SMALL LAUNCH VEHICLE CONCEPT DEVELOPMENT FOR AFFORDABLE MULTI-STAGE INLINE CONFIGURATIONS

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ABSTRACT

The Advanced Concepts Office at NASA's George C. Marshall Space Flight Center conducted a study of two configurations of a three-stage, inline, liquid propellant small launch vehicle concept developed on the premise of maximizing affordability by targeting a specific payload capability range based on current and future industry demand. The initial configuration, NESC-1, employed liquid oxygen as the oxidizer and rocket propellant grade kerosene as the fuel in all three stages. The second and more heavily studied configuration, NESC-4, employed liquid oxygen and rocket propellant grade kerosene on the first and second stages and liquid oxygen and liquid methane fuel on the third stage. On both vehicles, sensitivity studies were first conducted on specific impulse and stage propellant mass fraction in order to baseline gear ratios and drive the focus of concept development. Subsequent sensitivity and trade studies on the NESC-4 concept investigated potential impacts to affordability due to changes in gross liftoff mass and/or vehicle complexity. Results are discussed at a high level to understand the impact severity of certain sensitivities and how those trade studies conducted can either affect cost, performance, or both.

INTRODUCTION

Within the last decade, the commercial sector has seen increased demand for affordable Small Launch Vehicles (SLVs) capable of delivering 10 – 450 lb_m (5 – 200 kg) payloads to suborbital and Low Earth Orbit (LEO) destinations. A variety of potential cost effective designs have been proposed throughout industry, so NASA is seeking to expand its knowledgebase in order to help facilitate growth in the 100 – 150 lb_m (45 – 70 kg) range as NASA sees this capability range as most likely to yield the best opportunity, and therefore the highest customer base, as seen by said proposals.

The Advanced Concepts Office (ACO) Earth-To-Orbit (ETO) team at NASA's George C. Marshall Space Flight Center (MSFC) has developed two generalized in-house concepts in order to better understand the viability of those proposals set forth by commercial entities. The focus of this particular study was to establish generic but affordable three-stage, inline, liquid propellant vehicle concepts that yield low Gross Liftoff Mass (GLOM) while ultimately targeting the aforementioned payload capability range. A future study is planned within ACO to investigate an

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optimized clustered, multi-stage, liquid propellant vehicle concept that utilizes common core boosters, like that of the Delta IV Heavy, to achieve orbit.[1] In using existing and near-term technologies, NASA has gained insight into what generic and affordable SLV concepts may resemble under the Ground Rules and Assumptions (GR&As) outlined in the *Launch Vehicle Concept Definition* section.

RESULTS AND DISCUSSION

The strategy taken to conduct this study was to employ key learning points from ACO's experience in designing large liquid launch vehicles and other NASA internal guidance and then mesh them into a serial burn, three-stage, all liquid SLV at the higher end of the performance scale. Doing so fostered a better understanding of just how small a launch vehicle could be and also where opportunities lie in advancing this technology in future studies.

Ground Rules and Assumptions (GR&As) were established for both generalized vehicle concepts and were integrated upfront into various portions of the standard ACO design process, which is introduced in the subsequent section. Initial sensitivity studies were conducted to provide a sense of how the designs would be impacted due to future optimizations especially relative to their different stages. After deciding that it was more worthwhile to optimize only one of the two vehicles, additional trade studies and analyses were conducted to determine what an optimized vehicle concept may resemble.

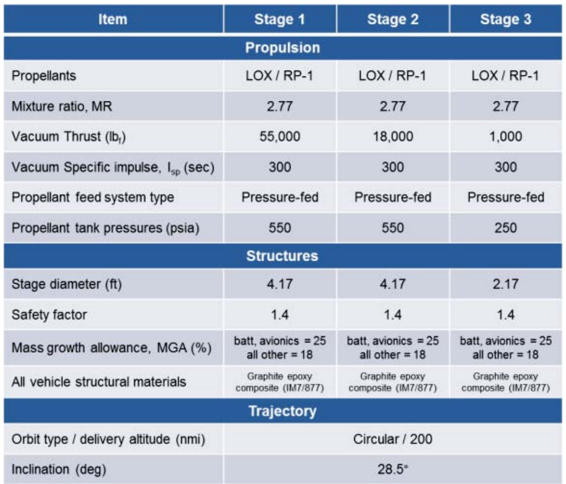
LAUNCH VEHICLE CONCEPT DEFINITION

All concepts and configurations discussed herein were developed using a suite of preexisting tools established by NASA: INTegrated ROcket Sizing (INTROS) and Launch Vehicle Analysis (LVA) via MSFC and Program to Optimize Simulated Trajectories (POST) via Langley Research Center, which was implemented by MSFC for this study.[2,3] Since INTROS was originally built to design Large Launch Vehicles (LLVs) like the Space Launch System (SLS), it was necessary to refine the tool with more appropriate Mass Estimating Relationships (MERs) for select subsystems as to facilitate the designs of the NESC-1 and NESC-4 SLV concepts described below. The updated subsystem MERs include: stage separation, Thrust Vector Control (TVC), propulsion feed and pressurization systems, avionics, and power.

NESC-1 GROUND RULES AND ASSUMPTIONS (GR&A)

The NESC-1 baseline concept was established using the GR&As listed in Fig. 1. Liquid oxygen (LOX) and rocket propellant grade kerosene (RP-1) were employed in all stages due to their availability from current LLV industry demands and the propellant combination assumed to yield an ideal vacuum specific impulse (I_{sp}) of 300 seconds at a conservative Mixture Ratio (MR) of 2.77.[4] All propulsion systems were pressure-fed by Helium in order to impart the propellant tank pressures shown in Fig. 1. Thrust levels were based on conceptualized engines where corresponding engine masses were predicted using a MER built from both NASA and industry heritage hardware. Keeping affordability in mind, it is possible that thrust levels could be achieved either by a single engine or a cluster of smaller ones, however system complexity and thus cost would be affected. Initial diameters of 50 in. (4.17 ft) for the first and second stage and 26 in. (2.17 ft) for the third stage were chosen as an arbitrary starting point. The Mass Growth Allowance (MGA) and Safety Factor (SF) shown in Fig. 1 are standard values as defined by ACO. The standard ACO payload shroud geometry was scaled down from LLVs and, since no hard requirements were provided, the cylindrical section length was adjusted to maintain a standard payload density of approximately 6.5 – 7.5 lb_m/ft^3 for all SLV configurations.

