Development of Test Motors for Advanced Controllable Propellants

D. C. Sayles*
Advanced Technology Center, Huntsville, Ala.

As a fallout of the development program which was carried out by the Army Advanced Ballistic Missile Defense Agency, (currently the Ballistic Missile Defense Advanced Technology Center), for a pintle-regulated controllable interceptor motor, two test motors were developed which were used to comparatively evaluate different thrust vector control systems and propellant extinguishment under different conditions of motor free volume and under different thrust levels. A total of five motors were fired under this effort. This paper will discuss the various aspects of these motors. This will consist of such topics as motor designs and design changes; motor processing; some of the motor fabrication problems; multiple ignition system; and test results.

Introduction

THERE were two by-product test motors which resulted from the development program undertaken by the Army Advanced Ballistic Missile Defense Agency for a pintle-regulated, interceptor-type, solid-propellant propulsion subsystem. The first test motor, identified as the "thrust vector control gas generator," served as the source of rocket exhaust gases for the comparative evaluation of thrust vector control systems. To date, the performance of two such thrust vector control systems was evaluated under simulated altitude conditions at high and low thrust levels. These were the gimballed, supersonic splitline movable exit cone and the Techroll movable nozzle. This has paved the way for the evaluation of other thrust vector control systems which are presently under development. The second test motor developed under this program could be called the "propellant extinguishment motor" and was used to demonstrate the extinguishability of controllable propellants. The design of this motor is such that the controllable propellant was ignited, extinguished, reignited four times, and extinguished four times.

Discussion

The refinement of interceptor propulsion subsystems to increase their performance so that the interceptor can counter the threat of maneuvering re-entry vehicles can be improved through the incorporation of thrust vector control systems into the motor. These improvements will provide the interceptor with increased flexibility and maneuverability. As a result, the interceptor would be capable of flying widely different trajectories, of performing more complicated maneuvers, and of providing a commandable defense against sophisticated end-gaming targets.

The most developed method of accomplishing thrust modulation[1-9] of a solid-propelled motor is dependent on varying the throat area of the nozzle. This is achieved through the use of a hydraulically-actuated, strutted-mounted pintle which is moved in and out of the nozzle's throat.

Pintle-Regulated Nozzle

The schematic of the pintle-regulated nozzle, which is depicted in Fig. 1, illustrates the principle which is involved. A hydraulically actuated pintle centerbody, mounted in a strutted housing, moves back and forth, upon command, along the motor's longitudinal axis. This movement produces the variations in the annular throat area which are necessary to provide the variable thrust. Extinguishment of the motor is brought about when the pintle centerbody is retracted into the strutted housing to the full open position, and, thus provides the maximum throat area. This retraction causes the operating motor pressure to drop to a pressure which is below the minimum pressure necessary for sustaining the combustion of the controllable propellant, the motor undergoes extinguishment, and thrust terminates. When the pintle centerbody is extended fully into the nozzle throat, the throat area is at its minimum, and the motor then operates at maximum pressure, producing maximum thrust. If the pintle centerbody is positioned at some intermediate position between fully retracted and fully extended, the motor operating pressure and the thrust level that is delivered is determined by the interior ballistic properties of the propellant, especially the burning rate exponent of pressure or the rate with which the burning rate of the propellant changes with the operating pressure of the motor. Consequently, a high burning rate exponent, of the order of 0.85 to 0.95 is desirable.

Pintle Actuation and Control

During the simulated altitude test, the pintle centerbody was actuated by a separate hydraulic system which consisted of a continuous flow pump which had a capacity of 4,500 psig and a 5-gpm reservoir system. Pressurized accumulator systems were used to provide for higher transient flow requirements. A 20-gal accumulator system was used to provide 127 gpm at 3,500-psi differential across the servovalve.

