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DESIGN AND TESTING OF AMROC'S 250,000 POUND THRUST HYBRID MOTOR

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Abstract

The American Rocket Company is developing a 250,000 pound thrust liquid oxygen/polybutadiene hybrid rocket motor for use on future space launch vehicles. Designated the H-1800 hybrid motor, this commercial development effort is unique in that it is being funded solely by private investment. The first test of the motor, Development Motor number one (DM-01) was conducted in January 1993. This paper describes the development project that led to the test firing and the basic performance parameters of the motor. Test stand and data acquisition and control system features will be discussed. The test results will be presented and compared with performance predictions. Schedules for future testing and implementation of this hybrid booster will be described.

Nomenclature

$\dot{r}$	fuel regression rate (in/sec)
G_t	total mass flux ($lb_m/sec/in^2$)
L	port length (in)
A	empirical constant in equation (1)
n, m	empirical constants in equation (1)
SPL	sound pressure level (dB)
X	distance (ft) from nozzle in equation (4)
SIsp	side specific impulse (sec)
θ	thrust vector angle (deg)

Introduction

The American Rocket Company (AMROC) is dedicated to the development of hybrid rocket motors for space boosters. Hybrid propulsion, which consists of a solid fuel and liquid oxidizer, is the only non-explosive space launch propulsion technology available today. Hybrid propulsion systems represent a shift in technology from today's solid and liquid rocket propulsion systems, and offer significant advantages over both of these conventional technologies in terms of safety, cost and operational flexibility. Although AMROC has fired numerous motors at thrust levels from 60 lb_f to 250,000 lb_f, hybrid propulsion is less developed than either solids or liquids and, thus it is AMROC's immediate goal to bring this technology to commercial flight status.

The American Rocket Company plans to offer commercial launch services throughout the 1990s on its Aquila (pronounced Ak-wil-la, Latin for "Eagle") orbital launch vehicle for delivering payloads to low Earth orbit (LEO). Aquila is a four-stage orbital launch vehicle capable of delivering 2,000 lb_m to LEO and will be available for launch services from Vandenberg AFB beginning in the Fall of 1996.[1]

The Aquila launch vehicle will be propelled by the AMROC 250,000 lb_f thrust H-1800 hybrid rocket propulsion system. The H-1800 is a pressure-fed liquid oxygen/ polybutadiene hybrid rocket. The development of the H-1800 hybrid propulsion system and demonstrating it as a suborbital vehicle (the "HyFlyer") are key milestones in the Aquila development project. The first H-1800 flight will represent the introduction to the space launch industry of a new, safe, reliable and low-cost propulsion alternative to today's conventional liquid or solid rocket propulsion.

H-1800 Development

The H-1800 motor design, development, test, and evaluation (DDT&E) is based on the H-500 (75,000 lb_f thrust) motor design, with technology improvements added to the H-1800 baseline as they become available.[2] Improvements in motor internal structures, insulation materials, and fuel properties have been evaluated in burn rate motors (BR) and subscale motors (SP).

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In order to validate a new combustion port size before committing resources to the full scale motor design, it is possible to test only two ports of a multi-port hybrid motor. The full scale ports provide verification of internal motor ballistics and port scaling laws, as well as allow for design refinements prior to tooling for the full scale motor. The two port motor (FP-01), which consisted of two of the fifteen H-1800 full scale ports, was test fired in the Fall of 1991. In addition to verifying port scaling laws, technology improvements in injectors and nozzles were tested. Performance characteristics of a prototype liquid oxygen thrust vector control (LITVC) system were also obtained.

The full scale H-1800 motor development includes six static motor tests: five development motors and one qualification motor. The first development motor (DM-01) has an internal port shape which has been refined based on test results from the first full port motor. DM-01 is shown in Figure 1.

Subsequent motors will test further refined fuel grains (optimized for fuel utilization), injectors, nozzles, and liquid injection thrust vector control systems. The first two development motors will be tested using a LOx tank pressurized with nitrogen because the heated helium pressurization system will not be available. DM-03 will be the first test of a motor with the heated helium pressurization system. The first three motors will be tested numerous times in order to obtain test data at intermediate points in the motor burn. DM-04 and DM-05 will be full duration motor firings. The qualification motor (QM-01) will verify the performance of the entire H-1800 propulsion system. Figure 2 shows the H-1800 motor DDT&E program through the first HyFlyer launch.

