Launch Order, Launch Separation, and Loiter in the Constellation 1½-Launch Solution

Chel Stromgren, Grant Cates
Science Applications International Corporation
1710 SAIC Drive
McLean, VA 22102
703-676-6379 / 407-694-0899
chel.stromgren@saic.com / grant.r.cates@saic.com

William Cirillo
NASA Langley Research Center
1 North Dryden Blvd., MS462
Hampton, VA 23681
757-864-1938
william.m.cirillo@nasa.gov

Abstract—The NASA Constellation Program (CxP) is developing a two-element Earth-to-Orbit launch system to enable human exploration of the Moon. The first element, Ares I, is a human-rated system that consists of a first stage based on the Space Shuttle Program's solid rocket booster (SRB) and an upper stage that consists of a four-crew Orion capsule, a service module, and a Launch Escape System. The second element, Ares V, is a Saturn V-plus category launch system that consists of the core stage with a cluster of six RS-68B engines and augmented with two 5.5-segment SRBs, a Saturn-derived J-2X engine powering an Earth Departure Stage (EDS), and the lunar-lander vehicle payload, Altair.[1,2]

Initial plans called for the Ares V to be launched first, followed the next day by the Ares I. After the EDS performs the final portion of ascent and subsequent orbit circularization, the Orion spacecraft then performs a rendezvous and docks with the EDS and its Altair payload. Following checkout, the integrated stack loiters in low Earth orbit (LEO) until the appropriate Trans-Lunar Injection (TLI) window opportunity opens, at which time the EDS propels the integrated Orion–Altair to the Moon.

Successful completion of this "1½-launch" solution carries risks related to both the orbital lifetime of the assets and the probability of achieving the launch of the second vehicle within the orbital lifetime of the first. These risks, which are significant in terms of overall system design choices and probability of mission success, dictated a thorough re-evaluation of the launch strategy, including the order of vehicle launch and the planned time period between launches.

The goal of the effort described in this paper was to select a launch strategy that would result in the greatest possible expected system performance, while accounting for launch risks and the cost of increased orbital lifetime.

A Discrete Event Simulation (DES) model of the launch strategies was created to determine the probability of a second launch not occurring in a timely fashion (i.e., before the assets waiting in LEO expire). This data was then used, along with vehicle capability data, cost data, and design changes that increased loiter, to evaluate the impact of changes in strategy. The specific changes in strategy that were considered include decreasing the planned time between launches from 24 hours to 90 minutes, changing the launch order, and varying the LEO loiter capacity of the EDS and Orion systems.

An overview of the launch strategy evaluation process is presented, along with results of specific cases that were analyzed. A high-level comparison of options is then presented, along with the conclusion derived from the analysis.

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[2] IEEEAC paper #1314, Version 3, Updated December 30, 2008.

1. INTRODUCTION

The Constellation architecture that is being developed by NASA for crewed human lunar missions involves two independent launches from the Earth with a rendezvous in low Earth orbit (LEO). The Ares I vehicle launches the Orion crew vehicle into LEO, and the Ares V launches the Earth Departure Stage (EDS) and the Altair lunar lander into orbit. The Orion vehicle and the EDS-Altair stack rendezvous in LEO before performing a Trans-Lunar Injection (TLI) burn. This launch architecture is referred to as a "1½-launch" solution because of the relative size of the Ares I to the Ares V.

The 1½-launch solution imposes additional constraints on human lunar missions over a single launch scenario. The primary constraint involves the requirement for a LEO rendezvous between the two vehicles and the lifetimes of the elements in LEO. The Orion has a capability to loiter in LEO for a maximum of four days, limited by consumables. The EDS will have a maximum LEO loiter duration that is set by the amount of excess liquid oxygen and liquid hydrogen propellant that is available to account for the boil-off that occurs during LEO loiter. These maximum loiter durations for the Orion and EDS require that the two launches will have to occur within some discrete time period in order to support rendezvous and a successful lunar mission.

