Launch Vehicle Demonstrator Using Shuttle Assets

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The Advanced Concepts Office at NASA's George C. Marshall Space Flight Center undertook a study to define candidate early heavy lift demonstration launch vehicle concepts derived from existing space shuttle assets. The objective was to determine the performance capabilities of these vehicles and characterize potential early demonstration test flights. Given the anticipated budgetary constraints that may affect America's civil space program, and a lapse in U.S. heavy launch capability with the retirement of the space shuttle, an early heavy lift launch vehicle demonstration flight would not only demonstrate capabilities that could be utilized for future space exploration missions, but also serve as a building block for the development of our nation's next heavy lift launch system. An early heavy lift demonstration could be utilized as a test platform, demonstrating capabilities of future space exploration systems such as the Multi Purpose Crew Vehicle. By using existing shuttle assets, including the RS-25D engine inventory, the shuttle equipment manufacturing and tooling base, and the segmented solid rocket booster industry, a demonstrator concept could expedite the design-to-flight schedule while retaining critical human skills and capital. In this study two types of vehicle designs are examined. The first utilizes a high margin/safety factor 'battleship' structural design in order to minimize development time as well as monetary investment. Structural design optimization is performed on the second, as if an operational vehicle. Results indicate low earth orbit payload capability is more than sufficient to support various vehicle and vehicle systems test programs including Multi-Purpose Crew Vehicle articles. Furthermore, a shuttle-derived, hydrogen core vehicle configuration offers performance benefits when trading evolutionary paths to maximum capability.

I. Introduction

NASA plans to continue human space exploration and space station utilization. Launch vehicles used for heavy lift cargo and crew will be needed. The Advanced Concepts Office at George C. Marshall Space Flight Center has served an integral role in charting the course for the development of a new U.S. launch vehicle. Thousands of launch vehicle concepts have been analyzed in support of every agency and center-level launch vehicle study since Exploration Systems Architecture Study (ESAS) including, most recently, Human Exploration Framework Team (HEFT), Heavy Lift Prolusion Technology (HLPT), Heavy Lift Launch Vehicle (HLLV), and Space Launch Systems (SLS). The primary performance Figure-Of-Merit (FOM) for more recent studies has been maximum payload to Low Earth Orbit (LEO). However, as budgetary and scheduling challenges continue to arise, an emphasis

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has been placed upon minimizing cost, especially initial investment, and also upon closing the time gap in which the U.S. is without a civil heavy lift capability.

One of the current leading concepts for future heavy lift capability is an inline one and a half stage concept using solid rocket boosters (SRB) and based on current Shuttle technology and elements. Potentially, the quickest and most cost-effective path towards an operational vehicle of this configuration is to make use of a demonstrator vehicle fabricated from existing shuttle assets and relying upon the existing Space Transportation System (STS) launch infrastructure. Such a demonstrator would yield valuable proof-of-concept data and would provide a working test platform allowing for validated systems integration. Using shuttle hardware such as existing RS-25D engines and a partial Main Propulsion System (MPS), propellant tanks derived from the External Tank (ET) design and using 331 inch diameter tooling, and four-segment SRB's could reduce the associated upfront development costs and schedule when compared to a concept that would rely on new propulsion technology and engine designs, thus addressing the crucial FOM's.

There are potentially several other additional benefits to this demonstrator concept. Since a concept of this type would be based on man-rated flight proven hardware components, this demonstrator has the potential to evolve into the first iteration of heavy lift crew or cargo vehicle and serve as a baseline for block upgrades. This vehicle could also serve as a demonstration and test platform for the Multi-Purpose Crew Vehicle (MPCV) Program. Critical spacecraft systems, re-entry and recovery systems, and launch abort systems of the MPCV could also be demonstrated in early test flights. Furthermore, an early demonstrator of this type would provide a stop-gap for retaining important workforce and infrastructure while affording the current emerging generation of young engineers opportunity to work with and capture lessons learned from existing STS program offices and personnel, who were integral in the design and development of the Space Shuttle before these resources are no longer available.

II. Study Methodology

A. Ground Rules and Assumptions (GR&A)

This study followed the GR&A produced and utilized for the NASA Heavy Lift Launch Vehicle (HLLV) Architecture study of 2009. Some of these which are particularly influential to the study results are listed below.

