Development of the Explorer Solid Rocket Motor

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The successful launching of Explorer I on an accelerated schedule was due in part to the extensive design and developmental testing effort accomplished in support of the U.S. Army's Sergeant missile system. The ⅕-scale solid rocket motor used in the missile developmental in conjunction with a modified Redstone rocket became the basis for the Jupiter-C launch vehicle, which launched the first U.S. satellite. A description of the solid rocket motor and its development for use as part of the upper stages of the Jupiter-C is presented.

Introduction and Background

DURING its tenure under the sponsorship of the U.S. Army Ordnance Corps, the Jet Propulsion Laboratory (JPL) was engaged in the research and development of rocket propellants, solid rocket motors, and liquid-propellant engines. Other research activities included electronics both for guidance and for communication. From this background, JPL designed and developed the liquid-propelled Corporal guided missle and began the development of a solid rocket successor, the Sergeant missile. The approach for the proposed solid rocket motor development was based on using a ⅕-scale model for testing propellant formulations, grain perforation design, ignition characteristics, internal ballistic performance, and materials. It was concluded that the use of a small-scale model would speed development and be cost effective.

During this period (1950–1953), the subject of space exploration was becoming of increasing interest at JPL. The forthcoming International Geophysical Year activities in 1957–1958 gave added momentum to JPL's interest. In 1954, a proposal was submitted jointly by JPL, the U.S. Army Ballistic Missle Agency (ABMA), and the Office of Naval Research (ONR). The proposal was based on a launch vehicle that consisted of an upgraded Redstone having upper stages consisting of clusters of LOKI missiles. The LOKI was a JPL-designed and -built 2.75-in. ground-to-air missile, which, at that time, was being considered as an alternative to the Nike as an antiaircraft missile. The number of LOKI rockets needed to achieve Earth orbit and their predicted reliability indicated that the probability of a malfunction would be unacceptably high. It was suggested that a revised proposal be submitted to replace the LOKI with the ⅕-scale solid rocket motor being used in the development of the Sergeant missile. The upper stages on the Redstone then would consist of three stages of scaled-down Sergeants: a second stage having 11 motors, a third stage with 3, and a fourth stage with 1 motor and an integral payload (Fig. 1). This launch vehicle configuration was designated the Jupiter-C (Fig. 2).

A committee established to select the U.S. satellite program picked the Vanguard proposal over the Army-ONR-JPL proposal. One significant factor affecting the decision was a presidential decision that essentially banned the use of military rockets for nonmilitary scientific research. Instead of killing the Army-ONR-JPL efforts, however, the decision merely drove them to seek other means of achieving their goals for space exploration.

Concurrent with the satellite proposal activity, the Army and the Air Force were engaged in a struggle for primary responsibility for the development and use of intermediate-range ballistic missiles (IRBMs). In addition to the competition between the rocket boosters, there was competition in the designs of the re-entry warheads: the Army Jupiter vs the Air Force Thor, and the ablative nose cone of the Army vs the beryllium heat sink approach favored by the Air Force. Based on the proposal for launching a satellite, the Army requested ABMA and JPL to modify the Jupiter-C configuration to propel a scaled-down IRBM ablative payload on a trajectory that would simulate the actual IRBM re-entry conditions.

This request provided JPL and ABMA with the justification and support needed to proceed from a proposal phase to a firm design, development, and testing phase. Teams at JPL and ABMA could now focus their efforts on establishing requirements for all of the interfaces, electrical and mechanical; for the performance of the stages; for tracking and telemetry; and for ground support at Cape Canaveral.

Development of the Sergeant Rocket Motor

Research on solid propellants at JPL in the 1940s led to the development of polysulfide-based propellants capable of being case bonded. Small motors (6 in. in diam) were successfully fabricated and tested. Studies showed that larger motors could be fabricated. An early version of the Sergeant was built, having a diameter of 15.0 in. and containing 1500 lb of propellant. This demonstration of the feasibility of fabricating and loading large solid rockets led to the development of the General Electric-Thiokol Hermes A-2 motor and culminated in four successful flight tests. The Hermes A-2 program provided the design basis for the Sergeant missile motor.

