcooled from the nominal design point. In this manner, the comparison of heat load and pressure drop to those of the previous water cooled testing would be established without jeopardizing the hardware or requiring elaborate sequencing.

Fuel and oxidizer inlet temperature, together with boundary layer coolant (BLC), were planned to be varied on subsequent tests while gradually reducing OF_2 flow towards nominal. Study of chamber heat loads, coolant pressure drop, performance, and wall deposit effects was to be conducted to establish values of these parameters for the later testing. A balanced operation was to establish the best operating point to be selected for long duration operation demonstration.

Partial bypass operation with the injector oxidizer fed with a portion of the jacket flow was planned to be studied in the following test series. During this series the start/shutdown sequence was to be evaluated and a mixture ratio survey conducted. A 10-second test following this effort was to establish interim nearly stable cooling condition to provide data for a final planned long (50 second) test demonstration.

Due to the propellant toxicity and evening darkness factors, the test program outlined was conducted on a Saturday/Sunday time schedule, weather and wind direction/intensity permitting. Initial short tests were multiple to reduce the number of test days. Longer test durations were accompanied by injector/ chamber cleaning operations between test days.

B_2H_6 propellant was transferred from the JPL furnished storage tank without difficulty. The Calary storage tank represented a substantial improvement in terms of dry ice consumption and also in terms of hand valve operation for transfer operations.

OF_2 transfer from the gaseous bottles supply bank was accomplished by individually bleeding each bottle in succession to a low pressure until a sufficient quantity had been liquified in the LN_2 chilled run tank.

Test Summary

Table 5 illustrates the test program conducted during the Task VII study. A total of 9 test operations including B_2H_6 and $OF_2/F_2/O_2$ blowdowns and passivations were conducted.

Test 000. An initial B_2H_6 blowdown was conducted on 11 November 1972 for a two second duration to establish venturi stabilization inlet pressures and temperatures. A calibration was made and compared to previous data.

Test 001. A second 2.0 second B_2H_6 blowdown was conducted at a 0.63 lb/sec (0.29 kg/sec) flow on 11 November 1972 to define the chill characteristics of the thrust chamber jacket for the colder propellant temperature (-190 F, 150 K) compared to the previous Task IV data. Figure 37 illustrates the comparative discharge temperature versus time. After a 1.2 second period the fuel discharge temperature was lowered to a -65 F (220 K) level. On the basis of these results a 0.72 second fuel lead was indicated as a sufficient chill, prior to OF_2 and F_2/O_2 valve opening, to establish a good fuel jacket prime.

TABLE 5. TASK VII TEST SUMMARY FOR OF_2/B_2H_6 REGENERATIVE CHAMBER TESTING

TEST NO.	DATE (1972)	TEST OBJECTIVE	MAINSTAGE TIME (SEC)	MIXTURE RATIO (o/f)	$\overline{P}^*_o$, PSIA (N/m^2) x 10^{-5}	COMMENTS
0	11-11	B_2H_6 BLOWDOWN	2.0	0	13.8 (0.95)	SATISFACTORY
1	11-11	B_2H_6 BLOWDOWN	2.0	0	13.8 (0.95)	
2	11-11	OF_2 BLOWDOWN	2.0	∞	13.8 (0.95)	
3	11-25	SHORT DURATION	1.5	2.94	41.0 (2.82)	
4	11-25	SHORT DURATION	3.0	3.15	86.7 (5.93)	
5	11-25	LONGER DURATION/ MR	5.0	3.70	103.7 (7.08)	
6	11-25	MR VARIATION	5.0	2.67	104.7 (7.22)	
7	12-16	PLANNED 10 SEC	10.0	2.94	96.5 (6.65)	
8	12-16	PLANNED DURATION	22.0	2.80	96.5 (6.65)	OF_2 LINE FAILURE

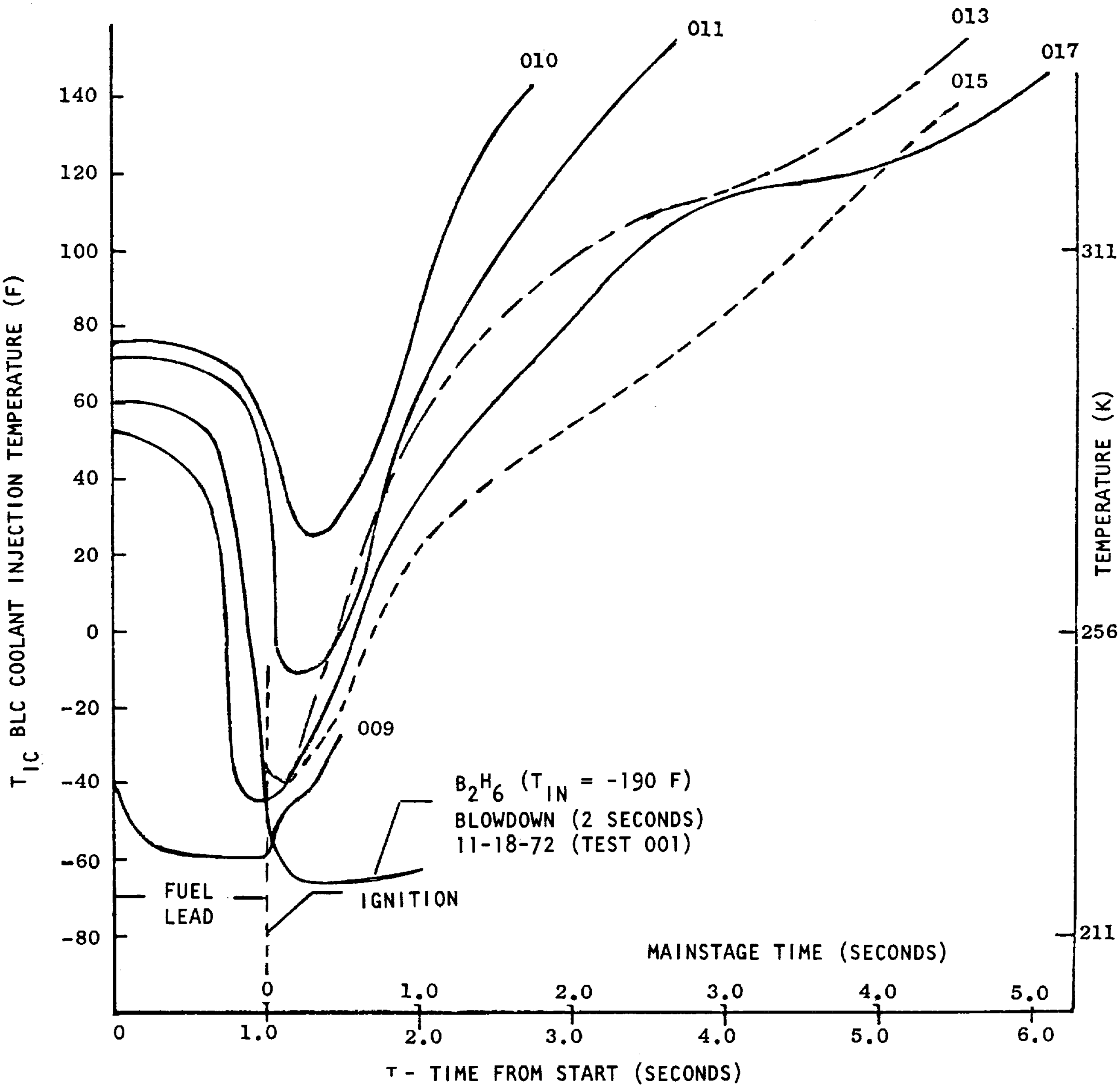


Figure 37. Comparison of Regenerative Chamber BLC Injection Temperature Transients During Ignition and Early Mainstage

Test 002 A and B. F_2/O_2 oxidizer calibrations were performed on 11 November 1972 to establish the servosystem control limits for 1.9 lb/sec (8.6 kg/sec) flow. Initial low pressure (30 psia, 2.07×10^5 N/m^2) passivation blowdowns were performed, followed by several F_2/O_2 blowdowns at near rated flow. A satisfactory bracketing of the servocontrol limits was accomplished during this testing.

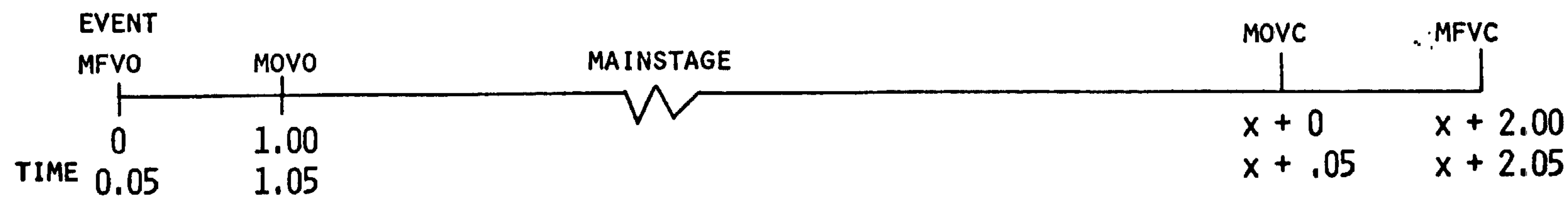
Subsequent to the F_2/O_2 blowdowns an OF_2 flow passivation and calibration was performed to establish compatibility and OF_2 valve cycling characteristics. Satisfactory characteristics on all of these functions were attained.

Further testing during this test day was suspended as a result of a facility helium system pressure decay to a critically low level. Transfer of the OF_2 and B_2H_6 propellants back to their storage vessels was, however, achieved satisfactorily.

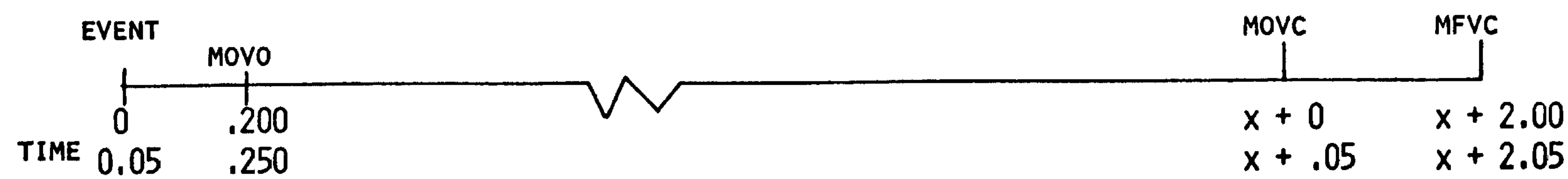
Test 003. This test was planned to be a short duration (1.5 seconds) test to achieve ignition and short mainstage heat transfer and performance characteristics with a nominal mixture ratio. A scheduled duration was achieved with a chamber pressure of 40 psia and mixture ratio of 3.0 was achieved. Figure 38 illustrates the valve sequencing used for this and subsequent testing.

As a result of problems incurred from the helium system failure, this test was conducted with the OF_2 jacket discharge directly plumbed to the injector. Reduction in the B_2H_6 valve lead time to 0.2 second was accomplished to ensure a high jacket metal temperature and thermal capacitance. B_2H_6 jacket and OF_2 jacket discharge temperatures obtained were 15 F (264 K) and -26 F (241 K), respectively.

Test 004. This test was conducted for a planned 3.0 second duration at 3.15 mixture ratio. An 84 psia (5.8×10^5 N/m^2) chamber pressure was achieved. Fuel and OF_2 jacket discharge temperatures of -2 F (255 K) and -180 F (155 K) were reached. Fuel and OF_2 jacket inlet pressures of 169 psia (1.16×10^6 N/m^2) and 93 psia (6.42×10^{-5} N/m^2) were indicated. Temperature and pressure



TASK IV STUDY: B_2H_6 REGENERATIVE COOLING



TASK VII STUDY: OF_2/B_2H_6 COMBINED REGENERATIVE COOLING (TESTS 003-008)

Figure 38. Fuel and Oxidizer Run Valve Operating Sequence Conditions

stabilization were shown to be not yet accomplished due to the large thermal capacitance of the workhorse test hardware. Visual assessment of the deposits indicated only a small powdery deposit on the injector and thrust chamber wall surfaces. This confirmed the result of previous testing which indicated a satisfactory deposit condition at mixture ratio values ≥ 3.0 with the F_2/O_2-B_2H_6 combination.

Test 005. A planned 5.0 second duration was accomplished with an achieved chamber pressure of 105 psia (7.24×10^5 N/m^2). A mixture ratio excursion to 3.7 was obtained. Fuel injection temperature reached a 403 F (479 K) value with a fuel jacket inlet pressure of 256 psia. Post shutdown inspection indicated a lack of injector and chamber deposits confirming the shorter duration Test 004 results.

Test 006. Test 006 was planned to define conditions of performance, heat load, and deposit conditions at lowered mixture ratio. A 5 second test achieved a chamber pressure of 104 psia (7.2×10^5 N/m^2) and mixture ratio of 2.67. As a result of the low mixture ratio, post shutdown inspection and photos, Fig. 39 and 40 indicate loose peripheral face and chamber deposits which were not present during higher mixture ratio operation (Test 005). B_2H_6 and OF_2 discharge temperatures achieved were -31 F (238 K) and -170 F (161 K), respectively. Jacket inlet fuel and oxidizer pressures were 242 and 127 psia.

H_2O flow tests conducted post test 006 after 48 hours indicated deposits in 40 channels located from the 3:30-8:30 o'clock positions. The most extensive deposits were in bottom channels at the 6 o'clock position with progressively less deposits at the 3:30 and 8:30 locations. No channel deposits were indicated at any of the locations above these positions.

Cleaning of the channels was accomplished with 0.026 OD x 0.006 wall tubing supplied by 900 psig water pressure. Spectograph analysis indicated absorbence, Fig. 41 and 42 , in the following ranges

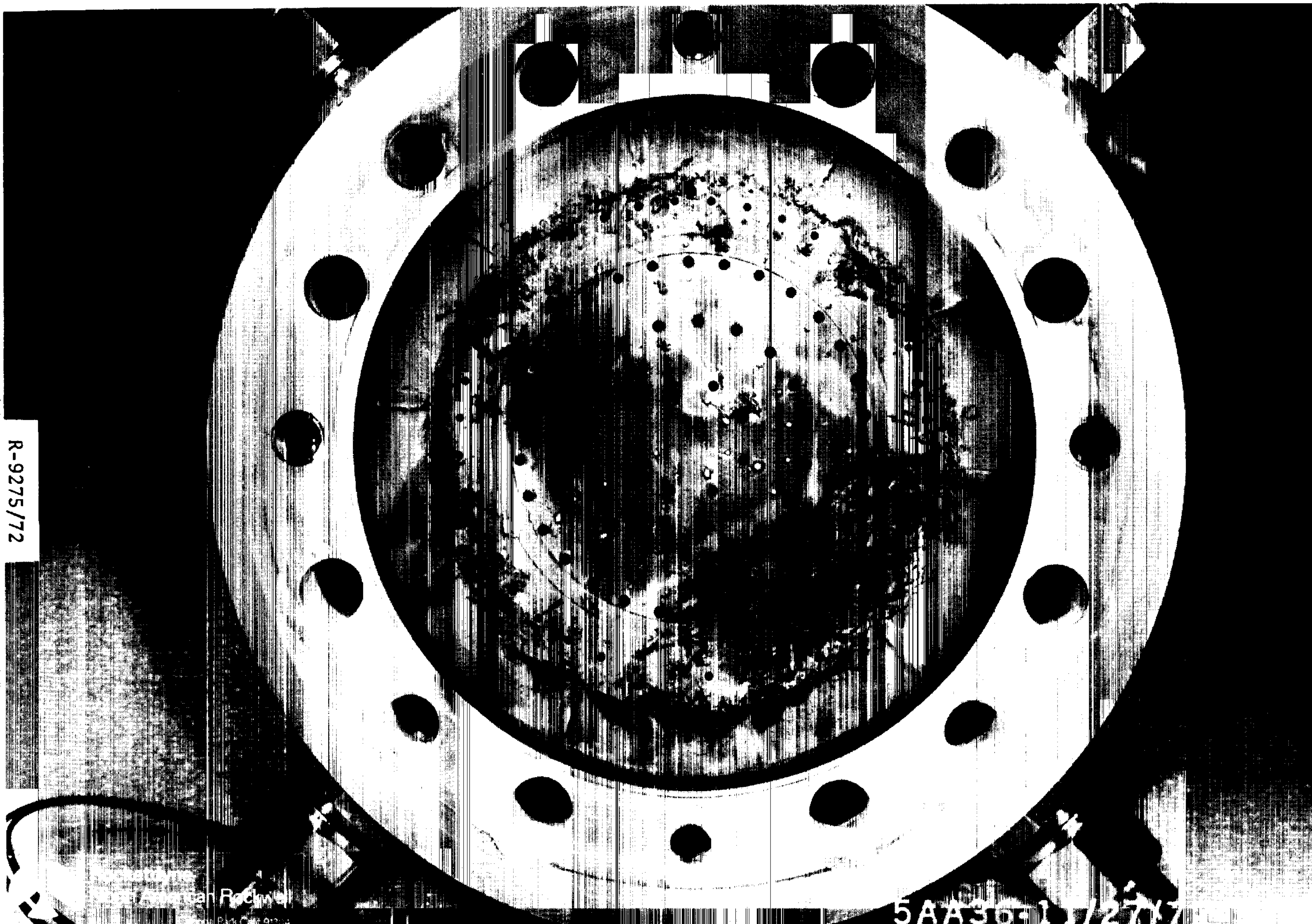


Figure 39. OF_2/B_2H_6 Triplet Injector Illustrating Peripheral Deposits Resulting From Low Mixture Ratio (2.6) Operation (Post Test 006)

