39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference
Huntsville, Alabama 20 – 23 July 2003

NON-TOXIC DUAL THRUST REACTION CONTROL ENGINE DEVELOPMENT FOR ON-ORBIT APS APPLICATIONS

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ABSTRACT

A non-toxic dual thrust proof-of-concept demonstration engine was successfully tested at the Aerojet Sacramento facility under a technology contract sponsored by the National Aeronautics and Space Administration's (NASA) Marshall Space Flight Center (MSFC). The goals of the NASA MSFC contract (NAS8-01109) were to develop and expand the technical maturity of a non-toxic, on-orbit auxiliary propulsion system (APS) thruster under the Next Generation Launch Technology (NGLT) program. The demonstration engine utilized the existing Kistler K-1 870 lbf LOX/Ethanol orbital maneuvering engine (OME) coupled with some special test equipment (STE) that enabled engine operation at 870 lbf in the primary mode and 25 lbf in the vernier mode. Ambient testing in primary mode varied mixture ratio (MR) from 1.28 to 1.71 and chamber pressure (P_C) from 110 to 181 psia, and evaluated electrical pulse widths (EPW) of 0.080, 0.100 and 0.250 seconds. Altitude testing in vernier mode explored igniter and thruster pulsing characteristics, long duration steady state operation (>420 sec) and the impact of varying the percent fuel film cooling on vernier performance and chamber thermal response at low P_C (~4 psia). Data produced from the testing provided calibration of the performance and thermal models used in the design of the next version of the dual thrust Reaction Control Engine (RCE).

INTRODUCTION

The National Aeronautics and Space Administration's (NASA) George C. Marshall Space Flight Center (MSFC) has contracted with Aerojet to develop and expand the technologies necessary to support non-toxic, on-orbit auxiliary propulsion system (APS) needs for the Next Generation Launch Vehicle Technology (NGLT) program. Contract NAS8-01109 has been issued to Aerojet to develop a dual thrust Reaction Control Engine (RCE) that utilizes oxygen and ethanol as the propellants. For the purposes of this contract, thrust levels of 870 lbf and 25 lbf have been selected for the primary and vernier mode, respectively.

The Aerojet contract is divided into three separately funded phases: Basic, Option 1 and Option 2. The completed Basic phase tested the existing Kistler K-1 Orbital Maneuvering Engine (OME) with contract designed STE hardware in vernier and primary modes, the results of which are discussed herein. Option 1, which is currently in work, uses the resulting test data from the Basic program to design, fabricate and test an integrated dual thrust RCE demonstration engine. Option 2, which is a future effort, utilizes the Option 1 test data to fine tune the dual thrust RCE design, leading to a Critical Design Review (CDR) and to the final fabrication of three deliverable prototype thruster assemblies for the NASA White Sands Test Facility (WSTF). These three thrusters are to be installed in an on-orbit APS simulator and to undergo system level hot-fire testing in GFY 2005.

The feasibility of the dual thrust RCE was demonstrated by testing performed at NASA WSTF in New Mexico.[1] A 600-lbf GOX/Ethanol Reaction Control System (RCS) workhorse thruster developed by Aerojet in the 1980's for NASA Johnson Spaceflight Center (JSC) was utilized for the WSTF testing. The workhorse RCS thruster incorporated a center-mounted spark-initiated torch igniter. Some modifications were made to the RCS thruster hardware to permit igniter operation in conjunction with reduced auxiliary GOX

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flow through the injector face, and with reduced ethanol boundary layer cooling (BLC). These hardware modifications permitted simulation of the function of the current Space Shuttle 25 lbf vernier reaction control subsystem (VRCS) engine for short test durations (~30 sec).

Hot-fire testing of the existing Kistler K-1 OME hardware has been performed during the Basic phase of the contract to continue in the path of the NASA JSC sponsored WSTF testing. The Kistler K-1 OME is an 870-lbf engine that utilizes LOX and ethanol as its propellants, and incorporates a GOX/Ethanol center-mounted spark-initiated torch igniter for igniting these propellants. Although the Kistler OME has undergone some previous testing in steady state mode, as well as limited testing in pulse mode,[2] additional testing of the Kistler OME hardware during the Basic phase of the contract has extended the test database. This additional testing has achieved significantly longer vernier steady state durations and some vernier pulse mode operation. The primary mode testing evaluated a variety of mixture ratio and chamber pressure conditions, as well as pulse mode conditions. The completed testing has provided the data necessary to support the subsequent design effort in Option 1 for the dual thrust LOX/Ethanol RCE.

TEST OBJECTIVES

There were multiple test objectives associated with the planned testing of the Kistler OME hardware at 25-lbf thrust (vernier) and 870-lbf thrust (primary) conditions. One main objective of the vernier testing was to evaluate the Kistler torch igniter with and without augmented propellant flow at the vernier operating conditions. The igniter produced 5 to 6 lbf of thrust by itself, so it was necessary to provide auxiliary fuel and oxidizer to achieve the 25-lbf thrust level for the vernier mode. Initial tests evaluated igniter only operation, while subsequent tests determined the effects of coupling augmented propellant flow with the igniter flow to achieve the desired 25-lbf thrust. Two additional objectives of the vernier testing were to determine the effect of varying the percentage fuel film cooling (FFC) and the effect of two different chamber L′ lengths (5.75 and 9.00 inches) on engine performance and thermal response. Finally, vernier pulse mode response and repeatability characteristics were to be evaluated for the pulse train definitions of Table I.

There were several objectives associated with the primary testing of the Kistler OME hardware. One of the objectives was to determine engine performance and thermal response for varying mixture ratio and chamber pressure conditions utilizing an injector developed by Kistler. In addition, engine performance and thermal response were to be determined for two different chamber L′ lengths (4.50 and 8.50 inches). Finally, primary pulse mode response and repeatability characteristics were to be evaluated for the pulse train definitions of Table I.

The hardware thermal response to be evaluated in vernier and primary modes consisted of the thrust chamber heat load and the injector head-end heating for the conditions tested. The chamber heat load characteristics were determined from thermocouple temperature data measured at the chamber backside wall and the injector head-end. The temperature data established heat transfer coefficients and recovery temperatures to correlate the Aerojet SCALE thermal prediction code. This correlation of the SCALE code will enable predictions to be made for different thrust levels and chamber configurations, as defined by system architectures evaluated for the NGLT program. These thermal predictions will provide temperature profiles for use in design related activities such as fatigue life analyses, as well as in assessing engine head-end heat rejection to the propellant valves under steady state, pulsing and heat soakback (after shutdown) conditions.

