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System Engineering Challenges in Development of LOX-Isrosene Booster Stage for Future Launch Vehicle of ISRO

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Abstract

Liquid Propulsion Systems Centre (LPSC) of ISRO is pioneer in the design and development of liquid propulsive stages. It has undertaken development of Semi-Cryogenic propulsion stage, which will be the largest liquid stage developed so far. The stage with Liquid Oxygen (LOX) and Kerosene based fuel (Isrosene) as its main propellants helps to enhance the payload of GSLV MkIII launcher to beyond 5 tonnes. Design of liquid propulsion stage is complex as it involves components like valves, regulators, flow control devices, functional modules and control sub systems. A typical liquid propulsion stage will have more than 25 sub-systems, each having its own set of components, operating conditions and specification. Systems engineering plays major role in development and realization of such complex Liquid Propellant stages of launch vehicle. Major challenges that are anticipated during mechanical design and development of the LOX-Isrosene (semi-cryogenic) stage are handling large temperature gradients between propellant tanks, its unique storage as well as assembly requirements and management of thermal stresses in adjacent structures. It also warranted the need of combining the system engineering practices followed for Cryogenic and Earth Storable liquid propellant stages, without compromising on the sub system performance. The Semi-Cryogenic stage being developed is planned as a replacement of core booster stage of GSLV-MkIII, heaviest launcher developed by ISRO so far. Though this method reduces development time and cost, it induced additional constraints on the stage development. System engineering practices are utilized for complete assessment of stage systems and for finalization of system configuration with an objective of reduction in development time, cost and without any changes in the remaining systems of the launch vehicle. This paper presents the relevance of systems engineering for launch vehicle development, complexities involved in design and development of Semi-Cryogenic liquid propellant stage and solution strategies implemented for overcoming the design challenges with selected examples.

Keywords: *Semi-Cryogenic, LOX, Launch Vehicle, System engineering*

1. Introduction

Liquid Propellant stages find a major share in launch vehicles because of their wider operating flexibility, restart capability, reuse capability, throttling etc. A typical bipropellant liquid stage utilizes oxidizer and fuel, stored in independent tanks, for generation of thrust.

Many launch vehicles that are currently in operation like Soyuz, Falcon, Atlas use a semi-cryogenic propellant combination (purified kerosene and liquid oxygen) for large booster stages in view of the advantages that it offers like high density impulse, eco-friendly nature and cost effectiveness. Liquid Propulsion Systems Centre (LPSC), ISRO's lead center for development of liquid propellant stages, is developing a Lox-Isrosene (purified kerosene) engine which can deliver 2000kN thrust for booster stage. This engine will become workhorse engine that will power all semi-cryogenic stages developed by ISRO. Extensive mission studies with different vehicle configurations, wherein semi-cryogenic stages can be either core booster stages and/or strapon stages, were carried out and the payload capabilities assessed. An innovative plan is worked out to design a semi-cryogenic stage that will fit into the existing GSLV-MkIII by replacing the earth-storable lower booster stage. This approach provides the earliest opportunity to demonstrate the Semi-Cryogenic technology in a

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qualified vehicle, in addition to increasing the payload of the GSLV MKIII launcher. The overall vehicle configuration, interfaces with adjacent stages and mission profile remains unchanged, minimizing the development work. However, this method poses additional development challenges in terms of overall configuration, thermal management etc.

2. SYSTEM ENGINEERING-AS APPLICABLE TO LAUNCH VEHICLE DEVELOPMENT

Launch vehicles are designed to place the satellite or the payload into the desired orbit with specified velocity. This objective can be met only with the synchronized effort of all different stages of the launch vehicle and all sub systems of each stage. Hence, the interactions, constraints and responses of various subsystems are to be understood clearly to arrive at an optimum configuration, which makes the design and development of any launch vehicle complex. It involves not only several iterative design procedures and interactions but also certain key design considerations [1]. Sub systems of launch vehicle are complex, combining multiple technical disciplines, and their development posed engineering challenges significantly beyond those that had been presented earlier. Systems engineering, as we know it today, developed to meet these challenges [2].