In addition to providing motor design confirmation, the DM-02 and DM-04 motors will also be used to evaluate the structural integrity of the motor case. The motor cases will be hydrotested, after the

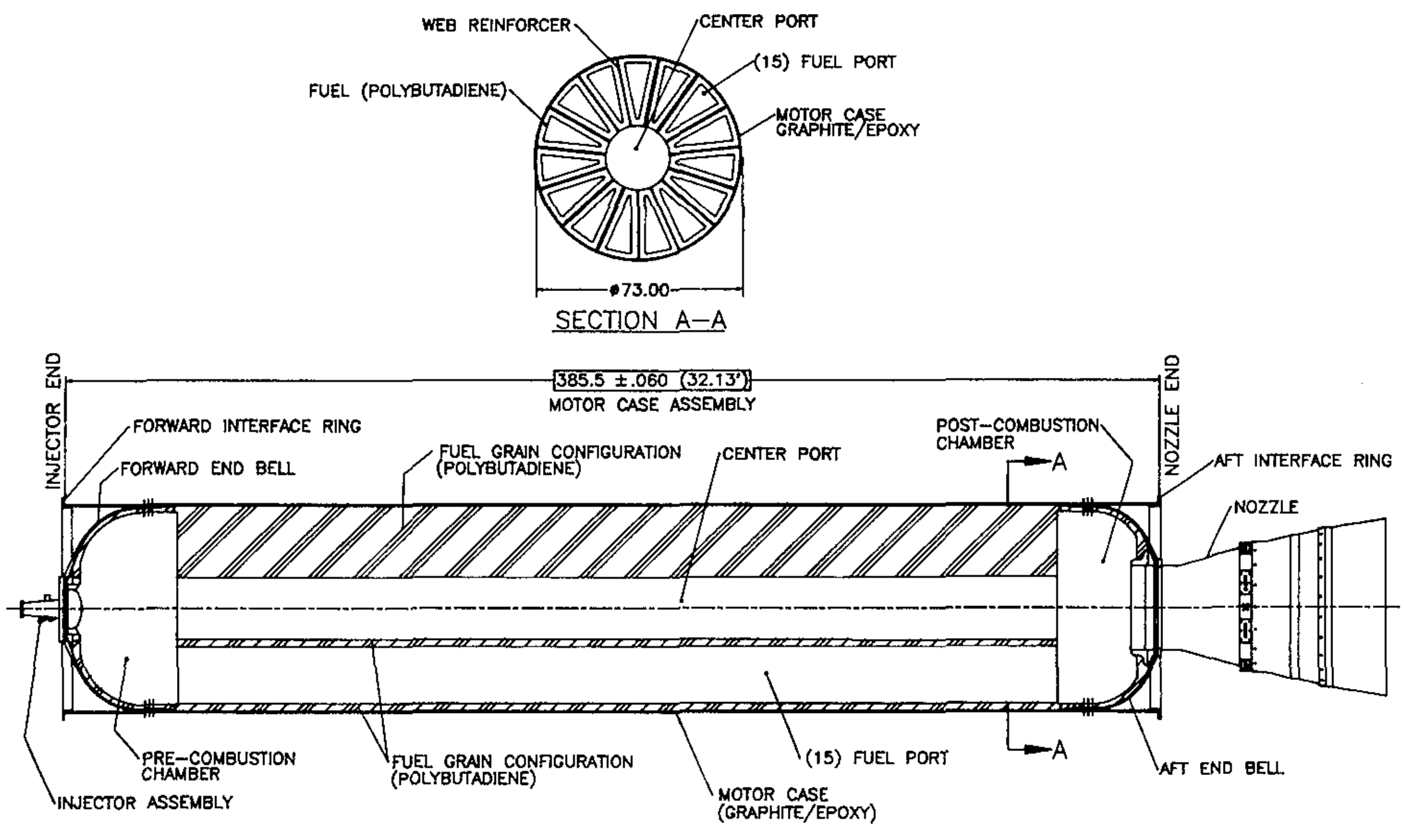

Figure 1. DM-01 Hybrid Motor Schematic

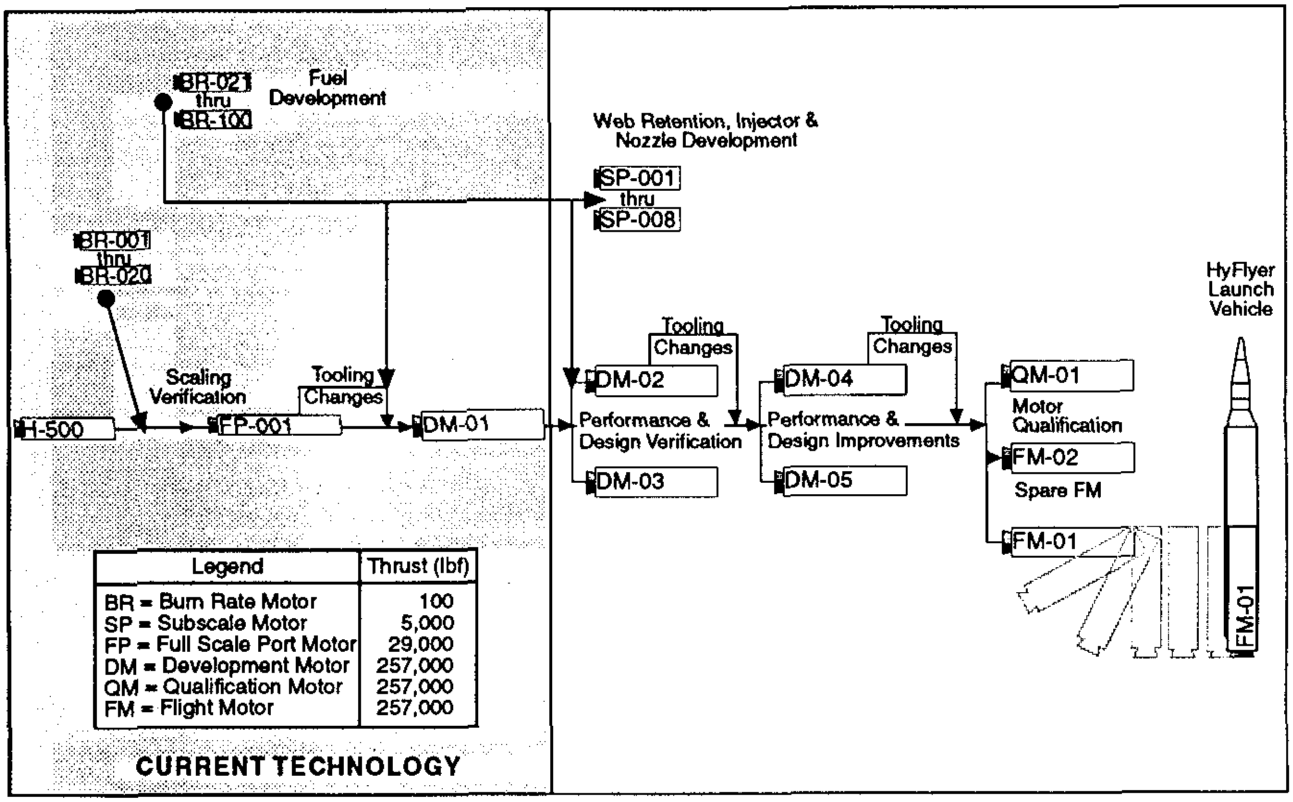

Figure 2. H-1800 Hybrid Motor Development Plan.

motor firings are completed, to determine their actual burst pressure. This will help to validate the structural analysis of the motor case.

The H-1800 hybrid propulsion system development will culminate with the successful flight of the HyFlyer suborbital launch vehicle. This first HyFlyer flight in 1995 will be a significant step towards the first flight of the Aquila launch vehicle in the Fall of 1996.

H-1800 Performance

The performance requirements for the H-1800 hybrid propulsion system are based on the design requirements of the Aquila launch vehicle. The Aquila uses two H-1800 hybrid boosters for the 1st stage; one H-1800 booster for the 2nd stage; an ORBUS 21™ solid rocket motor for the 3rd stage and one U-75 nitrous oxide/polybutadiene hybrid motor for the 4th stage. The H-1800 boosters can be throttled for thrust balancing, trajectory shaping, and structural load reduction.

Key design parameters of the H-1800 motor are shown in Table 1.

Table 1. H-1800 Design Parameters.

Avg Vac Thrust (lb_f)	257,000
Avg Vac Specific Impulse (sec)	280
Total Vac Impulse (lb_f sec)	18.5×10^6
Avg. Chamber Pressure (psia)	400
Burn Time (sec)	72

DM-01 Development

