SPACE SHUTTLE ORBITAL MANEUVERING ENGINE PLATELET INJECTOR PROGRAM

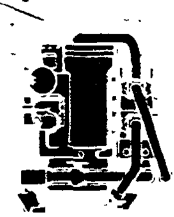
NAS 9-13133

NASA CR-147480

SUMMARY REPORT

(NASA-CR-147480) SPACE SHUTTLE ORBITAL MANEUVERING ENGINE PLATELET INJECTOR PROGRAM Final Report (Aerojet Liquid Rocket Co.) 49 p HC $4.00 CSCL 21H
N76-16231
Unclas
G3/20 13771

REPORT NO. 13133-F-2
1 DECEMBER 1975



Aerojet Liquid Rocket Company
SACRAMENTO
CALIFORNIA 95813

SPACE SHUTTLE

ORBITAL MANEUVERING ENGINE

PLATELET INJECTOR PROGRAM

Summary Report

13133-F-2

Prepared by

Aerojet Liquid Rocket Company
A Division of Aerojet-General Corporation
Sacramento, California 95813

Contract NAS 9-13133

Prepared For

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Primary Propulsion Branch
Houston, Texas 72058

FOREWORD

Aerojet Liquid Rocket Company submits this Summary Report as part of the OME Platelet Injector Program, Contract NAS 9-13133.

This work was conducted under the cognizance of Mr. R. C. Kahl of NASA/JSC, who is the contract monitor. Aerojet personnel include L. B. Bassham, Program Manager, Dr. R. J. LaBotz, Project Manager, and R. W. Michel, Project Engineer.

Key Aerojet personnel contributing to the program include:

S. D. Mercer, Project Engineering
D. F. Calhoon, WSTF Test Engineer
J. L. Pieper, Performance Analysis
R. L. Ewen, Thermal Analysis
R. A. Hewitt, Stability Analysis
E. V. Hron, Manufacturing
R. S. Gross, Test
P. F. Stretch, Test
P. D. Hill, Altitude Test
K. Y. Wong, Design
L. J. O'Connell, Contracts
J. D. Duey, Data Analysis
G. A. Godfrey, Typographical

ABSTRACT

The OME Platelet Injector Program, Contract NAS 9-13133, was undertaken to evaluate a platelet-face injector for the fully reusable Orbit Maneuvering System on the Space Shuttle as a means of obtaining additional design margin and lower cost. This summary report gives a brief overview of the entire program.

The program was conducted in three phases. The first phase evaluated single injection elements, or unielements (6 lbf thrust): it involved visual flow studies, mixing experiments using propellant simulants, and hot firings to assess combustion efficiency, chamber wall compatibility, and injector face temperatures. In the second phase, subscale units (600 lbf thrust) were used to further evaluate the orifice patterns chosen on the basis of unielement testing. In addition to combustion efficiency, chamber and injector heat transfer, the subscale testing provided a preliminary indication of injector stability. Full scale testing (6000 lbf thrust) of the selected patterns was performed in the third phase. Performance, heat transfer, and combustion stability were evaluated over the anticipated range of OMS operating conditions. The effects of acoustic cavity configuration on combustion stability, including cavity depth, open area, inlet contour, and other parameters, were investigated using sea-level bomb tests at ALRC. Prototype injector and chamber behavior was evaluated for a variety of conditions at NASA/WSTF; these tests examined the effects of film cooling, helium saturated propellants, chamber length, inlet conditions, and operating point, on performance, heat transfer and engine transient behavior. Helium bubble ingestion into both propellant circuits was investigated, as was chugging at low pressure operation, and hot and cold engine restart with and without a purge.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

The Orbit Maneuvering Engine Platelet Injector Program, Contract NAS 9-13133, was awarded to Aerojet Liquid Rocket Company (ALRC) for the design, evaluation, and demonstration of a platelet injector suitable for the Space Shuttle Orbit Maneuvering System (OMS) 6000 lbf thrust engine. The contract was started September 25, 1972, and completed on June 15, 1975. It consisted of three phases involving single injector elements of 6 lbf thrust, subscale injectors of 600 lbf thrust, and finally, full scale injectors for the 6000 lbf application.

The face of a platelet injector is formed from a stack of thin metal platelets which are diffusion bonded into a single unit; propellant orifices and flow passages are photoetched into or through each platelet prior to bonding. The platelet concept was selected because of several unique features including ease of manufacture, low cost, potential high performance with reduced chamber lengths, and ease of pattern rework allowing economical and expeditious engine development. The first phase of the program, unielement evaluation, consisted of cold flow and hot fire testing of single candidate elements to determine performance, hydraulics, and compatibility and to obtain an underst[illegible]ng of general pattern behavior. The second phase, subscale evaluation, involve[illegible] testing of the most promising elements to determine performance, stability[illegible]le life, and compatibility under multielement firing conditions. The final phase of the program comprised design, fabrication, and testing of full scale injectors to substantiate performance, stability, and compatibility characteristics in flight-type hardware.

Full scale testing included evaluation of demonstration regeneratively cooled chambers. For the most part, demonstration chamber testing was conducted under altitude conditions at NASA/WSTF. The WSTF testing, which included 300 firings, served as a demonstration of the regenerative chambers and in addition, evaluated such factors as: film cooling, chamber length variations, effect of helium saturated propellant, ingestion of helium bubbles into the propellant circuits, start and shutdown transient behavior, simulation of the vehicle pod feed system, chugging, restart with and without a purge, postfire propellant evacuation and heat soakback characteristics, purge definition, chamber heat transfer, and performance. Full scale testing at ALRC, which comprised some 362 firings, was primarily concerned with combustion stability and the effects of acoustic cavity configuration.

I, Introduction (cont.)

The entire program, in particular the full scale testing at WSTF, was guided in its planning and progress by the philosophy that it must provide a design base for the OMS Engine. This contribution included early identification and solution of potential problems, both in regard to hardware design and fabrication as well as engine behavior and operating limits as determined under simulated altitude test conditions.

II. SUMMARY

The primary objective of the program was to demonstrate a platelet face injector for application on the OMS engine. This engine is to develop 6000 lbf thrust using nitrogen tetroxide, N_2O_4, and monomethylhydrazine, $N_2H_3CH_3$, as propellants, with a chamber pressure of 125 psia and a mixture ratio of 1.65. The program was conducted in three phases which proceeded from a single injection element to the full scale configuration, namely: (1) unielement testing, (2) subscale testing, and (3) full scale testing.

A. UNIELEMENT TESTING

Six fundamentally different injection elements were conceived and tested in the unielement phase of the program. These were selected on the basis of fabricability using platelet construction techniques plus the usual considerations of performance, compatibility, and stability. Thirty-nine geometrical variations of the six basic elements were built and tested to some degree.

As a result of unielement testing, two element configurations were selected for subscale evaluation. One was a splash plate which indicated high performance, and insensitivity to operating point and propellant temperature. The other was an X-doublet which showed lower performance and also lower heat flux levels.

B. SUBSCALE TESTING

Subscale testing consisted of eighty-seven hot fire tests and fourteen cold flow tests. The purpose of the latter was to investigate pattern, hydraulic, and propellant distribution characteristics. In the hot firings, three patterns were tested: the splash plate, the X-doublet, and a mixed element consisting of the splash plate and X-doublet patterns. Two variations of the splash plate and three variations of the X-doublet element were used.

The stability of the high performing splash plate pattern was found to be very sensitive to operating point chamber length and propellant temperature. The moderate performing X-doublet indicated insensitive operation and was, therefore, chosen as the primary candidate pattern for the first full scale design.

C. FULL SCALE TESTING

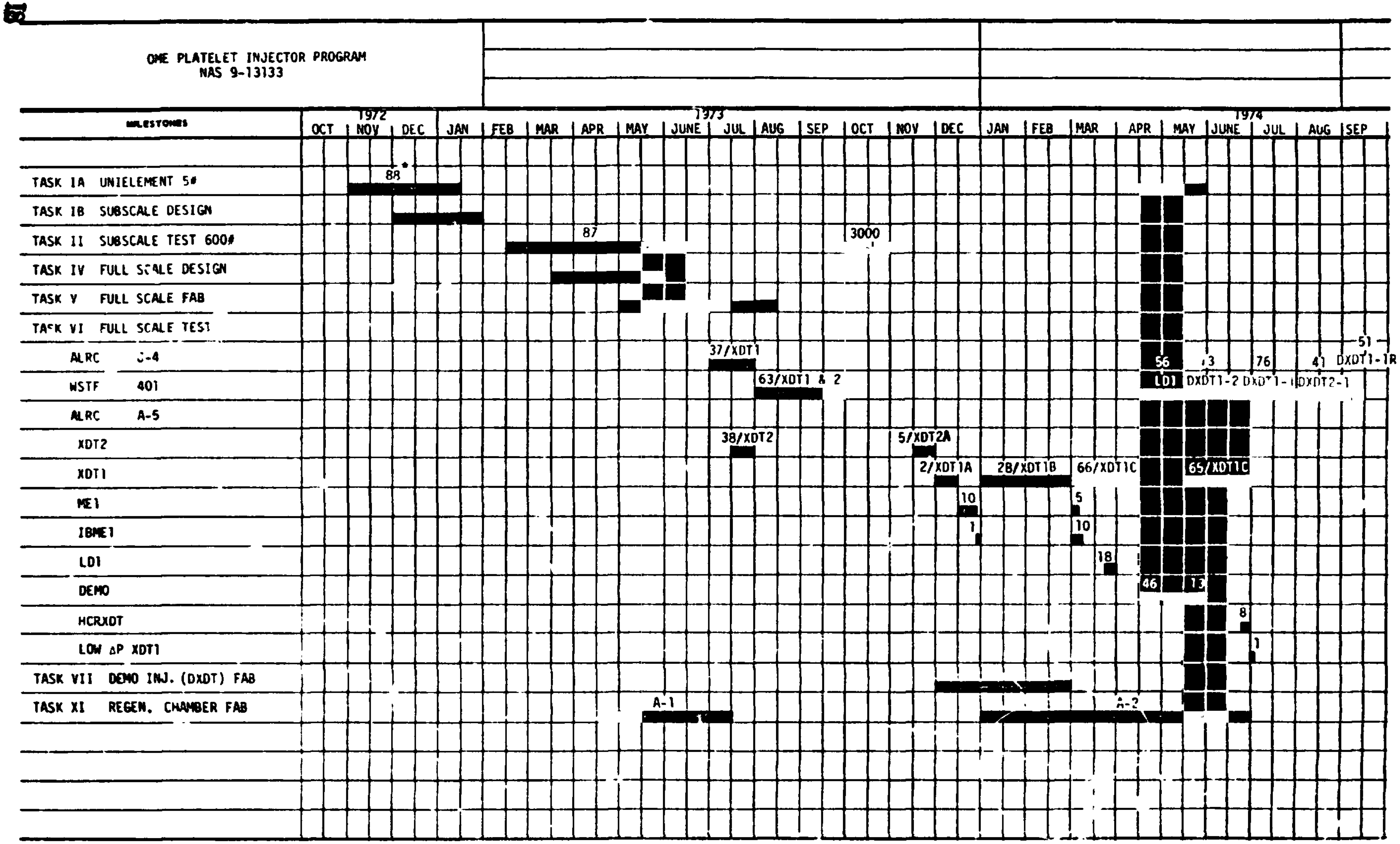
Full scale sea level and altitude testing at ALRC was conducted primarily to identify the effects of injector pattern, cavity configuration, chamber length, and operating point on stability characteristics and performance. The period of testing extended over one year and in part was tandem to the WSTF testing. Five basic injector designs were utilized, and twelve individual faces were actually fired. There were 362 firings at ALRC, with a total duration of 819 sec.