Table I. Pulse Train Definitions

Pulse	Characteristics	Vernier	Primary
A	On Time, EPW – sec	0.250	0.250
	Coast Time, ECW – sec	1.00	1.00
	Duty Cycle – %	20.0	20.0
	Pulse Quantity	10	10
B	On Time, EPW – sec	0.250	0.100
	Coast Time, ECW – sec	0.500	0.250
	Duty Cycle – %	33.3	28.6
	Pulse Quantity	30	30
C	On Time, EPW – sec	0.250	0.080
	Coast Time, ECW – sec	0.250	0.100
	Duty Cycle – %	50.0	44.4
	Pulse Quantity	50	50

TEST HARDWARE DESCRIPTION

The test hardware consisted of the Kistler K-1 OME hardware, and some additional hardware consisting of an injector simulator, a special test equipment (STE) FFC ring, a FFC ring adapter, and a 4-inch L′ spool section. The Kistler OME hardware of

Figure 1 was comprised of an igniter assembly, igniter valves, a spark exciter, an injector assembly, injector valves and a thrust chamber.

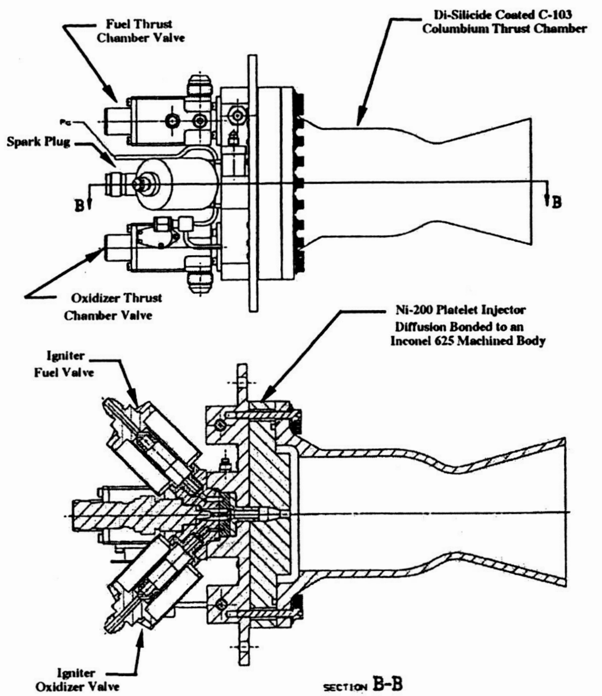


Figure 1. Kistler K-1 OME Hardware

The Kistler igniter was a GOX/Ethanol spark-initiated torch type, the design of which was well characterized by extensive testing on a variety of programs[3,4,5] for over 30 years, and specifically for GOX/Ethanol on NASA Contract NAS9-16639 in the 1980's.[6] The igniter valves were direct-acting solenoid-type.

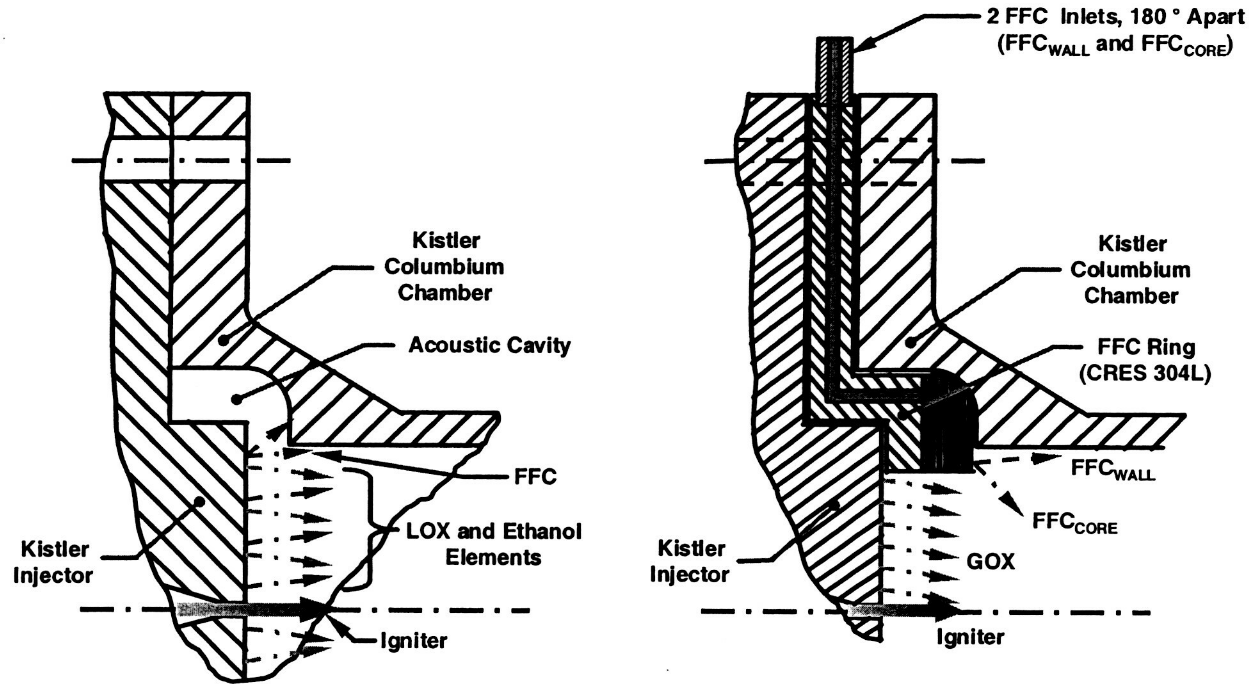
The Kistler injector assembly consisted of individually photo-chemically machined nickel platelets that were diffusion bonded to a machined Inconel injector body. The injector body provided for direct mounting of the flanged thrust chamber valves and the igniter assembly, as well as provided for instrumentation ports for high frequency (Kistler) and standard (Tabor) pressure transducers. The injector was developed during the Kistler K-1 program, as were the thrust chamber valves.

