Crew Launch Vehicle (CLV) Independent Performance Evaluation

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The crew launch vehicle is a new NASA launch vehicle design proposed by the Exploration Systems Architecture Study (ESAS) to provide reliable transportations of humans and cargo from the earth's surface to low earth orbit (LEO). ESAS was charged with the task of looking at the options for returning to the moon in support of the Vision for Space Exploration. The ESAS results, announced in September 2005, favor the use of shuttle-derived launch vehicles for the goals of servicing the International Space Station after the retirement of the STS and supporting the proposed lunar exploration program. The first launch vehicle to be developed is the Crew Launch Vehicle (CLV), which will be operational by 2012, and will be derived from a four-segment Shuttle Solid Rocket Booster (SRB) and an upper-stage powered by an expendable version of the Space Shuttle Main Engine (SSME). The CLV will be capable of sending approximately 60,000 lbs to LEO in the form of a Crew Exploration Vehicle (CEV) as well as a Service Module (SM) to support the CEV.

The purpose of this paper is to compare the published CLV numbers with those computed using the design methodology currently used in the Space System Design Laboratory (SSDL) at The Georgia Institute of Technology. The disciplines used in the design include aerodynamics, configuration, propulsion design, trajectory, mass properties, cost, operations, reliability and safety. Each of these disciplines was computed using a conceptual design tool similar to that used in industry. These disciplines were then combined into an integrated design process and used to minimize the gross weight of the CLV. The final performance, reliability, and cost information are then compared with the original ESAS results and the discrepancies are analyzed. Once the design process was completed, a parametric Excel based model is created from the point design. This model can be used to resize CLV for changing system metrics (such as payload) as well as changing technologies.

Nomenclature

CAD	=	computer aided design
CER	=	cost estimating relationship
CES	=	crew escape system
CEV	=	crew exploration vehicle
CLV	=	crew launch vehicle
DDT&E	=	design, development, test, & evaluation
DSM	=	design structure matrix
ESAS	=	Exploration Systems Architecture Study
ETO	=	Earth to orbit
GLOW	=	gross lift-off weight
Isp	=	specific impulse, sec
KSC	=	Kennedy space center
LCC	=	life cycle cost
LEO	=	low earth orbit
LH2	=	liquid hydrogen

LOX	=	liquid oxygen
MECO	=	main engine cutoff
MER	=	mass estimating relationship
MR	=	mass ratio (gross weight / burnout weight)
RSRB	=	reusable solid rocket booster
SSME	=	space shuttle main engine
STS	=	space transportation system
TFU	=	theoretical first unit

I. Introduction

The crew launch vehicle is a new NASA launch vehicle design proposed by the Exploration Systems Architecture Study (ESAS) to provide reliable transportations of humans and cargo from the earth's surface to low earth orbit (LEO). The ESAS results, announced in September 2005, favor the use of shuttle-derived launch vehicles for the goals of servicing the International Space Station after the retirement of the STS and supporting the proposed lunar exploration program. The CLV is a space shuttle derived launch vehicle. The CLV uses shuttle heritage components such as the reusable solid rocket booster (RSRB) and the space shuttle main engine (SSME) to both reduce overall development costs as well as take advantage of the significant effort already spent on increasing the reliability of the shuttle components. The focus on this paper will be the design of the launch vehicle itself including a crew escape system. The crew exploration vehicle and the service module are treated as payload for the CLV and therefore only their weights are considered in this design.

The CLV design is a two stage shuttle derived launch vehicle. The first stage consists of a space shuttle derived RSRB. The second stage is a new stage designed around a single SSME. The second stage will consist of a single LOX tank and a single LH2 tank constructed of Aluminum. The payload of this vehicle is a capsule-style CEV with a supporting service module. The total weight of this payload is approximately 59,900 lbs and it is injected into a 30 X 100 nmi orbit at 60 nmi. The CLV is also designed to improve the reliability of human launch beyond that of the space shuttle. This is accomplished by utilizing the flight proven elements of the shuttle system, and eliminating the potential problems now plaguing the shuttle fleet. This includes eliminating the potential for damage to the reentry heat shield by placing the CEV at the top of the launch vehicle and keeping the thermal protection system shielded through the ascent. The crew escape system further decreases the probability of a loss of crew event. The resulting overall reliability of the system is 0.9988 or 1.19 failures per 1000 flights.

The purpose of this paper is to compare the published CLV numbers with those computed using the design methodology currently used in the Space System Design Laboratory (SSDL) at The Georgia Institute of Technology. This multi-disciplinary conceptual design process is used to create the CLV design. This design process was completed using a disciplinary design tool for each of the following disciplines: external configuration and CAD was completed using ProEngineer, aerodynamic analysis was conducted with APAS[1], trajectory optimization used POST[2], mass estimation and sizing was completed using mass estimating relationships[3] (MERs), Cost estimating was conducted using NAFCOM[4] cost estimating relationships (CERs), and reliability was completed using Relex[5]. Each of these tools was used to analyze their respective disciplines and was iterated to close the CLV design.