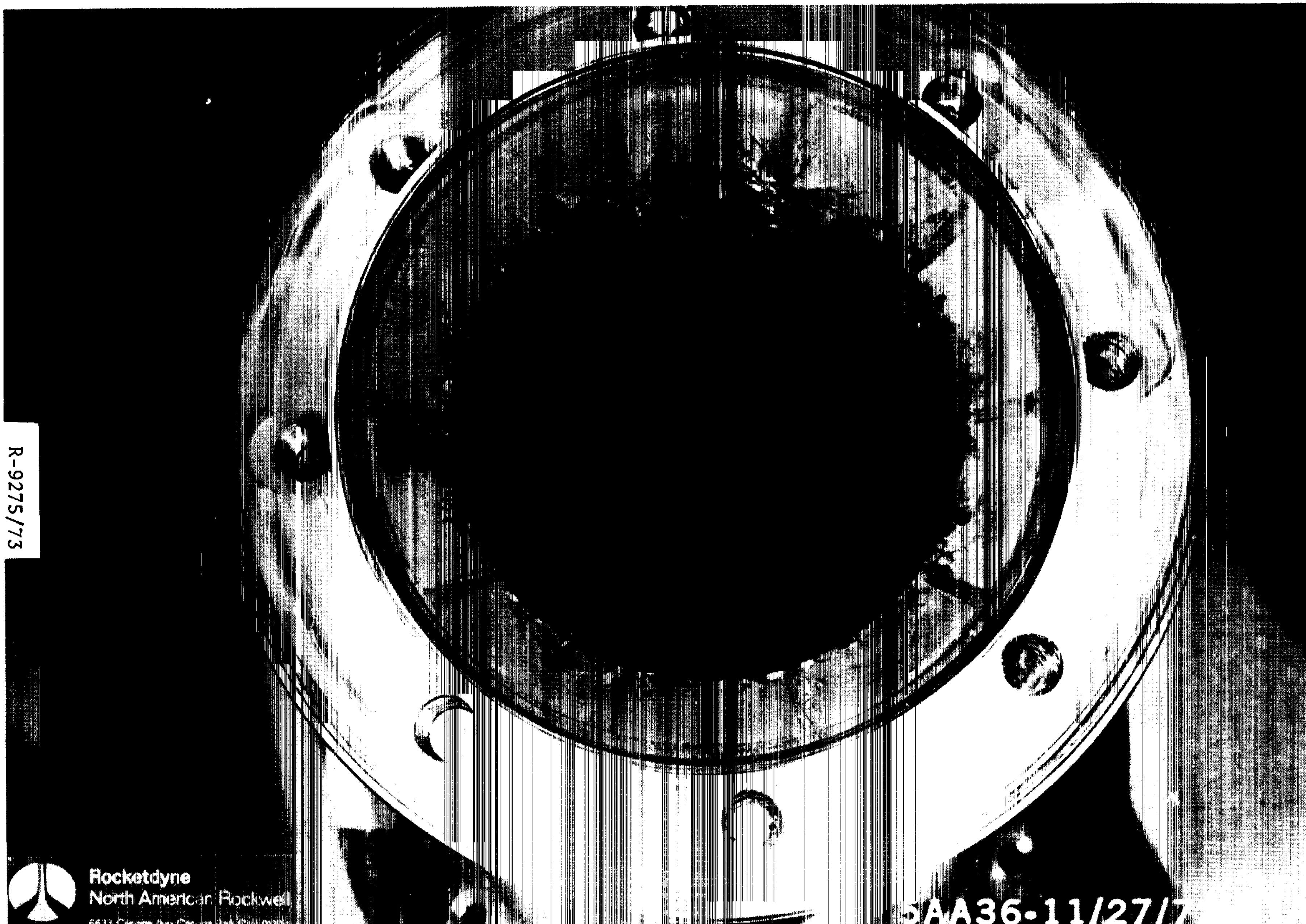


Figure . 40. OF_2/B_2H_6 No. 1 Regenerative Chamber Illustrating Deposits Resulting From Low Mixture Ratio Operation (Post Test 006)

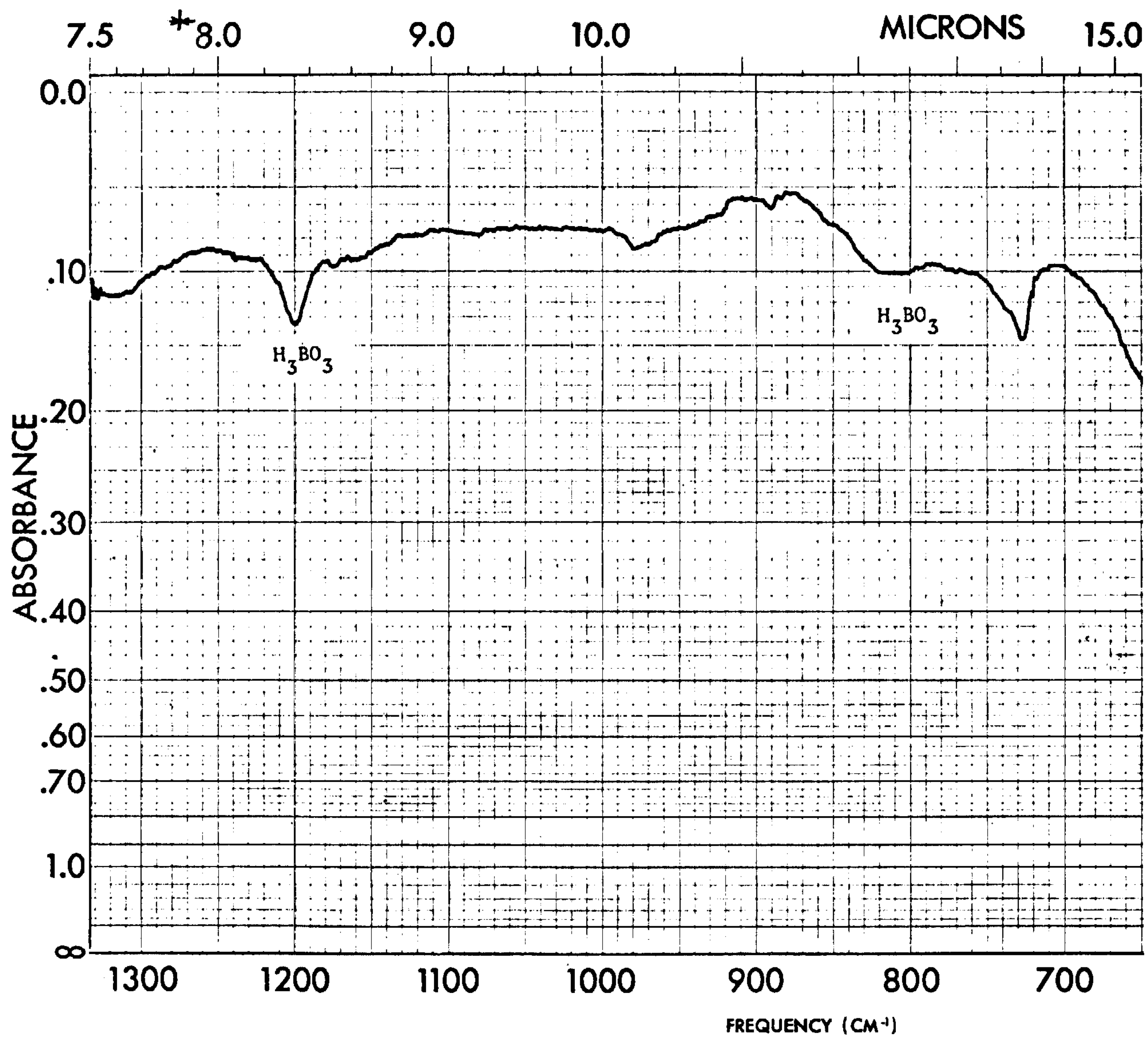


Figure 41. Absorption Spectrum of B_2H_6 Coolant Channel Deposits 7.5-15 Microns

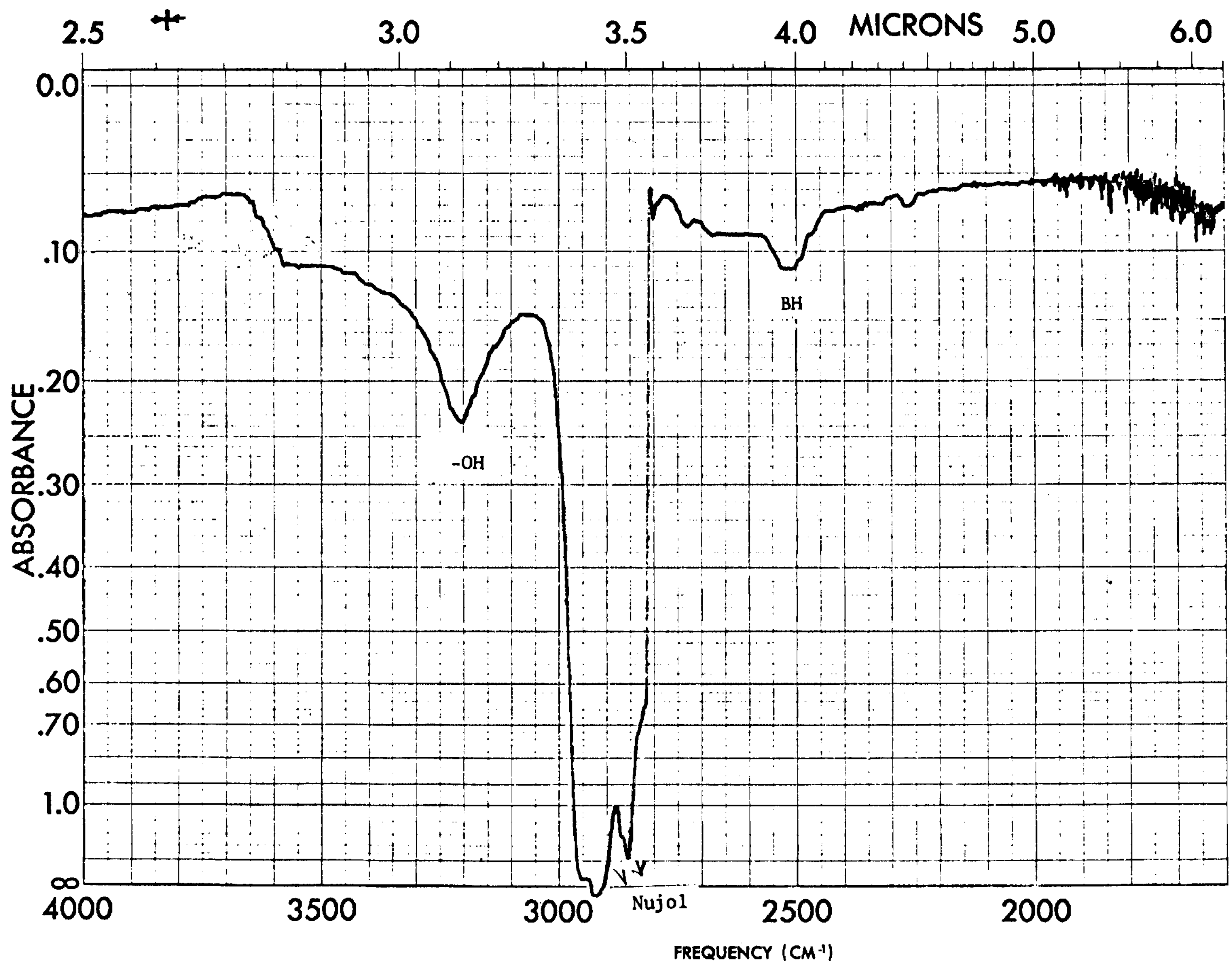


Figure 42. Absorption Spectrum of B_2H_6 Coolant Channel Deposits (2.5-6 Microns)

OF (ion)	3.1 micron
BH	4.0 micron
H_3BO_3	8.3 micron
H_3BO_3	14 micron

The deposits were found to be soluble in water (particularly warm water) and basically were H_3BO_3 compounds.

It was hypothesized that an inadequate purge post shutdown resulted in the combining of warm fuel residuals with air to form H_3BO_3 channel deposits. Remedial action was provided for the next test series through an improved shutdown sequence and a lengthy high pressure fuel purge.

Test 007. Test 007 (conducted on 16 December 1972) was a planned 10-second duration test with the simultaneous fuel and oxidizer jacket cooling, preliminary to the final 50-second duration test. The planned duration was achieved with a 2.94 mixture ratio and at a 96.5 psia (6.65×10^5 N/m^2) stagnation chamber pressure. As a result of examination of the test data, the mixture ratio was slightly lowered (to 2.80) to ensure no inadvertent red line cuts were intercepted on the B_2H_6 fuel side for the final duration demonstration. All performance parameters appeared satisfactory on this run. Figure 43 and 44 illustrate the combustor and injector deposits for Test 007-008.

Test 008. Test 008 (conducted on 16 December 1972) was a scheduled final 50-second duration demonstration to establish the steady state heat transfer, design integrity, and performance characteristics. A 22-second observer test cut occurred when fire was observed during the test emanating from the OF_2 upper manifold and injector inlet feed line.

Figure 43. OF_2/B_2H_6 Triplet Injector Illustrating Deposit Conditions (Post Test 007-008)

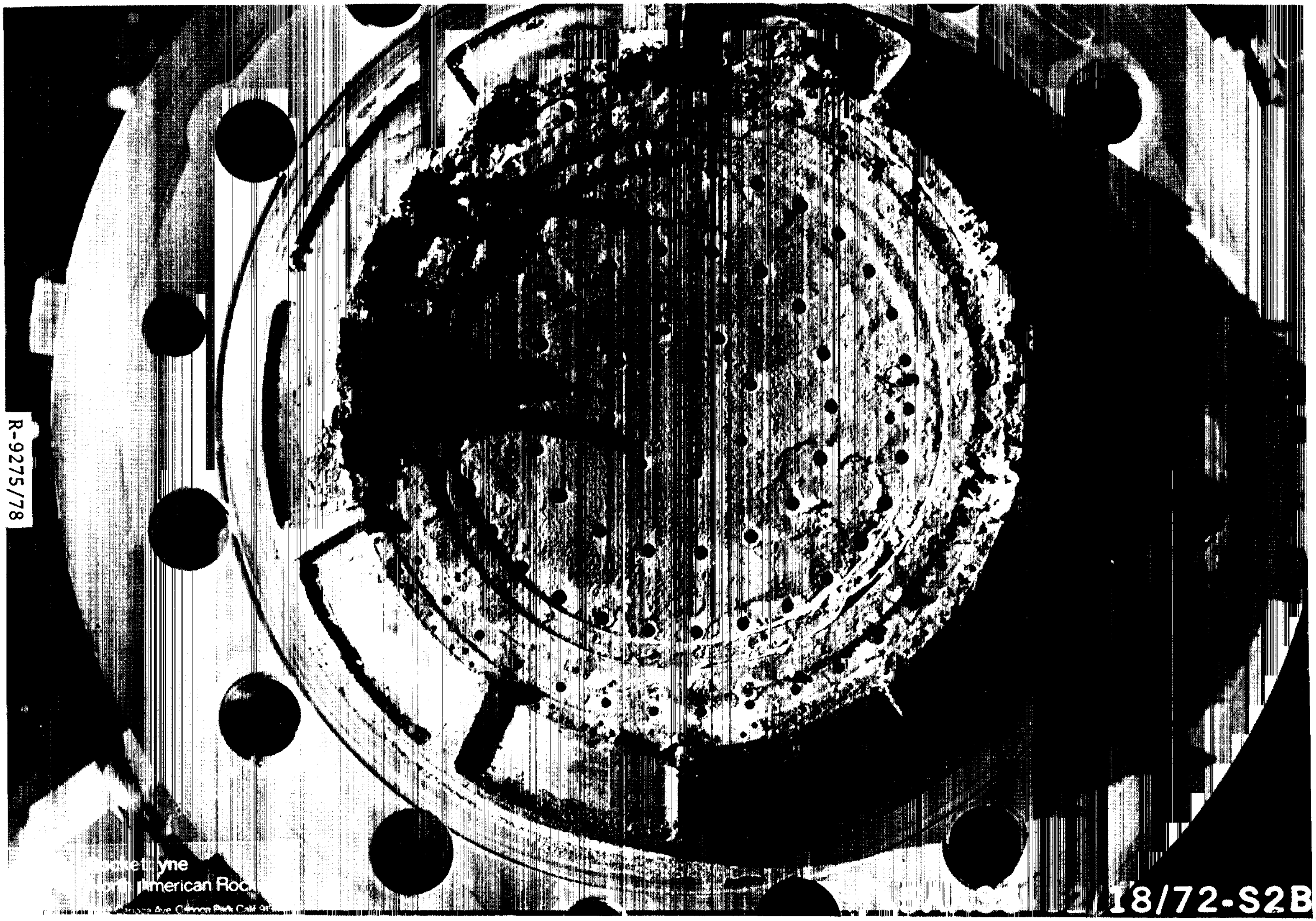


Figure 44. OF_2/B_2H_6 Regenerative Chamber Illustrating Combustion Side Deposits (Post Test 007-008)

Figure 45 illustrates the hardware post test 008. A review of the motion pictures taken during Test 008 indicated a small pin hole leak in the oxidizer feed line which at test start glowed red around the fine OF_2 flow jet emanating from the line. At 21 seconds into the test, a conflagration of the line and and adjacent hardware was noted. It was hypothesized post test that the OF_2 line (CRES 0.083 inch, 2.1 mm wall thickness) initially had a small imperfection which was magnified through bend forming which stretched the flaw into a weak spot. This, in turn, then opened up to pinhole size as a result of the previous testing (up to Test 008). Ignition of the metal subsequently occurred when the friction of the flow achieved a sufficient level. A sequence of events for this hypothesis is shown in Table 6 .