The servoactuator was controlled by means of a closed-loop, servocontrol system. It incorporated an analog computer, a command signal generator, and a hydraulic supply

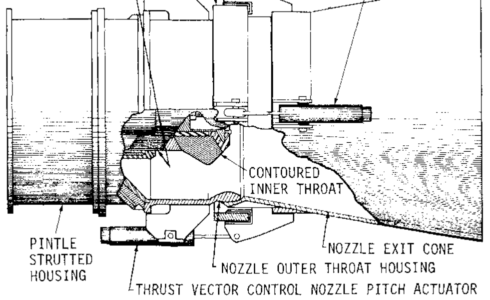

Fig. 1 Schematic of pintle-controlled nozzle and supersonic splitline thrust vector control system.

Presented as Paper 73-1206 at the AIAA/SAE 9th Propulsion Conference, Las Vegas, Nevada, November 5-9, 1973; submitted November 30, 1973; revision received November 14, 1974.

Index categories: Rocket Engine Testing; Solid and Hybrid Rocket Engines; LV/M Subsystem Design.

*General Engineer, Missile Directorate, Ballistic Missile Defense.

system. The pintle controller generated the command voltages for the servoactuator as a function of motor pressure feedback and for the potentiometer for positioning the actuator. A command signal generator was used to provide the time-sequenced reference voltages to the controller.

For ignition, the pintle centerbody was maintained in its position by the potentiometer which supplied a reference voltage to the servocontrol loop. After ignition, a transfer was made to motor pressure feedback voltage control, and the potentiometer reference was replaced by a computer reference voltage corresponding to the target motor pressure feedback voltage.

Change in Throat Area of Pintle-Regulated Nozzle with Pintle Centerbody Position

The changes which occurred in the throat area of the thrust vector control gas generator as a function of pintle position are depicted in Fig. 2. Movement of the pintle centerbody of 4.875 in from the fully extended to the fully retracted position produced a change in the geometric throat area from 59 in.^{2} to 151.^{2} Such an area change permitted control of the motor pressure from approximately 1900 psia to 100 psia and extinguishment.

Controllable Propellant

The controllable propellant was specifically developed for this application. It had a combination of several unique features, of which high burning rate and high pressure exponent were the more critical for the achievement of throttling, stop-start, and extinguishment. This propellant differed from the conventional composite propellants by containing flake aluminum powder instead of spheroidal aluminum powder, an extinguishment aid, and or ammonium perchlorate decomposition catalyst. More importantly, it contained ammonium percholorate which had been thermally decomposed to provide controlled porosity in the crystal lattice.

Buffer Propellant

The buffer propellant contains a combustion suppressant whose function is to generate large quantities of coolant exhaust gases slowly, and retard heat transfer from the pintle centerbody and nozzle into the controllable propellant and prevent its premature reignition.

Processing Procedures for Controllable Solid Rocket Motors

The processing procedure for the fabrication of these controllable motors is a decidedly complex operation and is presented in outline form in Fig. 3. A summary of this procedure is as follows:

a) Installation of insulation

The motor's interior is first grit-blasted, solvent-wiped, and dried. A vinyl phenolic primer is applied to the motor's interior; cured; solvent-wiped, and dried. Next an epoxy primer is applied, followed by an epoxy adhesive. The asbestos-filled polybutadiene-acrylonitrile insulation is fitted into the motor, and teflon tape applied over the aft boot release area. A porous asbestos bleeder mat is installed over the entire insulation to prevent the insulation from sticking to the pressure bag which is used to hold the insulation in place while it is being cured. The bag, bleeder, and Teflon tape strips are removed; the insulation is trimmed, abraded, solvent-wiped, and dried.

b) Installation of liner

Before the liner (whose purpose is to ensure adhesion between the insulation and the propellant) is applied, a porous asbestos bleeder mat is applied on the aft boot, and the core tooling installed. The motor is preheated for 8 hr. at 135°±5°F, and the liner is applied by brush over the insulation, and cured at 135°F.

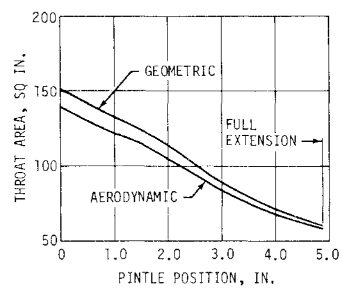

Fig. 2 Change in throat area of pintle-regulated nozzle with pintle centerbody position.