II. Crew Launch Vehicle Configuration

The crew launch vehicle is a two stage launch vehicle designed to transport the CEV and service module to low earth orbit. The CLV design utilizes propulsion elements from the current space shuttle. The first stage is a reusable solid rocket booster. This RSRB is the same as the current shuttle solid boosters. The second stage is propelled by one SSME. An SSME was chosen to give the desired thrust to weight (~0.86) on the upper stage, while still providing the efficiency (Isp = 452.1) of a staged combustion LOX/LH2 engine. The SSME design will be modified to start at altitude as well as simplified to limit production costs. These simplifications are thought to limit production costs due to the expendability of the engine without sacrificing reliability.

The CLV is designed to carry a payload of approximately 59,900 lbs into a 30 X 100 nmi orbit injected at 60 nmi. This payload weight was chosen as a result of the ESAS study for the CEV and service module design. This orbit will allow the CEV to rendezvous with the prelaunched Earth departure stage and lunar lander in LEO and continue on to the Moon. The resulting vehicle is 309 ft tall and weights 1.840 million pounds.

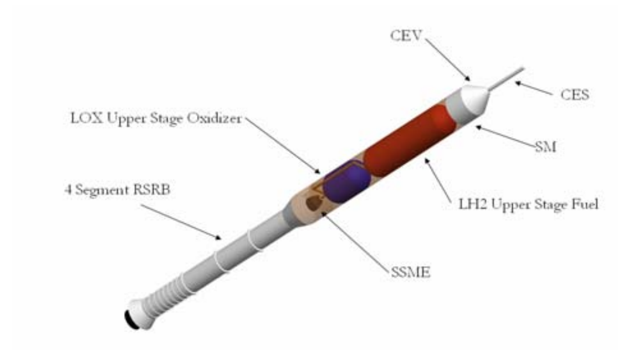

Figure 1. CLV Configuration.

In the design of the CLV reliability and safety are the main concerns. The CLV is designed to provide reliability 10X greater than that of shuttle. This is accomplished by taking reliable shuttle components and eliminating the fault paths discovered in the shuttle program. The main differences between the shuttle and the CLV are that the CLV is a completely inline system. This system eliminated the possibility of ejected pieces from contacting the vital crewed compartment of the vehicle. This eliminates the possibility of insulation damaging the heat shield. The CLV also uses the RSRB on the first stage. This is a highly reliable rocket motor with over 200 successful flights with only one failure. This failure was extensively investigated and resulted in a redesign of the RSRB. The final addition to the CLV to improve safety is the addition of the crew escape system. This system consists of a solid motor placed on top of the CEV. This system will engage if a failure occurs in either stage of the vehicle. It is assumed that if a failure in the launch vehicle occurs the CES has a 90% chance of separating the CEV from the CLV and safely recovering the crew. The resulting calculated reliability of the CLV is 0.9988, which is at least 10X better than the demonstrated shuttle reliability.

As Figure 2 shows the CLV is comparable with other previously existing expendable launch vehicles. The CLV is very similar in overall gross mass with the Titan IV launch vehicle. It is significantly taller than the Titan IV due to the large LOX/LH2 upperstage. The CLV is significantly smaller than the Saturn V in overall height and only a third of the weight. This is due to the limited payload capacity of the CLV (The CLV only launches the capsule and the SM, while the Saturn V launched the lunar module and earth departure stage as well).

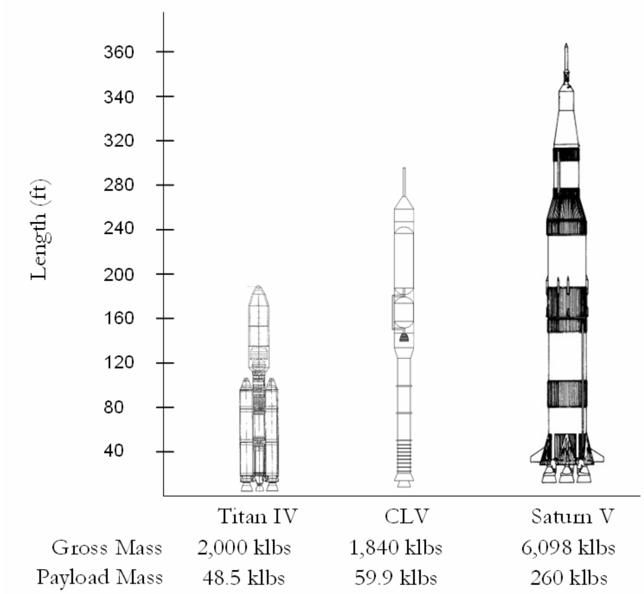

Figure 2. Comparison of CLV with other Expendable Launch Vehicles.

III. Multidisciplinary Design Process

The conceptual design methodology used in the design of the CLV combined analyses from several different disciplines. A different tool was used for each disciplinary analysis, as shown in Table 2. Each tool acts as a contributing analysis to the overall design of the vehicle. In some cases, iteration between two or more analysis tools is required. This coupling can be best visualized as a Design Structure Matrix (DSM) or "N-squared" diagram. Each box along the diagonal represents a contributing analysis, and the lines represent the flow of information. Information that is fed-forward through the design process is represented by lines on the upper right of diagonal, while the lines in the lower left are feed-back.

The DSM for the CLV design is shown in Figure 3. The feedback between the Trajectory analysis and the Weights & Sizing analysis closes the performance and configuration of the launch vehicle. The feedback between Operations, Reliability, and Cost closes the economics of the vehicle.