1) Demo concepts utilize air start of RS-25D engines at altitude of 450 ft
2) LAS mass of 16,500 lbm, jettisoned 30 s after SRB separation
3) Insertion orbit of -11x100 nmi @ 29.0˚ for demonstration vehicles
4) Insertion orbit of -11x100 nmi @ 51.6˚ for operational crew vehicles
5) Insertion orbit of 30x130 nmi @ 29.0˚ for operational cargo vehicles
6) Demo concepts utilize structural overdesign which is discussed in further detail
7) Shuttle ET LH_2 tank dimensions

B. ACO Launch Vehicle Design Tools

INTegrated ROcket Sizing (INTROS) is an analytical tool that was developed at MSFC to facilitate launch vehicle design and sizing. Written in Visual Basic for Applications, INTROS assists the engineer in four basic tasks: vehicle architecture, launch vehicle sizing, technology and system trade studies, and parameter sensitivity studies.[1] Launch vehicle design and sizing are based on stage geometry and mass properties. Mass properties are established from a large master list of launch vehicle systems, subsystems, propellants and fluids. Mass calculations are based on Mass Estimating Relationships (MERs) that are automatically generated from a large database that is built into the program. Program mass calculation accuracy for existing and historical launch vehicles has been verified to be well within 5%.

Launch Vehicle Analysis (LVA) is a standalone application written at MSFC in Visual Basic that provides quick turnaround launch vehicle structural design and analysis. An important note, this program does not use weight estimating or scaling routines, but supplies detailed analysis by using time proven engineering methods based on material properties, load factors, aerodynamic loads, stress, elastic stability, deflection, etc. For the fastest turnaround, the program is designed to work with the absolute minimum of input data. The output data is purposely limited to the least possible quantity to prevent the analyst from having to dig through a large amount of data for the necessary information. LVA and its predecessors have been serving NASA for over 25 years. Maximum dynamic pressure and acceleration are run as the maximum for the class of vehicle. Loads are run as a single combined worst case.

Program to Optimize Simulated Trajectories (POST3D) is a FORTRAN 77 based legacy code developed by NASA Langley for detailed trajectory simulations.

POST is a generalized point mass, discrete parameter targeting and optimization program. POST provides the capability to target and optimize point mass trajectories for a powered or unpowered vehicle near an arbitrary rotating, oblate planet. POST has been used successfully to solve a wide variety of atmospheric ascent and reentry problems, as well as exoatmospheric orbital transfer problems. The generality of the program is evidenced by its N-phase simulation capability which features generalized planet and vehicle models. This flexible simulation capability is augmented by an efficient discrete parameter optimization capability that includes equality and inequality constraints.[2]

C. ACO Launch Vehicle Performance and Sizing Process

The process used for the preliminary performance and sizing of the launch vehicle concepts is shown in Fig. 1. Based upon the mission requirements for the particular concept under study and within the framework of the ground rules and assumptions established, a preliminary concept is sized using the MERs in INTROS. An initial trajectory of this vehicle is flown in POST to determine the ascent flight environments (accelerations, dynamic pressure, payload capability, etc.) and then the initial vehicle weights and trajectory outputs are sent for more detailed structural sizing by LVA. Loads, forces, material properties, and design techniques are all considered within the LVA analysis and new structural weights are calculated for the launch vehicle concept. INTROS then incorporates these new structural element weights and estimates a total injected mass based on the total ideal delta velocity from the previous POST output. POST then determines a new total injected mass and ideal delta velocity. INTROS takes these values from POST and estimates a new propellant load and stage mass and continues to iterate with POST until the POST total injected mass is within 0 lbm to 300 lbm of the INTROS estimated value. If at any time during the iteration process the max q or max g strays beyond a nominal value, the LVA analysis is repeated. The performance and sizing analysis for this concept is then considered closed and a vehicle summary is generated.

If a cost analysis of the concept is to be performed, the vehicle configuration description and mass summary for the vehicle and its elements are then sent to the cost team. Likewise, if a reliability analysis is to be performed, the vehicle configuration description and closed case trajectory summary are sent to the reliability team. For the vehicles described in this report, cost and reliability analyses were not requested; however, engine-out analysis was performed on the three-engine operational crew concept.

