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Advanced Space Motor Demonstration

Russell A. Ellis and Ralph N. Hammond
United Technologies, Sunnyvale, Calif.
and
Paul Donguy
Societe Europeenne de Propulsion, Saint-Medard-en-Jalles, France

The test firing demonstration at simulated altitude of a space motor incorporating several advanced technologies—a 90% solids HTPB/A1/AP/HMX propellant, a head-end web grain in a Kevlar chamber, a free-standing integral throat and entrance (ITE), an ultralightweight nozzle, and an extendible exit cone (EEC) deployed by inflatable actuators—is reported. The demonstration culminated a two-year research and development effort. The specific impulse achieved is believed to be a record for a composite propellant in prototype motor hardware.

Introduction

A TEST firing at the U.S. Air Force Rocket Propulsion Laboratory (AFRPL), Edwards Air Force Base, Calif., on Nov. 15, 1979, is believed to have demonstrated the most advanced solid propellant space motor yet tested. The motor test culminated a two-year research and development effort. The 30-in. (762-mm) diam motor was test-fired at a simulated altitude of over 100,000 ft (30,480 m) for 56.6 s, achieving a maximum thrust of 4910 lb (21,840 N) and a maximum pressure of 605 psia (4171 kPa, 41.2 bar). Average thrust was 4074 lb (18,121 N) and average pressure over action time was 506 psia (3489 kPa, 34.4 bar). Expansion ratio at ignition was 149.41. The specific impulse achieved, 302.9 lbf-s/1bm (297 N-s/kg) corrected to absolute vacuum, is believed a record for a composite propellant.

The EEC of the nozzle was designed for predeployment in keeping with the space motor application and was successfully deployed at vacuum conditions prior to motor ignition.

The motor (Fig. 1) embodied technological advances in the fields of propellant, grain design, EEC, nozzle, chamber, and insulation.

Insulated Chamber Design

Chamber

The chamber is of Kevlar/epoxy construction with a high strength carbon/epoxy skirt, and aluminum polar fittings and mounting flange. The total weight of the chamber with attachments is 19.8 1b (9.0 kg); the weight of the composite material alone is 10.47 1b (4.748 kg). The chamber diameter is 30.0 in. (762 mm); the mounting flange diameter is 31.48 in. (799.5 mm); and the overall length between polar adapters is 25.02 in. (635.4 mm). Internal volume is 12.937 in.^{3} (212 liter).

Insulation

GSM 55, a 1.1 g/cc EPDM rubber with silica fillers, was the insulation selected. Because this propellant had limited insulation performance data and because it was to be used with the first head-end web grain design combined with a filament-wound motor, the insulation design was very conservative. Thickness (Fig. 2) ranged from 0.140 in. (3.56 mm) throughout the forward dome, to 0.58 in. (14.7 mm) adjacent to the nozzle. Total insulation weight was 35.09 lb (15.95 kg).

Propellant, Grain, and Igniter Design

Propellant

The selected propellant was UTP-19,687, a HTPB formulation with 90% solids, 20% aluminum, and 12% HMX.

Grain

A head-end web grain design with an aft-end conocyl (Fig. 3) was selected for high volumetric efficiency. As compared to a center-perforated grain in an identical chamber, propellant weight was increased 3.1% [from 740.8 lb (336 kg) to 762 1b (346.4 kg)] despite the very conservative insulation design which added 16.1 lb (7.3 kg) more insulation. Again, this was the first use of the head-end web configuration in a filament-wound chamber.

Igniter

A nonflight-type igniter consisting of a paper tube filled with boron potassium nitrate pellets was selected for economy.