Three factors will have a major impact on the probability of success of conducting both launches in the available time period: the order that the vehicles are launched in, the maximum LEO loiter duration of the Orion and the EDS, and the separation time between the two launches.

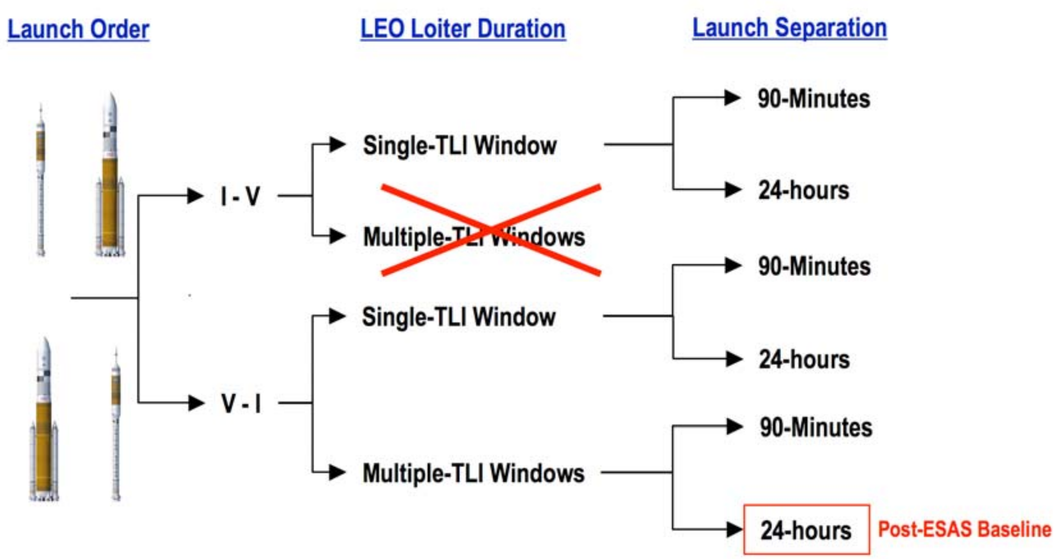
NASA completed a study to address the operational issues surrounding the 1½-launch solution and to compare various options for launch operations. The ultimate goal was to develop a "point-of-departure" operational launch option that would maximize the expected performance of the transportation system. Options were evaluated for launch order of the vehicles, loiter duration in LEO of the Orion and EDS, and the time separation between launches.

The options that were evaluated are depicted as a trade tree in Figure 1. Two options were considered for launch order: launching Ares I first, followed by Ares V, identified as "I-V"; and launching Ares V first, followed by Ares I, identified as "V-I". In addition, two types of LEO loiter duration were considered. The first loiter option was to support only a single TLI window. The second loiter option was to support multiple TLI windows. Because of the limited loiter duration of the Orion crew module in LEO, the option to support multiple TLI windows is applicable only to a V-I launch order. Finally, options for the planned separation between the two launches of 90-minutes and 24-hours were evaluated. The baseline established after the Exploration System Architecture Study (ESAS) of a V-I launch order, a loiter duration that supports multiple TLI windows, and a launch separation of 24-hours is identified in Figure 1.

The selection of a point-of-departure does not represent the final determination of a launch option for the Constellation architecture. Rather, the point-of-departure represents a baseline from which on going lunar mission studies will be conducted. The baseline architecture may be changed in the future as further studies or revised data warrant.

2. BACKGROUND

The basic Constellation transportation architecture was initially defined as part of the ESAS [1] and in efforts immediately following that study [2]. As part of the baseline option developed at that time, it was assumed that the Ares



V heavy launch vehicle would launch first, with a capability to loiter for up to 95 days in LEO. The Ares I and Orion would then nominally launch 24 hours later and rendezvous with the EDS and lunar lander. If the Ares I failed to launch 24 hours later, multiple relaunches could be attempted over the remainder of the 95-day loiter period, covering multiple TLI opportunities. The 95-day loiter period was selected to ensure that the crew could launch before the EDS operational lifetime expired.

