Probabilistic Cost, Risk, and Throughput Analysis of Lunar Transportation Architectures

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Abstract[1,2]—The President's Vision for Space Exploration presents a need to determine the best architecture and set of vehicle elements in order to achieve a sustained human lunar exploration program. The Lunar Architecture Stochastic Simulator and Optimizer (LASSO), a new simulation-based capability based on discrete-event simulation, was created to address this question by probabilistically simulating lunar transportation architecture based on cost, reliability, and throughput figures of merit. In this study, two competing lunar transportation architectures are examined for a variety of launch vehicle scenarios to determine the best approach for human lunar exploration. Additionally, the two architectures are also compared for varying available ground infrastructure and desired flight rates. It is concluded that an expendable architecture is favored, using man-rated versions of existing evolved expendable launch vehicles (EELVs) for crew launches and developing a heavy-lift launch vehicle for cargo launches.

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1. INTRODUCTION

In the President's Vision for Space Exploration, President Bush called for a return to the Moon no later than the year 2020 [1]. In order to do so, however, it is necessary to determine the best architecture and suite of vehicles within that architecture in order to accomplish the President's Vision. Historically, many of these decisions have been made based on deterministic mass and performance-based analyses. Metrics such as cost, reliability, and the ability to meet a given campaign schedule have been considered later in the design process after many architecture and vehicle decisions have already been made, generally increasing the overall cost of the mission. Therefore, the ability to rapidly measure cost, reliability, and schedule impacts of top-level architecture and individual element decisions represents a significant improvement over the current deterministic analysis capabilities for top-level decision making. Allowing this knowledge to be brought forward in the design process will help to reduce the overall program costs down the road.

This capability is provided by LASSO, the Lunar Architecture Stochastic Simulator and Optimizer, which was developed in order to conduct this study. LASSO is a simulation-based capability, based upon discrete-event simulation (DES), that provides the ability to probabilistically simulate and optimize an overall lunar transportation approach. Discrete-event simulation is a fairly new tool to the space industry. Some work has begun, however, in using DES to model aspects of space missions, although it has generally been limited to modeling only ground operations. For example, NASA Kennedy Space Center has developed GEM-FLO (A Generic Simulation Environment for Modeling Future Launch Operations) using discrete-event simulation to model the launch operations processing for space transportation systems [2]. RLVSim (Reusable Launch Vehicle Simulation) was created at Georgia Tech, and is also a discrete-event simulation model for reusable launch vehicle ground operations [3].

Using LASSO, two competing architectures for lunar exploration are examined – an expendable, Apollo-style architecture and a highly-reusable next generation architecture. The main trade study examines the merits of each architecture, based on cost, reliability, and mission throughput, for a set of launch vehicle options. The two

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[2] IEEE Paper#1436

architectures are also compared against each other as a function of varying flight rates. Based on the architectures considered in this study, some conclusions are drawn as to the better architecture choice for the planned lunar transportation missions.

This paper begins with a brief overview of the tool and methodology used to conduct the lunar architecture trade study. It is followed by a description of each architecture and the key assumptions made. Finally, the results of the architecture study are presented along with conclusions as to the preferred architecture choice for lunar exploration.

2. MODELING APPROACH AND ASSUMPTIONS

Modeling Approach

The two architectures under consideration were simulated using LASSO, which integrates three existing software programs to model, analyze and optimize lunar exploration architectures: Rockwell Software's Arena, Microsoft Excel, and Phoenix Integration's ModelCenter®. A database of flight elements for each architecture is available in Excel, and includes launch vehicles, in-space propulsive stages, lunar landers, and crew exploration vehicles (CEVs). For each element, Excel contains pertinent metrics such as gross mass, propellant mass, payload capacity, cost, reliability, and cycle times. The elements contained in the database are a combination of existing flight elements and conceptual designs.

Arena, a discrete-event simulation package, is then used to create full end-to-end models of each architecture, including manufacturing of all the necessary transportation elements, payload and launch vehicle integration, launch, in-space propulsive segments, Earth re-entry, and turn-around processes for any reusable elements. Finally, the Arena models, along with the Excel database, are integrated into ModelCenter, to allow for design space exploration and optimization, as well as to facilitate parametric studies, as will be presented in this study.

For more information on LASSO, consult references [4] and [5].

Lunar Architecture Concepts

Each architecture modeled in this study has some common mission assumptions, as outlined below:

- Orbit characteristics:
    - LEO rendezvous orbit = 400 km × 28.5°
    - LLO rendezvous orbit = 100 km × 90°
- Trajectory:
    - Time of Flight (LEO to LLO) = 3.5 days
    - TLI Delta-V = 3100 m/s
    - LOI/TEI Delta-V = 840 m/s
- Lunar mission specifications:
    - Number of crew = 4
    - Time on lunar surface = 4 days
    - Payload to lunar surface = 500 kg
    - Payload from lunar surface = 100 kg

The expendable architecture, shown in Figure 1, consists of all expendable elements, as its name suggests. All the cargo elements are first launched into low Earth orbit on one or more cargo launch vehicles, depending on the payload capacity of the launch vehicle chosen. The crew is then launched in the CEV, along with the TEI stage, on a man-

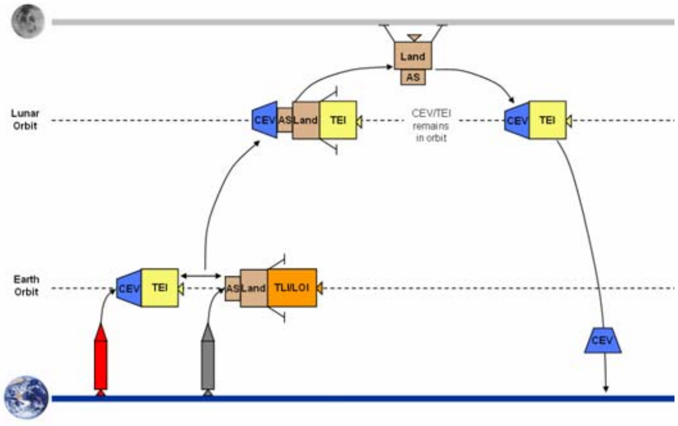

Figure 1 – Expendable Lunar Architecture

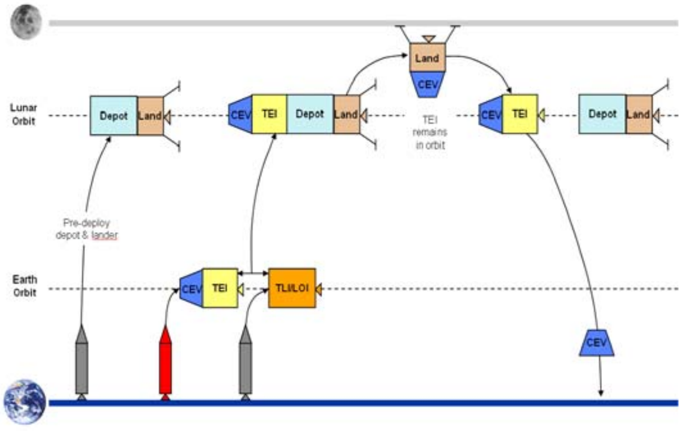

Figure 2 – Reusable Lunar Architecture

rated launch vehicle. All of these elements dock in Earth orbit, before beginning their transit to the Moon. Once in lunar orbit, the lunar lander ferries the crew to the lunar surface, while the CEV and TEI remain in lunar orbit. The chosen lander has a built-in habitat in the ascent stage, but if another surface habitat is desired, it would have to be pre-deployed. The lander descent stage remains on the lunar surface, while the ascent stage then launches the crew back to lunar orbit, where it docks with the CEV and TEI. The crew transfers to the CEV, which travels back to Earth for a direct entry to the surface.

The major difference in the reusable architecture, shown in Figure, is the use of a reusable lunar lander and propellant depot in lunar orbit. Again, the cargo launches first on one or more launch vehicles, followed by the crew in the CEV, along with the TEI stage. The propellant depot and lander are pre-deployed along with a surface habitat if desired. At the beginning of the simulation, an empty depot is assumed to already be located lunar orbit, and the lander is launched fully fueled before the first human lunar mission. Once the CEV/TEI and TLI have launched, they dock in Earth orbit and travel to the moon as a single stack. Upon arriving in lunar orbit, the lander ferries the CEV to the surface (the reusable lander does not have a built-in habitat), while the TEI remains in lunar orbit. Upon completion of the lunar mission, the lander launches the CEV back to lunar orbit, where it docks with the TEI for Earth-return. The lander refuels from the propellant depot and remains in lunar orbit until the next lunar mission is launched. The lander must be periodically replaced when it lifetime expires. Additionally, dedicated propellant launches to lunar orbit are required to periodically refill the depot with propellant.

Modeling Assumptions

Several key assumptions were made in the modeling of these architectures. Most importantly, the LASSO architecture models model only the transportation-related elements along with their associated costs. This includes associated processes such as manufacturing, integration with the launch vehicle, and in-space segments, as well as costs such as DDTE, production, and operations. The transportation aspect of the lunar exploration program, however, comprises only a portion of the overall life-cycle cost of an actual program. In addition to the transportation elements, there are also costs associated with science payloads, technology development, precursor missions, etc.

