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Impact of Solid Rocket Propellant Grain Manufacturing Limitations on Launch Vehicle Capability

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ABSTRACT

It is examined if any limitations in existing solid rocket propellant grain manufacturing methods adversely affected the payload capability of recent space launch vehicles. It is seen if the transition from heavy, segmented metal rocket motor casings to lightweight monolith composite casings is possible without loss of ability to design and realize high-performance grain configurations using simple and safe methods. Considering payload fraction as the comparative performance metric, recently flown solid rocket-propelled, small-lift launch vehicles were surveyed and ranked. Solid rocket boosters of underperforming launch vehicles were investigated for manufacturing factors influencing payload fraction by comparing them to boosters of better-performing launch vehicles in their weight class. Relationships between payload fraction and the solid boosters' mass fractions, casing construction, shape of thrust profile, propellant grain configuration and method employed to manufacture the grain were analysed. It is shown that those launch vehicles that did not possess or use the technology necessary to manufacture high-performance grain configurations like undercut finocyl in monolith composite casings ended up having boosters delivering poor thrust profiles with high inert mass ultimately leading to low payload fractions.

Keywords: Launch vehicle; Payload fraction; Solid rocket booster; Undercut finocyl grain; Casting mandrel

1. INTRODUCTION

All over the world, the quest for cost-competitive access to space has driven continuous research efforts towards finding new ways to make space Launch Vehicles (LVs) more efficient in terms of their payload capability, manufacturing cost and time, launch preparation activities, safety and reliability. Among expendable space LVs, Solid Rocket Boosters (SRBs) based LVs are considered less complex, more economical and as reliable when compared to their more energetic liquid and cryogenic counterparts[1]. Also, solid rockets have been a preferred option for small-lift launchers[2]. They have a low part count and take less preparation time on the launchpad. Also, they are compact, inert and easy to start. However, they cannot be pre-flight-tested on the ground, throttled, easily stopped or restarted. Still, they are widely used as LV core boosters, strap-on motors, upper-stage motors and satellite kick motors. Some, like Space Shuttle SRBs and LVM3 HS200s, are even human-rated. Therefore, R&D towards their continued improvement is essential and justified.

Overall LV performance capability can be calculated in terms of its Payload Fraction (PLF). Various factors influencing PLF are illustrated using Ishikawa's cause-effect fishbone diagram in Fig. 1.

Describing the major influence of propulsion systems on LV performance, Sutton & Biblarz in their textbook[3] state, "only a few flight vehicle performance improvements do not depend on propulsion systems". Past efforts towards performance improvements in SRB-based LVs have primarily focussed on increasing propellant specific impulse (Isp), improving propellant grain volumetric loading fraction, reducing flight vehicle inert mass and/or decreasing booster burn time[3-5]. A literature review of recent advancements revealed that adding energetic binders[6] and powerful yet less-toxic oxidizers[7] to the traditional HTPB-AP-Al-based composite propellant can improve Isp by more than 10 s. However, associated synthesis methods, stability, sensitivity, cost, etc are reportedly not yet viable enough for bulk production and safe usage in LVs.

NASA space vehicle design criteria monographs[8-9] from the 1970s recommended simple grain perforations with uniform cross sections that can be easily and safely manufactured. Propellant grain machining was strongly discouraged. Since then, booster grain requirements have evolved in terms of dense loading, ability to generate mission-specific thrust profiles, good structural integrity, high burn rates, etc. Enabling technologies for advanced space solid propulsion systems of today and tomorrow are discussed by Caveny[10]*, et al.* & Guery[11]*, et al.* For instance, to cast very large monolith grains efficiently, continuous mixing techniques are projected. For a wide range of payload mass brackets, modular LVs with a variable number of solid strap-on motors (0, 2 or 4 nos.) like in Ariane-6 and H-3 are proposed. The same strap-on motors play the role of core boosters in small LVs.

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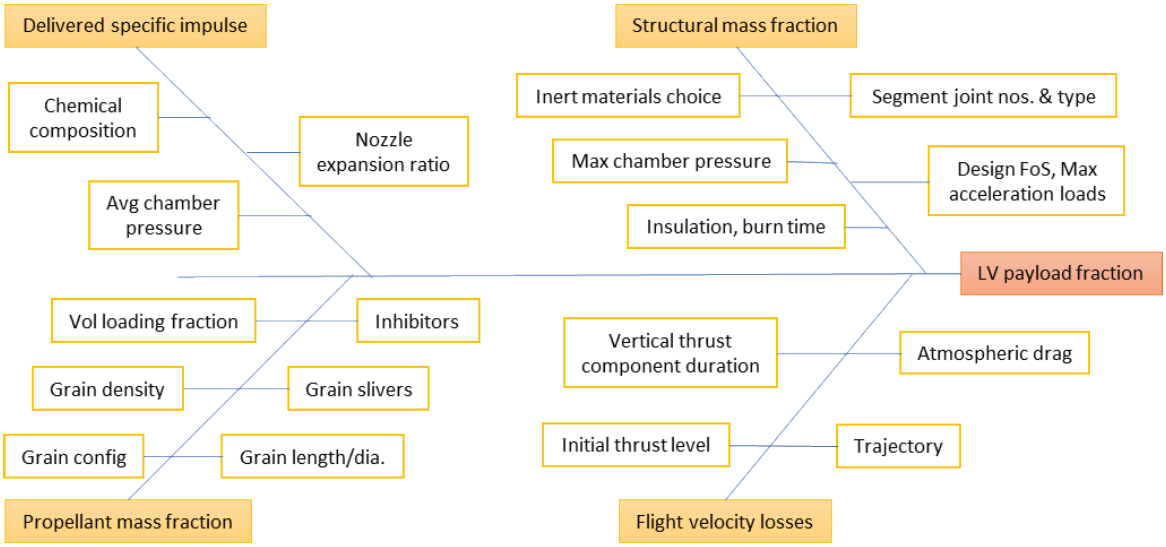

Figure 1. Fishbone diagram showing various factors affecting launch vehicle performance.