The ascent profile modeled for all NESC-1 concepts included a tower launch and due east trajectory out of Kennedy Space Center (KSC) to a 200 nmi circular orbit. All three stages burned at 100% throttle until stage depletion with a four second coast interval that accounted for spent stage separation and subsequent stage ignition. Maximum acceleration and maximum dynamic pressure were unconstrained and therefore outputs of the analysis.



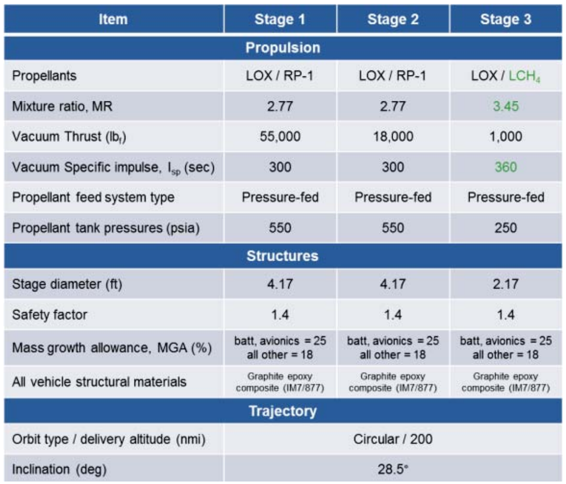
Item	Stage 1	Stage 2	Stage 3
Propulsion			
Propellants	LOX / RP-1	LOX / RP-1	LOX / RP-1
Mixture ratio, MR	2.77	2.77	2.77
Vacuum Thrust (lb_f)	55,000	18,000	1,000
Vacuum Specific impulse, I_{sp} (sec)	300	300	300
Propellant feed system type	Pressure-fed	Pressure-fed	Pressure-fed
Propellant tank pressures (psia)	550	550	250
Structures			
Stage diameter (ft)	4.17	4.17	2.17
Safety factor	1.4	1.4	1.4
Mass growth allowance, MGA (%)	batt, avionics = 25 all other = 18	batt, avionics = 25 all other = 18	batt, avionics = 25 all other = 18
All vehicle structural materials	Graphite epoxy composite (IM7/877)	Graphite epoxy composite (IM7/877)	Graphite epoxy composite (IM7/877)
Trajectory			
Orbit type / delivery altitude (nmi)	Circular / 200		
Inclination (deg)	28.5°		

Figure 1. NESC-1 Baseline Concept Ground Rules and Assumptions.

The vehicle structural material was modeled as being comprised entirely of graphite epoxy composite (i.e., IM7/877 quasi-isotropic layup) with the exception of propulsion systems and propellant feed lines. The composite density used in this study was $\rho = 0.065\ lb_m/in^3$ but is highly dependent on the layup scheme. In other words, all propellant tanks, skirts, intertanks, and interstages, in addition to the payload fairing are graphite epoxy composite. Furthermore, the structural components were analyzed using a combined worst case approach such that each component experienced all major pre-launch and flight loads simultaneously. The pre-launch wind load was given a 1% risk value for exceeding peak wind at KSC with one day of exposure.[5] Each component was built with a structural buckling knockdown factor of 0.65 and all pressurized structures were allowed to utilize pressure relief of flight loads. A 3-sigma dispersion was placed on the angle of attach calculated by POST.

NESC-4 GROUND RULES AND ASSUMPTIONS (GR&A)

The NESC-4 baseline concept was established using GR&As similar to those of the NESC-1 concept (Fig. 1 and Fig. 2) with the exception of the third stage. With the outlook that SLVs could serve as a technology development test bed for utilizing in situ resources elsewhere in the solar system, the third stage employed LOX and liquid methane fuel (LCH_4) which in a vacuum yields a higher ideal vacuum I_{sp} of approximately 360 seconds at a higher MR of 3.45. It is worth noting that although this propellant combination has not yet been extensively flight proven, the technology is currently being developed through some small entity endeavors.



Item	Stage 1	Stage 2	Stage 3
Propulsion			
Propellants	LOX / RP-1	LOX / RP-1	LOX / LCH_4
Mixture ratio, MR	2.77	2.77	3.45
Vacuum Thrust (lb_f)	55,000	18,000	1,000
Vacuum Specific impulse, I_{sp} (sec)	300	300	360
Propellant feed system type	Pressure-fed	Pressure-fed	Pressure-fed
Propellant tank pressures (psia)	550	550	250
Structures			
Stage diameter (ft)	4.17	4.17	2.17
Safety factor	1.4	1.4	1.4
Mass growth allowance, MGA (%)	batt, avionics = 25 all other = 18	batt, avionics = 25 all other = 18	batt, avionics = 25 all other = 18
All vehicle structural materials	Graphite epoxy composite (IM7/877)	Graphite epoxy composite (IM7/877)	Graphite epoxy composite (IM7/877)
Trajectory			
Orbit type / delivery altitude (nmi)	Circular / 200		
Inclination (deg)	28.5°		

Figure 2. NESC-4 Baseline Concept Ground Rules and Assumptions.

In later trade studies within the NESC-4 configuration evolution, an expendable MK 70 Mod 1 ER strap-on Solid Rocket Booster (SRB) was modeled in quantities of two or four to increase payload capability as they are low cost and readily available from the military. The assumption was made that 99% of the propellant was consumed prior to jettison.

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STUDY METHODOLOGY

PRELIMINARY SENSITIVITY STUDIES

The first set of sensitivity studies conducted on both the NESC-1 and NESC-4 concepts included I_{sp} and Propellant Mass Fraction (PMF). Because some small commercial entities are focusing on developing engines that utilize LOX and LCH_4 propellants, this warranted that emphasis be placed more on the NESC-4 concept development rather than the NESC-1 concept, which utilized LOX and RP-1 propellant on all three stages. Consequently, the I_{sp} and PMF sensitivity studies were the only analyses conducted on the NESC-1 concept. Examining the vehicle's sensitivity to changes in PMF with respect to stage burnout mass (propellant loads are always fixed) provided a guide to drive subsequent trade studies by means of defining stage "gear ratios". A stage's gear ratio describes how sensitive the vehicle's payload capability is to changes in that stage's burnout mass, since propellant loads are fixed, thereby providing a basis for whether or not certain trade studies are worthwhile. For example, a stage's gear ratio is 6:1 if for every 6 lb_m of mass added to that stage results in 1 lb_m degradation in payload capability.