Full scale testing at WSTF was conducted in two phases, one in the Fall of 1973 and the other in the Summer of 1974. During Phase I, the A-1 or workhorse regenerative chamber was used primarily with the X-doublet (XDT-2) injector for a total duration of 642 sec and 63 hot firings. A heat sink 72:1 area ratio nozzle was employed. These tests evaluated engine performance, chamber heat transfer, the performance variations with helium saturated propellants, and fuel film cooling. As a result of successful completion of the testing, the XDT-2 pattern was selected as the primary candidate for prototype evaluation. However, because of the large body of empirical data subsequently accumulated at ALRC with the XDT-1 pattern, the latter was designated as the demonstration injector for the phase II program.

II,C, Full Scale Testing (cont.)

In 1974 WSTF testing (phase II), the A-1 chamber accumulated a further 882 sec of hot firing in 159 tests and the demonstration A-2 chamber accumulated 410 sec duration in 78 tests. Three basic injector patterns were tested, two X-doublets which were platelet face injectors, and a conventional like-doublet injector in which the orifices were formed by electrical discharge machining. These tests evaluated the effects of film cooling, helium saturation, chamber length, inlet conditions, and operating point on performance, heat transfer and engine transient behavior. Helium bubble ingestion into both propellant circuits was investigated, as was chugging at low pressure operation. Hot and cold engine restart with and without a purge was examined. Single propellant boil-off tests and purge tests were conducted to establish purge requirements, and longer coast periods were investigated on hot firings to characterize postfire propellant evacuation and thermal soakback responses.

The entire program schedule is given in Figure 1.



*Figures above time bars refer to number of hot firings

Figure 1. OME Platelet Injector Program Schedule

III. RESULTS AND CONCLUSIONS

The results and conclusions listed below derive mostly from WSTF testing, which was the principal evaluation of the demonstration injector as chamber fired under altitude conditions.

A. PERFORMANCE

Delivered specific impulse for the platelet injectors at the nominal design point is between 314 and 317 seconds, as extrapolated to the flight system exit area ratio. The conventional like-doublet injector shows comparable performance. Performance degradation due to helium saturation of the propellants is negligible. Performance improves from 0.2 to 1.2 seconds as propellant temperature is raised from 40 to 110°F.

B. HEAT TRANSFER

Maximum gas-side regenerative chamber temperature at the throat is 765°F for the prototype injector at nominal conditions. Corresponding cycle life for the flight chamber is estimated at 1350 cycles. Nominal coolant bulk temperature rise is 165°F. The burnout safety factor (R_{BO}^{-1}) for the flight hardware at nominal conditions is estimated to be 1.40. Helium bubbles up to 8 ft long were ingested into each propellant circuit without damage to the injector or regenerative chamber; the largest bubbles momentarily extinguished combustion.

C. STABILITY

The demo (DXDT1) injector pattern was entirely stable over the range of operating conditions tested in conjunction with the OMS baseline cavity configuration. Other configurations were frequently unstable in a hybrid mode called resurging, however. Resurging is characterized by repetitive bursts of high frequency instabilities.

Resurging seems to be unique to the X-doublet injection element. Among the factors that influence it are (1) acoustic communication within the face ring manifolds, (2) fuel temperature, (3) acoustic cavity depth, (4) cavity open area, (5) cavity entrance configuration. Resurging is considered to be an element and pattern-related phenomenon, apparently originating with the peripheral row of injection elements. Elimination of resurging may be possible by pattern modification of the peripheral row.

III,C, Stability (cont.)

Numerous pops of small amplitude and short duration (~ 1 msec) were experienced under altitude conditions; some were attributed to intermediate product detonation during start, others to explosion of propellant agglomeration on the chamber wall at the flange joint location of the workhorse hardware.

Chugging could be induced only at chamber pressures below 70 psia.

D. START AND SHUTDOWN TRANSIENTS

Thrust overshoot may exceed the allowable 50% limit as given in the OMS design specification. Start impulse and time to 90% thrust are within specification. Shutdown impulse variation may be excessive; off-nominal shutdowns may require correction to bring impulse values within specification. Time from full thrust to 10% thrust was acceptable. Helium saturation has no effect on engine transients. Chamber pressure oscillations are characteristic of cold engine shutdowns.

E. EVACUATION AND SOAKOUT CHARACTERISTICS; PURGE

Fuel circuit evacuation times extended to 100 or 150 sec, depending on hardware and propellant temperature. Oxidizer evacuation times ranged from 10 to 20 sec. Oxidizer freezing occurred regularly, without detriment. Fuel freezing did not occur as cell pressures were never below the fuel triple point pressure. Maximum chamber soakout temperatures ranged from 200 to 300°F.

The necessity for a fuel circuit purge cannot be disproven without testing below the fuel triple point pressure (approximately 200,000 ft altitude equivalent), to assess potential fuel frost formation on the gas-side chamber wall and the attendant danger of detonation. Except for that there is no reason to purge the fuel circuit. The purges tested did not appear to be totally effective in expelling the fuel. The current OMS purge, 380 standard cubic inches of nitrogen, is probably adequate but not optimum.

III, Results and Conclusions (cont.)

F. FABRICABILITY

The fabricability of full scale OMS injectors using platelet techniques was demonstrated in both flat faced and baffled configurations. A very desirable benefit of this fabrication technique was the ease of pattern rework, which allowed a completely new face to be installed on an injector body at a fraction of the cost and time associated with conventional rework methods. This benefit had been demonstrated with four injector bodies, with one having been reworked eight times.

G. CYCLE LIFE

The bonded joint between the platelet face stack and the injector body was subjected to 1500 full thermal cycles without incident. The same joint with a redundant electron beam weld was also subjected to 1500 thermal cycles without incident. Cracking evidenced on the top plate of the X-doublet injection element during this series indicated the need for a backup structural plate to prevent the recurrence.

H. COMPLIANCE WITH OMS SPECIFICATION

Table I compares prototype engine behavior as determined in the 1974 WSTF test program with the OMS design specification.

TABLE I

COMPLIANCE WITH OMS DESIGN SPECIFICATIONS

Spec. Item	Conclusion
1. Performance: Minimum specific impulse, I_s = 310 sec at nominal conditions.	1. Acceptable: I_s = 314-317 sec at nominal.
2. Heat Transfer: Minimum burnout safety factor, 1.4, R_{BO} = 0.70	2. Acceptable: Safety Factor = 1.40
3. Temperature: Outer surface of chamber: 500°F Maximum	3. Acceptable: $T_{max} \approx$ 300°F (postfire soak).
4. Stability: Consistent with CPIA Spec. 247	4. Prototype injector had one instability under non-spec restart conditions.
5. Start Transient:	5.
a. P_c Overshoot: 50% maximum	a. Marginal: Several tests had greater overshoot based on thrust; additional work required.
b. Start Impulse: Repeatable within ± 50 lb-sec run to run, ± 100 lb-sec engine to engine.	b. Acceptable: Repeatable within ± 50 lb-sec.
c. Time to 90% thrust: within 0.8 sec, nom ± 0.1 sec range.	c. Acceptable: Variation within ± 0.1 sec.; duration less than 0.8 sec.
6. Shutdown transient:	6.
a. Impulse: Repeatable within ± 300 lb-sec run to run, ± 600 lb-sec engine to engine.	a. Acceptable on flight prototype, if correction can be made to account for pressure and temperature effects; workhorse chamber marginal.
b. Time to 10% thrust: Within 0.925 sec, nom ± 0.175 sec range.	b. Acceptable: Variation within 0.150 sec., duration less than 0.925 sec.
7. Helium saturation and bubbles.	7.
a. Must meet performance with helium saturation at 25 psi above inlet pressure.	a. Acceptable: Nominal performance not degraded by helium saturation.
b. Must be able to ingest any amount of undissolved helium without external damage.	b. No detrimental effects with helium bubbles in either propellant circuit large enough to momentarily extinguish combustion.
8. Blowdown of either or both propellant tanks without external damage.	8. Not Tested
9. Cycle Life: 1000 firings, 1250 sec. max. continuous	9. Beyond scope of tests.
10. Minimum Coast: a. 30 sec, abort mode - may degrade engine; b. 120 sec, nominal	10. Acceptable restarts after 30 sec. with purge (shorter durations not tested), after 10 sec. without purge.
11. Propellant Temperature: with a 10F max. variation between fuel and oxidizer: (a) 40 to 100F range in steady state, (b) 30 to 125F in start transient (7 lbm fuel and 10 lbm oxidizer).	11. Acceptable: tested approximate range of 40 to 100F in steady state, fuel temperatures to 250F (unpurged residual) in transient.
12. Minimum firing duration: shutdown signal may occur any time after signal to start.	12. Acceptable minimum on-period (FS_1 to FS_2) tested was 1 sec, resulting in 1/2 sec. approximately at steady-state chamber pressure.

