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ABSTRACT

A shift in emphasis to a ground-based, ballistic missile defense structure, like the present GPALS concept, requires moderately advanced SRM technology but at significantly lower costs in order to be viable for FSD and/or deployment. Improving interceptor propulsion system performance while reducing overall weight and controlling costs continues to receive major emphasis within the construct of the Strategic Defense Initiative. This paper provides an update of advances being accomplished in interceptor solid rocket booster motors as part of the USASDC's Solid Propellant Booster Development (SPBD) Program (USASDC Contract DASG60-89-C-0086). Advanced, yet cost effective, tapered composite cases; high performance (low-weight) nozzles; high-slew-rate, high-response thrust vector control (TVC); laser-fibre optic ignition; and high-energy, versatile-burn-rate propellant are discussed in the context of an integrated SRM demonstration program. The SPBD Program has resulted in these advanced SRM technologies being demonstrated in a series of motor static tests that began in August 1991. A portion of the Thiokol TX868 SPBD motors may be fired with the advanced integrally-actuated (Thiovec®) TVC nozzle bearing. Developmental data are summarized and typical flight-test vehicle configurations are presented in this discussion.

BACKGROUND

The SPBD program was initiated to minimize the technical risk associated with the design, development, production, and deployment of an advanced anti-ballistic missile defense system by developing and demonstrating selected advanced and low cost interceptor propulsion system technologies. Huntsville Division of Thiokol Corporation was selected for this effort based partly on participation in interceptor development for the past thirty years, beginning with its work on the Nike-Zeus system in the late 1950's. Subsequently, work on the Spartan, Sprint, and Sentry (originally called LoADs) systems led the Division to a succession of technological advances in booster motor technologies, especially economical, high burn rate (HBR) propellants. The Sentry program's Interim Propulsion Test Vehicle (IPTV) motor, developed and tested at Huntsville Division in the early 1980's, served as a precursor to this program by setting standards of comparison for overall motor and component performance (prior to development and test of the SPBD, TX868 motor, the Sentry motor represented the most advanced motor of this type built). Sentry therefore was used as a starting point in developing the SPBD motor baseline design. The SPBD motor design evolved as expected to exceed by significant margins the performance of the older Sentry design.

SPBD OBJECTIVES

Original top-level objectives of the SPBD program consisted of further development and demonstration of a versatile class 1.3, non-detonable, high performance propellant in production-sized mixes; design and development of an advanced tapered composite (graphite epoxy) case; development of a low cost, lightweight PAN-fibre nozzle; further development of compatible case liner and insulation materials; application of a laser/fibre-optic ignition system; and finally, integration of all these technologies into a demonstrable rocket motor. Additional objectives have evolved during the course of the program and include conceptualization and design of a high response Thrust Vector Control (TVC) system; exploration of alternate propellant curing agents; characterization of the baseline propellant over a wide range of burn rates ("dial-a-rate"); continued propellant aging studies; and test of a longer-burn (3.5 sec) motor utilizing the intermediate rate formulation as characterized. Interest has also been expressed in adapting pulse motor technology to interceptor boosters and therefore a bulkhead concept was developed for the SPBD motor which takes advantage of its existing design features and tooling. Table I summarizes the overall program.

Technical challenges associated with achieving each of these objectives have been met head-on during the SPBD effort. In the propellant area, the chosen formulation has now been processed in typical production-size(1600-Liter) mix sizes. Effort was required to assure that this larger mix could be successfully processed while maintaining acceptable physical properties. The tapered motor cases presented a challenge in maintaining an acceptable performance-to-weight ratio, keeping the associated labor costs within a manageable range, and arriving at an acceptable trade-off on fibre strength-to-cost ratio. For a typical interceptor booster, the nozzle size and associated weight significantly drive the overall motor performance (e.g. mass fraction). SPBD's challenge was to develop lighter-weight, yet lower cost nozzle processing/materials to contribute to a higher mass fraction with a more economical system. Laser/fibre-optic ignition systems offer advantages in both weight and cost for an interceptor booster when compared with conventional electro-mechanical safe/arms and initiators.