As solid rocket technologies evolved, some areas could have been improved at the cost of others. For example, heavy and segmented metallic rocket motor casings were replaced by lightweight, monolith composite casings. In the process, the ability to generate mission-optimal thrust profiles using grains that were easily realizable with simple monolith casting mandrels has been lost. By finding and addressing such conflicting requirements, LVs can be made more efficient in terms of their payload capability, cost, safety and reliability.

Since the start of the space race, different methods have been proposed, studied, tested and implemented to enhance LV capabilities. What has not been sufficiently looked into though is how certain manufacturing aspects are influencing design decisions and ultimately affecting LV performance. To address the problem holistically, it is important to consider the methods employed to make the LV solid rocket booster grains too and study their influence on delivered performance. Therefore, this study focuses on identifying those manufacturing difficulties that limit design options for better performance. Real-world data from the latest operational LVs were collected and critically analysed to find gaps in the existing state of the art.

2. METHODOLOGY

The objective of the research study was to examine how limitations (if any) in existing solid rocket propellant grain manufacturing technology prevented space launch vehicles from maximizing their payload potential and reducing space launch cost and time. The outline of the study design follows:

2.1 Selection of Candidates

- Recently flown small-lift (up to 2 tons to low earth orbit) launch vehicles^{2} using solid rocket propulsion were surveyed for the research study. In the space domain, solid rockets are predominantly used as core boosters by small launchers due to their inherent simplicity and lower cost. Medium and heavy-lift LVs were left out of the study as they generally rely on liquid or cryogenic rocket propulsion for their core and upper-stage requirements
- Each LV employed at least two solid rocket booster stages
- For parity, only those LVs launched from land or sea and capable of placing satellite(s) in polar orbits were considered. Air-launched LVs were ignored
- Necessary limited technical details of the LVs and their boosters were sourced mainly from primary sources like LV user's manuals, rocket manufacturer's product catalogue, published journal and conference papers and patents. In some instances, to fill in incomplete data, news and website reports have been referenced. No space agency shares the complete design and performance details of its LVs
- To ensure that the chosen candidates are contemporary and relevant to today's technology levels, only currently operational LVs and those launched during the last three decades (since 1990) were considered
- A limited number of subjects were available for the study because only a handful of aerospace agencies have been able to successfully develop and fly solid rocket-based space LVs. Also, the space LV domain involves high cost and high technology with explosive hazards due to which strict safety norms are enforced by governments on the few licensees
- The selected LVs belonged to space agencies of different countries from around the world.

2.2 Research Methodology

- Payload fraction (PLF = max payload mass over total vehicle mass) was the metric chosen for comparing the performance of LVs
- For comparison of performance on equal terms, LV payload fractions were rationalized to a 500 km reference Sun-Synchronous Polar Orbit (SSPO)
- The candidate LVs were ranked according to their payload fractions
- The mean value of the payload fractions was calculated and those LVs lying outside 1-standard deviation limits were identified for investigation

- Underperforming LVs were compared with better-performing LVs in their weight class in terms of the following manufacturing-related propulsion design and performance parameters:
    - LV propellant mass fraction
    - Stage structural mass fraction
    - Casing material and construction
    - Thrust profile shape
    - Grain configuration
- Relations between the above parameters among themselves and with LV payload fraction were determined. Ishikawa's fishbone diagram from Fig. 1 was used to map all possible major manufacturing factors contributing to subpar performance in LVs. Grain manufacturing techniques employed in different LV boosters were analyzed for their pros and cons concerning capabilities, ease of use and safety
- Next, Sakichi Toyota's '5-whys' technique was used to perform root cause analysis on each of the identified LV to confirm if and how existing manufacturing limitations contributed to underperformance in that LV
- Deficiencies in existing state-of-the-art were highlighted for further R&D. Possible improvements in future versions of the underperforming LVs were identified.

3. RESULTS AND DISCUSSION

3.1 Payload Fraction

After a survey of solid rocket-propelled, small-lift LVs launched from the year 1990 to 2023, fifteen LVs were found to meet the selection criteria. They are tabulated in ascending order of their lift-off mass in Table 1. Values of LV PLF calculated with rationalized payload for 500 km SSPO are plotted in Fig. 2.

Table 1. A comparison of recent small-lift, solid rocket-propelled launch vehicles

Launch vehicle	Country	First flight, year	Missions flown till Dec 2023	Stages (S) Solid (L) Liquid	Lift-off mass, (ton)	Length x major Dia, (m)	Payload to 500 km SSPO (kg)
KZ-1A[12]	China	2017	22	3(S)+1(L)	30	19.4 x 1.4	240
Ceres-1[13]	China	2020	11	3(S)+1(L)	33	20.0 x 1.4	300
Minotaur-I[14]	USA	2000	12	4(S)	36	19.2 x 1.7	350
Start-1[15]	Russia	1993	7	4(S)	47	22.7 x 1.8	300
LM-11[16]	China	2015	17	4(S)	58	20.8 x 2.0	400
Athena-I[17]	USA	1995	4	2(S)+1(L)	69	18.9 x 2.4	360
Minotaur-IV[18]	USA	2010	7	4(S)	86	23.9 x 2.4	1050
Epsilon[19]	Japan	2013	6	3(S)+1(L)	96	24.4 x 2.5	590
SSLV[20]	India	2022	2	3(S)+1(L)	120	34.0 x 2.0	300
Athena-II[17]	USA	1998	3	3(S)+1(L)	124	28.2 x 2.4	1220
Kinetica-I[21]	China	2022	2	4(S)	135	30.0 x 2.65	1500
Vega[22]	EU	2012	21	3(S)+1(L)	137	30.0 x 3.0	1440
M-V[23,24]	Japan	1997	7	4(S)	139	30.7 x 2.5	950
Vega-C[25]	EU	2022	2	3(S)+1(L)	210	35.0 x 3.4	2340
PSLV-CA[26]	India	2007	17	2(S)+2(L)	230	44.0 x 2.8	1100