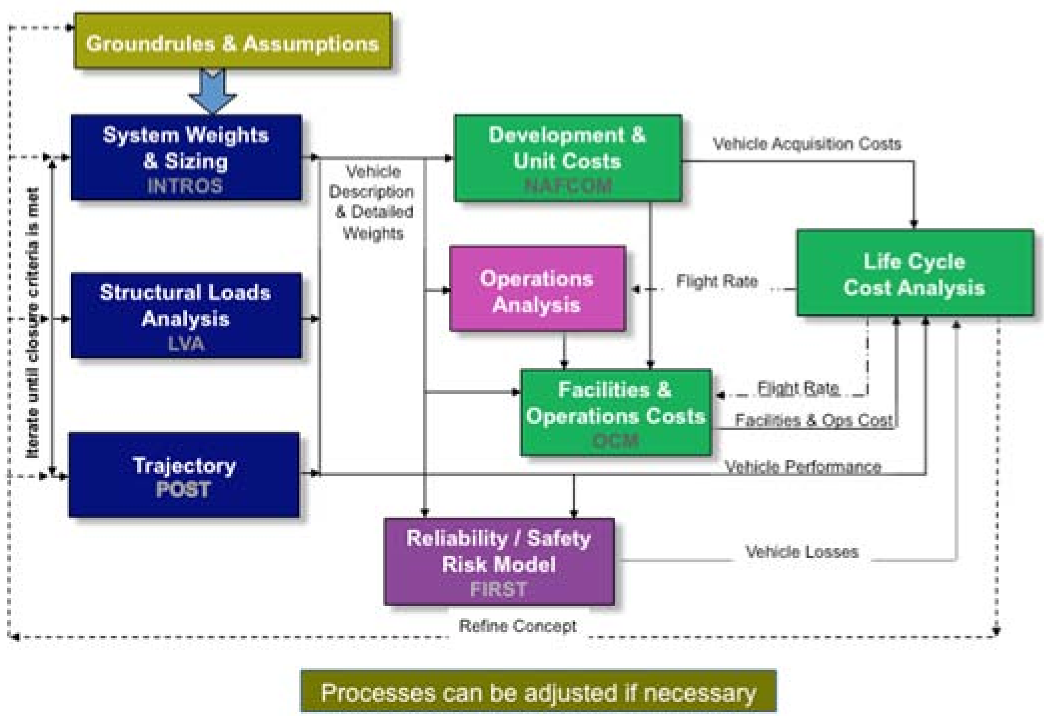


Figure 1. ACO Design Process.

III. Concept Configurations and Performance Results

A. Concept Configurations

Two concept configurations were used as baselines for all subsequent performance runs; these being a two engine and three engine variant of a commonly-equipped 1.5-stage vehicle (Fig. 2). Each vehicle was individually analyzed for either a crew or cargo mission with either a MPCV/LAS or cargo shroud respectively. The crewed missions operated with an insertion orbit of -11x100 nmi @ 29.0˚ (51.6˚ for operational vehicles) while the cargo missions were flown to 30x130 nmi @ 29.0˚. As discussed in the sections, “Demonstrator Concepts” and “Operational Concepts”, preliminary design concepts were generated using two structural design methodologies. The demonstrator design premise was based on being able to design, build, and fly a test vehicle quickly and inexpensively with assumed dry mass penalties incurred from robust structures. The operational design principle determined the actual expected performance of concept vehicles using optimized structural design routines and standard safety factors.

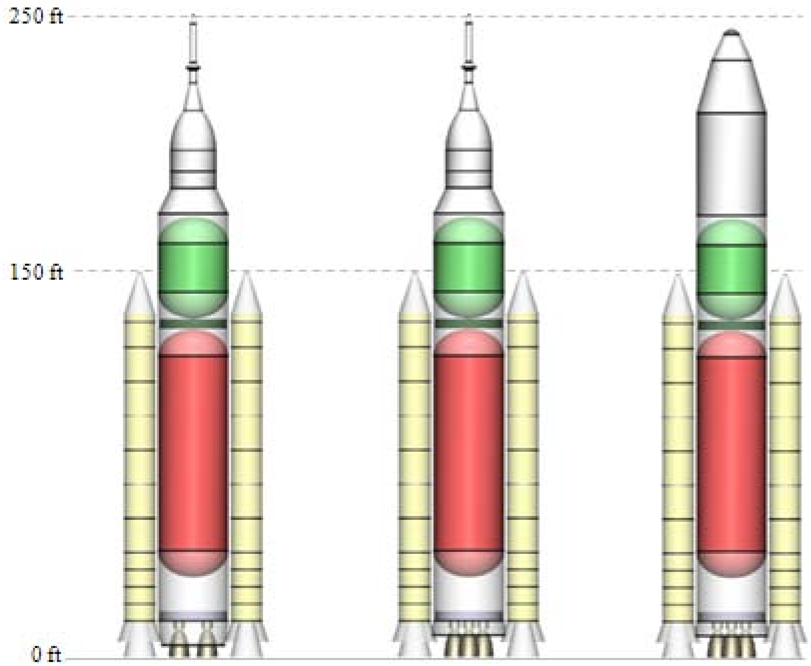


Figure 2. Baseline Vehicle Configurations.