As an outgrowth of the Sergeant program, a 6-in.-diam scale model of the Sergeant was developed to test many of the features of the full-scale rocket motor before it was manufactured in large quantities. The scaled-down motor had approximately ⅕ (6/31) the linear dimensions and 1/125 the mass of the full-scale motor. The scale model permitted evaluation of a range of propellant formulations, mandrel configurations, and case and nozzle materials to be accomplished in a timely and cost-effective manner. Its size also allowed the load and test firings to be done within the existing JPL facilities in Pasadena, CA. Over 100 motors were successfully loaded and test fired during the Sergeant development.

The principal characteristics of the scale-model motor, as reported in the Solid Propellant Information Agency Jet Assisted Take Off (SPIA JATO) Manual, Solid Propellant Information Agency/Manual 1 (SPIA/M1), are shown in Tables 1 and 2 in Figs. 3–5.

Re-Entry Test Vehicle—Precursor to Explorer

After the selection of the Vanguard as the U.S. satellite program and the rejection of the Army-ONR-JPL proposal,

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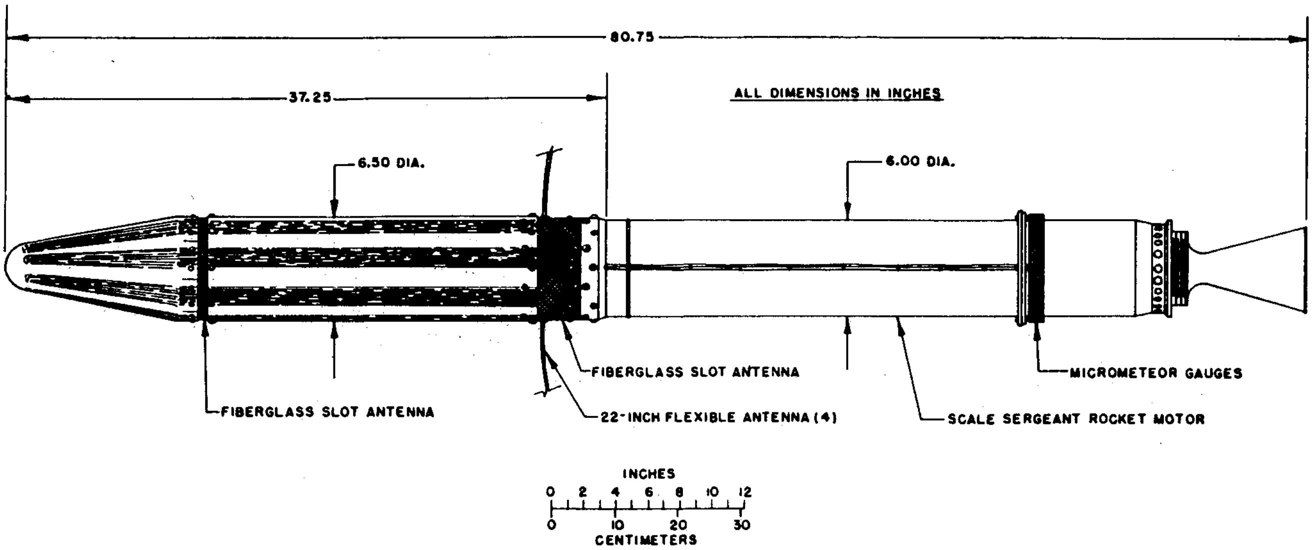

Fig. 1 Explorer fourth-stage motor and payload.