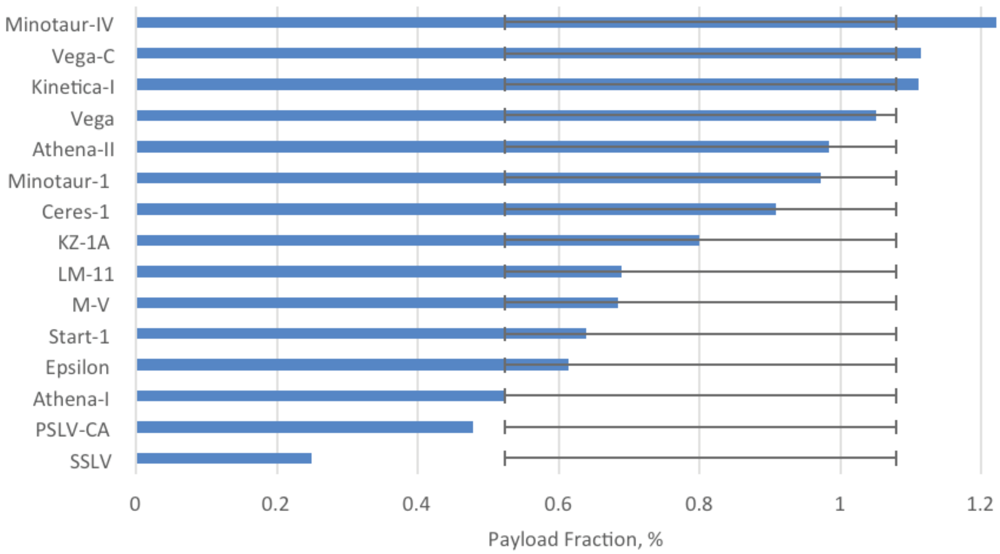

Figure 2. Comparison of the capability of small-lift launch vehicles to 500 km SSPO.

The survey shows significant variation in LV PLF – with an arithmetic mean of 0.80 % and 1-standard deviation (1-SD) of 0.29 %. LVs with extremely low and high PLF are of interest to this study.

From Fig. 2, it can be seen that PLF of Athena-I (0.52 %), PSLV-CA (0.48 %) and SSLV (0.25 %) are near or below 1-SD (0.52 %) and those of Vega (1.05 %), Kinetica-I (1.11 %), Vega-C (1.11 %) and Minotaur-IV (1.22 %) are near or above 1-SD (1.08 %). In line with the stated method, low-performing LVs are compared to high-performing LVs in their lift-off weight class and analysed in detail.

Athena-I is comparable to LM-11 and Minotaur-IV in weight class (69 vs. 58 & 86 tons). Since the available literature on LM-11 is inadequate, Athena-I is compared only with Minotaur-IV.

PSLV-CA and Vega-C are comparable in lift-off mass (230 vs. 210 tons). Therefore, their propulsion design and performance parameters are compared in the study.

SSLV, Athena-II, Kinetica-I, Vega and M-V belong to the same weight class (120 to 139 tons). However, in terms of payload fraction, M-V falls short (0.68 %). Technical literature on Kinetica-I is limited. Therefore, SSLV is compared with Vega and Athena-II.

3.2 Launch Vehicle Propellant Mass Fraction

Propellant mass fraction (PMF = usable propellant mass over total vehicle mass) is a crucial LV performance parameter with a logarithmic relation to the maximum attainable payload velocity at the end of the propulsion phase[1]. Higher values indicate better flight performance. Hence, LV designers strive to maximize PMF. For large solid rockets, reported PMF values range between 0.880 and 0.945[3,27]. Overall PMFs for the LVs under study are calculated and compared using mass data from Table 2.

With only a 10 % increase in structural mass, Minotaur-IV carries about 30 % more propellant mass and one more stage than Athena-I. This leads to an impressive PMF above 0.9 and the highest PLF in its class (1.22 %). While Athena-I boosters were designed for commercial purposes, Minotaur-IV's were originally military boosters which are usually built for compactness and performance rather than economy.

Between PSLV-CA and Vega-C, as seen in Fig. 3, total propellant mass (~190 tons) and distribution among stages are almost the same. But the PMF of PSLV-CA (0.83) is significantly less than that of Vega-C (0.90) as seen in Fig. 4. This additional 7 % of total LV mass contributed by PSLV's non-energetic elements has partly led to its lower payload fraction.

In the case of SSLV vs. Vega vs. Athena-II, except for first stage propellant mass (~88 tons) of SSLV & Vega, neither total propellant mass (99 vs. 123 vs. 108 tons) nor PMF (0.83 vs. 0.90 vs. 0.87) of the three LVs match. Propellant distribution in

Table 2. Propellant and inert mass distribution in selected launch vehicle stages

Launch Vehicle	Stage propellant mass (ton)				Stage structural mass (ton)			
	S1	S2	S3	S4	S1	S2	S3	S4
Athena-I	48.99	9.77	0.24*	---	4.08	0.85	---	---
Minotaur-IV	45.40	24.50	7.08	0.78	3.60	3.20	0.65	0.11
PSLV-CA	138.20	42.00*	7.65	2.50*	30.20	5.30	1.10	0.92
Vega-C	141.63	36.24	10.57	0.74*	13.39	4.24	1.43	0.70
SSLV	87.00	7.70	4.50	0.05*	18.00^	1.10^	0.65^	---
Vega	87.71	23.81	10.57	0.58*	7.33	2.85	1.32	0.15
Athena-II	48.99	48.99	9.77	0.24*	4.08	4.08	0.85	NA

(S1, S2… booster stages; * liquid propulsion; ^ assumed value)

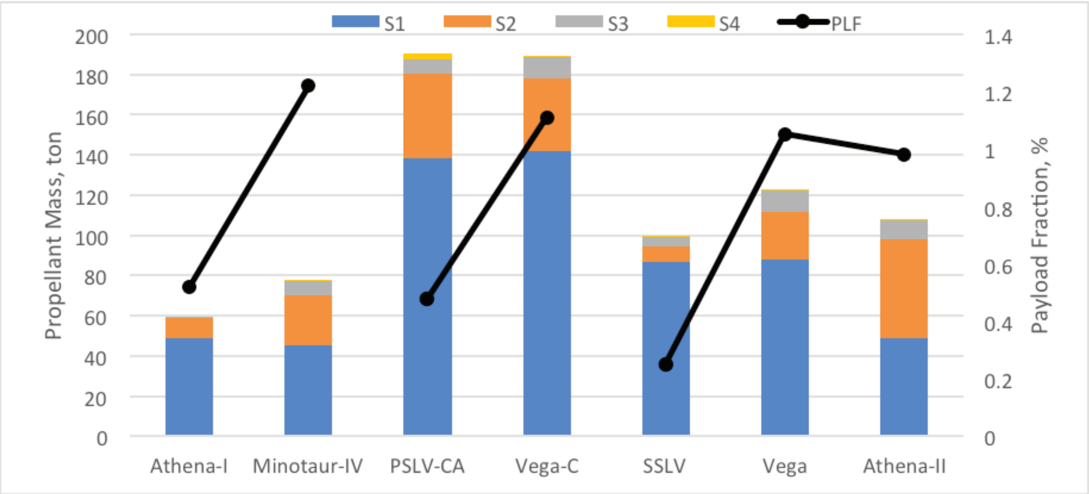

Figure 3. Launch vehicles stage-wise propellant distribution.