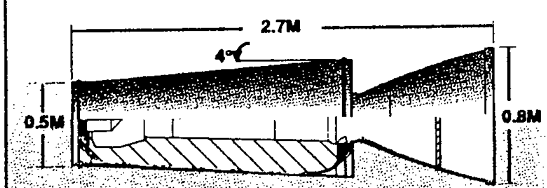
REQUIREMENTS & PERFORMANCE PREDICTIONS

The SPBD Technical Requirements Document (TRD), dated December 7, 1988 (a revised TRD has recently been implemented) provided general guidance in non-critical areas and specific requirements where technologies contributing to the design, development, and fabrication of an advanced interceptor booster are drivers. The motor has an forward interface (splice ring) with 511 cm (20.12 in) outside diameter (identical to that used on the Sentry motor) and an aft skirt ring with a 733 cm (28.9 in) diameter. The forward skirt was designed to withstand full static test thrust loads with adequate margins which yields a robust design for typical flight applications.

Figure 1 shows typical performance for the TX868-2 (3.5 sec burn) motors. Considerable effort was expended to maintain as near to a neutral trace as possible. The motor grain consists of a head-end-slotted, tapered cylindrical-perforated (CP) design. The slot depths, core taper, and nozzle throat diameter were varied within other imposed constraints (operating pressure range, burn rate, etc) to achieve the desired trace shape. A PMAX/PAVG value of about 1.06 resulted.

TABLE I - SPBD PROGRAM DESCRIPTION

FAST BURN BOOSTER DESIGN



- HIGH BURN RATE PROPELLANT
  - SAFE (HAZARD CLASS 1.3 - FLAMMABLE)
  - STABLE (NO COMBUSTION INSTABILITY)
  - LONG SHELF LIFE
- ADVANCED MATERIAL TECHNOLOGY
  - COMPOSITE MOTOR CASE
  - COMPOSITE NOZZLE
- LASER IGNITION SYSTEM

TECHNOLOGY APPLICATION

- VALIDATED BOOSTER TECHNOLOGY FOR ENDO INTERCEPTORS
  - E^2I; THAAD, ERINT; ARROW; ENDO PROJECTILE

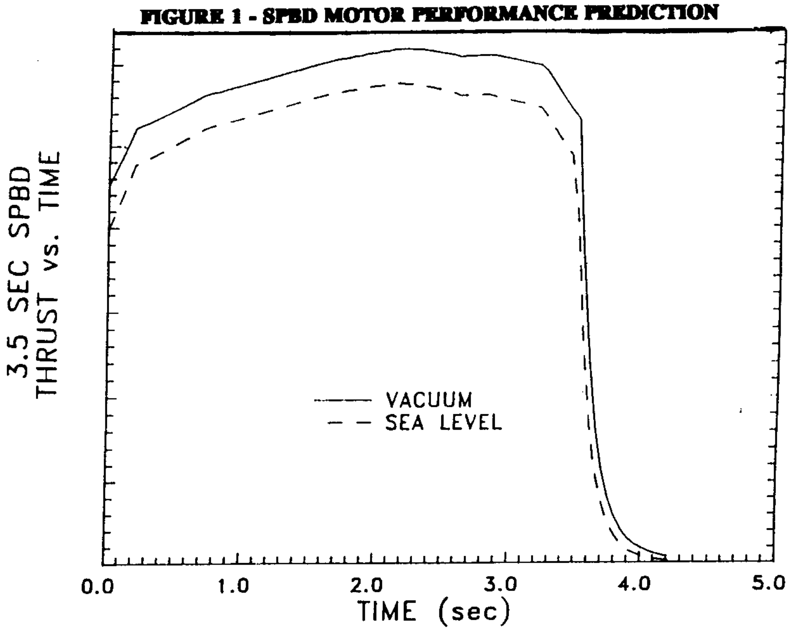
SATISFIES SYSTEM NEED FOR

- CLOSE-IN ENDO TARGET ENGAGEMENTS
- GROUND TARGET ACQUISITION AND TRACK SENSORS
- DECREASED FLIGHT TIME FOR HIGH ENDO MaRV INTERCEPTS AND ALLOWS ENDO RV DISCRIMINATION
- HIGH PERFORMANCE
- SAFETY AND LOW COST

CRITICAL ISSUES

- PRODUCIBILITY OF SCALED UP FAST BURN MOTOR
- LOW COST ALTERNATIVE BURN RATE CATALYST
- COMBUSTION STABILITY
- MEETING HBR I.M. PROPELLANT REQUIREMENTS
- RADIATION HARDENED IGNITION SYSTEM