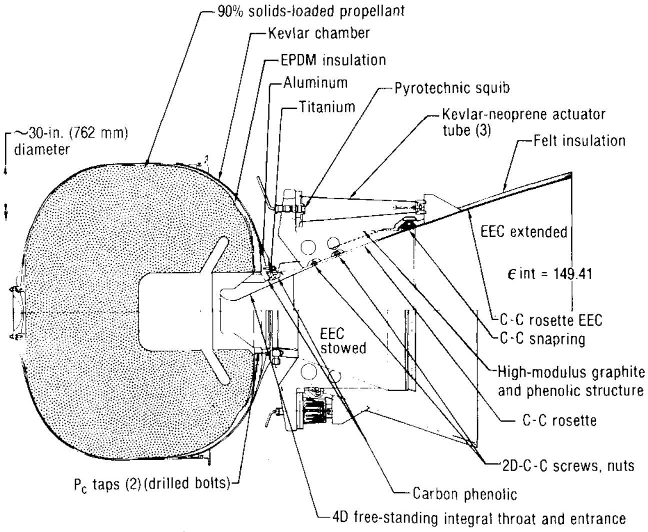

Fig. 1 SEP/CSD space motor.

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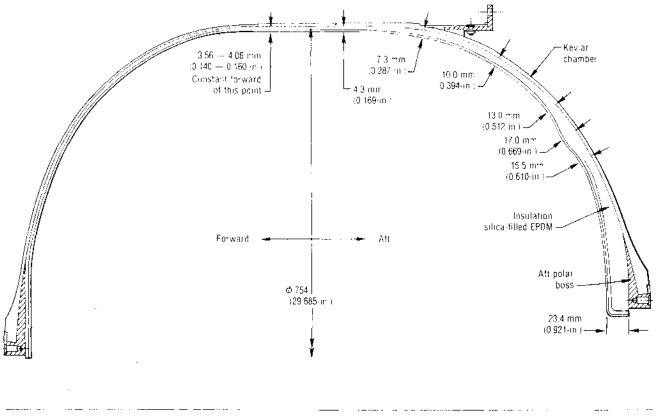

Fig. 2 Insulation design.

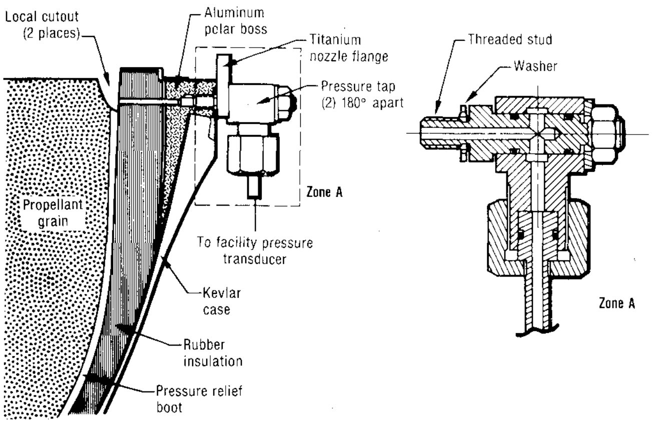

Fig. 4 Chamber pressure measurement system.

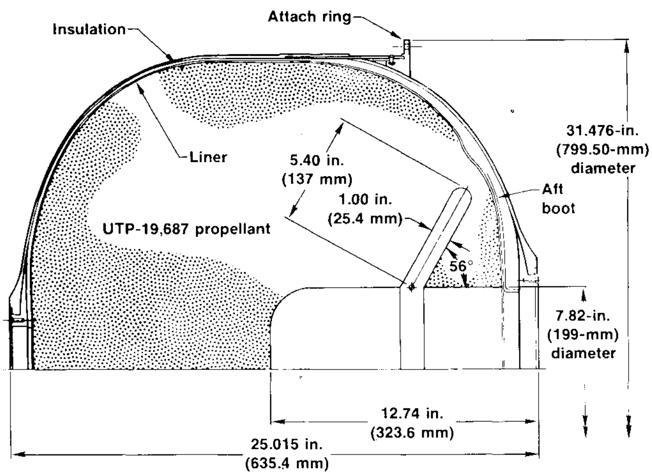

Fig. 3 Loaded case configuration.

Chamber Pressure Measurement

The head-end web configuration makes chamber pressure measurement through the forward port impractical. With head-end web grains in metallic chambers, pressure has been measured with taps through the aft dome chamber wall, but this also is impractical in a filament-wound chamber. Since this was the first use of the head-end grain in a filament-wound chamber, it was necessary to develop a new method.