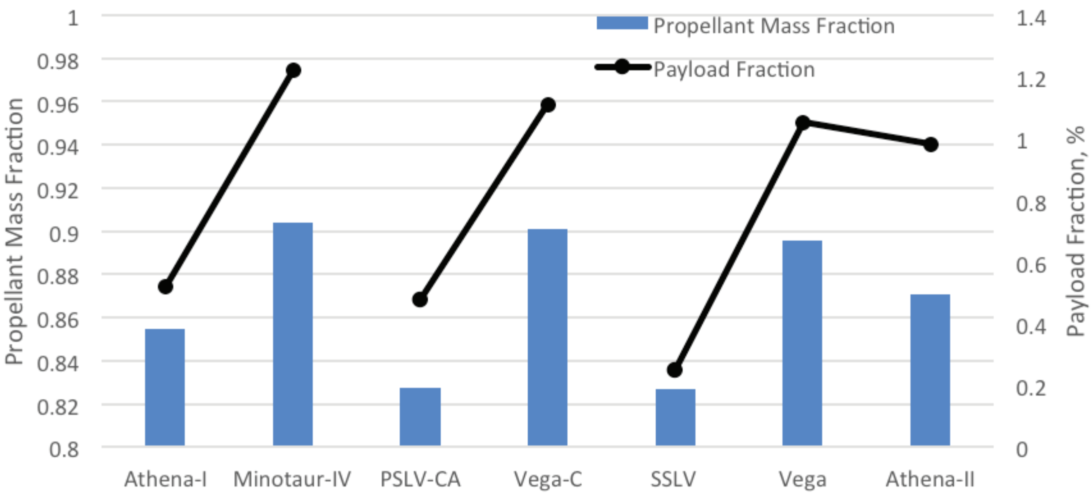

Figure 4. Lunch vehicle propellant mass fraction.

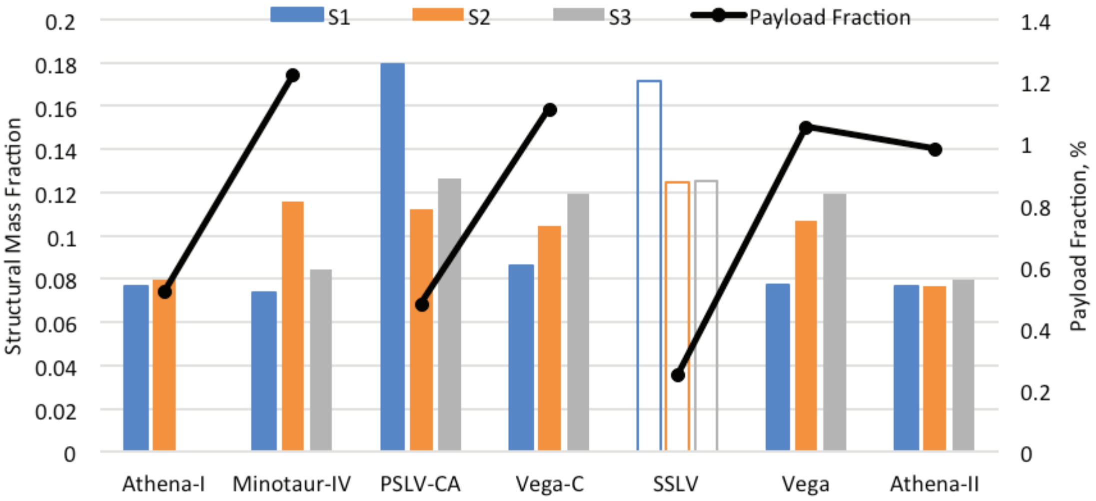

Figure 5. Structural mass fraction of launch vehicle stages.

the upper stages of SSLV seems to be disproportionately low. The low PMF of SSLV appears to have contributed to some extent to its low payload capability.

3.3 Stage Structural Mass Fraction

Structural Mass Fraction (SMF) of a stage is its inert mass over the total stage mass. Inert mass is contributed by chosen casing material (metal or composite), construction (monolith or segmented), Maximum Expected Operating Pressure (MEOP), insulation, inhibitor, igniter, nozzle and all other non-energy adding elements. Calculated values of SMF for different LV stages are plotted in Fig. 5. Values for SSLV boosters are figured considering their pedigree with PSLV and are shown differently.

From Fig. 5, the following observations can be made:

- Between Athena-I and Minotaur-IV, the former has slightly better SMFs. But Minotaur-IV aces in PLF due to its 3-stage configuration and higher Isp (Table 3) delivered using extendable nozzle exit cones in upper stages[29].
- Owing to its segmented metallic casing, S1 of PSLV-CA has the highest value of SMF (17.9 %) whereas S1 of Vega-C with almost the same mass of propellant (140 tons) in monolith composite casing has only 8.6 %. Upper stages are comparable in SMF. In terms of Isp, especially in the upper stages where its sensitivity is high, the difference is small.
- In SSLV vs. Vega and Athena-II, the latter LVs have the best S1 SMF (< 8 %) in the study. Despite superior overall SMF, Athena-II PLF is lower than Vega's. This can be attributed to its modular staging which is not optimal from a propellant distribution point of view but has its benefits in terms of inventory and cost. In the case of SSLV, while its upper stage values are comparable to those of Vega, its 3-segmented metallic first-stage booster seems to be the main cause for its low PLF.