FIGURE 1 - SPBD MOTOR PERFORMANCE PREDICTION



Continued development of catalyzed high-burn-rate propellant is a major program focus. Table II lists a comparison between the Sentry propellant (TP-H8295) and the SPBD TP-H8316 formulation. The latter formulation is a lower-cost version of TP-H8295 propellant demonstrated in Sentry (the Ultra-Fine Ammonium Perchlorate, UFAP, has been removed). TP-H8316 contains 7 percent binder, 5.0 percent CATOCENE® burn rate catalyst, 20 percent aluminum, and 68 percent Ammonium Perchlorate oxidizer. Over 32,000 pounds of this propellant family have been processed at Huntsville Division since 1979. The major challenge is to scale-up to production-size (1600-Liter) mixes and to demonstrate its reproducibility and producibility. To date, all physical, ballistic, and aging data show that TP-H8316 meets or exceeds all propellant requirements as specified, although a short potlife (and high viscosity near the end of casting) was encountered on the first SPBD production-sized mix. This phenomenon was traced to a raw materials anomaly and corrective action has been identified for the all future mixes.

TABLE II - SENTRY AND SPBD PROPELLANT COMPARISON

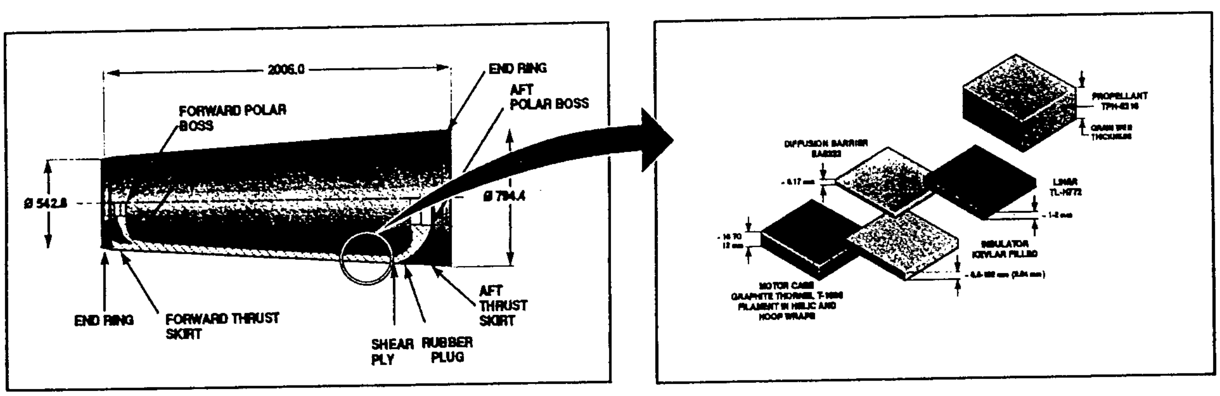
	TPH-8295	TPH-8316
UFAP CONTENT (% OF AP)	21	0
TOTAL SOLIDS	86	88
CATOCENE, %	5	5
MAXIMUM STRESS, N/M^2 (PSI)	1.90 x 10^6 (277)	1.62 x 10^6 (235)
STRAIN AT MAXIMUM STRESS, %	37	31
TANGENT MODULUS, N/M^2 (PSI)	5.9 x 10^6 (855)	6.0 X 10^6 (867)
IMPACT SENSITIVITY, KG-CM	50	71
SPARK SENSITIVITY, JOULES	0.125	2.65
FRICTION SENSITIVITY, N (LBS)	222 (50)	193 (43.3)
HAZARDS CLASSIFICATION CLASS	1.3	1.3
IMPULSE DENSITY, g-sec/CM^3 (LB-SEC/IN^3)	473 (17.1)	487 (17.6)
COST		43% LESS

Specific system requirements were not imposed regarding vibration induced as a result of rocket motor combustion but, there was concern expressed over the un-predicted pressure/thrust oscillations exhibited by the Sentry motor. Stability analyses codes available at that time did not properly account for the phenomenon of in-flow (or "distributed") combustion of the propellant aluminum, a phenomenon that is primarily peculiar to high-burn-rate situations. Significant SPBD efforts have been directed towards updating the Standard Stability Prediction (SSP) code for this effect and inputting the most recent T-burner data (generated by NWC). A stability margin for the SPBD motor was generated using the modified code and the latest propellant information. The new code predicted a comfortable stability margin for the TX-868 and no significant oscillations were measured during the duration of the first static test. Additional test data is required to ascertain the degree of improvement in prediction techniques, however, this initial data are encouraging. A post-test prediction of the Sentry motor using the updated code properly predicts the combustion trends noted in the 1980's tests.