The Kistler thrust chamber was machined from a forged billet of C-103 columbium, and was di-silicide coated to provide oxidation protection. When attached to the Kistler injector, the resulting chamber L′ was 4.5 inches, which was the shortest L′ tested. The 15-degree half-angle conical nozzle was truncated at an expansion area ratio of 3:1 to accommodate ambient testing and to facilitate extrapolation of performance (I_{SP}) to higher area ratios.

To test the Kistler OME hardware in vernier mode required some adjustments, as well as some additional test hardware. The Kistler injector was originally designed for the 870-lbf thrust level only, with a nominal LOX flow rate of 1.8 lbm/sec, and was suitable for primary testing; however, the nominal augmented LOX flow rate to achieve 25 lbf thrust in the vernier mode was 0.046 lbm/sec. Therefore, the desired vernier LOX flow rate was only 2.6 percent of the original Kistler design LOX flow rate. This extreme difference between vernier and primary LOX flow rates would require virtually all of the oxidizer orifices to be blocked off to achieve the same margin of chug stability during operation in vernier mode. Blocking this many orifices defeated one of the intended purposes of having augmented LOX flow from the face of the injector, namely to provide injector face cooling during vernier operation. Therefore, Aerojet tested the Kistler injector using GOX to augment the igniter oxidizer flow in the vernier mode, thus permitting full flow through all of the oxidizer orifices.

The Kistler injector was similarly oversized on the fuel circuit for vernier mode testing, having orifices far too large to accommodate the reduced fuel flow rate required to augment the igniter fuel flow. In lieu of using the existing fuel orifices on the Kistler injector, the STE FFC ring was designed to provide the reduced auxiliary fuel flow rate required for augmenting the igniter fuel flow during vernier mode operation. This FFC ring contained two separate fuel circuits, with each circuit having 18 fuel elements on the face. Half of the elements were directed along the chamber wall to perform fuel film cooling and were denoted FFC_W for wall. The other 18 fuel elements were directed inward toward the GOX flowing through the injector face, to enhance mixing and thus performance. These inward directed elements were denoted FFC_C for core. The two FFC ring fuel circuits, FFC_W and FFC_C, were independently controlled to determine the sensitivity of the venire mode performance and thermal characteristics with respect to the flow splits on these two circuits.

The STE FFC ring was designed to fit between the Kistler injector flange and the C-103 chamber flange, occupying the volume of the original Kistler acoustic cavity, as shown in Figure 2. Due to some dimensional constraints in the FFC ring design, an



Original Kistler (870 lbf) Configuration

RCE Vernier (25 lbf) Test Configuration with Kistler Hardware

Figure 2. Special Test Equipment FFC Ring for Vernier Testing

adapter ring was designed to provide a transition between the FFC ring and the Kistler C-103 columbium chamber. Some reduced size radial acoustic cavities were machined in the backside of the FFC ring to provide some damping capability, if it was required.

The remaining additional test hardware consisted of the injector simulator and the 4-inch L′ spool section. The injector simulator had no propellant circuits, and was used for the initial igniter-only testing in vernier mode. The 4-inch L′ spool section enabled two different chamber L′ lengths to be tested in each operating mode: 5.75 and 9.00 inches in vernier mode and 4.50 and 8.50 inches in primary mode.

TEST SETUP

The testing required two different test bays. The primary testing could be performed at ambient conditions with the Kistler OME hardware; however, the vernier testing required an altitude facility because of the very low vernier chamber pressure (P_C ~4 psia). Therefore, the vernier testing was performed in the altitude facility of Test Cell A-2 at Aerojet, which was able to simulate approximately 175,000 feet at the beginning of a test, and to maintain a sustained equivalent altitude of 90,000 feet. The primary testing was performed at ambient conditions in the Aerojet Test Cell A-5.

Vernier Test Hardware Configurations

Three different test hardware configurations were used during the vernier testing. The first configuration consisted of the Kistler igniter assembly, the injector simulator, and the Kistler chamber, which was used to perform the initial igniter-only testing. The second configuration incorporated the Kistler igniter assembly, the Kistler injector assembly, the STE FFC ring and adapter, and the Kistler chamber. This configuration, shown in Figure 3 resulted in an effective chamber L′ length of 5.75 inches, the shortest L′ tested during the augmented flow tests in vernier mode. Finally, the long L′ hardware configuration of Figure 4 substituted the 4-inch L′ spool section for the FFC ring adapter, resulting in a chamber L′ length of 9.00 inches. A close-up view of the second test hardware configuration is shown in Figure 5, mounted within the test cabin of Test Cell A-2 at Aerojet. An overall view of the test cabin in the altitude test cell is shown Figure 6.