Using Table 3 data, Fig. 6 is plotted. It may be noticed that the general range of SMF over rocket chamber pressure is between 8 % and 12 %, with the first stages being the lowest. PSLV S139's low MEOP (60 kg/cm^2) has not helped to reduce its high SMF (18 %). For composite casings, however, irrespective of the stage, the average value of SMF is found to be about 10 %. It is observed that motors with higher MEOP tend to have lower SMF. The phenomenon can be explained

Table 3. LV booster casing material, construction and performance parameters

LV	Stage	Booster	Casing material	No. of segments	Dia, (m)	MEOP, (kg/cm^2)	SMF, (%)	Isp vac (s)
Athena-I&II[28]	S1, S2	Castor120	Carbon composite	1	2.36	111	7.7	280
	S2, S3	Orbus21D	Kevlar composite	1	2.34	58	8.0	293
Minotaur-IV[29-31]	S1	SR118	Kevlar composite	1	2.34	98~	7.3	284
	S2	SR119		1	2.34	98~	11.6	308
	S3	SR120		1	2.34	40~	8.4	300
	S4	Orion 38	Carbon composite	1	0.97	45	10.8	287
PSLV-CA[32]	S1	S139	Maraging steel	5	2.8	60	17.9	269
	S3	HPS3	Kevlar composite	1	2.0	60	12.6	295
Vega-C[25,33]	S1	P120C	Carbon composite	1	3.4	105	8.6	279
	S2	Z40		1	2.4	115	10.5	294
	S3	Z9		1	1.9	75	11.9	296
SSLV[34]	S1	SS1	15CDV6 steel	3	2.0	NA	17.1^	NA
	S2	SS2	Carbon composite	1	2.0	60	12.5^	NA
	S3	SS3		1	2.0	NA	12.5^	NA
Vega[22, 33]	S1	P80	Carbon composite	1	3.0	88	7.7	280
	S2	Z23		1	1.9	94	10.7	288
	S3	Z9		1	1.9	75	11.9	296

(~ average chamber pressure; ^ assumed value)

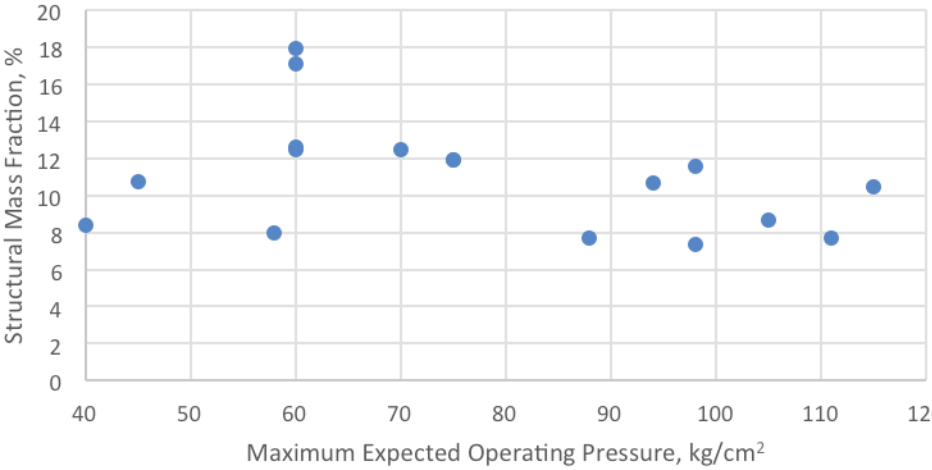

Figure 6. Booster chamber pressure vs stage structural mass fraction.

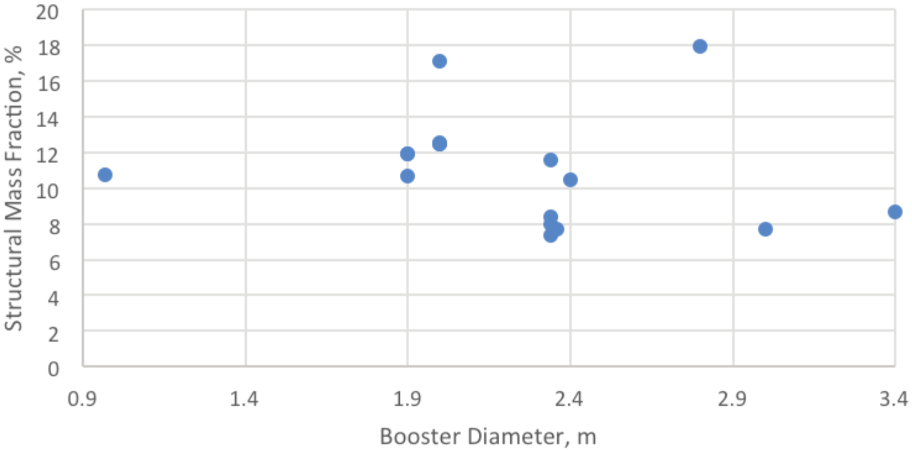

Figure 7. Booster diameter vs stage structural mass fraction.

thus. High operating pressures require thicker and heavier casing walls. But high MEOP also translates to smaller nozzle throat diameter and consequent smaller casing end-aperture and lighter casing-nozzle interface. Also, the nozzle divergent can be smaller for the same expansion ratio. Mass reduction due to a smaller throat is seen to be more than mass addition from higher composite casing wall thickness.

As per Fig. 7, bulkier composite motors have lower SMF. But bigger diameters are associated with higher drag in the atmospheric phase of flight. In practice, however, booster diameter is traded off with length to reduce overall LV length. To minimize SMF, optimization studies must be done before finalizing MEOP, motor diameter, nozzle expansion ratio, etc.

3.4 Shape of Thrust Profiles

Solid booster thrust profiles are pre-programmed in grain design. They are stage-wise optimized for performance in different regimes of atmospheric and space flight. A typical first stage or ground booster thrust profile has the following requirements / constraints[35] from start to end for achieving mission objectives efficiently without overstressing the payload:

- Thrust force above a minimum value (maximum thrust) at lift-off
- Reduced thrust level near max dynamic pressure (Qmax) regime
- Restricted thrust level at maximum acceleration limit
- Repeatable thrust tail-off for controllable stage separation
- Minimal burn time for burnout (for minimizing gravity losses).