The solution (Fig. 4) was to drill a port through the center of two of the studs attaching the nozzle to the motor, drill a corresponding hole through the insulator, and locally remove the propellant and a piece of boot flap to ensure full pressure reached the hole in the insulation. The aft end of the stud was mated with fittings to transmit pressure to the facility transducers. These fittings were proofed at 1000 psia (6895 kPa) after assembly, before installation in the motor.

Nozzle and EEC Design

The nozzle configuration is presented in Fig. 5. The two main features of this lightweight nozzle are a free-standing ITE and an EEC.

The free-standing ITE leads to a nozzle containing a minimum amount of metal; only a stub titanium attach ring to mate with the chamber adapter. The exit cone and the "nested cone" EEC are made of carbon-carbon (C-C) involute material. The EEC is designed for predeployment. The deployment system consists of three Kevlar-reinforced Neoprene rubber tubes inflated by independent squibs. The initial throat diameter is 54.86 mm (2.16 in.) and the EEC exit diameter is 670.5 mm (26.4 in.), which results in a 149.4 initial exit area ratio. The wall contour of the exit cone is designed to take into account the EEC. The ITE is made of four directionally reinforced (4D) C-C material, one reinforcement direction being along the nozzle centerline. The axial reinforcement is made of 1.8 mm (0.07 in.) rods and the reinforcements in the other directions are made of 0.7 mm (0.03 in.) diam. rods. The specific gravity is 1.92 g/cc.

The nozzle blowoff load is transmitted to the titanium attach ring through a C-C nut (made of the same 4D material as the ITE) and a carbon/phenolic insulation.

The exit cone thickness is tapered from 5 mm (0.2 in.) to 3 mm (0.12 in.). A groove is provided on the outside diameter near the exit for the EEC latching mechanism.

The EEC thickness is tapered from 3 mm (0.12 in.) to 2 mm (0.079 in.). The increased thickness of the entrance is achieved with an additional threaded C-C involute ring. The EEC is latched to the basic exit cone by a C-C snapring.

The EEC deployment system consists of three Kevlar-reinforced rubber tubes linked to the cones by high strength carbon cloth/phenolic brackets. These brackets are bonded to the cones by graphite cement and by C-C screws and nuts. These rubber tubes are inflated by the gas coming from independent squibs.

The external insulation of the two cones is performed by a silica-alumina felt blanket bonded by a refractory cement. The felt thickness on the basic cone is 25 mm (0.98 in.) and 15 mm (0.59 in.) on the EEC.

The total weight of the nozzle with the EEC and the deployment system is 12.16 kg (26.8 lb.) and the weight of the external insulating blanket is 3.5 kg (7.7 lb).

Insulated Chamber Development and Fabrication

Insulation Development

The insulation thicknesses were sized based on analysis. The analysis was based on the results of firings of TM-3 test motors which contained both the GSM-55 insulation and insulations for which a large data base existed.

Insulation Fabrication

The insulator was fabricated in two sections, forward and aft, by layup of calendered sheets of rubber which were then vulcanized. A nylon scrim cloth was applied to the inner surface during vulcanization to provide a rougher surface more suitable for propellant bonding.

Insulated Chamber Proof and Burst Tests

Extensive chamber testing was conducted to ensure low risk of a chamber failure and to provide precise chamber deformation data for the grain structural analysis. Two identical insulated chambers were fabricated. Each was proof-tested above maximum expected operating pressure (MEOP), and the twin to the one test-fired was burst while monitored with extensive instrumentation. The instrumentation con-