The first full scale H-1800 development motor (DM-01) was designed and produced from February to November of 1992. This effort required the development of numerous components including: a 74 inch diameter, 386 inch long graphite/epoxy motor case; an 9:1 area ratio silica/phenolic nozzle; a 400,000 lb_f thrust horizontal test stand; composite port molds, motor casting fixtures, fuel mixers, and motor manufacturing procedures. The total project duration, from initial design to the completion of testing, was thirteen months.

DM-01 Production

Most of the tooling design and fabrication was done at AMROC's Research and Development facility in Camarillo, CA, which has since been moved to Ventura, CA. Some of the motor tooling, including port molds and large metal end plates, as well as the motor case and nozzle were supplied by AMROC's team of subcontractors. AMROC's previous H-500 motors have been produced in Camarillo, however, because of the size of the H-1800 motor case and tooling, the Camarillo facility was too small for the DM-01 motor production. AMROC entered into a Joint Operating Agreement with the U.S. Air Force for Building 1900 at Vandenberg AFB (formerly known as the Peacekeeper Rail Garrison Integration and Refurbishment Facility) for DM-01 Motor casting and assembly operations. This agreement was part of an overall Commercialization Agreement that AMROC has with the Air Force for use of facilities at Vandenberg, including the use of the ABRES A-3 launch site. The Air Force's willingness to allow AMROC to use Building 1900 is a strong endorsement of the fundamental safety and environmental cleanliness inherent in the production of hybrid rocket motors.