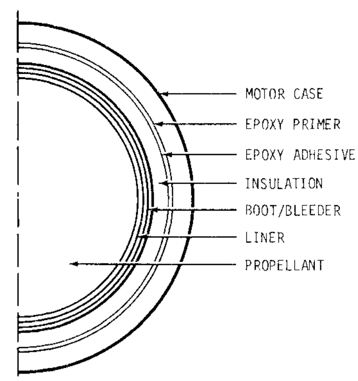

Fig. 3 Processing procedure for controllable solid-propelled motor. a) Motor preparation; application of primer and adhesive; installation of insulation, boot, and bleeder cloth. b) Installation of liner. c) Main propellant grain casting. d) Buffer propellant grain casting. e) Motor assembly

c) Main propellant grain casting

For main propellant casting, the motor is placed in the vacuum bell, the propellant mandrel assembled, and the propellant cast into the motor. The motor is vibrated for 5 mins. and the propellant is cured at 135°F to the required Shore hardness. The mandrel and casting tooling is removed, and the aft face of the propellant grain is trimmed to configuration.

d) Buffer propellant grain casting

The motor is reinstalled into the vacuum casting bell, and the casting tooling installed. The buffer propellant is cast onto the aft end of the main propellant grain, and cured at 110°F to the required Shore hardness (4 days). The cast tooling is removed, and the buffer propellant grain trimmed to its final configuration.

Repetitive Ignition System

Because of the limited number of restarts required, a cluster of conventional igniters was selected for the repetitive ignition system. The ignition system was sized so that each igniter was capable of restarting the motor under all conditions, ranging from the minimum free volume when the motor had a full propellant load to the maximum free volume when most of the propellant had been consumed.

A cross-sectional drawing of the final design of the repetitive ignition system appears in Fig. 4. It consisted of three identical, conventional-type igniters for the thrust vector control gas generator, and five igniters for the multiple extinguishment motor. Each igniter was mounted individually to a flat plate which was attached to the forward head of the motor.

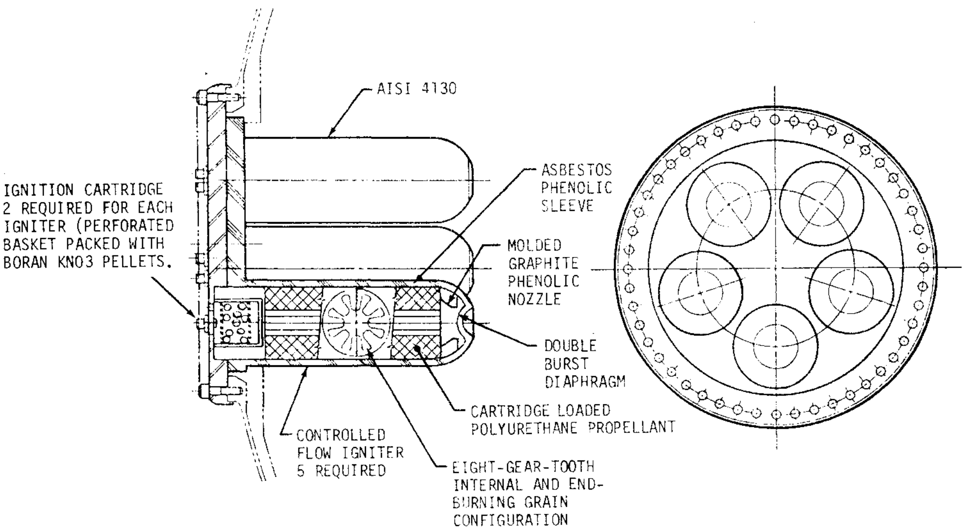

Fig. 4 Ignition system for full-duration motors.