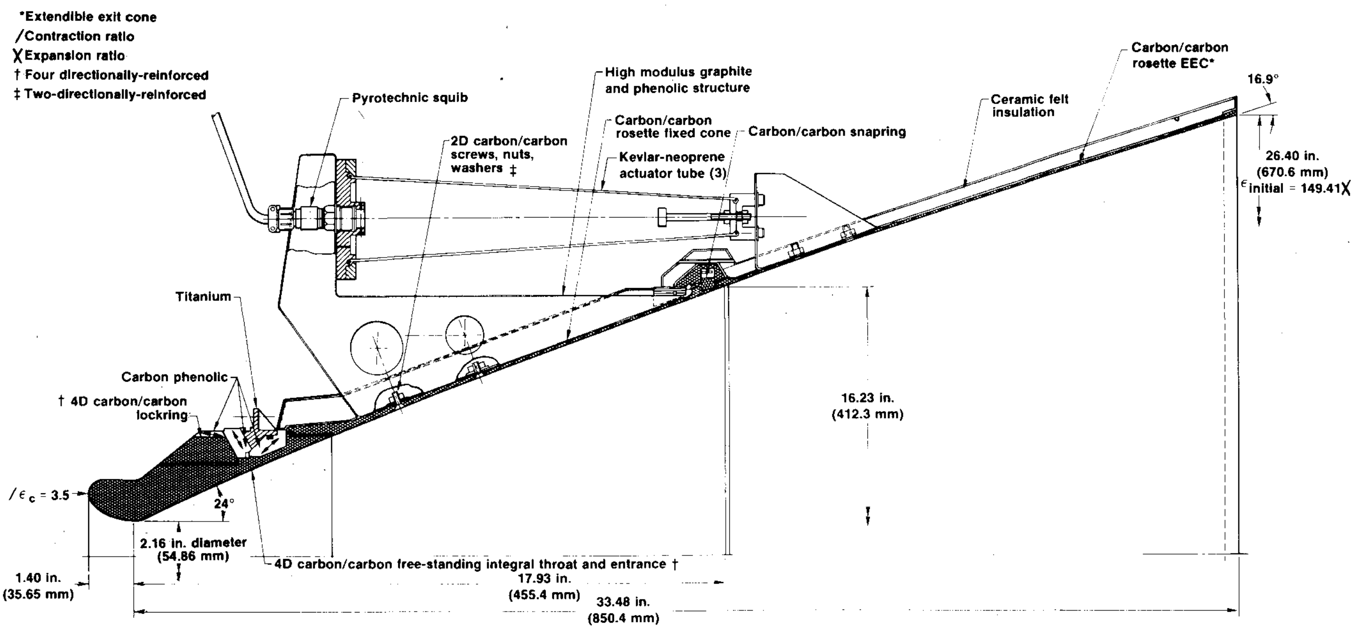

Fig. 5 Nozzle configuration.

sisted of pressure transducers, displacement gages, and unidirectional and tridirectional strain gages.

One chamber was then pressurized to failure at the rate of 14.7 psia/s (101 kPa/s, 1 bar/s).

The chamber failed at 1058 psia (7300 kPa, 72 bar) by means of tensile failure of the fibers in the cylindrical section. The burst pressure represents a factor of safety over MEOP of 1.49, and 1.86 over predicted maximum pressure. All test objectives were met.

Propellant Grain Analysis and Manufacture

Grain Structural Analysis

The propellant grain was analyzed for typical space motor thermomechanical loads. Margins of safety, incorporating a 1.5 safety factor for 1) cure, cooldown, and long-term storage, 2) pressurization during firing, and 3) acceleration, were all found to be positive under all typical environmental conditions.

Propellant and Liner

A standard liner for HTPB propellants, UTL-0040A, was used. This liner has been used with all CSD HTPB propellants and its compatibility, specifically with UTP-19,687, was fully demonstrated on previous programs.

Grain Manufacture

The 90% solids, 20% aluminum, 12% HMX propellant was manufactured in accordance with CSD specifications. The chamber was loaded with 762 lb of UTP-19,687 propellant cast from a single 400-gal production mix.

Following completion of the propellant casting, the motor was sealed and pressurized during cure to minimize residual cooldown stresses. Following propellant cure, the casting tooling was removed, and the grain machined to print.