NESC-4 SENSITIVITY AND TRADE STUDIES

Following the preliminary sensitivity studies, the delivery altitude effect on payload capability was the first sensitivity study conducted on the NESC-4 baseline concept. A circular orbit trajectory was maintained for each of the three delivery altitudes studied, including 200 nmi, 160 nmi, and 120 nmi, which corresponded to the NESC-4A, NESC-4B, and NESC-4C configurations, respectively. The NESC-4C configuration was chosen as the baseline concept for the subsequent propulsion feed system trade study as it was assumed that SLV sized payloads would not typically necessitate high power requirements. Therefore, longer duration missions at higher altitudes were deemed unnecessary. As would be expected, the NESC-4C configuration also yielded the largest payload capability since it targeted the lowest altitude.

The NESC-4C configuration was originally developed with all Helium pressure-fed propulsion systems to induce first, second, and third stage propellant tank pressures of 550 psia, 550 psia, and 250 psia, respectively (Fig. 2). Pressure-fed propulsion systems require additional volume to store pressurant tanks as well as stronger propellant tank walls to accommodate the higher pressures necessary to produce the required thrust. With a pump-fed propulsion system these attributes present a potential mass savings as long as it is not exceeded by the addition of an engine pump mass. The NESC-4D configuration employed pump-fed propulsion systems on the first and second stages and was chosen as the baseline configuration for the subsequent SF trade study since analysis showed this configuration to yield the lowest structural mass.

The standard SF for ACO concepts is 1.4 and was already employed in all previous configurations. The NESC-4E configuration studied the effects of lowering the SF from 1.4 to 1.2. Incorporating additional risk was deemed a worthwhile study since SLV sized payloads are not man-rated nor of extremely high value; however, the NESC-4D configuration was chosen as the baseline for the MGA sensitivity study for reasons discussed in later sections.

As shown in Fig. 2, the standard MGA as defined by ACO is 25% for batteries and avionics components and 18% for all other vehicle components and was also applied as such in previous configurations. In general, designing SLVs and their payload(s) are simpler with respect to the Space Shuttle and Curiosity rover, for example. This comparison translates to a greater ability to track SLV MGAs which, in turn, could further translate to a substantial mass savings, although it inherently adds risk in the form of potential performance degradation if MGA is ultimately surpassed. Two configurations, NESC-4F and NESC-4G, were developed on this premise by reducing MGA by 50% and 75%, respectively. Despite accepting an increase in risk, the NESC-4F configuration was chosen as the baseline for the subsequent group of sensitivity studies.

The next set of sensitivity studies consisted of the following: (1) a MR reduction for both LOX/RP-1 stages, (2) first stage propellant load optimization, and (3) second and third stage propellant load optimizations. The first study, NESC-4H, reduced the first and second stage MR from 2.77 to 2.50. The second study, NESC-4i, modified the NESC-4H configuration by reducing the first stage propellant load until it depleted at approximately ten seconds past the time of maximum dynamic pressure. Designing the liftoff stage such that it can at least overcome maximum dynamic pressure is typical of LLVs and was therefore considered to be the optimum design.[1,6] Through a series of additional configurations, the last study, NESC-4J, reduced the second stage propellant load of the NESC-4i configuration and relocated its equivalent mass to the third stage thereby maintaining overall vehicle GLOM. A combination of all three modifications was used as the basis for the subsequent vehicle diameter sensitivity study.