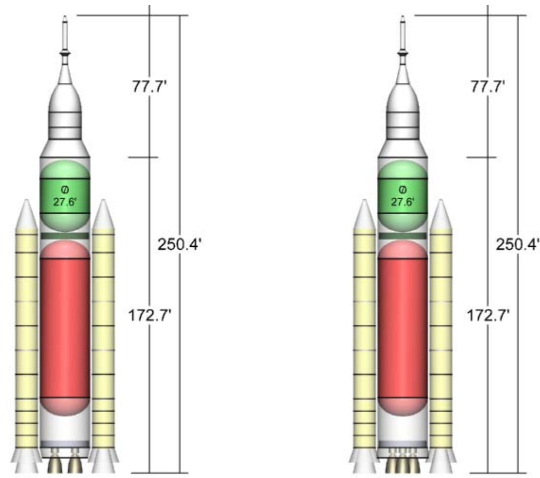
This matrix of vehicle concepts all utilize some common elements. Core dimensions for each are baselined from the shuttle ET. The LH_2 tank is 27.6 ft in diameter and has a barrel length of 76 ft. The LOX tank does not utilize the ogive dome found on ET and is sized using the given RS-25D mixture ratio with requisite allowances for ullage and internal tank equipment. LOX held in the Main Propulsion System (MPS) feedlines is also included in the tank sizing routine. Tank domes retain the existing eccentricity of 0.661. Full propellant loads for each configuration are on the order of 1.6M-lbm plus or minus a few thousand pounds for residuals, as well as startup requirements for the ground start concepts. The core height of 173’ (without MPCV adapter) is as much a function of SRB thrust takeout beam placement (130’ to beam center) as propellant load. Stage dry mass and structural design considerations are discussed in later sections.

Propulsion is provided by either two or three Pratt & Whitney Rocketdyne (PWR) RS-25D engines in combination with two standard STS 4-segment SRB’s. The engines are SSME inventory, utilize a 104.5% power level, and have a nominal vacuum thrust on the order of 490,000 lbf each. For this study, the engines were flown using a minimum guaranteed specific impulse (I_{sp}) as provided by the MSFC Engine Systems organization. The boosters are Alliant Techsystems Inc. (ATK) Reusable Solid Rocket Motors (RSRM), which utilize Polybutadiene acrylonitrile (PBAN) propellant and produce an average thrust of around 2.6M-lbf. The shuttle thrust trace was flown with 1% percent thrust degradation at 61˚ Propellant Mean Bulk Temperature (PMBT). Each booster is 150’ nozzle to tip and has a gross mass just under 1.3M-lbm.

Sitting atop the stack is either a crew vehicle or cargo shroud. The crew vehicle follows MPCV design parameters, current as of March 2011. The Launch Escape System (LAS) is held at a constant 16,500 lbm and is jettisoned 30 s after SRB burnout. Mass for the crew vehicle itself is treated as a variable function of vehicle performance, except for the two-engine out scenario, which holds MPCV mass at 25 t. Doing such identifies the demonstrator's ability to support a large array of preliminary design missions as well as provide excess capability mass margins, allowing test articles to grow beyond flight hardware-predicted masses. Further concept performance runs, simulating cargo missions, were made with a shroud in place of the MPCV. The shroud is 27.6' in diameter and has a 40' cylindrical section with a bi-conic nosecone. Total length of the shroud is 72.9' and is constructed using Al-Li 2195. Shrouds were sized based upon performance capability and were specified relative to reasonable cylindrical payload packing density calculations.

B. Demonstrator Concepts

The launch vehicles in the group (Fig. 3) utilize a "battleship" design philosophy, which results in a simple, low cost and robust structure that is heavier than an optimized design. One of the key features of this design philosophy is monocoque, or unstiffened, structures. The walls of the tanks and dry structure were designed to be fabricated of thick metal plate without the need of machining stiffeners into the metal or the attachment of stiffeners to thin metal plate. The weight effect of this design philosophy can be quite high. However, in a demonstration vehicle where the maximum payload capability is not necessary, this is a minimal impact. The demonstration launch vehicles are also designed with a safety factor of 2.0 instead of the usual safety factor of 1.4. This further decreases the cost and the necessity of testing. As an additional cost saving measure, the propellant tank domes were assumed to be a constant thickness. Normally, the tank dome thickness would be tailored to the local stress, which would create additional cost but save weight. Here, the domes are one uniform thickness. The overall weight penalty for the "battleship" design is an approximately 25% increase in the main structural weight of the vehicle.



Vehicle ID	107.02.00	107.03.00
# RS-25D	2	3
Booster	4-seg PBAN SRB	4-seg PBAN SRB
Payload Element	MPCV	MPCV
GLOW (M-lbf)	4.14	4.54
Propellant Offload	21.3%	-
Payload (t)	42.6	67.0
Insertion Orbit	-11x100nmi @ 29.0°	-11x100nmi @ 29.0°

Figure 3. Battleship Concepts Specifications.

