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Prototype Development of a Solid Propellant Rocket Motor and an Electronic Safing and Arming Device for Nanosatellite (NANOSAT) Missions

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PROTOTYPE DEVELOPMENT OF A SOLID PROPELLANT ROCKET MOTOR AND AN ELECTRONIC SAFING AND ARMING DEVICE FOR NANOSATELLITE (NANOSAT) MISSIONS

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Introduction

Background

NASA/GSFC Nanosatellite Propulsion Development Program

Recently, there has been an increased interest in using nanosatellites in space science missions due to many unique science mission architectures that are only possible with a nanosatellite constellation. Hundreds of small and lightweight nanosatellites can form an intelligent constellation acting as a distributed network of instruments. In this way, measurements can be obtained that are not possible with traditional single spacecraft architectures. Such a constellation could take simultaneous, *in situ* measurements of dynamic phenomena in the Earth's magnetosphere. This type of data is considered to be a critical element in the NASA Sun-Earth Connection (SEC) roadmap. Currently, the SEC roadmap features several nanosatellite constellation missions under consideration for potential future use. One such mission currently in a study phase at NASA's Goddard Space Flight Center (NASA/GSFC) is the Magnetospheric Constellation (MagCon) mission.

The Magnetospheric Constellation Mission Concept

The MagCon mission architecture calls for a constellation of about 100 nanosatellites launched from a single deployer ship. The nanosatellites perform individual orbit raising maneuvers to enter elliptical orbits with apogees from 3 to 50 r_e to provide simultaneous, multipoint observations of the Earth's magnetospheric environment. Figure 1 shows the current configuration of the nanosatellite as an octagonal disk of 30 cm in diameter and 10 cm in height. Each nanosatellite is spin-stabilized about its major axis with a primary attitude control mode of spin axis precession. Figure 2 illustrates the current deployer ship concept. While each nanosatellite has a mass of no more than 10 kg, it is designed to carry a multi-instrument suite of particle and field detectors to perform "research quality science." In addition, nanosatellites are designed to form an intelligent constellation of a distributed instrument network, enabling nanosatellites to autonomously reconfigure the network to quickly respond to dynamic magnetospheric events. The constellation autonomy requires that each nanosatellite be capable of space-to-space communication. In addition, each nanosatellite requires a propulsion system providing both the attitude control and orbit-changing capabilities to be able to reconfigure the constellation.

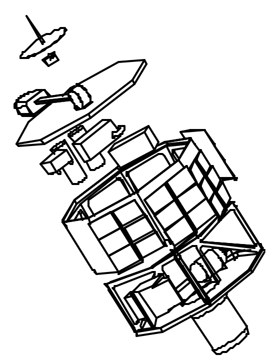

Figure 1. Exploded View of the Nanosatellite for the MagCon Mission

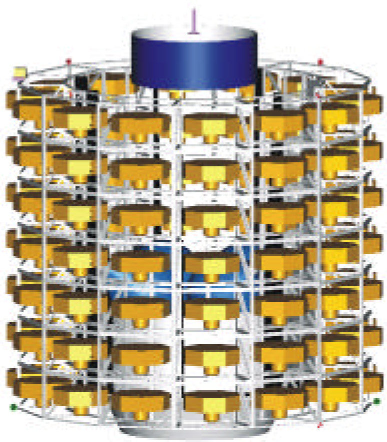

Figure 2. Nanosatellite Deployer Ship Concept

To build such small, lightweight, and intelligent spacecraft poses a tremendous challenge. Existing spacecraft components designed for larger size spacecraft would not work with nanosatellites due to the severely limited power and volume constraints imposed by nanosatellites. Indeed, the study results show that virtually every spacecraft subsystem requires breakthroughs in fully functional miniaturized components in order to make the intelligent nanosatellite constellation feasible. Thus, the MagCon mission study is also focusing on the identification and development of spacecraft component technologies that are suitable for the MagCon and future nanosatellite missions.