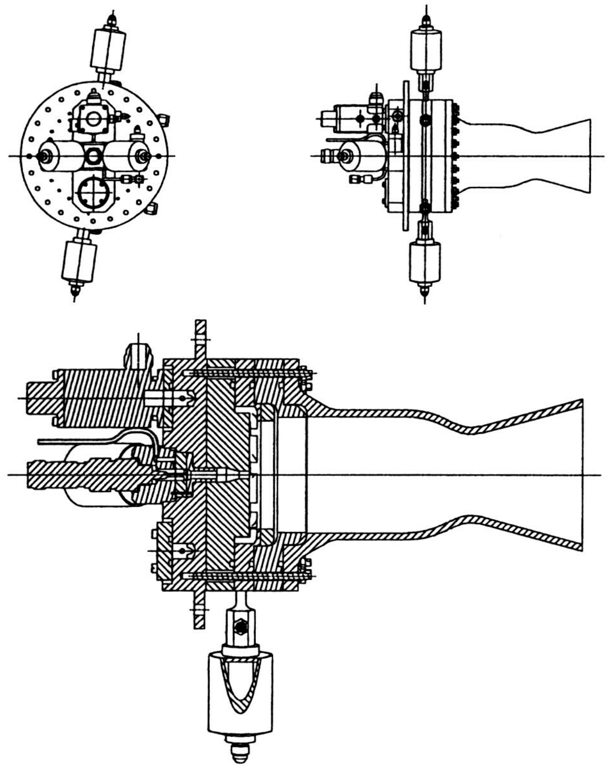


Figure 3. Vernier Test Configuration – 5.75-inch L´

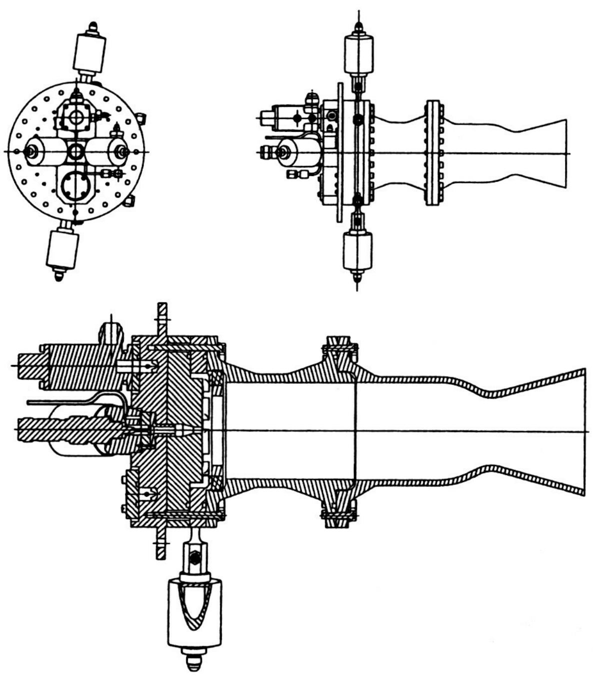


Figure 4. Vernier Test Configuration – 9.00-inch L´

Primary Test Hardware Configuration

Two test hardware configurations were used during the primary testing. The first configuration was the basic Kistler K-1 OME hardware, which consisted of the igniter assembly, the split triplet injector, the main thrust chamber valves, and the columbium chamber. This configuration, shown in Figure 7, had an effective chamber L´ length of 4.50 inches. The second configuration added the 4-inch L´ spool section between the injector and chamber, as shown in Figure 8, resulting in a chamber L´ length of 8.50 inches. Views of the first and second configurations installed on the test stand are shown in Figures 9 and 10, respectively. Primary testing was conducted at ambient conditions in Test Cell A-5 at Aerojet.

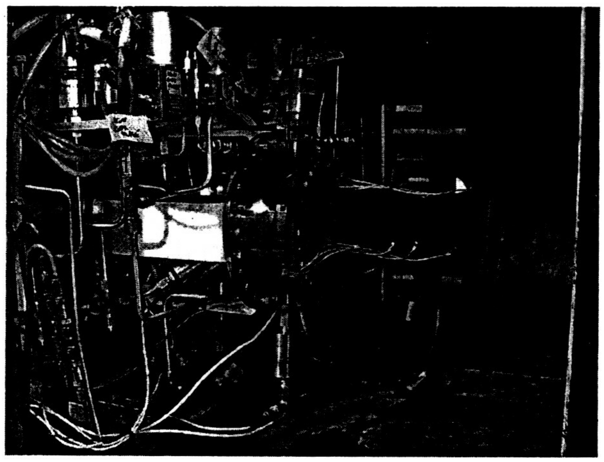


Figure 5. Vernier Hardware Mounted in Test Cell

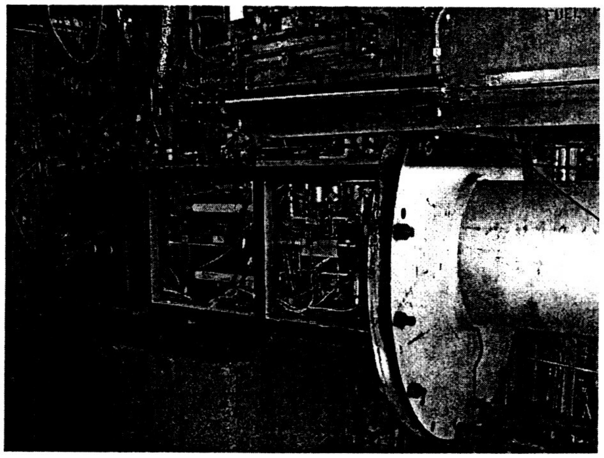


Figure 6. Vernier Altitude Test Cell with Cabin Doors Removed

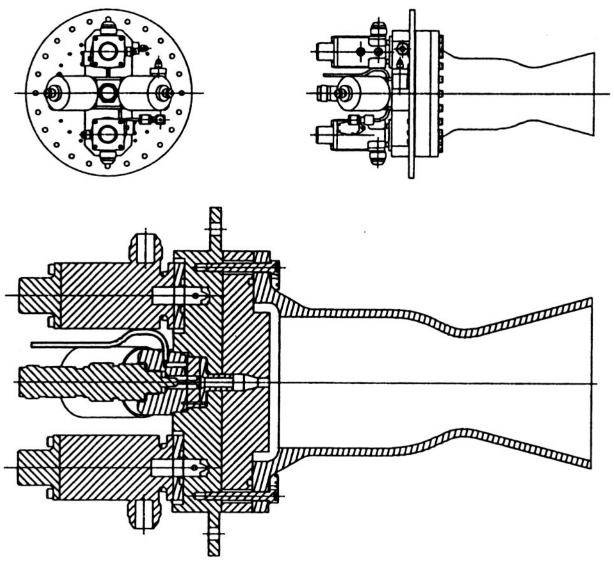


Figure 7. Primary Test Configuration – 4.50-inch L′

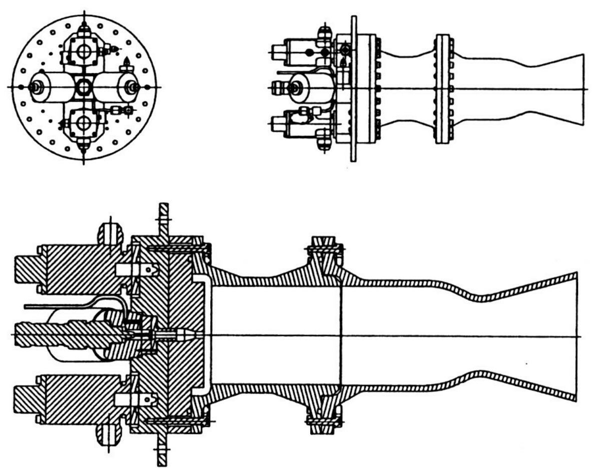


Figure 8. Primary Test Configuration – 8.50-inch L′

TEST RESULTS

Vernier Testing

A total of 51 vernier tests were conducted. These hot fire tests included steady state and pulsing tests in igniter only mode, as well as in the augmented flow mode, for the L′ length of 5.75 inches. Several steady state tests were completed for the L′ length of 9.00 inches for the purposes of comparing performance and thermal characteristics. A summary of the vernier tests is provided in Table II for the types of tests, test quantity, and test duration. A view of one of the vernier hot fire tests is captured in Figure 11.