IV. RECOMMENDATIONS

A. INJECTION ELEMENTS

1. Development of the splash plate element should be pursued. This pattern showed excellent performance with reduced chamber lengths but its stability was sensitive to operating point and propellant temperature.

2. The V-doublet element should be tested at the full scale level.

3. Further exploration is recommended of mixed element patterns which combine the desirable features, while eliminating the undesirable features, of the constituent elements.

B. STABILITY TESTING

1. The interaction between the cavity entrance and the injector pattern, and the resulting effect on stability, should be further investigated with new injector patterns. The resurging instability should be explored.

2. Additional testing of the integral baffle injector with modified patterns should be conducted to determine stability requirements for the baffled unit.

3. Bomb testing with helium-saturated heated propellant should be conducted.

C. ENGINE OPERATION

1. More testing at high chamber pressure and high mixture ratio is required, as is additional testing with hot propellants, since limited testing was conducted at these conditions.

2. Testing should be conducted to simulate the design specification condition wherein the initial slug of both propellants is at the limiting temperature value, 30°F or 125°F, while the remainder is at the nominal value.

IV, C, Engine Operation (cont.)

3. Effects of helium bubble froth in either propellant should be investigated.

4. Testing at cell pressures below the fuel triple point is imperative to determine the necessity and effectiveness of the fuel circuit purge.

5. Hot restarts after short coasts (less than 10 sec) should be investigated further because of the several instabilities encountered under these conditions.

6. Excursions in the chamber gas-side wall temperature warrant further investigation.

7. Start transient overshoot may exceed allowable levels and require redefinition of the design specification.

8. Shutdown impulse variation may also exceed allowable limits; the design specification could be simplified.

9. Chug frequency margin testing should be conducted.

V. APPLICATION OF RESULTS

The primary application of the results of this program has been the baseline design definition of the Space Shuttle OMS engine. In addition, however, the technology is relevant to several other rocket engine applications.

5-10 lb Thrust Vernier Engines

The unielement program, Task I, clearly demonstrated the use of single injection elements, fabricated of platelets, at the 6 lb thrust level. These novel devices achieved high performance in minimal chamber length with minimum propellant volumes. The low cost flexibility of the concept provides a solid foundation for the application of unielements to this thrust class of rocket engine.

10-1000 lb Thrust RCS Engines

The subscale program, Task II, demonstrated the multielement flexibility of the platelet concept at the 600 lb thrust level. Various injector designs achieved high performance, good chamber compatibility, stability, and excellent cycle life. Low cost fabrication techniques coupled with the rework capability of platelet construction allow for expeditious development of engines in this thrust class. Moreover, injector thrust capability can be scaled up or down quite simply by photographic enlargement or reduction processes.

6000 lb Thrust Maneuvering Engines

The full scale demonstration programs, Tasks VI and VII, not only defined a baseline design for the OMS engine but also showed additional benefits to the platelet injector concept. Mixing of platelet elements by merging the artwork of two or more patterns allows the design emphasis to be shifted to stability, performance or cooling margin as required. The rework feature provides for injector development with an inexpensive and rapid fabrication cycle. The program also demonstrated that the platelet

V, Application of Results (cont.)

concept is applicable to a baffled injector with the fabrication of an integral baffle unit having three separate injector compartments. These various design options clearly illustrate the inherent flexibility of the platelet injector concept as applied to engines in this higher thrust category.

VI. CONTRIBUTIONS OF OME TO OMS

The major accomplishment of the OME program has been to establish a firm technology base for the design and development of the OMS, and to provide a fundamental understanding of engine behavior for a variety of conditions that may or will be encountered in actual flight operation. The most significant contributions relate to the design of the injector, chamber, and acoustic cavity, and to operation of the engine.

A. INJECTOR

1. Pattern - The x-doublet pattern as developed on the program met all requirements of the OMS procurement.

2. Cycle Life - Cycle life of 1500 cycles was twice demonstrated in subscale testing.

3. Hydraulics - Hydraulic design of the full scale injector was developed and demonstrated.

4. Fabrication Sequence - A low cost fab sequence was devised and shown to be satisfactory.

5. Rework Capability - Successful refacing of injector bodies was accomplished, allowing pattern changes to be made at low cost.

VI, Contributions of OME to OMS (cont.)

B. CHAMBER

1. Fabrication Technique - The techniques for fabricating the electroformed jacket/milled slot chamber were identified and appear to be satisfactory.

2. Heat Transfer Evaluations - Heat flux, wall temperature, and coolant bulk temperature rise data acquired in full scale tests expedited the analytical thermal design of the OMS chamber.

3. Cycle Life - Acceptable cycle life capability for the OMS chamber could be predicted on the basis of these data.

C. ACOUSTIC CAVITY

1. Design - The OMS will use the twelve compartment dual tuned acoustic cavity design with the same area, tune, and inlet geometry.

2. Stability Margin - The stability margin of this configuration in conjunction with the XDT-1 platelet injector was fully evaluated.

3. Critical Factors - Critical factors in the design, fabrication and instrumentation of acoustic cavities were identified.

4. Operating Point Sensitivity - The influence of chamber pressure, mixture ratio, and propellant temperature on cavity tune were investigated.

D. ENGINE OPERATION

1. Helium Saturation - The effect of helium saturation of the propellants on engine transients and performance was fully analyzed.

2. Helium Bubble Ingestion - Ingestion of large helium bubbles into each propellant circuit was examined.

3. Operating Point Sensitivity - The influence of chamber pressure, mixture ratio, and propellant temperature on performance, heat transfer, and engine transient behavior was evaluated.

VI, D, Engine Operation (cont.)

4. Chugging - The threshold chamber pressure for chugging was established.

5. Propellant Lead - The influence of propellant lead effects was investigated.

6. Film Cooling - The need for and effect of film cooling was determined.

7. Engine Transients - Start and shutdown transients of the engine have been characterized.

8. Engine Restart - Altitude restart of hot and cold engines, purged and unpurged, with hot and cold propellants, has been investigated.

9. Propellant Evacuation - Postfire propellant evacuation was assessed for a range of engine and propellant temperatures.

10. Postfire Heat Soakback - Postfire heat soakback characteristics and maximum coast temperatures have been determined.

11. Purge - Purge effectiveness for a variety of purge parameters was evaluated.

12. Compliance with OMS Specification - Except for minor deviations compliance with the OMS design specification has been demonstrated.

13. Future Testing - Areas that require additional test evaluation, including high temperature propellants, purge effectiveness, and reduced cell pressures, have been identified.

VII. UNIELEMENT TESTING

A. INTRODUCTION

Unielement testing provided the initial screening of candidate patterns for the full scale application, unielements being the basic injection element generally consisting of one oxidizer and one fuel orifice. Thirty-nine variations of six basic patterns were tested to some degree. Three types of tests were conducted.

B. UNIELEMENT DESIGN

The entire unielement fixture was made of platelets; it had a diameter of 0.650 in. and a thickness of 0.150 in. and contained both propellant manifolds and the injection element.

The six basic patterns tested were: X-doublet, unlike-doublet, splash plate, like-doublet, V-doublet, and vortex element. Table II summarizes pertinent dimensions of the thirty-nine variations of these patterns.

Two uncooled chambers were used for hot-firing purposes, one with a length of 2 in., the other with a 4 in. length. Figure 2 shows a photograph of the two chambers and three of the unielement injectors.

C. TESTING

The three types of tests conducted were: (1) atomization tests with water, allowing visual observation of both injectants, separately and together; (2) mixing tests with immiscible simulants to enable mapping of mixture ratio and mass flux profiles; (3) hot fire tests to determine performance, pattern sensitivity to operating point and propellant temperature, and face and wall compatibility.

TABLE II

SUMMARY OF UNIELEMENT PATTERNS TESTED

I. X-Doublet

a. Offset Fans

	Offset	Orifice Size Fuel	Orifice Size Oxidizer	Slot Size Fuel	Slot Size Oxidizer
XD-2	.000	.020x.020	.024x.024	.020x.080	.024x.096
XD-2	.020	.020x.020	.024x.024	.020x.080	.024x.096
XD-4	.040	.020x.020	.024x.024	.020x.080	.024x.096
XD-01	.000	.020x.020	.024x.024	.020x.060	.024x.060
XD-02	.000	.020x.020	.020x.024	.020x.060	.020x.060

b. In-Line Fans

	Offset	Orifice Size Fuel	Orifice Size Oxidizer	Slot Size Fuel	Slot Size Oxidizer
XDI-1	-	.020x.020	.024x.024	.020x.080	.020x.080
XDI-2	-	.020x.020	.020x.024	.020x.080	.024x.080

II. Unlike-Doublet

	Oxidizer Orifice	Fuel Orifice
UD-1	.029x.024	.020x.020
UD-2	.031x.022	.020x.020
UD-3	.026x.024	.020x.020

III. Splash Plate

	Orifice Diameter Fuel	Orifice Diameter Oxidizer
SP-1	.020	.024
SP-2 (relieved)	.020	.024
LSP-1	.025	.030
LSP-2 (relieved .015)	.025	.030
4SP (four elements)		

IV. Like-Doublet

	Cup Size Fuel	Cup Size Oxidizer
LD-B	.049x.100	.055x.100
LD-FD	.059x.100	.055x.100
LD-FWD	.059x.120	.055x.100
LD-FOWD	.059x.129	.065x.120

V. V-Doublet

	Included Angle	Inlet Fuel	Inlet Oxidizer	Outlet Fuel	Outlet Oxidizer
VDT-1	60	.020x.020	.024x.024	.020x.020	.024x.024
VDT-2	60	.024x.020	.024x.024	.020x.020	.024x.024
VDT-3	60	.020x.020	.024x.024	.0226 dia	.0271 dia
VDT-4	60	.024x.020	.024x.024	.0226 dia	.0271 dia
VDT-5	90	.020x.020	.024x.024	.020x.020	.024x.024
VDT-6	90	.024x.020	.024x.024	.020x.020	.024x.024
VDT-7	90	.020x.020	.024x.024	.0226 dia	.0271 dia
VDT-8	90	.024x.020	.024x.024	.0226 dia	.0271 dia