During subsequent design iterations of the transportation elements, a number of factors were identified that called the initial baseline launch option assumptions into question. The primary issue revolved around the ability of the EDS to provide for a 95-day LEO loiter. As the EDS orbits the Earth and is heated by the sun, the cryogenic fuel within the EDS tanks boils off at a rate of approximately 40 kg per day. In order to reserve a sufficient amount of fuel for the lunar mission, either the boil-off gasses must be reliquefied and returned to the tanks, or the boil-off must be vented and an additional amount of fuel carried to account for lost propellant.

However, both of these solutions would have severe adverse impacts to the overall transportation architecture. With no re-liquefaction, the mass of extra propellant required to achieve a 95-day loiter capability would be at least 3,800 kg. In addition, added mass penalties would be incurred for extra tank volume to hold the additional propellant. Because the total launch capability of the Ares V to LEO is limited, launching additional EDS propellant directly reduces the effective cargo at LEO. This, in turn, will limit the total lander mass, and the mass delivery capacity to the lunar surface.

In addition, long loiter periods would result in a substantial increase in the complexity and dry mass of the EDS. Photovoltaic arrays would be required for power generation, reboost would be required, and additional micrometeoroid/orbital debris (MMOD) protection might be needed. None of the selected Ares V launch vehicle options could support an EDS with a 95-day loiter and a viable lunar lander.

Reliquefaction of the boil-off would significantly reduce the need to carry additional propellant. However, the reliquefaction equipment would add additional mass to the EDS, similarly limiting lunar lander performance. Initial estimates for a reliquefaction system indicated that the mass could be similar to or greater than that of the additional 95 days of propellant. In addition, the technology readiness level (TRL) of this technology is relatively low, and a major development effort would be required to include such a system on the EDS. For these reasons, reliquefaction was not investigated as a final solution. However, note that design reference missions for Constellation-based crewed Mars missions require a significant number of Ares V launches over an extended time period. So, ultimately, this type of technology may be required to support future exploration activities.

Other issues regarding the operational concept for the 1½-launch solution were also raised in the design iterations that followed ESAS. The time separation between the two launches was also identified as an important parameter. Analysis showed the probability of no second launch (PnSL) increased significantly as the period between launches increased, whereas a lower PnSL is desirable. This increase is primarily due to the possibility of weather or sea state change to unfavorable conditions in the interim period but is also impacted by possibility of a failure on the second vehicle during the separation period. The 24-hour launch separation that was identified as part of the initial architecture could result in a relatively high probability of no second launch.

The final issue that was identified concerned the launch order of the Ares V and the Ares I and the difference in the consequences of a missed launch between the launch orders. For the baseline option, with the Ares V launching first, referred to as V-I in the analysis, a failure to launch the Ares I within the LEO duration of the EDS would result in the loss of the EDS and the Altair lander. Each of those elements would have to be replaced to re-fly the mission. The Ares V and the Altair are the most expensive elements in the transportation system. This type of loss would represent a large fraction of the total transportation element cost. In addition, concerns were voiced that the loss of an Ares V and Altair could impose substantial delays in establishing a permanently crewed lunar outpost.

An alternate option, reversing the launch order, with the crewed Ares I launching first and the Ares V launching second, is referred to as I-V in this analysis. If the Ares V was not launched in time, the crew would be forced to return directly to Earth. In this case, an Ares I and an Orion service module would have to be replaced, and the Orion crew module would have to be refurbished in order to re-fly a mission. This type of loss would carry significantly less replacement cost than in the V-I option.