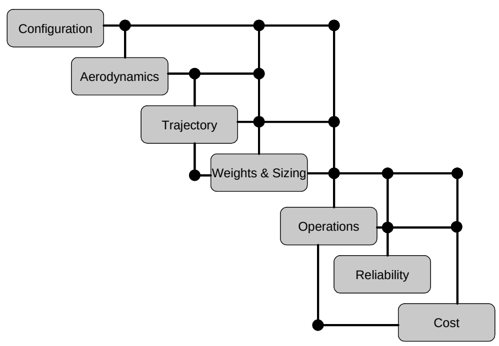

Figure 3. DSM for CLV Design.

Table 1. CLV Design Tools.

Discipline	*Analysis Tool*
Configuration	Pro/E
Aerodynamics	APAS (HABP)
Trajectory	POST 3-D
Weights & Sizing	MS Excel
Operations	AATE
Reliability	Relex
Cost	TRANSCOST

IV. Crew Launch Vehicle Closure Results

Each of the design disciplines depicted in Figure 3 and Table 1 are explained below in this section. Each of these design disciplines were iterated and closed to get the final CLV design. In designing and closing the CLV, there were constraints that had to be taken into account. As a human-rated launch vehicle it is important that the maximum dynamic pressure (or "max-q") remain low in order to enable crew escape. It was desired to have a max-q below 740 psf, which was that experienced by the Saturn V rocket[6]. The CLV was closed at a max-q of 700 psf, below that of the Saturn V. However, in order to study what would be required to further reduce the loads on the crew during a crew escape event, certain changes were made to the SRB thrust profile that allowed a maximum dynamic pressure of 600 psf to be obtained. Results from both designs are presented in the following sections.

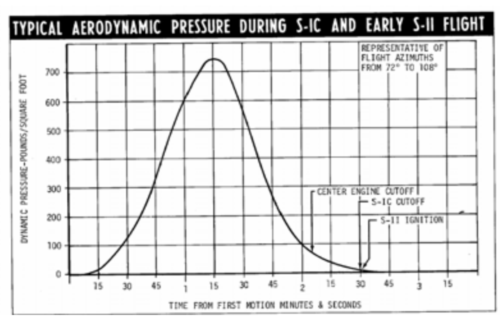

Figure 4 - Saturn V Dynamic Pressure versus Time[6]

A. Internal Configuration and Layout

As noted previously the CLV consists of two flight elements. The first stage is the four segments solid rocket booster from the shuttle program. The second stage is a new LOX/LH2 stage that is 124 feet tall and has the same diameter (18.04 feet, 5.5 meters) as the CEV. This second stage provides a significant portion of the ΔV requirement (74%) to get to LEO. A summary of the individual components follows as Figure 5 and Figure 6.

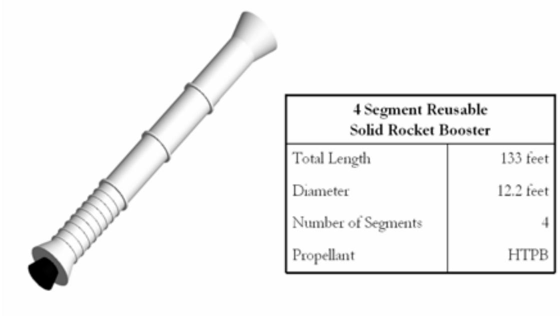

Figure 5. 1st Stage Configuration RSRB.

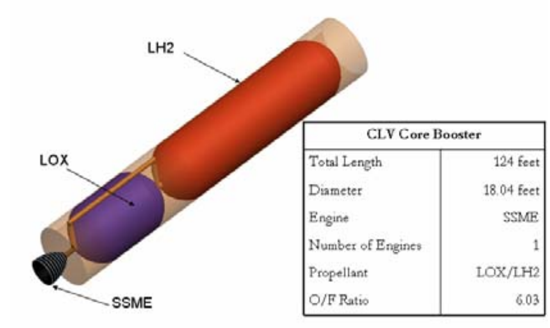

Figure 6. 2nd Stage Configuration (SSME).

B. Propulsion Design

The CLV utilizes two shuttle-derived propulsion systems that both have high demonstrated reliability over the more than two decades of shuttle operation. The first is the Shuttle 4-Segment Solid Rocket Booster, which functions as the sole booster stage of the CLV. During the initial design process, an off-the-shelf 4-segment SRB was used, which has the same performance and thrust profile as the current Shuttle SRBs. However, during design space exploration, it was found that due to the high thrust levels through the lower (and therefore denser) parts of the atmosphere, the vehicle design did not close for a max-q less than 700 pounds per square foot. In order to reduce the acceleration experienced by the crew during an abort, it may be desirable to reduce the max-q to 600 psf. When this constraint was added to the trajectory optimization code used in the CLV analysis, the trajectory code and weights and sizing tools did not converge to a closed vehicle design.