A significant part of the nanosatellites' component development effort deals with developing suitable propulsion components. Currently, there are very few propulsion components that are expressly designed for nanosatellites. It is expected that as nanosatellites evolve, greater demand will be placed on the propulsion subsystem to provide complex maneuvers required to maintain an autonomous, intelligent constellation. In an effort to meet these needs, the Propulsion Branch of NASA/GSFC has embarked on a program to develop nanosatellite propulsion components that will fulfill the requirements of both current and future nanosatellite constellation missions. After a conceptual study phase to determine the feasibility and the applicability to nanosatellite missions, flight-like prototypes of selected technology will be fabricated for testing. The development program will further narrow the effort to those technologies that are considered "mission-enabling" for future nanosatellite missions. These technologies will be flight-qualified with the potential of being flown on upcoming nanosatellite missions. One such program is the development of the nanosatellite solid motor prototype (NSMP). Table I shows the propulsion requirements for the MagCon nanosatellites. The NSMP is currently being developed by Thiokol to meet the requirements for the orbit-raising phase of the MagCon mission.

Table I. Current Propulsion Requirements for Nanosatellite Missions

	Orbit Raising (NSMP Motor)	Attitude Control
Total impulse	3000 N-s max	2.4 N-s
Thrust	445 N max	1.0 N
Input power	< 1 watt peak	< 1 watt peak
I_{sp}	280 sec	60 sec
Minimum I_{bit}	–	0.044 N-s
Pulse rate	–	1 Hz
Cycle life	–	>1000 cycles
Bus voltage	3.3 V	3.3 V

Motor Design, Fabrication, and Testing

Design and Fabrication

The goal of the NSMP program was to design, develop, and fabricate a motor and ignition system that met preliminary NASA requirements for the MagCon mission. These requirements are shown in Table I. Further, the program would demonstrate processing techniques and materials while identifying problems associated with fabricating and operating a motor of this size. Finally, the program would establish material and system performance characteristics to aid in the design of future flightweight motors and satellites.

The NSMP design was primarily driven by cost, weight, and performance considerations. Initially, trade studies were performed that looked at various materials for use in the case structure. It was found that for the size and performance envelope envisioned, a composite case design was optimum. An end-burning grain configuration was selected to maximize propellant load within the restricted nanosat envelope. In order to minimize program costs and optimize technology development, surplus propellant blocks were used to fabricate the main and ignition grains. The propellant selected was a space-qualified HTPB-based formulation identified as TP-H-3399. The moderate burn rate of this propellant coupled with the end-burning grain configuration provide a low (<100 lb_f) peak thrust to minimize attitude control disturbances of the very low mass nanosatellites. The motor consists of the grain, a molded insulator with an integral forward polar boss, the aforementioned case, nozzle assembly, and an ignition system.

The nozzle assembly consisted of an aft polar boss, an insulator and exit cone, and a throat insert. The case is a filament-wound, graphite-fiber/epoxy design.

Igniter development was not part of the prototype program. Thus, a simple and effective, sea-level igniter was used.

The NSMP program consisted of the fabrication of three motors. The first motor was an inert motor that was sectioned and delivered to NASA. The motor was used as a pathfinder from a processing standpoint. The second motor fabricated was the first live motor, and was fired at sea level. This motor is shown in Figure 3. The third motor,

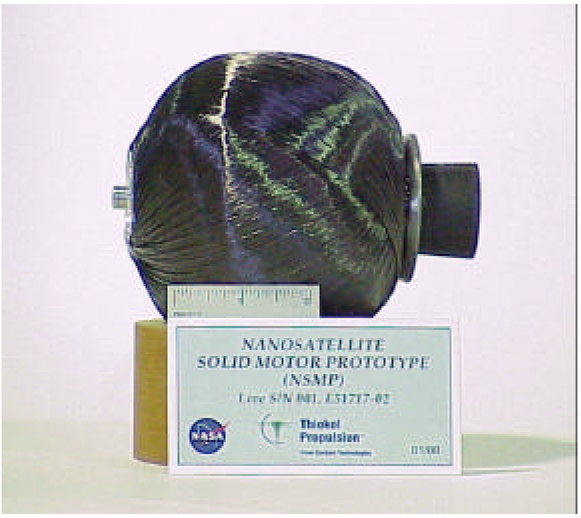

Figure 3. S/N 001 NSMP Motor Fired at Sea Level

also live, incorporated a modified electronic safe-and-arm (ESA) in the ignition train. This motor, shown in Figure 4, was fired at vacuum conditions. The modified ESA, referred to as N-ESA for this application, is another new technology under development at Thiokol and is targeted to replace heavy safe-and-arm devices.