The difference in consequence between the two options brought into question the baseline launch order. Although there is a strong initial reaction that it is most appropriate to launch the Ares V first so as not to risk the crew until the EDS and the lander are safely in orbit, the stark difference in consequence for these two options indicated that it might be preferable to reverse the launch order, launching the crew in the Ares I first and then launching the Ares V. In this case, the Ares V/EDS/Altair stack would not be lost if the Ares I could not be launched in time. Of course, in this case, the crew would be exposed to additional risk if the mission has to be repeated due to a missed second launch.

The study that is described in this paper was intended to address the operational issues surrounding the 1½-launch solution and to compare various options for launch operations. The goal of the effort was to develop an updated concept for 1½-launch operations that would balance the PnSL, the consequence of no second launch, and any added risk to the crew. The operational concept would include the order of vehicle launch, the planned separation between the launches, and the loiter periods for the Orion and the EDS. Orion loiter periods were limited to four days, as dictated by the current Orion design.

Note that the updated operational concept for the 1½-launch option that was developed as a result of this effort is used only as a current reference. NASA is still leaving open the option to change the operational concept as more data become available or to develop a system that is capable of supporting multiple operational concepts, including launch order.

3. Launch Opportunities and TLI Windows

The baseline separation between the launch of the two vehicles was originally set at 24 hours. This separation allows the second vehicle to launch as the first passes over on the same approximate launch orbit one day later. Other launch options include a 90-minute separation, where the second vehicle would launch to meet the first after it has completed its first orbit, and any increment of 24 hours. For the purposes of this effort, only planned launch separations of 24 hours and 90 minutes were investigated. Separations of greater than 24 hours would only compound issues regarding weather and sea state change.

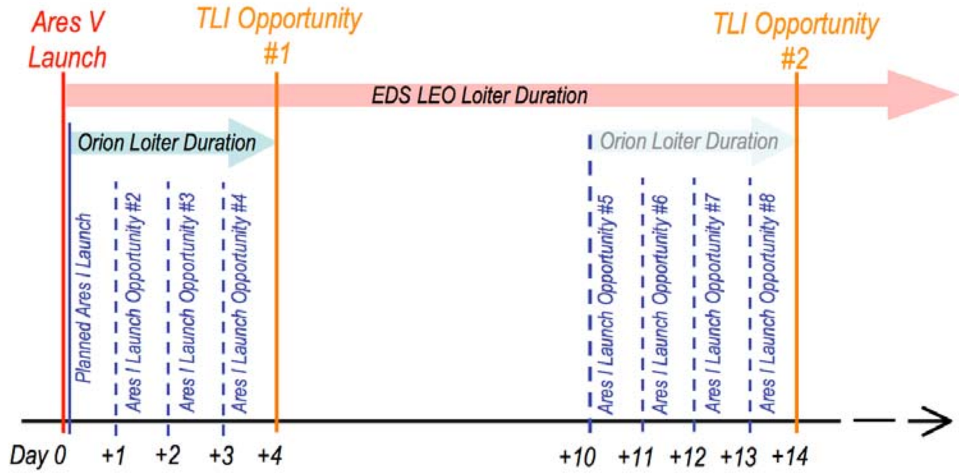
The options available for the two-launch operational concept are limited by the timing of opportunities for TLI. The TLI opportunities for a particular lunar site occur at average intervals of approximately 9-10 days. The combined EDS/Altair/Orion stack must depart within a limited time window at TLI. The actual intervals vary somewhat from this average based on orbital mechanics. However a limited number of TLI opportunities occur at spacings greater than 10 days.