All demonstrator vehicles followed a similar trajectory layout. Some general events applied to all vehicles. The trajectory simulation for all vehicles started with the ignition of the SRB's on the launch pad. Once the tower clear criteria of 450 feet was reached the core engines, either a cluster of 2 or 3 RS-25D's, would ignite and burn at 104.5% throttle. Air-starting the main engines at tower clearance offers the advantage of minimal launch pad impact, further reducing development schedule. Since the main engines and SRB's are in the same lateral plane, as opposed to shuttle's offset geometry, air-starting the core engines should minimize flame trench modifications to launch complex 39 at Kennedy Space Center (KSC).

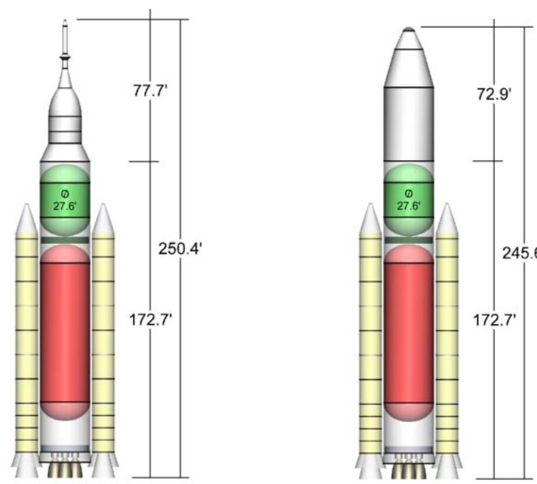
Continuing after main engine ignition, a gravity turn is initiated to reduce aero-loads during peak dynamic pressure. SRB's are jettisoned in accordance with existing shuttle flight plan and the optimized pitch profile begins. For crewed missions, the LAS is jettisoned 30 s after SRB separation. If a cargo vehicle is being analyzed, instead of LAS drop, the cargo shroud is jettisoned at a point in the trajectory determined by a free molecular heating rate. This ensures that the payload is not exposed until the thermal environment surrounding the vehicle is determined to be one in which the payload can survive.

At some point toward the end of the trajectory, prior to orbital insertion, several vehicle concepts may reach a maximum acceleration limit. The groundrule for this limit is 4 g's for crew vehicles and 5 g's for cargo. Once this acceleration limit is reached the core engines begin to throttle continuously to maintain the specified rate. If, for any cases where the throttle level reached the minimum RS-25D throttle level, engines were shutdown and the remaining lit engines were held at the minimum throttle level.

There was a minor additional optimization performed on all 2 engine core vehicles. The original sizing of the core was based on ET constraints and the attach interface of the SRB's with the core; this meant the propellant load of the core was sized to handle 3 engines burning to deplete the propellant. Having the same propellant load for 2 core engines would detract from the maximum deliverable payload. To account for this the optimal amount of propellant offload was solved for on the 2 engine trajectory runs.

C. Operational Concepts

As of this writing, the inline, shuttle-derived vehicle configuration is a front-running candidate for an operational SLS. Given this, it is important to illustrate initial operating capabilities of an initial-block concept. Although the dimensions between the groups are static and all propulsion elements remain unchanged, the operational design group (Fig. 4) has undergone a structural design optimization in which margins and factors of safety are brought in line with typical ACO analysis, as opposed to the previously discussed group. The trajectory simulations were ran in a similar fashion as previously described; however, the main engines were ground started rather than at 450 ft, the crew mission inclination is 51.6˚ rather than 29.0 ˚, and the cargo mission flew to an insertion orbit of 30 nmi x 130 nmi @ 29.0˚.



Vehicle ID	107.03.05	107.03.06
# RS-25D	3	3
Booster	4-seg PBAN SRB	4-seg PBAN SRB
Payload Element	MPCV	Cargo Shroud
GLOW (M-lbf)	4.53	4.54
Propellant Offload	-	-
Payload (t)	73.1	74.5
Insertion Orbit	-11x100nmi @ 51.6˚	30x130nmi @ 29.0˚

Figure 4. Operational Concepts Specifications.

The launch vehicles in this group utilize stiffened structure for a flight weight design. A stiffened structure has a much higher strength-to-weight and stiffness-to-weight ratio than a monocoque structure. The vehicles in this group were designed using an optimized isogrid stiffening pattern that is machined into a thick metal plate (Fig. 5). The machining increases the manufacturing cost significantly but also markedly increases the payload carrying capability of the launch vehicle. The safety factor was also reduced to the typical 1.4, requiring the structure to at least go through a standard round of mechanical testing. Also, the propellant tank dome thickness is tailored to the local stress.