An alternate thought is that local ignition of a nonpassivated small spot on the line occurred. Refutation of this is seen through the fact that ignition of the flow did not occur until 21 seconds after the pinhole leak was observed. Pretest inspection included visual bubble leak check only at joint locations under 30 psig pressure. Passivation before testing was performed by low pressure OF_2 purging (30 psi) through the LOX clean OF_2 pressure lines.

Potential remedial action areas for future OF_2 and F_2 work in line flow passages includes the following:

- Pretest (initial) inspection of line system with sharp edges, bends and stress raisers
- Comprehensive pretest (test to test) OF_2 line system leakage and pressure check tests
- Possible elimination of all stainless or Inconel materials in high velocity and/or pressure thrust chamber/engine feed line systems
- Utilization of high thermal conductivity copper/nickel (or alloys) to prevent localized metal ignition where flow friction could occur
- Further OF_2 passivation study for metallic surfaces.

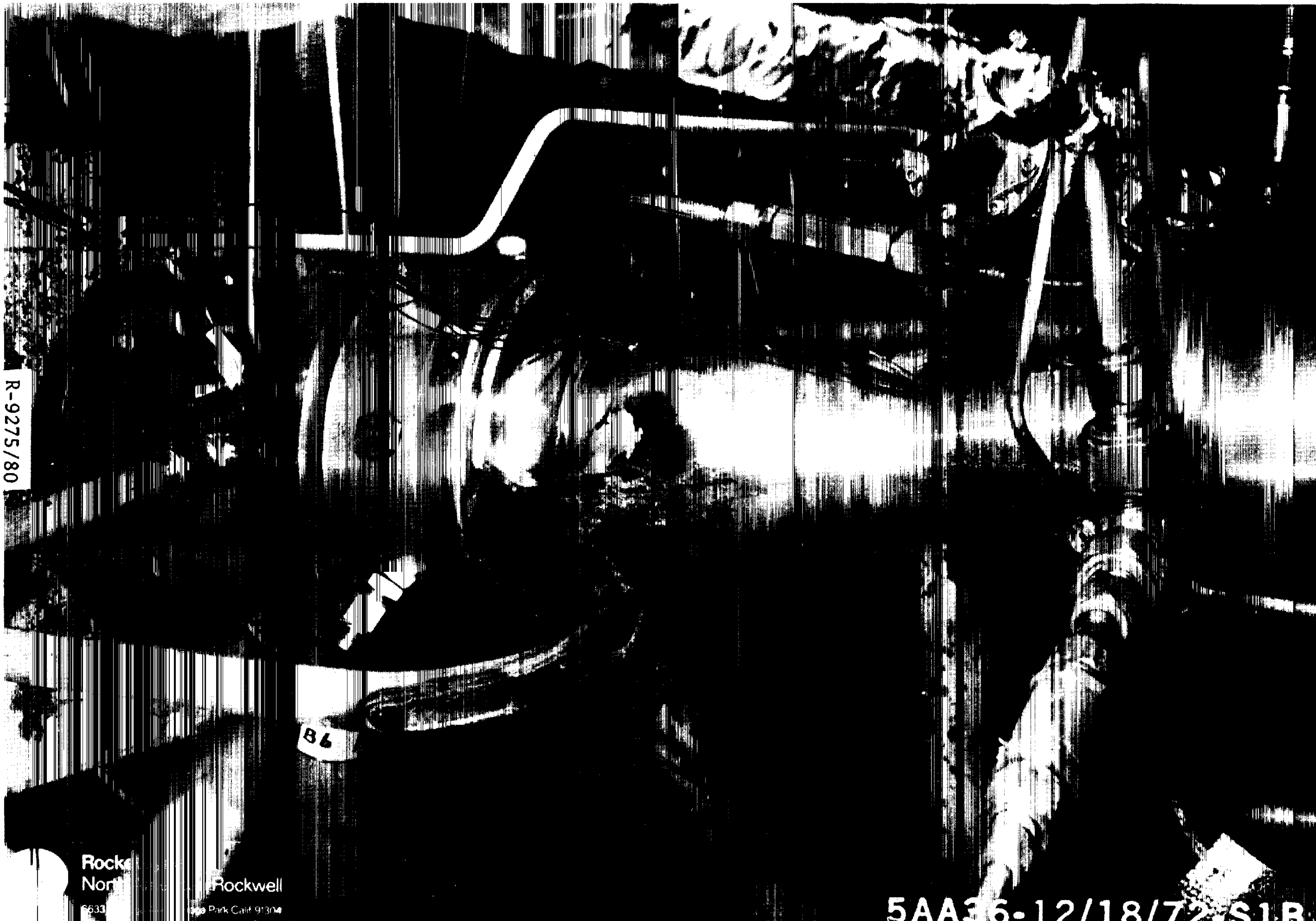


Figure 45. Thrust Chamber Hardware Post Test 008 Indicating Line Failure Results

TABLE 6. HYPOTHESIZED SUMMARY OF OF_2 LINE FAILURE SEQUENCE OF EVENTS

- OF_2 Jacket to Injector Line Pinhole Noted Early in Test 008 on Motion Picture
- Pinhole Locsted in Outside Bend Surface of OF_2 Transfer Line
- Ignition of Tube Resulted With Subsequent Large OF_2 Flow Discharge
- Line Ignition, Conflagration to Injector Location Noted
- Chamber Upper End Damage Incurred by OF_2 Fire
- OF_2 Transfer Line Consumed (Unavailable for Post-Test Analysis)
- Triplet Injector in Excellent Condition
- Test Terminated by Manual Observer Cut at 22 Seconds

Delivery of the No. 1 chamber and triplet injector and run valves to JPL for further review and analysis has been made. A second undamaged chamber (No. 2) has also been shipped, however no OF_2 jacket (for hardware comparison) is present on this chamber.

TEST DATA ANALYSIS AND RESULTS

The test data developed as a result of thrust chamber/injector testing included the engine wall temperature profile, OF_2 and B_2H_6 coolant temperature rises and pressure drops and the injector propellant flows and pressure drops. Table 7 illustrates the OF_2/B_2H_6 regenerative test chamber data summary for flows, pressures, and temperature conditions. The following describes the results and evaluation of the testing data.

Start and Shutdown Summary

On the basis of blowdown test data for the fuel jacket chill, a reduction in the fuel lead to 0.2 second was indicated. A satisfactory ignition start with a 0.2 second fuel lead was subsequently demonstrated with the JPL OF_2 and B_2H_6 integral valves. Mainstage chamber pressure buildup is illustrated in Fig. 46 for Test 003-008. Thermal capacitances of the system result in a 3.5 second delay in chamber pressure rise to the 90 percent P_c level. The chamber pressure buildup is smooth indicating no adverse behavior of the double jacketed fuel and oxidizer cooling approach.

Figure 47 and 48 illustrate the behavior of the chamber pressures for Test 007 and 008. In Figure 47 a chamber pressure surge is noted at shutdown due to the shutdown 200 psia (1.38×10^6 N/m^2) purge. (On Test 008 a reduced purge pressure was employed.)

Figure 48 of the Test 008 chamber pressure history shows a 5 psi (0.35×10^5 N/m^2) variance due to throat boron deposit buildup for the Test 008 2.8 mixture ratio condition. At slightly higher mixture ratio levels (3.0-3.2), the wall deposit buildup (Ref. 1) will be less resulting in a lesser fluctuation of chamber pressure.

Shutdown data for the tests conducted was masked by the substantial cutoff purge instituted to ensure no deposit formation within the cooling channels (based on Test 006 results). Shutdown time periods based on previous Task IV testing were expected to be substantially less than 1.0 second.

TABLE 7. TASK VII - OF_2/B_2H_6 REGENERATIVE CHAMBER DATA SUMMARY

1 Test Number	2 Main-stage Duration (sec)	3 Chamber Type	4 Oxidizer Venturi Temp. (F)	5 Oxidizer Venturi Pressure (psia)	6 Oxidizer Flowrate (lb/sec)	7 Fuel Venturi Temp. (F)	8 Fuel Venturi Pressure (psia)	9 Fuel Flowrate (lb/sec)	10 Film Coolant (% W_f)	11 Total Flowrate (lb/sec)	12 Mixture Ratio (o/f)	13 Throat Area A_T (in^2)	14 Nozzle* Stagnation Pressure (psia)	15 Fuel Jacket Inlet/Outlet Pressure (psia)	16 Fuel Jacket Outlet Temp. (F)	17 OF_2 In/Out Temp. (F)	18 B_2H_6 ΔT (F)	19 OF_2 ΔT (F)	20 Q B_2H_6 (Btu/sec)	21 Q OF_2 (Btu/sec)	22 Q Total (Btu/sec)
0	2.0	No. 1	---	---	---	-190	---	.62	---	---	---	5.305	---	---	---	---	---	---	---	---	---
1	2.0		---	---	---	-190	---	.59	---	---	---	5.305	---	---	---	---	---	---	---	---	---
2	2.0		-250	---	1.92	---	---	---	---	---	---	5.305	---	---	---	---	---	---	---	---	---
3	1.5		-272.6	509.6	1.893	-193.3	429.0	.636	30	2.529	2.98	5.305	39.8	155/87	15	-231/-26	205	205	196	68.7	264.7
4	3.0		-272.6	553.7	1.973	-190.1	418.6	.627	30	2.600	3.15	5.305	84.3	169/117	-2	-242/-180	188	62	178	90.0	268.0
5	5.0		-272.6	551.8	1.970	-183.2	307.6	.533	30	2.503	3.70	5.305	100.8	256/147	403	-237/-166	586	71	272	134.7	406.7
6	5.0		-276.6	476.5	1.830	-185.3	497.9	.685	30	2.515	2.67	5.305	101.8	242/152	-31	-237/-170	154	67	187	66.4	253.4
7	10.0		-273	515.8	1.905	-170	448.8	.649	30	2.554	2.94	5.305	93.8	258/192	182	-250/-172	352	78	243	122.7	366.4
8	22.0		-273	507.8	1.890	-145	492.8	.675	30	2.565	2.80	5.305	93.8	241/182	0	-210/-167	145	43	169	85.0	254.0
	(sec)		(K)	$N/m^2 \times 10^{-6}$	(Kg/sec)	(K)	$N/m^2 \times 10^{-6}$	(Kg/sec)	(%)	(Kg/sec)	MR	cm^2	$N/m^2 \times 10^{-6}$	$N/m^2 \times 10^{-6}$	(K)	(K)	(K)	(K)	j/sec $\times 10^{-3}$	j/sec $\times 10^{-3}$	j/sec $\times 10^{-3}$
0	2.0	No. 1	---	---	---	270	---	0.231	--	---	---	---	---	---	---	---	---	---	---	---	---
1	2.0		---	---	---	270	---	0.220	--	---	---	---	---	---	---	---	---	---	---	---	---
2	2.0		144	---	0.716	---	---	---	30	---	---	---	---	---	---	---	---	---	---	---	---
3	1.5		104	3.513	0.706	267	2.957	0.237	30	0.944	2.98	34.22	2.74	1.07/.599	264	127/241	114	114	207	72.5	280
4	3.0		104	3.817	0.736	270	2.885	0.234	30	0.970	3.15	34.22	5.81	1.17/.807	255	121/211	104	34	188	95.0	283
5	5.0		104	3.804	0.735	276	2.120	0.199	30	0.934	3.70	34.22	6.95	1.76/1.01	480	123/163	325	39	287	143	430
6	5.0		102	3.285	0.683	273	3.432	0.256	30	0.939	2.67	34.22	7.02	1.67/1.05	239	123/161	86	37	198	70	268
7	10.0		103	3.550	0.711	289	3.094	0.242	30	0.953	2.94	34.22	6.47	1.78/1.32	351	122/159	195	43	257	130	387
8	22.0		103	3.500	0.705	314	3.397	0.252	30	0.957	2.80	34.22	6.47	1.66/1.25	255	138/157	81	24	179	89.7	268

* Uncorrected Injector End Measured Value

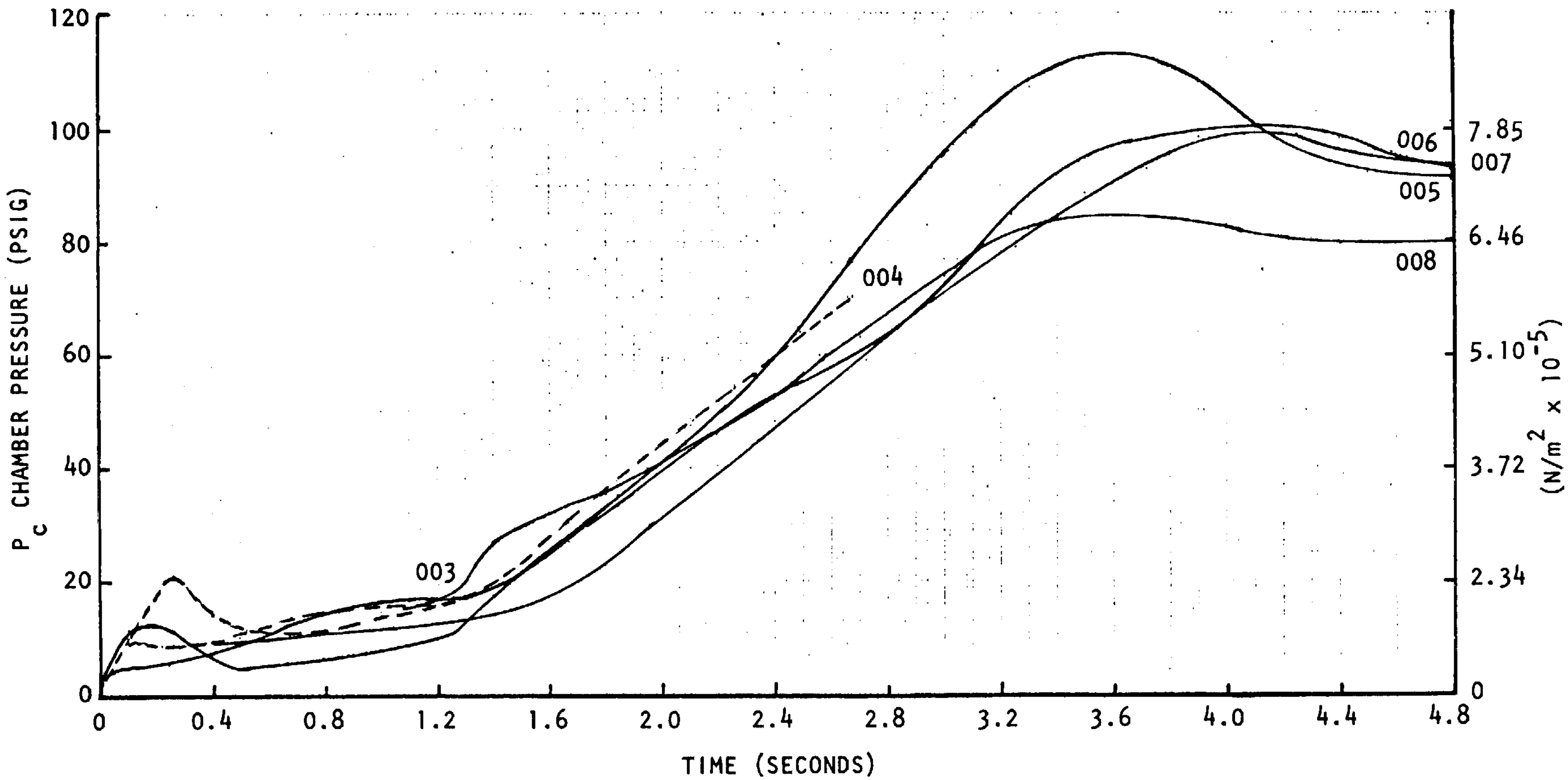


Figure 46. OF_2/B_2H_6 Chamber Pressure Buildup vs Time (Tests 003-008)