VI. Vortex

	Exit Config	# of Inlets	Cup Diameter Fuel	Cup Diameter Oxidizer	Exit Diameter Fuel	Exit Diameter Oxidizer
VTX-A	Circular	1	.120	.100	.029 dia	.033 dia
VTX-B	Circular	2	.120	.100	.027 dia	.030 dia
VTX-C,Ca	Circular	1	.140	.120	.030 dia	.034 dia
VTX-D,Da	Circular	2	.140	.120	.028 dia	.031 dia
VTX-E	Elliptical	1			.0204x.0408	.0234x.0468
	Rectangular	1			.020x.0287	.020x.0354
VTX-F	Elliptical	2			.0204x.0408	.0234x.0468
	Rectangular	2			.020x.0287	.020x.0354
VTX-G	Triangular	1			.0108bx.0093h	.0131bx.0113h
	Cross-Shaped	1			.012	.012
VTX-H	Triangular	2			.0108bx.0093h	.0131bx.0113h
	Cross-Shaped	2			.012	.012

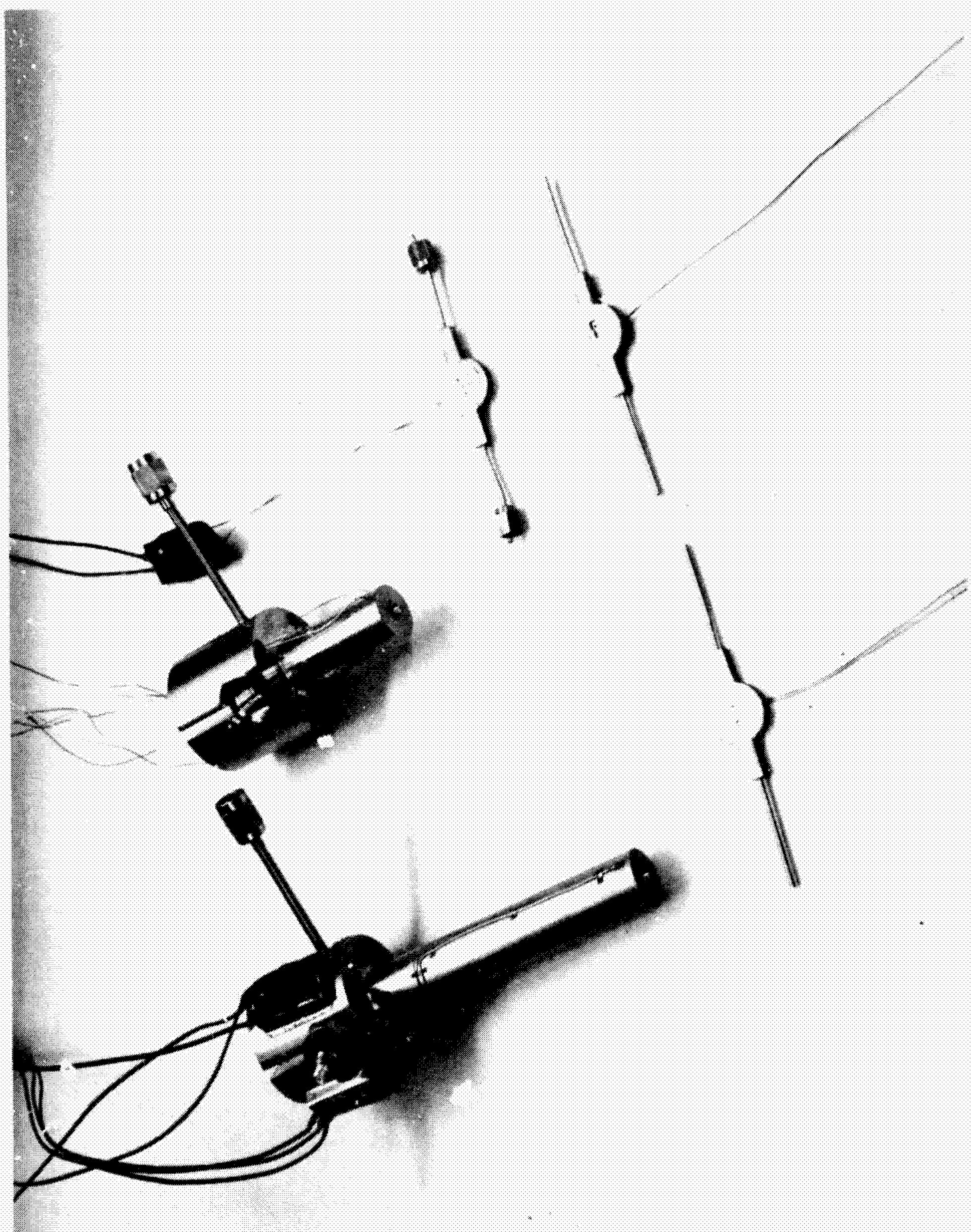


Figure 2. Unielement Chambers and Injectors

VIII. SUBSCALE TESTING

A. INTRODUCTION

Subscale testing furnished the first screening of candidate element patterns with multielement injection. The subscale units produced 1/10 of the full scale thrust, i.e., 600 lbf. Three basic injector patterns were tested in hot firings, with variations of each basic element.

B. HARDWARE

The three patterns tested were the splash plate, X-doublet, and a mixed element consisting of splash plate and X-doublet elements. The splash plate had two variations and the X-doublet pattern had three. All injectors were of platelet face construction, with conventionally machined concentric ring manifolds similar to those in the full sclae injector.

The heat sink chamber was fabricated from 304L stainless steel. The chamber length was 4.0 in. Cylindrical L* section with a cumulative length of 8 in. could be used in conjunction with the chamber, as could separate film coolant and acoustic cavity rings.

Figure 3 shows a photograph of the chamber and injector.

C. TESTING

Propellant distribution tests were conducted to establish injection mass flux and mixture ratio profiles. Eighty-seven hot fire tests were run to investigate performance, heat transfer, and stability. Stability bombs were used in fifty-five of the firings. Chugging tests were run. The variation in performance and chamber heat transfer with film cooling was also investigated. Two series of tests each comprising 1500 thermal cycles were conducted to assess cycle life capability of the platelet bonding techniques. One injector face so tested was diffusion-bonded to the injector body; the other was diffusion bonded and had redundant electron beam welds along the channel lands.

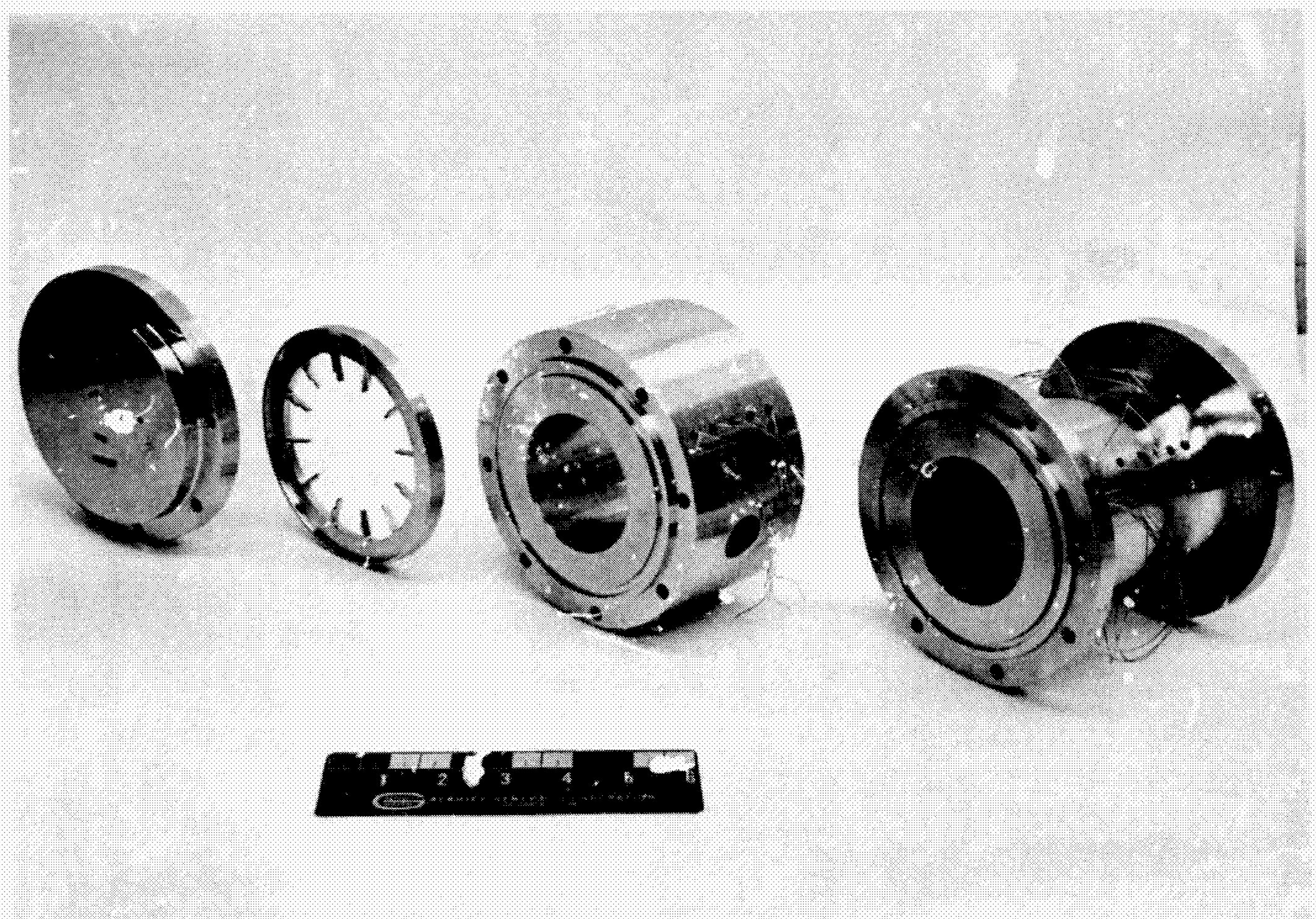


Figure 3. Subscale Chamber

IX. FULL SCALE TESTING AT ALRC

A. INTRODUCTION

Full scale testing at ALRC was conducted in tandem with both of the WSTF test programs and lasted approximately one year. The purpose of the testing was, broadly, to evaluate performance, stability, and heat transfer characteristics, and more specifically, to identify the effects of injector pattern, cavity configuration, chamber length, and operating point on those characteristics. The primary thrust of much of the testing was directed toward evaluating and improving stability margin and exploring the limits of stable operation; thus, many of the firings were stability bombed. Testing was conducted both in the J-4 altitude and A-5 sea level facilities, primarily in the latter. Some 362 tests were conducted with a total duration of 1459 seconds.

