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SOLID ROCKET PROPULSION FOR SMALL-SATELLITE APPLICATIONS

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Thiokol CORPORATION, TACTICAL OPERATIONS, Elkton Division

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ABSTRACT

Thiokol Corporation has been a leading producer of space motors for more than 25 years. During this time, more than 2000 motors have successfully flown, representing a 0.998 reliability. These motors have ranged in size from 5 to 63 in. in diameter with propellant loadings of 4 to 7167 lbm and were designed to allow performance tailoring in order to meet specific customer requirements.
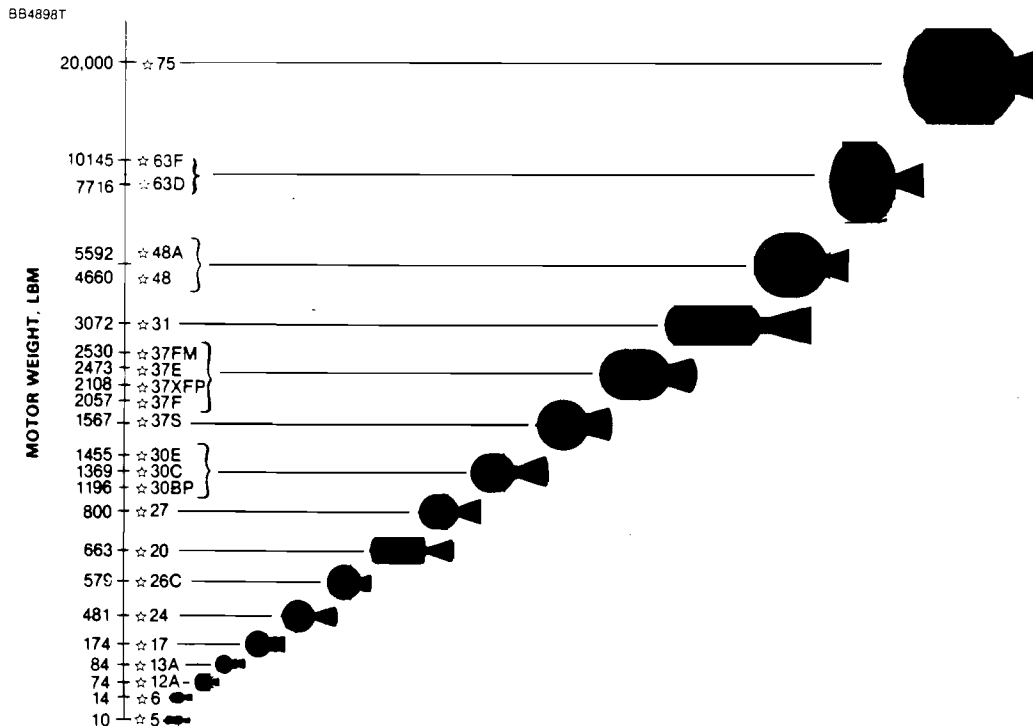
Thiokol offers many mature small motor designs that offer high reliability at a low cost for small-satellite applications. Motors used for small-satellite applications in the past generally had mass fractions of less than 0.89 and effective specific impulses of less than 288 lbf-sec/lbm. Recently, newer, higher-performing, higher-mass-fraction small space motors have been developed with higher-performing propellants, graphite cases, and thrust vector control. This paper discusses the availability, reliability, and motor modifications for existing designs and outlines new technologies available for small space motors.

SPACE MOTOR HISTORY

For more than 30 years Thiokol Corporation has provided solid rocket propulsion for spacecraft, upper stages, and boosters for a variety of commercial and governmental agencies. The Elkton Division of Thiokol Corporation has provided a key element in space propulsion with its STAR motor product line (see Figure 1). The Elkton Division, located in Elkton, Maryland, has designed and developed motors ranging up to 7 ft in diameter and 15 ft in length and containing up to 20,000 lbm of high-energy solid propellant. More than 60 STAR motor configurations exist; a STAR motor has flown on virtually every major launch vehicle in the free world.

The STAR motor family ranges from 5 to 75 in. in diameter and consists of propellant loadings from less than 4 lb to 20,000 lb. The materials used in the construction of the various STAR motors include:

- Pressure vessels - titanium, steel, Kevlar®, fiberglass, graphite

- Propellant - carboxyl-terminated polybutadiene (CTPB), hydroxyl-terminated polybutadiene (HTPB), and other binders

- Exit cones - carbon-phenolic, silica-phenolic, carbon-carbon

- Throat insert - high-density graphite, multi-D carbon-carbon

BB4898T

MOTOR WEIGHT, LBM

20,000 — ☆75

10145 — ☆63F
7716 — ☆63D

5592 — ☆48A
4660 — ☆48

3072 — ☆31

2530 — ☆37FM
2473 — ☆37E
2108 — ☆37XFP
2057 — ☆37F
1567 — ☆37S

1455 — ☆30E
1369 — ☆30C
1196 — ☆30BP

800 — ☆27

663 — ☆20

579 — ☆26C

481 — ☆24

174 — ☆17
84 — ☆13A
74 — ☆12A-
14 — ☆6
10 — ☆5

Figure 1. Thiokol/Elkton Division STAR Motor Product Line

Since 1959 more than 3230 STAR motors have been flown and tested. The STAR motor family reliability is greater than 0.9975 at a 95% confidence level.

The intent of this paper is to discuss the smaller STAR motors. STAR motors such as the 27, 30, 37, and 48 series are available for applications where additional total impulse is required. (The performance of these motors is summarized in Table 1.)

In March 1959, the first STAR 20 spherical motor was launched for a NASA flight experiment. Since that time the STAR motor product line has been used for retro motors and orbital insertion motors on such programs as Mercury, Gemini, Apollo, Surveyor, Pioneer, Voyager, TIROS, Defense Meteorological Satellite, and Global Positioning Satellite (GPS). The STAR motor line has been used as upper stages on such launch vehicles as Delta, Scout, Atlas, Titan, Japanese N, Ariane, and the Space Shuttle. Most recently, the STAR motor line, particularly the smaller-diameter motors (less than 27 in.), has found new applications in various flight experiments. A performance and experience summary for a major portion of the STAR motor product line is listed in Table 1.

In the mid-1960s when spacecraft weights were relatively low, motors such as the STAR 13 and 17 were developed as apogee kick motors. These motors as well as the larger STAR 37 provided the technology and experience building blocks from which the high-performance and high-mass-fraction motors such as the STAR 30BP, STAR 37XFP, and STAR 48B were developed. Generally over the past two decades, the trend has been toward larger satellites that require larger propulsion systems. Recently, however, with the emphasis on Lightsat and the desire for quick-response-communication reconstitution by the various military branches, the need for smaller satellites and therefore smaller propulsion systems has been identified.