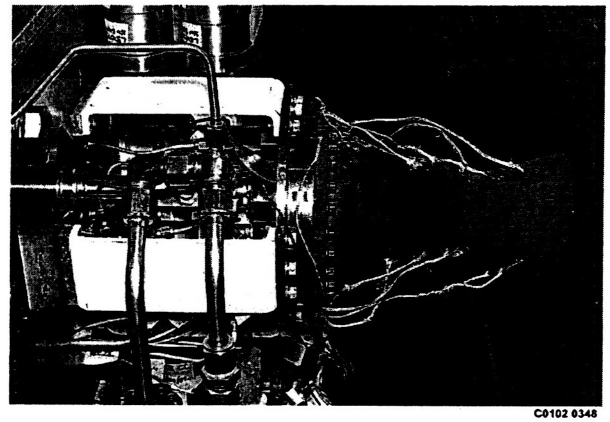


Figure 9. Primary Test Hardware with 4.50-inch L′

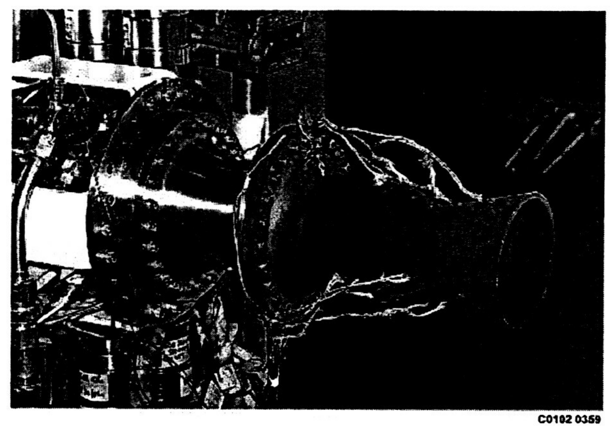


Figure 10. Primary Test Hardware with 8.50-inch L′

Table II. Summary of Vernier Testing

Test Description	No. of Tests	Duration, sec
Igniter Only Tests		
Steady State	9	126.25
Pulsing	3	32
Subtotal:	12	158.25
Augmented, 5.75-inch L′		
Steady State	10	340
Long Steady State	2	689
Pulsing	7	419.7
Subtotal:	19	1,448.7
Augmented, 9.00-inch L′		
Steady State	4	195.5
Subtotal:	4	195.5
Total for Vernier Testing:	**35**	**1,802.45**

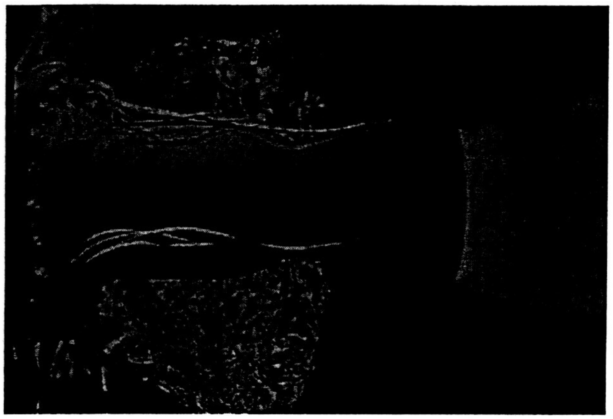


Figure 11. Vernier Hot Fire Test

The nominal vernier operating conditions at the nominal vernier thrust level were a mixture ratio (MR) of 1.5 and a chamber pressure (P_C) of about 4 psia. During the augmented flow tests of the vernier testing, the percent fuel film cooling (%FFC) was varied from 37.7 percent to 19.6 percent, with values between approximately 26 and 32 percent providing acceptable chamber thermal conditions at the smaller chamber L′ of 5.75 inches. The total augmented fuel flow rate was held constant, so if the %FFC were increased, there would be a corresponding decrease in fuel core flow, and vice-a-versa. A long steady state test of 422 seconds allowed the thrust chamber to achieve thermal steady state, as evidenced by the relatively flat temperature plots of Figure 12. This long duration test was a major achievement of the vernier testing.

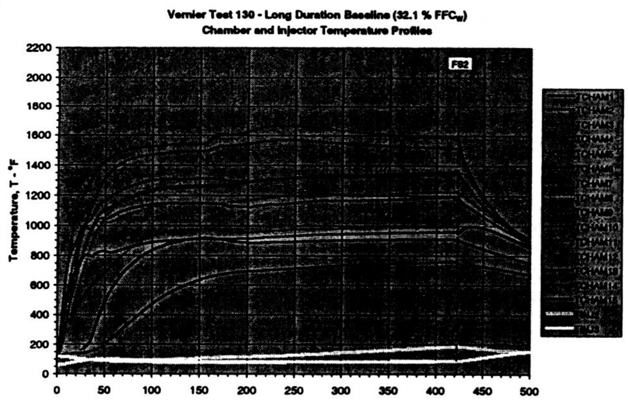


Figure 12. Chamber Temperatures for 422 sec Steady State Vernier Test.

Augmented pulsing tests consisted of 219 pulses at an electrical pulse width (EPW) of 0.250 seconds and 20 percent duty cycle, and of 85 pulses at an EPW of 0.250 and 33.3 percent duty cycle. Pulsing tests were discontinued after the main injector GOX valve failed to close properly on two pulses during the last pulse train attempted (Pulse Train B). Pulse trains were relatively short, i.e., 40 to 85 pulses, due to the difficulty in running the pulse tests with the STE FFC ring and its disproportionately large dribble volume.