The dynamic pressure versus time plot for the closed vehicle trajectory with a max-q of 700 psf is shown in Figure 7. Also shown on the same plot is the thrust profile of the SRB. The max-q occurs at around 50 seconds, about the time that the thrust reduces to about 2.4 million pounds (point 1). One way of reducing the max-q further would be to reduce the vehicle thrust even further at this point in the trajectory. This could be accomplished by tailoring the grain of the propellant. However, it was desired to keep the total impulse provided by the SRB constant. This is accomplished by increasing the thrust at point 2, while keeping the area under the curve equal to that of the original thrust profile.

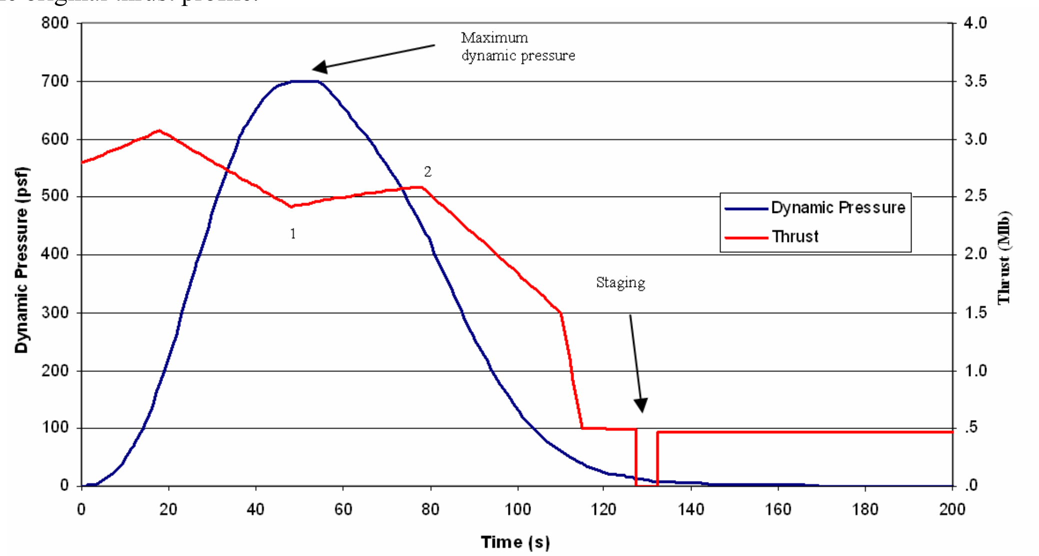

Figure 7. Dynamic Pressure (Max q limited to 700psf) with original SRB Thrust Profile.

The resulting trajectory is shown in Figure 8. With the new thrust profile, the trajectory and sizing analyses were easily able to converge to a closed vehicle design.

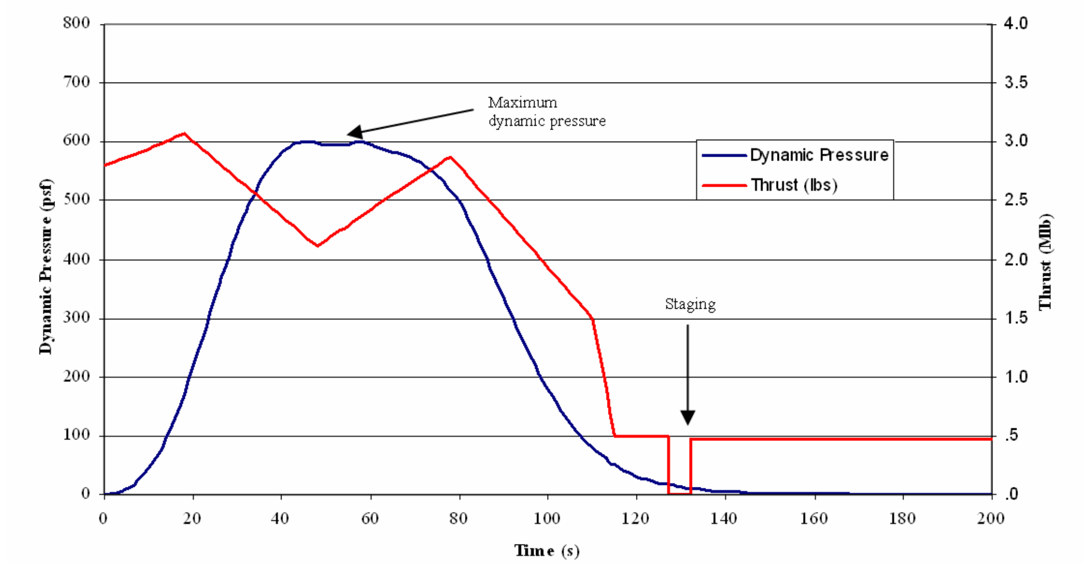

Figure 8. Dynamic Pressure (Max q limited to 600psf) with modified SRB Thrust Profile.

The upper stage propulsion of the CLV is assumed to be a single Space Shuttle Main Engine (SSME), manufactured by Boeing-Rocketdyne. The SSME is staged-combustion engine that runs on liquid oxygen and liquid hydrogen propellants. It has performed very reliably on ever Space Shuttle mission. The SSME used on the Space Shuttle, however, is started using equipment on the launch pad. In order to start the SSME at altitude, modifications must be made to its hardware which adds to the development cost of the propulsion system of the CLV. Other than the air-start capability, however, the same performance characteristics as the current SSME Block II were assumed (Figure 9).