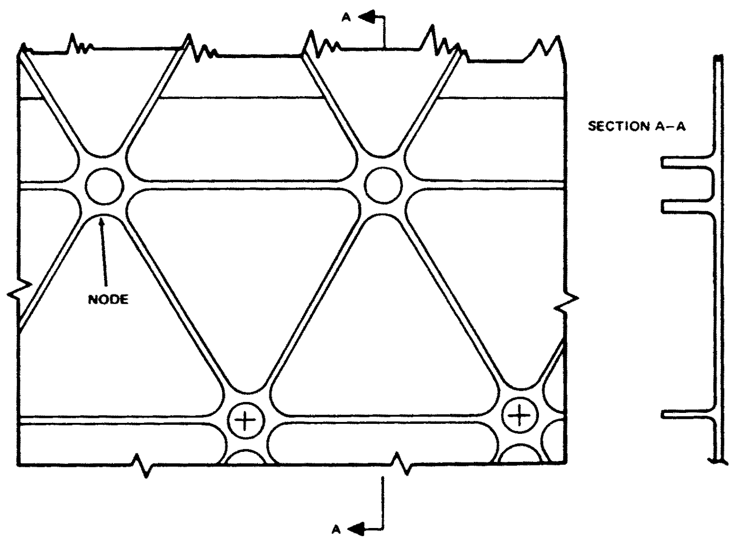


Figure 5. Isogrid Stiffening Pattern.[3]

Furthermore, the 3-engine crew and cargo variants share common structural element mass. After evaluating each case individually, the element masses were compared. After ensuring the most robust structure was applied to each vehicle, the performance evaluation was redone. Doing this highlights the performance implications when flying a shroud versus a crew capsule and LAS combination. Notable differences are: element mass, aerodynamic effects, and jettison times. Generally, the mission dependent target orbit led to the greatest differences in performance between the two vehicles. As indicated in Fig. 4 the crew vehicles were flown to -11 nmi x 100 nmi with the insertion altitude at an arbitrary 70 nmi. The cargo vehicle was flown to a 30 nmi x 130 nmi orbit with an insertion altitude of 85 nmi. The primary reason for the higher insertion altitude of the cargo vehicle was driven by the free molecular heating constraint of the shroud drop criteria. This ground rule difference led to an 87 s difference between the related mass drop events, which results in a significant injected mass difference. The final trajectory related difference pertains to the acceleration limits of each vehicle. Groundrules state that a crewed vehicle is not to exceed 4 g's. So when that 4 g limit is reached the core engines begin to throttle to maintain the limit. The cargo vehicle is limited to 5 g's; however, the cargo vehicle never reaches that limit so does not have to throttle.

D. Engine-Out Analysis

In addition to maximum performance runs, ACO also analyzed a couple of engine out scenarios designed to illustrate Loss of Mission (LOM) risk. The first scenario followed the pre-described 'operational' trajectory sequence by ground starting the main engines. One second following ignition, flow from one of the three core engines was terminated. The effects if this were measured by flying the vehicle into the same -11 nmi x 100 nmi @ 51.6˚ orbit. Specifying a 16,500 lbm LAS and with full propellant tanks the vehicle was able to inject 240,683 lbm. This translated into 33.5 t of payload. Assuming an operational MPCV of 25 t indicates a margin of 8.5 t, which would factor favorably in reliability estimates.

With the next engine out performance run, ACO sought to define the earliest possible time during ascent in which a second core engine out could occur while still making mission delivery expectations. This run utilized the same 3-engine configuration and identical dry masses as the previous engine out case. Other than payload, the only difference in Gross Liftoff Weight (GLOW) is due to Flight Propellant Reserve (FPR) loading which, among other things, is a function of injected mass. The same sequence of ground starting the SRB's and core engines and simulating a single engine out at +1.0s was followed. However, instead of optimizing the trajectory for maximum injected mass, a target injected mass was calculated and applied which would deliver approximately 25 t to the ISS insertion orbit. A one engine burn to Main Engine Cutoff (MECO) was run for various increasing time steps until the resultant delivery matched the target value. This process identified 547.9 s as the earliest time during ascent in which the vehicle could endure a worst case, two-engine out scenario and still make a 25 t mission to the required orbit.