Table 1. STAR Motor Performance and Experience Summary
(Record as of September 1, 1989)

STAR Designation	Model Number	Nominal Diameter, in.	Total Impulse, lb-sec	Specific Impulse, lbf-sec/lbm	Propellant Weight, lbm	Propellant Mass Fraction	Flights and Tests
5	TE-M-500	5.05	895	189.0	3.8	0.870	15
5A	TE-M-863-1	5.125	1350	259.7	5.07	0.945	7
5C	TE-M-344-15	4.76	1252	268.0	4.58	0.465	892
6	TE-M-541-3	6.2	3,077	287.0	10.7	0.795 ⎫	294
6A	TE-M-542-3	6.2	2,063	285.3	7.2	0.723 ⎬	
6B	TE-M-790-1	7.3	3,686	273.0	13.5	0.595	22
10	TE-M-195	10.0	6,600	251.0	26.3	0.676	46
12	TE-M-236	12.0	10,350	252.0	40.3	0.660	510
12A	TE-M-236-3	12.1	13,745	270.0	50.2	0.670	**
13	TE-M-458	13.5	18,800	273.0	68.3	0.869	9
13A	TE-M-516	13.5	20,200	286.5	73.3	0.870	8
13B	TE-M-763	13.6	26,040	285.7	90.0	0.870	3
13C	TE-M-345-11/12	13.5	18,200	218.0	66.5	0.795	256
13D	TE-M-375	13.5	17,200	223.0	63.0	0.810	12
13E	TE-M-385	12.7	14,200	211.0	55.4	0.822	105
13F	TE-M-444	13.5	21,190	240.0	73.5	0.830	5
15	TE-M-456-2	15.0	24,500	228.0	99.5	0.926	21
17	TE-M-479	17.4	44,500	286.2	153.5	0.881	10
17A	TE-M-521-5	17.5	71,800	286.7	247.5	0.890	19
20 Spherical	TE-M-251	20.0	66,600	234.0	253	0.934	2
20	TE-M-640-1	19.7	173,500	286.5	602.3	0.908	36
20A	TE-M-640-3	19.7	184,900	291.9	630.0	0.910	2
20B	TE-M-640-4	19.7	173,500	286.5	602.3	0.907	11
24	TE-M-604	24.5	126,000	282.9	440.6	0.916 ⎫	
24A	TE-M-604-2	24.5	112,400	282.4	393.8	0.903 ⎪	
24B	TE-M-604-3	24.5	126,230	282.9	441.4	0.915 ⎬	15
24C	TE-M-604-4	24.5	138,000	282.1	484.0	0.917 ⎭	
25	TE-M-184-3	25.1	134,720	240.0	477.6	0.917	11
26	TE-M-442	26.0	138.500	271.0	508.5	0.860 ⎫	
26B	TE-M-442-1	26.1	142,759	271.7	524.0	0.910 ⎬	27
26C	TE-M-442-2	26.1	139,800	272.1	511.4	0.880 ⎭	

*STAR motors that have been replaced by other STAR motors
**Classified

T889054 (1 of 2)

Table 1. (Continued)

STAR Designation	Model Number	Nominal Diameter, in.	Total Impulse, lb-sec	Specific Impulse, lbf-sec/lbm	Propellant Weight, lbm	Propellant Mass Fraction	Flights and Tests
27	TE-M-616	27.3	213,760	287.8	735.6	0.924	
27A	TE-M-616-1	27.3	197,790	287.7	680.8	0.919	
27B	TE-M-616-4	27.3	203,550	288.2	699.3	0.921	
27C	TE-M-616-5	27.3	195,300	287.5	672.8	0.918	47
27D	TE-M-616-8	27.3	195,550	287.5	673.6	0.921	
27E	TE-M-616-9	27.3	194,740	287.4	671.0	0.921	
*30	TE-M-700-2	30.0	300,940	293.0	1,021.7	0.943	4
*30A	TE-M-700-4	30.0	302,350	294.7	1,021.0	0.942	
*30B	TE-M-700-5	30.0	328.200	293.0	1,113.0	0.941	44
30BP	TE-M-700-20	30.0	328,200	292.0	1,113.0	0.931	20
30C	TE-M-700-18	30.0	371,400	284.6	1,293.9	0.937	7
30E	TE-M-700-19	30.0	400,120	289.2	1,370.6	0.932	4
31	TE-M-762	30.1	840,000	293.5	2,835.0	0.929	17
*37	TE-M-364-1	36.8	356,200	260.0	1,230.0	0.899	57
*37B	TE-M-364-2	26.8	417,900	291.0	1,440.0	0.910	23
*37C	TE-M-364-18	36.8	608,600	285.5	2,125.0	0.921	9
*37D	TE-M-364-3	36.8	417,900	266.0	1,440.0	0.910	34
*37E	TE-M-364-4	36.8	654,200	283.6	2,290.0	0.926	91
*37F	TE-M-364-19	36.8	549.536	286.0	1,909.3	0.928	19
37FM	TE-M-783	36.8	685,934	289.8	2,350.7	0.928	5
*37G	TE-M-364-11	36.8	671,809	289.9	2,348.0	0.925	4
*37N	TE-M-364-14	36.8	357,500	290.0	1,232.0	0.898	9
*37S	TE-M-364-15	36.8	420,329	287.3	1,449.5	0.925	19
*37X	TE-M-714-1	36.8	685,148	295.6	2,350.7	0.928	1
*37XF	TE-M-714-6	36.7	571,470	290.0	1,950.4	0.929	19
*37XF	TE-M-714-8	36.7	526,670	291.1	1,796.2	0.924	
37XFP	TE-M-714-16	36.7	570,450	289.9	1,948.2	0.924	8
37XFP	TE-M-714-17	36.7	570,450	289.9	1,948.2	0.924	
*37Y	TE-M-714-2	36.8	701,000	297.0	2,360.0	0.930	2
40	TE-M-186-2	40.1	443,026	207.0	1,995.0	0.925	10
*48	TE-M-711-3	49.0	1,269,610	286.6	4,405,0	0.946	49
*48	TE-M-711-8	49.0	1,296,300	292.9	4,405.0	0.945	
48A	TE-M-799-1	49.0	1,525,299	283.9	5,336.2	0.946	1
48B	TE-M-711-17	49.0	1,275,740	286.0	4,430.0	0.941	15
48B	TE-M-711-18	49.0	1,303,705	292.1	4,430.0	0.939	
62	TE-M-731	62.0	1,600,000	294.0	5,420.0	0.940	1
63D	TU-936	63.0	2,033.000	283.0	7,166.5	0.929	7
63F	TE-M-963	62.6	2,827,520	298.1	9400	0.926	3
75	TE-M-775-1	75.0	4,795,730	288.0	16,541,7	0.930	1

Various other space motor tests and flights	361

Total (excluding the classified flights)	**3,235**

*STAR motors that have been replaced by other STAR motors

The STAR 13 and 17 motors are continuing to be used as orbital insertion motors; however, the STAR 5C and the newer STAR 5A and 6B motors are finding new applications in the small-satellite market segment. New technology is being developed for high-mass-fraction and high-performance motors that have direct application to small-satellite propulsion requirements. Performance flexibility within the STAR motor line also provides the user with the ability to tailor the motor's performance to the specified requirements thereby provides greater mission flexibility.