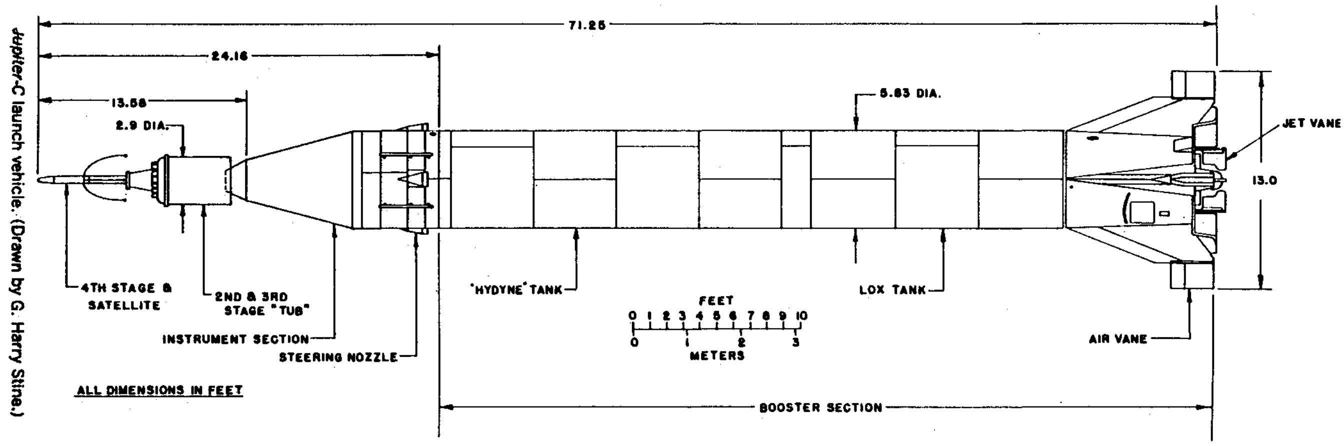

Fig. 2 Jupiter-C launch vehicle.

Table 1 Internal ballistics of 6-in. solid rocket motor

Design parameters	Values
Initial K_N	207
Port-to-throat area ratio, 1/J	1.85
Surface-to-port area ratio, JK	112
C_f λ vac	1.686
Performance at 80°F:	
Effective burning time, s	5.35
Total burning time, t_{10}, s	6.70
Maximum head end pressure, psia	527
Effective head end pressure, psia	496
Maximum vacuum thrust, lb	2100
Effective thrust, F_{eff}, lb	1975
Total impulse, I_t, lb-s	10566
Vacuum specific impulse, I_{sp}, s	219.8
Thrust-to-pressure conversion factor	0.2512

Table 2 Composition of T17-E2 propellant

Component	Percent by weight
NH_4ClO_4 (oxidizer)	63.00
LP 33 (fuel)	33.17
GMF (curing catalysts)	2.32
DPG (curing catalysts)	1.16
Sulfur (curing catalysts)	0.02
Nylon tow (reinforcing agent)	0.33

JPL and ABMA began the effort to bring the re-entry test vehicle (RTV) project to life. The design requirements and interfaces were defined, and each organization began the process of design, testing, and fabrication. The qualification requirements of the Sergeant scale-model motor were compared to the RTV application so as to assess any new untested requirements. The significant unverified factors were vacuum ignition and the ability to withstand the centrifugal forces resulting from the high spin rate (750 rpm). (The second and third stages contained no guidance or attitude control system and depended on spinning to maintain attitude pointing.) A qualification program was then designed to verify the structural integrity of the case, nozzle, and grain under spin conditions.

A spin stand was constructed in which two scale-model motors were mounted as they would be in the second stage (the worst case for spin forces). The setup is shown in Fig. 6. Ignitor and transducer leads were carried through slip rings. Nonfiring spin tests were first made using stroboscopic lights to observe any deformations in the five-pointed internal star grains. No visible deflections were observed. After spinning, the grains were examined by boroscope for cracks. None were found. The two motors were then test fired successfully, one statically and the other while spinning.

Additional spin firing tests were done at various spin rates. Instrumentation included strain gauges, deflection gauges, temperature sensors, and pressure gauges. Comparison of pressure-vs-time curves between static and spin firings showed some differences, principally in the tailoff region. (See Fig.