Additionally, the user can input the number of ground facilities available, such as vehicle manufacturing facilities, integration facilities, and launch pads. The cost of building these facilities, however, is also beyond the scope of the Arena models. Therefore, the total cost reported by Arena can not be taken as the actual total cost of a lunar program.

Additional assumptions are made about the choice of launch vehicles. For a given architecture simulation, the user has a choice of three different launch vehicles: one each for crew, cargo, and propellant. The propellant launch vehicle is used in the reusable architecture to launch propellant to the lunar

Table 1. Inputs to Arena Lunar Architecture Models

Input	**Baseline**	**Description**
Missions per Year	2	Number of scheduled lunar missions per year (can be a fractional value).
Program Duration	10	Number of years in lunar program (starting with first mission launch).
Vehicle Indices		Index number corresponding to an entry in the database for each element type (CEV, TLI, Lander, TEI, LV crew, LV cargo, and LV propellant).
Integration Time	28 days	Expected time for payload integration with launch vehicle.
Pad Time	14 days	Expected time for payload/launch vehicle stack to spend on launch pad prior to launch.
Pad TAT	14 days	Expected turn-around time of launch pad.
Investigation Time	365 days	Expected length of stand down time resulting from loss of crew event.
Manufacturing Capacities		Number of a particular element that can be built at one time (one variable each for CEV, TLI, TEI, and lander).
Integration Capacities		Number of launch vehicles that can be integrated with their payloads at a given time (one variable each for crew, cargo, and propellant).
Launch Pads		Number of launch pads available to that particular launch vehicle (one each for crew, cargo, and propellant).
Depot Capacity	50,000 kg	Propellant capacity of propellant depot (if applicable).

propellant depot. Additionally, if a propulsive stage is too heavy to launch fully fueled, it is assumed that it can be launched empty or partially fueled, and a dedicated propellant launch will be responsible for on-orbit propellant transfer to that stage. Therefore it is assumed that the technology for on-orbit propellant transfer exists at the time of the lunar missions. Each type of launch vehicle has a set of dedicated facilities (payload integration and launch pads). The launches always occur in the following order: cargo, propellant (if necessary), and crew. The crew do not launch until all other elements have successfully reached Earth orbit. If a cargo or crew launch is unsuccessful, that particular mission is cancelled. If a propellant launch, fails, however, another is launched to replace it.

Finally, each event during the lunar mission has some probability of failure associated with it. When there is no abort option, or the abort is unsuccessful, a loss of crew event occurs. A stand down time then results, and all missions scheduled to launch during that time period are cancelled.

Inputs and Outputs

The important inputs to the simulation are presented in Table 1, along with the baseline values used for this study. In addition to those listed below, each of the vehicles chosen has its own relevant variables, such as weight, cost, and turn-around time (for reusable elements). Each of the cost and time variables has a triangular distribution assigned to it within Arena, in order to account for the uncertainly in the given value.

Because the inputs to the simulation are probabilistic, the Arena models must be repeated numerous times in order to generate output distributions on the figures of merit. Arena samples values from the input distributions, similar to a Monte Carlo simulation, and outputs cumulative distribution functions (CDFs) for each output variable. The number of replications was limited to one hundred for each case due to the long run times required in Arena. For the results presented in this study, 90% confidence values were used. The key figures of merit are listed below, and they encompass the three primary areas of interest: cost, reliability, and mission throughput:

- *Life cycle cost* – Total transportation-related program cost (includes DDTE, production, fixed and variable operations, launch, and propellant).
- *Cost per mission* – Life cycle cost divided by the number of missions launched.
- *Loss of crew* – Probability per mission that a loss of crew event occurs (number of loss of crew events divided by number of launched missions).
- *Loss of mission* – Probability per mission that a loss of mission event occurs (includes loss of crew events).
- *Mission capture %* - Percent of scheduled missions that are launched during the program duration.
- *Launch delay time* – Average time between scheduled launch date and actual launch date of a particular mission.
- *Time in LEO* – Average time between first and last launch for a particular mission. Used to determine the longest amount of time a particular element must spend in LEO.
- *Bottleneck statistics* – Average waiting time in queues (manufacturing, integration, launch pads, turn-around processes). Used to determine the limiting ground infrastructure.

These figures of merit comprise an overall evaluation criterion (OEC) which is used to evaluate the overall merit of each architecture being examined.

Launch Vehicle Trade Study Scenarios

In the first part of the study, four different launch scenarios (each with several subcategories) are examined for each architecture, in addition to a baseline case. These were chosen to be representative of the launch options that had been under consideration for human lunar exploration. All of these launch scenarios assume that any dedicated propellant launches are carried out using the same launch vehicle as the cargo launches. Table 2 summarizes the various launch options examined in this study.

In addition to the launch vehicle combinations, several ground infrastructure scenarios are examined for each case, as listed below:

- Infrastructure Scenario #1: Unlimited ground infrastructure.
- Infrastructure Scenario #2: Limited launch infrastructure; unlimited manufacturing capacity.
- Infrastructure Scenario #3: Limited launch infrastructure and manufacturing capacity.

Table 2. Performance of launch vehicles examined for trade study (A=Atlas, D=Delta)

	Launch Scenario	**Crew L.V. Payload**	**Cargo L.V. Payload**
	Baseline	23 mt	100 mt
1a(A)	Existing EELVs	10 mt	19 mt
1a(D)	Existing EELVs	9 mt	23 mt
1b(A)	Existing EELVs	19 mt	19 mt
1b(D)	Existing EELVs	23 mt	23 mt
2a(A)	Evolved EELVs	19 mt	40 mt
2a(D)	Evolved EELVs	23 mt	40 mt
2b(A)	Evolved EELVs	19 mt	70 mt
2b(D)	Evolved EELVs	23 mt	40 mt
3a	HLVs	35 mt	100 mt
3b	HLVs	35 mt	140 mt
4a	Shuttle-Derived	20 mt	77 mt
4b	Shuttle-Derived	34 mt	77 mt

First, unlimited ground infrastructure will be considered such that the mission capture rate will be 100%, and the launch delay time and the time of elements in LEO will be essentially zero (assuming that launches occur at the same time). Unlimited ground infrastructure will enable comparison between the various launch scenarios based solely on cost and reliability. Next, a limited set of launch infrastructure will be used, with unlimited manufacturing capacities. This scenario assumes that the companies responsible for manufacturing each element will be able to upgrade their facilities as necessitated by the demand. Using this scenario, the various launch scenarios can be compared based on scheduling metrics: mission capture percentage, launch delay time, and time in LEO. Finally, the last scenario will examine both limited launch and manufacturing capacities, also to compare launch options based on the scheduling metrics. From this scenario, the limiting capacity in the system can be determined by examining the bottleneck statistics.

3. LUNAR ARCHITECTURE STUDY RESULTS

For this study, a baseline set of vehicle elements is used, with only the choice of launch vehicles being varied, as listed in Table 2.

Expendable Architecture—First, the expendable architecture is examined. Figure 3 (see Appendix for all subsequent figures) plots the life-cycle cost for each launch scenario based on the unlimited ground infrastructure scenario. As can be seen, life-cycle cost ranges from approximately $53 to $72 billion for 20 lunar missions in a ten-year period, with cost per mission ranging from $2.9 to $3.9 billion. The results represent a trade-off between increased DDTE and launch costs for heavy-lift launch vehicles, but with fewer flights required per lunar mission. If a launch vehicle configuration were to be chosen based only on cost, clearly the baseline option would be chosen.

Reliability is then examined for each launch scenario. Figure 4 plots the loss of crew (LOC) and loss of mission (LOM) probabilities for each case. The baseline case falls somewhere in the middle of the launch options being traded. The variations in LOC and LOM are due entirely to the choice of launch vehicles, with LOC variation due mainly to the reliability of the crew launch vehicle. The loss of mission numbers can be attributed to a combination of the reliability of the cargo launch vehicle and the number of cargo launches. Since a mission is cancelled if a cargo launch fails, more cargo launches results in a higher LOM if the reliabilities are similar. The HLV options seem to have the best overall reliability if both loss of crew and loss of mission are considered.

Next, infrastructure scenario #2 was considered, where there is only one available integration facility and launch pad for each type of launch vehicle (crew, cargo, propellant). It is expected that the launch configurations that require more launches should have a lower mission capture percentage, a longer launch delay, and a longer time in LEO. Even using the limiting case (capacity of one for all infrastructure and launch pads), the mission capture rate is 100% for all cases except for 1a(A) and 1b(A). Even for these two launch options, the capture rate is still 98%. Therefore, at a launch rate of two missions per year, the launch infrastructure is not a limiting factor in meeting the mission demand. The launch delay is also essentially zero for all cases, since on average the first launch per mission launches on time.

The key statistic for this infrastructure scenario is the average time in LEO – that is, the average time between the first and last launch per mission. As this time increases, the mission becomes more infeasible, since elements have to remain in orbit for long periods of time before departing for the Moon. For example, engines must be able to start after a long time in orbit and propellant boil-off must be considered. The more launches that are required, the longer the time in orbit should be. This is confirmed by Figure 5, which plots the average time in Earth orbit for each launch option. For the Existing EELV options, the time in LEO ranges from three months to just over five months, which begins to become prohibitively long for elements to remain in orbit. Additionally, this launch option would not be able to achieve a greater mission demand, since it already takes almost half a year to launch one mission. If more than two missions a year were desired, the mission capture rate would fall below 100%. For the Evolved EELV and Shuttle-derived options, the time in orbit is around one month, and there is almost no time in orbit for the baseline and HLV options.