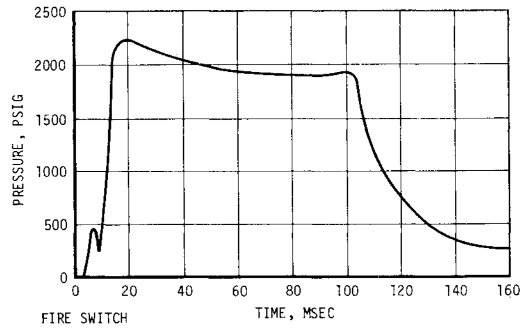

Fig. 5 Typical igniter firing pressure-time curve and performance data. Peak pressure = 2300 psig; average chamber pressure = 2000 psig; web duration = 85-90 msec; grain surface area = 270-275 in^2; grain weight = 4.9-5.0 lbm.

The overriding factor in the design of the igniter's inert components was their ability to withstand the pressure generated during the period that the motor was operating. To prevent this pressure from entering the igniter, the igniter nozzle was sealed off from the main motor pressure by means of a double-burst disk assembly which was capable of withstanding the main motor's operating pressure. The disk was insulated with a low-strength rubber insulator which was prescored to fail easily. It was designed so that it would undergo selective rupture when the igniter reached its operating pressure and to retain all metal fragments upon burst so that no physical damage would occur to the main motor's pintle nozzle assembly.

Before motor startup and before each reignition, the pintle centerbody was prepositioned to provide the proper throat area so that the same pressure was built-up in the main motor when ignition occurred. This was to compensate for the buildup of excessive pressure during motor startup when the free volume in the motor was small, or for the existence of low pressures during the final phases when the free volume was large.

A typical igniter firing pressure-time curve and igniter performance data are depicted in Fig. 5. The peak pressure developed within the igniters was approximately 2,300 psig. The grain charge weight was about 5.0 lb and web duration was 85 to 90 ms.

Thrust Vector Control Gas Generator

The first subscale motor that was developed was identified as the thrust vector control gas generator. A cross-sectional drawing of it is depicted in Fig. 6. The motor itself was 30 in.

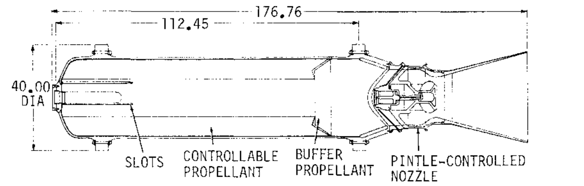

Fig. 6 Cross-sectional drawing of thrust vector control gas generator.

in diameter and 106 in. in length. Its performance characteristics appear in Table 1. The loaded motor was designed to have a low mass fraction, and have a sizable free volume at the aft end of the motor to ensure against the possibility of reigniting the main controllable propellant by the thermal radiation emanating from the hot nozzle components. As additional protection against such reignition, the aft end of the main propellant grain was restricted with a slow-burning buffer propellant whose combustion gases contained ingredients which underwent thermal decomposition, and helped dissipate the heat that was generated during the motor's operation. A description of the thrust vector control gas generator can be summarized as follows:

The propellant charge weight was about 3000 lb. The configuration of the grain perforation can be described as a forward finocyl, i.e., cylindrical perforation with five symmetrical, 2-in. wide fins. The stresses developed during the curing of the propellant and during thermal cooldown were relieved by the use of an aft-released boot or flap. The propellants were fully bonded to the motor case except in the aft boot region. The liner was derived from a polyurethane resin, and the insulation was a filled V-44 nitrile rubber, and a V-45 nitrile rubber was used for the fabrication of the aft boot.

Table 1 Performance characteristics of the thrust vector control gas generator

total impulse (lbf-sec)	549,700
propellant weight (lbm)	2800
total burn time (sec)	16.90
web action time (sec)	16.03
iginition interval (sec)	0.071
maximum thrust (lbf)	161,000
maximum throat area (in.^{2})	155
minimum throat area (in.^{2})	90
nozzle half angle (deg)	15
nozzle exit area (in.^{2})	875
pressure exponent of burning rate	0.7 to 0.9