Nozzle Development

Free-Standing ITE Retention to the Chamber

The critical point of this nozzle design was the linking of the free-standing ITE with the chamber and the EEC. A nozzle simulating this retention was test-fired in January 1979 on a TM-3 motor filled with a 90% solids and 18% aluminum HTPB propellant.

EEC

A bench test rig was made including the C-C entrance of the EEC and C-C exit of the basic cone with the latching system and the three inflated rubber tubes. Twenty tests were performed with pneumatic inflation of the rubber tubes, fifteen tests in vertical position, and five tests in horizontal position. Two other tests were performed with a pyrotechnic inflation of the rubber tubes in horizontal position, the first at sea level pressure, the second in a vacuum condition.

Pretest of the EEC on the Nozzle

The final development test was conducted with the all up nozzle eventually test-fired in horizontal position with pyrotechnic charges at sea level pressure. This test was the last check before sending the nozzle and the EEC to the U.S. for the final tests.

Demonstration Firing

Installation and Leak Check

The loaded chamber was mounted to the test stand adapter, then the nozzle was mated. The EEC actuators were disconnected and the movable cone was manually pulled aft and allowed to latch prior to assembly to preclude accidental shearing of shear pins in the EEC actuator assemblies. The EEC was then retracted and the EEC actuators were reconnected to the movable cone.

EEC Extension Test

Since deployment over the plume is not a requirement for space motors (e.g., IUS), the EEC extension system for this test was designed for prefiring deployment. For realism, it was desirable to extend the EEC at high altitude conditions. This could be done either immediately prior to ignition or during the Combined Systems Test (CST) AFRPL conducts as a facility check a day or two prior to the firing. For conservatism, the EEC was deployed during CST so that it could be visually checked after the CST for proper latching prior to firing.

The CST was conducted on Nov. 14, 1979, the day prior to the firing. The cell was brought to simulated altitude (over 100,000 ft or 30,480 m) and the pyrotechnic squibs in the EEC actuators were ignited with a common firing circuit. Extension and latching were observed by television. After the cell was returned to ambient pressure, personnel entered the cell and verified that the movable cone had properly latched.

Test Firing

The igniter was installed through the nozzle the morning of the test. The igniter leads were threaded through a vent hole in the throat plug, and the plug was bonded to the 4D C-C aft of the throat.

The test firing took place as scheduled on Nov. 15, 1979. The only anomaly observed on the television was apparent expulsion of molten particles from the nozzle near the EEC actuator brackets a few seconds before tailoff. These were later proven to be particles of SiO_2 melted out of the felt overwrap when the C-C exit outer surface exceeded the SiO_2 melting point. This localized melting of the SiO_2 was expected and did not result in any problems. The felt functioned properly, nevertheless, and the thermocouples on the outer surface for the felt and on the aft of the motor stayed below 200°F (93°C) through tailoff.

All data systems functioned properly and all data were close to predictions. When the cell was entered, all components were in excellent condition. The test appeared to be 100% successful as confirmed by the subsequent post-test analysis.

Post-Test Analysis

Hardware Analysis

The fired hardware was returned to CSD's Sunnyvale facility where the chamber and nozzle were separated.

As can be observed in Fig. 6, the fired chamber was in excellent condition with no evidence of thermal damage. After the cutting of the chamber, the insulation was examined and was also found to be in excellent condition (Fig. 7). The remaining thicknesses of insulation were measured and then compared to the drawing nominals in Fig. 8.

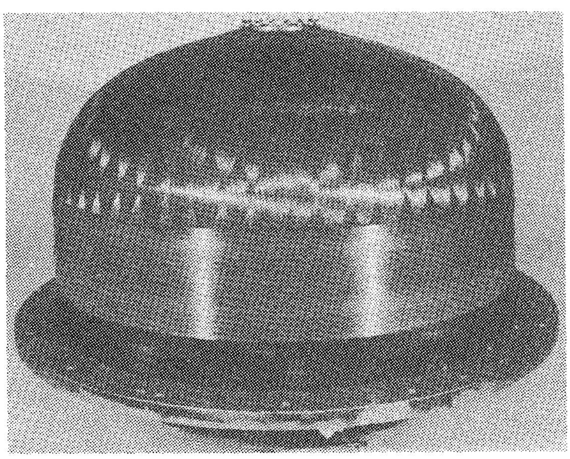

Fig. 6 Fired chamber.