Finally, infrastructure scenario #3 was taken into account, where in addition to the limited launch infrastructure, only one of each element type can be manufactured at a time. While the minimum launch infrastructure did not provide a limiting case to mission throughput, the minimum manufacturing capacities do reduce the mission capture percentage below 100%. With the exception of the launch vehicles, the same elements were used for each case. Therefore, the results of limiting the ground infrastructure did not vary across the different launch scenarios. Table 3 lists the average wait time in the queue for each manufacturing process. This represents the time between when an order is placed for an element and when it actually begins manufacturing.

Table 3. Manufacturing Queue Wait Times for Launch Vehicle Trade Study (Expendable Architecture)

Manufacturing	Wait Times (days)
CEV	1060
Lander	1060
TLI	20
TEI	580

Clearly, the CEV and Lander manufacturing are causing the biggest bottleneck in the system, with the TEI manufacturing causing the next biggest bottleneck. The manufacturing capacity seems to be sufficient, however, for the TLI. Because the manufacturing capacities affect each launch option equally for the baseline mission scenario, there is no launch option that would be favorable based on the least investment required in ground facilities. For the expendable architecture, however, the minimum required ground infrastructure to achieve 100% mission capture is as follows:

- Launch pads – 1 each
- Launch vehicle integration facilities – 1 each
- Manufacturing – 2 each for CEV, Lander, TEI; 1 for TLI

The only small exception were the two launch options (1a(A) and 1b(A)) that did not quite meet 100% mission capture with the limited launch infrastructure.

Finally, it is useful to examine a combined cost-reliability-throughput overall evaluation criterion (OEC) to examine the trade between the various figures of merit. This OEC is defined as follows:

$$OEC = \left[\frac{1}{3} * \left(\frac{LCC}{200000}\right)\right] + \left[\frac{1}{3} * \left(\tfrac{1}{2} LOC + \tfrac{1}{2} LOM\right)\right] + \left[\frac{1}{3} * \frac{LEO\,Time}{1000}\right] \tag{1}$$

Cost, reliability, and time in LEO each have a weighting of 1/3. Each metric is normalized such that each falls in the range zero to one. Figure 6 plots the new OEC for each launch configuration. Because the baseline launch case did well in all three categories, it was the best overall launch option, with the heavy lift launch vehicles finishing a close second.

Expendable Architecture Summary—In general, when looking at cost, reliability, and throughput, the results for the launch vehicle trade tend to favor launch options that require fewer launches per mission. Cost depends on a trade between number of launches and cost per launch. Fewer launches do not necessarily translate to a lower life-cycle cost. When looking solely at cost, both the Existing EELVs (which require up to eight launches per mission) did as well as the HLVs (which required only two launches per mission). Reliability (particularly LOM), however, is strongly affected by the number of launches required, since there is not a large variation in the reliability of the actual launch vehicles being examined. Furthermore, as the launch infrastructure is limited, fewer required launches also translates into less time in LEO, which makes an architecture more feasible based on today's technology.

Additionally, for any of the launch options examined, no significant infrastructure investment needs to be made. One launch pad and an integration facility with a capacity of one for each type of launch vehicle are sufficient to launch all missions on time. Of course, to reduce the time in LEO for some of the launch options, more launch pads and integration facilities would have to be built, making those launch options more unattractive. Manufacturing capacities of two are also sufficient to meet the mission demands, which is a reasonable value to expect.

For all of the scenarios and launch options examined for the expendable Lunar Architecture, the baseline launch configuration remains the best option, in terms of a combination of cost, reliability, and scheduling. Next best are the two HLV launch options, which actually have the best reliability of all the launch options. If reliability were the primary concern, with less weighting on cost, the HLV options would be chosen. The baseline configuration does well overall though, because it uses an HLV as its cargo launch vehicle, while using smaller man-rated launch vehicle to launch the crew. Therefore, based on the overall consideration of cost, reliability, and scheduling, the baseline configuration is chosen as the best launch option for the expendable lunar architecture.

Reusable Architecture—The same launch vehicle options were considered for the reusable architecture, again looking at the three different infrastructure scenarios. Figure 7 plots the life-cycle cost for this architecture, based on the unlimited ground infrastructure scenario. Immediately apparent is the increased cost over the expendable architecture. The life-cycle costs range from \$91B to \$137B, with the cost per mission ranging from \$4.9B to \$7.4B. Although for some launch cases, there are fewer launches required per lunar mission, the added cost of launching propellant to lunar orbit significantly increases the life-cycle cost over the expendable architecture. For the reusable architecture, the baseline launch vehicle combination actually does not come out the least expensive. Both Shuttle-derived options and the HLV option with the 140 mt cargo launch vehicle are the least expensive. Overall, these options require the fewest launches, both for the lunar missions and the depot refueling missions.

Figure 8 plots the reliability for all of the launch options. As expected, the launch options with the least number of cargo launches per lunar mission have the lowest loss of mission probability. The propellant and depot launches will not affect reliability, since those missions are simply re-launched if there is a failure. Loss of crew is again a function of the reliability of the crew launch vehicle. The highest values of LOC occur for options #1a, where a crew escape system does not fit in the launch vehicle.

Limiting the launch infrastructure should have a significant effect on the reusable architecture, because of the additional launches required for refilling the propellant depot. When all of the integration capacities and number of launch pads are set to 1, the mission capture percentage for all of the Existing EELV launch options drops significantly below 100%, to approximately 60%. This is due to their smaller payload capacities coupled with the increased launch demand to resupply the propellant depot. As the capture rate decreases, the launch delay time also increases. For the Existing EELVs, the launch delay ranges from 662 days to 789 days. The longest average time in LEO is also the highest for the Existing EELVs, as expected, since it requires the most cargo and propellant launches for each lunar mission. Figure 9 plots the average time in LEO for each of the launch options.

As with the expendable architecture, an OEC is created to consider cost, risk, and scheduling metrics. Both LEO Time and Mission Capture % are included since each addresses a different issue. Capture percentage relates to the ability to actually meet the mission demand, while time in LEO relates to the feasibility of the architecture. As was seen with the expendable architecture, an architecture with a mission capture rate of 100% can still have a significant time in LEO penalty. The new OEC can therefore be written as follows:

$$OEC = \left[\frac{1}{3} * \left(\frac{LCC}{200000}\right)\right] + \left[\frac{1}{3} * \left(\tfrac{1}{2} LOC + \tfrac{1}{2} LOM\right)\right] + \left[\frac{1}{3} * \left(\frac{1}{2} * \frac{LEO\,Time}{1000}\right) + \left(\tfrac{1}{2} * \left(1 - Capture\%\right)\right)\right] \qquad (2)$$

Mission capture rate is written as *(1-Capture%)*, since OEC is a quantity to be minimized and capture percentage should be maximized. Figure 10 plots this new OEC for each of the launch options. As expected, the HLVs, Shuttle-derived, and baseline launch options come out best, since they did well across all the figures of merit.

Finally, the launch options are examined with the minimum possible launch infrastructure and manufacturing capacities. As in the expendable architecture trade study, manufacturing queue wait times are used as the bottleneck statistics for the each of the architecture elements. Table 4 lists the bottleneck statistics described above, as an average across all launch options, since each launch option uses approximately the same number of elements for the lunar missions. If the standard deviations are examined, this variance is not significant. The CEV and TEI wait times are approximately equal to those for the expendable architecture, as expected, since the lunar mission schedule is the same. Whereas TLI manufacturing did not cause a bottleneck in the expendable architecture, it does in the reusable architecture because more TLI stages are required for the depot launches.

Table 4. Manufacturing Queue Wait Times for Launch Vehicle Trade Study (Reusable Architecture)

Manufacturing	Wait Times (days)
CEV	1110
Lander	490
TLI	450
TEI	620

Also unlike the expendable architecture, limiting the ground infrastructure has a significant effect on the mission capture percentage for the reusable architecture. The Existing EELV options are lower than the others since they are also affected by the limited launch infrastructure. The average capture percentage of the remaining launch options is approximately 37%. Additionally, the time in LEO and the launch delay time both follow the same trend observed in the limited launch infrastructure case, just with higher values of launch delay time. The reusable architecture will therefore require a more significant infrastructure investment to reach 100% mission capture and reduce the time elements spend in LEO.

Reusable Architecture Summary— As with the expendable architecture, the best launch option for the reusable lunar architecture when considering cost, reliability, and throughput is heavily dependent on the number of launches. This architecture is particularly sensitive to the payload capacity of the launch vehicles, since extra launches are required to continuously refuel the LLO propellant depot. Fewer overall launches tend towards a lower cost solution, while fewer cargo launches per lunar mission tend towards a lower loss of mission probability. Additionally, as the launch infrastructure and manufacturing capacities are limited, the launch options requiring more launches take a particularly big hit in terms of mission capture percentage and launch delay time.