COMPONENT DESIGNS AND CURRENT STATUS

Filament-Wound Composite Case. The older Sentry motor design employed a hybrid (Kevlar-graphite) filament-wound case. For SPBD, only higher performance graphite fibres are employed. Brunswick Defense (Lincoln Plant) was selected to design, develop, and manufacture the SPBD case for Thiokol. Originally, a T650 (4450 MPa tensile Strength) fibre was selected based on its low cost. After program start up, this baseline selection was revisited and T40, higher strength fibre was chosen. Continued refinement of the baseline design during the design integration phase indicated that significant improvement to overall motor mass fraction (0.81 to 0.835) could be achieved with T1000GB fibre (6500 Mpa tensile strength) and a cut helical (removing the un-needed helical wraps near the case headend) design. No cost or schedule impact resulted from this change and the payoff was substantial. The final case design employes the T1000GB, one of the highest performance fibres currently in production. Yet, has a cost essentially equivalent to T40. The SPBD case design is shown in **Figure 2.**

FIGURE 2 - SPBD's GRAPHITE-EPOXY FILAMENT WOUND CASE



COMPOSITE PROPERTIES	T1000GB FIBER	LRF545 RESIN
TENSILE MODULUS, MPa	296,400	3514
TENSILE STRENGTH, MPa	6500	83.4
DENSITY g/cc	1.78	1.19

7075 - T76 ALUMINUM PROPERTIES	
TENSILE MODULUS, MPa	71,000
TENSILE STRENGTH, MPa	482
SHEAR STRENGTH,MPa	276
DENSITY, g/cc	2.8

BURST PRESSURE TEST

DESIGN

37 MPa (5495 psi)

ACHIEVED

39.6 MPa (5747 psi)

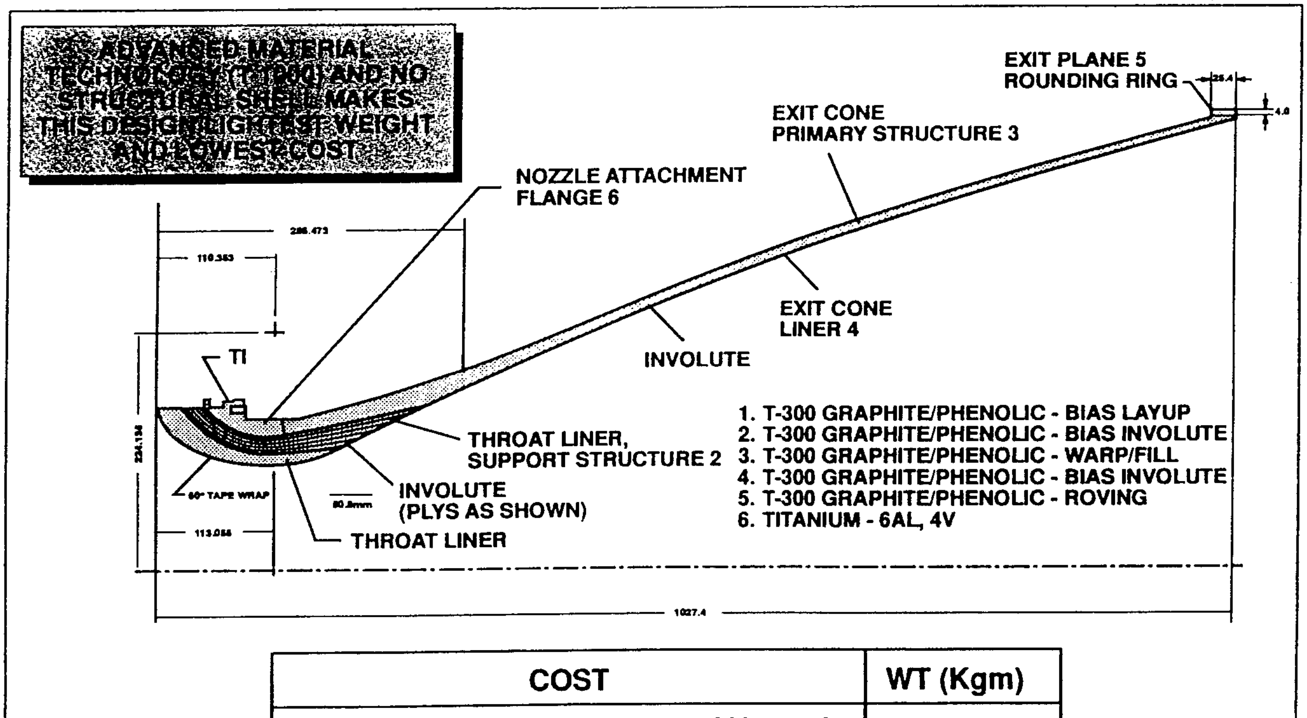
Co-cured bonded "Y-joints" were used to attach both the aft and forward skirts. The Y-joints use FM-123-5 film adhesive between the case and skirt structures. In order to verify the Y-joint bond system, tests were conducted using filament-wound concentric rings bonded together with film adhesive and pulled to failure. These tests validated the design allowable for the joints. A new Brunswick resin formulation (LRF-545), which does not contain the recognized carcinogen MDA (found in many other resin formulations), was chosen for SPBD. LRF-545 is also lower cost than other typical formulations and when used with the T1000GB fibre, resulted in smoother processing and higher translation of predicted strengths when compared to T40 fibre with other resins.