Test Facilities

The DM-01 motor was tested at AMROC's *test facility located at Phillips Lab (PL) Area I-56* Edwards Air Force Base (EAFB). Area I-56 consists of a 400,000 lb_f six component thrust stand, an IBM PC/Macintosh based data acquisition and control system, a 3,000 gallon liquid oxygen (LOx) storage dewar, a 1,600 gallon LOx run tank, 1,080 ft^3 supply of 6,000 psig gaseous nitrogen, an 1,890 ft^2 shop and office area, an 1,280 ft^2 electronics bunker, a 2,470 ft^2 control bunker, and a storage area for hazardous materials.

Test Stand

The test stand is a horizontal six component (three principal and three moment) rocket motor static test stand. The stand is capable of reacting 400,000 lb_f axial thrust and 40,000 lb_f side force. The accuracy of the test stand is based upon alignment and flexure restraint. The final accuracy of the measurement is estimated at 0.5% or better based upon load cell calibration accuracy, the data recording system, and the magnitude of restraint corrections.

The load cell strings consist of two flexures, a load cell, and an extension arm. All load cell strings are adjustable for alignment and/or offset prior to motor installation. The load cells and flexures were manufactured by Ormond, Inc. of Santa Fe Springs, California.

The test stand has a motor center line 56 inches above the grade and can accommodate motors up to 80 inches in diameter and 34 feet in length.

Data Acquisition and Control System

AMROC's data acquisition and control system (DACS) is based upon an IBM compatible PC and an Apple Macintosh PC.

The human interface to the DACS is through the Macintosh which has the test schematic depicted in a process flow diagram displayed on the monitor. The valve icons displayed become active buttons that allow easy operation of valves and the valves current state. Selected analog data channels are displayed on the flow diagram. Figure 3 presents the flow diagram for the DM-01 test.

The IBM PC performs the tasks of analog to digital (A/D) conversion, discrete input and output, data recording, and test timing and sequencing as requested by the user through the Macintosh.

Fifty six channels of data were recorded during each DM-01 burn. The recorded data includes: 6 accelerometers, 6 forces, 3 flow rates, 15 strains, 1 valve position, 2 LVDT's, 6 temperatures, and 17 pressures.

Test Results

The DM-01 motor was tested in a series of four static firings. The first burn was successfully conducted on 22 January 1993. The second burn was successfully conducted on 17 February 1993. The third burn was successfully conducted on 11 March 1993. On 24 March 1993, the fourth burn prematurely ended when the motor case failed

Table 2 presents the average measured motor performance values for burns one through four.

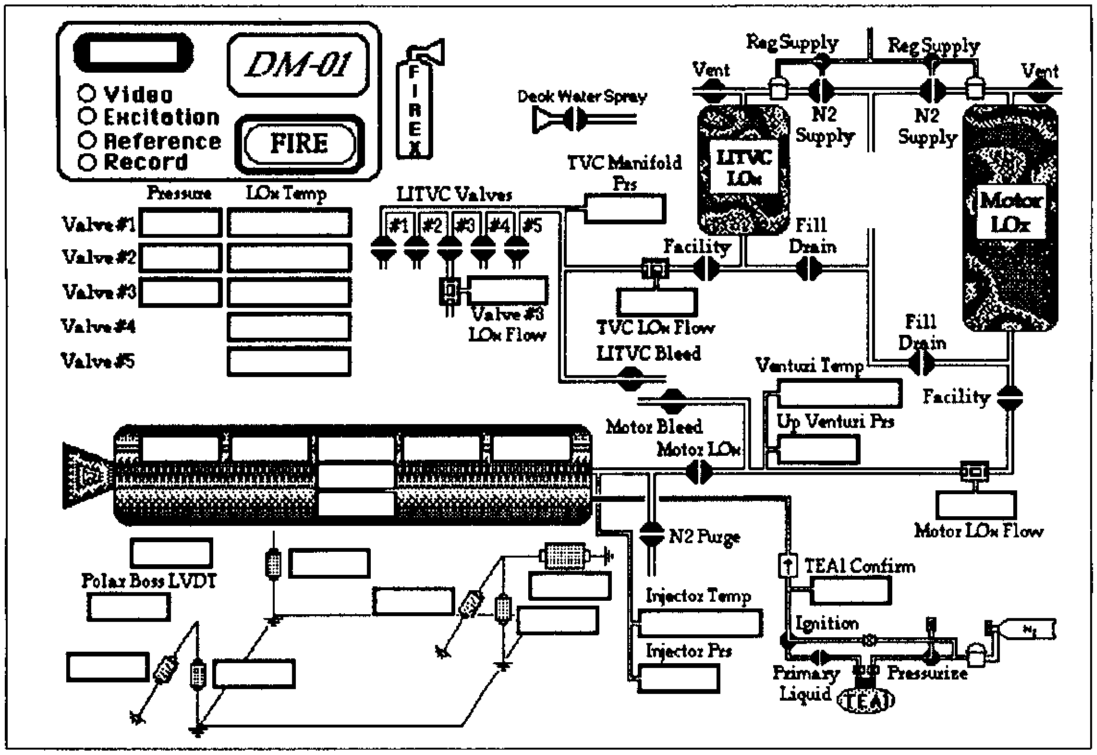

Figure 3. DM-01 Process Flow Diagram.