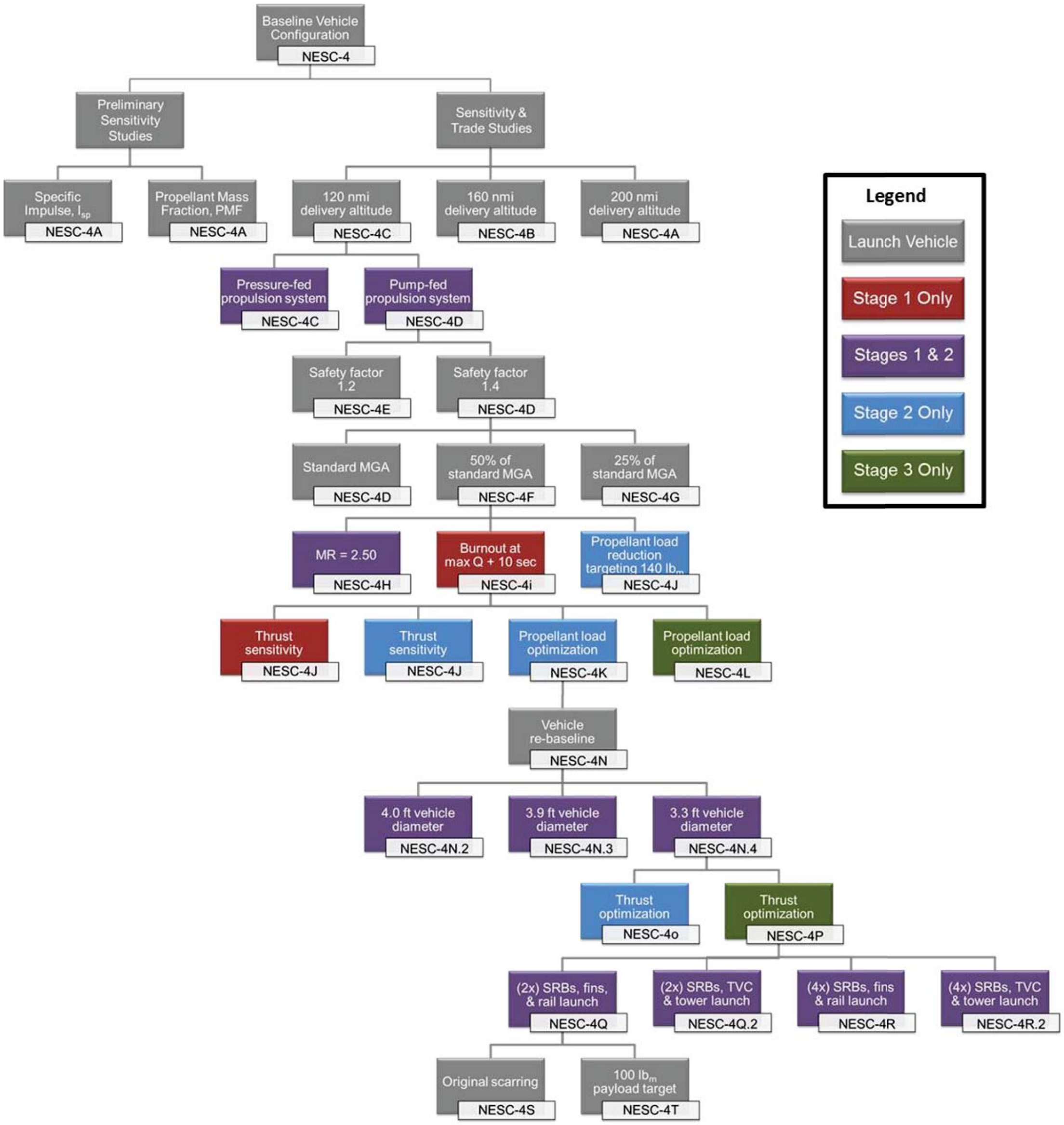

Figure 3. NESC-4 Concept Evolution.

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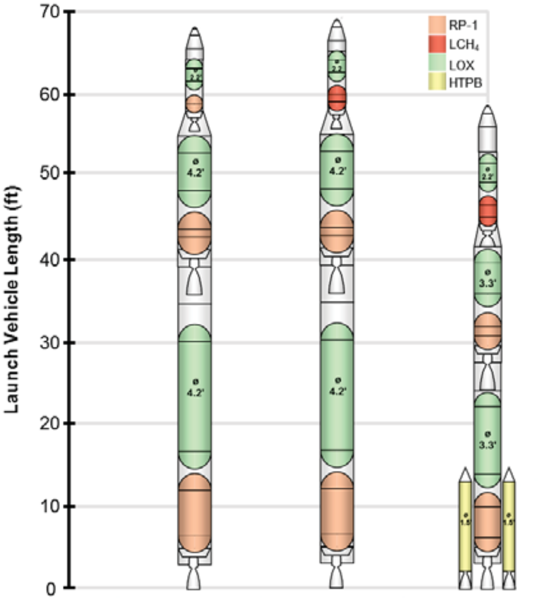
The NESC-4N configuration series studied the effects of reducing the first and second stage diameters while increasing overall length in order to maintain vehicle GLOM. The NESC-4N baseline configuration had 4.17 ft diameter first and second stages. Both stage diameters were equally and simultaneously decremented to 4.00 ft and 3.85 ft, NESC-4N.2 and NESC-4N.3, respectively, and then finally to 3.30 ft for the NESC-4N.4 configuration to optimize the vehicle's L/D ratio. The intertanks and forward and aft skirts were shortened according to the decreased height of the propellant tank domes due to the change in diameter. In doing so, the original interstage lengths were held constant. The NESC-4N.4 configuration was used as the baseline for subsequent upper stage thrust optimization sensitivity studies.

Thrust sensitivity studies were conducted on the second and third stages in order to optimize thrust for the NESC-4o and NESC-4P configurations, respectively. The NESC-4P configuration was built on the results of the NESC-4o thrust study and was therefore used as the baseline for the SRB trade studies.

The next group of trade studies focused on examining the payload capability effects when adding SRBs in quantities of two and four, NESC-4Q and NESC-4R, respectively. Secondary emphasis was placed on exchanging active (NESC-4Q.2 and -4R.2) for passive (NESC-4Q and -4R) guidance systems, or TVC for fins, on the first and second stage and tower (NESC-4Q.2 and -4R.2) for rail (NESC-4Q and -4R) launch systems. The third stage did not include fins as the vehicle would be sufficiently high in the atmosphere such that aerodynamic forces would be negligible. The fins were solid and, like the vehicle, were comprised entirely of graphite epoxy composite. An additional trade study, NESC-4S, was also conducted using the original vehicle scarring from the NESC-4Q.1 configuration to determine payload capability upon SRB removal. The NESC-4Q configuration was chosen as the baseline for the final study, targeting a 100 lb_m payload capability.

The final sensitivity study, NESC-4T, consisted of equally reducing each of the first and second stage propellant loads in order to target a 100 lb_m payload capability. The only other modification made to this configuration was the addition of hollow graphite epoxy composite fins for both stages.

A graphic representation of the aforementioned vehicle evolution path is shown in Fig. 3 while Fig. 4 depicts the NESC-1 and NESC-4 baseline configurations and the culminating, fully optimized NESC-4T configuration according to this study.



Configuration	NESC-1	NESC-4A	NESC-4T
GLOM (lb_m)	37,133	37,187	22,378
LEO Payload (lb_m)	75	142	98
Delivery Orbit (nmi)	200 circ	200 circ	120 circ

Figure 4. Baseline and Final Configurations.

STUDY ANALYSES

PRELIMINARY SENSITIVITY STUDIES

The first sensitivity study concentrated on payload capability versus changes in stage burnout mass and thus PMF. It is important to remember the following: (1) in comparing the NESC-1 and NESC-4 configurations, the third stage propellant changed from LOX and

RP-1 to LOX and LCH_4, (2) stage propellant load mass was held constant such that PMF deltas only reflected changes to stage burnout mass, and (3) when adjusting the burnout mass of a given stage, the other stages were held constant.

As the NESC-1 first stage PMF increased by 2%, thereby adding performance to the stage, its payload capability increased by 16 lb_m to a total of 91 lb_m (Fig. 5). Similarly, if PMF was increased in the third stage by 2%, the payload capability improved by 39 lb_m to achieve 114 lb_m. The impact to payload capability was greater when the PMF was increased on the third stage due to it having a lower gear ratio, or inverse of the slope (Fig. 7). In other words, although the change in mass was substantially higher for the first stage than for the third stage, it took a much larger mass change for the first stage to dramatically affect payload capability. This notion can be seen more clearly by looking at Fig. 5 through Fig. 8 where the first stage slopes are shallower than the third stage slopes.