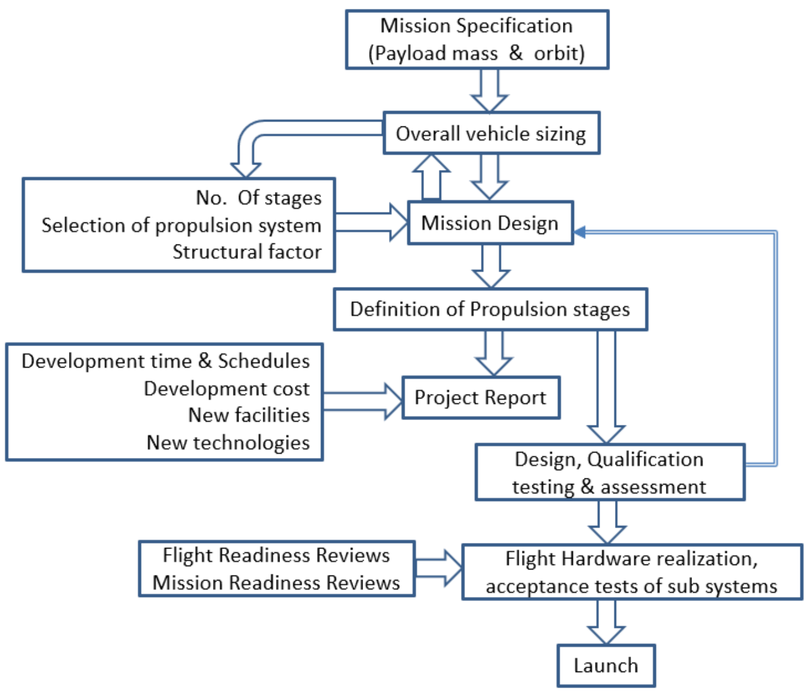

Figure 1: Flow diagram depicting major phases in the development of Launch Vehicle

Design, development, testing and evaluation of any new launch vehicle typically requires a cycle time of not less than 8 to 12 years, especially when new technologies are involved. Hence, the total development activities are divided into major milestones that are considered themselves as independent projects. Figure 1 shows main phases in development of any launch vehicle starting from mission specification till launch. Teams with specialization in materials, mechanical, electronics, propulsion, control and guidance systems have to work in tandem to attain the mission objectives along with exercising strict control on system mass, schedule and budget. Considering the number of disciplines involved, varying type of activities and huge budget, multiple challenges are expected during sub system design. Wherever conflicting requirements are to be met due to the imposed challenges, detailed

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assessment to be made and specification/requirements of some of the systems to be revisited/adjusted in a way to achieve the goals at integrated level. Today, operational procedures of all launch vehicle missions are worked out based on system engineering approach as it provides the ability to guide such complex development activities with superior knowledge of the system as a whole, its operational objectives and all the technical factors that go into its development.

Gibson et.al. [3] states the importance of system engineering aspects on launch vehicle performance. It analysed many published works and presented a system engineering process performance model that was developed to examine the relationships among management support, organizational commitment, systems engineering support, and systems engineering process performance in US launch vehicle organizations. The hand book [4] gives description of the system engineering methods implemented in launch vehicle programmes of NASA. It lists all the major phases of the design and development of launch vehicle, flow diagrams depicting the interactions between various aspects of the development and also technical risk management.

3. SUBSYSTEMS OF LOX-ISROSENE LIQUID STAGE

A typical liquid propellant stage requires mechanical, propulsion, control systems for its successful functioning. Major load bearing structures that forms external shape of the stage comes under the mechanical systems. Propulsion systems provide smooth flow of propellants to the engine at required inlet conditions and ensure functioning of engine as per requirement. Control systems provide stability and steering of the total vehicle. Auxiliary systems consist of thermal protection, health monitoring, separation/pyro systems etc., and are equally important for successful completion of mission objectives. Table 1 gives summary of major sub systems of Semi-Cryogenic stage. There are 27 sub systems that are to be worked together for the successful functioning of the stage.

Table 1: Major Sub Systems of SemiCryogenic Stage

Mechanical Systems	**Propulsion Systems**		**Control Systems**	**Auxiliary Systems**
	LOX	**Kerosene**		
1. Oxidizer Tank	1. Pressurization	8. Pressuri-zation	1. Anti-Slosh	1. Avionics
2. Fuel Tank	2. Fill and Drain	9. Fill and Drain	2. POGO	2. Insulation
3. Inter Tank Structure	3. Propellant condition-ing	10. Feed	3. Pitch and Yaw control	3. Umbilicals
4. Base Shroud	4. Feed		4. Roll Control	4. Instrument-ation
5. Thermal Shroud	5. Vent and Relief			5. Destruct
6. Flexible thermal boot	6. Command			6. Pyro
7. Nozzle Closure	7. Engine Purge			

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Thrust, structural factor and propellant loading to impart required velocity forms the major specification of the stage. The definition and specification of each sub system are derived from the stage definition and specification parameters. Figure 2 shows major steps involved in development of any new liquid stage. Different options and configurations for each of the sub system is worked out and finalized based on thorough review of pros and cons of each configuration. Preliminary design of the finalized configuration is carried out considering influence and requirements of other subsystems, fabrication easiness, integration, testing and launch pad interfaces. Qualification testing will be carried out at various levels, viz, component, sub system and integrated stage, to identify and mitigate the design problems, if any, at the earliest opportunity. Detailed assessment of the sub system performance and the stage performance as a whole will be done and configuration/design of any sub system will be modified, if required.