The architecture investment required for the reusable architecture (with the exception of the Existing EELV options) is slightly more than for the expendable architecture, although it is still not enough to make the architecture infeasible. All of the manufacturing capacities are three or less, and the launch infrastructure is at a minimum. The Existing EELVs would require a more significant investment, particularly to the launch infrastructure. Most likely, however, these launch options would not be chosen because they also performed so poorly in cost and reliability.

Of the launch options examined, the ones that performed the best were the baseline, the HLVs and the Shuttle-derived vehicles. Because the Shuttle-derived vehicles did so poorly in reliability, however, neither of these will be chosen as the preferred launch option. The best overall of the remaining choice in terms of cost, reliability, and scheduling is the second HLV option, using the 140 mt cargo launcher. This launch configuration does so well because it only requires one cargo launch per lunar mission and one launch per depot refueling mission. Looking at the launch vehicles, available, however, another option was considered. While the cargo heavy lift launch vehicle is a good choice for the cargo and propellant launches, the man-rated version is over-designed for the crew launches. Only 22 mt must be launched and its payload is 35 mt. An Existing EELV is sufficient to launch the CEV with a crew escape system and the TEI at a lower per launch cost. This “baseline improved” option was then run through LASSO and determined to have a lower OEC than any of the previous launch options considered.

Reusable Launch Vehicle Trade Study

The launch vehicle trade study assumed that the same launch vehicle was used for both cargo and dedicated propellant launches. Another case to be examined is using a reusable launch vehicle for the dedicated propellant launches, for the scenarios where the propulsive stages had to be launched empty of propellant. The advantage of a reusable launch vehicle is its fast turn-around time and its cheaper launch costs. A conceptual design for a horizontal take-off, horizontal landing reusable launch vehicle is assumed. Furthermore, it is taken to be a commercial venture, such that there is no DDTE cost incurred. NASA would simply pay for each launch as needed. Figure 11 plots the life-cycle cost when the reusable launch vehicle is used for the dedicated propellant launches. For each case, using a reusable launch vehicle significantly increases the life-cycle cost, except for the scenarios where no propellant launches are required. Although the price per launch is significantly less, the payload is also less, requiring more propellant launches per mission. The fast turn-around time of a reusable launch vehicle is also not a factor in this case, since unlimited ground infrastructure is assumed for all cases.

Clearly, it does not make sense economically to use this reusable launch vehicle to deliver propellant to Earth orbit, at least when turn-around time is not an issue. If the same launch vehicle were to be offered at a discounted price, then it may become competitive with the expendable launch vehicles. Based on this analysis, the launch price of a reusable launch vehicle would have to be less than approximately $100M per flight to become competitive against the expendable launch vehicles, and would have to be reduced even further to become beneficial across the board.

Annual Funding Considerations

In the previous launch vehicle trade studies, cost was evaluated based on undiscounted life-cycle cost and cost per mission. Another important factor, however, is the maximum peak annual funding required. Generally a program is allocated a given budget on a yearly basis, not a lump sum that can be spent each year as needed. Therefore, while a chosen architecture may fit within a ten or twenty year budget, each year’s spending must also fit within that given year’s budget. The two architectures will be thus compared across all of the launch options in terms of yearly spending. It is assumed that DDTE costs are spread evenly across the first five years of the program. Production will then start the following year, with costs assigned to the year in which production of a particular element starts. Over the ten years where missions are flown, costs are broken down into production, launch, and operations costs. Finally, there are no launches in the last year of the program, but fixed operations costs are still incurred.

As an example, Figure 12 plots the annual funding required for the expendable architecture using the baseline launch configuration. The costs are broken down into DDTE, launch, production, and operations. For the baseline, there is a significant amount of DDTE costs up-front, and then the annual costs decline once lunar missions begin. Production costs decrease each year as the learning curve decreases the cost of producing each element. All of the costs shown are in 2005 dollars.

Depending on the choice of architecture and architecture elements, the cost distribution will be different than for the baseline case. For example, the baseline expendable architecture can be compared to the Existing EELV launch option #1a(D), as shown in Figure 13. Both of these launch options did well overall in terms of cost ($53B and $55B for the baseline and #1a(D), respectively). How their costs are spread out over the entire program, however, could have an impact on which is chosen depending on budget constraints. The baseline case has a higher DDTE (over $1B per year), but lower annual costs once lunar missions start. This results from the baseline launch vehicles having higher DDTE costs, but lower launch costs overall. Therefore, if more money were available up-front, the baseline case would make more sense financially, particularly if the program duration were increased. The lower annual costs will pay off even more as the number of missions flown increases. If the program duration were reduced, however, the baseline would become more expensive, since more money was invested up-front. If less money were available up-front for DDTE, then the Existing EELV option would have to be chosen. This would then result in higher costs down the road.

The same charts can be created for the reusable architecture. Figure 14 shows the annual costs broken down by DDTE, depot resupply launches, lunar mission launches, production costs, and operations costs. For the reusable architecture, manufacturing takes place for two years before the first lunar mission, as opposed to one year for the expendable architecture. This is due to a longer manufacturing time for the reusable lander as well as the need to build three landers up front. The costs between the two architectures are actually fairly similar on a yearly basis, with the exception of the added cost of the propellant depot resupply launches. Although more TLIs need to be built per year, no landers are built on a yearly basis, which evens out the production costs. Therefore, the added cost in the reusable architecture can be accounted for in the cost of propellant launches to the lunar depot.

The baseline improved launch option can also be compared to the Existing EELV launch option #1a(D) for the reusable architecture, as shown in Figure 15. The same trend is seen as for the expendable architecture. While the baseline improved launch configuration requires a higher up-front cost, its annual costs once the lunar missions begin are significantly lower.

Finally, the peak annual funding required must be considered for each launch option for both architectures. While life-cycle cost and average cost per mission are important metrics, it is also important to consider the maximum annual cost in order to stay within a given budget. Obviously, lower is better. Figure 16 plots the peak annual cost for each launch option for both architectures. The reusable architecture, which has higher life-cycle costs, also has significantly higher peak annual costs. For the expendable and reusable architectures, the best launch options chosen based on the previous studies are the baseline and baseline improved, respectively. These also have the lowest peak annual cost. Therefore, the funding profile further confirms the selection of these launch configurations as the best choices for each architecture.

Flight Rate Trade Study

In general, when comparing a reusable architecture against an expendable architecture, it is expected that at some flight rate, there will be a crossover between which architecture is more affordable. In general, reusable architectures should require more infrastructure investment up-front, but as the number of missions flown increases, money should be saved since the variable costs per mission are much less. Expendable architectures, however, employ more of a "pay as you go" approach. There is less up-front investment, so you are basically paying for each mission as it is flown. Expendable architectures therefore tend to be favorable for low flight rates, while reusable architectures are favored for high-flight rates.

This theory was thus tested for the reusable and expendable architecture modeled for this study, by varying the flight rate and plotting the costs at each flight rate. Figure 17 plots the cost per mission for each architecture, assuming unlimited ground infrastructure. The launch vehicles used are the best options resulting from the launch vehicle study. For the expendable architecture, the crew launch on a man-rated EELV and the cargo launches on a 100mt heavy lift launch vehicle (baseline option). For the reusable architecture, the crew also launch on a man-rated EELV and the cargo and propellant launch on a 140mt (baseline improved option).

As can be seen, there is no flight rate where a crossover in cost will occur. In fact, the two curves are diverging. The intended advantage of the reusable architecture is a reduction in the number of launches required per lunar mission, since a lander does not need to be launched for each mission. Additionally, fewer landers need to be produced, since a single reusable lander is used for multiple missions. The reusable lander, however, requires the addition of a propellant depot in lunar orbit that must be periodically refilled. Because the lander requires 35 mt of propellant per lunar mission, on average this much propellant must be launched to lunar orbit for every manned mission. Additionally, a TLI stage must also be launched to ferry the propellant module out to lunar orbit. Therefore, anything gained by pre-deploying a reusable lander is counteracted by the addition of propellant launches to the depot and the production cost of more TLI stages.

The two architectures can also be compared in terms of capture percentage for a given ground infrastructure as the flight rate is varied. Figure 18 plots the mission capture percentage as a function of number of missions per year. As can be seen, for the ground infrastructure available, the expendable architecture achieves a higher capture percentage across all flight rates, since it requires fewer launches and fewer TLI stages (even though it requires more landers, but this does not produce a significant bottleneck).

For a given ground infrastructure, there is a maximum number of missions per year that can be achieved for each architecture. Therefore, as the desired number of missions per year increases, the actual number of missions flown will remain constant once the maximum is reached. This result is presented in Figure 19, which plots the actual number of missions achieved per year by each architecture. As expected from the above results, the expendable architecture is able to fly more missions. It plateaus around 2.4 missions per year, while the reusable architecture has a maximum of 1.8 missions per year for the given ground infrastructure.