B. HARDWARE

1. Injectors

In addition to the XDT-1 and XDT-2 injectors which were used in the 1973 WSTF series, and the DXDT1, DXDT2, and like-doublet injectors, which were used in the 1974 WSTF series, the ALRC testing also evaluated mixed element flat faced and integral baffle injectors. The integral baffle unit was also a platelet face injector and demonstrated the fabricability of baffled injectors with platelet technology. The unit proved unstable, however, and testing was discontinued after only a few tests.

There were, apart from the integral baffle and like-doublet injectors, four basic injector bodies used in the ALRC and WSTF test series. The two used in conjunction with the XDT1 and XDT2 injectors were designated as workhorse bodies; the other two were more representative a flight-type design and were referred to as demo bodies. Both workhorse bodies were refaced three times. One of the

IX, B, Hardware (cont.)

demo bodies was refaced once, the other was reworked by the addition of an EB weld to the existing platelet face. Table III summarizes the history of the four bodies and their numerous faces for the entire program.

2. Chambers

With the exception of twelve regenerative chamber tests, all of the ALRC testing involved uncooled chambers. Three such chambers were fabricated, with chamber lengths of 4, 8, and 12 in. Three L* sections with lengths of 2, 3, and 4.125 in., were also made. Thus, considerable variation in chamber length could be achieved.

A film coolant ring could be mounted at the forward end of the chamber, downstream of the acoustic cavity, as desired.

3. Cavity Configurations

Considerable variation in cavity configuration was also possible. Cavity depth was adjustable by means of blocks which were attached to the bottom of the cavity. Entrance area was changed by the insertion of axial blocks of various widths decreasing both volume and area. Cavity width was also altered by changing the width of the cavity partitions. Injector overlap variations were achieved by several overlap rings. Finally, several variations in cavity inlet contour were evaluated.

C. TEST SUMMARY

The ALRC test series are not readily described, primarily because of the many configuration changes that were made. Table IV summarizes the purpose of various test sequences but does not go into significant detail regarding actual hardware configurations.

TABLE III

INJECTOR SUMMARY

Body	Face	Tested	No. Firings	Duration (sec)	Notes
Workhorse #1	XDT-1	J-4	38	170	No face ring dams.
		WSTF	9	22	Unstable.
		A-5	5	10	Confirmed need for dams.
	XDT-1A	A-5	2	4	High injector pressure drop.
	XDT-1B	A-5	38	76	Face leak developed.
	XDT-1C	A-5	134	268	Evaluation of cavity configurations.
Workhorse #2	XDT-2	A-5	24	48	No face ring dams; stability "fixes" evaluated.
	XDT-2A	A-5	14	28	Dams installed; stability achieved.
		WSTF	54	620	Test objectives satisfied.
	Mixed Element	A-5	17	33	High performing, unstable
	Low ΔP	A-5	1	2	Interpropellant leak.
Integrated Baffle	-	A-5	12	24	Unstable
Like-Doublet*	-	A-5	18	36	Evaluation of cavity configurations
		WSTF	56	350	Test objectives satisfied.
Demo #1	DXDT1-1	A-5	33	68	Evaluation of cavity configurations.
		WSTF	76	448	Two orifices slightly burned.
	DXDT1-1R	WSTF	51	220	Also in 40 cold flow tests, 40 sec total duration.
Demo #2	DXDT1-2	A-5	26	52	Chamber length, bomb location, and stability evaluations.
		WSTF	13	90	Delaminated platelet stack, burned face.
	DXDT2-1	WSTF	41	181	Replaced with more representative unit.
			662	2750	

*IR&D residual

TABLE IV

PURPOSE OF ALRC FULL SCALE TEST SEQUENCES

Test Sequence	Injector	Purpose
1-1 to 9	XDT-1	Initial checkout; determination of cavity configuration requirements.
2-1 to 5	XDT-2	Evaluate remedies for resurges;
-6, 7	"	Evaluate remedies for resurges; face ring dams installed.
3-1 to 3	ME	Stability and heat transfer evaluations.
4-1	XDT-1A	Evaluation of high ΔP injector.
5-1a	XDT-1B	Baseline evaluation.
-2a		Chugging tests.
-1 to 3		Stability margin tests with reduced cavity depth + area, contoured inlet.
-4 to 7		Determine if contoured inlet changes effective length of cavity.
5-8, 9	XDT-1C	Confirm baseline behavior with XDT-1C
-10, 11		Confirm destabilizing effect of contoured inlet.
-12		Evaluation of partial contour inlet.
-13, 14		Evaluation of reduced inlet contour.
-15 to 20		Evaluation of partial contour and rectangular inlets with cavity length variations.
-21 to 24		Determine effect of high C_D on inlet contour.
-25		Check stability without cavities.
6-1 to 4	ME-IB	Checkout of baffled injector.
7-1	L-D	Evaluation of high C_D inlet with like-doublet.
-2, 3		Test with contoured inlet, reduced cavity length.
-4		Review with rectangular cavities.
-5		Check stability with cavities blocked.
8-1 to 5	DXDT1-1	Investigate overlap effects, cause of pops; chug tests.
9-1a, 1	DXDT1-2	Verify stability.
-2		Reduce chamber length.
-3, 4		Determine effect of bomb location.
10-1	XDT-1C	Overlap investigation.
-2 to 5	"	Determine if inlet radius reduces effective overlap.
11-1	XDT-1C	Confirm destabilizing effect of shorter chamber.
-2 to 7		Determine stability margin by reducing cavity depth + area.
-8		Check stability without 3-T cavities.
-9		Determine if actual or effective cavity area is important.
-10		Reduce 3-T cavity area.
-11		High contraction ratio chamber tests, chugging tests.
12-1	XDT-1	Evaluation of low ΔP injector.

X. 1973 WSTF TESTING

A. INTRODUCTION

The purpose of the 1973 WSTF test series was to demonstrate the platelet injector with a milled slot electroformed nickel closeout regenerative chamber to establish a technology base for OME-type engines. Testing extended from September 7 to October 17, 1973, and took place in Test Stand 401 of the facility. The workhorse A-1 chamber was used in these tests, in conjunction with the XDT-1 and XDT-2 injectors. The XDT-1 injector was used in the first test sequence and suffered resurging combustion instabilities. It was returned to ALRC for evaluation of remedial measures; the instabilities were eliminated by means of dams at the null points in the ring manifolds. Testing at WSTF was resumed and completed without incident. Sixty-three firings with a total duration of 642 sec were conducted.

B. HARDWARE

1. Injectors

Two injectors were utilized in the 1973 testing, both with X-doublet patterns, designated XDT-1 and XDT-2. The two were identical except for the outer row of elements which on the XDT-2 produced a fuel fan parallel to the chamber wall and on the XDT-1 a fan canted 30° to the wall. Figure 4 shows a photograph of the injector body and manifold; the small blocks shown were installed in the bottom of the cavities to change cavity "tune".

2. Chamber

All testing was accomplished with the 12 in. A-1 or workhorse regenerative chamber. Coolant enters at the aft end of this chamber, by

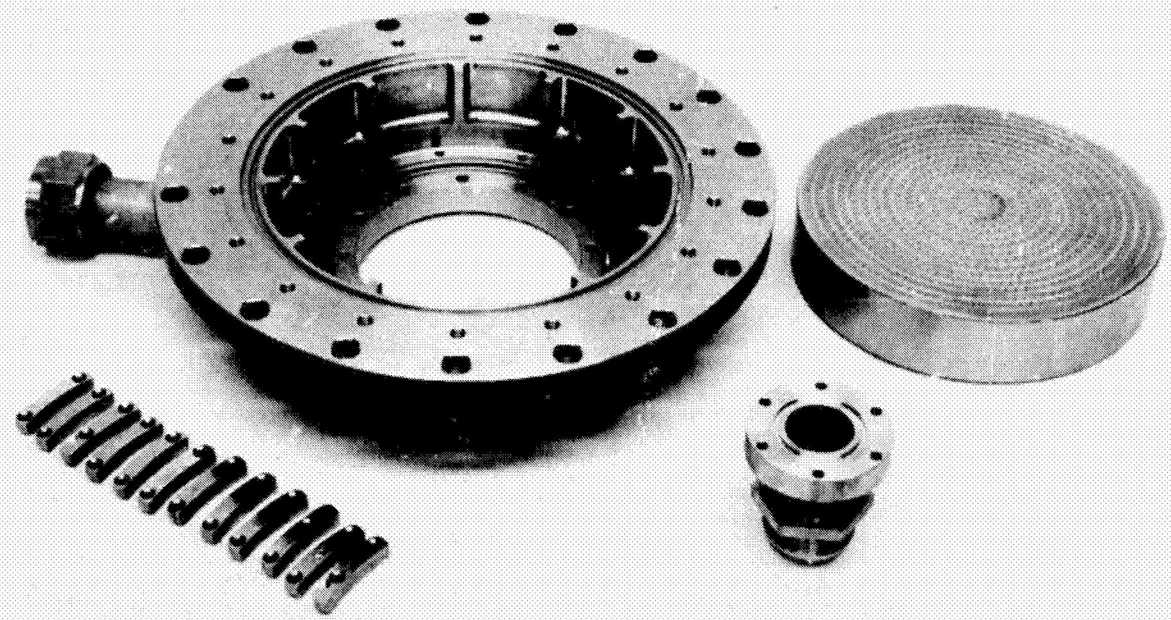


Figure 4. Full Scale Injector Assembly

X,B,2.Chamber cont.

means of a circular manifold, and passes through 180 slots milled in the 304L stainless steel inner liner. The outer wall of the chamber and coolant channel close-out is made from electroformed nickel. After passing through the channels, the fuel is collected in another circular manifold and passed through a U-shaped line to the injector manifold. Figure 5 shows a drawing of the chamber.