Considerable attention was paid to analyzing the SPBD case. Thiokol directed Brunswick in conducting a finite element analysis (FEA) of the case in addition to the usual conservative netting, compression, and shear-lag analyses. Of particular interest was the expected "rotation" of the forward and aft pole pieces as this affects the igniter and nozzle seals respectively. The initial proof test of the SN001 SPBD case resulted in greater-than-predicted rotation in both joints. Although the case passed proof and burst testing, the joint designs were subsequently modified to insure that the forward igniter joint "closes" at the seal during operation and the aft joint rotation remained within allowable tolerances.

Five (5) SPBD cases have been manufactured and have all met or exceeded expected performance. The successful demonstration of the SPBD T1000GB/LRF-545/Cut Helical case represents a significant advance in composite case technology.

<u>Nozzle Design</u>. The selected technology for the SPBD nozzle has likewise resulted in a substantial technology advance. American Automated Engineering's (AAE) Rogersville, Alabama was downselected for nozzle final development and fabrication. The SPBD design shown in Figure 3 results in considerable weight and cost savings when compared to previous multi-component, metal-shelled nozzles. The design originally incorporated a monolithic-cured PAN-based graphite fibre ablative liner/structure but a bonded-in throat insert was eventually adapted to counter problems associated with the differences in thermal expansion of the material at different ply orientations. The nozzle employs a small titanium nozzle attach flange. One major advance in the SPBD nozzle design/fabrication technology is the use of "fibre-on-film" (FOF) prepreg technology which ultimately results in substantially more uniform resin content and better finished part physical properties. Increased physical performance, especially in the exit cone shear direction, results in the ability to design a much lighter-weight nozzle.

FIGURE 3 - THE ADVANCED SPBD PAN FIBRE NOZZLE



	COST		WT (Kgm)
	10 UNITS	1000 UNITS	
SPBD	54.7 (30.8)	17K	33
OTHER	>74.5	>22K	>38

* LIGHT WEIGHT, LOW COST, HIGH PERFORMANCE NOZZLE

SPBD nozzles were fabricated in a female mold starting with the exit cone and support structure using T-300 continuous-bias PAN material laminated in the FOF process with Durez DP-25-10 unfilled, phenolic resin. The warp/fill primary structure laminate plies are laid up next followed by the exit cone bias involute. The subassembly was vacuum bagged and oven debulked. Next, the throat involute support structure was laid up, debulked, and the entire composite subassembly, with the 6A1,4V Titanium attachment flange in place, was hydroclave cured. After cure, the support structure was machined to accept a separately cured "dixie-cup" layup throat insert.

Previous experience with fast burn booster nozzles was used to predict very benign thermal effects could be expected. Nozzle erosion is in the order of 1.0 mm and less than 2.0 mm at the throat and impinging flow regions, respectively. Design of the nozzle is driven by structural requirements. High Motor operating pressure drives the nozzle expansion ratio and the nozzle structure size can significantly effect overall motor mass fraction. Reducing nozzle weight is inversely equated to nozzle "performance".

PDA Engineering conducted a FEA analysis of the SPBD nozzle design. Results of this analysis indicate substantial margins throughout the component. In addition, Thiokol and AAE manufactured and tested structural cylinders of representative diameter in order to validate the design allowables used in the analyses. All cylinder tests met or exceeded expectations.

Some difficulties with low-density, porosity, and thermal-expansion-induced cracking in the co-cured throat insert area were encountered with the first two nozzles fabricated. Changes in the cure pressure and temperature cycle were incorporated which corrected these processing anomalies. A bonded-in throat insert eliminated the cracking due to after-cure cooldown experienced early in that region of the part. Nozzle performance has been acceptable and the basic composite design approach has been validated during static test.