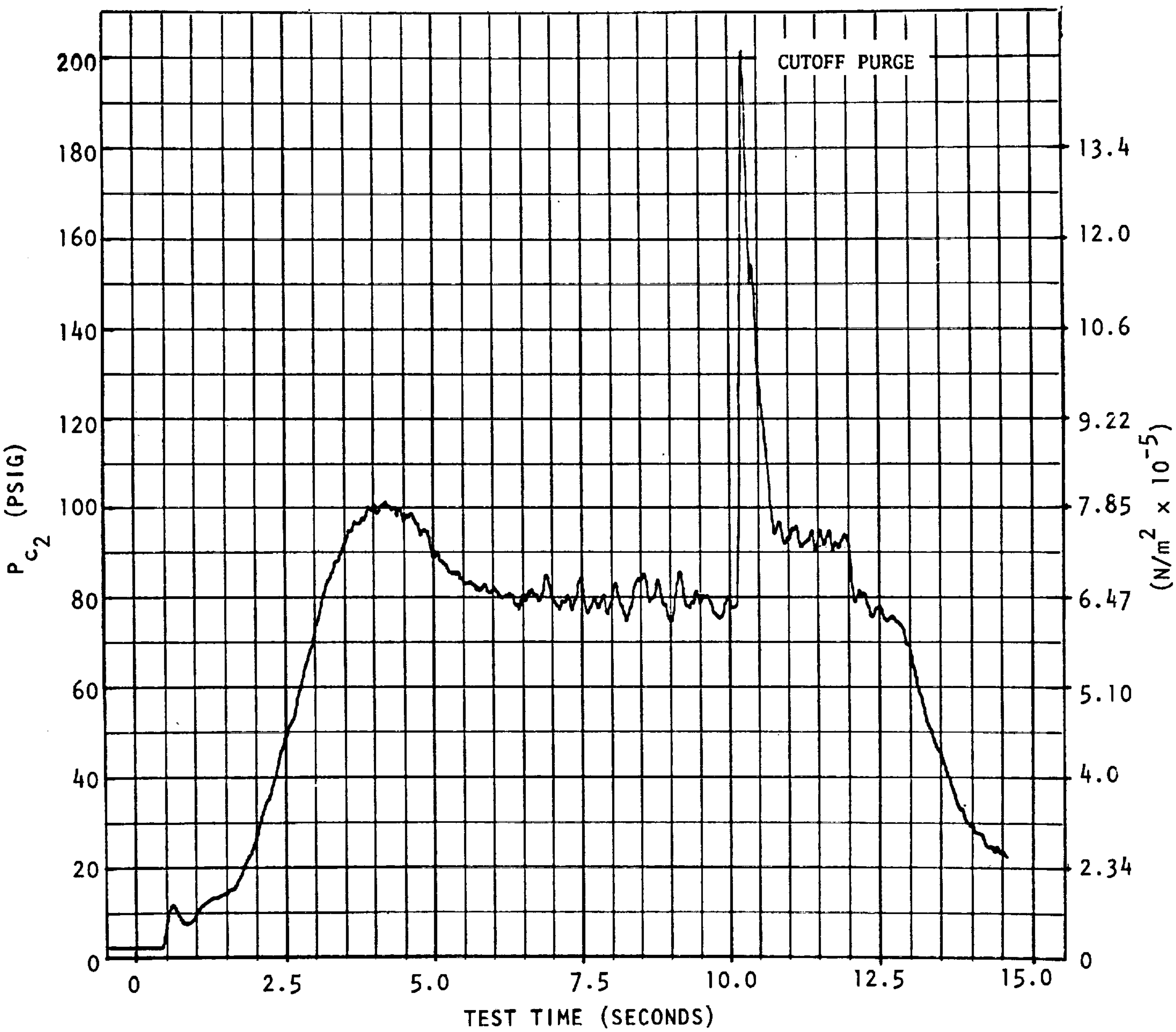


Figure 47. OF_2/B_2H_6 Regenerative Chamber Pressure vs Time (Test 007)

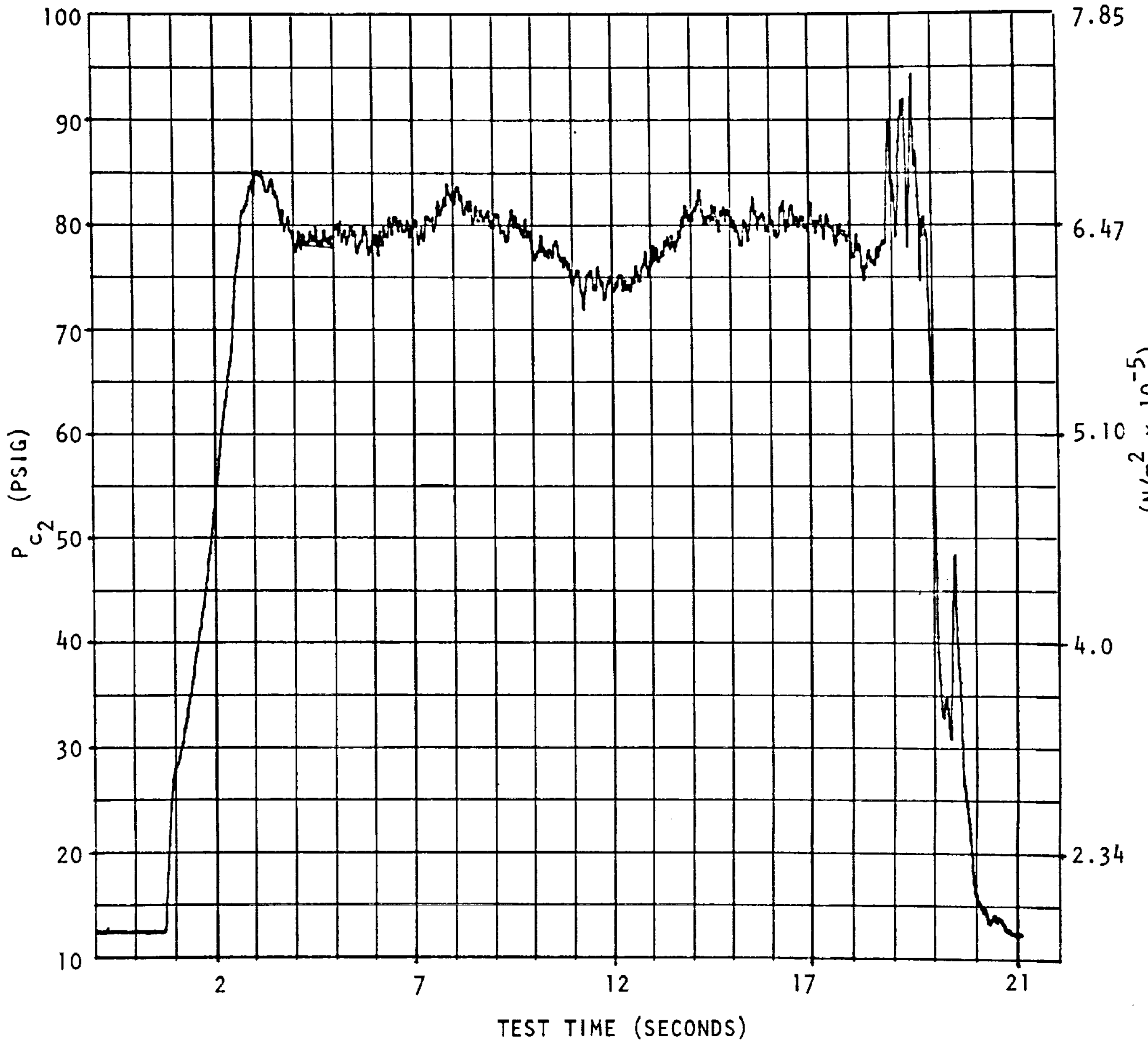


Figure 48. OF_2/B_2H_6 Regenerative Chamber Pressure vs Time (Test 008)

Improvements in the start and shutdown times will be substantial with reduced chamber and nozzle wall thermal capacitances and coolant passage volumes as noted in the previous Task VI analysis section.

B_2H_6 and OF_2 Jacket Inlet Pressure/Pressure Drop

A summary of measured engine parameters is shown in Table 8 . Figure 49 illustrates the B_2H_6 jacket inlet pressure downstream of the JPL run valve. Limited stabilization is achieved at 4 seconds with final stabilization (due to thermal capacitances) at 12 seconds. A pressure level of 240 psig (1.76×10^6 N/m^2) is shown based on a comparatively high injection pressure drop. For flight applications reduction in injector and manifolding pressure drop would reduce the fuel inlet pressure to below 200 psia (1.38×10^6 N/m^2).

Figure 50 illustrates a summary of the OF_2 jacket inlet pressures vs time. The effect of a slightly lower mixture ratio in Test 008 contributes to a reduction in OF_2 jacket inlet pressure compared to that for Test 007. A level of 130 psig (9.86×10^5 N/m^2) is shown for Test 007 for a 2.94 mixture ratio condition. For a flight design application added OF_2 jacket coolant pressure drop would be provided to allow a higher heat input to the OF_2 with a resulting lower jacket discharge density.

A summary of B_2H_6 coolant jacket pressure drops is shown in Fig. 51. A B_2H_6 coolant jacket pressure drop of approximately 65 percent of chamber pressure is shown. Reduction in parasitic inlet manifold and dishcarge manifold pressure drops will result in a reduced B_2H_6 coolant jacket pressure loss percentage for a flight design.

A summary of the OF_2 coolant jacket pressure drops is shown in Fig. 52 . A jacket loss of 40 psi (2.76×10^5 N/m^2) is shown for a 100 psia chamber pressure level, for a mixture ratio of 3.0 (Test 007). Lower inlet/exit OF_2 manifold losses combined with a smaller channel flow area in portions of the OF_2 jacket will allow the pressure drop for a flight design to remain about at this level.

TABLE 8. MEASURED ENGINE PRESSURE PARAMETERS FOR TESTS 003-008

Pressure Time (sec)	Test Number					
	003	004	005	006	007	008
	4.0	5.2	7.5	7.5	12.5	22.0
PC1	24 (1.65)	70 (4.82)	86 (5.92)	87 (5.99)	78 (5.37)	~ 65 (4.48)
PC2	25 (1.72)	71 (4.89)	87 (5.99)	88 (6.06)	80 (5.51)	80 (5.51)
PIOX	31 (2.14)	80 (5.51)	102 (7.03)	95 (6.54)	92 (6.34)	~ 78 (5.37)
$PVOF_2$	494 (34.0)	540 (37.2)	538 (37.0)	463 (31.9)	502 (34.6)	494 (34.0)
POF_2IN	44 (3.03)	91 (6.27)	152 (10.47)	117 (8.06)	130 (8.96)	103 (7.10)
PIC	76 (5.24)	106 (7.30)	133 (9.16)	140 (9.65)	179 (12.3)	168 (11.6)
PIF	71 (4.89)	102 (7.03)	130 (8.95)	137 (9.44)	178 (12.3)	167 (11.5)
PFM	142 (9.78)	155 (10.7)	240 (16.5)	242 (16.7)	244 (16.8)	227 (15.6)
PVF	415 (2.86)	405 (27.9)	294 (20.3)	485 (33.4)	435 (30.0)	479 (33.0)

Note: All Parameters in psig ($N/m^2 \times 10^{-5}$)

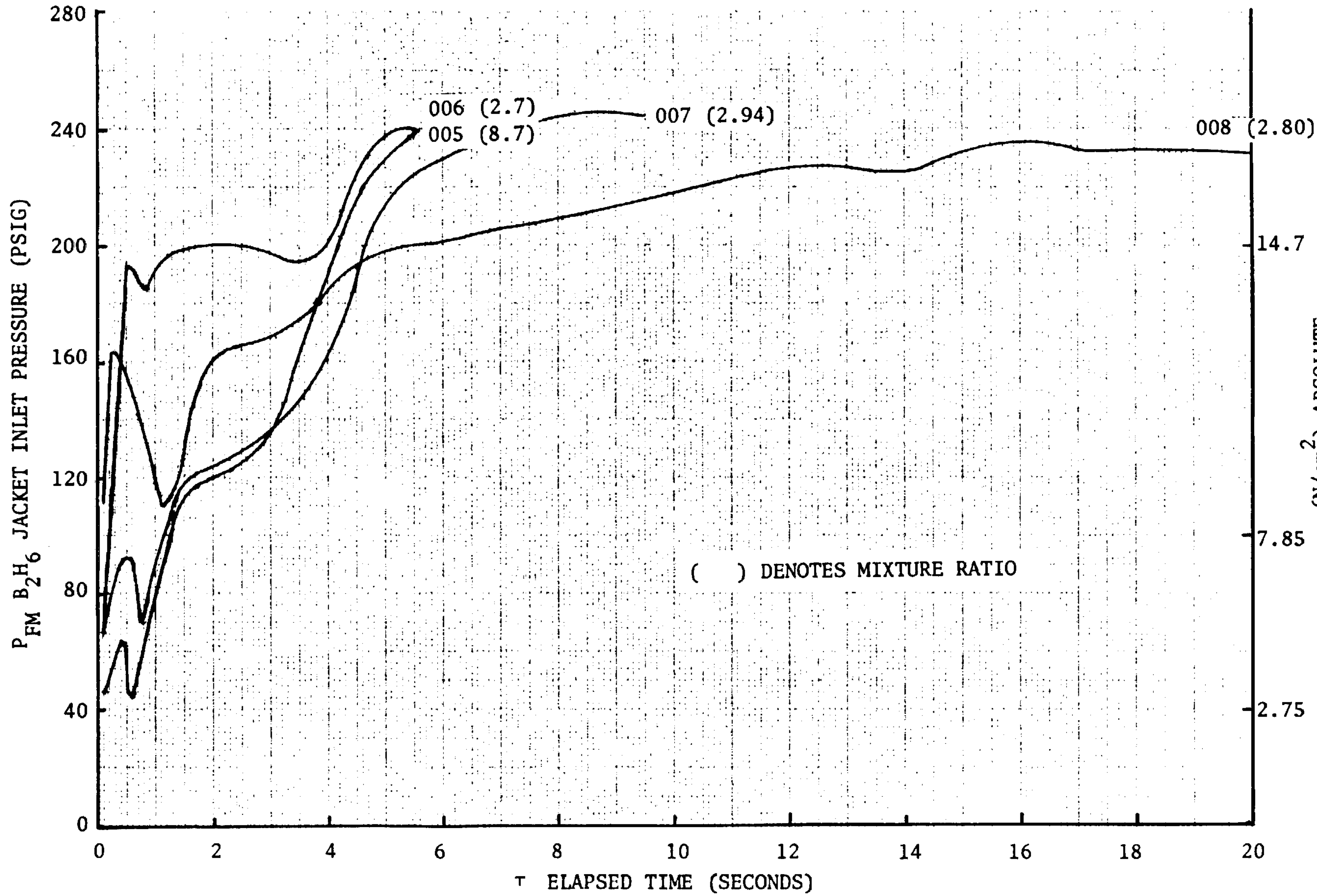


Figure 49. B_2H_6 Fuel Manifold Pressure vs Elapsed Run Time (Tests 005-008)