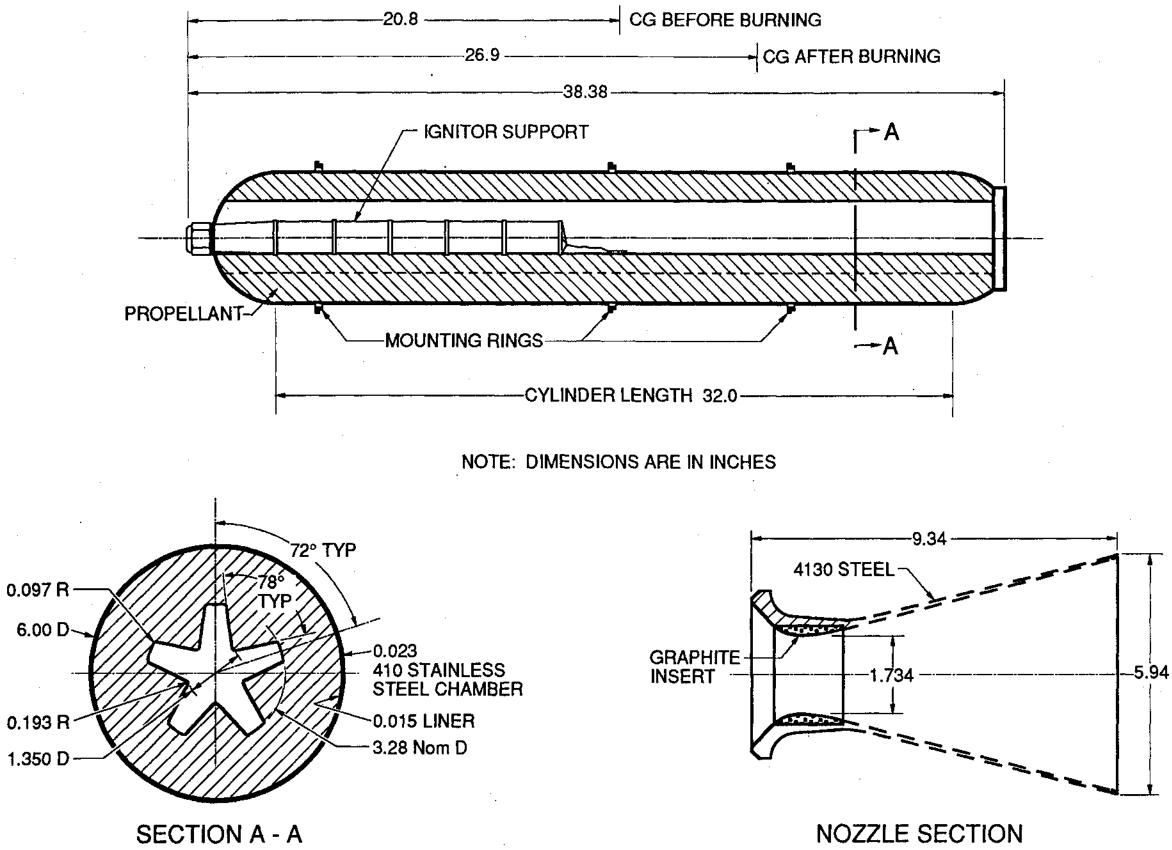

Fig. 3 Cross-sectional diagram of propellant grain and loaded motor (propellant T17-E2, Mandrell design 427).