Ignition System. The overall concept for the SPBD ignition system consists of a Boron-Potassium Nitrate (BPN) pyrotechnic charge vented from a fiberglass-filled phenolic tube onto the forward portion of the motor grain. The main igniter charge is initiated by a laser-fibre optic squib. Laser energy to fire the squib is provided via a silica core GLPC fibre cable from a laser diode arm-fire unit. The igniter tube is designed to survive the motor firing so as not to eject debris into the motor chamber. Pyrotechnic igniters (as opposed to cast grain "pyrogens") have proven to be cost effective and reliable for low altitude ignition. The SPBD igniter was derived from the Sentry, having a like charge and tube configuration.

The SPBD igniter provides reliable and reproducible ignition of the TX-868 motor form -32 to 60 degrees C with a delay to 75 percent of maximum chamber pressure of less than 40 milliseconds under all conditions. The first static firing validated the ignition transient prediction as all criteria were met.

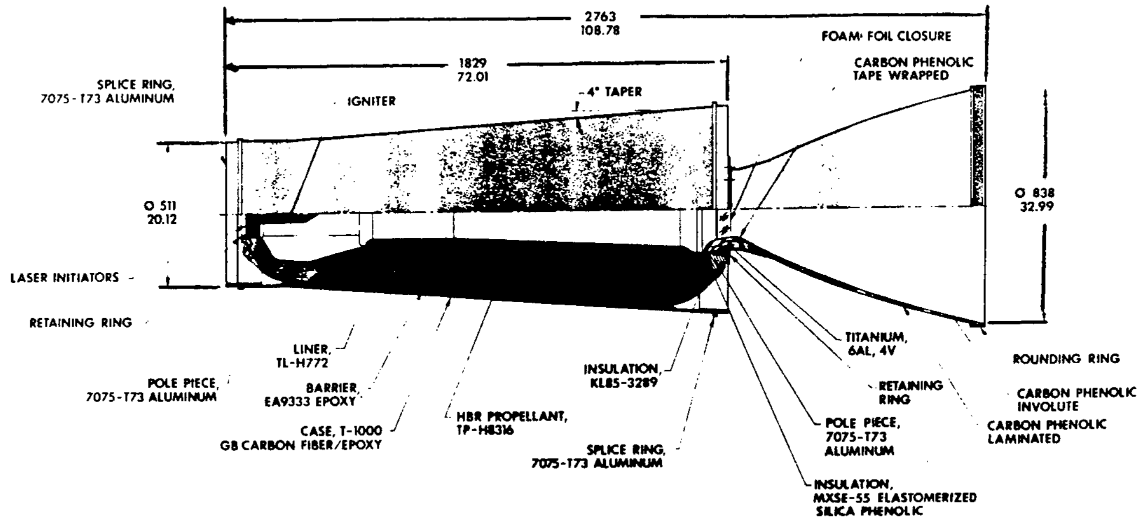
The laser initiator and laser arm-fire device have not been demonstrated at the relative high acceleration environment of an interceptor booster although they have been tested on several tactical and strategic systems. Nevertheless, the following advantages outweigh the risks involved in application of the laser system to interceptor propulsion: increased safety (not susceptible to EMI, ESD, or EMP; auto built in continuity test; laser unit safe-arm function); both volume and mass reductions for multiple events; less expensive for multiple events (laser incorporates safe-arm function and eliminates expensive electro-mechanical systems; multiple events can be triggered by a single laser arm-fire device). The ignition system consists of a laser arm-fire device (LAFD) which houses the laser head, a fibre optic cable to transfer energy from the LAFD, and finally the laser squib itself. A typical LAFD provides the same type features as its electro-mechanical counterpart such as a mechanical barrier, simultaneous outputs, and discrete inhibits/initiation signals. The laser squib is similar to other squibs except that the electrical bridgewire is replaced with a laser sensitive pyrotechnic mix. The hermetically sealed glass window (also found on most electrical squibs to seal around the connector pins) now acts to transmit the laser energy from the fibre optic cable.

Subsequent to an igniter open-air test which utilized the laser squib, minute cracks and some "crazing" was detected in the glass window which provides a high pressure seal in the squib. It has been determined that this is a manufacturing process related to how the metal shell and window assembly are welded together. HI-SHEAR, the SPBD laser squib supplier, has been evaluating the problem. A new process will be implemented prior to remake of the original squib lot. Meanwhile, other sources for the laser initiator have been contacted for potential participation in the SPBD program.