Table 2. Average Measured Performance Parameters.

Parameter	Burn 1	Burn 2	Burn 3	Burn 4
Thrust (lb_f)	216,900	231,900	215,400	214,800
Fuel mdot (lb_m/sec)	357	351	339	310
LOx mdot (lb_m/sec)	569	600	619	587
Isp (sec)	234	244	225	239
O/F Ratio	1.59	1.71	1.82	1.89
Chamber Prs (psia)	412	419	378	369
Nozzle Area Ratio	8.33	8.00	7.61	3.70
Throat Area (in^2)	364	381	402	418

The derived vacuum thrust and specific impulse for burns one through four are presented in Table 2.

Table 3. Average Derived Performance Parameters.

Parameter	Burn 1	Burn 2	Burn 3	Burn 4
Vac Thrust (lb_f)	257,000	272,300	255,800	235,200
Vac Isp (sec)	278	286	267	262

Description of DM-01 Motor Tests

The first burn of DM-01 achieved the planned test duration of fifteen seconds. The motor ignition was smooth with no chamber pressure overshoot. Three chamber pressure spikes were observed at various points through out the test; the motor exhibited sufficient dynamic stability to dampen the oscillations and provide stable motor operation. The suspected cause of the chamber pressure pulses was the ejection of fuel pieces from patching fuel grain voids caused during the fuel casting process. The LOx system exhibited good dynamic stability and did not increase the severity of the motor chamber oscillations.

The second burn achieved the planned test duration of ten seconds. The motor ignition was smooth with no chamber pressure overshoot. The motor and LOx feed system exhibited smooth stable operation throughout the entire motor burn.

The third burn of DM-01 achieved a test duration of fourteen seconds. The first ignition attempt for this burn was aborted by the data acquisition and control (DAC) computer. The DAC computer requires a pressure rise in the TEA1 ignition line prior to opening the main LOx valve. The TEA1 ignition valve opened as planned at T - 0.5 second, but a faulty transducer downstream of the ignition valve did not sense the pressure increase and the DAC computer aborted the test. The faulty transducer was replaced and a second successful test attempt was made one hour later. The motor ignition was smooth with no chamber pressure overshoot. The motor and LOx feed system exhibited smooth stable operation throughout the entire motor burn.

Prior to the fourth test, the nozzle exit cone extensions were cut off. The resulting nozzle area ratio was 3.7. At the end of burn three, the hand lay up glass phenolic exit cone delaminated and buckled due to high erosion rates.

The fourth burn of DM-01 achieved a test duration of 6.37 seconds. The test was terminated prematurely by the structural failure of the motor case. The motor ignition was smooth with no chamber pressure overshoot. The motor exhibited smooth stable operation. A chamber pressure pulse was observed at 4.7 seconds into the burn; as in the first test, the motor and LOx feed system exhibited sufficient dynamic stability to dampen the oscillations and provide stable motor operation.

The cause of the forth burn motor case failure was traced to combustion gasses leaking through the motor case insulation and exiting through the case cylinder to dome interface. This weakened the graphite epoxy material at the interface and caused the forward dome to fail.

Fuel Regression Rate

The hybrid rocket motor fuel regression rate may be expressed by

$$\dot{r} = AG_t^n L^m \qquad (1)$$

The average fuel regression rate was obtained for motor burns one through three. The time- and space- averaged fuel regression rate was determined from physical measurements of the port geometry obtained after each burn. A two dimensional representation of equation (1) was determined as

$$\dot{r}' = \frac{\dot{r}}{L^m} = 0.3G_t^{0.76} \qquad (2)$$

Equation (2) and AMROC's measured fuel regression points are presented in Figure 4. Equation (1) accurately predicts the performance of over forty motors varying in thrust from 100 lb_f to 250,000 lb_f (port hydraulic diameters of 1.5 inches to 14 inches) with an average error of less than 4.8%.

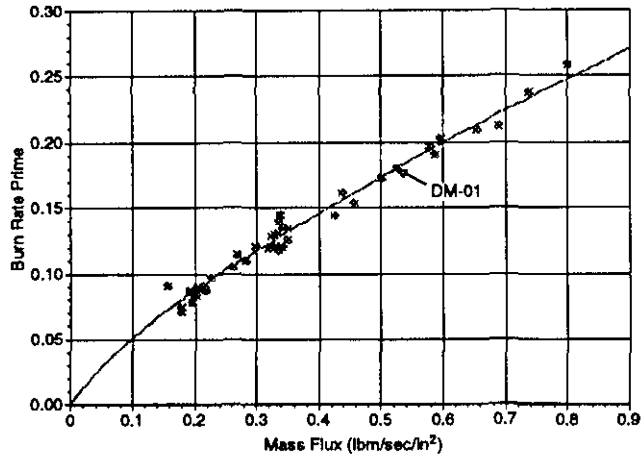

Figure 4. Measured Fuel Regression Rate.