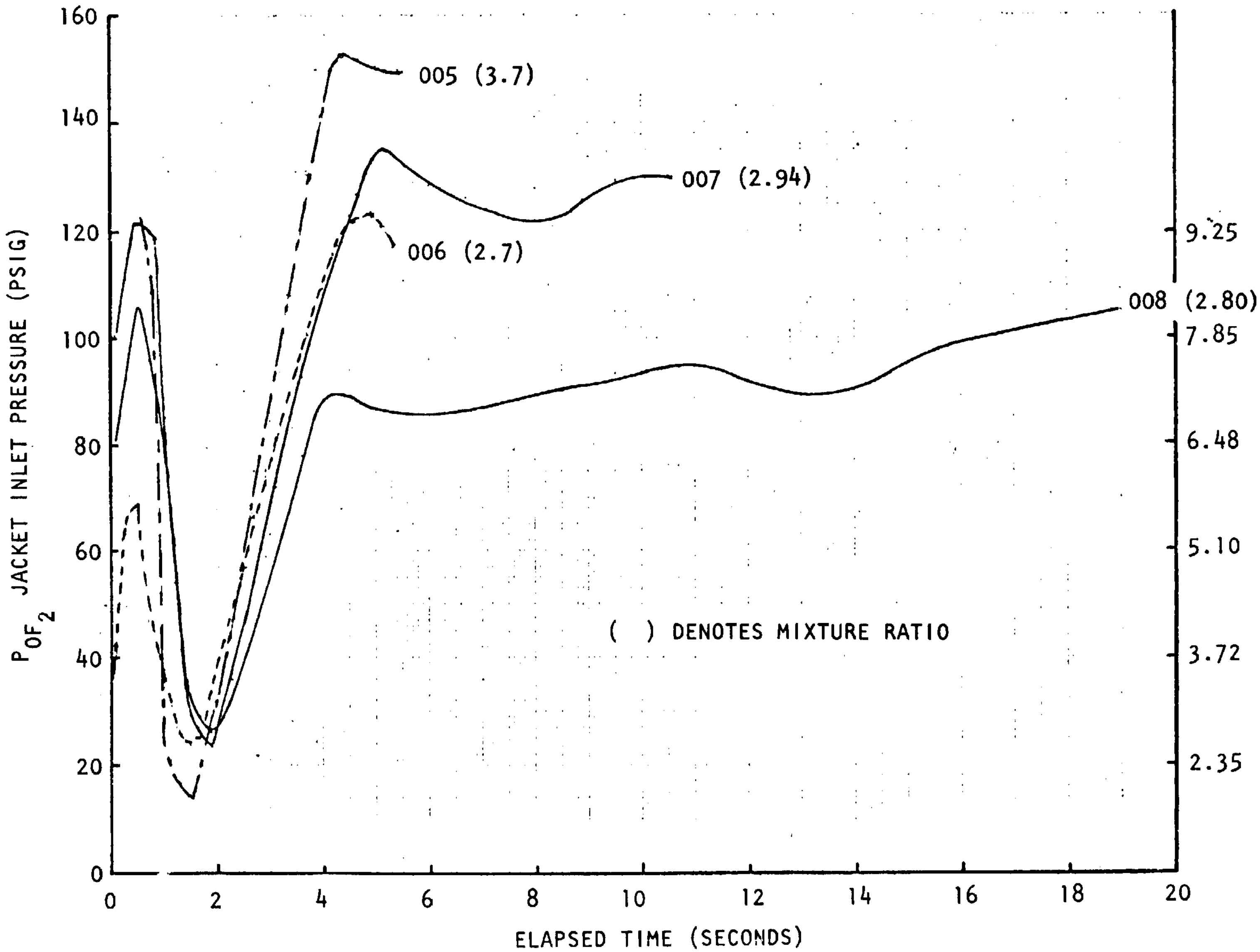


Figure 50. Summary of OF_2 Jacket Inlet Pressure vs Elapsed Run Time (Tests 005-008)

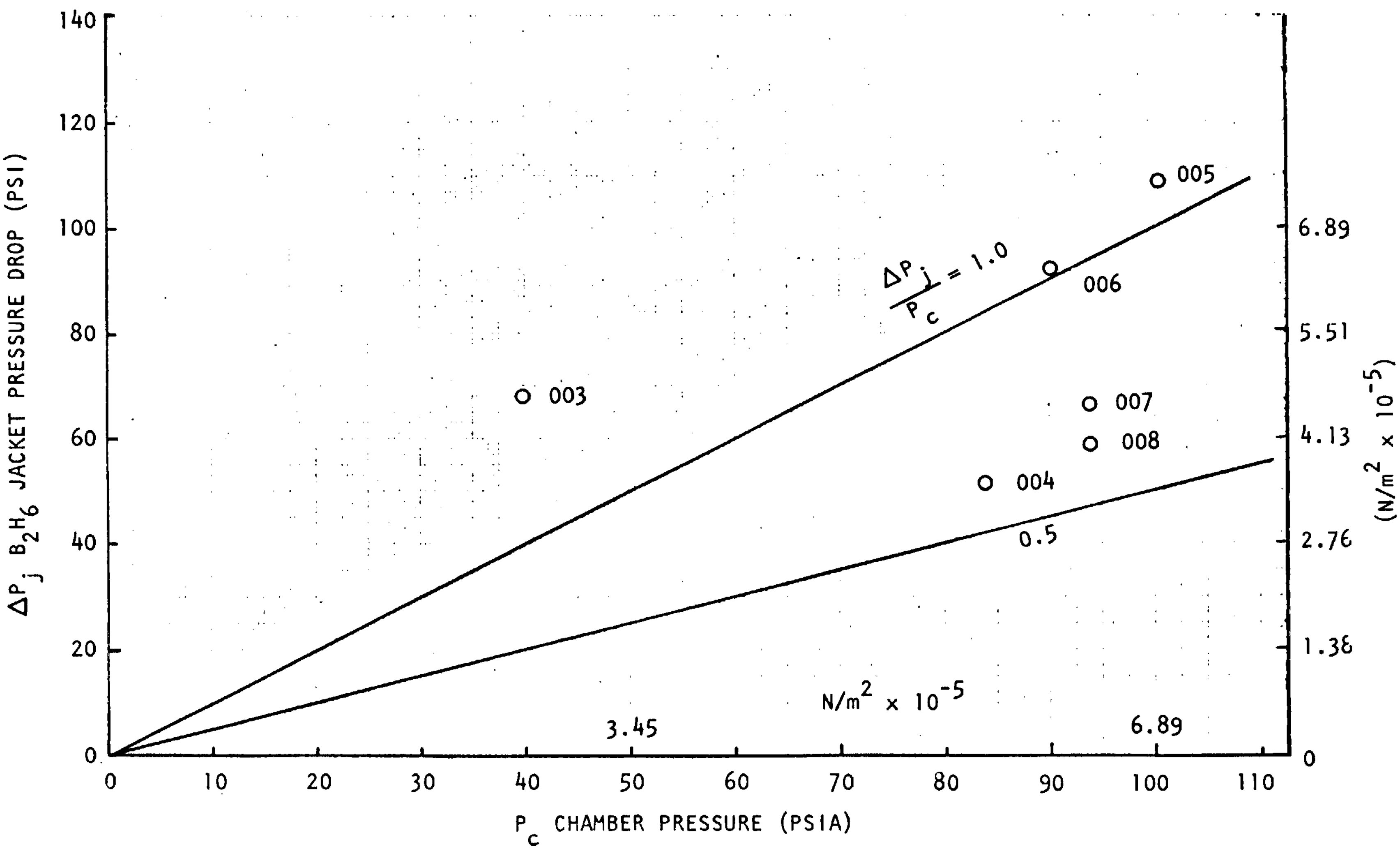


Figure 51. B_2H_6 Coolant Jacket Pressure Drop vs Chamber Pressure (Tests 003-008)

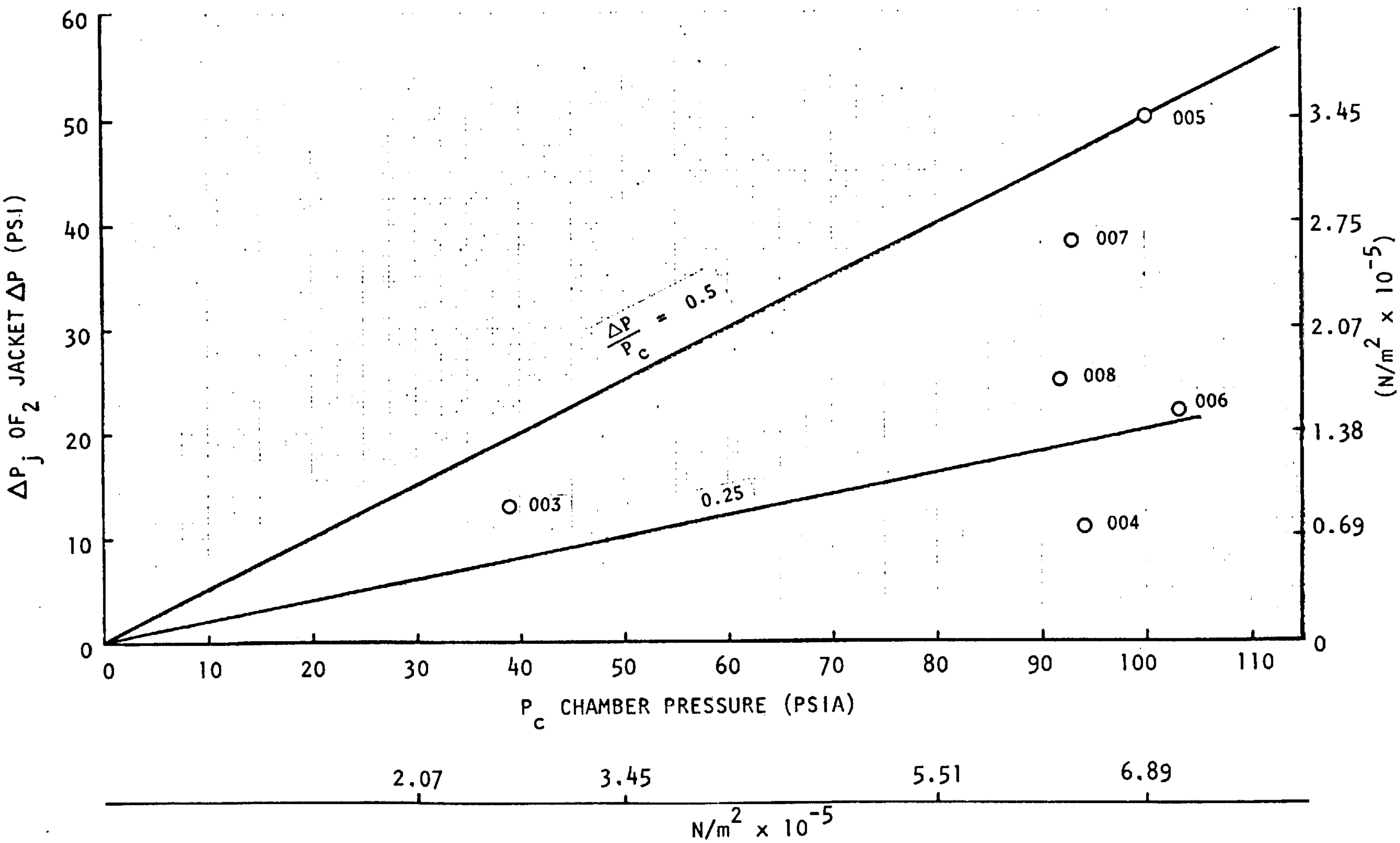


Figure 52. OF_2 Jacket Pressure Drop vs Chamber Pressure (Tests 003-008)

Injector Pressure Drops

Figure 53 compares the fuel and oxidizer pressure drop flow relationships for the tests conducted. The effect of a high B_2H_6 injection temperature with the long duration (≥ 10 seconds) cooling tests indicates a larger than required pressure drop corresponding to a reduced injector inlet density condition. For a satisfactory injector performance condition and as well to provide a lowered pressure drop for a flight pressure fed system, enlargement of the fuel orifices is required to reduce fuel injector ΔP to about 20 psid (1.38×10^5 N/m^2).

On the OF_2 injector side, during the current testing, pressure drops are shown to range from 10-16 psi (0.69×10^5 to 1.11×10^5 N/cm^2). A reduction in this level from the past testing is due to the reduced OF_2 injection temperature. Modification of the OF_2 jacket coolant passages to ensure a greater percentage share of the heat transfer would bring the OF_2 injector ΔP into the 25 psi (1.73×10^5 N/cm^2) range which would be acceptable for a flight design; as a consequence no change in oxidizer orifice size would be anticipated.

Engine Temperature Conditions

A summary of reduced data for the coolant and wall temperatures measured are shown in Table 9. Data measured included three combustor thermocouples, four nozzle thermocouples. Fuel film and main B_2H_6 and OF_2 flow injection temperatures, and OF_2/B_2H_6 inlet temperatures. Additional parameters measured included injector face temperatures and flow venturi inlet temperatures for flow density evaluation purposes.

Engine Inlet Temperatures

For the tests conducted a summary of the engine fuel and oxidizer inlet temperatures is shown in Table 9. OF_2 jacket inlet temperatures ranged from -210 to -250 F (139 to 117 K) which is in the flight design range.

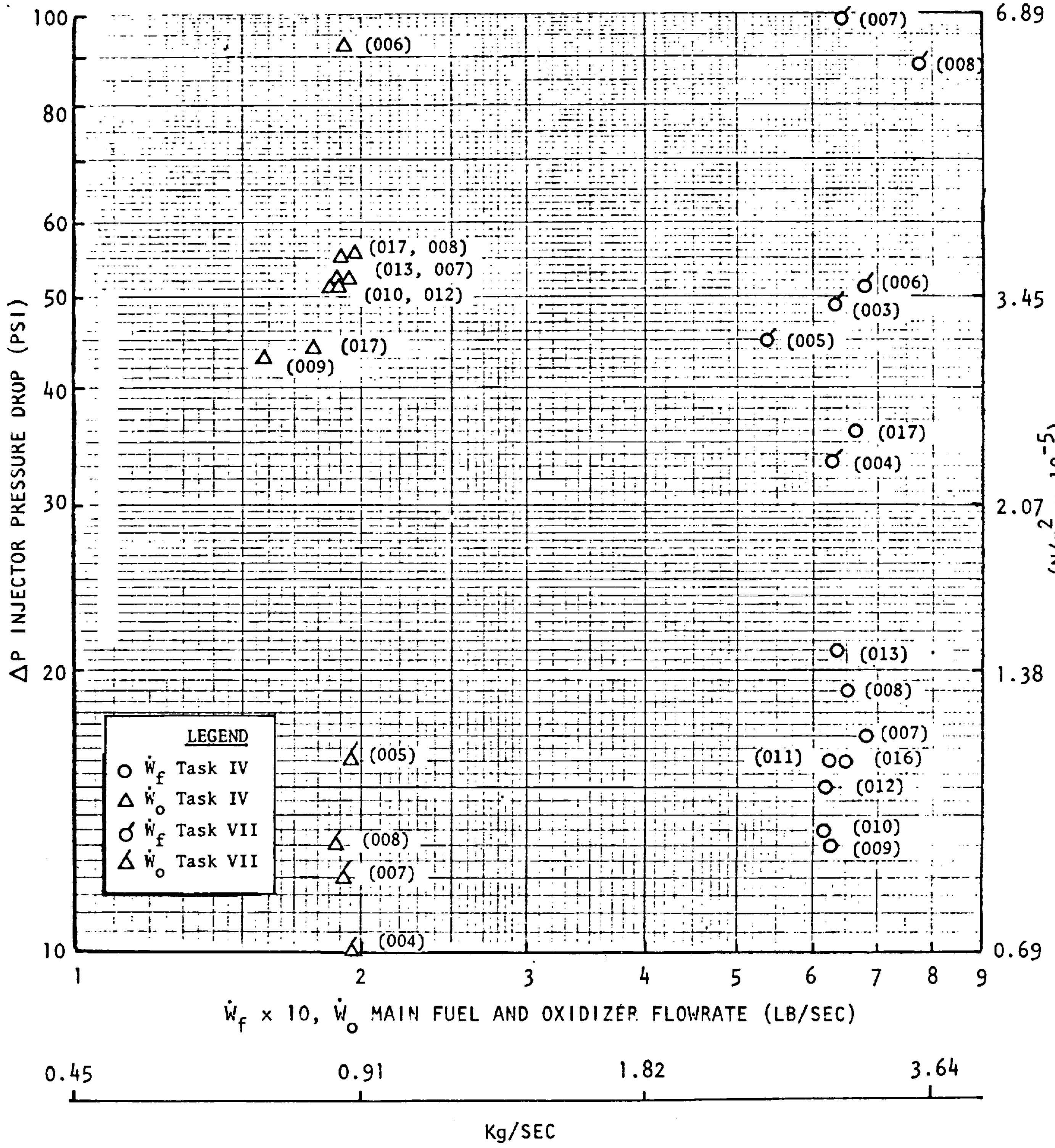


Figure 53. Calorimeter/Regenerative Chamber Testing-Injector Pressure Drop vs Flowrate Summary for Task IV and VII

TABLE 9 . SUMMARY OF OF_2/B_2H_6 THRUST CHAMBER THERMOCOUPLE READINGS AT ENGINE SHUTDOWN TIME

Temperature	Test Number					
Elapsed Time (sec)	003 4.0	004 5.5	005 7.5	006 7.5	007 12.5	008 23.0
TCS1	96 (309)	105 (314)	378 (466)	106 (315)	262 (402)	112 (318)
TCS2	121 (323)	175 (353)	520 (544)	235 (387)	480 (522)	--- (---)
TCS3	127 (326)	170 (350)	320 (433)	158 (343)	357 (454)	-123 (187)
TN1	159 (344)	200 (367)	218 (377)	192 (363)	243 (391)	320 (434)
TN2	147 (337)	185 (359)	205 (369)	179 (355)	121 (323)	96 (309)
TN3	130 (328)	162 (348)	183 (358)	162 (346)	145 (336)	-60 (222)
TN4	115 (320)	139 (333)	110 (317)	3 (257)	198 (366)	20 (267)
TINJ1	69 (293)	5 (258)	-167 (162)	-170 (161)	-170 (161)	-157 (168)
TINJ2	232 (385)	340 (444)	580 (577)	568 (569)	710 (650)	455 (509)
$TLOF_2$	-315 (80)	-301 (88)	-305 (86)	-306 (86)	-294 (98)	-306 (86)
$TVOF_2$	-272.6 (103)	-272.6 (103)	-272.6 (103)	-272.6 (103)	-272.6 (103)	-272.6 (103)
TOF_2IN	-232 (127)	-220 (133)	-240 (122)	-238 (123)	-250 (117)	-210 (138)
TIOX	-28 (240)	-160 (167)	-168 (162)	-171 (160)	-172 (160)	-167 (162)
TLF	-197 (146)	-184 (153)	-137 (151)	-188 (151)	-169 (161)	-139 (178)
TVF	-192 (149)	-173 (159)	-184 (152)	-185 (152)	-170 (161)	-145 (175)
TIC	15 (264)	0 (255)	403 (480)	-31 (238)	182 (154)	0 (255)
TIF	70 (294)	52 (285)	104 (313)	54 (285)	130 (328)	123 (324)

Note: Temperature Parameters in F (K)

Fuel jacket inlet temperatures (TVF) are shown to range from -145 to -192 F (175 to 149 K). Engine fuel inlet temperatures were adjusted by the Freon line chill loop controller.