INTEGRATED TECHNOLOGY SPBD MOTOR

Figure 4 illustrates the TX-868 SPBD interceptor booster and shows the unique features previously discussed. The resulting overall motor length is 2.76 meters with a forward interface diameter of 0.511 meter, an aft nozzle diameter of 0.838 meter, and an overall weight of 813.4 kilograms. The baseline TX-868 motor will expend its 677.4 kilograms of propellant in 1.84 seconds (25 degrees C). The TX-868 basic motor has a fixed nozzle configuration with the TVC option implemented in the TX868-1 version. Every technology area in the TRD is addressed in the motor's design.

FIGURE 4 - THE INTEGRATED TECHNOLOGY TX868 SPBD MOTOR



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Huntsville Division

SPBD

A typical flight application of the TX-868 SPBD motor is shown in Figure 5 wherein the motor is used as a second stage for a component flight test vehicle (CFTV). It is estimated that this configuration would give burnout velocities in excess of 5 km/sec (40 kg typical payload). Although there was no contractual requirement for the TX-868 to be flightworthy, every effort has been made within present cost and schedule constraints to incorporate flight requirements. Depending upon the chosen launcher mechanism, the motor might require addition of a launch lug or other such attachments. Such modifications should be minor and the SPBD motor could be delivered for flight within 6-9 months after completion of the current program. Figure 6 shows potential applications for SPBD technologies.

FIGURE 5 - SPBD MOTOR FLIGHT TEST CONCEPTS

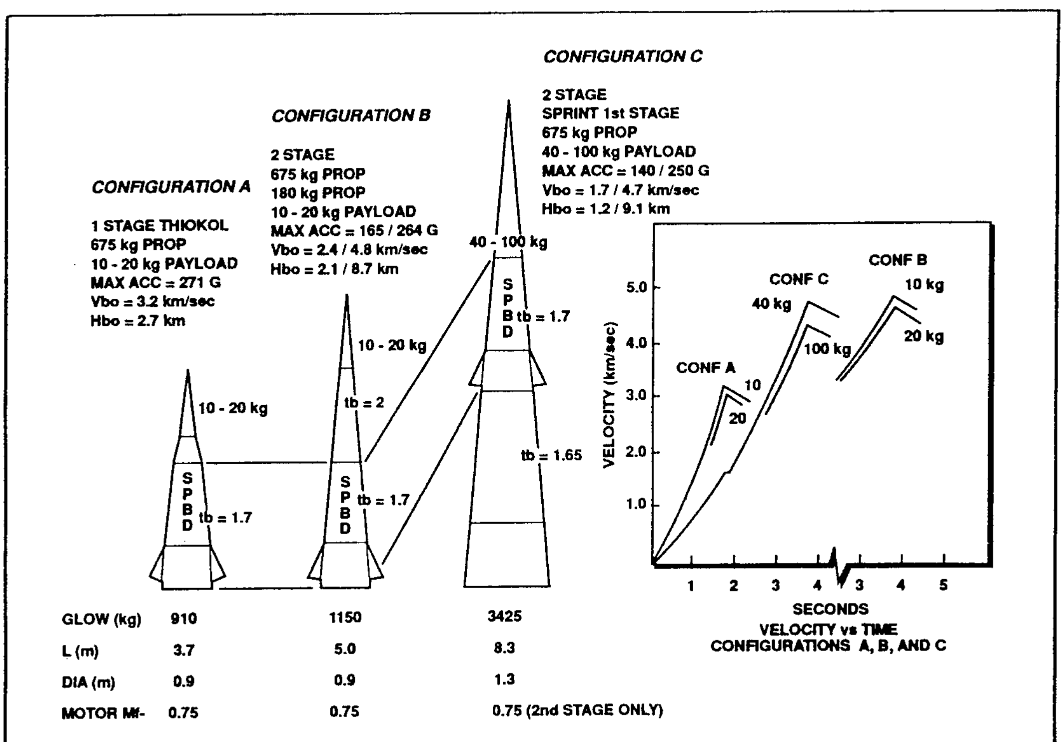
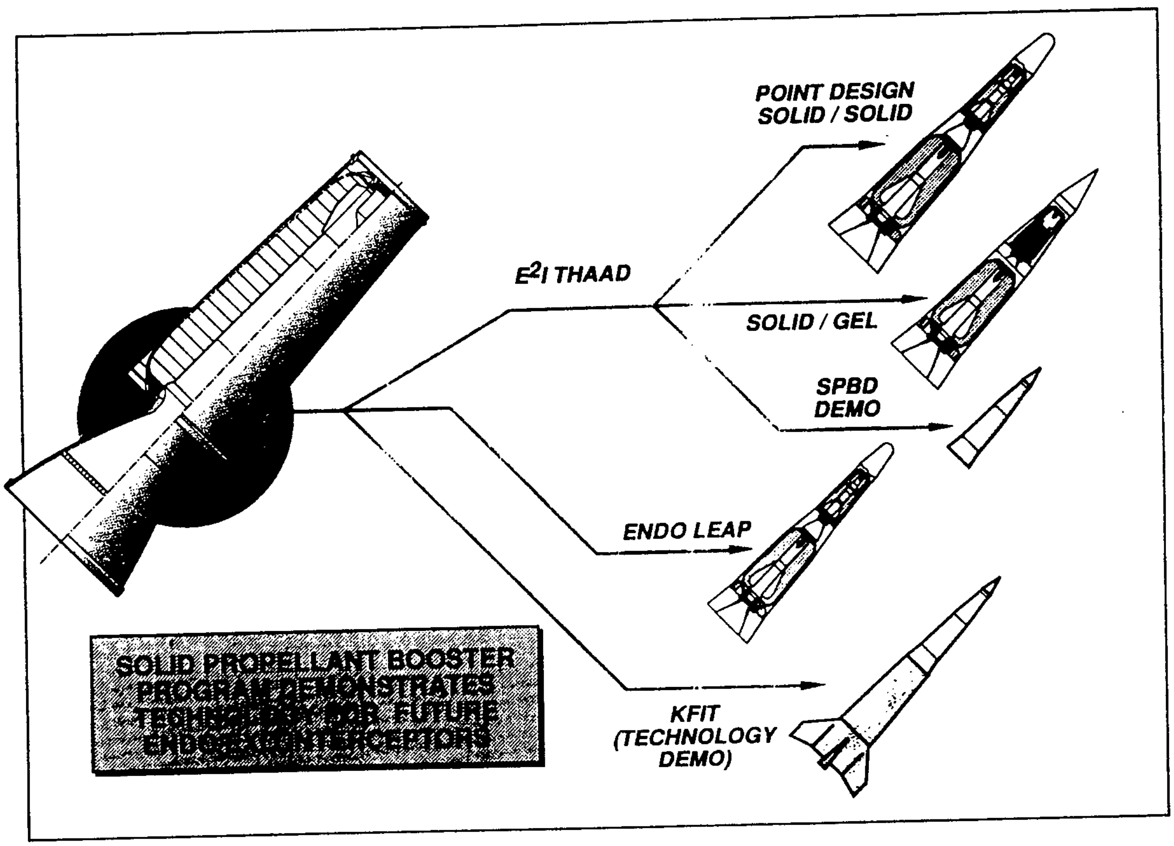