The chamber could be used with or without a 4 in. long heat sink L* section located at the forward end. This 3/4 in. thick cylindrical section, which is shown on the above drawing, limited firing durations to less than 10 sec since it was not cooled.

The acoustic cavity housing contained 12 compartments which were cooled by means of a circular fuel manifold. Eight cavities were turned to the first tangential acoustic mode and four were tuned to the third.

Pertinent design details for the engine are presented in Table V.

C. TEST SUMMARY

Eight test series were conducted as summarized in Table VI. The first of these evaluated the XDT-1 injector which proved subject to resurging instabilities and was returned to ALRC for remedial testing. The XDT-2 injector, with dams installed at the null points of the face ring manifolds, was used upon resumption of WSTF testing.

The second series was for checkout purposes and the third for acquiring heat transfer and performance data with the 12.9 in. chamber and 20:1 nozzle. The fourth and fifth series evaluated performance with this 72:1 nozzle and chamber lengths of 12.9 and 16.4 in.

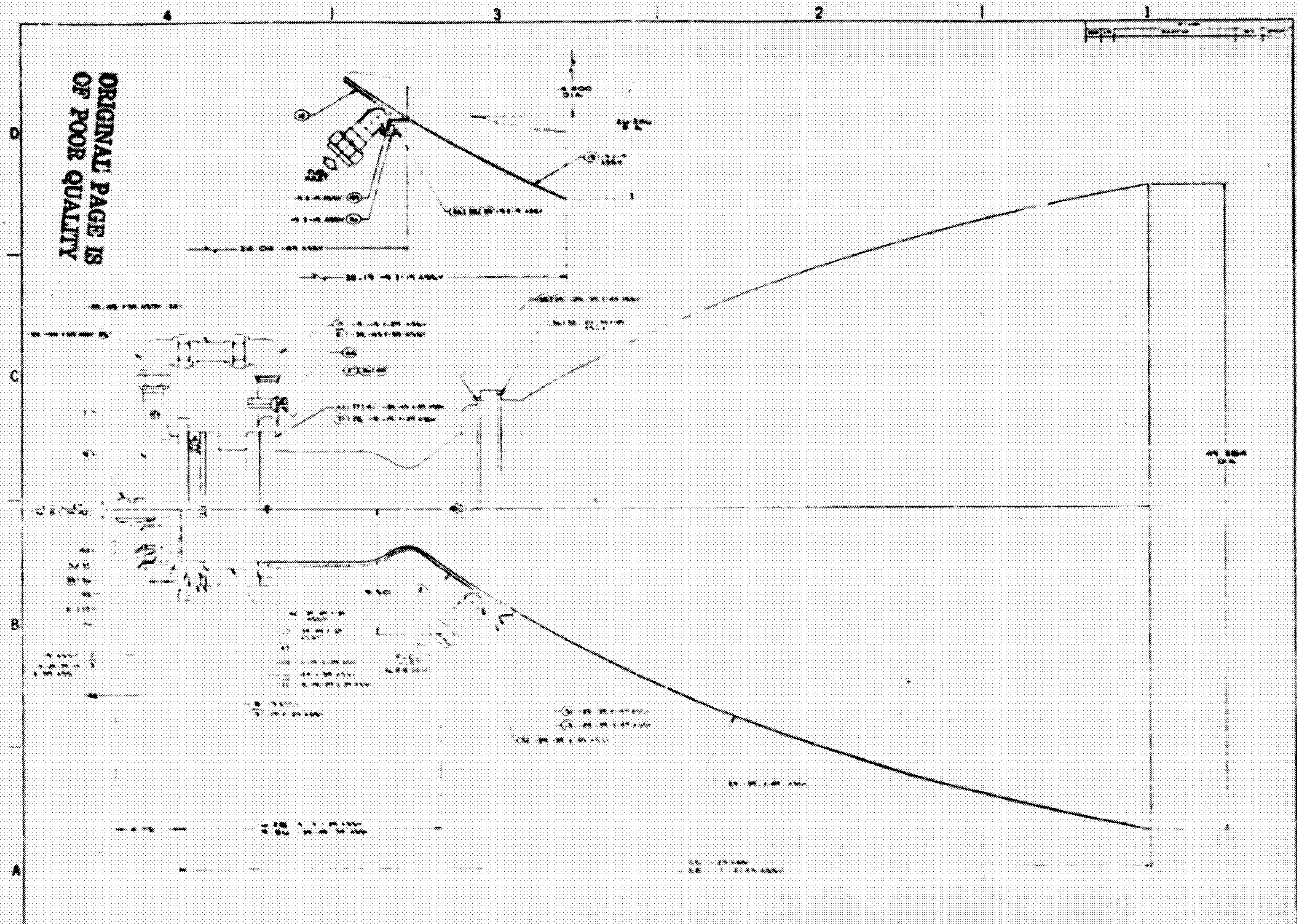


Figure 5. A-1 Chamber

TABLE V

ENGINE DESIGN DETAILS

OME Platelet Injector Program
Engine Design Details

INJECTOR

15 ELEMENT RINGS
867 "X" DOUBLET ELEMENTS
8.11 IN. INJECTOR DIAMETER
38 PSI OXIDIZER PRESSURE DROP
47 PSI FUEL PRESSURE DRCP
CRES 304L FACE & BODY

ENGINE

6052 LBS THRUST (MEAS)
1.65 MIXTURE RATIO
125 PSIA CHAMBER PRESSURE
71 AREA RATIO
314.2 SEC VACUUM SPECIFIC IMPULSE

CHAMBER

180 MILLED SLOT CHANNELS
304L LINER
ELECTROFORM NICKEL CLOSEOUT
141 °F TEMPERATURE RISE
16.5 PSI PRESSURE DROP
11.225 IN. REGEN. CHAMBER LENGTH
6:1 REGEN. AREA RATIO
0.047 IN. CHANNEL WIDTH
0.040 IN. GAS SIDE WALL THICKNESS
0.130 - 0.070 - 0.150 CHANNEL DEPTH
0.096 - 0.057 - 0.206 LAND WIDTH
0.125 NICKEL CLOSEOUT THICKNESS

ACOUSTIC CAVITY

8 - 1T CAVITIES
4 - 3T CAVITIES
CRES 304L MATERIAL
1300 - 1800°F TEMPERATURE

TABLE VI

1973 WSTF TESTING SUMMARY

OME Platelet Injector Program
WSTF Testing Summary

SERIES	TESTS	DATE	INJ.	MR	P_C	PROP. TEMP. O/F	HELIUM SAT.	FFC	DUR.	AREA RATIO	L'	REMARKS
I-I	9	9/7	XDT-1	1.55-1.75	120-125	AMB/AMB	NO	NONE	2.0	20	12.9	SYSTEM CHECKOUT
VI-I	12	9/25	XDT-2	1.45-1.85	110-140	AMB/45	NO	NONE	10.0	20	12.9	INJECTOR/CHAMBER CHECKOUT
I-II	12	9/26	XDT-2	1.45-1.85	110-140	AMB/AMB	NO	NONE	10.0	20	12.9	1. PERFORMANCE 2. HEAT TRANSFER
II-I	12	10/4	XDT-2	1.45-1.85	110-140	AMB/AMB	NO	NONE	10.0	71	12.9	PERFORMANCE
VII-I	6	10/10	XDT-2	1.45-1.85	110-140	AMB/AMB	NO	NONE	10.0	71	16.4	PERFORMANCE
VIII-I	5	10/11	XDT-2	1.45-1.85	110-140	AMB/AMB	YES	NONE	10.0	71	16.4	HELIUM SAT. INFLUENCE
IX-I	5	10/12	XDT-2	1.45-1.85	110-140	AMB/AMB	NO	7.50	10.0	71	16.4	FUEL FILM COOLING INFLUENCE
X-I	2	10/17	XDT-2	1.65	125	AMB/AMB	NO	NONE	150.0	6	12.1	DURATION INFLUENCE
TOTAL	63		2	5	3	1/2	1	2	642	3		

X,C, Test Summary cont.

The sixth series investigated the effects of helium-saturated propellant. The seventh investigated the effect on performance and heat transfer of fuel film cooling with the film coolant fraction nominally 8% of the total fuel flow.

The last series consisted of two tests, the second of which lasted 150 sec and was intended to examine the effect of extended firing durations on injector face and chamber wall integrity and on acoustic cavity operation. No damage was experienced.

D. CONCLUSIONS

Following installation of the face ring dams, the injector operated stably over the remainder of the test series - 54 tests with a total duration of 620 sec.

No hardware damage occurred.

Altitude performance for a 55:1 OMS prototype nozzle was determined to be 314.9 sec specific impulse as extrapolated from the 72:1 nozzle tests. The effects of helium saturation, film cooling, operating point, and chamber length on performance were also determined.

The maximum measured chamber wall temperature, at the throat, was 850°F, for which the corresponding cycle life is calculated to be 1125 cycles. The nominal coolant bulk temperature rise for the 12 in. chamber regenerative length was 145°F. The effects of helium saturation, film cooling, operating point, and chamber length on wall temperature and bulk temperature rise were also determined.

XI. 1974 WSTF TESTING

A. INTRODUCTION

The 1974 WSTF testing was directed to a more comprehensive examination of the engine behavior, emphasizing in particular, early identification of potential problems on the OMS, and was as well the first testing of the demonstration injector combined with the 16 in. demonstration chamber. In addition to the usual performance and heat transfer evaluations -- concerning the effects of film cooling, helium saturated propellants, inlet condition, and operating point -- there were also test sequences involved with: helium bubble ingestion into both propellants, chugging thresholds at low pressure operation, hot and cold engine restarts with and without a fuel circuit purge, purge effectiveness, and long coast periods to characterize propellant evacuation and heat soakback behavior. The majority of these sequences served to establish a basis for understanding and predicting engine behavior in space flight.