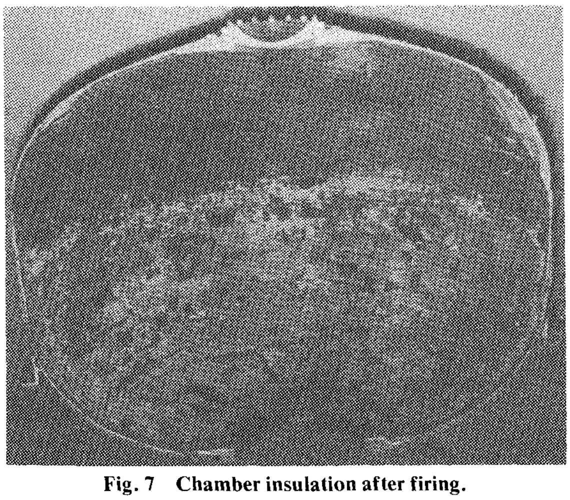

Fig. 7 Chamber insulation after firing.

As seen in the figure, there was no measurable insulation ablation in the forward dome. In a flightweight design with a factor of safety of 1.25 on ablation, the insulation weight could have been reduced from 35.09 lb (15.95 kg) to 16.21 lb (7.37 kg).

The fired nozzle was examined thoroughly after removal from the motor and found to be in excellent condition. The postfired ITE is shown in Fig. 9.

The ITE average erosion profile is presented in Fig. 10.

The average throat erosion is 0.067 mm/s (2.65 mils/s), which is less than predicted. This may be due to the high axial reinforcement volume fraction. Outside erosion of the ITE is unusual and seems due to the very high temperature of the ITE at the end of the firing. Reduction of the alumina by the carbon is being investigated as the probable cause.

The postfired wall of the exit cone and the EEC experienced no particle impingement. The C-C screws and nuts, used to

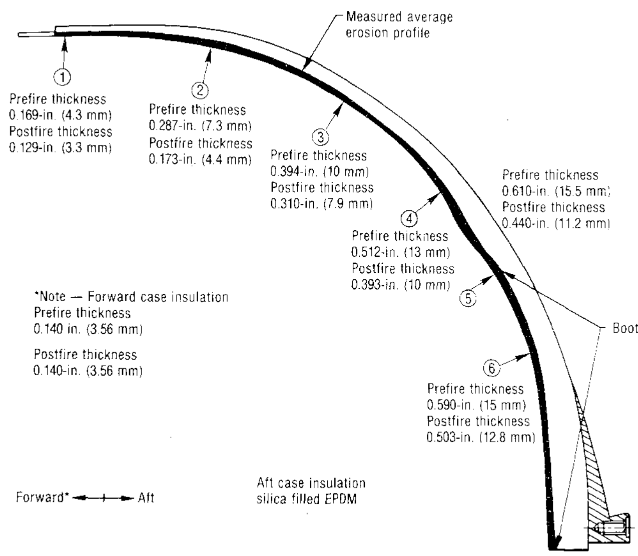

Fig. 8 Comparison of average insulation thicknesses after firing to drawing nominal thickness.