For upper stages which predominantly operate in near vacuum, a different set of constraints apply. As the flight vehicle continuously loses mass, booster acceleration levels must reflect that.

- High thrust at the start to meet side force needs to compensate for possible disturbances during stage separation
- Regressive thrust profile in the second half to limit peak loads on sensitive payload and keep design factors of safety reasonable.

In general, minimizing booster burn time will also reduce inert masses while keeping gravity losses minimal. Vacuum thrust vs. time data for the subject LV boosters is plotted for ground and upper-stage boosters separately in Fig. 8 & Fig. 9.

Almost all first-stage boosters generate the classical ‘M-type’ thrust profile with thrust levels temporarily reduced near Qmax. However, thrust duration varies much. Burnout of Vega and PSLV S1 boosters after 100 s seems to have been timed to wait for lower dynamic pressure and consequently minimal disturbances during stage separation. As Minotaur-IV was originally a military LV, its boosters could have been designed for quicker ascent and burnout. Castor-120 of Athena burning for about 80 s could be a tradeoff between long-burn S1 and short-burn S2 modular requirements.

A near-uniform trend is observed in upper-stage boosters. Almost all of them start or touch peak thrust fairly early. However, only in the case of HPS3 of PSLV / SS2 of SSLV, a progressive thrust profile is seen. No mission requirement for such a profile could be envisaged. In the case of SSLV, the low initial thrust from SS2 could be a reason for prolonging SS1 burn to ensure stage separation at higher altitudes with lower dynamic pressure.

3.5 Grains Configuration and Manufacturing Method

Stage-wise booster details of grain segment(s) geometry and manufacturing steps including the employed grain shaping method are tabulated in Table 4.

Athena’s Castor-120[36-37] is a unique booster with the provision to change the grain configuration in every manufactured motor to meet first-stage, second-stage or strap-on motor requirements. Deep conical slots around the moulded central core are subsequently machined using a patented tool[38]

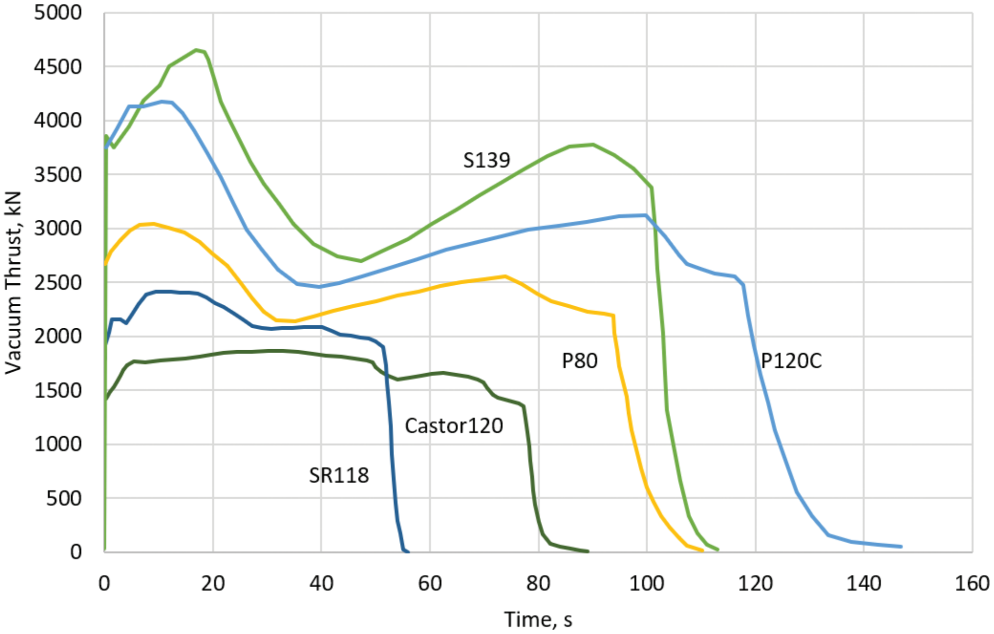

Figure 8. Thrust profiles of first-stage boosters.

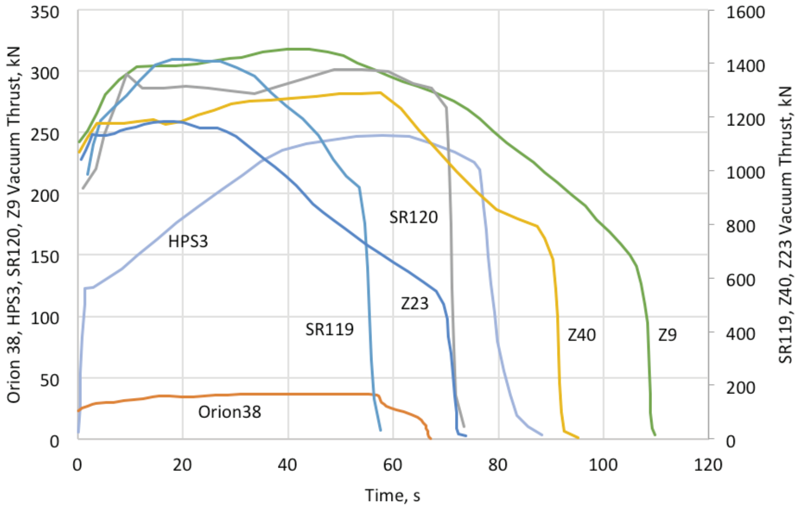

Figure 9. Thrust profiles of upper-stage boosters.