- Staged-Combustion Cycle
- LOX/LH2 Propellants
- Thrust: 469,000 lb (Vacuum)
- Isp: 452.1 s (Vacuum)
- Weight: 7000 lb
- Exit Area: 120 sq. ft
- Expansion Area: 69
- Chamber Pressure: 3000 psi

http://www.boeing.com/defense-space/space/propul/SSME.html

Figure 9. SSME Performance Characteristics.

- 4-segment Solid Rocket Booster
- Propellant: PBAN
- Useable Propellant: 1,108 klb
- Burnout Weight: 180 klb
- Max Thrust: 3,300 klb (Vacuum)
- Isp: 268 s (Vacuum)

http://www.space.com/imageoftheday/image_of_day_031118.html

Figure 10. RSRB Performance Characteristics.

C. Performance

The trajectory of the CLV is optimized using POST 3-D[2]. The simulated trajectory was required to deliver approximately 30 tons to a 30 x 100 nmi transfer orbit, using a SRB booster stage and SSME powered upper stage.

The CLV trajectory is optimized to minimize the gross weight of the CLV by changing the pitch angles during the ascent. The constraints on the trajectory are: the final orbit, the g forces for the ascent must not be greater than 4 g’s, the maximum dynamic pressure, and the final payload must be 30 tons. The staging point was not changed, due to the fixed burn time of the SRB first stage.

The trajectory plots for the two closed CLV designs are shown in Figures 11-14.

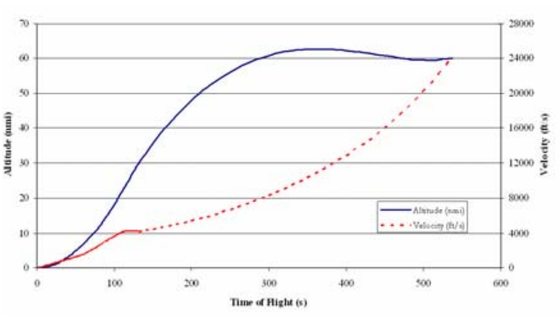

Figure 11. Altitude and Velocity versus Time with original SRB Thrust Profile.

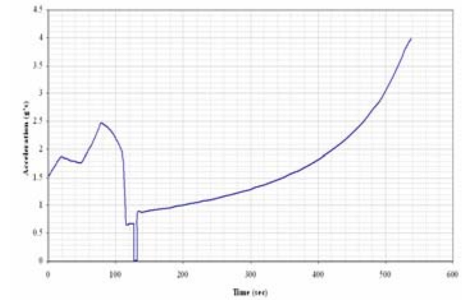

Figure 12. Axial Acceleration Sensed by CEV with original SRB Thrust Profile.

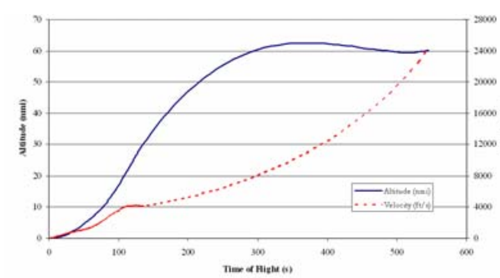

Figure 13. Altitude and Velocity versus Time with modified SRB Thrust Profile.

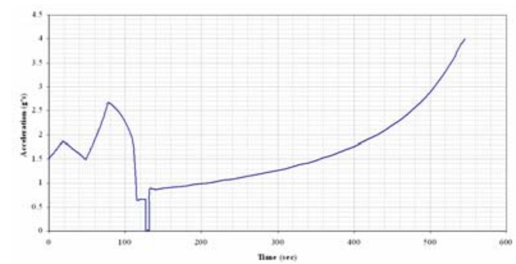

Figure 14. Axial Acceleration Sensed by CEV with modified SRB Thrust Profile.

The differences between the two trajectories can be seen in the acceleration experienced by the CEV Occupants on the two different vehicles. The second peak in acceleration is higher on the 600 psf vehicle, because that corresponds to an increase in thrust of the modified SRB over the original. The two trajectories are similar in most other respects.

Table 2. 700 psf CLV Propellant Breakdown.

Fuel	*Value*
First Stage PBAN	1,108 klb
Second Stage LOX	361 klb
Second Stage LH2	60 klb

Table 3. 600 psf CLV Propellant Breakdown.

Fuel	*Value*
First Stage PBAN	1,108 klb
Second Stage LOX	368 klb
Second Stage LH2	61 klb

Note the difference between the two is only in the upper stage. This is because achieving the lower max-q involves “lofting” the trajectory, which causes the upper stage to take on more of the burden of achieving orbital velocity.

D. Mass Estimation & Structural Design

Mass estimation followed two methodologies. For previously designed elements, such as the booster stage and the upper stage rocket engine, historical masses have been used. The masses of elements of the CLV that will be newly developed, such as the upper stage tanks, interstage adapter, thrust structure, and vehicle subsystems are estimated using MERs[3].

Each subsystem and structural element has a unique MER based on regression of historical data. Tank MERs, for example, are based on the volume of the tanks, the type of propellant being stored inside, and the pressure of the tank.