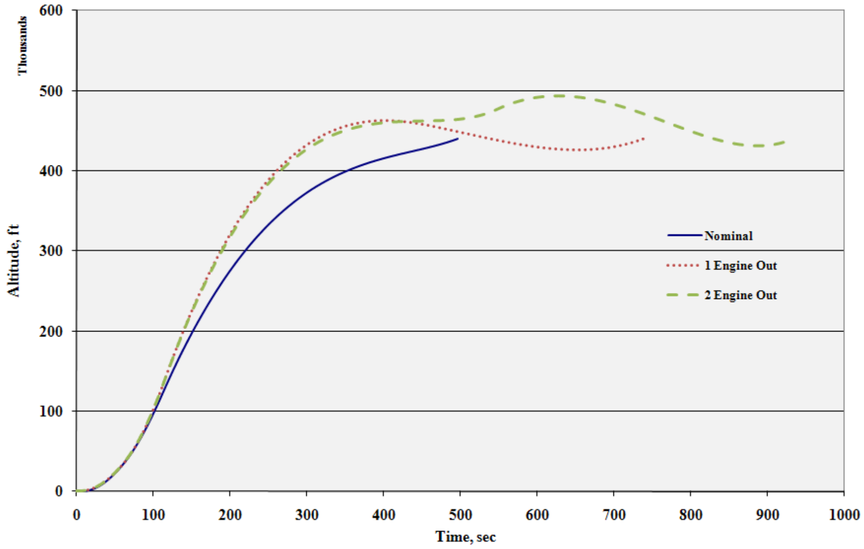


Figure 6. Altitude vs Time for nominal and engine out cases.

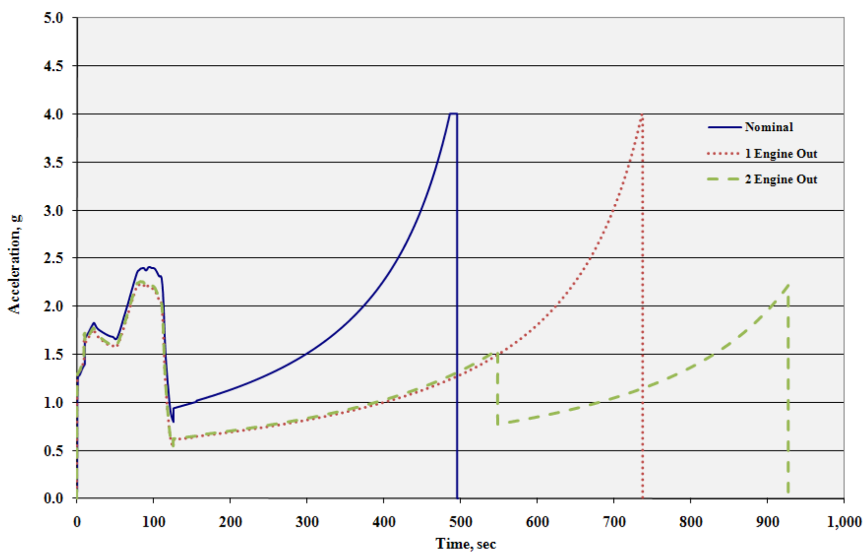


Figure 7. Acceleration vs Time for nominal and engine out cases.

IV. Conclusion

Utilizing shuttle and shuttle-derived assets in a pre-operational launch vehicle demonstrator program could prove advantageous on a variety of levels. Perhaps most important are the savings in time and money. The high margin, all metallic "battleship" structural design will drastically reduce development and testing schedule as well as use existing shuttle manufacturing assets. The use of existing SSME inventory will further contribute to the lower development time and monetary investment. Having an initial capability with a relatively brief design-cycle-to-flight timeline affords the ability to demonstrate and test future HLV hardware, systems, and procedures. This exercise chiefly applies to a more rapid maturation on the MPCV and related systems, but the practice may also be used to supplement testing and development of: vehicle processing, ground operations, GSE, launch procedures and software, etc.

In the instance that a shuttle-derived HLV is the agency's chosen concept configuration, a demonstrator as described offers multiple pathways to maximum heavy lift capability (Fig. 8). There is potential to increase both the number of core engines as well as the power level, especially if initiating an expendable RS-25 engine program. Facilitating the propellant load desired by five RS-25 engines at, potentially, a higher power level would require stretching the core. Introducing a 5-segment SRB, derived from the Ares I PBAN, and lengthening the core to support the new forward thrust takeout location could coincide and produce lift capability in the 100t arena. According to the study results, structurally optimizing the 4-segment, 3 engine core and flying to operational orbital insertions yields a 10 t payload increase. This indicates that an operational version of the demonstrator core may not be the most practical subsequent step and that moving from a test program directly to a 5-segment SRB-based core is the more sound option. From the 100 t vehicle, moving into the 125t payload range could progress in one of two ways; either upgrading the 5-segment SRB propellant from PBAN to Hydroxyl-Terminated Polybutadiene (HTPB) with a composite case or developing an upper stage which uses either 1 RS-25 or 2 J-2X derivatives. Reaching the most demanding heavy lift payload requirements would require a combination of HTPB 5-segment boosters as well as an upper stage. This is only one of many possible evolutionary pathways. Upgrades and evolutions would be ultimately sensitive to funding schedules and desired payload targets as a function of mission requirements.