Table 4. Boosters propellant grain configuration and manufacturing method

LV	Booster	Grain configuration	Propellant distribution (ton)	Manufacturing method
Athena-I&II	Castor 120	Monolith grain: Conocyl	49	Intermediate shape casting - Monolith mandrel - Conical slots machining
	Orbus 21D	Monolith grain: Cylindrical port	10	Monolith mandrel
Minotaur-IV	SR118	Monolith grain: Undercut finocyl	46	Not available
	SR119	Monolith grain: Undercut finocyl	24	Not available
	SR120	Monolith grain: Annular slot	7	Not available
	Orion 38	Monolith grain: Undercut finocyl	1	Not available
PSLV-CA	S139	5-segment grain: Star + 4 cylinders	138 (18+30+30+30+30)	Intermediate shape casting - Monolith mandrels (3 types) - Segment ends trimming
	HPS3 (also SSLV SS2)	Monolith grain: Annular slots	8	Intermediate shape casting - Monolith mandrel - Slots machining
Vega-C	P120C	Monolith grain: Undercut finocyl	142	Net-shape squeeze casting - Undercut mandrel assembly
	Z40	Monolith grain: Undercut finocyl	36	
SSLV	SS1	3-segment grain: Star + 2 cylinders	87 (27+30+30)	Intermediate shape casting - Monolith mandrels (3 types) - Segment ends trimming
	SS3	Monolith grain: Annular slots	5	Intermediate shape casting - Monolith mandrel - Slots machining
Vega	P80	Monolith grain: Undercut finocyl	88	Net-shape squeeze casting - Undercut mandrel assembly
	Z23	Monolith grain: Undercut finocyl	24	
	Z9 (also Vega-C S3)	Monolith grain: Undercut finocyl	11	

to get the user's mission-specific thrust profiles. Its use in the first as well as second stages of Athena-II, with only different grain geometries, allows for a smaller unique part count. On the demerit side, Castor-120 needs a long manufacturing duration – after casting, curing and decoring, almost 1500 kg of propellant needs to be remotely machined out at the rate of 10 kg/hr. That would be about 19 days of hazardous operation, assuming 8 machining man-hours per day. Maybe for the said reasons, conocyl grains are not found elsewhere.

PSLV S139's 'star + cylinders' configuration is found in previous generation LV boosters like the 3-segment booster of European Space Agency's Ariane-5[39]. It is ideal for generating an 'M-type' thrust profile. But its major demerit would be the necessary metal casing segments with large apertures and thus heavy joints. Without using any complex undercut mandrels, the deep star and cylindrical grain segments can be cast using monolith mandrels like the ones shown in Fig. 10. SSLV's three-segmented SS1 is also assumed to be using a similar method. Another important aspect to be considered with the segmented booster is the time taken to manufacture, prepare, inspect and integrate the segments with adhesive between grain ends and Tang-Clevis field joints between casing segments

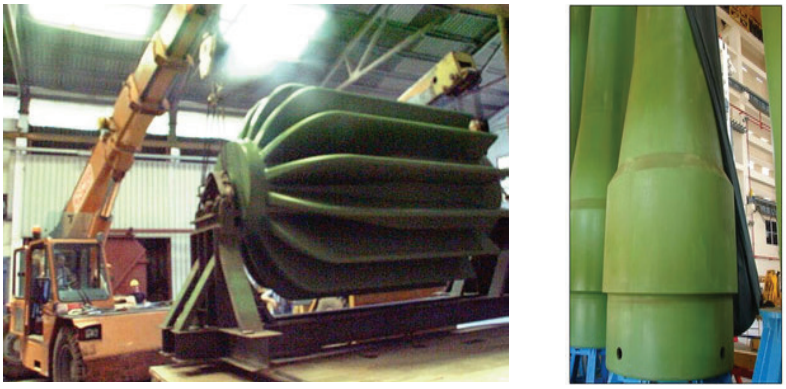

Figure 10. Monolith casting mandrels of LVM3 S200 head-end and nozzle-end grain segments[40].

using a large number of pins. Going for monolith construction “is a key for reduced recurring cost”[41]. HPS3 of PSLV / SS2 of SSLV uses lightweight CRMC with a small aperture (about 33 % of motor diameter). After decoring a cylindrical mandrel, 2 shallow radial slots (not larger than the casing aperture) are machined into the grain. The resulting progressive thrust profile unnecessarily increases burn time, insulation thickness and terminal acceleration (max 7g)[42]. The benefits of inert mass saving from the composite casing are partially lost due to the grain configuration.

All Vega/Vega-C boosters have composite casings with undercut finocyl grains of varying geometries. A proprietary squeeze casting technique using segmented mandrels[43] seems to be employed. The method allows highly desirable net-shape casting of the complex grain geometries. The viscosity of propellant slurry during squeeze casting can be quite high, as it is a last activity. Also, slivers formed between the squeeze-casting mandrels can be a cause of safety concern during decoring,

3.6 Root Cause Analysis

Using the ‘5-whys’ method, core reasons for low payload fraction in LVs were determined. After the problem is defined, the question ‘why?’ is raised repeatedly till the root cause is found. Answers are to be read in the order a-a-a, b-b-b…

Athena-I

Problem	**Payload fraction of Athena-I is low (0.52)**
Why?	a) It has only 3 stages instead of common 4 b) Its second stage has less propellant mass
Why?	a) It has a modular booster design with Athena-II b) Its second stage was an existing motor also employed in Athena-II third stage
Why?	a) First-stage booster Castor-120 is used in the second stage also in Athena-II. Except for grain configuration, all other parts are common among Castor-120 variants. b) To reduce LV development time and for modularity
Why?	a, b) To reduce inventory, time and cost
Root Cause	To cater for two different segments of payload (max 360 vs. 1220 kg) economically, Athena-I & II seem to have employed modular design with common but configurable boosters. Consequently, the incomplete version Athena-I has less payload capability.

PSLV-CA

Problem	**Payload fraction of PSLV-CA is low (0.48)**
Why?	a) Low propellant mass fraction (0.83 vs. 0.90 in others) b) High S1 structural mass fraction (0.18 vs. <0.09 in others) c) Low S1 specific impulse (269 vs. 280 s in others) d) Third stage HPS3 thrust profile is sub-optimal (progressive) in shape
Why?	a) In S139, the star grain configuration has a low volumetric loading fraction. Also, volume is lost in 4 pairs of segment-end inhibitors b) First stage booster has metal casing with 4 heavy and less reliable segment joints c) Low chamber pressure (60 vs 100+ kg/cm^2 in others) d) Chosen grain configuration has two shallow radial slots along central port. Casing has too small an aperture (~33% of casing diameter) for star or finocyl grain to produce neutral thrust