As each run of POST 3-D is performed, the weights & sizing spreadsheet is updated to match the propellant required to achieve the trajectory. As the propellant weight changes, the CLV tank and structure is appropriately resized, and therefore the dry weight changes. The new dry weights are then inputted into POST 3-D, and the analysis rerun. As this iteration continues, the vehicle design will converge to a closed design. A summary of the closed weights for the 600 and 700 psf closed vehicles are shown in Tables 4 and 5.

Table 4. CLV (max-q = 700 psf) Mass Summary.

Weight Breakdown Structure	*Mass*
Booster Dry Weight	180 klb
Booster Propellant	1,108 klb
Interstage Adapter	5.5 klb
Booster Gross Weight	**1,294 klb**
Upper Stage Structure	25 klb
Upper Stage Subsystems	2.2 klb
Upper Stage Propulsion	8.7 klb
Growth Margin	6.3 klb
Dry Weight	**42 klb**
Reserves and Residuals	4.2 klb
CEV	60 klb
Crew Escape	9.3 klb
Propellant	421 klb
Upper Stage Gross Weight	**538 klb**
CLV Gross Weight	**1,831 klb**

Table 5. CLV (max-q = 600 psf) Mass Summary.

Weight Breakdown Structure	*Mass*
Booster Dry Weight	180 klb
Booster Propellant	1,108 klb
Interstage Adapter	5.5 klb
Booster Gross Weight	**1,294 klb**
Upper Stage Structure	25 klb
Upper Stage Subsystems	2.2 klb
Upper Stage Propulsion	8.7 klb
Growth Margin	6.3 klb
Dry Weight	**42 klb**
Reserves and Residuals	4.2 klb
CEV	60 klb
Crew Escape	9.3 klb
Propellant	429 klb
Upper Stage Gross Weight	**547 klb**
CLV Gross Weight	**1,840 klb**

The gross weight for both vehicle designs is around 1.8 million pounds. This is slightly heavier than the Delta IV Heavy, which has a gross weight of 1.6 million pounds, and a smaller payload to LEO. It should be noted that while the gross weight increased for the second closed vehicle design, the increase in dry weight was less than 300 lb. Most of the extra mass is extra propellant required to fly the more lofted trajectory.

E. Reliability

The reliability for the CLV is calculated using the software RELEX[7]. Among other capabilities, RELEX can create and calculate a fault tree analysis like the one shown below for the CLV. For this analysis, it was assumed that Loss of Vehicle (LOV) and Loss of Crew (LOC) were the same. No distinction is made between the 600 psf CLV and the 700 psf CLV because the only differences are in configuration and weight; the failure modes are assumed to be the same. The majority of the input numbers were taken from a Futron study on launch vehicle reliability[10]. The SSME reliability is referenced from the Boeing Co[8]. There have been no assumptions regarding increases in reliability; all of the numbers used are traced from demonstrated systems. This heritage uses older technology, and thus it could be reasonable to assume that this is a conservative estimate of CLV reliability. Finally, even though the SRB first stage has a demonstrated failure rate of lower than 0.004, the authors of this paper decided to continue with a conservative analysis and calculate the reliability with a full bottoms-up approach. The fault tree is illustrated in Figure 15.

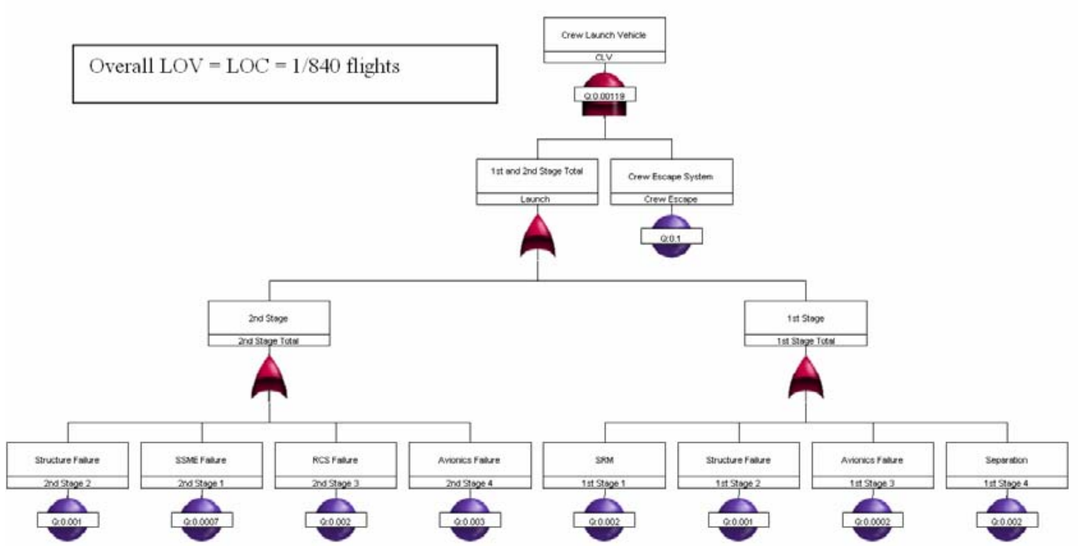

Figure 15. Fault Tree Analysis of CLV

The calculated reliability of the CLV is very high. This can be attributed to two main factors. First, on the SRB stage, the majority of the components are from well demonstrated solid rocket systems. The lack of complexity when using solid rockets will typically manifest itself in reliability calculations. This is one reason why solid boosters are chosen even though they lack the performance that can be achieved with a liquid rocket engine. This first stage also reflects the knowledge gained from the experience with the STS system and thus a high reliability is achieved.