The STAR 5A, 5C, and 6B have been designed and developed as retro and orbital insertion motors. The motor designs are shown in Figures 2, 3, and 4 and the performance for these motors is listed in Table 2. The STAR 5A completed qualification in 1988 and, in addition to environmental testing, was static tested five times. The STAR 5A has been delivered and will be flying on an upcoming DoD flight. The STAR 5A was designed to provide a low level of thrust (51 lbf) over a long burn time (25 sec). The STAR 5A uses an aluminum case and a silica-phenolic nozzle. In comparison, the STAR 5C provides approximately the same amount of total impulse in 2.8 sec at a thrust level of 439 lbf. The STAR 5C was qualified in the mid-1960s and has flown on various Titan launch vehicles more than 665 times. A steel case and closure and a silica-phenolic exit cone are used on the STAR 5C. Qualified in 1984, the STAR 6B was designed as a kick motor for use on reentry experiments. The STAR 6B case is aluminum and the exit cone is tape-wrapped carbon-phenolic. The STAR 6B provides 3686 lbf-sec of total impulse at an average thrust of 565 lbf.
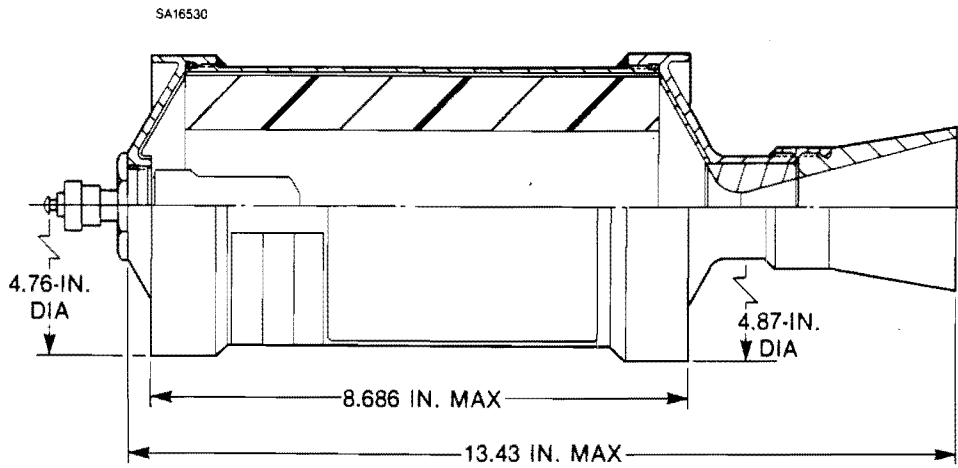
Table 2. STAR 5 and 6 Motor Performance

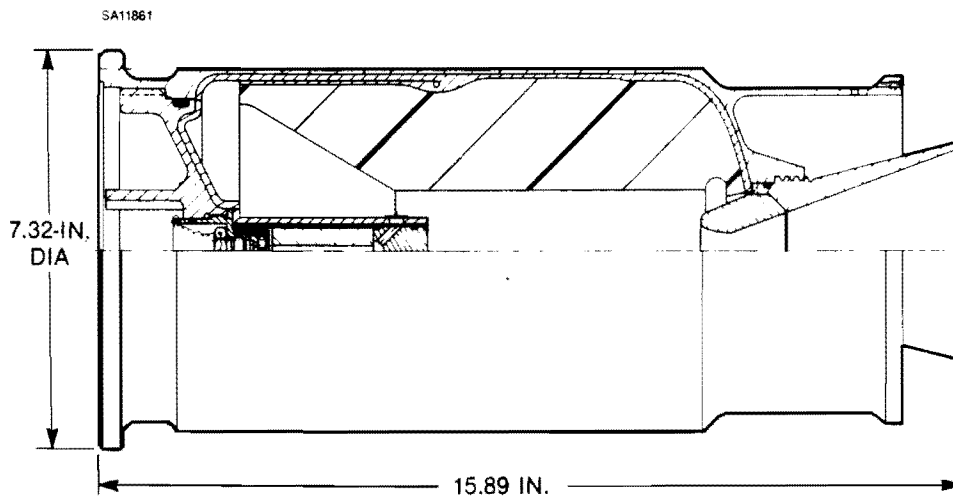|	STAR 5A	STAR 5C	STAR 6B
Total weight, lbm	10.24	9.86	22.62
Propellant weight, lbm	5.07	4.58	13.45
Inert weight, lbm	5.17	5.28	9.17
Burn time, sec	24.70	2.80	5.9
Total impulse, lbf-sec	1350	1252	3686
Average thrust, lbf	51	439	565

Y687012D [110]

The STAR 13 series has been flying since the mid-1960s. There have been more than 385 STAR 13 tests and flights on Titan, Gemini, Burner II, and other missions. The STAR 13B motor has been used recently on several SDIO missions. The designs of the high-performance STAR 13A and 13B motors are shown in Figures 5 and 6. The STAR 13B is an elongated version of the 13A, which was accomplished by the addition of a cylindrical section between the case hemispheres. This 2-in. cylinder length provides the volume for an additional 18 lb of propellant. A performance summary for the STAR 13A and 13B is listed in Table 3. The STAR 13A and 13B motors have a 6Al-4V titanium case, silica-phenolic exit cone, graphite throat, and redundant pyrogen igniters.