<u>Primary Testing</u>

The nominal primary operating conditions at the nominal primary thrust level were a mixture ratio (MR) of 1.5 and a chamber pressure (P_C) of 150 psia. In the primary mode, a total of 31 hot-fire tests were attempted, with 21 yielding meaningful data. These hot-fire tests consisted of a series of steady state tests covering chamber pressures (P_C) from 110 to 181 psia and mixture ratios (MR) from 1.28 to 1.71 using the short chamber L′ of 4.50 inches. The FFC was fixed at 11.5 percent. A significant number of pulsing tests were also run with the short L′. A single steady state test was run for the long chamber L′ of 8.50 inches for the purposes of comparing performance and thermal characteristics. A summary of the primary tests is provided in Table III, listing the types of tests, test quantity, and test duration. A view of one of the primary hot fire tests is pictured in Figure 13.

A P_C / MR survey was performed with the short L′ to determine the impact on chamber wall temperatures and engine performance. Figure 14 shows a summary plot of the P_C and MR for each of the tests performed. The maximum chamber wall temperatures were between 1,900 and 1,950 °F, not varying significantly with test conditions. By contrast, the maximum chamber wall temperature was about 2,280 °F for the one steady state test performed at nominal conditions with the long chamber L′ of 8.50 inches.

Some long pulse trains were run in the primary mode with the short L′. The primary pulsing tests included the following: 325 pulses at an EPW of 0.250 seconds and 20 percent duty cycle, 200 pulses at an EPW of 0.100 seconds and a 28.6 percent duty cycle, and 806 pulses at an EPW of 0.080 seconds and a 44.4 percent duty cycle. The pulse trains were of sufficient quantity/duration to achieve thermal steady state in the combustion chamber for all three EPW's tested. No appreciable difference (~50 °F) in the maximum wall temperature was detected between steady state tests and long duration pulsing tests where thermal equilibrium was achieved. The shortest EPW of 0.080 seconds had the highest chamber temperature for any of the short L′ tests of approximately 2000 °F.

Table III. Summary of Primary Testing

Test Description	No. of Tests	Duration, sec
Tests with 4.50-inch L′		
Checkout	3	7
Steady State (P_C & MR)	9	270
Pulsing	8	666.2
Subtotal:	20	943.2
Tests with 8.50-inch L′		
Steady State	1	18.9
Subtotal:	1	18.9
Total for Primary Testing:	**21**	**962.1**

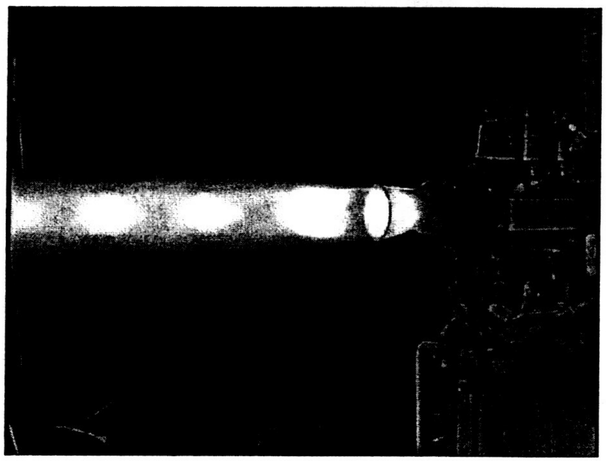


Figure 13. Primary Hot Fire Test

Vacuum corrected specific impulse ($I_{SP,\ VAC}$) for the Kistler 3:1 conical nozzle was measured between 239.6 and 245.7 lbf-sec/lbm for the short chamber L′. For the long chamber L′, the $I_{SP,\ VAC}$ was determined to be 249.6 lbf-sec/lbm, slightly higher due to the increased chamber length. A summary plot of these performance values is given in Figure 15. Extrapolated primary performance for a chamber L′ of 4.50 inches, an 11.5 percent FFC, and a 75 percent Bell nozzle with a 22:1 expansion area ratio was estimated to be 282 lbf-sec/lbm.

POST TEST ANALYSIS

Upon completion of the vernier and primary test series using the Kistler K-1 OME hardware, a post test analysis of the chamber thermocouple temperature data was performed to establish the gas-side conditions along the chamber wall. Specifically, the heat transfer coefficients and recovery temperatures were inferred as a function of chamber axial position from the vernier and the primary test temperature data. These heat transfer coefficients and recovery temperatures are shown in Figures 16 and 17 for the vernier tests, and in Figures 18 and 19 for the primary tests. There was significant data scatter for the vernier tests, but the curves for the heat transfer coefficient and recovery temperature were showing the correct trend. In contrast, the data for the primary tests was better behaved, and the curves for the heat transfer coefficient and recovery temperature have matched the data very well.