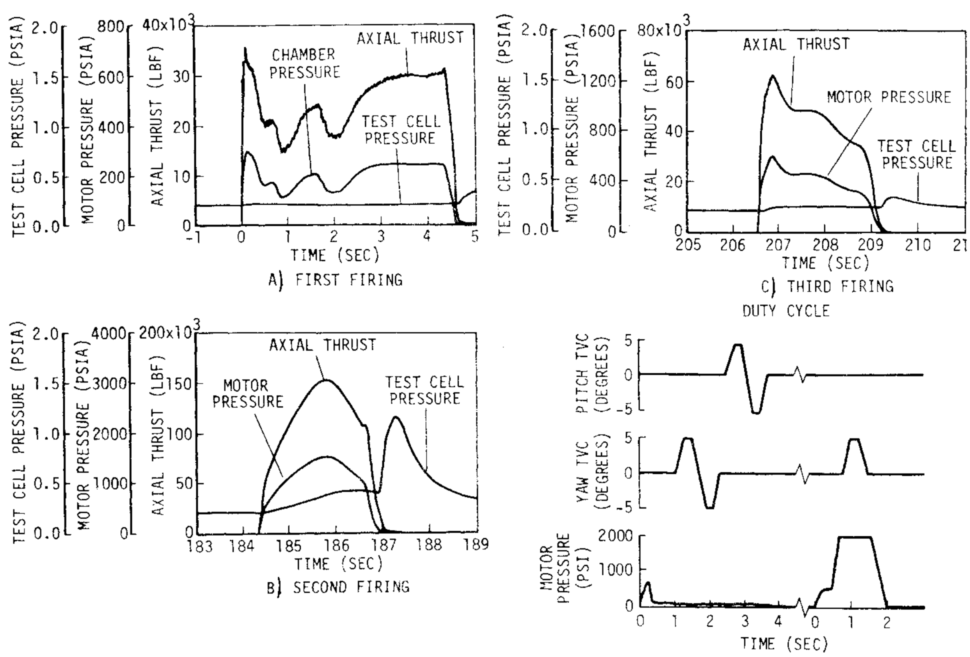

Fig. 7 Time histories of vacuum axial thrust and motor pressure of TVC/GG.

Duty Cycle of Thrust Vector Control Gas Generator

The planned duty cycle of the Thrust Vector Control Gas Generator is depicted in the lower left corner of Fig. 7. It consisted of three incremental firings: sustain, boost, and burnout. The actual histories of the vacuum axial thrust, chamber pressure, and test cell pressure were as follows. The motor was ignited at a simulated pressure altitude of 95 kft, and burned at an average motor pressure of 200 psia (target 250 psia) for the programed 4.1 sec. Extinguishment was then commanded, and the chamber pressure decayed from an initial level of 240 psia to approximately 51 psia, at which time extinguishment occurred. The motor remained extinguished throughout the programed 180-sec coast period.

The motor was then reignited and burned at an average motor pressure of 1240 psia (target 1886 psia) for the programed 2.0 sec. Maximum chamber pressure and thrust that were achieved were 1530 psia and 150,000 lbf. Extinguishment was again commanded, the chamber pressure decayed from an initial level of 1050 psia to approximately 40 psia, and then the motor underwent extinguishment. The motor remained extinguished throughout the programed 20-sec coast period. The motor was reignited for the third firing, and burned approximately 3.0 sec until the residual propellant was burned out.

Propellant Extinguishment Motor

The second subscale controllable motor, referred to as the propellant extinguishment motor, which was developed during this program, is depicted in Fig. 8 had the following dimensions: overall length—163 in.; motor length—98 in.; diameter—47 in. It contained 6000 lbs of propellant. The propellant grain had a finocyl configuration similar to that of the thrust vector control gas generator. It had seven fins in the forward section instead of five. The motor free volume, propellant charge, and mass fraction were considerably larger than in the thrust vector control gas generator. The primary utility of this motor was to evaluate the extinguishability of the controllable propellants under simulated altitude conditions over a spectrum of motor free volumes. The reason for the selection of the seven finned finocyl propellant grain configuration was that it burned progressively, and produced an increasingly greater extinguishment margin as the motor free volume became larger and as extinguishing the motor becomes progressively more difficult.

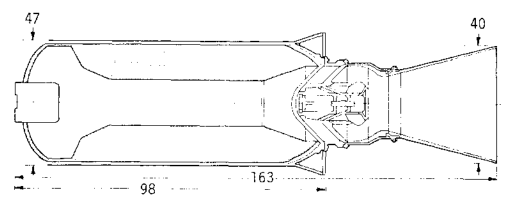

Fig. 8 Propellant extinguishment motor.