Motor Performance

AMROC's hybrid performance prediction computer program HyPRED© was used to reconstruct the motor burns to obtain combustion and nozzle efficiencies. The HyPRED input consisted of the fuel geometry, fuel density, LOx mass flow rate, and the empirical constants from Equation (1). HyPRED calculates the motor chamber pressure based on a lumped parameter steady state version of the conservation of mass, energy, and species equations.[3]

Figure 5 presents the measured LOx mass flow rate used for the reconstruction of burn two. Burn two reconstruction is presented on its own as a representative of all burn reconstruction's.

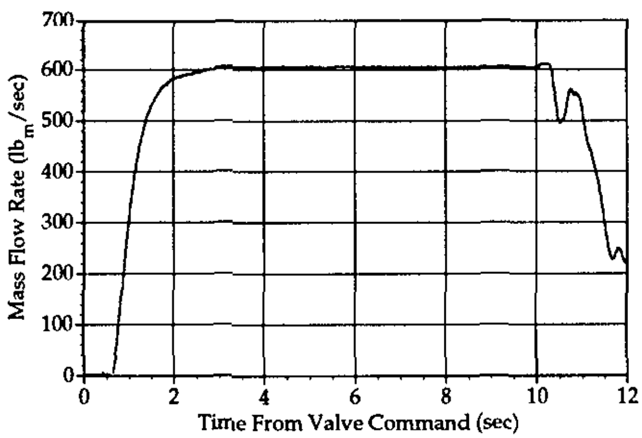

Figure 5. DM-01 Burn Two LOx Mass Flow Rate.

Figures 6 and 7 present the burn two measured pressure and thrust with the HyPRED reconstructed data respectively. A C* efficiency of 0.96 was required to match the reconstructed pressure to the data. A C_f efficiency of 0.977 was required to match the reconstructed thrust to the data. The C* and C_f efficiencies were obtained by HyPRED calculating a "best-fit" curve matching the measured data.

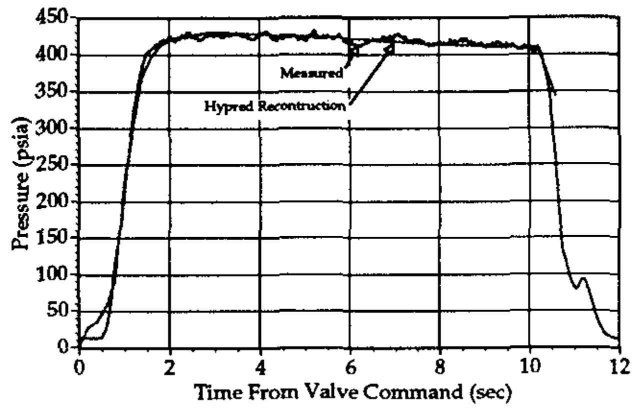

Figure 6. DM-01 Burn Two Reconstructed Chamber Pressure.

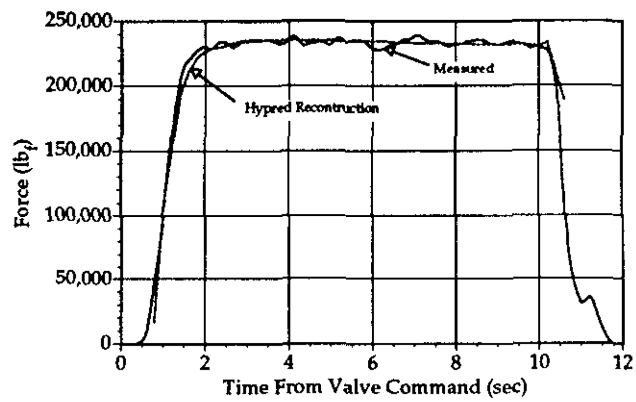

Figure 7. DM-01 Burn Two Reconstructed Thrust.

Similar efficiencies were obtained for burns one, three, and four.

Combustion Stability

Due to the pressure independence of the hybrid combustion process, exponentially growing combustion instabilities characteristic of solid rocket motors, are not observed. Regular, periodic pressure oscillations in the low-frequency (≈ 2 to 4 Hz) and medium frequency (≈ 100 to 200 Hz) range have been observed in previous AMROC motors. Maximum chamber pressure fluctuations of ± 25% of the mean chamber pressure were recorded in the early days of AMROC's development of the 75,000 lb_f thrust H-500 motor. Design improvements were implemented which eliminated such oscillations.