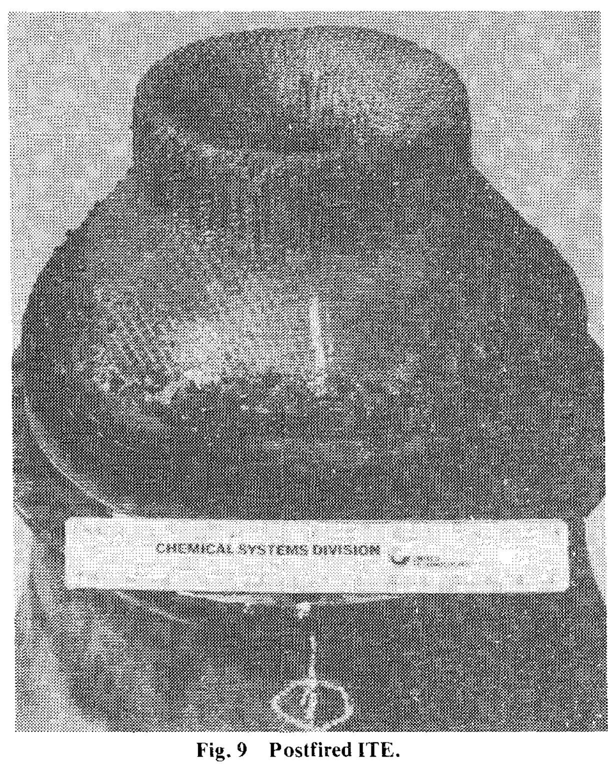

Fig. 9 Postfired ITE.

Table 1 CDS/SEP apogee motor comparison of measured and predicted parameters (vacuum, 70 F)

	Measured	Pretest prediction	Difference, %
Action time			
Time, s	56.6	57.4	−1.41
Average pressure psia (kPa; bar)	506 (3489; 34.4)	485 (3344; 33.0)	+4.15
Average thrust, lbf (N)	4074 (18,121)	3995 (17,770)	+1.98
Duration			
Time, s	57.8	57.5	+0.52
Total impulse, lbf-s (N-s)	230,840 (1,026,776)	229,360 (1,020,193)	+0.64
Delivered I_{sp}, lbf-s/lbm (N-s/kg)[a]	302.9 (2971)	301.0 (2952)	+0.64
Effective I_{sp}, lbf-s/lbm (N-s/kg)[b]	300.4 (2946)	299.5 (2937)	+0.30
Maximum pressure, psia (kPa; bar)	605 (4171; 41.2)	570.0 (3930; 38.8)	+5.78
Maximum thrust, lbf (N)	4910 (21,840)	4910 (21,840)	0
Characteristic velocity, ft/s (m/s)[c]	4980 (1518)	5116 (1559)	−2.75
Throat diameter, in. (mm)			
Initial	2.160 (54.86)	2.16 (54.86)	0
Final	2.449 (62.20)	2.571 (65.30)	−4.98
Average[d]	2.290 (58.17)	2.332 (59.23)	−1.83
Expended inerts, lbs (kg)	6.5 (2.95)	3.8 (1.73)	–
Average nozzle erosion rate, mils/s (mm/s)	2.55 (0.065)	3.57 (0.091)	–

[a] $I_{sp_D} = I_T / W_{p_{exp}}$ where $I_T = \int F dt$.
[b] $I_{sp_{eff}} = I_T / (W_p + W_{inerts})$ where $I_T = \int F dt$.

[c] $C^* = \left[\int_0 (\text{Total time}/P_{c_I}\,dt) \right] \times [(A_t g / W_p)]$.

[d] $A_t = \int_0^t \text{total } A_t dt / t_{total}$ and $D_t = \sqrt{4\bar{A}_t/\pi}$

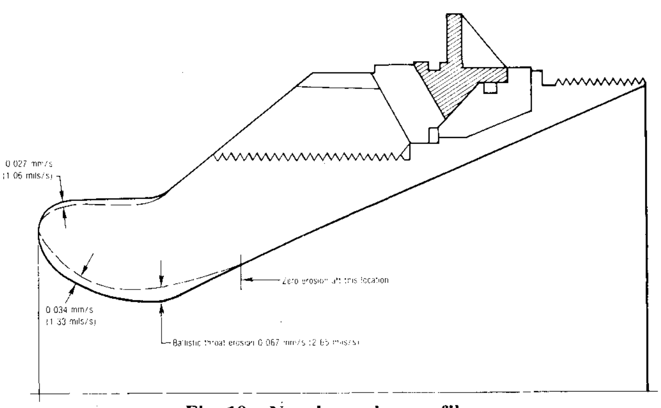

Fig. 10 Nozzle erosion profile.