4. CONCLUSIONS

The purpose of this study was to evaluate two representative lunar exploration architectures in terms of cost, reliability, and mission throughput. The primary trade study was to examine various combinations of launch vehicles for each architecture, based on current leading candidates for the planned lunar missions. The best option for the expendable architecture, based on an overall evaluation criterion including cost, reliability, and scheduling, was to use a man-rated version of an EELV for crew launches and a 100 mt heavy lift launch vehicle for cargo and propellant launches. The best option for the reusable architecture was to use the same man-rated EELV for crew and a 140 mt heavy lift launch vehicle for cargo and propellant. In general, the trade study showed that heavy-lift launch vehicles were favored, particularly for the cargo and propellant missions, since they required fewer launches per mission. The Shuttle-derived vehicles also did fairly well in terms of cost (not so for reliability), but these costs were based on pre-CAIB estimates. Therefore, if the actual Space Shuttle launch costs were to increase, the Shuttle-derived vehicles would become significantly less attractive from a cost-standpoint. The Existing Evolved Expendable Launch Vehicles also did very well in terms of cost, but because of the increased number of launches required, their loss of mission probability and scheduling metrics suffered. Unless the mass of the mission elements could be reduced, the only way to improve the scheduling metrics for the Existing EELVs would be to increase the number of launch pads available or to decrease the turn-around time of the pads. The loss of mission probability for the EELVs could be improved, however, by changing some of the mission assumptions. Instead of canceling a mission when a cargo launch fails, that element could simply be re-launched if an extra were kept available for such a situation. As a result, launch configurations requiring more cargo launches per lunar mission would not be penalized in terms of mission reliability simply because more launches are required. This change would make the Existing EELVs more competitive, albeit still worse than the HLVs for a given ground infrastructure due to their throughput capabilities. Therefore, it appears that investing in a heavy-lift launch vehicle would be beneficial. This of course assumes that the money is available up-front for the development of such a launch vehicle since their DDTE costs are much higher. If this were the case, it could save significant money down the road in terms of the lunar transportation costs.

Regardless of the launch option chosen, however, the expendable architecture appears to be favorable. Although the loss of mission probability decreases slightly in some cases for the reusable architecture, the life-cycle cost and cost per mission increase significantly. The transportation-related life-cycle and per mission costs range from $53B to $72B and from $2.9B to $3.9B for the expendable architecture. For the reusable architecture, they range from $86B to $137B and from $4.7B to $7.4B. As a point of comparison, Apollo cost $19.4B[6] over twelve years, which translated into 2005 dollars would cost approximately $68B. Apollo included seven attempted lunar landings (six of which were successful), while the baseline program for this study includes twenty attempted lunar landings over a 17-18 year program. Furthermore, the Apollo program cost not only includes the development, production, and operations costs associated with the transportation elements, but also includes costs associated with other program aspects that are not modeled in LASSO, such as science payloads and advanced technology development studies. Even the cheapest option for either launch architecture had a life-cycle cost of $53.3B for just the transportation elements. When the remaining programs are included, this cheapest option will begin to exceed the

Apollo program budget, albeit for more lunar missions. Even though more missions could be flown for around the same cost as the Apollo program, the budget is more restricted today than it was in the 1960's and 1970's. At its peak, Apollo spent $2.9B ($13.3B is 2005 dollars) in 1967, which comprised 70% of NASA's total budget [6]. The latest NASA budget request (FY 2006) allocates $3.16B per year to the Exploration Systems directorate, which is responsible for the human lunar exploration. This is only 19% of NASA's total budget, and yearly increases through FY 2010 are only planned to account for inflation [7]. Even considering only the transportation-related costs modeled in LASSO, the cheapest architecture option does not fit within NASA's current budget request. Reducing program costs, therefore, is of utmost importance in selecting a lunar transportation architecture.

In addition to transportation-related costs, the expendable architecture also has the added advantage of requiring less infrastructure investment for a given flight rate and launch option. Manufacturing capacities are not an important factor, since for the capacities required (less than five in all cases examined), it is assumed that the production facilities would be expanded to meet the required demand. More launch pads and launch vehicle integration facilities would have to be built however. Currently, the Shuttle has two available launch pads at KSC, and the Atlas V and Delta IV Heavies each have one at Cape Canaveral [8]. Additionally, if the flight rate were to be increased beyond the baseline of two missions per year, the reusable would be the first of the two architectures to require increased launch infrastructure beyond what is currently available.

The reliability of both architectures was also examined. In general, the loss of crew probability ranged anywhere from 0.058 to 0.113 per mission. This probability represents the entire mission, so it encapsulates the reliability of the launch vehicles, in-space propulsive stages, the lunar lander, and the CEV reentry. Statistically, a 5% LOC will result in one loss of crew event every twenty missions, which is the baseline number of missions for this study. The LOM numbers, of course, are higher, and range from 0.128 to 0.316. This implies that at best, approximately one in eight missions will be unsuccessful. As a comparison, Apollo had a loss of mission probability of 0.143 for the lunar landing missions, and even lower if the remaining Apollo missions are considered.

From this study and the assumptions it contains, it appears that the reusable architecture should not be chosen over the expendable architecture, regardless of the launch configuration. This is not necessarily the case for general reusable vs. expendable architectures. It is still expected that a reusable architecture could be designed that would perform better in terms of cost for higher flight rates, even if it still requires more infrastructure investment up-front. Several improvements could be made to the current architecture that should make it more competitive. In particular, there could be more flexibility in the choice of launch vehicles for the depot resupply launches or in the packaging of all the elements for those missions. Although this study did not do an extensive launch vehicle optimization, this could improve the attractiveness of the reusable architecture. For the specific architectures studied, however, the expendable architecture is superior, although reusable architectures should not be definitively eliminated as a viable option for sustained human lunar exploration. Further study into other reusable architectures would be required to ascertain their overall effectiveness.

Based on the LASSO results, several key conclusions can be drawn in regards to the architecture choices that must be made for human lunar exploration, as outlined below. It is important to remember that these conclusions are based on the architectures modeled and the mission and vehicle assumptions contained in this study.

(1) An expendable architecture is favored over a reusable architecture, based on cost, reliability, and scheduling figures of merit.

(2) Man-rated versions of Existing EELVs are most cost-effective for crewed launches.

(3) Expendable launch vehicles should be used for dedicated propellant launches (an RLV tanker was shown to not be cost effective).

(4) Heavy-lift launch vehicles are preferred for cargo and propellant launches, because of the fewer launches required per lunar mission.

These considerations are critical to establishing a cost-effective and sustainable human lunar exploration program. If only performance metrics are used during the conceptual stage of the design process, a program can run into budget and schedule problems down the road, when they will be more difficult and expensive to correct. Therefore the capability to evaluate space exploration architectures based on cost, reliability, and scheduling figures of merit will be essential to successfully implementing the President's Vision for Space Exploration through the next several decades.

NOMENCLATURE

CAIB – Columbia Accident Investigation Board

CEV – Crew Exploration Vehicle

DDTE	Design, Development, Test, & Evaluation
EELV	Evolved Expendable Launch Vehicle
HLV	Heavy-Lift Launch Vehicle
LASSO	Lunar Architecture Stochastic Simulator and Optimizer
LOC	Loss of Crew
LOM	Loss of Mission
OEC	Overall Evaluation Criterion
RLV	Reusable Launch Vehicle
TEI	Trans-Earth Injection
TLI	Trans-Lunar Injection

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BIOGRAPHY

Kristina Alemany *is a graduate research assistant in the Space Systems Design Lab at Georgia Tech in Atlanta, GA. Her research thus far has focused on the conceptual-level modeling and simulation of lunar transportation architectures. She is currently working towards her PhD in Aerospace Engineering, focusing on lunar trajectory design and analysis. She received her M.S. in Aerospace Engineering from Georgia Tech and her B.S.E. in Mechanical and Aerospace Engineering from Princeton University. She has spent summers working at NASA Langley in Hampton, VA and Lockheed Martin in Littleton, CO. Kristina originally hails from Briarcliff Manor, NY*

APPENDIX

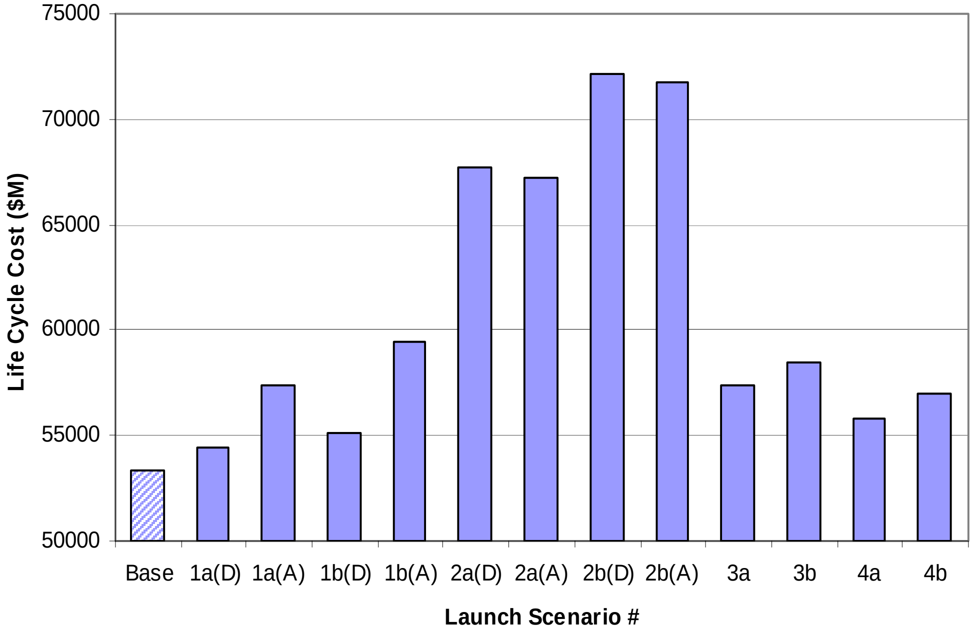

Figure 3 – Life Cycle Cost for Launch Vehicle Trade Study (Expendable Architecture)