For the second stage, the SSME is expected to be the main driver for LOC. Yet, its reliability is also very high due to its heritage. This engine is one of the most extensively tested rocket engines, and thus an excellent failure rate is achieved. The rest of the second stage inputs are determined from historical liquid rocket systems. With a typical driver of LOC having a high reliability, the whole system will then realize a high reliability. Finally the addition of a crew escape system aids in ensuring a low LOC number.

F. Operations

The operations costs for the CLV are calculated using estimates based on the STS program. The entire first stage is an STS component, which makes this analysis appropriate. In addition, the 2nd stage uses the SSME; this is another reason for why these estimates can be used. However, because these components are derived from the STS program, they will inherit some of its cost structure. The CEV component was not considered in these costs; therefore, additional costs for the turnaround of the CEV, along with its facilities are not included here. Also, the cost of modifying facilities for the CLV are not included in these costs. The lack of reliable data for which to base these estimates upon is the major reason that facility modifications are not included.

The variable cost per flight is estimated at $43.9M FY '04. The annual fixed costs for operations are estimated at $741.5M FY '04. These costs are driven from a derivation of shuttle hardware. However, when comparing to the STS program, these costs are a fraction of what the fixed and variable costs used to be. It is acknowledged that the CEV has not been included, nor has any impact of the future Heavy Lift Vehicle been estimated. Yet, with the goal of sustained exploration, these operations costs help the CLV fit within initial budget estimates for achieving sustained access to space with these future systems.

G. Cost & Economics

To estimate the rest of the costs for the CLV design, weight-based cost estimating relationships (CERs) were used. The CERs were used to calculate an overall design, development, testing, and evaluation (DDT&E) cost. Initial production costs are also calculated. Finally, with the use of a 90% learning curve, production costs based upon the number of flights is estimated. These costs are then broken down by stage to see what the main cost drivers are. The CERs are created from data in the NAFCOM[4] model used in cost estimating. An initial summary of the costs are listed in Table 6 (All costs are presented in $M FY 2004 dollars at an undiscounted rate). The margin has already been built in to the costs and is included for more information.

Table 6: CLV DDT&E and TFU Costs ($M FY '04)

			600 Psf	700 Psf
RSRM				
	DDT&E		$589	$417
	Production		$58	$54
	Total RSRM		$647	$471
	Margin (20%)		$107	$78
Upper Stage				
	DDT&E			
		Airframe	$1,465	$1,460
		Engine	$902	$902
	Production			
		Airframe	$283	$282
		Engine	$49	$49
	Total Upper Stage		$2,699	$2,693
	Margin (20%)		$449	$446

While the SRB has been used before, it was assumed that some DDT&E will be needed to prepare it to carry a new upper stage. Additionally, the SRB will now have a different separation sequence, which will require some DDT&E before it can be flight qualified for human travel. The 600 psf will require more DDT&E because that SRB will have to undergo a grain re-design. The 700 psf case uses an off the shelf SRB; however, in order to achieve the lower dynamic pressure, the thrust profile of the SRB must be changed. Hence, there is an increase in the DDT&E of the 600 psf vehicle. The production costs are similar because the grain casting technique should be similar. However, there will be some increase in cost due to a different grain pour.

The second stage will require more development funding than the SRB first stage, due to the fact that it is a new second stage that must be qualified for human flight. Additionally, the "air lighting" of an SSME will require a redesign and re-certification of this engine. Since the SSMEs used on the CLV are expendable, many will be produced for this architecture, and the manufacturing techniques will also be changed. Thus, there will be a learning process during this time which will give the SSME development a cost almost equivalent to a new engine development. However, once this development has taken place, the production cost of the new SSME will be more in line with its original predecessor. The slight differences between costs of the 600 psf CLV and the 700 psf CLV for the 2nd stage can be attributed to weight differences. Since weight based CERs are being used, and these vehicles have slightly different masses, it is reasonable to expect slight differences in their 2nd stage costs. However, since they are using the same "airlight" SSME, these costs will be the same.

The Life Cycle Cost (LCC) for the CLV is based upon a 15 year campaign and a flight rate as illustrated in Figure 16. The calculation includes the DDT&E cost, plus the production costs (dependent upon flight rate), plus the annual fixed cost, plus the variable cost (also dependent upon flight rate). Figure 17 shows the 600 psf case. Illustrated on the graph are both the total costs per flight along with the recurring costs per flight. The two costs are very close; this is because the development cost spread over 15 years does not add greatly to the total cost per flight. The variable and fixed cost per year will easily eclipse the development costs for this vehicle when the total LCC is calculated. This was the trade off made with the decision to use shuttle derived hardware.