In this series, two platelet face injectors and a conventional EDM machined like-doublet were tested in conjunction with two regenerative chambers for a total duration of nearly 1300 sec in 237 hot firings.

B. HARDWARE

1. Injectors

The like-doublet injector which was used in the first two test series was residual from a company funded program. It was used to establish a baseline of comparison for the platelet injector characteristics.

Two platelet face patterns were tested on demo bodies. To differentiate the demonstration injectors from those used in the 1973 testing, they were designated DXDT1 and DXDT2, followed by the serial number. The major differences between the demo injectors and those used earlier were that

XI, B, Hardware (cont.)

in the demo units: (1) the "pie" manifolds (entrance manifolds to the ring manifolds) were tapered, (2) the downcomers between the "pie manifolds and the ring manifolds had less flow area, and (3) fuel from the chamber was fed directly around the acoustic cavity to the pies rather than with a separate line and collector manifolds of the earlier A-1 design. Figure 6 shows a drawing of the demo injector body prior to welding the back (pie manifold) cover into place.

2. Chambers

The A-1 or workhorse chamber used in the 1973 testing was used again in the early 1974 testing. A flight prototype or demonstration chamber was also tested. The demonstration unit, designated as A-2, differed from the A-1 primarily in that the chamber and acoustic cavity housing were fully regeneratively cooled, the coolant inlet manifold was tapered to give better flow distribution, the coolant exited directly into the injector and the regenerative length was extended to 16 in. A drawing of the A-2 chamber assembly is reproduced in Figure 7.

The A-2 was originally identical to the A-1. It was reworked by adding an 8 in. cylindrical section with acoustic cavities to an existing 8 in. chamber. Because of poor surface preparation prior to electroforming the additional length, a poor bond was achieved between the electroformed outer jacket and the inner liner. After 78 firings and 410 sec firing duration, the chamber failed by virtue of an inward bulge of the inner liner over an area approximately 3 in. by 10 in. The failure was contained entirely by the outer wall. Later sectioning of the wall showed the bond to be poor or nonesistent over much of the interface of the additional length.

C. TEST SUMMARY

Table VII summarizes the entire test program insofar as test purpose, engine operating point, and propellant temperature.