If the PMF of a given stage increases, its velocity capability (ΔV) and the vehicle's payload capability increase while the vehicle's GLOM and the ΔV required by the other stages both decrease. Alternatively, if the PMF is subtracted from a given stage, the remaining stages are forced to compensate for the performance loss by increasing their ΔV capabilities and thus increasing their gross masses but only if payload capability is to remain constant.

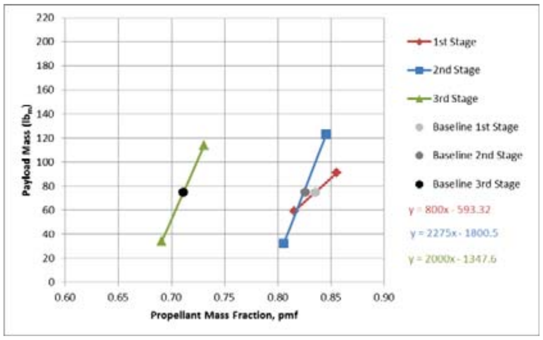


Figure 5. NESC-1 PMF Sensitivity Results

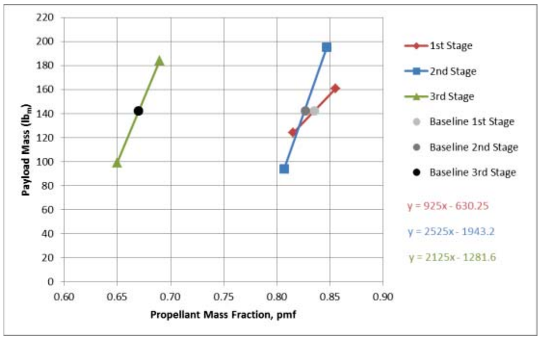


Figure 6. NESC-4 PMF Sensitivity Results

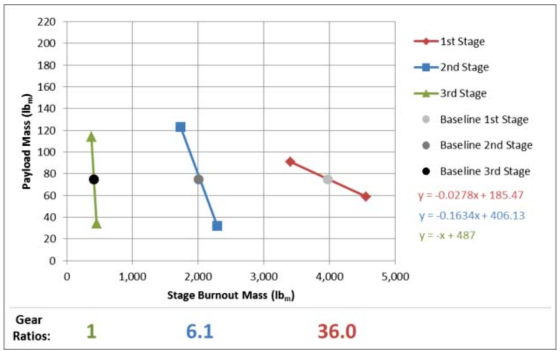


Figure 7. NESC-1 Gear Ratios

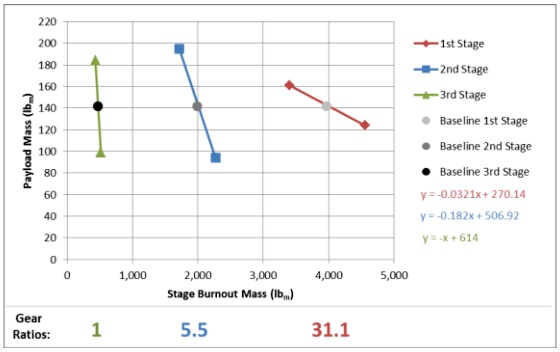


Figure 8. NESC-4 Gear Ratios

In comparing the NESC-1 and NESC- 4 configurations, it is interesting that gear ratios were lower for the NESC-4 despite having a better performing upper stage. Although at first this phenomenon may seem counterintuitive, the trend where lower stages are affected by changes in subsequent stage efficiencies has also been noticed in LLV studies. Keep in mind, too, that the payload capabilities are rather different for the NESC-1 and NESC-4 configurations, at 75 lb_m and 142 lb_m, respectively.

The second sensitivity study focused on determining how payload capability would be affected due to changes in stage I_{sp}. While maintaining equal propellant loads in similar stages for each vehicle, the first and second stage I_{sp} indicated a higher sensitivity to change for the NESC-4 configuration while the third stage proved more sensitive for the NESC-1 configuration (Fig. 9 and Fig. 10). Despite both configurations having a 1:1 gear ratio for the terminal stage as is the case for all vehicles, there was a lower payload capability sensitivity for the NESC-4 upper stage because it employed a more efficient propellant combination of LOX and LCH_4 compared to the LOX and RP-1 combination employed in the NESC-1 upper stage. The higher I_{sp} compensated for the increased payload mass thus forcing the two lower stages to become more sensitive. In other words, employing the same propellant combination throughout the entire vehicle causes I_{sp} sensitivity to spread more evenly among each of the three stages as in the NESC-1 configuration.

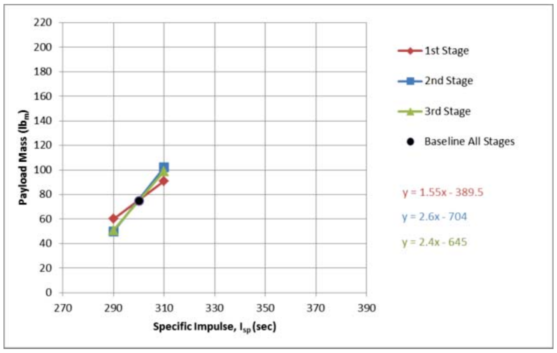


Figure 9. NESC-1 I_{sp} sensitivity study results.

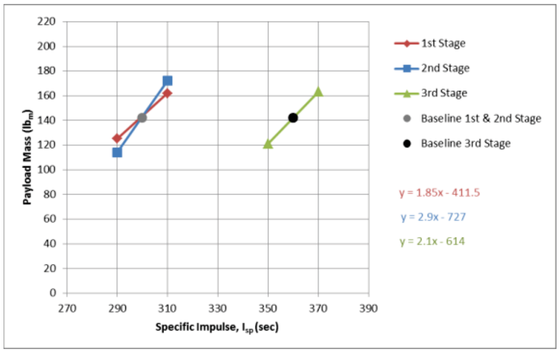


Figure 10. NESC-4 I_{sp} sensitivity study results.