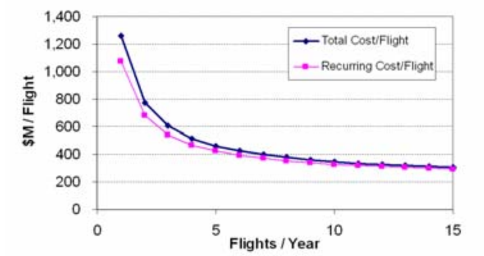

Figure 16: CLV 700 psf Cost Per Flight ($M FY '04), 15 Year Campaign

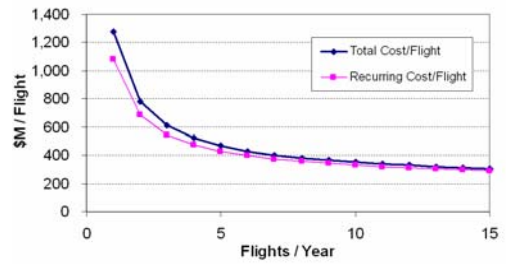

Figure 17: CLV 600 psf Cost Per Flight ($M FY '04), 15 Year Campaign

The next figure shown is Figure 16, which is the 700 psf case. The same trends exist as before: the total cost per flight and the recurring cost per flight are very close. Again this is because the development cost is small compared to the LCC contribution made by the annual fixed and variable costs. The two launch vehicles are very close when compared for overall LCC. The 600 psf vehicle will invariably cost more because it spends more on development for the new grain design. Additionally, more is spent on production of the 600 psf vehicle. Both are comparable in operations costs, thus the difference in development and production costs will account for the slight difference in total LCC. However, both are very close.

The total costs of these vehicles are within projected budgets for exploration. A flight rate of 2 per year will result in a cost of $783M FY '04 for the 600 psf CLV and $773M FY '04 for the 700 psf CLV. With a doubling of flight rate, these costs can be moved into the $500M range. However, this figure can be misleading because it incorporates the DDT&E costs; these costs will already have been paid for by the time of the first flight. Therefore, with a cost of $684M and $680M FY '04 for the 600 and 700 psf vehicles, respectively, the goal of achieving sustained exploration can be reached.

V. Comparison with ESAS Results

It is now appropriate to compare the completed CLV design computed with the GT methodology to the closed ESAS design[9]. This comparison follows as Table 7.

Table 7. Comparison of GT and ESAS Results.

	GT	NASA ESAS
Gross Weight (inc. CEV and CES)	1,840,344 lb	1,775,385 lb
First Stage		
Dry mass	180,399 lb	180,399 lb
Gross mass	1,293,517 lb	1,292,655 lb
Height	133 ft	133 ft
Diameter	12 ft	12 ft
Second Stage		
Dry mass	42,084 lb	38,597 lb
Gross mass	477,629 lb	405,541 lb
Height	124 ft	105 ft
Diameter	18.04 ft	16.40 ft

As this table shows the GT results compare very closely with the NASA ESAS results. The major difference was the weight of the second stage. The GT results are indicative of flying a "lofted" profile to limit the maximum dynamic pressure. This limit, as discussed above, was to limit the acceleration sensed by the astronauts on abort (the higher the max dynamic pressure, the larger the abort engines, and the higher the g's on a low dynamic pressure abort). The ESAS studies smaller mass could be a result of further tailoring of the ascent profile, or an introduction of higher technology structures (i.e. Al-Li) to limit the structural weight of the second stage. The resulting extra mass of the GT design still results in a feasible vehicle for the reference payload.

VI. Conclusions

The CLV is a new NASA launch vehicle design proposed by the Exploration Systems Architecture Study (ESAS) to provide reliable transportations of humans and cargo from the earth's surface to low earth orbit (LEO). The CLV uses shuttle heritage components such as the reusable solid rocket booster (RSRB) and the space shuttle main engine (SSME) to both reduce overall development costs as well as take advantage of the significant effort already spent on increasing the reliability of the shuttle components. The CLV design is a two stage shuttle derived launch vehicle. The first stage consists of a space shuttle derived RSRB. The second stage is a new stage designed around a single SSME. The second stage will consist of a single LOX tank and a single LH2 tank constructed of Aluminum. The payload of this vehicle is a 18 ft conical CEV with a supporting service module. The total weight of this payload is approximately 59,900 lbs and it is injected into a 30 X 100 nmi orbit at 60 nmi. The resulting CLV design is over 1.840 million pounds and stands 309 ft tall. These results are just slightly larger then the reference ESAS design.

The CLV is also designed to improve the reliability of human launch beyond that of the space shuttle. This is accomplished by utilizing the flight proven elements of the shuttle system, and eliminating the potential problems now plaguing the shuttle fleet. This includes eliminating the potential for damage to the reentry heat shield by placing the CEV at the top of the launch vehicle and keeping the thermal protection system shielded through the ascent. The crew escape system further decreases the probability of a loss of crew event. The resulting overall reliability of the system is 0.9988 or 1.19 failures per 1000 flights. This increases reliability over shuttle is achieved at a significant savings over the existing shuttle design. The total costs of these vehicles are within projected budgets for exploration. A flight rate of 2 per year will result in a cost of $783M FY '04 for the 600 psf CLV. With a doubling of flight rate, these costs can be moved into the $500M range. However, this figure can be misleading because it incorporates the DDT&E costs; these costs will already have been paid for by the time of the first flight. Therefore, with a cost of $684M for the 600 psf CLV, the goal of achieving a sustainable exploration architecture can be reached.

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