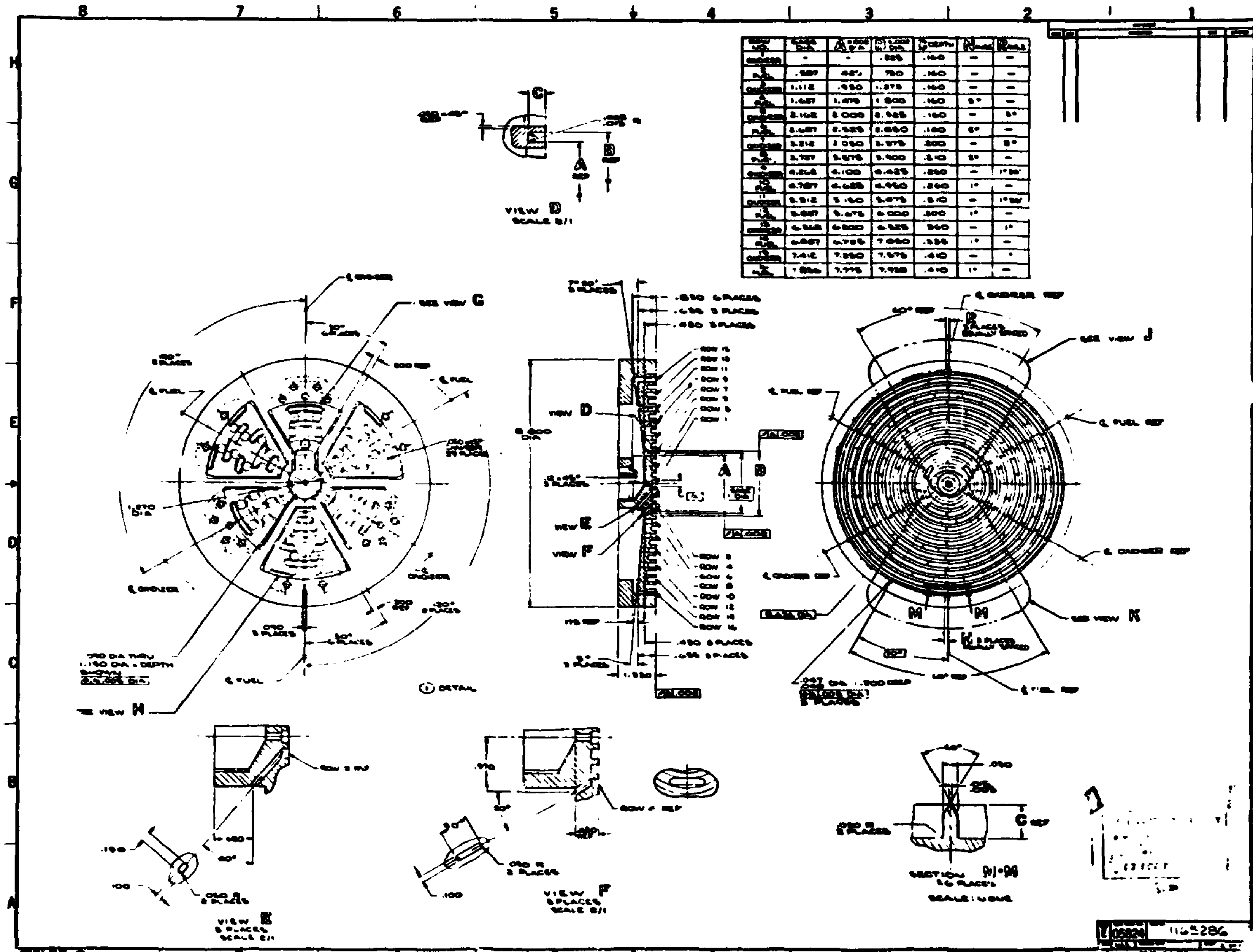


Figure 6. Demonstration Injector Design

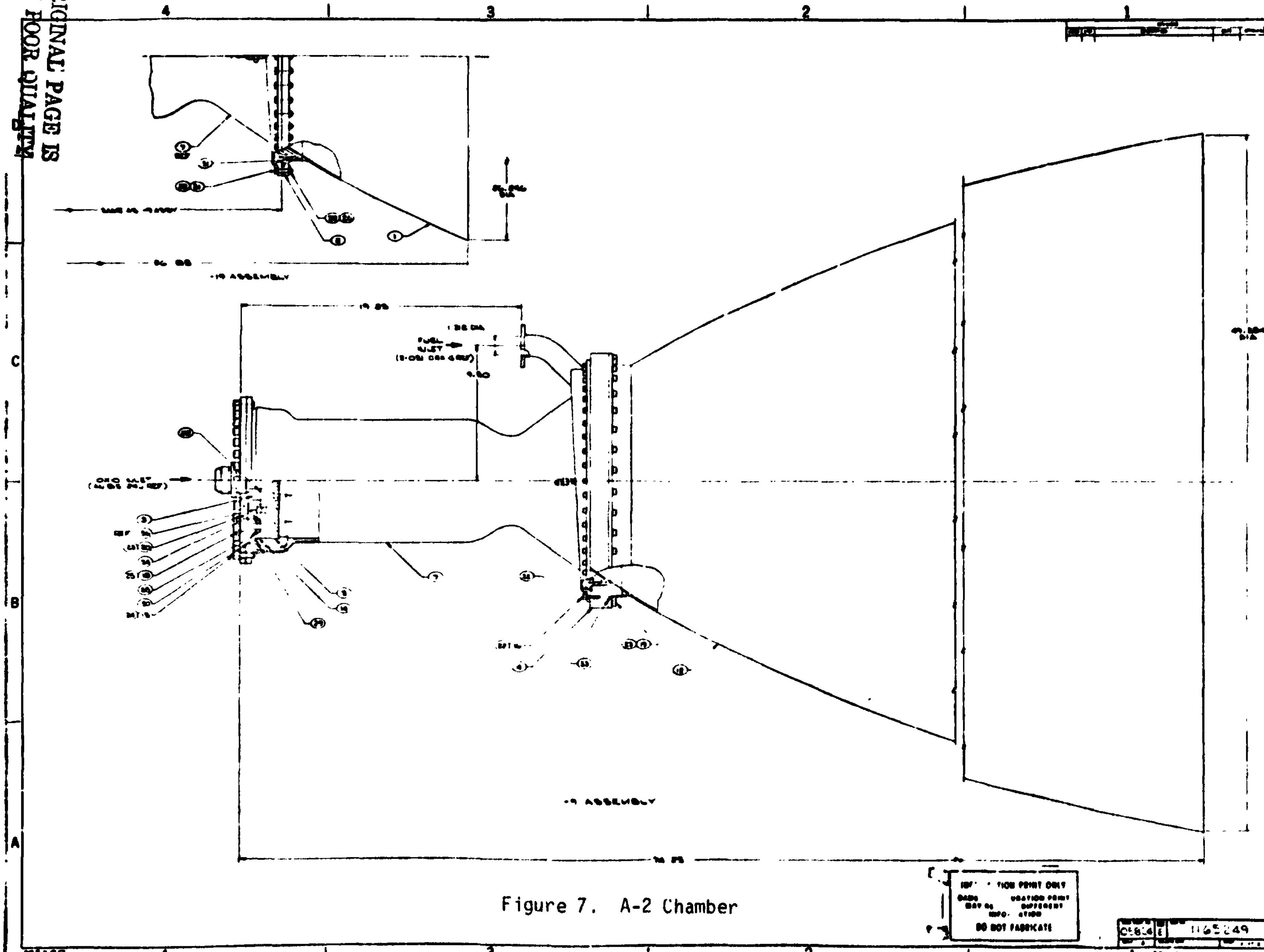


Figure 7. A-2 Chamber

Nominal: Pc = 125; O/F = 1.65
Matrix: Pc = 100,125,150
O/F=1.40,1.65,1.90

TABLE VII

SUMMARY OF TESTS AND INTENDED ENGINE OPERATING CONDITIONS

TEST SEQUENCE	O/F Pc	Propellant Temperature (F)	Purpose
I-1	Nominal	70	Engine/facility procedural checkout
2	Matrix	70	Performance survey of like doublet injector with film cooling
3	Matrix	70	Performance survey with helium saturated propellants
4	Matrix	70	Performance evaluation without film cooling
5	Matrix	70	Chamber length/performance evaluation; purge tests
II-1	Nominal	70	Ox circuit bubble ingestion tests
III-1	Matrix	70	Performance survey of DXDT1-2 injector
2	Matrix	70	Performance survey of DXDT1-1 injector,long coast evaluation
3	Matrix	70	Helium saturated propellants; simulated pod feed system
4	Matrix	70	High Pc/high O/F matrix deleted because of facility difficulties
5	Matrix	40	Cold propellant performance tests
6	Matrix	100	Hot propellant performance tests
7	Low P_c Matrix	40	Chug test series
IV-1	Nominal	70	Fuel circuit helium bubble ingestion tests
V-1	Nominal	70	Checkout of A-2 chamber
2	Matrix	70	DXDT1-1 injector and demo engine performance survey
VI-1	Nominal	70	DXDT2-1 injector and demo engine performance survey
2	Matrix	70	DXDT2-1 injector and demo engine performance survey
3	Nominal	70	Hot engine unpurged restarts, ambient propellant
4	Nominal	40	Hot engine unpurged restarts, cold propellant
5	Nominal	70	Cold engine unpurged restarts, ambient propellant
VII-1	Nominal	70	Cold engine, unpurged restarts, hot engine restarts with and without purging
VIII-1	Nominal	70	Facility vector capability evaluation
IX-1	Nominal	40	Boil-off tests, hot and cold engine restarts
2	Nominal	100	Hot propellant hot and cold engine restarts
X-1	Fuel only	40	Fuel purge evaluation cold flows

XI, 1974 WSTF Testing (cont.)

D. CONCLUSIONS

Table I in Section III summarizes the numerous conclusions drawn in the 1974 WSTF testing by means of comparing engine behavior with the actual OMS design specification.

In general, the demonstration injector and chamber were found to be acceptable in the areas of performance, heat transfer, and stability over the specified range of operating conditions. Start transient overshoot may exceed desired OMS limits, however. Shutdown impulse may likewise exceed OMS limits if not corrected for inlet temperature and pressure effects; such corrections are allowable but correctional correlations have not been developed.

BIBLIOGRAPHY

The following bibliography summarizes the contents of all the monthly progress reports (M-1 through M-32) and WSTF test reports (S-1, -2, -3), Test Plans and Oral Reviews.

<u>Monthly Reports</u>

13133-M-1, covering October 1972: plexiglas element models, concept selection evaluation, spray tests, unielement chamber design and injector details.

13133-M-2, covering November 1972: unielement fab and testing, flow calibration spray comparisons, mixing evaluation, hot firings.

13133-M-3, covering December 1972: unielement mixing results, energy release and specific impulse from hot firings, conclusions regarding unielement configurations and test program.

13133-M-4, covering [illegible]ry 1973: unielement data analysis, mixing patterns of cand[illegible] elements, hot firing results, subscale injector and chamber [illegible]s.

13133-M-5, covering [illegible]ry 1973: expanded unielement testing, hydraulic and hot fire test results.

13133-M-6, covering March 1973: hydraulic, mixing, and hot fire test results with subscale hardware (SP1 and XDT injectors) including bomb stability tests.

13133-M-7, covering April 1973: hot fire results from XDT, XDI and SP2 subscale configurations, including bomb tests.

13133-M-8, covering May 1973: subscale stability comparison of XD and SP injectors; thermal analyses, flat face and baffled full scale injector designs, bonding experiments.

13133-M-9, covering June 1973: subscale mixed element performance, full scale injector hydraulics.

13133-M-10, covering July 1973: initial full scale sea level altitude uncooled and regen cooled tests at ALRC including performance, heat transfer, stability.

13133-M-11, covering August 1973: additional altitude regen testing at ALRC; initial WSTF tests.

13133-M-12, covering September 1973: sea level stability tests at ALRC and altitude tests at WSTF to remedy stability problem, stabilization with manifold dams.

Bibliography cont.

13133-M-13, covering October 1973: subscale thermal cycle tests, ALRC testing of XDT2 injector performance and heat transfer.

13133-M-14, covering November 1973: full scale mixed element injector heat transfer and performance results at ALRC, injector hydraulics.

13133-M-15, covering December 1973: full scale mixed element testing A-50, XDT-1A testing, A-2 chamber design and fabrication details, stress and thermal/hydraulic analysis of A-2 chamber.

13133-M-16, covering January 1974: full scale XDT-1B and mixed element testing, baffled injector, test plan for proposed WSTF testing, heat transfer analysis of bubble ingestion and chugging.

13133-M-17, covering February 1974: full scale baffled injector tests, XDT-1B tests, resonator inlet evaluation, XDT-1B heat flux data, test matrices for proposed WSTF testing.

13133-M-18, covering March 1974: additional unielement concepts, full scale large thrust per element injector, high contraction ratio chamber, resonator inlet evaluation, undamped testing of XDT-1B and like-doublet injectors, XDT-1B rework.

13133-M-19, covering April 1974: full scale DXDT1-1 stability tests at ALRC, resonator differences in A-1 and A-2 chambers.

13133-M-20, covering May 1974: full scale DXDT1-2 stability testing at ALRC, heat flux data from DXDT1-1 and -2, XDT-1C testing, DXDT1-2 mixing tests.

13133-M-21, covering June 1974: additional unielement design details and spray test results: full scale XDT-1C injector testing at ALRC, high contraction ratio chamber test, low pressure drop injector, cavity inlet thermal analysis, cavity temperatures, like-doublet testing at WSTF, DXDT1-2 injector testing at WSTF.

13133-M-22, covering July 1974: full scale high contraction ratio chamber stability and thermal analyses, fuel circuit helium bubble tests at WSTF, postfire inspection of DXDT1-2 injector, XDT-1C tests at ALRC, pop analysis, postfire thermal effects and propellant evacuation.

13133-M-23, covering August 1974: full scale A-2 chamber checkout tests at WSTF, DXDT2-1 instabilities at high O/F and during hot restart.

13133-M-24, covering September 1974: full scale hot and cold engine restarts with DXDT2-1 at WSTF, repeat with DXDT1-1R injector, A-2 chamber failure.

Bibliography cont.

13133-M-25, covering October 1974: primary activity consisted of WSTF test data analysis and documentation.

13133-M-26, covering November 1974: primary activity consisted of analysis and documentation of WSTF tests, hardware and test summary of WSTF testing; stability tests of XDT-1C injector at ALRC.

13133-M-27, covering December 1974: primary activity consisted of analyzing WSTF data: stability tests at XDT-1D and XDT-1E at ALRC.

13133-M-28, covering January 1975: primary activity consisted of analyzing WSTF data and preparing WSTF Final Report; stability tests of XDT-1F at ALRC.

13133-M-29, covering February 1975: primary activity consisted of preparing WSTF Final Report.

13133-M-30, covering March 1975: primary activity consisted of preparing the program final report.

13133-M-31, covering April 1975: primary activity consisted of preparing the program final report.

13133-M-32, covering May 1975: primary activity consisted of preparing the program final report.

Special Reports

S-1 WSTF Test Report, covering 1973 WSTF testing: summary of tests, hardware, measurements, results and conclusions: analysis of performance, heat transfer, hydraulics, and dynamics; test plan, data summaries, computer program for calculating performance, analog data.

S-2 Test Summary Report Summarizing ALRC Testing at WSTF (1974): summary of hardware and test facility, description of test series, summary of individual tests, contents included in S-3 below.

S-3 1974 WSTF Test Report: technical analysis of 1974 WSTF testing in areas of performance, heat transfer, stability, start and shutdown transients, evacuation and soakout characteristics of purged and unpurged engine, nickel compatibility tests; results, conclusions, recommendations, compliance with OMS specification; includes S-2 above.

Program Plans

Program Plan - 10/20/72 - Defines program logic task description and schedule.

Task IA Test Plan - 10/30/72 - Unielement cold flow and hot test plans, hardware and test system description.

Task II Test Plan - 1/23/73 - Subscale cold flow and hot test plan, hardware and test system description.

Task VI Test Plan - 5/11/73 - Full scale altitude and sea level test plan, operating procedures, requirements, data analysis, hardware and test system description.

Task VII Test Plan - 8/17/73 - 1973 WSTF test program, operating procedures and requirements, data analysis, hardware and test system description.

Task VII Test Plan - 2/1/74 - 1974 WSTF test program, operating procedures and requirements, hardware and test system description.

Program Oral Reviews

10/30/72 - NASA/JSC - Program plan, logic, task description ard schedule

1/5/73 - NASA/JSC - Unielement test results, subscale design

1/16/73 - RI/Downey - Unielement test results

3/20/73 - NASA/JSC - Subscale test results, expanded unielement test results, full scale design review

4/17/73 - NASA/JSC - Subscale program review, full scale injector selection

4/26/73 - RI/Downey - Full scale design review, subscale test program results

6/31/73 - NASA/JSC - Overall program review, preliminary full scale test results

8/17/73 - RI/Downey - Full scale test program results, WSTF test program plan

9/25/73 - NASA/JSC - Stability results from full scale test program

Program Oral Reviews cont.

10/19/73 - RI/@ ALRC WSTF test results review, full scale design selection analysis

10/30/73 - NASA/JSC - WSTF test program results and full scale design selection

12/12/73 - NASA/JSC - Mixed element injector results, diffusion bonding, demo injector design

3/12/74 - NASA/JSC - Acoustic cavity operation, stability results, demo injector test plan

5/7/74 - NASA/JSC - General stability review

6/30/74 - NASA/JSC - Overall program review, stability results summary

11/12/74 - NASA/JSC - Stability review

11/13/74 - NASA/JSC - 1974 WSTF test program results summary