Figure 4. Pretest Setup of S/N 002 NSMP Motor Fired at Vacuum

The current NSMP configuration allows for a low-cost proof-of-concept motor. The overall motor design used conservative strength and erosion values. Based on margins from test results, lightening of the insulation, throat, exit cone, and aft polar boss is possible.

Testing

Three types of tests were performed on the NSMP program. These tests included: 1) proof pressure, 2) ignition train, and 3) static tests.

The proof tests were performed on both live motors after fabrication at 1.25 X MEOP.

Ignition train tests were performed to verify N-ESA and ignition system performance in vacuum. The electrical power train functioned successfully in vacuum in bell jars, small vacuum chambers, and eventually the large static test facility tank. The igniter was developed for sea-level operation. As a result, both static test motors were fired with sea-level pressure in the motor chamber. This mitigated the need to modify the ignition system for vacuum operation, since successful ignition was obtained in the first sea-level static test. Further vacuum ignition work is indicated.

The first live motor, S/N 001 (see Figure 5), was static tested on January 31, 2000, at sea level and at a temperature of 21.1°C (70°F).

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Figure 5. Static Firing of First Motor S/N 001

The pressure vs time profile for this motor is shown in Figure 6 and thrust vs time profile in Figure 7. This test demonstrated the burn profile could be made to be neutral.

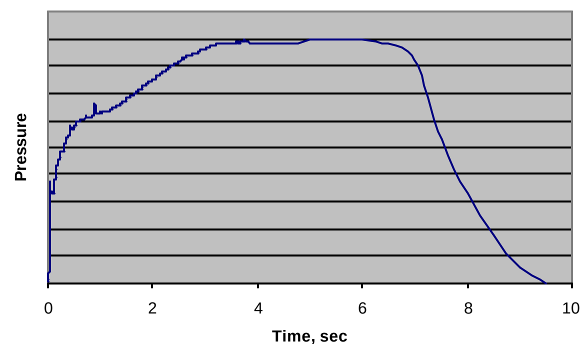

Figure 6. Pressure vs Time, S/N 001 NSMP, Sea Level

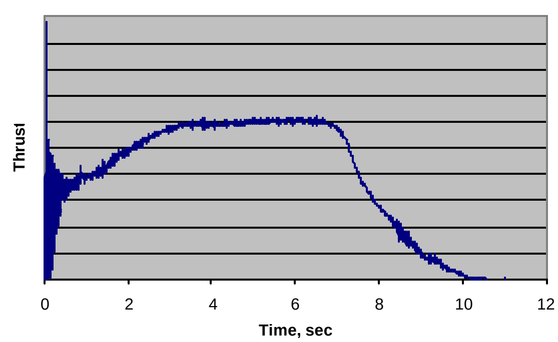

Figure 7. Thrust vs Time, S/N 001 NSMP, Sea Level

The second motor, S/N 002 (Figure 8), was static tested on June 8, 2000. The motor was conditioned to 21.1°C (70°F) and fired

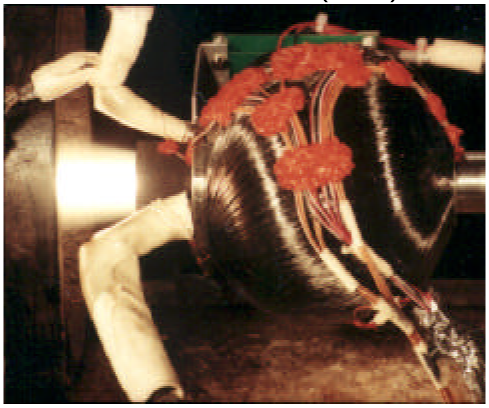

Figure 8. Static Firing of Second Motor S/N 002

at external vacuum conditions while internal motor pressure at T = 0 was at sea-level conditions. The pressure vs time profile for the motor is shown in Figure 9 and the thrust vs time profile in Figure 10. A “blip” occurred during the firing at about 3.5 sec.