As with the H-500 motors, the DM-01 motor exhibited stable performance.

The pressure pulses in burns one and four served as a large pulse test for the oscillatory modes of the combustion system. The low frequency mode showed good damping (decay in five to ten cycles) under such an excitation. Once excited, the medium frequency acoustic longitudinal modes required five to ten cycles to decay.

DM-01 burns two and three did not experience any pressure pulses. The random pressure fluctuations were within ± 2.5% of the mean chamber pressure.

Thrust Vectoring

Thrust vector events were recorded during burns one and three. No vector events were scheduled for burns two and four. DM-01 utilized liquid injection of LOx for thrust vector control. Four injection valves (valves #1, 2, 4, and 5) were placed 45° apart and centered on the horizontal axis. A fifth valve (valve #3) was placed directly on the horizontal axis. The area ratio at the point of injection was 3.52 at the start of burn one. These locations are shown in Figure 8.

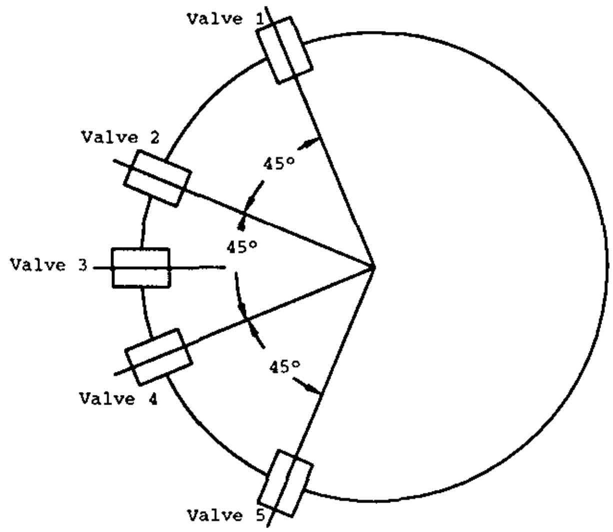

Figure 8. DM-01 LITVC Valve Locations.

Table 4 presents a summary of the thrust vector data obtained from burn one. All LITVC events were 1.5 seconds in duration.

Table 4. DM-01 Burn One Thrust Vector Summary.

	1	2	3
LITVC Valve Event	2 & 4	3	1, 2, 4, & 5
LOx mdot (lb_m/sec)	78	7	130
Vector Angle (deg)	2.9	0.9	4.6
Side Isp (sec)	162	485	133
Nozzle Area Ratio	8.46	8.40	8.31

Table 5 presents a summary of the thrust vector data obtained from burn three. All LITVC events were 1.5 seconds in duration.

Table 5. DM-01 Burn Three Thrust Vector Summary.

	1	2	3
LITVC Valve Event	2 & 4	3	1, 2, 4, & 5
LOx mdot (lb_m/sec)	107	12	209
Vector Angle (deg)	4.3	1.3	5.5
Side Isp (sec)	157	414	103
Nozzle Area Ratio	7.75	7.66	7.5

Figure 9 presents the DM-01 side specific impulse as a function of thrust vector angle. Also plotted is data from AMROC's FP-01 motor test that used LOx injected thrust vector.

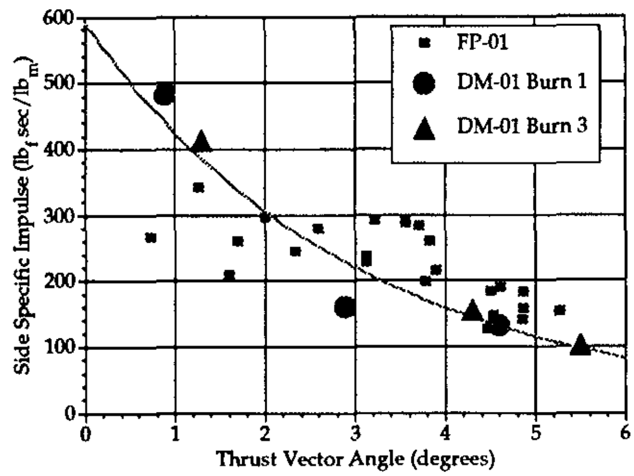

Figure 9. DM-01 Side Specific Impulse Vs. Thrust Vector Angle.

The DM-01 side specific impulse can be expressed as a function of the thrust vector angle by the following equation.

$$SIsp = 590e^{-0.33\theta} \tag{3}$$

Figure 10 presents the percent axial thrust increase as a function of thrust vector angle. Data from DM-01 and FP-01 is plotted.