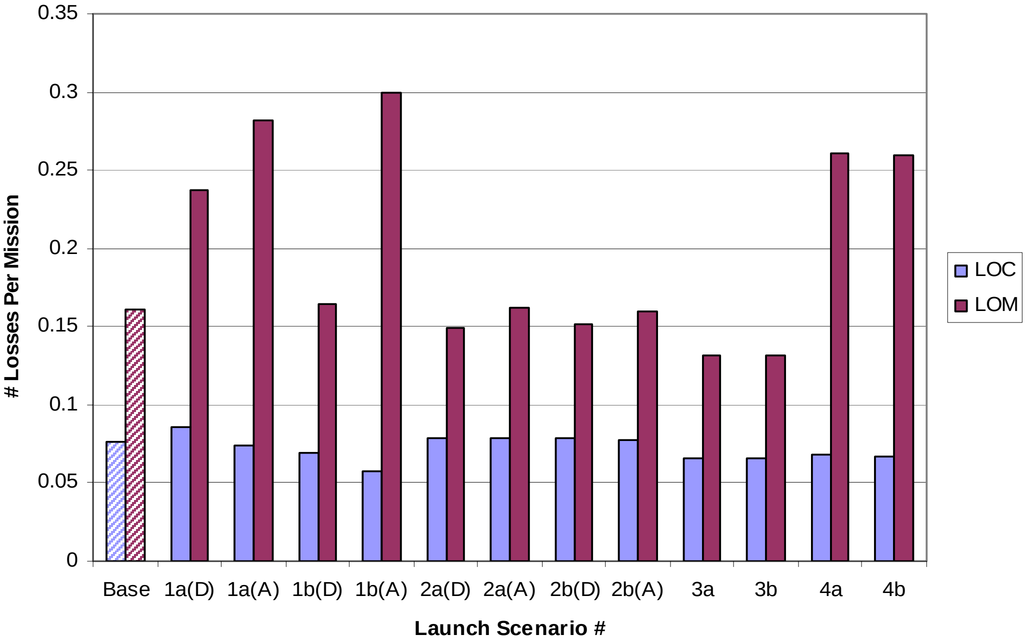

Figure 4 – Reliability for Launch Vehicle Trade Study (Expendable Architecture)

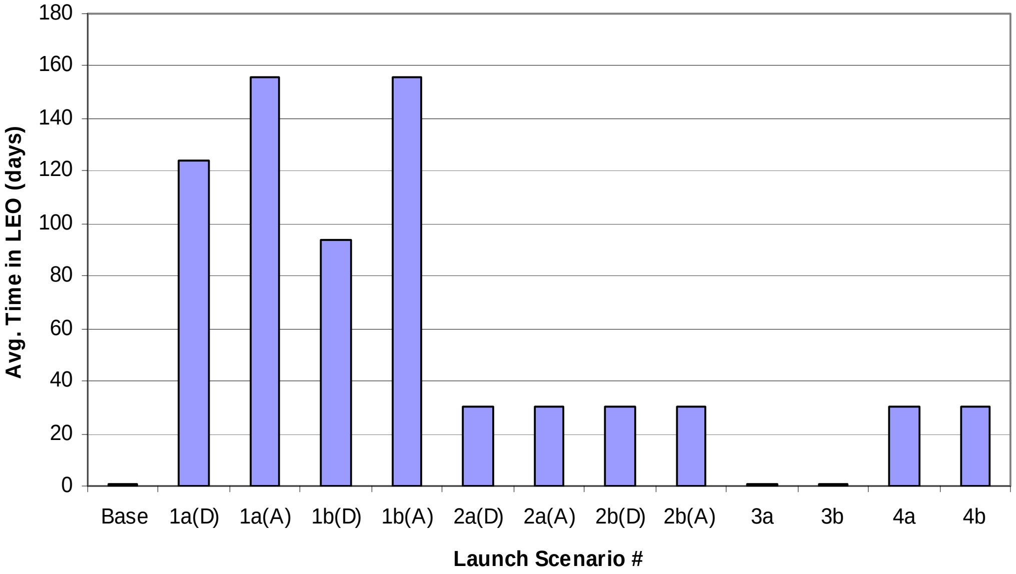

Figure 5 – Average Time in LEO for Launch Vehicle Trade Study (Expendable Architecture).

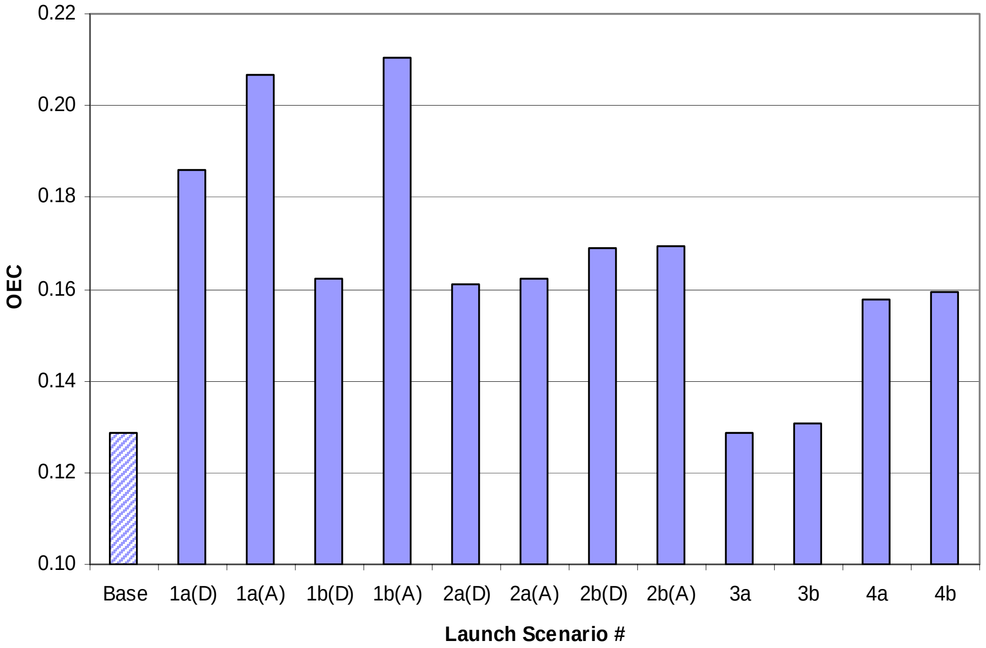

Figure 6 – Overall Evaluation Criterion (Cost, Reliability, and LEO Time) for Launch Vehicle Trade Study (Expendable Architecture)

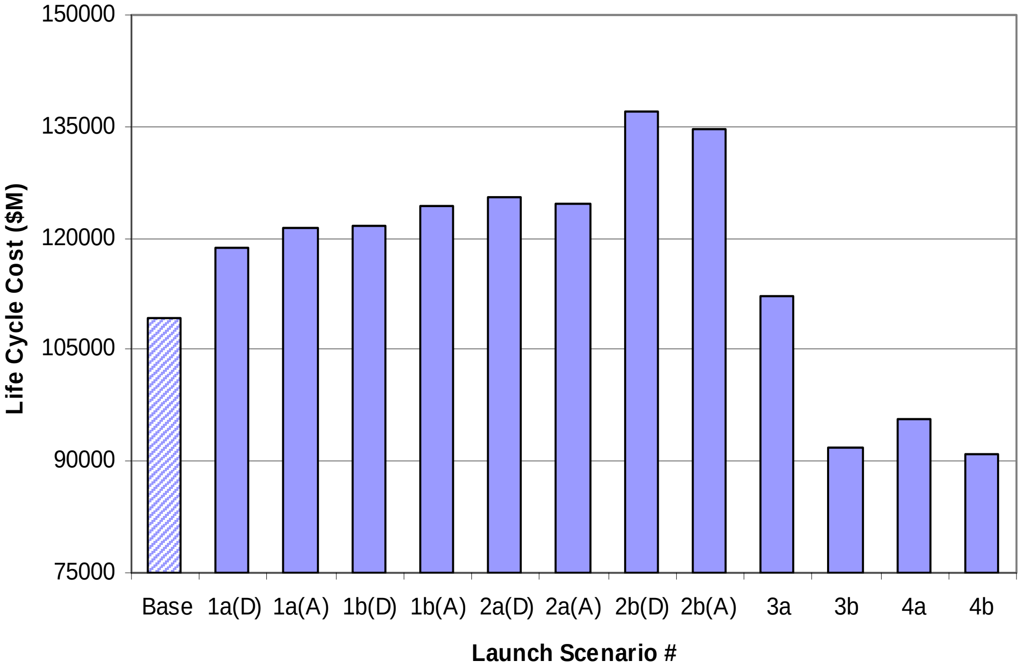

Figure 7 – Life Cycle Cost for Launch Vehicle Trade Study (Reusable Architecture)