Injector Inlet Temperatures

The injector inlet temperatures for the configuration tested are shown in Fig. 54 through 56. On Tests 003-006 fuel side as shown in Fig. 54 stabilization has not been obtained except in Test 006 where a low fuel jacket outlet condition exists as a result of low mixture ratio and insufficient fuel jacket heat input.

Figure 55 shows expanded scale results for Test 005-008. Fuel injection temperatures are shown to stabilize at 6-8 seconds with the chamber mixture ratio directly affecting the injection temperature. At the engine design mixture ratio of 3.0 a level of 200 F (366 K) is shown. Additional oxidizer heat input would reduce the fuel temperature accordingly. Perturbations in the fuel injection temperature are believed related directly to gas wall side deposit conditions.

Figure 56 shows the OF_2 jacket discharge temperature behavior vs time. Expected OF_2 injection temperature was in the range of 50-100 F (283-311 K). Reduction in the OF_2 injection temperature below the planned level was a result of a lower than expected OF_2 film coefficient (30 percent). Corresponding lower OF_2 jacket pressure drop and injector drop conditions were noted previously. OF_2 heat input and injector pressure drop conditions were compared with the results shown in Fig. 57 for the OF_2 percent vapor.

Wall Heat Input Conditions

Table 7 illustrates the OF_2 and B_2H_6 coolant heat input conditions. The OF_2 heat input for the design configuration tested represented 30 percent of the total heat input for the combined OF_2 and B_2H_6 cooling mode as compared to 50 percent for the H_2O/B_2H_6 cooling tests previously conducted. The wall heat

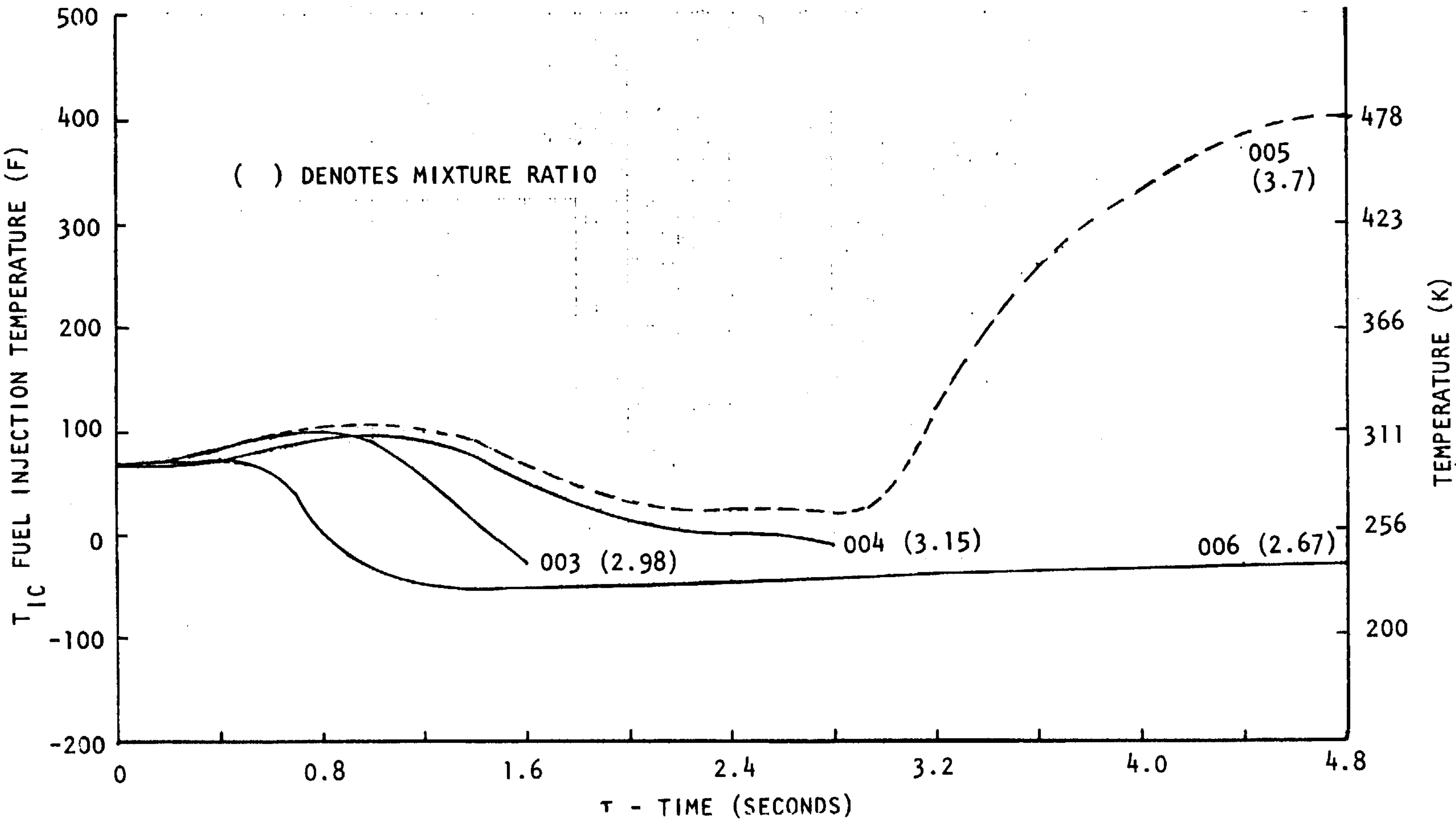


Figure 54. Injector B_2H_6 Fuel Injection Temperature vs Time (Tests 003-008)

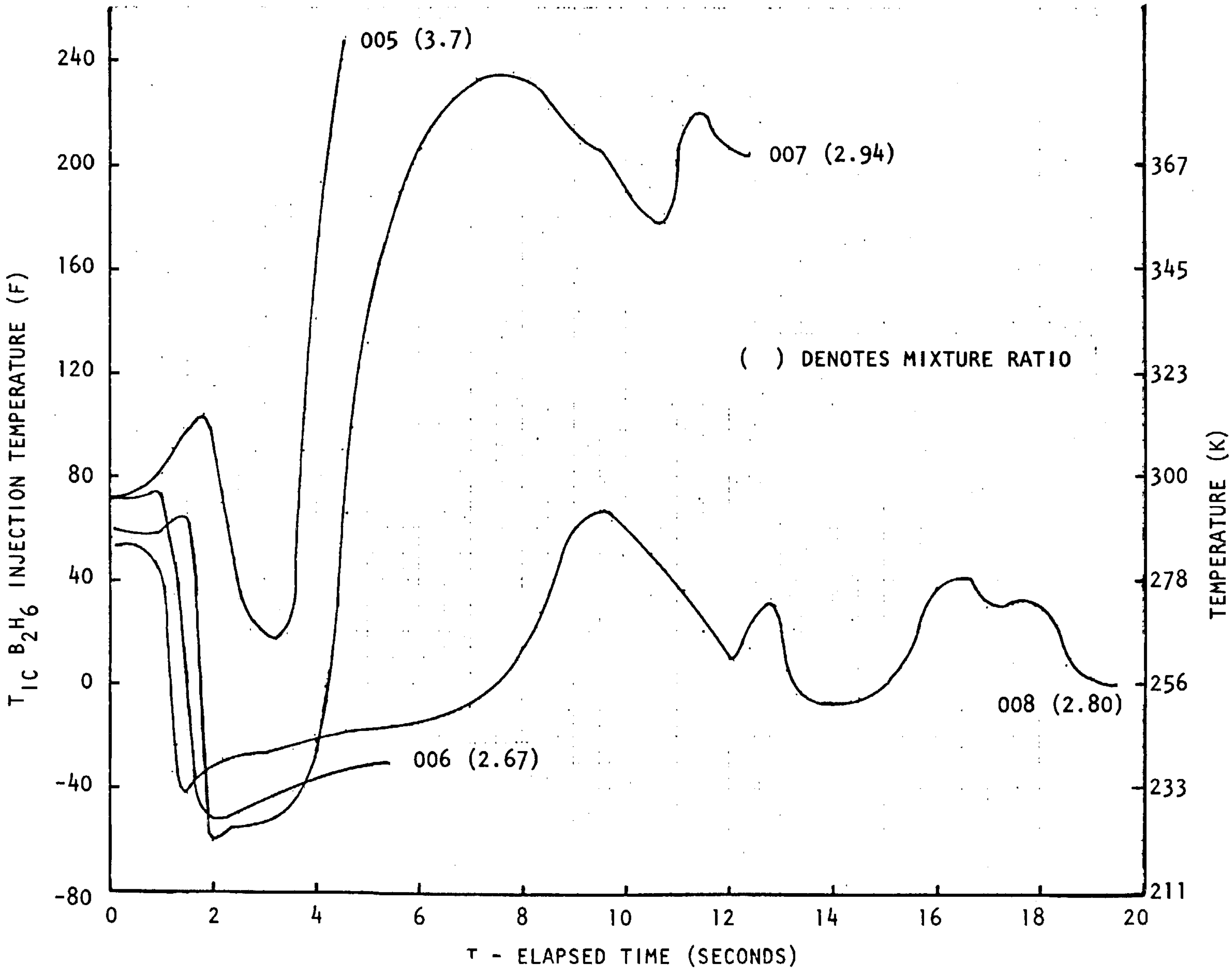


Figure 55. Fuel Injection Temperature vs Elapsed Time (Tests 005-008)

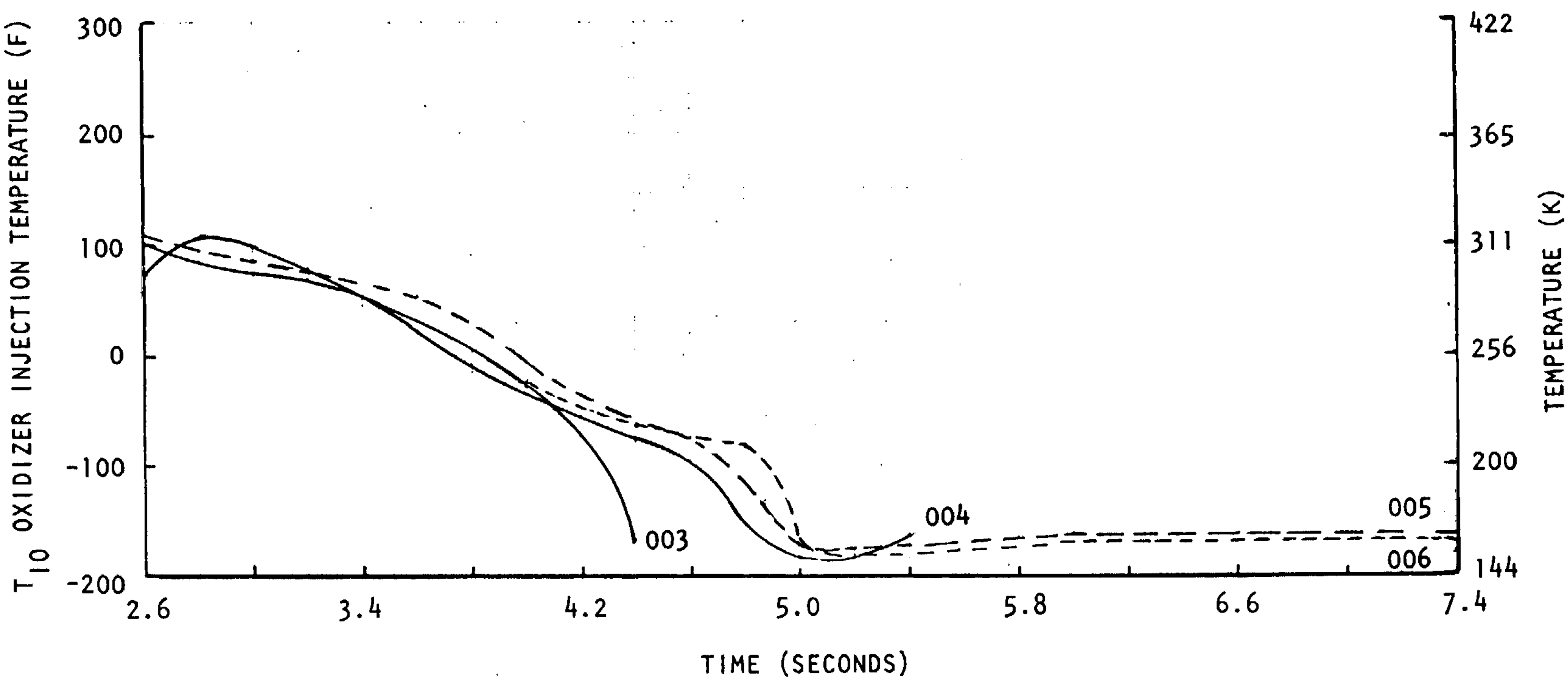


Figure 56. Injector OF_2 Fuel Injection Temperature vs Time (Tests 003-006)