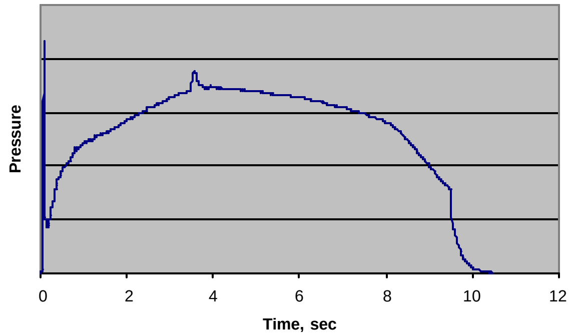

Figure 9. Pressure vs Time, S/N 002 NSMP, Vacuum

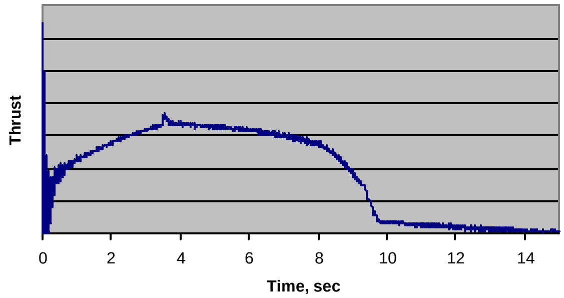

Figure 10. Thrust vs Time, S/N 002 NSMP, Vacuum

The cause of the small spike is process related and will be eliminated in future motors.

Posttest dissection of the motors revealed excellent performance of all motor components. Substantial margin in motor component design was demonstrated.

The N-ESA functioned properly on the second static test. The components of the N-ESA were on large circuit boards in the breadboard system. Substantial size and weight reduction is possible using the optimum board size and eliminating the mounting bracket and leadwire hardware.

Nanosatellite Electronic Safe-and-Arm (N-ESA)

Description

The available bus voltage and mass allocations for motor safing, arming, and initiation place stringent requirements on the ordnance systems for nanosatellite applications. The Thiokol breadboard N-ESA has the potential to provide an extremely low mass, low power, and compact physical envelope relative to conventional and proposed next-generation initiation systems. The very low power all-electronic N-ESA initiation system provides a high level of system safety.

The ESA currently under development by Thiokol was reconfigured for the nanosat application to operate at 3.0 Vdc spacecraft bus voltage. Successful operation of the N-ESA was demonstrated in bench testing down to 2.6 Vdc input and successful squib and motor firings were performed at simulated altitude conditions at 3.3 Vdc input.

The N-ESA prototype, shown in Figure 11, consists of two stacked electronic boards linked with leadwires. The output electrical fire signal from the N-ESA is routed to a squib that is installed in the motor. When the proper fire signal is received, the N-ESA fires the squib.

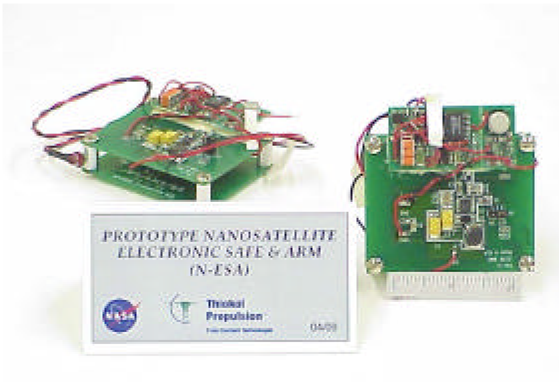

Figure 11. Breadboard N-ESA

The ESA is a microcontroller-based all-electronic system that provides two independent logic inhibits, arm and fire, and three independent MOSFET electrical inhibits. Single-fault tolerance is provided in the armed state. The system converts bus voltage to an operating voltage and locally stores the necessary firing energy, thus decoupling the instantaneous power draw of squib firing from the spacecraft power bus. Only two commands are required, a continuous ARM voltage, and a discrete FIRE signal. A built-in self-test feature provides an 8-bit digital telemetry word output which includes ESA status, safe/arm state, and bridge status. Safing of the system is accomplished by removing the continuous arming voltage. This also provides fail-to-safe response of the system in the event of signal interruption. Characteristics of the breadboard N-ESA and potential flight version of the N-ESA are summarized in Table II.