FIGURE 6 - POTENTIAL SPBD TECHNOLOGY APPLICATIONS



Applications that have been identified include a single stage configuration of the SPBD motor to achieve upwards of 4-5 km/sec with a small payload. Such tests would not only serve to provide a means of testing miniaturized payloads but would allow validation of the SPBD motor technologies in a simulated "tactical" flight environment. Use of the 3.5 sec burn motor for ENDO LEAP flight testing is also under study.

SUMMARY AND CONCLUSIONS

The SPBD program has provided advances in critical areas of solid propulsion technologies applicable to interceptor solid propulsion. Lower cost, non-detonable (Class 1.3) versatile burn rate propellant; advanced performance tapered composite case; lower cost, lighter weight nozzle (with high response TVC); laser ignition; and improved combustion modeling and performance have been the focus of the program. Additional tasks included evaluation of the HBR propellant aging characteristics, characterization of the propellant over a wide range of burn rates, additional combustion T-burner data, and work to further improve propellant processing. Future work includes attention to automation in production of the tapered composite case and nozzle; further reductions in nozzle weight; implementation and test of the Thiovec® TVC; and static test of a 3.5 sec burn motor version (TX868-2); evaluation and demonstration of pulse motor capability; vibration/shock testing of the laser fibre optic ignition system; and possibly flight test of a single-stage vehicle configuration to verify design margins. USASDC and Thiokol recognize the importance of advancing interceptor propulsion technologies to gain more performance and lower costs. When an advanced ballistic missile defense system is deployed, it must be affordable. SPBD is an important step in moving the applicable technologies towards that end.

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