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# Challenges in the development of a slow burning solid rocket booster

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ABSTRACT

Solid rocket motors always find a place in launch vehicles, especially as booster stages on account of their capability to deliver higher thrust needed during the initial phase of flight, most importantly during lift-off phase. The newly developed slow burning solid booster is chosen for the first stage of Reusable Launch Vehicle-Technology Demonstration (RLV-TD) flight programme. This suborbital two stage technology demonstration programme is aimed for a hypersonic re-entry of double delta wing vehicle from an altitude of nearly 65–70 km, where the first stage of vehicle is identified as solid booster. Therefore, the desirable Mach number of the vehicle at motor burnout (30–35 km) is essentially required to be minimum 6 to attain hypersonic re-entry. The contradictory mission requirements like achieving the desired Mach number and limiting the dynamic pressure demanded for design, development and qualification of a new motor with slowest burning solid propellant thereby an action time of nearly 90 s. The challenges faced in the design, development, realization and qualification of the motor through two successful static tests are discussed in this paper. The special attention given for motor case with 2 mm shell thickness, development of a slow burn rate propellant, ignition strategies for the slow burn rate propellant, stable burning of the low burn rate propellant and flow separation related issues for ground test are highlighted.





## 1. Introduction

Adoption of Reusable Launch Vehicle (RLV) instead of the current expendable launch vehicle (ELV) is being conceived as the future route to achieve low cost, reliable and on demand access to space. Studies clearly indicate that, two stage to orbit (TSTO) Reusable Launch Vehicle with a wing body configuration of first stage capable of landing horizontally like an aircraft and a second stage capable of landing vertically or horizontally is the most cost effective configuration for fully Reusable Launch Vehicle system. The hypersonic flight experiment (HEX) mission is the first step towards the demonstration of the technology. A solid motor has been selected to propel the two stage RLV-TD vehicle to the desired altitude with a Mach number greater than 6. In order to meet the stringent mission requirements, a new motor has been designed, realized and successfully qualified. The head and middle segments of the solid booster are cylindrical grain ports whereas the nozzle end segment is ten lobe deep slotted star configuration selected to avoid erosive burning. When the flow velocity over the grain surface is above a threshold value, burn rate increases drastically. For motors with large $L/D$ or lower $A_p/A_t$ ratio, pressure during initial few seconds will be higher. This behavior is called erosive burning.

The nozzle is straight conical convergent–divergent type with secondary injection thrust vector control (SITVC) system. All the nozzle liners including throat insert except SITVC inserts are made of carbon phenolic. SITVC with 3 pintle system is provided at four diametrically opposite locations at 90° apart in divergent section for pitch and yaw control during initial 10 s of motor action during the flight. Then the system will be in back up mode with fin tip control system. To achieve the action time requirement of nearly 90 s with a thrust level of 300 kN, a new slow burning propellant with a burn rate modifier is formulated. This new formulation is scaled-up to 350 kg level and several tests were carried out in the standard ballistic evaluation motor configuration. In the next stage of scale up, 1 t propellant mixing is done. One subscale simulation motor is cast from the mix. The simulation motor is designed to operate at the average pressure of the main motor with the same area ratio. Subscale motor was successfully static tested on 15th March 2007 and performance parameters were as per the predication. Stable burning of propellant at low average pressure (1.47 MPa) has been confirmed.

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**Nomenclature**

| | |
|---|---|
| Q-alpha total | Dynamic pressure times total angle of attack |
| $\gamma$ | Flight path angle |
| $H$ | Augmented heat flux |
| $H_u$ | Flux due to undisturbed flow |
| $h$ | Equivalent protuberance height |
| $\delta$ | Boundary layer thickness |
| $n$ | Index derived from post static test data of earlier motors with SITVC |
| $P_{DL}$ | Pressure below which a propellant will not burn |
| $a$ | Pressure co-efficient of ballistic steady burning rate, non-dimensional |
| $A_b$ | Area of the burning surface |
| $A_t$ | Area of the nozzle throat |
| $T_c$ | Combustion chamber temperature |
| $g_0$ | Standard acceleration gravity at sea level, 9807.0 mm/s$^2$ |
| $n$ | Pressure exponent of ballistic steady burning rate, non-dimensional |
| $P_c$ | Combustion chamber pressure |
| $r_b$ | Burning rate |
| $\Gamma$ | Dimensionless parameter defined in equation |
| $C_D$ | Coefficient of discharge |
| $R$ | Gas constant |
| $M$ | Molecular weight of the combustion products |
| $c^*$ | Characteristic velocity |
| $I_{sp}$ | Specific impulse |
| $\rho_p$ | Propellant density |