PSLV-CA

Problem	**Payload fraction of PSLV-CA is low (0.48)**
Why?	a) Star + cylinders grain configuration gives mission optimal thrust profiles b) Only a small star grain segment (18 ton) is needed for initial high thrust. The remaining long internal burning cylinder is segmented into 4 parts (30 ton each) for ease of handling and integration c) With metal casing, higher chamber pressure will increase mass significantly d) As HPS3 radial slots are located within a narrow grain port, conventional slot machining tool reach is limited. In the case of externally assembled segmented mandrel, the slot mandrel's maximum diameter should be less than the aperture's. Small aperture in the casing doesn't allow big finned monolith mandrel
Why?	b) Star and cylindrical grains can be manufactured using simple monolith mandrels c) With composite casing, higher chamber pressure is possible but then filament wound casing has to be monolith d) Deeper radial slots need complex telescopic slot-cutting tools like the one used in Castor-120
Root Cause	Due to lack of technology in early 1990s for making large monolith rocket casings and grains with undercut features, S139 has 5-segment maraging steel casing with ends-inhibited grain segments (high inert mass) and low chamber pressure (low Isp) Due to lack of cutting tool or mandrel for making deeper slots needed for high initial thrust, HPS3 produces progressive thrust

SSLV

Problem	**Payload fraction of SSLV is low (0.25)**
Why?	a) Disproportionate staging (~88 % propellant in SS1 vs. <75 % in others; <8 % in SS2 vs. >19 % in others) b) Low propellant mass fraction (0.83) c) High structural mass fractions in stages d) Poor thrust profile in SS2 (and possibly SS3) leading to high altitude separation of SS1
Why?	a) To make use of existing motor for SS2, proven expertise in 15CDV6 steel casing fabrication with existing vendor base for SS1 and existing vehicle integration facilities[44] b) Due to long & slender SS1, poor grain volumetric loading fraction (~86 %) c) Due to use of 3-segmented 15CDV6 steel casing in SS1; in upper stages thicker insulations due to long burns and bigger nozzles due to low chamber pressures d) Radial slotted grains producing long progressive thrust profile
Why?	a) To start production with minimal need for new technology transfer b) To reduce erosive burning, SS1 nozzle-end-segment has a large star-port grain. SS1 is slender because its diameter is same as SS2 derived from PSLV c) Not using monolith composite casing for first stage. Not using neutral or regressive burning grains for shorter burns in upper stages d) Small aperture in casing limits use of large monolith mandrel / deep slot machining tool
Why?	a) To get cost-competitive LV in market fast b) Star + cylinders grain helps achieve mission optimal 'M-type' thrust profile c, d) In case of monolith SS1 metal casing with same diameter, propellant slurry drop height would have been too much initially (~20 m). In case of composite casing, due to lighter inert mass, less propellant and shorter SS1 casing would've sufficed. But then, with small apertured composite casings, conocyl machining or undercut finocyl grain casting mandrel would have been needed. Same reason applies to upper stages too.
Root cause	From a performance point of view, choice of Φ2.0 m segmented metal casing for SS1 seems to have led to disproportionately large propellant requirement in first stage, increasing total LV mass significantly. If monolith composite casing were used, undercut finocyl casting mandrel would have been essential to derive full benefits. Low initial thrust from SS2 also seems to have delayed SS1 separation to 90+ km altitude[45]. Payload capability seems to have been traded off for economically getting the LV quickly operationalized by repurposing an available booster and using existing vendor fabrication expertise and integration facilities

3.7 Scope for Improvements

Alternatives or modifications in the chosen LVs that could deliver better results in their future variants are discussed.

Athena-I was essentially a 3-stage LV, an oddity when compared to all other 4-stage LVs. But modular staging allowed it to carry smaller payloads with one less stage and less cost. Athena-II, where Athena-I's first stage repeats in its second, has an above-average payload fraction of 0.98 %. Therefore Athena-I could be considered as a subset of Athena-II. Modularity helped with less inventory and better reliability. However, Castor-120 grain manufacturing method is hazardous and slow. Similar thrust profiles can be achieved safely and quickly using undercut finocyl grains that are net-shape cast.

With PSLV-CA, which was originally designed 3 decades ago, an upgrade of its first-stage booster with carbon fibre composite casing would straight away drop stage inert mass from 30 tons to less than 15 tons. Chamber pressure and thus specific impulse can be increased using a smaller nozzle. Monolith grain will eliminate scope for combustion instability associated with end-inhibitors of segmented grains protruding into port flow. To still achieve 'M-type' thrust profile, undercut finocyl grain and suitable casting mandrel would be essential. With a similar undercut mandrel, the upper stage thrust profile could be made near neutral and short. The improved PSLV-CA should be able to double its payload fraction.

SSLV was first flown in 2022. Although the 100-ton grain casting process was mastered by ISRO with S200 mid-segment in the early 2010s, 87 tons of SS1 grain seems to have been cast in 3-segments due to cost, fabrication and integration considerations rather than for simple performance reasons. But by reworking staging and using undercut casting technique in monolith composite casings to cast finocyl grains in all stages, it should be possible to quadruple SSLV payload fraction. Even by considering mean PLF of 0.8 % from Fig. 2, SSLV should have weighed just 37.5 tons for a 300 kg payload to 500 km SSPO.

Vega LVs have impressive payload capabilities. However, the squeeze casting technique used in net-shape casting of undercut finocyl grains in their boosters has some safety concerns. High-energy propellants could be more friction-sensitive. Also, compositions with higher solids content and faster viscosity buildup rate would not favour squeeze casting. Accidental ignition of slivers found between the squeeze-casting mandrels during decoring is possible. Vega mandrels could be simplified and made safer.

3.8 Further Studies

- Analysing and quantifying ease of use of existing undercut finocyl casting mandrels using Design for Manufacturability and Assembly (DFMA) tools
- Feasibility of new net-shape undercut casting mandrels without squeeze casting.

4. CONCLUSION

Purely from a technical point of view, it can be firmly concluded that the lack of a simple, safe and reliable undercut finocyl grain casting mandrel technology led to the segmentation of solid rocket boosters with metal casings even when making monolith composite casings and processing large grains were feasible. It also led to the employment of slow and hazardous manufacturing methods like propellant machining. All these have in turn reduced propellant mass fraction, increased stage structural mass fraction, increased flight velocity losses, increased risk, duration and cost of manufacturing, inspection and integration of solid boosters and ultimately lowered LV's payload fraction.

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