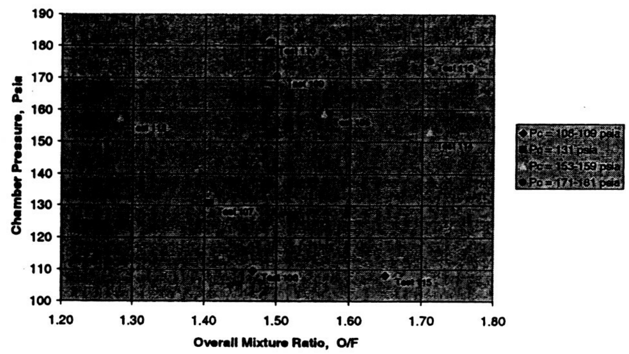


Figure 14. Summary Plot of Primary Mode P_C and MR Test Conditions

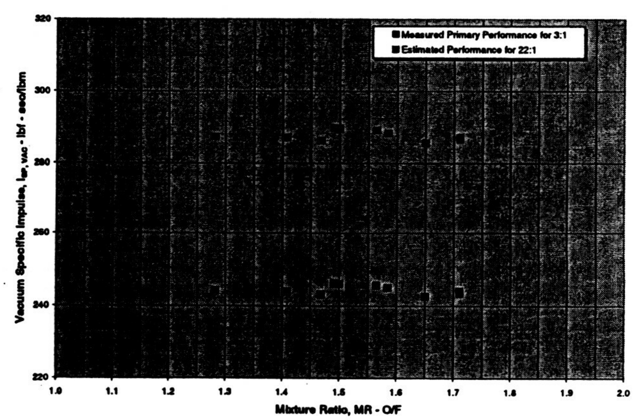


Figure 15. Vacuum Corrected I_{SP} for Primary Mode Tests

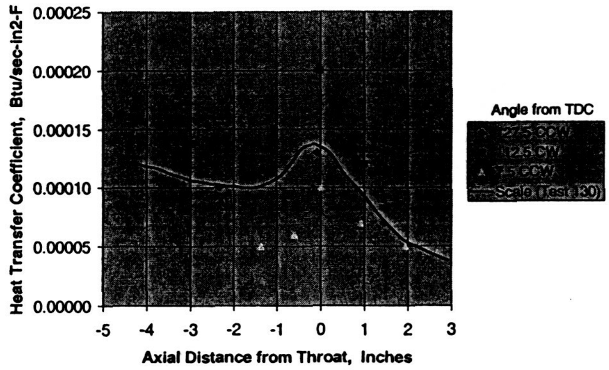
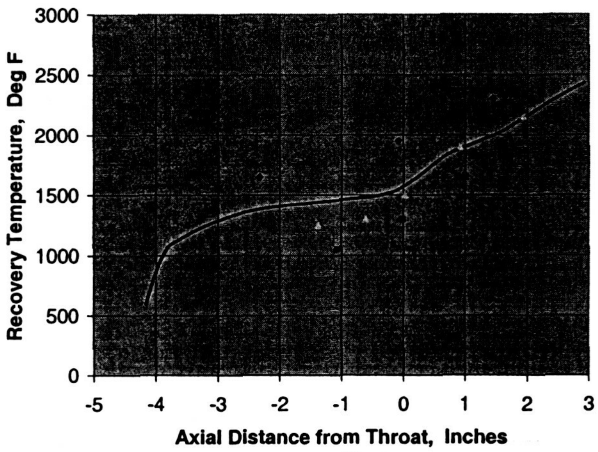


Figure 16. Inferred Heat Transfer Coefficient for



Vernier Tests

Figure 17. Inferred Recovery Temperature for Vernier Tests

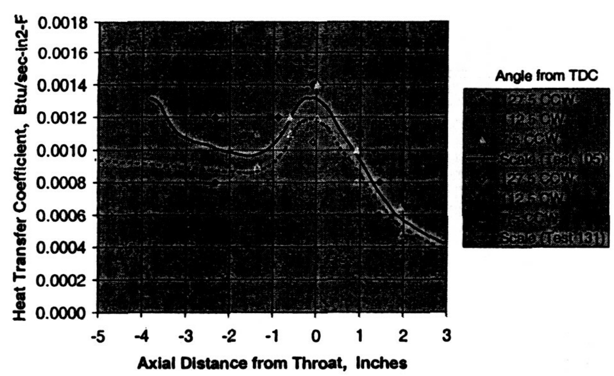


Figure 18. Inferred Heat Transfer Coefficient for Primary Tests

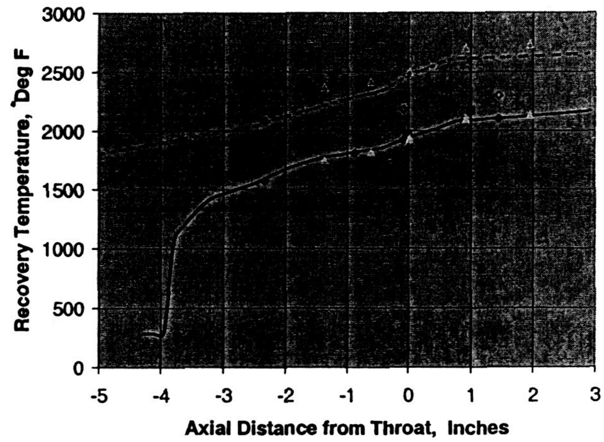


Figure 19. Inferred Recovery Temperature for Primary Tests

The inferred gas-side environments were used to correlate the Aerojet SCALE thermal prediction code. This correlation of the SCALE code compared very favorably with the primary mode temperature data for the various MR and P_C combinations tested. A comparison for the MR sensitivity in primary mode is given in Figure 20, where the solid color lines represent the SCALE predictions and the color markers are the actual test data. Similarly, a comparison for the P_C sensitivity in primary mode is shown in Figure 21, again where the solid color lines represent the SCALE predictions and the color markers are the actual test data. Both sets of SCALE predictions tracked very closely to the measured temperature data. The benefit of such a correlation will be the ability to perform thermal predictions for other thrust levels and chamber configurations, depending on system architecture requirements. This correlated SCALE code was used in the thermal design of the iteration of the dual thrust RCE, which is scheduled for primary and vernier testing in late summer 2003.