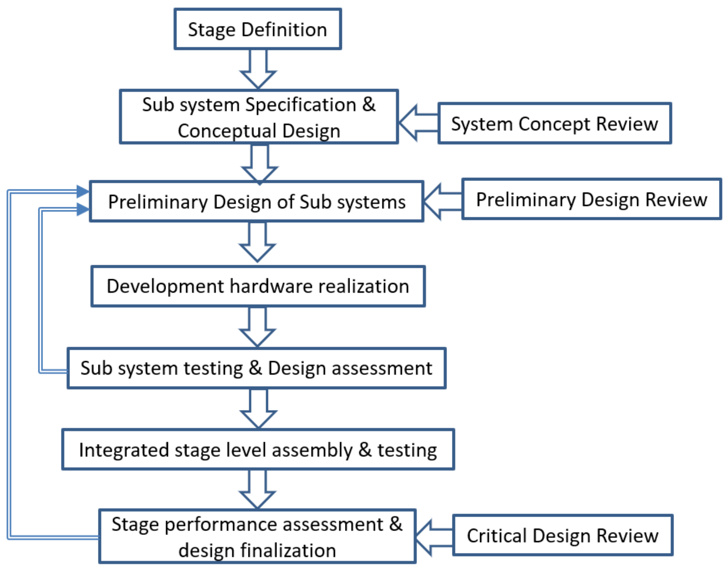

Figure 2: Various phases involved in development of Liquid Propellant stage

3.1. Challenges in Overall Stage Engineering

The Semi-Cryogenic stage under discussion is configured by maintaining the overall vehicle structure and envelope. With this constraint, maximum possible propellant loading is finalized. For this loading, mission design and mission optimization is done. This led to additional technical challenges as brought out in Table 2. Different studies are carried out with probable stage configurations and is optimized in an iterative process based on the feedback from various studies.

3.2. Design Challenge-1: Stage Configuration within the Available Height

As the stage height is already fixed, the total propellant loading that can be accommodated in the given envelope depends on the space available after accommodating the necessary structures like Inter stage/tank structures and base structure. The available space is allocated to the propellant tanks considering the Mixture Ratio (MR) and propellant budgeting. Detailed mission studies indicated that the obtained propellant loading gives sub optimal performance of the mission and doesn't increase the payload, which was one of the main objectives of the new stage development. The challenge here is to increase the propellant tank sizes within the available stage envelope and to deal with its influence on other systems.

Table 2: Major Design challenges faced during Semi-Cryogenic stage configuration phase

Design constraint	Affecting parameter	Solution strategy
Stage configuration within available height.	Propellant loading	Optimization of structure heights
Protection of cooling channels in nozzle divergent	Design and configuration of stage aft structures	Detailed aero and thermal studies with different aft structure designs. Jettisonable nozzle protection structure enclosing nozzle divergent
Maintaining auxiliary system layout as in adjacent stages	Cutouts on structures. Interfaces on tanks and structures.	Overall design adapted same as in the earth storable stage being replaced.
Utilization of existing fabrication and integration facilities	Configuration of tanks. Integration procedures.	Configuration of tanks as per established practices. Spatial grouping of LOX and Isrosene modules and systems in all structures.

3.3. Solution Strategy Implemented for Design Challenge-1

In order to maximize the propellant loading, one of the inter stage structure is dispensed with, thus increasing the propellant loading by around 7 tonnes. However, it affected many other sub systems and stage parameters leading to chain of changes. Figure 3 shows the solution strategy implemented, following system engineering practices. It introduced accessibility issues for the avionics sub assembly located in the upper structure and is managed by extension of fuel tank fore end ring. As the fuel tank is moved forward, very near to the strap-on thrust transfer joint, the structural loads have become non-uniform. To optimize tank mass, higher thickness is introduced only for the region where loads are higher. Vehicle loads for remaining structures and oxidizer tank also are re estimated and design is re assessed. Though the modified design induced additional complexities in design and realization of the fuel tank and affected many other systems, it is better trade-off considering the payload advantage gained by the additional propellant loading.