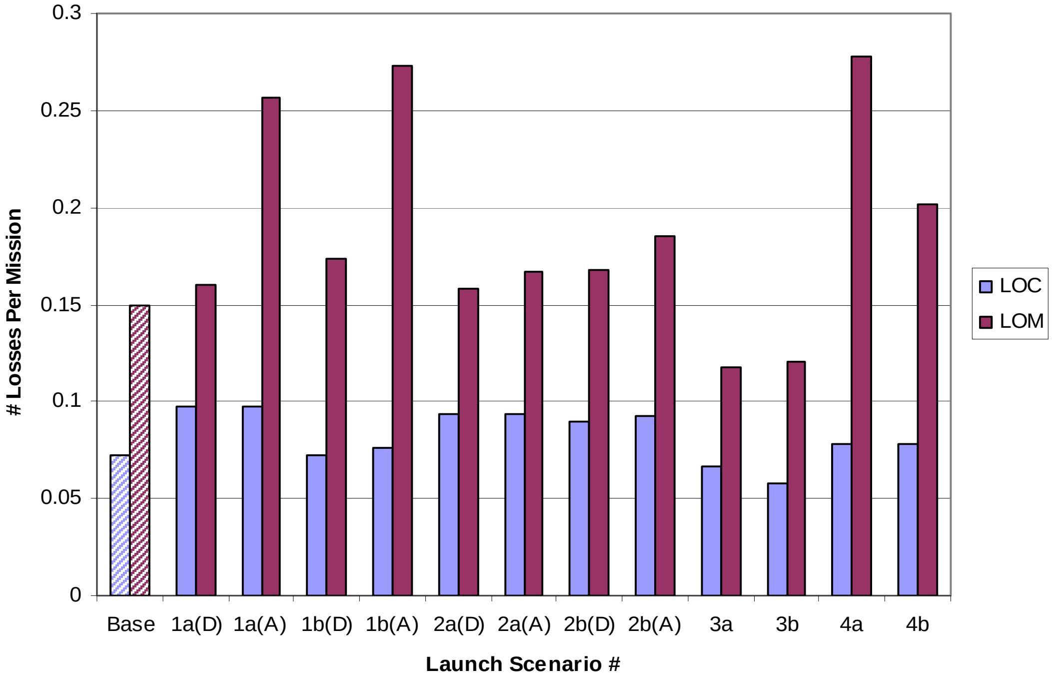

Figure 8 – Reliability for Launch Vehicle Trade Study (Reusable Architecture)

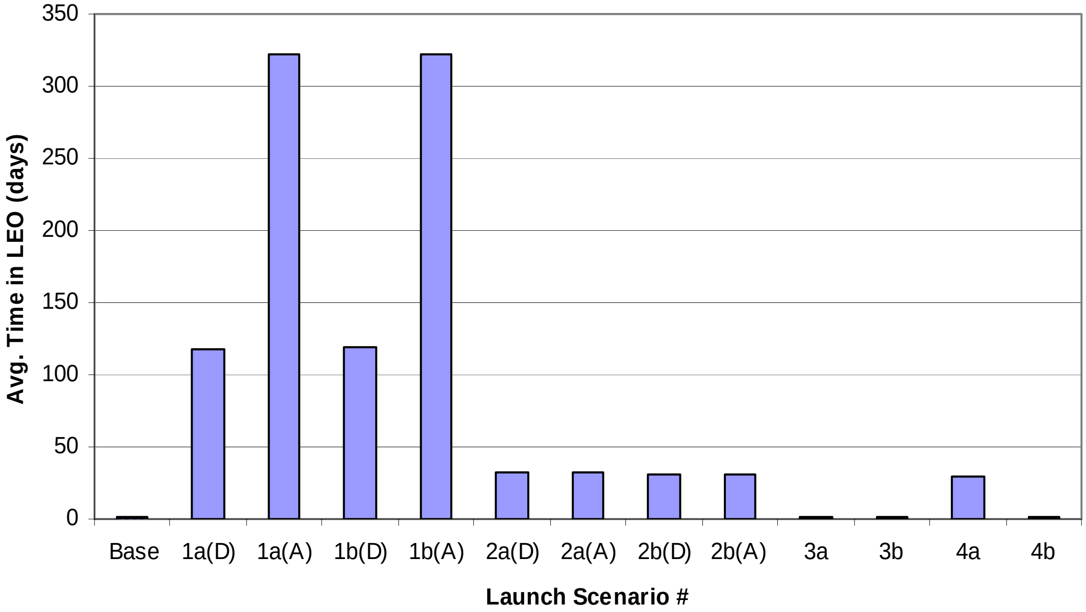

Figure 9 – Average Time in LEO for Launch Vehicle Trade Study (Reusable Architecture).

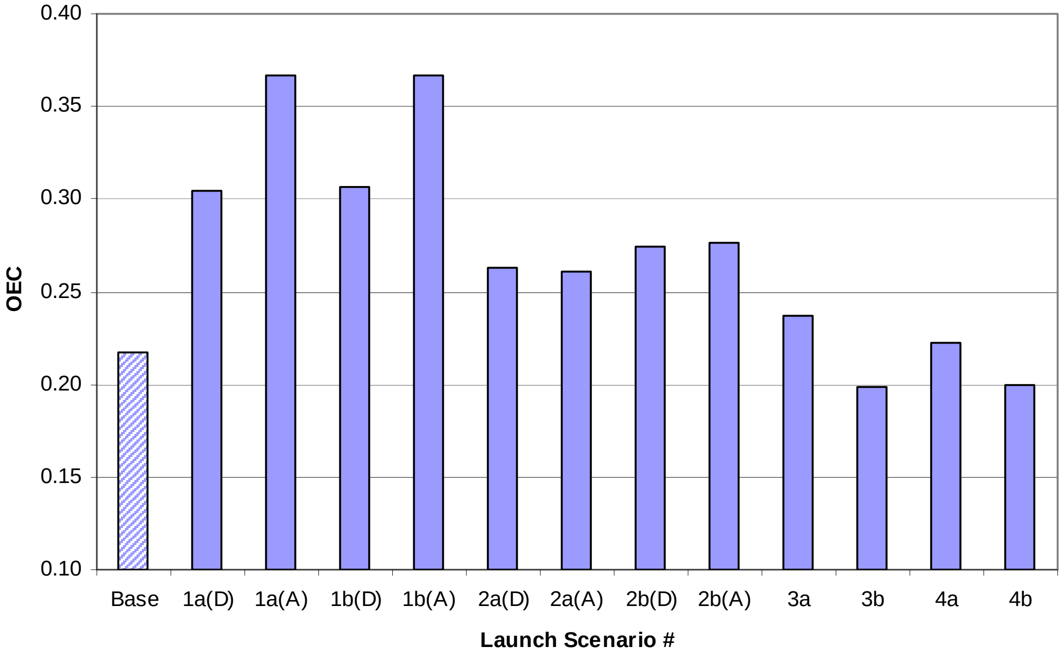

Figure 10 – Overall Evaluation Criterion (Cost, Reliability, and LEO Time) for Launch Vehicle Trade Study (Reusable Architecture)

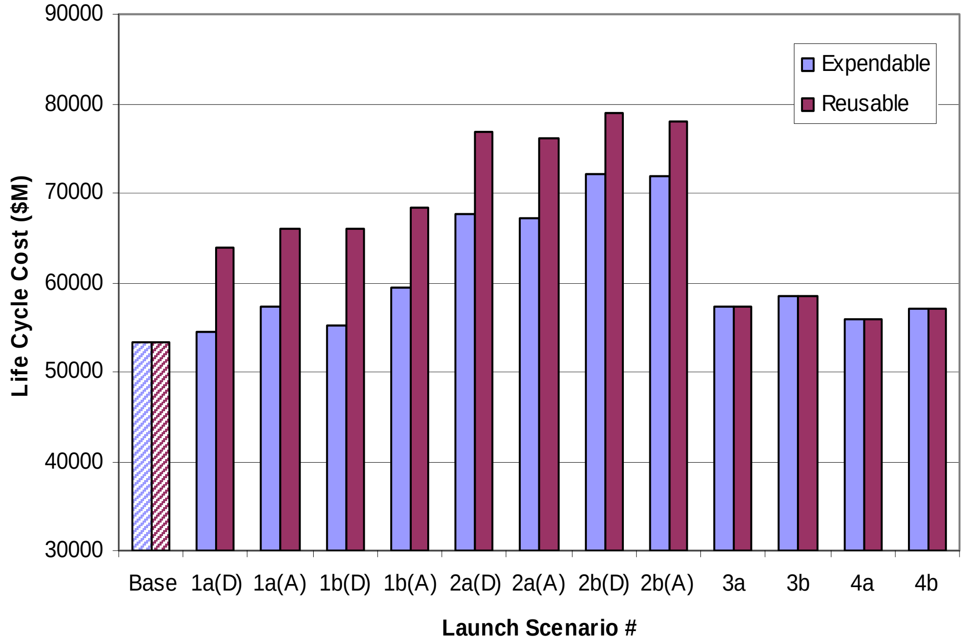

Figure 11 – Expendable vs. Reusable Launch Vehicle Trade for Propellant Launches (Expendable Architecture)