NESC-4 SENSITIVITY AND TRADE STUDIES

As previously mentioned, some entities within both the LLV and newly emerging SLV industries are currently developing vehicles that employ the LOX and LCH_4 propellant combination, which has a higher ideal vacuum I_{sp} than LOX and RP-1. Methane is widely used in dozens of industries and is therefore a cheap commodity. NASA has also been studying LCH_4 as an in situ resource especially in developing Mars mission architectures. So, looking to methane as fuel makes sense if cost is the primary SLV performance metric and a SLV platform could assist in further developing this technology for LLV applications. With that said, this SLV study chose to use the NESC-4 vehicle configuration with a LOX and LCH_4 upper stage as the baseline for conducting additional trade studies in an effort to reduce overall vehicle cost (Fig. 4).

The first step in optimizing payload capability was to minimize delivery altitude to support shorter duration mission architectures. Initially a circular orbit with an altitude of 200 nmi was chosen as a nominal starting point. As the altitude was decremented from 200 nmi down to 160 nmi (NESC-4B) and then again to 120 nmi (NESC-4C), the payload capability was free to change while the vehicle's GLOM and performance parameters remained fixed. As expected the payload capability increased as the delivery altitude dropped, gaining 42 lb_m to achieve a total payload of 206 lb_m (Fig. 11). A 120 nmi circular orbit was the lowest studied as this was the lowest that could still provide a reasonable stay time per vehicle launch cost.

The next series of trade studies focused on reducing vehicle GLOM by targeting the Main Propulsion System (MPS) as well as long-held ACO standards for SF and MGA from studying LLVs. The MPS mass was decreased by trading pressure-fed (NESC-4C) with pump-fed systems (NESC-4D). First and second stage propellant tank pressures were reduced from 550 psia to 50 psia and third stage pressure from 250 psia to 50 psia. The forward skirt on each stage was shortened to cover only the height of the LOX propellant tank dome since a pump-fed system does not require nearly as much pressurant atop each stage. The propellant feed and Helium-based pressurization subsystem masses were also adjusted to account for the lower propellant tank pressures. Together these changes totaled a mass savings of approximately 1,000 lb_m and 2.5 ft shorter overall vehicle length, which translated to a payload increase of 127 lb_m (Fig. 12) and a total length of 66.4 ft. It was found that employing a pump-fed propulsion system on the upper stage crossed the boundary of diminishing return such that a pressure-fed system actually resulted in higher payload capability. In other words, the mass differential between a pressure-fed engine and a pump-fed engine for low thrust applications (about 1,000 lb_f) was less than the latest mass estimate for a small pump.

Figure 11. Payload capability results per delivery altitude decrements.

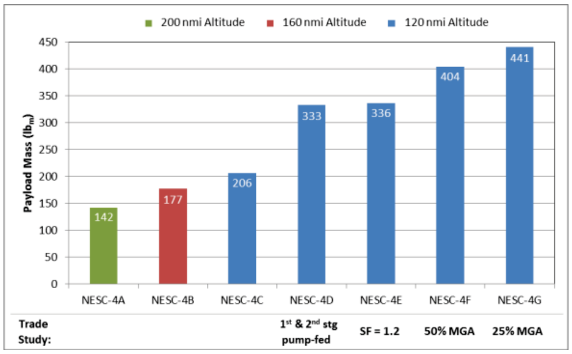


Figure 12. Payload capability results per pump-fed, SF and MGA trade studies.

The NESC-4E configuration studied the effect of reducing the vehicle's SF from 1.4 to 1.2 across all primary structures. As shown in Fig. 12, the payload increase was minimal as the vehicle only gained 3 lb_m to achieve a total capability of 336 lb_m. The resultant payload increase was low, as expected, because previous vehicle configurations were already being sized using lightweight IM7/877 graphite epoxy composites to a minimum gauge wall thickness of approximately 0.036 in. and at a combined worst case loading condition. Therefore, the vehicle saw very little overall mass savings when adjusting the SF downward.

The standard MGA margins implemented by ACO, 25% for batteries and avionics components and 18% for all other vehicle components, were lowered to 50% (NESC-4F) and 25% (NESC-4G) of those values to understand how much additional payload capability could be realized if one of these higher risk assumptions were used going forward. Cutting the MGA in half across all vehicle subsystems resulted in a mass savings of approximately 290 lb_m translating to 70 lb_m of additional payload capability while adjusting the MGA to 25% resulted in a 430 lb_m mass savings and 105 lb_m of additional payload. Although reducing MGA to 25% of the ACO standard yielded substantial payload increase, the NESC-4F configuration was chosen as the most viable option since it seemed to best balance additional risk with reality.

The second series of trade studies investigated avenues for vehicle optimization by means of propellant load adjustments (Fig. 13). The first adjustment (NESC-4H) was made by lowering the first and second stage MR from 2.77 to 2.50. After assessing a variety of existing LOX/RP-1 propulsion systems producing a wide range of thrust levels, the majority employed a MR ranging from approximately 2.25 – 2.77, therefore a MR of 2.50 was deemed as a more nominal case. Manipulating the MR was a feasible option as the vehicle employed only conceptualized engines; however, the vehicle GLOM was held constant such that only the LOX and RP-1 propellant loads were resized to match the MR refinement. The payload capability fell by only 2 lb_m to a total of 402 lb_m which is considered negligible as this mass differential falls within the noise of the ACO process.

The second adjustment (NESC-4i) reduced the first stage propellant load until the stage jettisoned at ten seconds past the time at which maximum dynamic pressure occurred. In previous configurations this ground rule did not exist and therefore staging events were allowed to float freely, but the maximum dynamic pressure event always occurred prior to first stage separation. Since the second and third stages were not resized to compensate for the first stage propellant removed, the vehicle GLOM dropped significantly, nearly 1,000 lb_m, and the payload capability decreased by 220 lb_m to a total of 182 lb_m. Consequently, the vehicle shortened by 11.1 ft to an overall length of 56 ft while the diameter remained constant. This significant propellant load reduction shifted the ΔV split such that the third stage now accounted for the majority of the ΔV capability lost from the first stage.

Final adjustments were made by optimizing the second stage propellant load (NESC-4J) followed by the third stage (NESC-4L). The second stage RP-1 tank length was minimized such that its shape was effectively a sphere, or dome-to-dome, but the MR = 2.50 was maintained. Approximately 3,000 lb_m of propellant were removed from the second stage while only 270 lb_m were added to the third stage. Although some of this exchange was accounted for in the higher third stage vacuum I_{sp} of 360 seconds compared to 300 seconds in the second stage, the payload capability was free to float thereby dropping 48 lb_m to a total of 134 lb_m. Keeping in mind that LCH_4 is less dense than RP-1, the second and third stage lengths also changed by –2.6 ft and +1.7 ft, respectively, and the majority of the ΔV capability shifted from the second to third stage.