SA21912

5.125-IN.
DIA

8.84 IN.
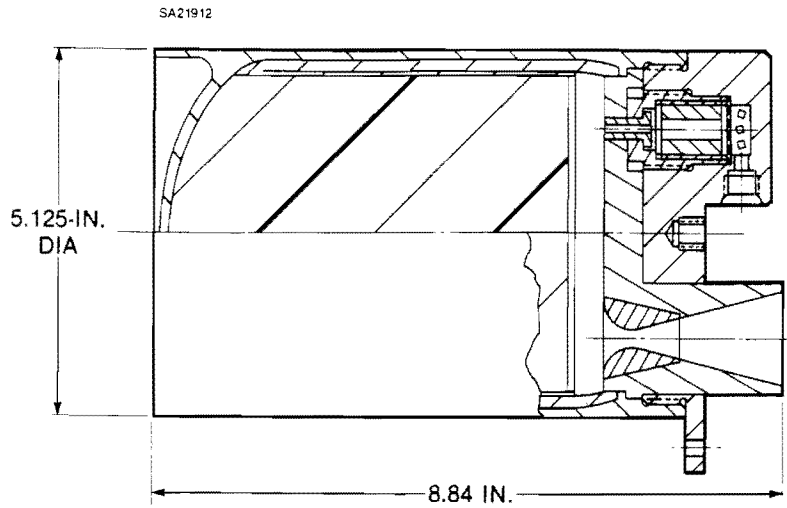
Figure 2. STAR 5A Motor Assembly

SA16530

4.76-IN.
DIA

4.87-IN.
DIA

8.686 IN. MAX

13.43 IN. MAX

Figure 3. STAR 5C Motor Assembly

SA11861

7.32-IN.
DIA

15.89 IN.
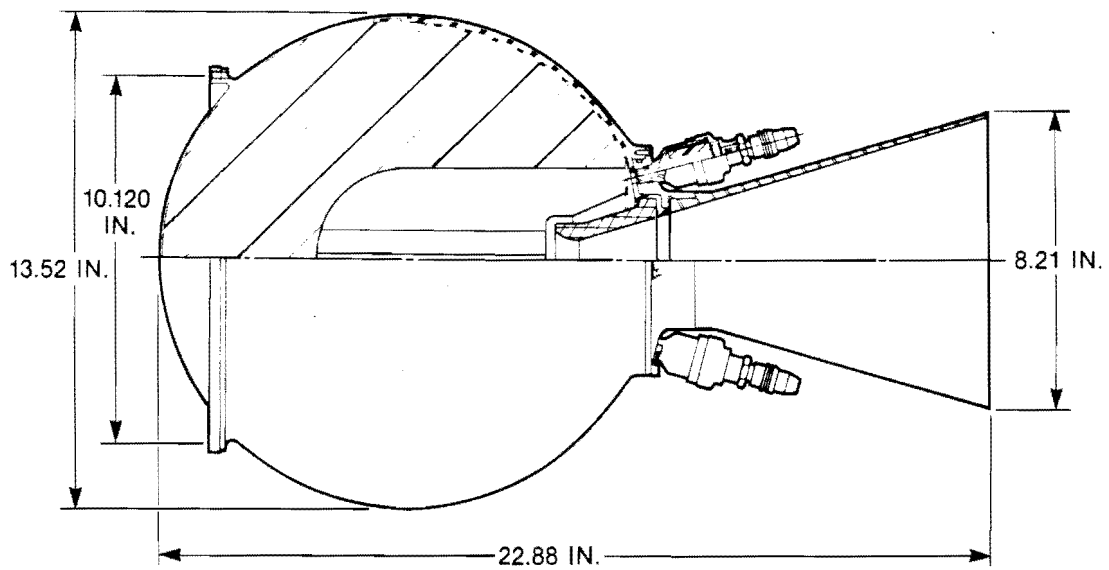
Figure 4. STAR 6B Motor Assembly

BC16794

Figure 5. STAR 13A Motor Assembly

BC13558
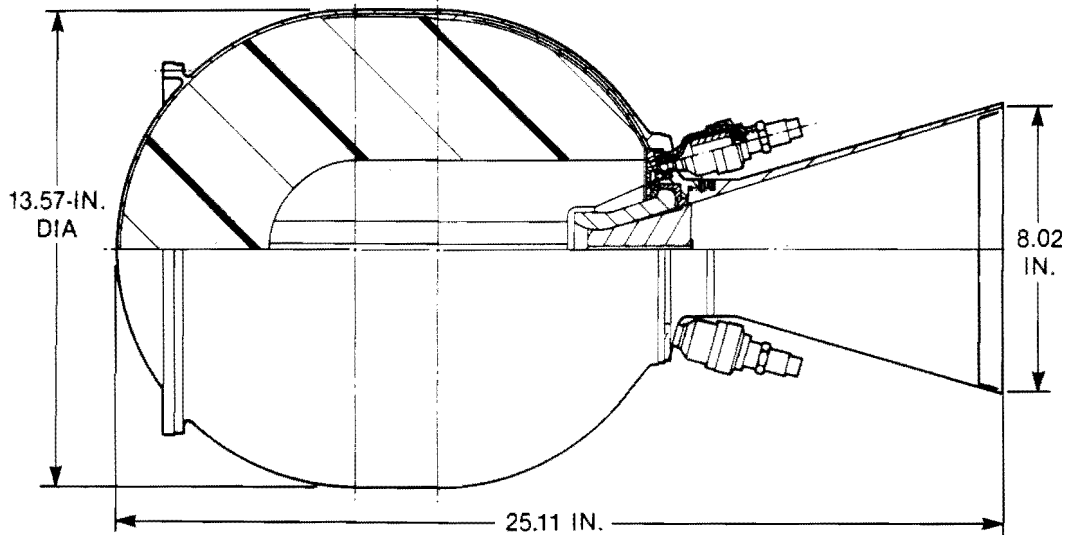
Figure 6. STAR 13B Motor Assembly

Table 3. Performance and Mass - STAR 13 Motors

	STAR 13A	STAR 13B
Total impulse, lbf-sec	21,050	26,040
Max thrust, lbf	1680	2160
I_{sp}, eff, lbf-sec/lbm	286.5	285.7
Total weight, lbm	84	103.7
Propellant weight, lbm	73	90.9

Y486262A [81]

E198-89

The STAR 17 and 17A motors have a mass fraction of greater than 0.88 and, like the STAR 13A, incorporate the use of a titanium case and silica-phenolic exit cone. Figures 7 and 8 show the STAR 17 designs and Table 4 lists the performance summary. The STAR 17 motor has been tested and flown 27 times, with the flights occurring on both Delta and Atlas launch vehicles. The STAR 17 and 13 motors use TP-H-3062, which is an 86% solids CTPB propellant.
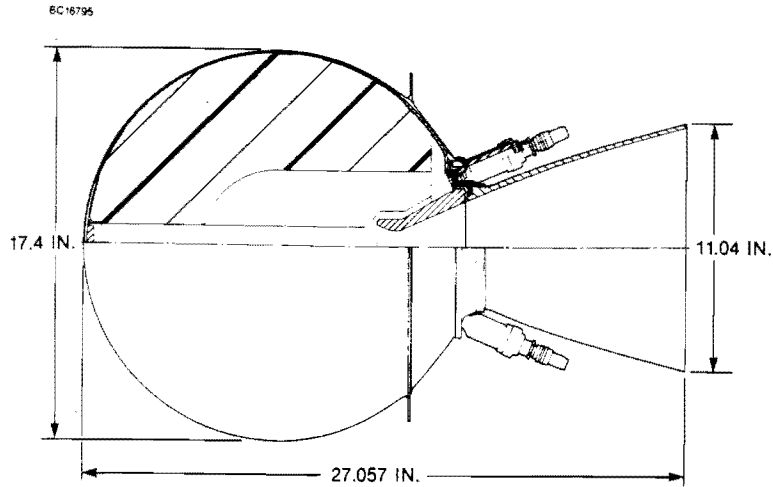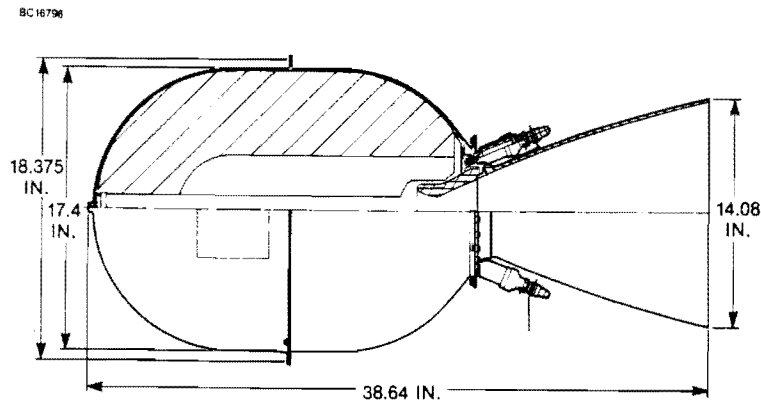