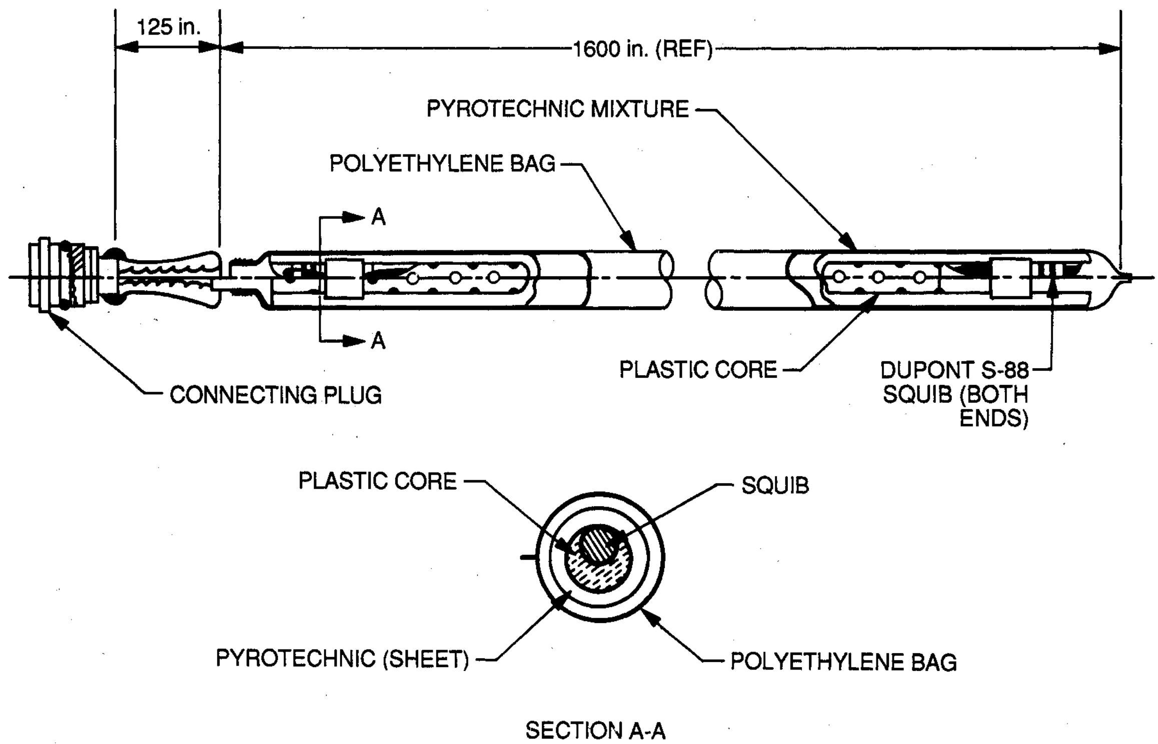

Fig. 4 Ignitor assembly.

7.) No adequate explanation of the differences was ever obtained; however, the spin-firing pressure-vs-time curves were consistently the same, and the total impulse for all of the spinning motors was the same as that of the static-fired motors.

It was found that at the maximum spin rate some permanent deflection of the cantilevered nozzles occurred. The nozzle design was modified to eliminate this deflection, even though the exhaust plume impingement indicated that the deflection occurred after the tailoff when maximum temperatures were reached in the nozzles (Fig. 8).

When operating under normal atmospheric conditions, the ignitors used in the 6-in. motor test program always operated successfully. The high-speed upper stages of the RTV, how-

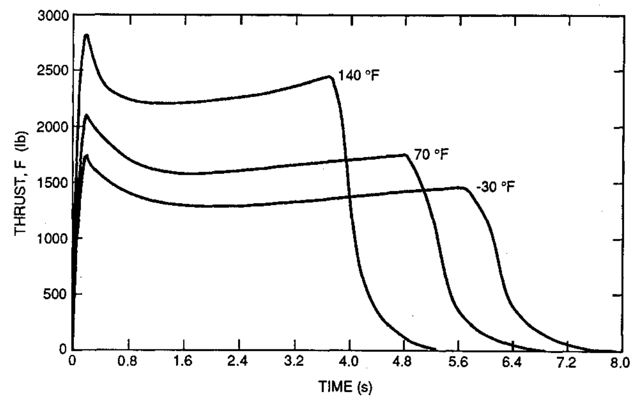

Fig. 5 Thrust vs time curves for scale-model sergeant motors.

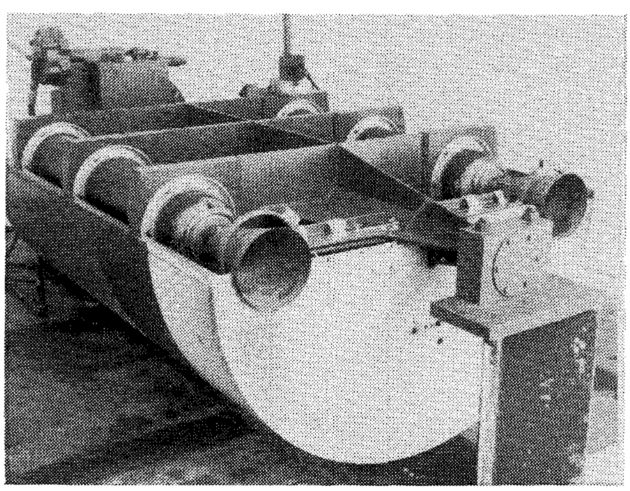

Fig. 6 Test setup for spin tests of scaled-down sergeant motors.