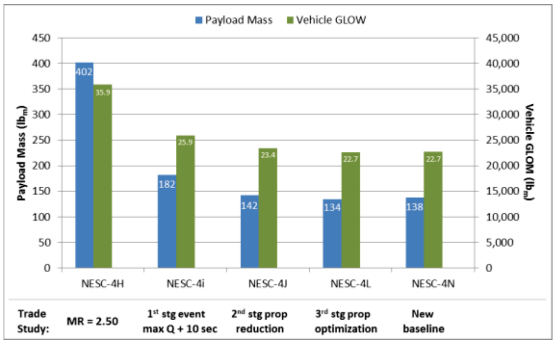


Figure 13. Payload capability and vehicle GLOM per MR and propellant optimization trade studies.

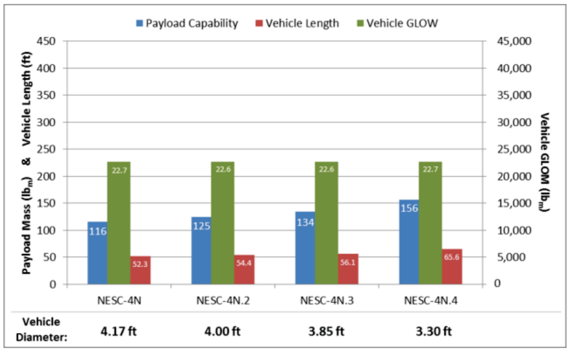


Figure 14. Payload capability results per 1^{st} and 2^{nd} stage vehicle diameter sensitivity study.

The next series of sensitivity studies focused on first and second stage diameter optimization and third stage thrust optimization. Both the first and second stages were twice decremented by step sizes of 0.15 ft while the vehicle GLOM and all performance parameters were held constant as shown in Fig. 14. Each of the three points were plotted and a minimum diameter of 3.30 ft was realized (NESC-4N.4). Overall vehicle length increased by 13.3 ft to a total of 65.6 ft and the vehicle gained 40 lb_m of payload capability to reach 156 lb_m. A L/D ratio of 20 was considered an upper limit as vehicles within this range could experience frequency response issues due to shifts in its Center of Gravity (CG) with respect to the radial axis. In this potentially fatal circumstance, the vehicle becomes too flexible and results in a lag in the interaction between the change in CG and the vehicle's control system. The ultimate result is a tumbling affect. The third stage thrust was then analyzed and found to be optimum at 1,200 lbf (NESC-4P) which only gained an additional 3 lb_m of payload (Fig. 15) to achieve 159 lb_m overall. A second stage thrust optimization was also conducted but ultimately did not change. Therefore, the first stage thrust was deemed optimized, within an error band of ±1,000 lb_f.

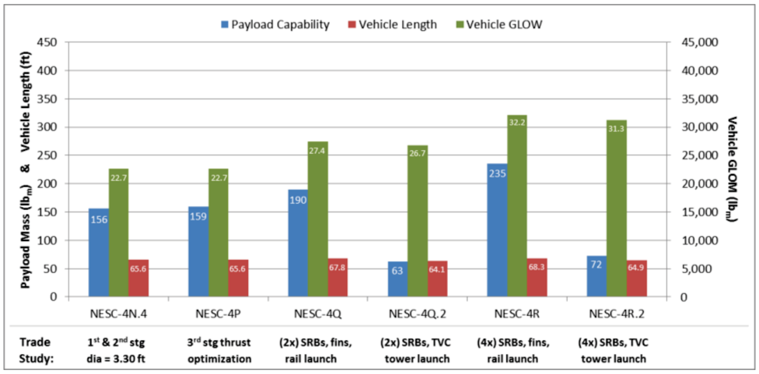


Figure 15. Payload capability results per thrust optimization, SRB and guidance, and launch method trade studies.

The third series of trade studies sought to understand how launch methods, thrust augmentation via strap-on SRBs, and TVC systems would impact payload capability. To simplify the analysis and allow for a direct comparison between all vehicles, all tower and rail launches were fixed to an inclination of 28.5°, however rail launches are also possible at other launch sites such as Wallops Flight Facility (WFF) depending on vehicle GLOM and total length. The first pair of configurations each employed two Mk 70 Mod 1 ER SRBs thus increasing maximum G's from 5.53 to 7.40 (NESC-4Q) and 7.62 (NESC-4Q.2). Launching from an optimized rail angle of 65° from local horizontal, the NESC-4Q configuration employed passive guidance on the first stage via four fins located symmetrically at 90° intervals in order to provide the vehicle with a stability margin range of 1.5 – 2.0, the distance between the CG (forward) and Center of Pressure (CP) (aft). The second stage was designed in a similar manner but with smaller fins and a stability margin of approximately 1.0. To produce adequate margins, all eight fins combined added an additional 504 lb_m of dry mass compared to the 109 lb_m TVC mass estimate for the NESC-4Q.2 configuration. However, payload capability increased substantially from 63 lb_m to 190 lb_m. In addition to the performance increase, an important side effect of removing TVC was that flight termination systems (FTSs) were no longer required thus substantially reducing operational costs by eliminating the necessity of live charges on the pad. Moreover, fins inherently decrease the size of the launch corridor resulting in a smaller clearance of surrounding marine vessels. In other words, the vehicle would surpass structural limitations before breaching the bounds of the launch corridor as opposed to flying a ballistic trajectory upon TVC failure.

The second pair of configurations each employed four Mk 70 Mod 1 ER SRBs and resulted in an increase of maximum G's from 5.53 to 10.89 (NESC-4R) and 11.24 (NESC-4R.2). The NESC-4R configuration was modeled and flown similar to the NESC-4Q configuration in that it employed first and second stage passive guidance via fin stabilization and was launched from a rail at an optimized rail angle of 59° from the local horizontal. After removing a total of109 lb_m of TVC mass and building in a total of 686 lb_m of fins, the vehicle's payload capability grew from 72 lb_m to 235 lb_m. In both the NESC-4Q and NESC-4Q.2 pair and the NESC-4R and NESC-4R.2 pair of configurations, the vehicle's primary structural mass did not noticeably increase due the change in guidance systems. Although by comparing the NESC-4Q and NESC-4R configurations it is evident that maximum dynamic pressure largely increased from 1,950 psf to 2,850 psf which caused a 170 lb_m increase in overall primary structural mass.