Figure 7. STAR 17 Motor Assembly

Figure 8. STAR 17A Motor Assembly

Table 4. Performance and Mass - STAR 17 Motors

	STAR 17	STAR 17A
Total impulse, lbf-sec	44,500	71,800
Max thrust, lbf	2775	3900
I_{sp}, eff, lbf-sec/lbm	286.2	286.7
Total weight, lbm	174.3	277
Propellant weight, lbm	153.5	247.5

PERFORMANCE TAILORING

Performance tailoring after motor development and qualification is necessary so that specific mission goals can be met without major motor redesign that would require requalification. Typical performance tailorings involve the removal of propellant weight, changes in thrust level, and changes in burn time.

Off-Loading. The removal of propellant or "off-loading" is done to reduce the amount of total impulse produced by the rocket motor. More specifically, off-loading reduces the amount of incremental velocity imparted to the spacecraft. Typically, propellant is removed from the aft end of the propellant grain where most of the ballistic control surfaces exist. These control surfaces, such as star points or slots, can be easily trimmed if the off-load is 5% of the full-load propellant weight. If the off-loaded weight exceeds 5%, then the control surfaces must be wholly redesigned as well as the entire grain. When the grain is wholly redesigned or just easily trimmed, the goal is to maintain the idenitical throat diameter, nozzle assembly, insulation, igniter, and use existing propellant machining tools to keep costs down. To date, we have been able to off-load up to 85% of a motor's propellant weight without making any other motor modifications. This approach to off-loading seems restrictive but ensures that near identical chamber pressures (within 1%) and specific impulses are reliably reproduced without the need for a requalification test.

Thrust Modification. Changes in thrust level may be necessary when a spacecraft cannot tolerate the g loading imparted by the rocket motor's boost or when a spacecraft requires an increase in incremental velocity. A reduction in thrust level is required when a spacecraft cannot tolerate the g loading.

Thrust can be reduced in a solid rocket motor by changing the grain design, lowering the burning rate, or reducing the nozzle expansion ratio. The grain can be simply modified by reducing the burning surface area at the maximum g-load point. Reducing the surface area lowers the internal pressure and in turn lowers the thrust level; therefore, the g load is reduced. An approach to lowering the surface area to reduce the thrust level is to decrease the web in a local area such that this web area reaches the case wall before the majority of the burning surface. The amount of web reduction can be adjusted so that the desired time and level of thrust or g's are attained within the maximum operating conditions of the motor. A typical grain change for a head-end web grain would be to extend the bore at a constant, reduced diameter towards the head end and an opening of the throat diameter.

A second approach to lowering the thrust level is to reduce the propellant burning rate. When the burning rate is reduced, the internal chamber pressure is reduced and therefore the thrust is reduced. The burning rate can be easily reduced by changing the oxidizer modal distribution to include coarser particle sizes. More drastically, the propellant type or formulation

can be changed, which would require more analysis and possibly static testing before a motor could be delivered. By simply changing the propellant's oxidizer modal distribution of an existing motor, a simple ballistic analysis is all that is required to verify the change in performance. Note that increases in burn time will occur and if they are large enough, motor case and/or nozzle insulation changes may be required.

A reduction in nozzle expansion ratio (Ae/At) will also reduce the thrust level. A simple truncation of the nozzle exit cone, which reduces the exit area (Ae) until the desired thrust level or specific impulse is obtained, is all that is required to lower performance. An increase in throat area (At) has the same effect except that motor burn time and pressure are affected. Basically, the expansion ratio is lowered, which in turn lowers the thrust coefficient and specific impulse.

To increase the thrust level, the opposite of the changes just described above can be performed. Adding propellant weight or using a higher-density, higher-total-solids propellant, increasing the burning rate, and increasing the nozzle exit cone length (by simply lengthening the exit cone before manufacture or by using extendible exit cones or gas-deployed skirts) will increase the thrust level.

Burn-Time Modifications. The purpose of modifying the burn time is to obtain extended or shortened pressure and thrust levels. Modifications to burn time are accommodated by changing the oxidizer modal distribution while keeping the same propellant formulation or increasing the grain web thickness. Changing the oxidizer modal distribution has been accomplished for many space motor and other rocket motor programs at Thiokol/Elkton. Burn rate changes up to 5% can be made without affecting combustion and specific impulse efficiencies. Greater changes in burn rate will require further testing to assure that predicted performance can be met. A simpler approach to extending the burn time is to lengthen the web thickness. This approach allows for the same pressure and thrust levels for an end-burning grain design, whether the grain is shortened or lengthened. If the web is lengthened for a center-perforate (CP) or head-end web (HEW) grain design, the propellant weight is increased, which decreases the average burning surface area and allows for pressure and thrust increases. The opposite is true for when the web thickness is shortened for CP and HEW grains. In combination with a minor throat diameter and grain changes, the pressure and thrust levels may be modified to the limit of the hardware.