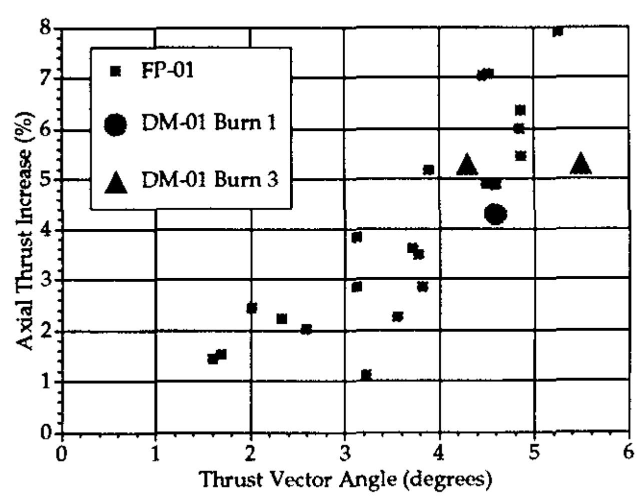

Figure 10. Axial Thrust Increase Vs. Thrust Vector Angle.

Sound Pressure Level

Five sound pressure level measurements were recorded during the first burn of DM-01. Two measurements were recorded at 100 feet and two were recorded at 250 feet. These were positioned 90° to the motor thrust axis in plane with the nozzle exit and at a distance above ground level corresponding to the height of the motor center line. A fifth microphone was located a distance of about 6,100 feet from the motor at PL Area I-52.

The average overall sound pressure level was 143.7 dB at 100 feet, 136.4 dB at 250 feet, and 92.3 dB at 6,100 feet (ref. 20 μPa). These sound pressure levels are within predictions based on jet nozzle noise theory and empirical directivity indexes. Figure 11 presents the 1/3 octave band average spectral levels during the motor burn.

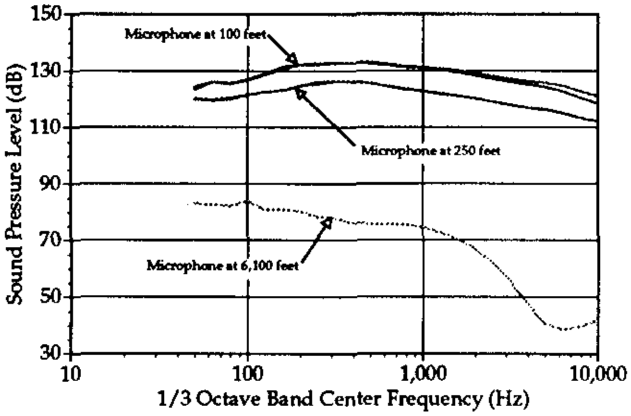

Figure 11. DM-01 Burn One Sound Pressure Level.

Figure 12 presents the DM-01 sound pressure level as a function of distance from the nozzle.

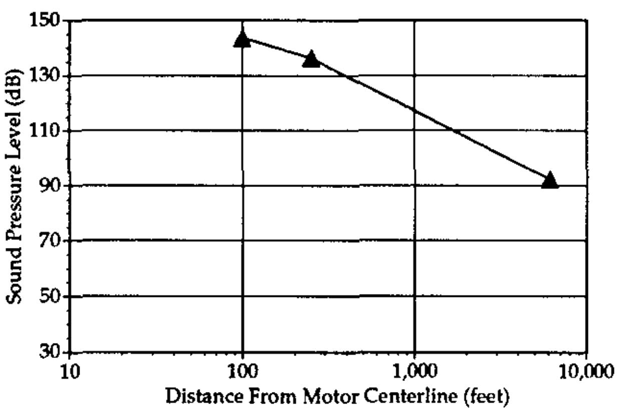

Figure 12. DM-01 Burn One Sound Pressure Level Vs. Distance

The sound pressure level as a function of distance can be expressed as

$$SPL = 204.8 - 2.84\ln(X) \tag{4}$$

Future Schedule

The first part of the H-1800 motor development has been completed with the successful test firings of the first 250,000 lb_f thrust hybrid motor, DM-01. The DM-01 project demonstrated the following successes:

- The initial performance of the H-1800 propulsion system,
- Scaling and stable combustion in a 250,000 lb_f thrust hybrid motor, and
- Production of a hybrid motor on a USAF base.

The next milestone in the H-1800 propulsion system development is the testing of DM-02. Based on DM-01 lessons learned, work is underway for design improvements in the motor case, nozzle, liquid oxygen feed system, data acquisition system, and manufacturing tooling and procedures. DM-02 is scheduled to be tested in the Spring of 1994.

The testing of the remaining development motors will follow the current development path. This approach will lead to the flight of the HyFlyer suborbital launch vehicle in 1995 and to the flight of the Aquila launch vehicle in 1996. The first H-1800 flight on the HyFlyer vehicle will represent the introduction to the space launch industry of a new, safe, reliable and low-cost propulsion alternative to today's conventional liquid or solid rocket propulsion.

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2. Kniffen, R.J., "Development Status of the 260,000 lb_f Thrust Hybrid Rocket Booster,", IAF-92-0631, 43rd Congress of the International Astronautical Federation, Washington, D.C., Sept. 5, 1992.

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