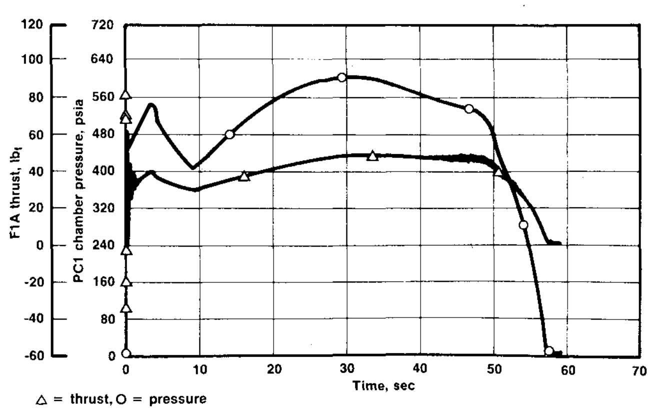

Fig. 11 Measured pressure and thrust.

link the cones with the brackets, remained tight and exhibited no problems. The external insulating blanket remained in place but was partly melted where it was in contact with the basic cone. At the end of the firing, the maximum measured temperature on the external skin of the blanket at the level of the basic cone was 45°C.

The deployment system remained in place, but the inflatable rubber tubes were partly burnt in front of the cone.

Ballistic Analysis

The measured pressure and thrust traces are presented in Fig. 11. Each trace is one of two recorded. The pressure trace shown, PC1, is believed to have no significant inaccuracies. The other, PC2, exhibited step changes, apparently from intermittent plugging of its pressure tap. There were no significant differences in the thrust traces. The thrust trace is quite neutral for a space motor. Table 1 tabulates the

Table 2 Mass fraction tabulations

	A As-fired		B Same chamber but flight-weight chamber insulation, nozzle insulation, and EEC extension system	
	lb	kg	lb	kg
Chamber	19.80	9.00	19.80	9.00
Kevlar and epoxy	10.47	4.75	10.7	4.75
Fittings, skirt	9.33	4.25	9.33	4.25
Chamber internal insulation	35.09	15.95	16.21	7.37
Chamber external insulation	7.00	3.18	—	—
Igniter, safe, and arm	(Facility igniter)		4.40	2.00
Nozzle assembly	34.45	15.66	29.66	13.47
ITE, insulated flange	10.75	4.89	10.75	4.89
Exit cones	13.16	5.98	13.16	5.98
EEC extension system	2.82	1.28	1.75	0.79
Exit insulation	7.72	3.51	4.00	1.81
Propellant	762.00	346.4	793.5	360.8
Total weight	861.1	391.4	866.3	393.4
Mass fraction (propellant weight divided by total weight)	0.885		0.916	

measured ballistic parameters and compares them to the predicted. The average chamber pressure was 4.2% higher and the maximum pressure was 5.8% higher than predicted. As can be seen from the throat diameter tabulations, the primary reason for this was that significantly less throat erosion was experienced during the firing than had been suggested by a recent motor firing used to predict the throat erosion.

The delivered specific impulse is 1.9 lbf-s/lbm (18.6 N-s/kg) higher than predicted. Most of the difference (1.3 lbf-s/lbm; 12.7 N-s/kg) is because of the combined effect of a higher-than-predicted average expansion ratio (133.1 compared to 128.6 predicted) and higher-than-predicted expended inerts (6.5 lb compared to 3.8 lb predicted).

Conclusion

A space motor incorporating several advanced technologies—a 90% solids HTPB propellant with HMX oxidizer, a head-end web grain in a Kevlar chamber, a free-standing ITE, an ultralightweight nozzle, and an EEC—was successfully demonstrated. The test demonstrates their readiness for application to future space motors.

The specific impulse achieved of 302.9 lbf-s/lbm (2971 N-s/kg) is believed the highest demonstrated with aluminized, composite propellants.

The mass fraction of 0.885 could be increased to 0.916 with a flightweight chamber insulator, flightweight external nozzle insulation, and a flightweight EEC extension system. Mass fraction tabulations are given in Table 2.