NEXT-GENERATION STAR MOTORS

The next generation of STAR rocket motors for satellite applications will be derived from space-based interceptor (SBI) technology. Existing technologies used in the STAR motor family, up to STAR 17, are 30 years old and are proven and reliable. Increased performance to this series of motors can be obtained by applying all or individual technologies. Recently, an SBI development motor, shown in Figure 9, has been statically tested and is presently under redesign to improve its mass fraction and performance. These new and future improved motors will have high operating pressures, advanced materials for case and nozzle components, consumable igniters, thrust vector control, and advanced propellant systems for all motor sizes to increase motor mass fraction and specific impulse.
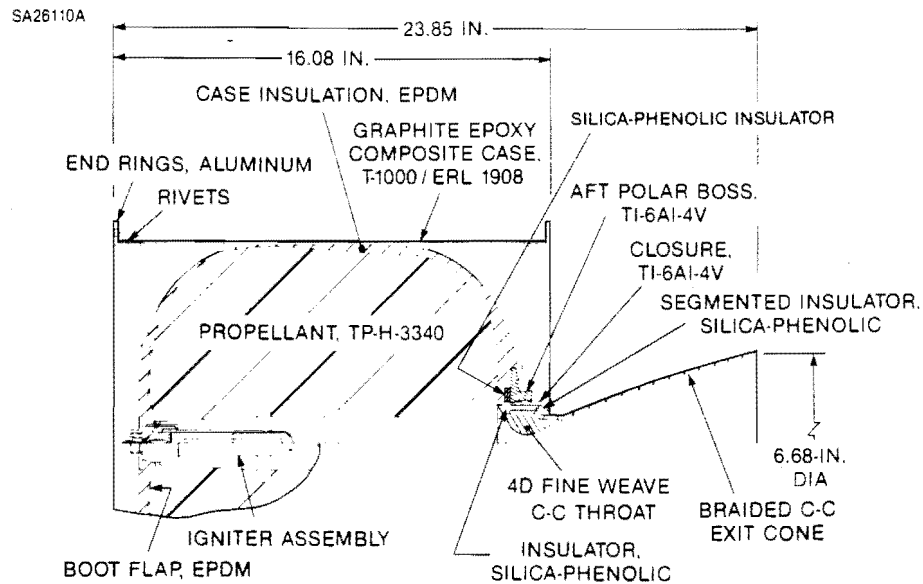
Figure 9. Conservative SBI Development Motor ($m_f = 0.87$)

Existing Technologies. Existing technologies in the STAR motor family, up to the STAR 17, have been designed and flown with proven, reliable propellants, materials, and components.

These STAR motors have been generally loaded with aluminized, ammonium perchlorate (AP) propellants using urethane, polysulfide, and CTPB as binders. These were typically 82 to 88% total solids (TS) and 14 to 16% aluminum (Al) formulations with low burning rates and adiabatic flame temperatures up to 5660°F. Nozzle materials of the present small-satellite STAR motors use silica-and carbon-phenolic, aluminum, steel, and fiberglass for exit cones; graphite and molybdenum for throat inserts; aluminum, steel, and titanium for closures; and phenolics for insulators. Case materials used then and still used today are aluminum, steel, and titanium, though titanium dominates most of the recent larger STAR motor designs.

Operating Pressures and Throat Erosion. Operating pressures for future STAR motors will range from 1000 to 2000 psia and use higher-energy propellants. High pressure is desired for increased expansion ratio. Higher-energy propellants (89 to 91% TS, 18 to 21% Al, ammonium perchlorate, beryllium [AP/Be]) yield higher adiabatic flame temperatures (>6000°F) and molecular weights and therefore produce higher theoretical specific impulses. In combination with higher pressures, the existing throat materials, such as the graphites, metals, and phenolics, do not erode at a rate so that expansion ratio and performance can be maintained. To overcome the increased throat erosion rates, throat erosion test from SBI work has shown that low-cost 4D carbon-carbon yields good performance at a comparable erosion rate of previous materials. Additional testing of throat materials with high-energy propellants has shown that improved performance can be obtained with pyrolytic graphite and 3D carbon-carbon materials up to 2500 psia, but at an additional cost and nozzle complexity. Therefore, next-generation STAR motors will have an optimized propellant, pressure, and throat material so that performance is maximized.

Advanced Materials. Advanced materials will be used to decrease the amount or weight of inert components (components other than propellant). The components using advanced materials are the motor case and nozzle.

The motor case has been typically fabricated from steel, aluminum, or titanium in some of the later STAR motors. Today, graphite-epoxy with either T40 or T1000 fibers provides a lighter and stronger pressure vessel per pound of weight than previous materials. The lighter weight results from the higher strength of graphite-epoxy versus titanium (960 ksi versus 165 ksi).

Presently, the bosses for a graphite-epoxy motor case are titanium, as shown in Figure 9. To obtain the proposed mass fractions for SBI, as shown in Figure 10, these bosses, as well as closures, can be manufactured from a lightweight composite material to reduce inert weights. As these technologies progress for SBI, the STAR motor family will absorb any advantages for increased motor performance.
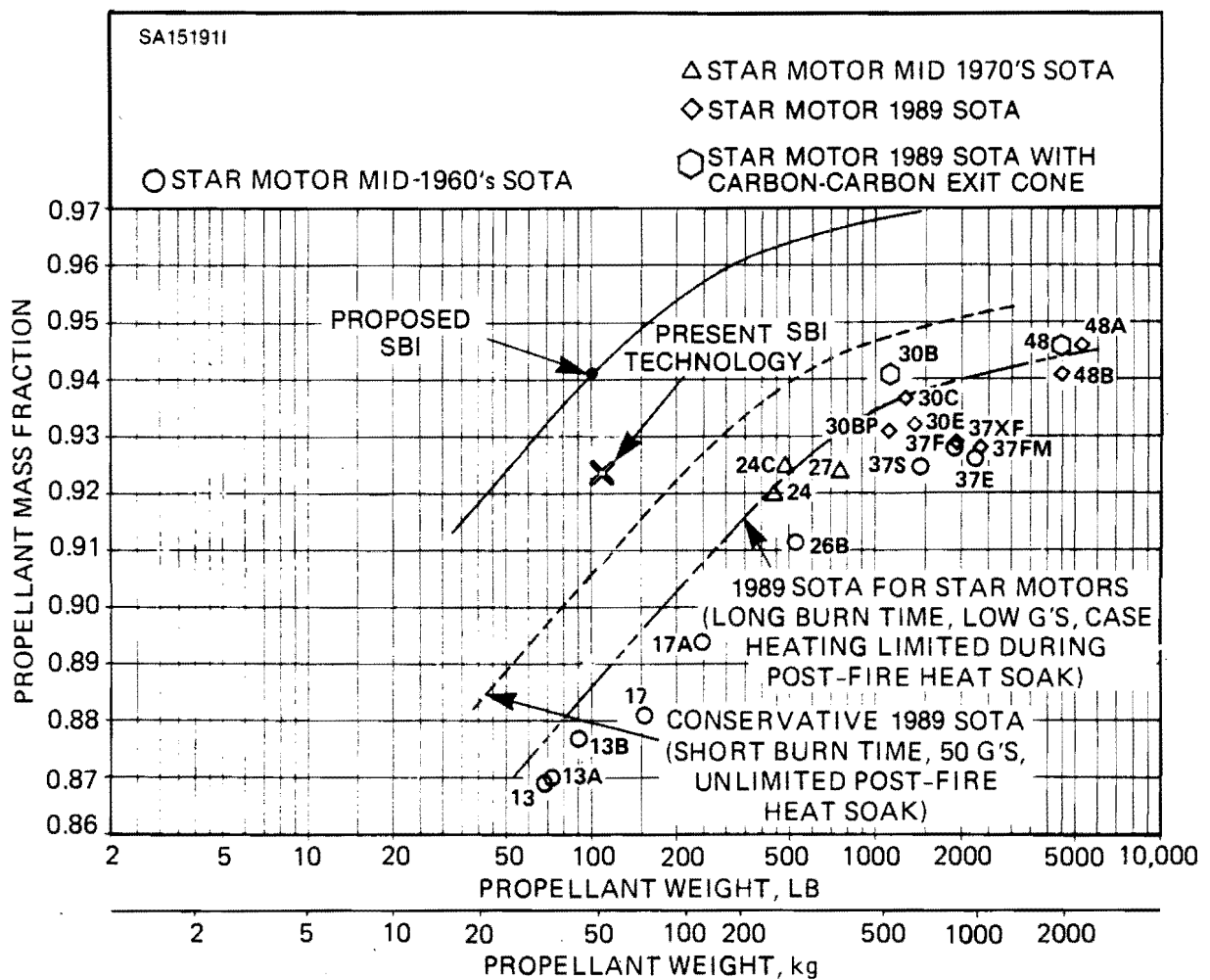
Figure 10. SBI Mass Fraction Improves Upon STAR Motor History