Table II. ESA Characteristics

	N-ESA Breadboard	N-ESA Flight (est.)
Weight	87 g	~30 g
Dimensions	2.75 in. x 2.75 in. x 0.88 in.	~2.0 in. x 2.0 in x 0.25 or less
Housing	None	Nonconductive conformal coating
Arm Signal	2.6 - 12 Vdc	3.3 Vdc ± 0.3 continuous
Time to Full Armed Charge	< 3-sec, 5-sec delay used in testing	< 3 sec
Fire Signal	2.6 - 12 Vdc, 20-msec duration	3.3 Vdc ± 0.3, 20-msec minimum
Quick Safe Time	< 30 msec	< 30 msec
Fail-Safe Time (<50% no-fire)	< 1 sec	< 1 sec
Firing Time	< 50 µsec	< 50 µsec

Testing

Testing of the breadboard N-ESA encompassed 1) bench testing as a component, 2) system testing as an integrated part of the altitude chamber and data acquisition system, and 3) static testing of the second NSMP at simulated altitude. Successful N-ESA operation was demonstrated at input voltages between 2.6 and 12.0 Vdc with both ambient and simulated altitude pressures using both dummy and live loads. Environmental testing will be required of the flight configuration. No vacuum-related performance issues were observed with the electronics.

For flight application, the N-ESA will be repackaged as a single board. Appropriate redundancy and ESD/thermal protection will need to be provided for prefiring protection of the flight N-ESA hardware.

Summary

In summary, the inert and two live test motors were successful demonstrations of processing techniques, material integrity, and operating viability. Also, the breadboard N-ESA successfully demonstrated low-voltage, low-power, and low-mass safing, arming, and initiation. The performance and characteristics of the NSMP motors and N-ESA closely match the current NASA requirements as summarized in Table III.

Characteristics and performance of a refined NSMP design is included in Table III. The design is based upon material heating margins from fired test motors.

Table III. Summary of the Requirements and Characteristics of the Motors Fired

	Units	Required	Actual S/N 001	Actual S/N 002	Future Possible
Total impulse, max	N-sec lb-sec	3000 674	2175 489	2647 595	2683[5] 603
Thrust (main grain), max[1]	N lb	445 100	312 70	378 70	445 100
Input power, max	Watt	1	~1	~1	1
Input voltage, max	Vdc	3.3	N/A	3.3[2]	3.3 ±0.3
Mass fraction of motor and N-ESA	–	–	0.69[3]	0.65	0.71[4]
Mass motor and N-ESA	Kg lb_m	–	1.415 3.12	1.501 3.31	1.393[4] 3.07
Motor length	cm in.	13.79 5.43	13.79 5.43	13.79 5.43	13.79 5.43
Motor O.D.	cm in.	11.4 4.5	11.51 4.53	11.48 4.52	11.4 4.5

[1]Ignition peaks not included; they were slightly over max and will change when igniters are developed for the motor
[2]2.6-12.0 Vdc demonstrated in bench testing
[3]Does not include any N-ESA hardware
[4]Further refinements are possible to better these numbers
[5]Further gains possible from nozzle optimization

Conclusions

Elements of new and existing technologies were incorporated into a small solid propellant rocket motor with integral electronic safing, arming, and initiation envisioned for nanosatellite applications. The prototype design functioned properly in both sea-level and vacuum environments meeting basic geometric, mass, electrical, and performance requirements currently envisioned for a MagCon boost motor system. Further, based on results from static tests of this design, it is apparent that improvement in performance and mass characteristics is possible. The data generated from the prototype program will play a key role in moving the design status of nanosatellite constellations from a conceptual stage to a viable, working model.