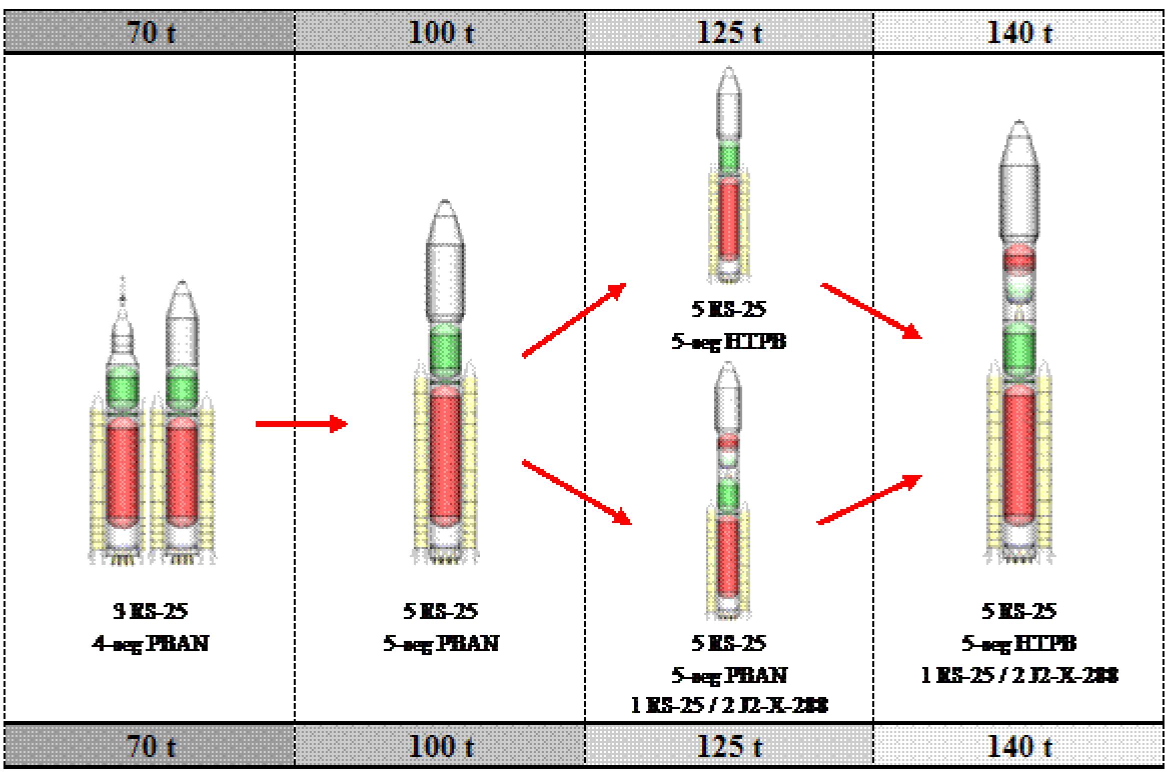


Figure 8. Hypothetical launch vehicle evolution to 140 t.

Nevertheless, HLV/SLS candidate configurations are not exclusively specifying the RS-25 engine family and large, segmented solid boosters. Some concept configurations make use of alternate LH2 engines, like the RS-68. Similarly, trades are underway which prioritize J-2-based upper stage development. Combining high thrust core engines with a high efficiency and relatively high thrust upper stage early in the development cycle could certainly cast doubt on the continued utilization of large segmented solids. Subsequently there is potential for movement towards the use of smaller monolithic solids, stand-alone or common core LRB's, or a combination of each in order to provide liftoff and lower atmosphere thrust augmentation. Still, other concepts take the alternate course and begin with a 5-segment booster. While this method would serve to eliminate recurring development costs, it would certainly require more initial investment for the core and the boosters, which the 4-segment, battleship configuration tends to reduce. Such configuration scenarios may dictate remaining SSME assets be flown, followed by a transition to the lower recurring cost options. However, this should not preclude the premise of utilizing a launch vehicle demonstrator making use of existing shuttle hardware, software, and human capital to efficiently bridge the gap in U.S. spaceflight capability.

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[2]Powell, R.W., Striepe, S.A.,Desai, P.N., Braun, R.D, Brauer, G.L., Cornick, D.E., Olson, D.W., Peterson, F.M., Stevenson, R., *Utilization Manual-Program to Optimize Simulated Trajectories (POST)*, Volume 2, Version 5.2, Oct 1997.

[3]Illustration of an isogrid stiffening pattern from the "Isogrid Design Handbook" NASA CR-127075 Revision A, McDonnell Douglas Astronautics Company, February 1973.