An additional feature of graphite-epoxy cases is the ability to manufacture the propellant grain first and then wind the case over the grain. This process is called the case-on propellant process and is less costly than the conventional process because of the reduced number of components during manufacture. To simplify the process even further, the nozzle assembly can be wound onto the case while the propellant is being wrapped, which further reduces motor cost.

The nozzle assembly is composed of four basic components: the exit cone, throat, closure, and insulator. The exit cone in a conservative design would be made from tape-wrapped carbon-phenolic, but in the SBI conservative design, a thin-walled carbon-carbon exit cone has been successfully tested. This thin-walled braided carbon-carbon exit cone is 0.080 in. thick at the exit plane and weighs less than 1 lb. Throat materials were discussed earlier and pyrolytic graphite would be the material of choice for high performance without regard to cost. A carbon-phenolic material would be more suitable for small-satellite applications where cost is a concern. The closures are made of titanium and will remain titanium until a lightweight, high-strength, and high-temperature composite is found. Insulators used in the conservative SBI design are molded silica-phenolic and will continue to be used.

Consumable Igniters. The advantage of a consumable igniter is that its inert weight is expelled during motor operation and reduces the overall system weight being propelled. A lightweight, aluminum cased pyrogen igniter, shown in Figure 11, has been successfully tested three times in the conservative SBI development motor. The reduction in inert weight is another small part of increasing motor performance.
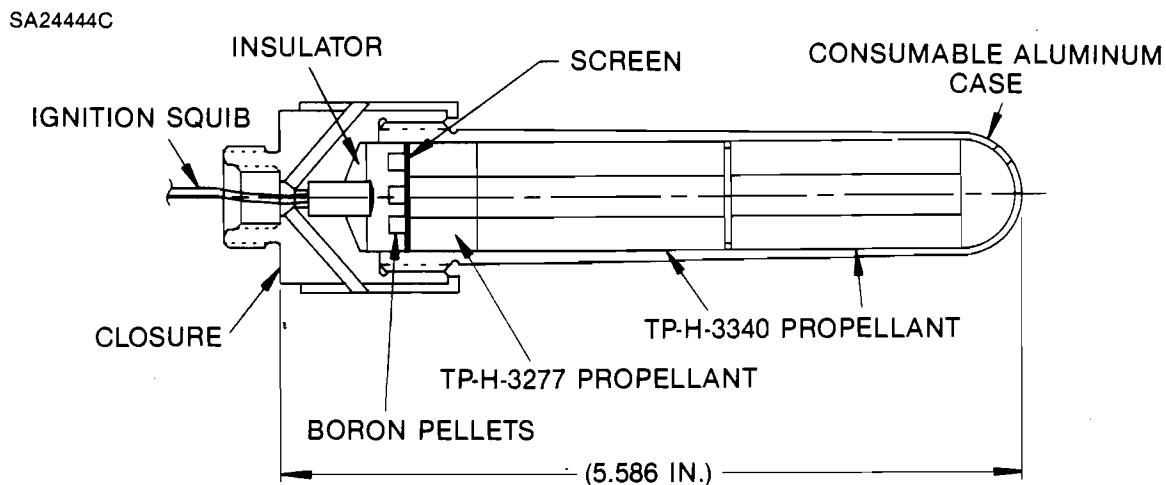

Figure 11. Consumable Pyrogen Igniter

Thrust Vector Control (TVC). TVC has been developed and tested on many motors at Thiokol/Elkton. This technology is applicable to existing STAR motors or the new SBI technology-based motors. The most applicable TVC system for small space motors is either the reversed-trapped-ball or flexseal design. The reverse-trapped-ball TVC nozzle has been developed and tested for the STAR 27 motor. The flexseal design uses polyisoprene and natural rubber and steel shims for the movable seal, and electromechanical or electrohydraulic actuators are used to move the nozzle.

Advanced Propellant Systems. Advanced propellants using higher total solids loading and higher-energy fuels and oxidizers will lead the way to lower stage weights and higher specific impulses. Higher-solids-loading propellants provide increased density and energy, yielding higher mass fractions and specific impulses. Propellants with 89 to 90% TS and 18 to 21% Al have flown in larger STAR motors (STAR 30, 37, 48, and 63) and can be easily adapted to existing smaller STAR motors. SBI is presently using Al/AP-type propellants for baseline evaluation before testing higher-energy propellants. Some of the higher-energy propellants considered by SBI programs and for possible future commercial use (if the toxicity issues are resolved) are shown in Figure 12. Beryllium (Be), beryllium hydride (BeH_2), and hydroxyl ammonium perchlorate (HAP) are three energetic ingredients that raise the theoretical specific impulse. As the figure shows, a BeH_2/HAP propellant shows a 60-sec increase in theoretical specific impulse. Though the delivered specific impulse will be somewhat lower, the performance and payload increases are tremendous when compared to conventional Al/AP propellants.
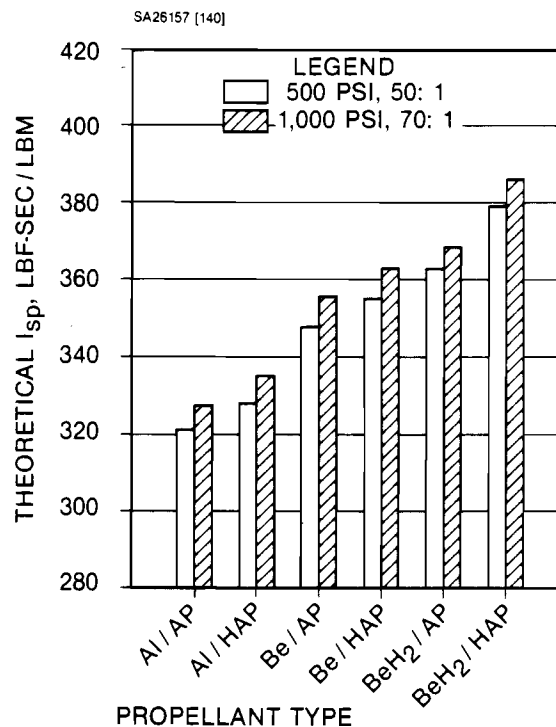
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Figure 12. Specific Impulse Versus Propellant Type

OTHER PROPELLANT SYSTEMS

Low aluminum and nonaluminized propellants are available for special applications where contamination of critical surfaces, such as sensors, is important. By reducing the aluminum content to 2% or less, the amount of aluminum oxide (Al_2O_3) in the exhaust gas species is lowered. Al_2O_3 is generally responsible for fouling the effectiveness of sensors and solar arrays. The STAR 6B motor is an example of a reduced-contamination motor utilizing a 2% Al propellant formulation.