The evaluation of the ballistic characteristics of a controllable propellant, such as start, stop, thermal soak, restart, stop, etc., can be readily done in this specially-designed motor. To achieve this, a simple duty cycle was adopted. It consisted of five identical pulses. For each pulse, the pintle centerbody was prepositioned so that the motor would operate at 400 psia for 3 sec; followed by operation at 2 sec at 90 psia; then the pintle centerbody was fully retracted into the strutted housing so that the operating pressure dropped below the extinguishment threshold pressure. Extinguishment was to occur in less than 0.2 sec, and the motor was to remain extinguished for 60 sec. After 15 sec of the extinguishment period, the centerbody was moved to its position for the next incremental firing. This was a precaution to insure that thermal radiation from the centerbody into the strutted housing did not damage its seals.

The static test firing results which were obtained with the particular controllable propellant which had been developed are depicted in Fig. 9. The reproducibility of each extinguishment pulse is illustrated in Fig. 9 which depicts the actual thrust-time curves and the actual chamber pressure-time curves for the five firing pulses, and the tailoffs and extinguishment point in each of the incremental firings. The extinguishment pressures were: 36, 26, 32, 30, and 26 psia. The times from the command-to-extinguish and extinguishment were: 0.61, 0.58, 0.43, 0.53, and 0.48 sec, which was somewhat longer than the planned 0.2 sec.

The most plausible explanation for the fluctuations which appear in the thrust and motor pressure traces was attributed to the controller which positioned the pintle. The controller was a well-worn piece of equipment, and it was not considered advisable to incur the cost of refurbishing if for this application since the primary objective of this test was to demonstrate multiple extinguishments.