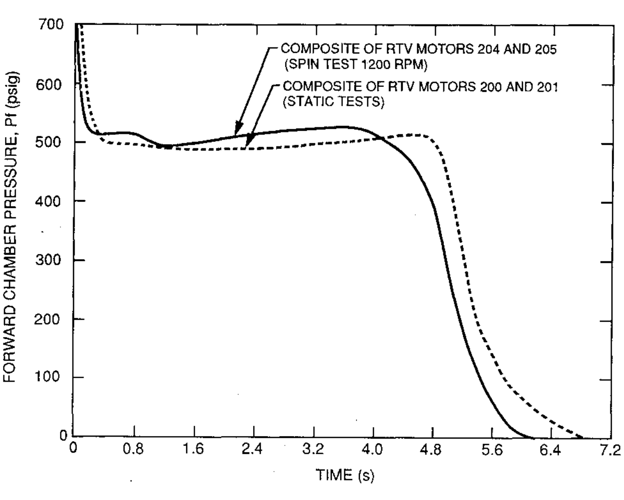

Fig. 7 Comparison of chamber pressures, static and spin tests.

ever, were to be fired at extremely high altitudes. It was, therefore, necessary to test the ignitors under vacuum conditions. These tests were carried out at the ABMA facilities at Redstone Arsenal.

During these tests, the original ignitors were subjected to 2 h of vacuum and, when firing current was applied, were found to be nonfunctional. The squibs functioned properly, but the ignition material (in the form of a jelly roll) failed to ignite. The ignitor material was changed from a Thiokol composition to a Hughes composition (Table 3). Although the Hughes mixture ignited and burned successfully, it did display a lack of reproducibility. To assure reliable and reproducible ignition, the entire ignitor was hermetically sealed in a plastic bag to maintain atmospheric pressure during ignition in space (Fig. 4).

In addition, a nozzle seal consisting of a thin copper sheet was soldered to the wall of the nozzle expansion cone to maintain atmospheric pressure in the motor grain. After these fixes were implemented, no further ignitor failures or erratic behavior were observed in either ground-based vacuum tests or in the RTV or Explorer flights.

A modification to the scale-model motor case was required in order to mount the motors within each of the upper-stage structures. The motors were to be mounted by attaching them via rings that were to be welded to the case (see Fig. 3). The rings produced high local stresses that were difficult to predict analytically. A series of hydrostatic pressure tests was carried out to determine the structural strength of the case-ring configuration. The case proof pressure value was 830 psi, and the actual burst pressure was 1730 psi. Deflection gauges also showed that the motor case deflections were well within the allowable range (i.e., the deflections were too small to result in an undue strain on the bolts connecting the motors to the stage bulkheads).

Performance Testing

The large number of scale-model motors that were static tested during the Sergeant development program formed the basis for estimating the flight performance and reliability of the RTV and Explorer. From these tests, data were obtained for pressure, thrust, and nozzle temperature as functions of time.

Performance characteristics of the solid propellant were determined by 1) direct measurements on the propellant (to determine density, structural properties, and burning rate), and 2) the static firing of batch test motors (to determine the characteristic velocity C^*). Typical results obtained from the static firing of the 6-in. motors are shown in Fig. 7 and Table 4.

Since there was no attitude-point capability for the RTV and Explorer after separation from the Redstone, the high-speed stages were spun at a high rate (750 rpm) for pointing stability. The requirement for mechanical alignment, center-of-mass (balance) control, and motor-to-motor reproducibility became very stringent. Control of the total dispersion angle at burnout had to be maintained to <1 deg.

With the propellant processing capability then available at JPL, it was not possible to mix, load, and cure all 11 6-in. motors that made up the second stage in a single propellant batch. This raised the question of what effect motor-to-motor variations would have and what could be done to minimize the variations.

Variations in solid propellant motors were broken down into two classes: 1) variations between motors when their propellants came from different batches (batch-to-batch variations and 2) variations between motors poured from the same propellant batch (within-batch variations). Data on propellant prepared at JPL indicated that batch-to-batch variations in thrust and burning rate were approximately 3%. The within-batch variation in thrust was approximatley 1.5%.