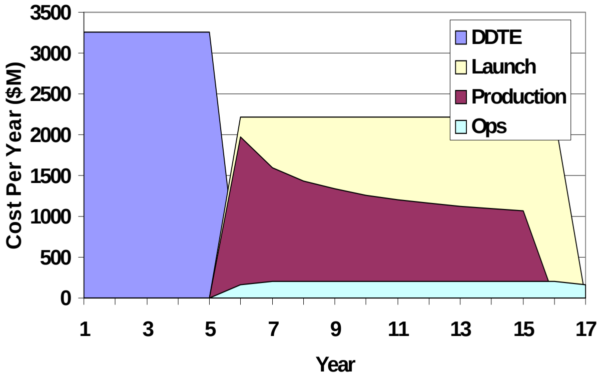

Figure 12 – Annual Costs for Expendable Architecture using Baseline Launch Configuration

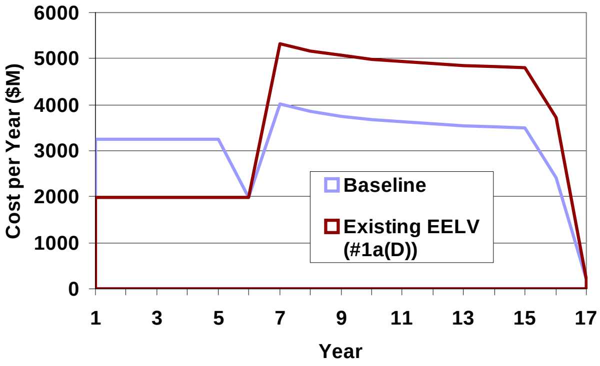

Figure 13 – Annual Costs for Expendable Architecture Comparing Baseline Launch Option and #1a(D)

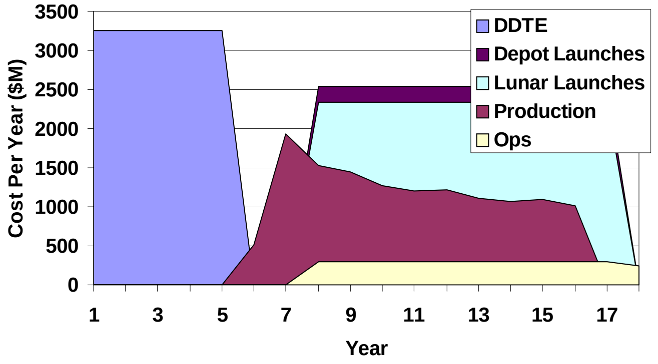

Figure 14 – Annual Costs for Reusable Architecture using Baseline Improved Launch Configuration

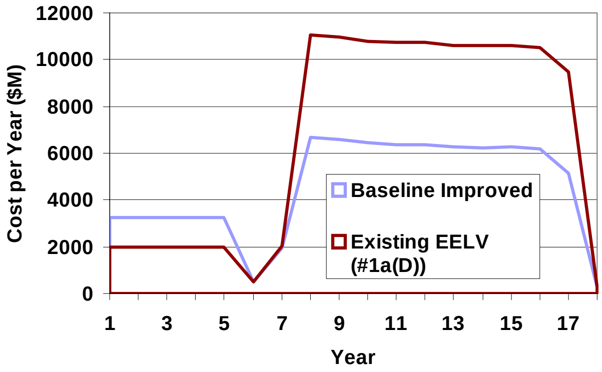

Figure 15 – Annual Costs for Reusable Architecture Comparing Baseline Improved Launch Option and #1a(D)

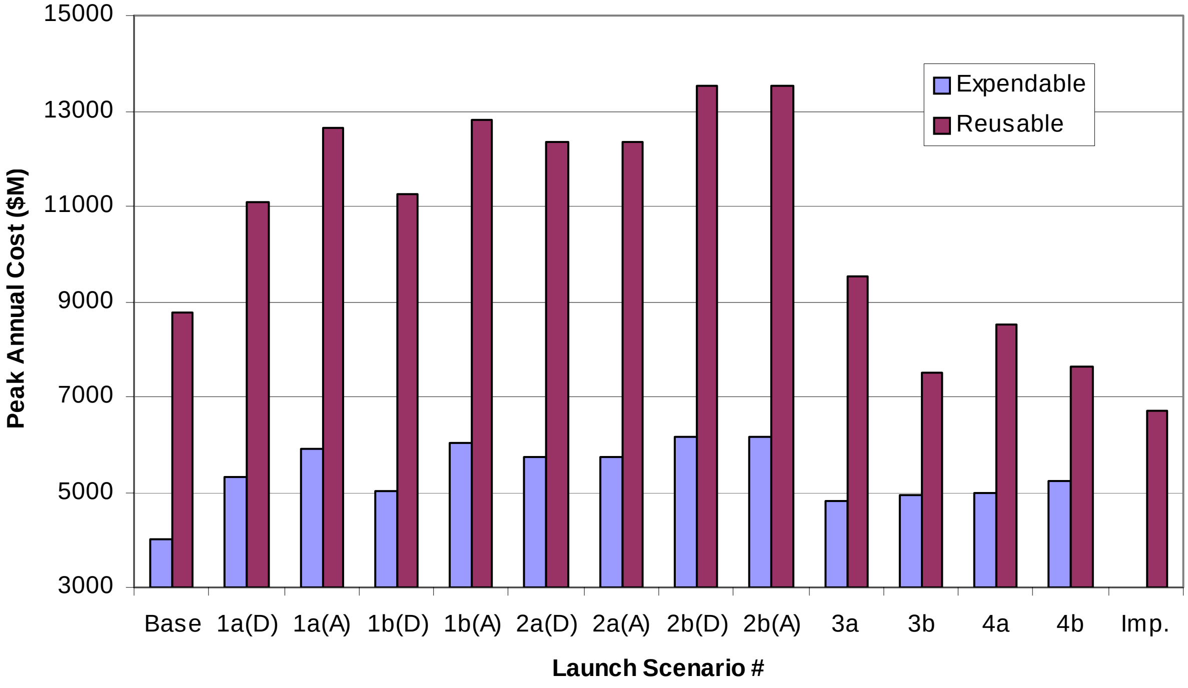

Figure 16 – Peak Annual Cost for Expendable and Reusable Architecture

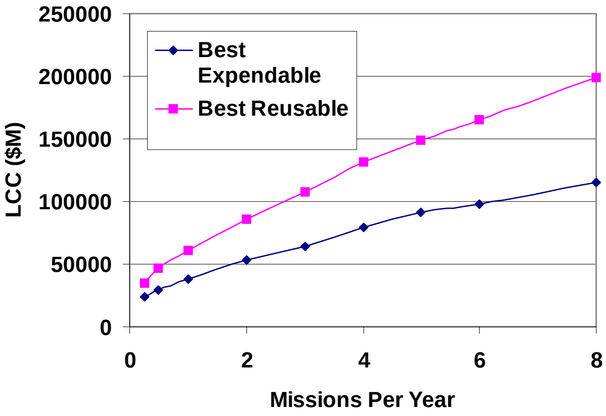

Figure 17 – Life Cycle Cost as a Function of Annual Flight Rate

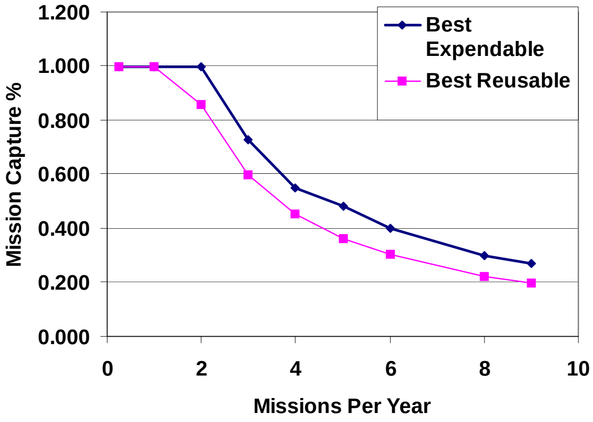

Figure 18 – Mission Capture Rate as a Function of Annual Flight Rate

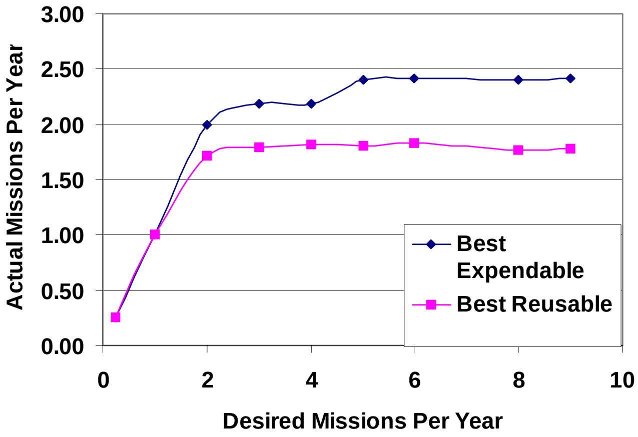

Figure 19 – Actual Number of Missions per Year as a Function of Desired Annual Flight Rate