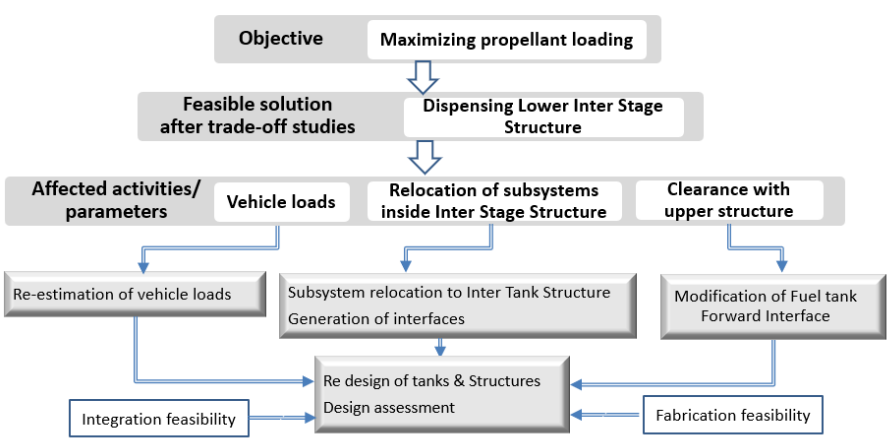

Figure 3: Flow chart of solution startegy for design challenge-1

3.4. DESIGN CHALLENGE-2: PROTECTION OF COOLING CHANNELS IN NOZZLE DIVERGENT

The regenerative cooling channels of nozzle divergent of the engine are filled with fuel before lift-off. However, engine gets ignited only after about 2 minutes in to the flight. During non-operational phase of the engine, nozzle divergent is to be protected from convective and radiative heat loads from exhaust gases of the strapons thereby controlling the temperature of stagnant fuel inside the regenerative cooling channels. The challenge here is to protect/enclose the nozzle divergent till engine ignition.

3.5. SOLUTION STRATEGY IMPLEMENTED FOR DESIGN CHALLENGE-2

To tackle the nozzle divergent heating, an additional nozzle closure is introduced at the stage aft end, interfacing with the thermal shroud. This nozzle closure will be commanded to separate just before engine ignition, using pyro-based devices. Introduction of nozzle closure lead to two distinct aero thermal regimes, before and after nozzle closure separation. Vehicle external configuration also changes during these events. The finalized contour of the nozzle closure and overall configuration of the base region is finalized based on detailed aero, thermal and separation studies. Figure 4 shows the stage base region with nozzle divergent enclosed with nozzle closure. Figure 5 presents the solution strategy implemented following the system engineering practices. The thermal shroud and nozzle closure are considered as a whole and aero studies are carried out for all possible configuration. Though ogive type aft end is the better configuration in aero loads perspective, conical shape with spherical end cap is selected as it provides fabrication and integration easiness.