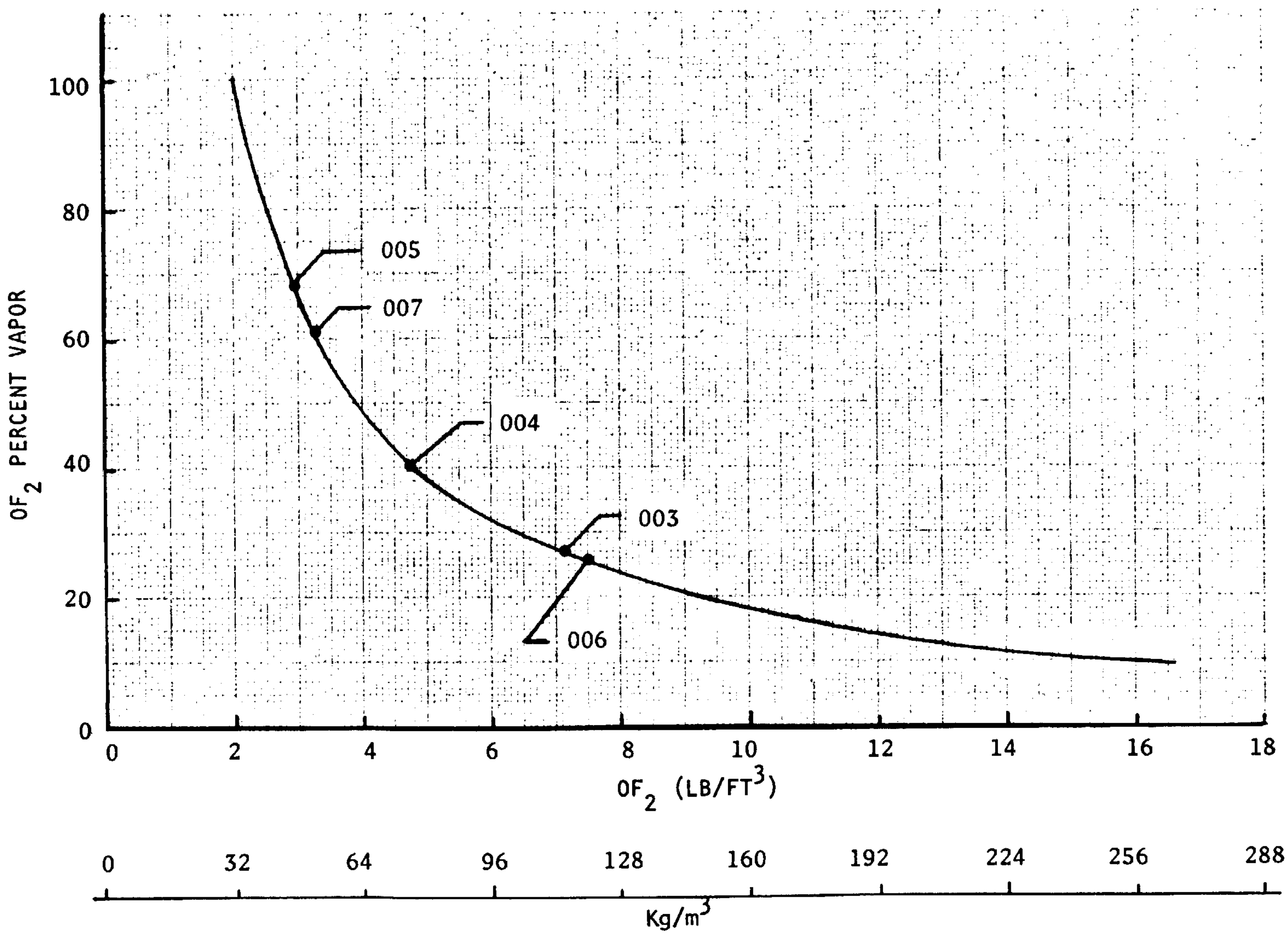


Figure 57. OF_2 Jacket Discharge OF_2 Quality vs Density (Tests 003-008)

input with time for the total input is shown in Fig. 58. Comparatively, water cooled and OF_2 cooled chamber results are shown in Fig. 59. Lower OF_2 heat inputs are indicated due to a lower OF_2 heat transfer coefficient and somewhat higher wall temperature.

Wall Temperature Results

A total of seven wall thermocouples were located on the chamber exterior wall with four nozzle thermocouples below the OF_2 inlet point and three located above the inlet manifold location. Figure 60 illustrates the axial positioning of these locations.

As illustrated by Fig. 61 , stabilized nozzle wall temperatures at lowered mixture (Test 008) results in a peak wall temperature of 300 F (422 K). As shown for Test 007 a high wall temperature results from a combined low fuel flow and higher wall heat input attendant with the higher mixture ratio. At the design mixture ratio (3.0) a level of 500-600 F (534-589 K) is anticipated from Task IV results. Some reduction in wall temperature for this section would be desirable to minimize thermal response time. The highest wall temperature was shown at the nozzle exit plane (ϵ = 14.5) due to low B_2H_6 film coefficients in the early two phase cooling regime.

Combustor (T_{CS3}) and throat (T_{CS2}) and nozzle (T_{CS1}) wall temperatures are shown in Table 9 and in Fig. 62 and 63. The stabilization on these readings occurs at 7-9 seconds.

The throat wall back side prediction at 3.0 mixture ratio was 251 F (396 K) compared to about 600 F (589 K) experimentally (T_{CS2}). Injector end predictions of 375 F (463 K) were in good agreement with a 350 F (450 K) (T_{CS3}) measured value. An OF_2 jacket inlet point prediction for wall temperature was 0 F (255 K) compared to a measured (T_{CS1}) level of 250 F (395 K). A 25 percent lower OF_2 film coefficient appears primarily responsible for the somewhat higher wall temperature conditions to that predicted.

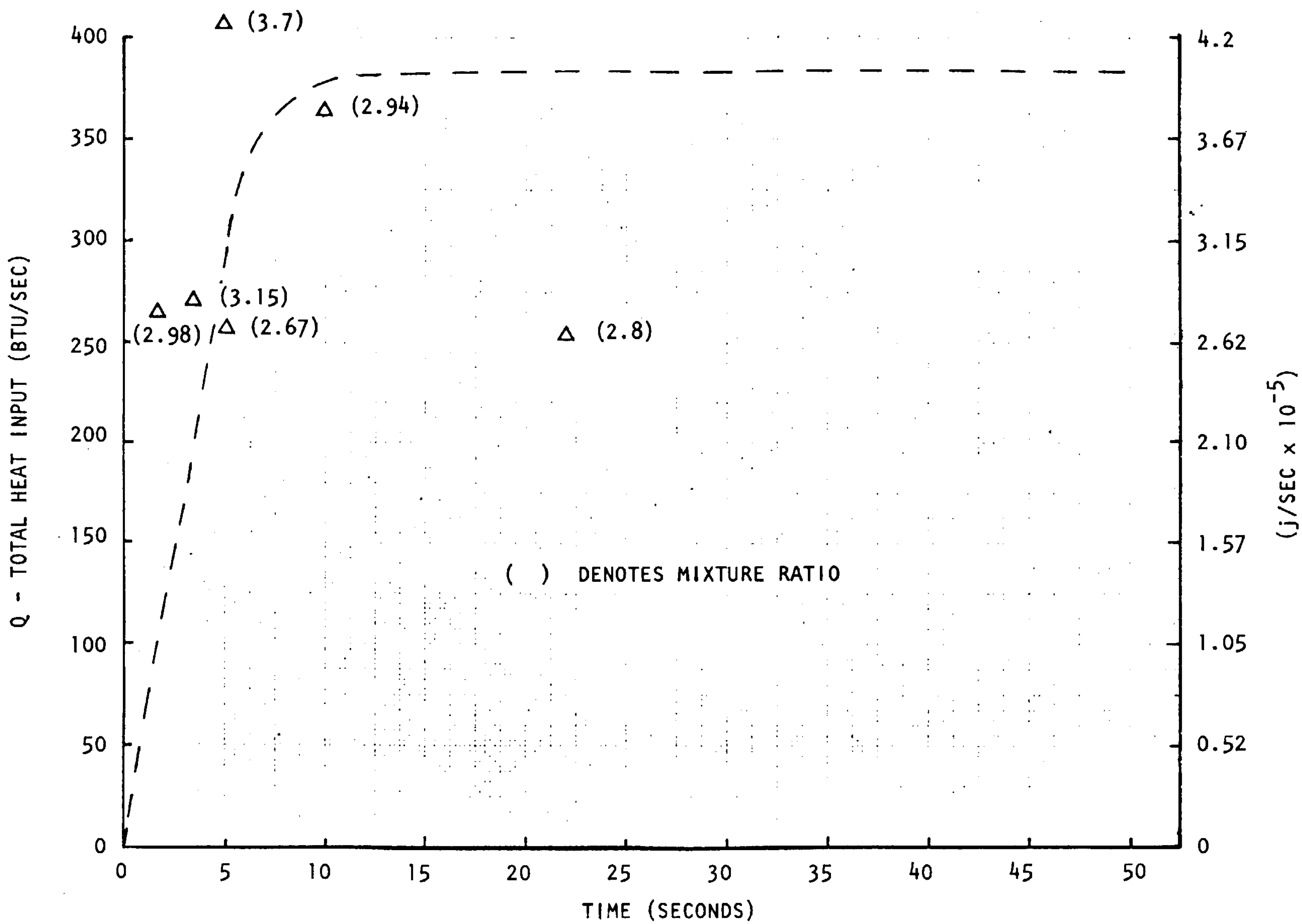


Figure 58. Total Coolant Heat Input vs Time From Task VII Regenerative Cooling Tests

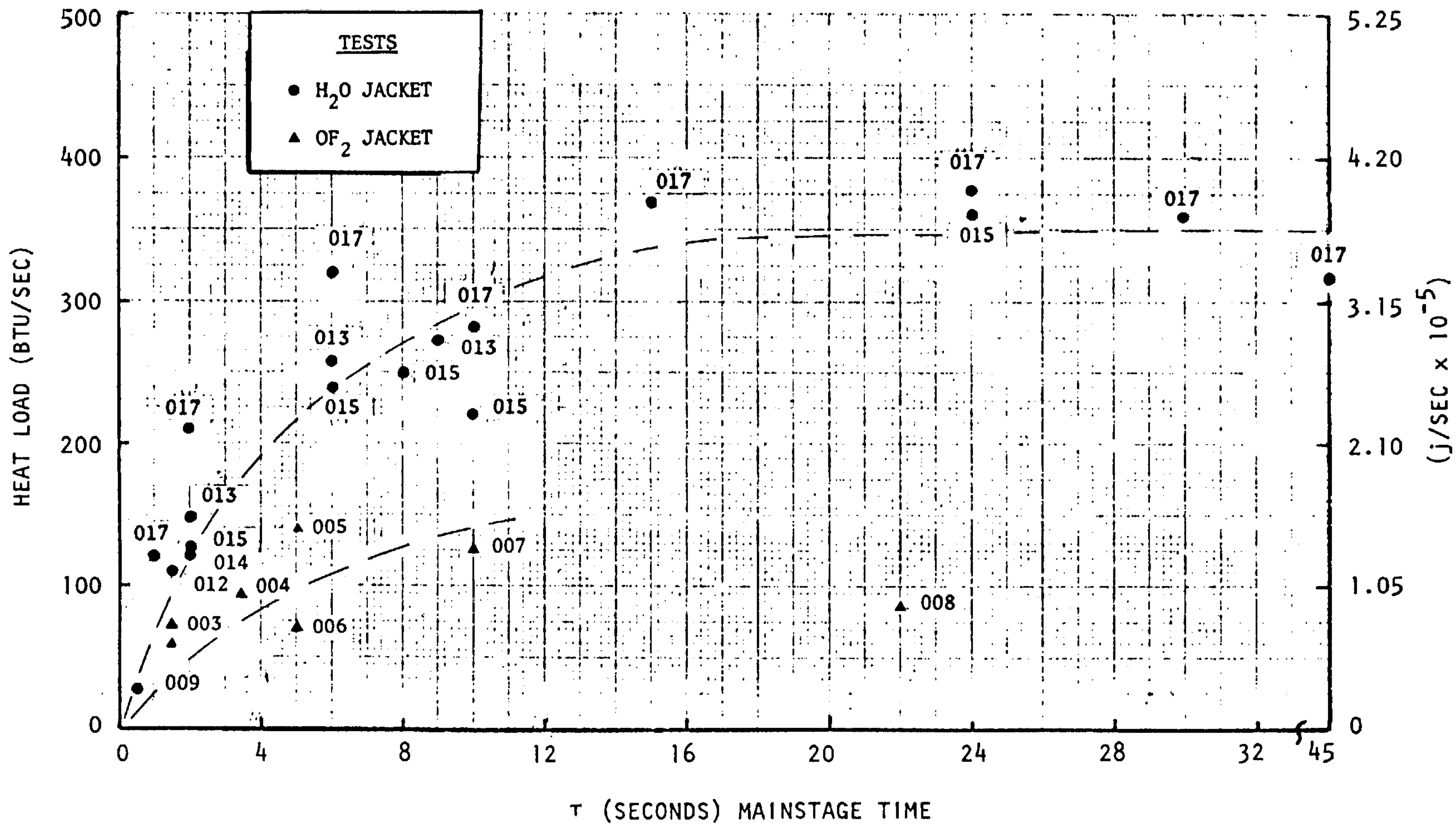


Figure 59. OF_2-B_2H_6 Regenerative Chamber Testing - OF_2 and H_2O Jacket Heat Load vs Time