MASS FRACTION AND PERFORMANCE

Mass fraction has been discussed as an important part of increasing the performance of future STAR motors through the use of SBI technology. Mass fraction is the ratio of propellant weight to the total weight of the rocket motor. The greater this value is means that the inert component weight has been minimized and the energetic part, the propellant, has been maximized. The STAR 13 to STAR 17 mass fractions range from 0.87 to 0.895, as shown in Figure 10.

Using the SBI-based technology and applying it to small-space-motor application, a kick motor like the one shown in Figure 13 has been designed. The motor has a total weight of 134.33 lbm of which only 10.07 lbm is the inert weight. A weight breakdown of the design is shown in Table 5. This yields a mass fraction of 0.925, which is higher than the existing technology used for small space motors. In referring to Figure 10, again, the mass fraction of this motor is approaching the proposed SBI mass fraction's goal of 0.94.

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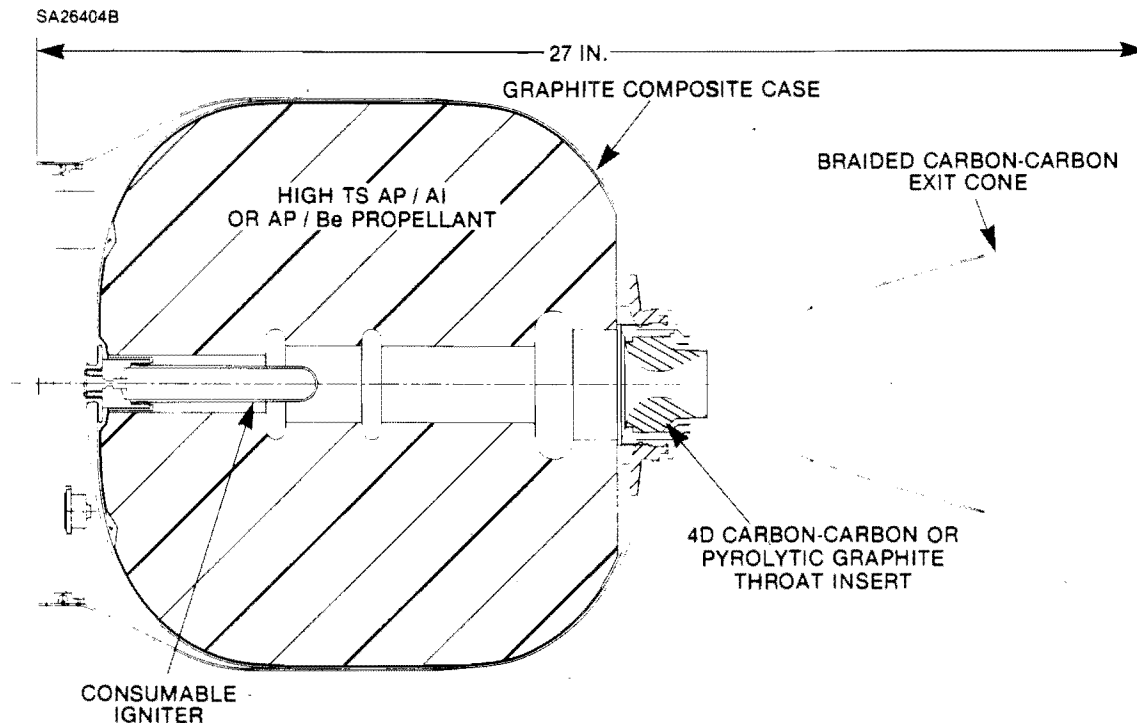
Figure 13. Next-Generation STAR Motor (Based on SBI-based Technology)
($m_f = 0.925$)

Table 5. SBI-based Technology STAR Motor Weight Summary

	lbm
Fiber	3.68
Aft pole piece	0.06
Forward pole piece	1.00
Insulation	1.92
Liner	0.31
Exit cone	0.95
Throat	0.39
Throat insulation	0.21
Closure	0.39
Igniter	0.38
Attachment ring	0.57
Shear ply	0.11
Miscellaneous	0.10
Total inert	10.07
Propellant (AP / Al)	124.26
Total loaded	134.33
Mass fraction	0.925
I_{sp}, lbf·sec / lbm	

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The specific impulse of the improved SBI-based motor is the same as the conservative SBI development motor, as shown in Table 6, since the grain design was kept the same and only the insulation thickness was reduced. The reduced insulation thickness provides more volume for propellant. The additional propellant weight raises the mass fraction and the total impulse and, therefore, either the payload weight or incremental velocity is increased. When a higher-energy propellant such as AP/Be is used, the mass fraction is slightly lowered to 0.92. However, the potential increase in delivered specific impulse outweighs the loss in mass fraction.

Table 6. SBI-based Motor Performance Summary

Motor Features	SBI / T-1, Sea Level	SBI / T-2, Vacuum	Flight*	Flight*
Propellant type	AP / Al	AP / Al	AP / Al	AP / Be
Total weight, lbm	134.8	131.5	134.33	126.60
Propellant weight, lbm	114.5	114.7	124.36	116.53
Inert weight, lbm	20.3	16.8	10.07	10.07
Burnout weight, lbm	19.3	15.0	8.3	8.3
Expansion ratio	45.3	45.4	45.4	36.1
Mass fraction	0.849	0.872	0.925	0.920
I_{sp} propellant, lbf-sec / lbm	N / A	290.4	290.4	Classified
I_{sp} effective, lbf-sec / lbm	N / A	286.6	286.6	Classified
*Predicted				

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CONCLUSION

The STAR motor line has played a significant part in satellite propulsion. Existing STAR motors with their high performance as well as ballistic flexibility have been the industry standard for orbit insertion motors. The next generation of small satellites will require high performance propulsion systems for orbital insertion. New technologies, such as those being developed in SBI efforts, have been and will continue to be incorporated into solid rocket motor propulsion for small satellites application so that performance and payload capability will be continually increased.