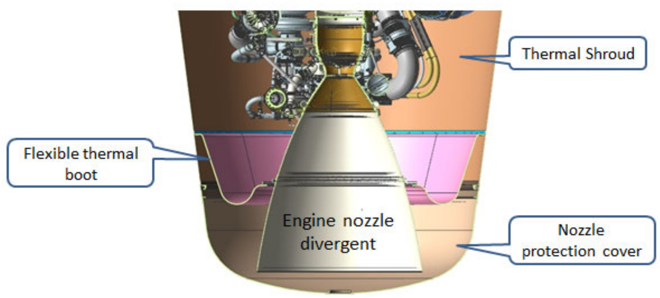

Figure 4: Stage aft end region showing the Nozzle protection cover

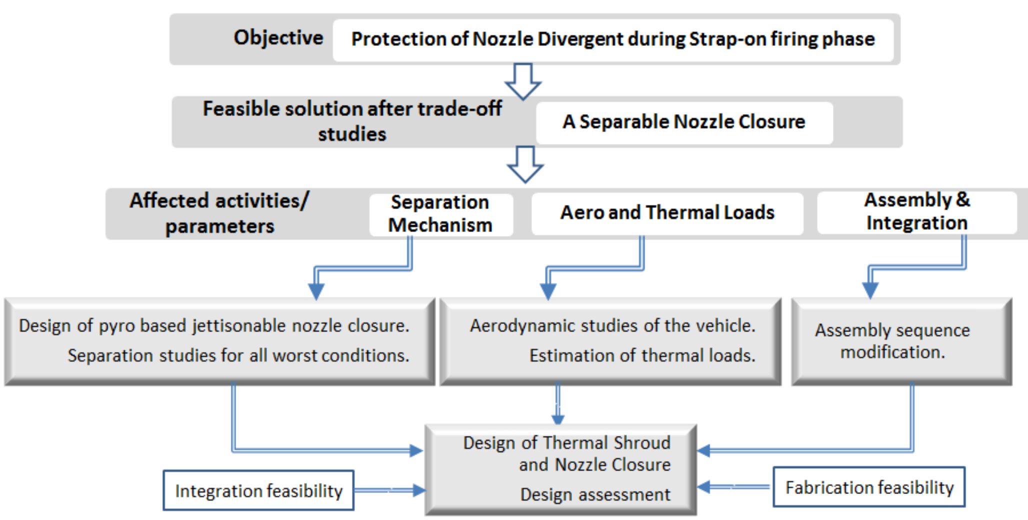

Figure 5: Flow chart of solution strategy for design challenge-2

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3.6. DESIGN CHALLENGE-3: MAINTAINING AUXILIARY SYSTEM LAYOUT AS IN ADJACENT STAGES

Auxiliary systems run over the total vehicle, providing instrumentation, power and servicing support independently to each stage and also between the stages. The challenge here is to configure the stage auxiliary systems in line with that of adjacent stages.

3.7. SOLUTION STRATEGY IMPLEMENTED FOR DESIGN CHALLENGE-3

Auxiliary system configuration and layout are maintained same as in the adjacent stages. However, it introduced constraints in working out propulsion sub system layout. The ideal layout of Isrosene feed pipe is found to interfere with that of strapon stage attachment links. Further system integration studies highlighted that the modified feed pipe is very near to external cable layout, introducing access and integration difficulties. Based on detailed studies, an optimum configuration of the structural and auxiliary system were arrived at.

3.8. DESIGN CHALLENGE-4: UTILIZATION OF EXISTING FABRICATION AND INTEGRATION FACILITIES

Cryogenic servicing and storage systems require stringent cleanliness requirements than that of Isrosene systems. Utilization of existing integration facilities requires independent preparation of the LOX and Isrosene tank sub assemblies in Cryogenic and Earth Storable assembly facilities respectively. However, engine also requires to be prepared with stringent cleanliness requirements as that of LOX tank. Hence, stage is configured with LOX tank, base structure and engine as a separate unit that can be assembled in Cryogenic facilities. However, for control system requirements and also for better NPSP margins at pump inlet, it is preferable to place LOX tank at the stage fore end region. Here, the challenge is to finalize the configuration considering the conflicting requirements from integration facilities and vehicle control and LOX feed system.

3.9. SOLUTION STRATEGY IMPLEMENTED FOR DESIGN CHALLENGE-4

Mission studies are carried out and vehicle loads are estimated with LOX tank at stage fore end and aft end. It is found that positioning of LOX tank at the aft increases the tank mass by 100 kg, but the configuration gives advantage on integration and lower stage protrusions. Vehicle controllability and stability with LOX tank at the aft and found to be acceptable. Hence, integration aspects are taken into the consideration and LOX tank is provided at the aft. The change calls for the redesign of tank thickness and change in aero load pattern. Tank design is revisited considering all influencing factors like pump head requirement, aerodynamic projection and structural interfaces.

The above examples gives gist of system engineering applications in design of booster stage with propellants stored at different temperatures and demanding different levels of integration requirement. Breakdown of the stage design into different systems, finding out optimum sub system configuration and integration of all these sub systems utilizing system engineering practices result in birth of optimum stage. Table 4 presents the overall gain in the project deliverables by due consideration from all different sub systems and activities of the stage development.

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Table 3: Improvement in the stage development activities/parameters

Parameter	Affecting parameter
Propellant loading	Increased by 7 tonnes
Development schedule	Reduced by more than 36 months
Development cost	Reduced by 40% with the utilization of existing facilities

4. CONCLUSIONS

This paper explains the relevance of systems engineering for launch vehicle development programme. A few major challenges faced during development of a large Semi-Cryogenic stage are discussed with the solution strategies. System engineering practices are followed from initial configuration phase till final qualification testing and an optimum solution is attained, considering the conflicting requirements from various sub systems. This approach also helped in increasing the stage performance as a whole.

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