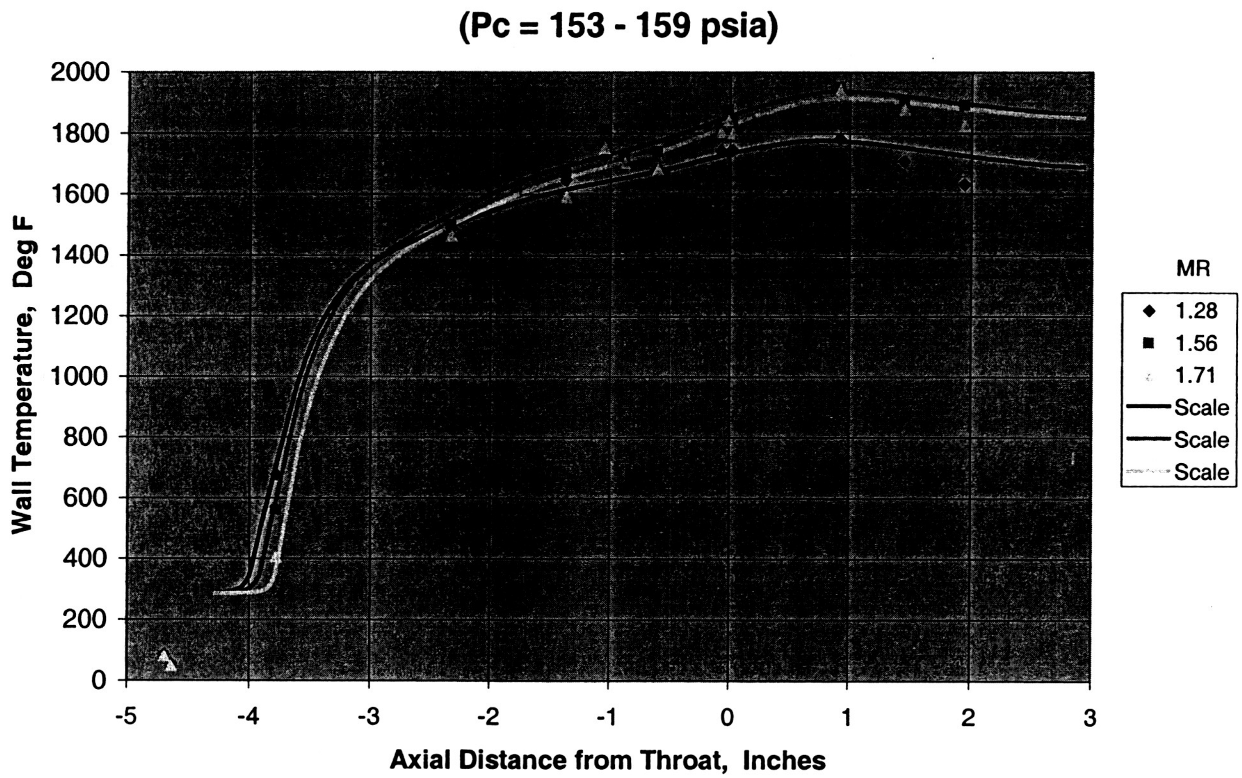


Figure 20. SCALE Code Predicts MR Sensitivity in Primary Mode

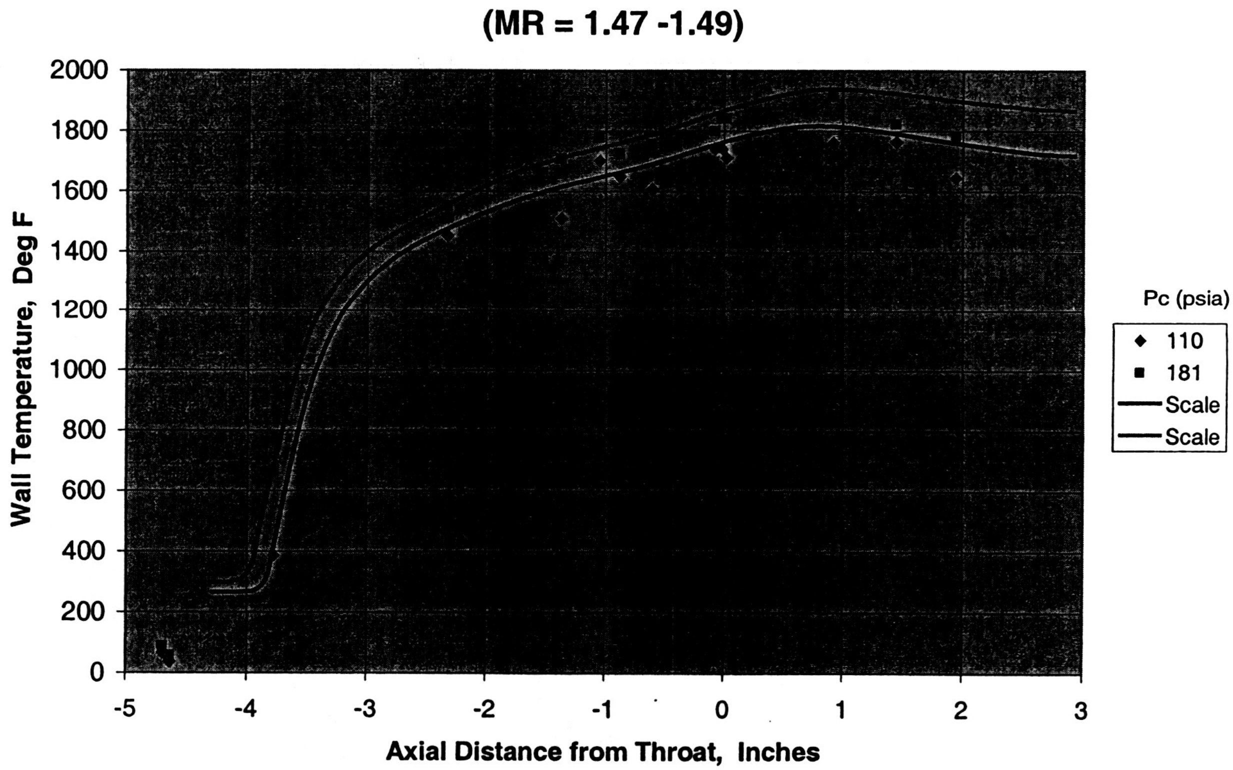


Figure 21. SCALE Code Predicts P_C Sensitivity in Primary Mode

CONCLUSIONS

Vernier Testing

The following conclusions were drawn from the results of the vernier testing:

- The vernier testing was successful in achieving long duration steady state firings with the modified Kistler OME hardware;
- The vernier FFC can be reduced from values around 32 percent to perhaps 22 – 24 percent by improving the FFC injection velocities at the vernier design point, and by not having the STE hardware between the injector and the thrust chamber;
- No chamber head-end heating was observed during limited pulse testing;
- The low vernier chamber pressure influenced the definition of the pulse profiles during pulse testing.
- Calibrated chamber thermal model correlates fairly well with the observed temperature data, enabling reliable predictions to be made for a design update to a fully dual thrust RCE.

Primary Testing

The following conclusions were drawn from the results of the primary testing:

- Variations in P_C and MR had little effect on the chamber wall temperature profiles, as well as on the maximum wall temperature achieved;
- Maximum chamber wall temperatures varied by +50 °F to –200 °F from the nominal steady state baseline test for the short L′ configuration, over the entire range of P_C and MR tested, as well as for all three pulse trains (A, B, and C);
- Estimated performance extrapolated for a 22:1 nozzle was approximately 282 lbf-sec/lbm;
- There was no evidence of any chamber head-end heating during any of the pulse testing, as the ethanol appears to be a very benign fuel film coolant, i.e., no decomposition issues;
- The chamber L′ of 4.50 inches provided good performance and acceptable wall temperatures with an FFC of 11.5 percent;
- Calibrated chamber thermal model correlates very well with the observed temperature data, enabling reliable predictions to be made for a design update to a fully dual thrust RCE.

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