An analysis of these values was carried out to determine the flight direction accuracy for the high-speed upper stages. It was found that, on the basis of the values stated earlier, inaccuracies in the flight direction angle would be acceptably small. The mixer capacity could accommodate enough propellant to load four scale-model motors (48.28 lb each) plus several small batch-check test motors and propellant test specimens. The 11 second-stage motors for a given flight were then loaded in three batches of four, four, and three. The batch-check motors were then fired to determine that internal ballistic properties were neither too high nor too low, and the propellant test specimens were tested to validate physical

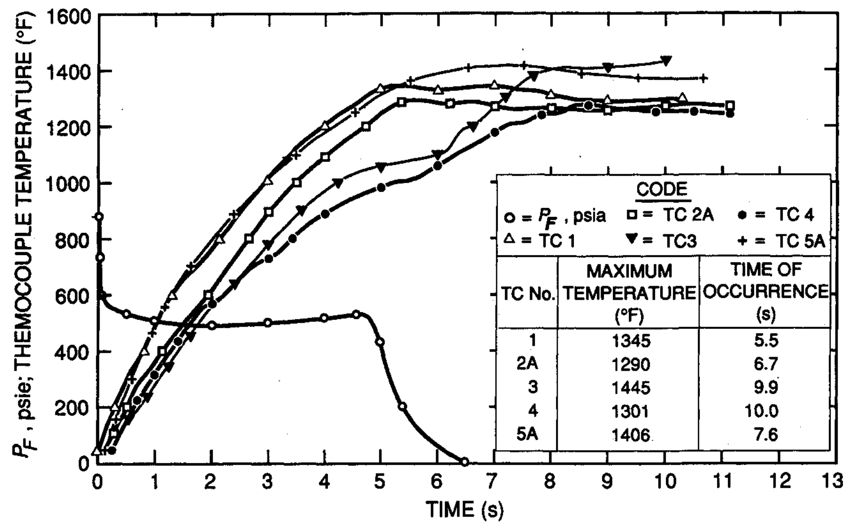

Fig. 8 Temperature history of a 1020 steel RTV nozzle.

Table 3 Ignitor compositions

Material	Weight %	Particle size (mesh)
Hughes Aircraft Co. (HAC) Composition:		
$KClO_4$	48.12	−200 to +250
Mg	48.12	−150 to +200
Polyisobutylene	3.76	
Thiokol X-225 Composition:		
$KClO_4$	72.3	
Ti	14.8	
B	6.9	
Polyisobutylene	6.0	

Table 4 Vacuum specific impulse: comparison of two methods of calculation

Motor design number	RTV	329	427	438
I_{sp} based on C* (s)	216.4	207.0	203.1	204.9
I_{sp} based on thrust measurements (s)	229.2	210.2	211.0	211.2
Number of motor tests giving thrust data	5	6	8	3
Nozzle-expansion ratios	11.73	6.13	4.91	5.39
Computed exit pressure (psia)	4.3	10.7	14.8	13.0

Table 5 Composition of JPL 136 propellant

Ingredients	Percent by weight
NH_4ClO_4[a]	
unground	50.52
ground (grind 8-IX)[b]	21.45
LP-33	25.67
GMF	1.71
Sulfur (flowers)	0.15
Monastrol fast blue (BT 284D)	0.50

[a]Specification of Aerojet General Corp.
[b]Model 1-SH micropulverizer grinder, hammer speed 9600 rpm, feed speed 80 rpm, screen 0.020-in. herringbone.

properties. The scale-model motors were trimmed to equal weight and loaded in a sequence so as to distribute the propellant batches as evenly as possible in the second stage. The third stage of three motors and the fourth-stage single motor were not a problem.

The second- and third-stage motors used the existing Sergeant propellant formulation designated T17-E2 (see Table 2). The fourth stage was loaded with propellant that had a slightly higher performance. It was designated JPL 136 (see Table 5). This departure from the standard formulation was justified because even a slight increase in the performance of the fourth stage resulted in a significant increase in payload mass.

Beyond Explorer

In addition to their use in the re-entry test vehicle and Explorer programs, the high-speed upper stages were also used in conjunction with the Jupiter IRBM (replacing the Redstone) to send two Pioneer payloads on lunar flyby missions in late 1958 and early 1959. The fourth stage for these two missions used titanium for the motor case. It is believed that this was the first application of titanium as a rocket motor case material.

After the initial successes of the RTV program and the first Explorer flights, proposals for applications of the Redstone-Jupiter high-speed stages to other missions were considered. These included replacing the third and fourth stages with other higher performance rockets. However, with the launching of the two Pioneers to the Moon and several more Explorer Earth satellites, the initial phase of space exploration utilizing existing hardware came to an end.

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