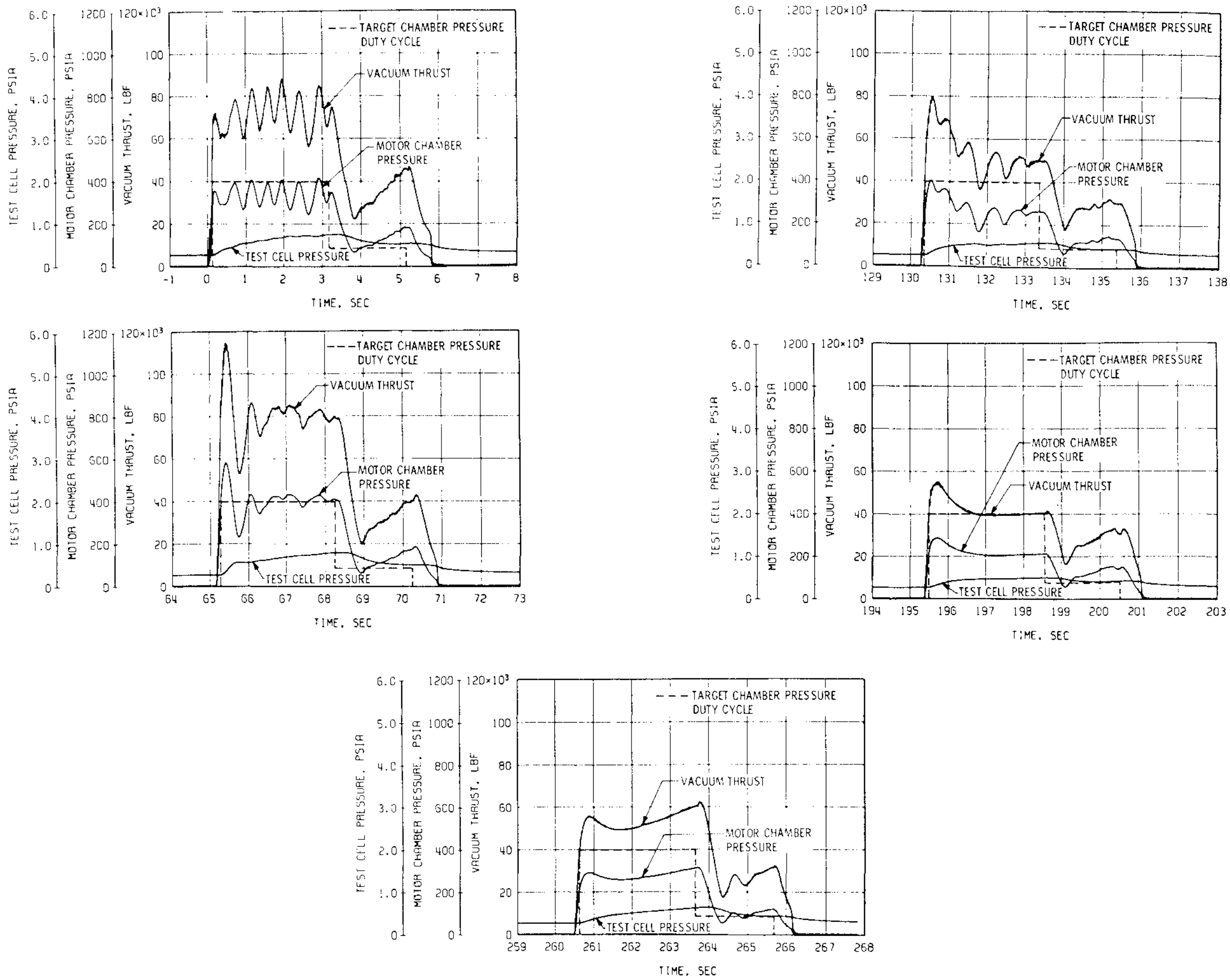

Fig. 9 Motor chamber pressure-, vaccum thrust-, and test cell pressure-time curves for the five incremental of the fourth controllable motor.

Conclusions

Two subscale, interceptor-type motors of the different size have been developed as by-products of an interceptor development program which contain 2000 lb and 6000 lb of propellant. These test motors have proven effective tools for the comparative assessment of the key ballistic parameters of controllable propellants, and of different thrust vector control systems, and can be used for the development of a flight packageable electronic control system to regulate the operation of the motor. These test motors can also be used to determine the scale-up effect on burning rate, pressure exponent, and extinguishment pressure.

References

[1]Mittermaier, N., Kobalter, J., and Levinsky, C.T., "L* and P-Dot Extinguishable Motor Development Program," Contract AF04-611-9889, Aerojet Solid Propulsion Co., Sacramento, Calif.

[2]Mittermaier, N., Kobalter, N., and Levinsky, C.T., "Single Chamber Controllable Solid Rocket Motor Program," Contract AF04-611-10820, Sacramento, Calif.

[3]Mittermaier, N., Kobalter, J., and Levinsky, C.T., "Variable Thrust Motor," Contract AF04-611-68-C-0003, Aerojet Solid Propulsion Co., Sacramento, Calif.

[4]Mittermaier, N., Kobalter, J., and Levinsky, C.T., "Single-Chamber Stop-Start Motor," Contract 4F04-611-68-C-0063, Aerojet Solid Propulsion Co., Sacramento, Calif.

[5]Mittermaier, N., Kobalter, J., and Levinsky, C.T., "Minimum Throttling Program" Contract AF04-611-69-C-077, Aerojet Solid Propulsion Co., Sacramento, Calif.

[6]Cauzza, J., "Selectable Two Area Nozzle," Contract N-00123-69-0480, Aerojet Solid Propulsion Co., Sacramento, Calif.

[7]Kobalter, J., "Air-To-Air Controllable Solid Rocket Program," Contract AF04-611-69-C-0054. Aerojet Solid Propulsion Co., Sacramento, Calif.

[8]Levinsky, C. T. and Mittermaier, N., "Controllable Solid Rocket for Advanced Interceptor Applications," Contract DAAH01-70-C-0275, Aerojet Solid Propulsion Co., Sacramento, Calif.

[9]Mittermaier, N.P. and Hardrath, A.O., "Controllable Solid Rocket Motor Program," Contract DAHC60-70-C-0063, Aerojet Solid Propulsion Co., Sacramento, Calif.