The qualification of the new motor with SITVC was carried out through two static tests. The first static test (ST-01) of this motor was successfully carried out on 19th November 2008. All the subsystems performed satisfactorily as expected. Motor performance and post test assessment of subsystems confirmed availability of required margin. However revised mission requirement necessitated modification to bring down the dynamic pressure. Web thickness at the star portion of the grain has been reduced and demonstrated in the second static test. The challenges faced in the design, realization and testing of the new motor is presented comprehensively.

## 2. Mission requirements

The specifications prescribed to meet the mission profile are in Table 1, booster stage shall be configured to boost the Technology Demonstrator (TD) payload to a desired Mach number and altitude.

### 2.1. RLV-TD mission requirements/specifications

Arriving at the desired thrust profile is a trade-off between the mission requirement and practical possibility from a solid motor. Project (RLV-TD) undertook mission optimization studies considering several ideal thrust-time profiles generated for the solid booster. The most optimum ideal thrust–time profile which meets all the mission requirements was derived by the above studies and is indicated in Fig. 1. The above sharp ideal thrust–time profile signifies the grain design to be made in such a way that lower thrust of nearly 160 kN to be achieved after first peak at around 310 kN over a period of 30 s. This requires a drastic change of the burning surface area just after the peak. The performance requirements/specifications for RLV-Solid Booster (RLV-SB) derived/translated in to the propulsion parameters after several rounds of refinements is given in Table 2.

**Table 1**
RLV-Solid Booster performance requirements/specifications.

| Sl. No. | Parameter | Specification |
|---|---|---|
| **1** | Mach number at motor burn out | >6 |
| **2** | Dynamic pressure (kPa) | ≤34 |
| **3** | Q-alpha total (Pa rad) | ≤180 |
| **4** | Flight path angle ($\gamma$) at burn out (°) | <25 |

## 3. RLV-SB motor grain design challenges

The real challenge for the grain design team was to achieve an action time of 90 s within the diameter constraint of 1 meter for the motor and meeting the prescribed Thrust–time profile. The challenge involved can be well appreciated by the comparison of

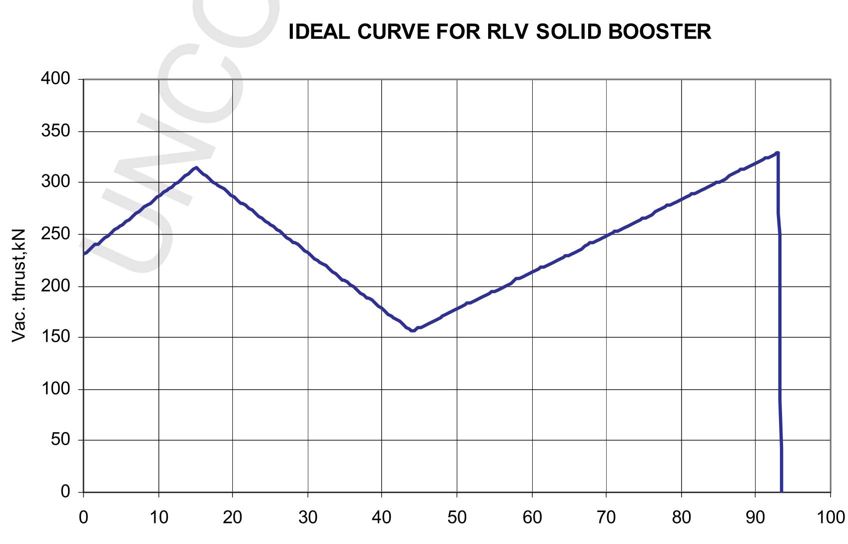


**Fig. 1.** Ideal Thrust-time profile for RLV solid booster



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