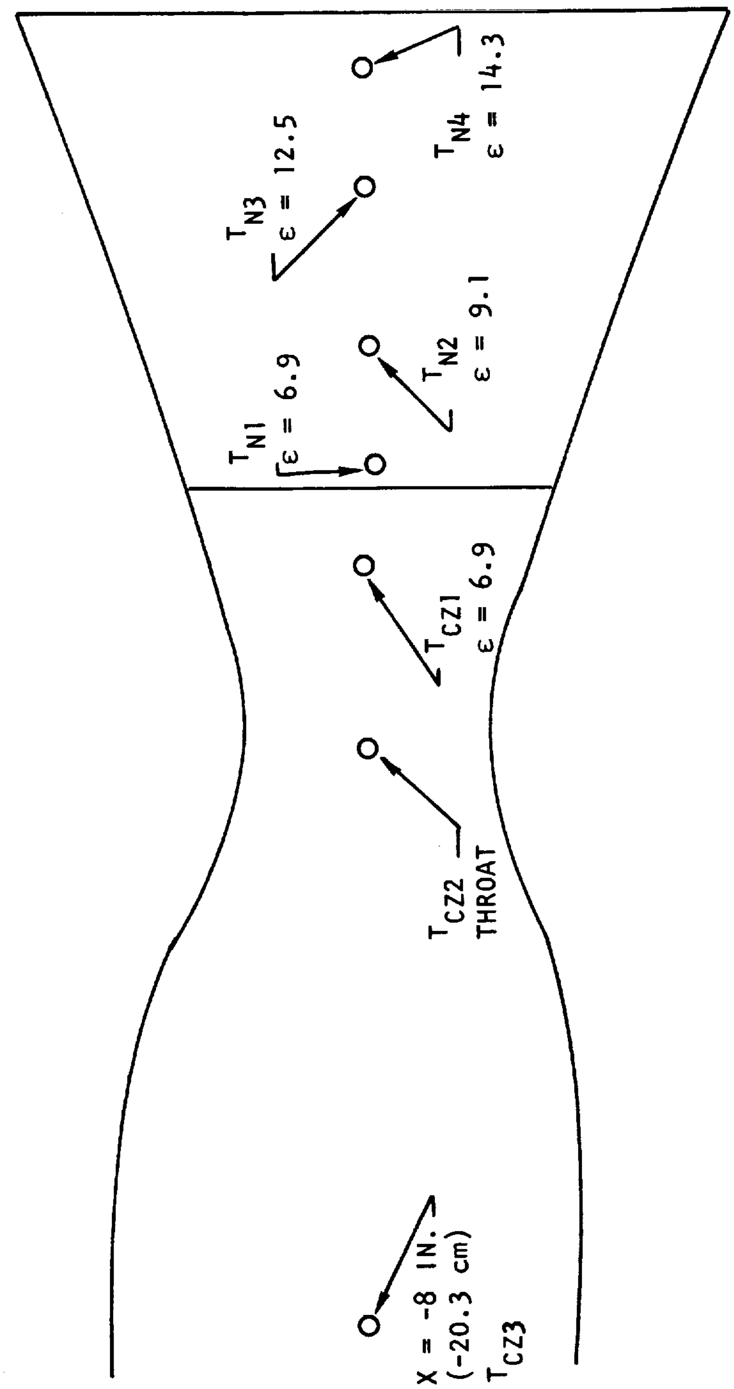


Figure 60. Test Nozzle Instrumentation Location

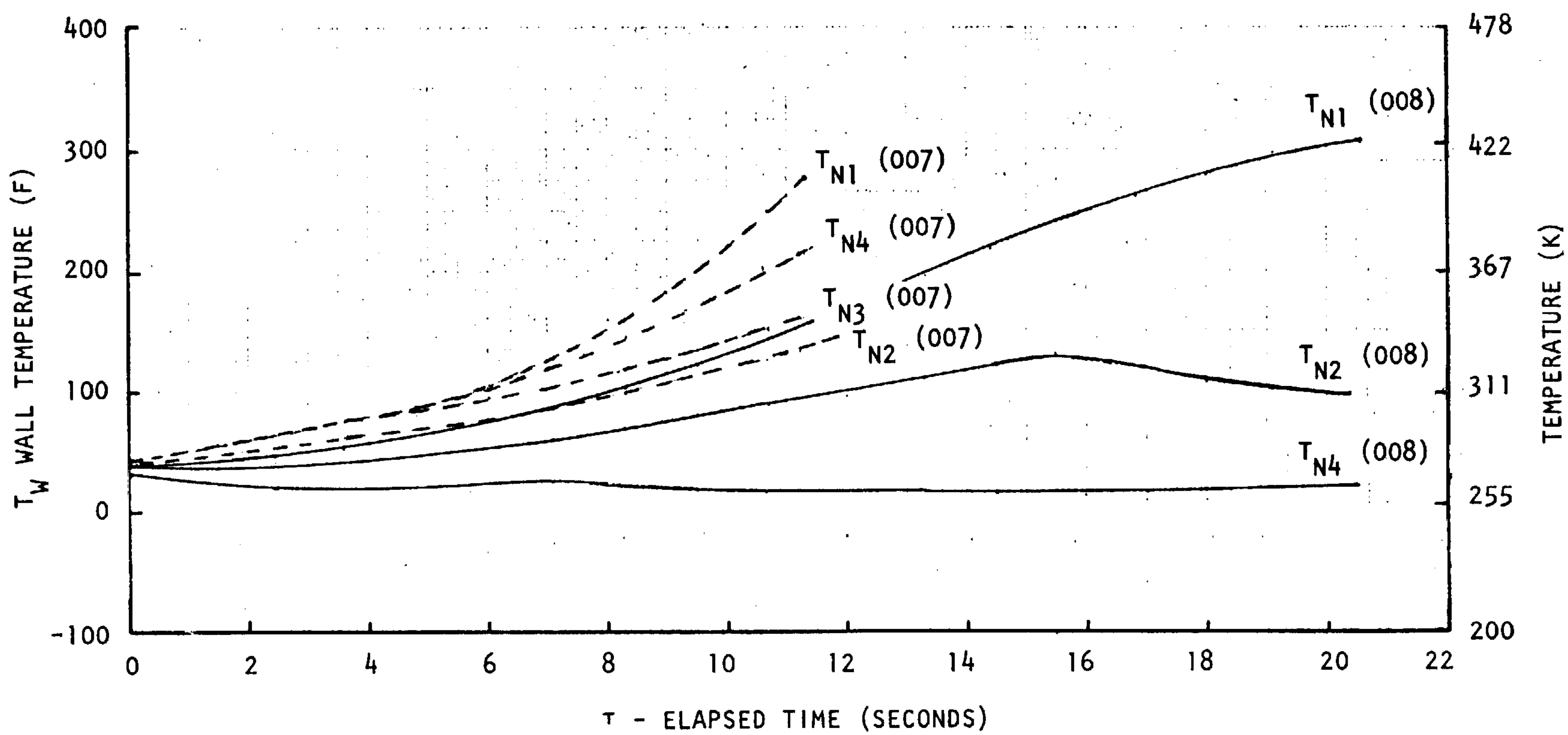


Figure 61. OF_2/B_2H_6 Nozzle Wall Temperature vs Run Time (Tests 007-008)

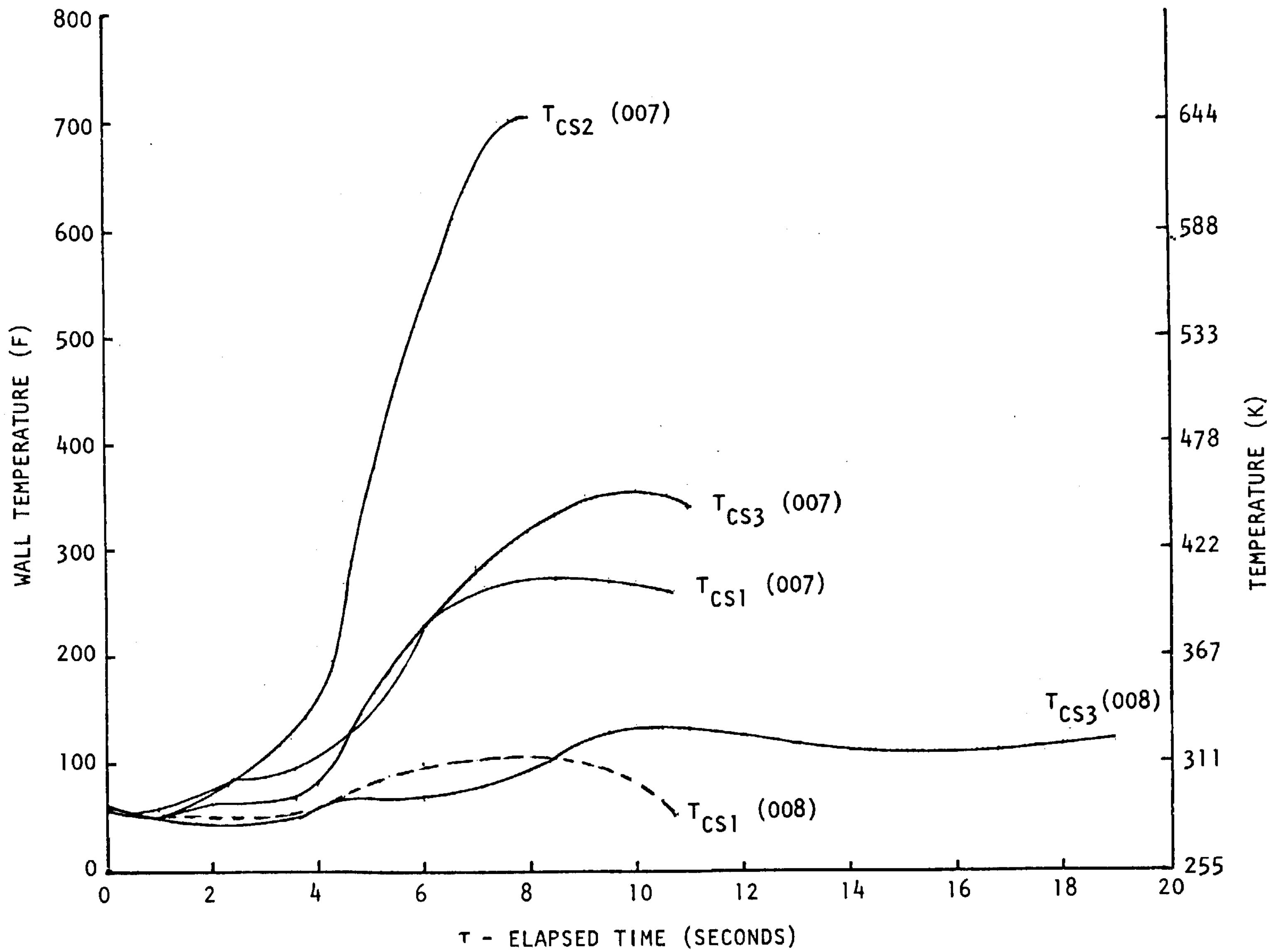


Figure 62. Combustor Wall Temperature vs Time (Tests 007-008)

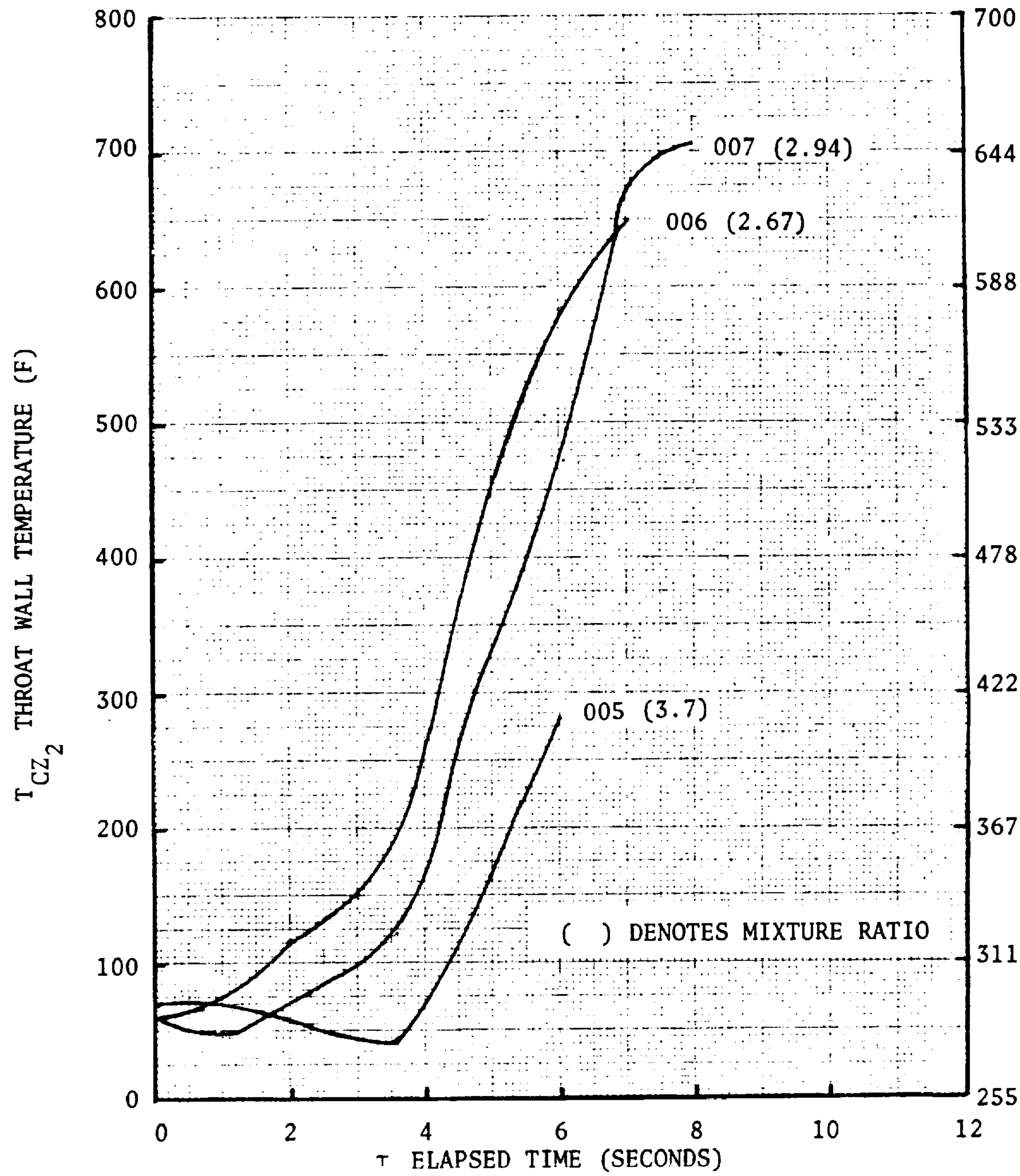


Figure 63. OF_2/B_2H_6 Regenerative Chamber Throat Wall Temperature vs Time

Characteristic Velocity Performance

Comparative thrust chamber C* performance data were reviewed from Test 003-008 with the results shown in Table 10. Mixture ratios ranged from 2.67-3.70 and chamber pressure maximum values reached 101.8 psia (7 x 10^5 N/m^2). Comparative C* efficiency ($\eta_{C^* \; ER,K}$) levels ranged from 90.7 to 99.8 percent. The longer duration runs, Test 007-008, appeared to indicate a 3-5 percent lower C* efficiency to previous calorimeter and Task IV regenerative testing. This is attributed to the lowered OF_2 injection temperature for the Task VII study resulting in an off design propellant injection velocity condition. Improvement of OF_2 jacket discharge temperatures through an improved OF_2 share of the wall heat input in future designs should remedy this.

Combustion Chamber/Injector/Channel Deposit Analysis

The testing conducted during this concluded series indicated that the boron deposit conditions on the chamber wall/injector surfaces becomes primarily dependent on the outer periphery BLC mixture ratio and the overall mixture ratio. Overall mixture ratio values less than 2.8 indicated a severe deposition condition to be present, values of 2.8-3.0 showed moderate deposits, and testing above 3.0 indicated an acceptable condition for this aspect.

For future OF_2/B_2H_6 designs minimization of peripheral boundary layer fuel bias flows is recommended with design mixture ratio levels tailored at 3.0-3.2. Specific performance in this range should be slightly improved.

Injector face boron deposits can be controlled through mixture ratio and injection velocity/angle control. For the triplet design (f-o-f) utilized, a decrease in injection distance will promote a more rapid combustion/recirculation of gases and ensure no highly fuel rich regions exist. Control of the face temperature at a level to retard deposition is also desirable.

TABLE 10. OF_2/B_2H_6 REGENERATIVE TESTING PERFORMANCE EVALUATION

Test No.	Mainstage Time (sec)	$\dot{W}_o$ lb/sec (Kg/sec)	$\dot{W}_f$ lb/sec (Kg/sec)	$\dot{W}_T$ lb/sec (Kg/sec)	MR	$P_{c_{INJ}}$ psia ($N/m^2 \times 10^{-5}$)	$\overline{P}^*_o$ psia ($N/m^2 \times 10^{-5}$)	C^*_{MEAS} ft/sec (m/sec)	C^*_{ODE} ft/sec (m/sec)	$\eta_{c^*_{TC}}$ (%)	$\eta_{c^*_{ER,K}}$ (%)
003	1.5	1.893 (0.859)	0.636 (0.289)	2.529 (1.150)	2.98	39.8 (2.74)	41.0 (2.83)	2671 (814)	7086 (2160)	37.6	37.5
004	3.0	1.973 (0.896)	0.627 (0.285)	2.600 (1.180)	3.15	84.3 (5.81)	86.7 (5.98)	5680 (1731)	7104 (2165)	80.0	79.8
005	5.0	1.970 (0.894)	0.533 (0.242)	2.503 (1.14)	3.70	100.8 (6.95)	103.7 (7.15)	7056 (2151)	7149 (2179)	98.7	98.5
006	5.0	1.830 (0.831	0.685 (0.311)	2.515 (1.14)	2.67	101.8 (7.02)	104.7 (7.22)	7090 (2161)	7023 (2141)	100.1	99.8
007	9.5	1.905 (0.865)	0.649 (0.295)	2.554 (1.16)	2.94	93.8 (6.47)	96.5 (6.65)	6435 (1961)	7075 (2156)	91.0	90.8
008	18.0	1.890 (0.858)	0.675 (0.306)	2.565 (1.16)	2.80	93.8 (6.47)	96.5 (6.65)	6408 (1953)	7048 (2148)	90.9	90.7

$A_T = 5.305\ IN^2$ (COLD), $34.22\ (cm^2)$

$A_T = 5.294\ IN^2$ (HOT), $34.15\ (cm^2)$

$$c^*_{MEAS} = \frac{\overline{P}^*_o\ A_T\ (HOT)\ g}{\dot{W}_T}, \quad \eta_{c^*_{TC}} = \frac{c^*_{EXP}}{c^*_{ODE}}, \cdot\ \eta_{c^*_{ER,K}} = \left(\frac{\eta_{c^*_{TC,EXP}}}{\eta_{c^*_{2D}}\ \eta_{c^*_{HL}}\ \eta_{c^*_{BL}}} \right) \quad \text{(Ref. 6)}$$

Coolant channel B_2O_3 deposit conditions encountered post test 006 were as a result of residual fuel trapped in the coolant channels post shutdown. This aspect can be minimized through reduced chamber thermal capacitances, reduced inlet manifold volumes, reduced wall temperatures, and adequate shutdown purging. For single start missions flight jacket purging may not be necessary; however for ground test or preflight accpetance, fuel jacket purging would be required.

Test Data Conclusions

Analysis of the developmental test data as described indicated satisfactory data results for application to a flight prototype design.

For the combined OF_2/B_2H_6 double jacketed cooling approach demonstration of the ability to regeneratively cool the thrust chamber at a design 3.0 mixture has been established. For prototype designs, (based upon the OF_2 heat pickup and OF_2 temperature rise) additional OF_2 coolant velocity (25-30) percent would be required to increase its share of the heat pickup.

Moreover, to reduce B_2H_6 incipent decomposition during and after shutdown, a reduction in throat wall temperature to 400-450 F by 10-20 percent increased B_2H_6 coolant velocity is proposed.

Nozzle wall heat input and wall surface temperature rise appears to govern the time to steady state of the jacket temperature and pressure conditions. Reduction in the wall temperature for this factor would be beneficial.

SYMBOLS

A	Area
B	Closure thickness
c^*	Characteristic velocity
C_p	Capacity
G	Mass velocity
h	Channel height
h_c	Coolant side heat transfer coefficient
h_g	Gas side heat transfer coefficient
K	Choking coefficient
Q	Heat rate
Q/A	Heat flux rate
MR	Mixture ratio
P	Pressure
t	Gas wall thickness
T_{AW}	Adiabatic wall temperature
T_c	Coolant temperature
W	Channel width, flow
x	Distance
ε	Area ratio
ρ	Density
η	Efficiency

SUBSCRIPTS AND SUPERSCRIPTS

BL	Boundary layer
c	Chamber
ER	Energy release
EXP	Experimental
f	Fuel
INJ	Injector
K	Kinetics
MEAS	Measured
o	Oxidizer
ODE	One dimensional equilibrium
T	Throat, total
2D	Two dimensional
*	Throat
-	Average

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