The final study, shown in Fig. 16, aimed at reducing the first and second stage propellant loads of the NESC-4Q configuration until about 100 lb_m of payload capability was reached in an effort to see how small of a GLOM could be achieved (NESC-4T). In summing both stages and maintaining constant stage diameters, a total of 2,334 lb_m of propellant were removed translating to a 9.8 ft reduction in overall vehicle length a drop in payload capability from 159 lb_m to 98 lb_m.

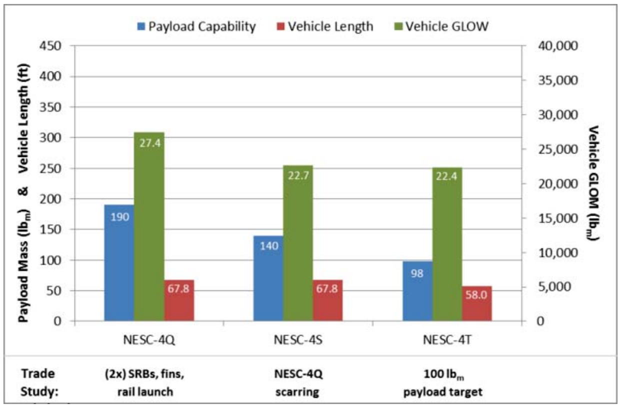


Figure 16. Payload capability results per SRBs and guidance, original scarring, and 100 lb_m payload target trade studies.

The first vehicle configuration in this evolution, NESC-4A, which did not contain any design optimizations, achieved a first, second and third stage PMF of 0.84, 0.83, and 0.67, respectively. The final vehicle configuration, NESC-4T, which comprised of all feasible design optimizations and the addition of two SRBs, achieved a first, second and third stage PMF of 0.80, 0.82, and 0.70, respectively. The ΔV split for the NESC-4A was such that the second stage produced the majority of the velocity and the fairing jettisoned during this burn, whereas these characteristics both migrated to the third stage for the NESC-4T configuration.

LESSONS LEARNED

Analysis has shown that in order to achieve a lightweight launch vehicle with an optimized payload capability, physics targets one with a maximum L/D ratio. A longer vehicle with a relatively small cross-sectional area inherently shifts a higher percentage of the vehicle's dry mass to the propellant tanks than in an alternative design. This occurs because the forward and aft skirts as well as intertanks will automatically become shorter with a reduction in cross-sectional area since domes will shrink in overall size and mass. It is also important not to surpass the maximum L/D ratio as it will become increasingly difficult for active guidance systems to accurately steer the vehicle during ascent consequently creating an unstable trajectory.

SUMMARY AND CONCLUSIONS

In order to establish a viable, inexpensive SLV design, it is critical to recognize that a paradigm shift is at play. Technology advancement is resulting in a dramatic volumetric shrinkage while capability is increasing in an equally dramatic fashion. Consequently, NASA's standard design mentality must be almost completely reversed and embraced if it is to truly grasp the future of SLV development. Performance metrics such as cost, COTS componentry, and modularity now dominate over performance and reliability. If successful, NASA will have fulfilled its purpose by being the first to overcome immense technical and programmatic challenges such that it can successfully lend itself to stimulating this industry, where a large number of small entities are emerging across the United States every day.

Small entities are being established with the intent to build low cost SLVs capable of inserting payloads on the order of 1 – 100 lb_m (0.5 – 50 kg) into LEO. With the rise in availability of low-cost technology, NASA sought to expand its knowledgebase from solely large launch vehicles with primarily medium to heavy lift capability, to SLVs that could one day provide a cost effective solution for raising Technology Readiness Levels (TRLs). It is evident that facilitating growth in this area could also help NASA provide higher education institutions with high frequency launches and thus extended flight time for CubeSat sized experiments at reduced cost.

NASA has continued to see an increase in proposals submitted by small entities that describe SLV concepts capable of delivering payloads within the aforementioned range. Despite advancements in composites and avionics technologies over the past few decade, it is clear the majority of these proposals are predicting very optimistic stage PMFs, particularly for upper stages in the range of 0.85 – 0.90, some stages of which are much smaller than even those used in this study. Keeping in mind key INTROS MERs were refined prior to this study, the NESC vehicle concepts are predicting lower PMFs ranging from 0.65 – 0.78 for third stages to 0.79 – 0.88 for first stages. The NESC vehicles are also assuming high I_{sp} propulsion systems and extremely lightweight graphite epoxy composite primary structures across the entire vehicle. This study concluded the necessity for a substantial amount of additional propellant load to graduate from sounding rocket capability to a vehicle that can not only deliver small payloads to LEO but one that can provide sufficient ΔV to *sustain* orbit. Furthermore, it proved that SLVs are just as sensitive to changes in vehicle architecture as heavy lift vehicles. To develop a viable SLV capable of sustaining orbit requires just as much attention to detail, if not more so, than LLVs. It is important to be aware that designing a SLV solely based on the ideal rocket equation will not suffice; like any project, it requires keen accounting of all mass properties, a detailed full vehicle structural analysis, and a well-defined trajectory from liftoff to deorbit.

In order to achieve a low cost, self-sustained SLV industry there is work still to do in helping the commercial sector gain experience in all that is required to design, build and fly SLVs capable of safely putting small payloads into LEO. This study aided NASA in understanding approximately how small of a launch vehicle is possible to pursue this endeavor and what it would cost to initiate growth in this area.

FUTURE WORK

Follow-on studies are already being conducted to determine where additional risk and technology infusion can be incorporated to further reduce overall size of the aforementioned vehicle concepts. The studies are targeting specific subsystems and their corresponding Subject Matter Experts (SMEs) particularly in rapidly evolving areas such as additive manufacturing and avionics. Although innovative ideas are constantly streaming in and will continue to be captured, it is important to note that until some SLV designs are actually built and successfully tested, designing vehicles strictly from a conceptual standpoint based on a yet-to-be proven design mentality will continue to be a difficult task.

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