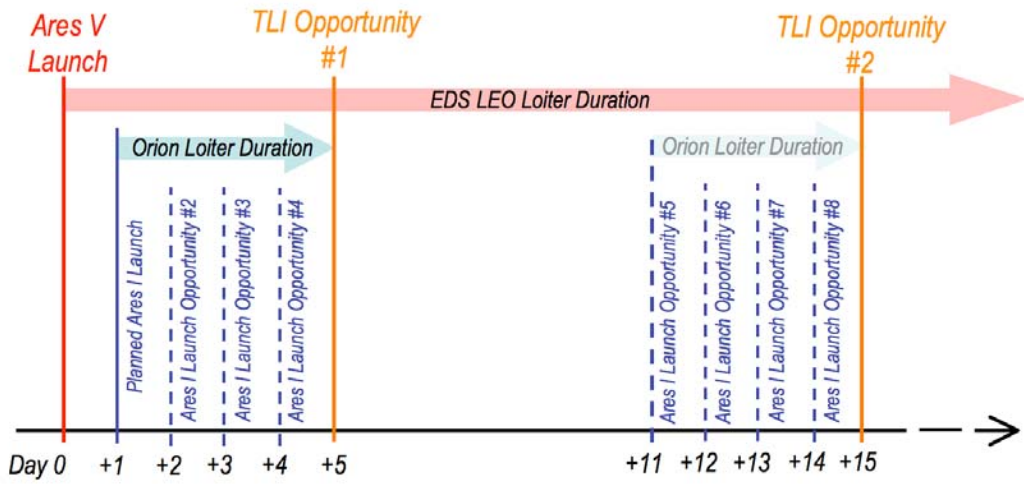
The spacing of TLI opportunities limits the set of loiter periods that would be effective for both the Ares V and the Orion. In the baseline V-I option, the Ares V would be launched five days before a TLI opportunity. The Ares I launch would then be initially planned for 24 hours later, four days before the TLI opportunity. If that launch failed to occur, three more Ares I launch opportunities would occur at 24-hour intervals before the TLI opportunity. If the Ares I failed to launch on any of those attempts, additional 4-day launch opportunities would be available prior to each TLI opportunity. These Ares I launch opportunities would be available for the duration of the Ares V loiter capability. The spacing of launch opportunities for the V-I launch order with 90-minute and 24-hour separation are further described in Figures 2 and 3, respectively.

Options for alternate Ares V loiter capability in the V-I order are dependent on the 10-day TLI interval. The lowest possible Ares V loiter that would be viable, with a 24-hour separation between launches, would be five days. That separation would provide for four Ares I launch attempts for a single TLI opportunity. Viable loiter durations would then increase in increments of 10 days, with each increment providing an additional four Ares I launch attempts. If the launch separation is decreased to 90 minutes, then each of the loiter periods would be deceased by one day, with a 4-day minimum and added increments of 10 days.

In a I-V option, the loiter duration of the Orion limits the launch attempts. In this option, the Ares I would always launch four days prior to the TLI opportunity. With a 90-minute separation between launches, the Ares V would attempt to launch on the next orbit. If that launch did not occur, then the Ares V could attempt to launch on additional three opportunities at 24-hour intervals prior to the TLI opportunity, for a total of four possible attempts. If the launch separation was 24 hours, then three possible launch attempts would occur for the Ares V. In either case, if the Ares V could not launch by the TLI opportunity, then the crew would have to return to Earth. Utilizing more than a single TLI opportunity is not possible in the I-V option. The spacing of launch opportunities for the I-V launch order with 90-minute and 24-hour separation is further described in Figures 4 and 5, respectively.

A loiter period of less than four days is also possible for either launch order. As part of this analysis, for the V-I launch order, EDS loiter periods of 1-4, 14, and 24 days were considered for the 90-minute launch separation, and 2-5, 15, and 25 days were considered for the 24-hour separation. For the I-V launch order, a 4-day loiter was used for Orion, which corresponds to a 4-day EDS loiter at 90-minutes separation and a 3-day EDS loiter at 24-hours separation. Table 1 details the full set of launch variables that were investigated as part of this study.


Ares V Launch
TLI Opportunity #1
TLI Opportunity #2
EDS LEO Loiter Duration
Orion Loiter Duration
Orion Loiter Duration
Planned Ares I Launch
Ares I Launch Opportunity #2
Ares I Launch Opportunity #3
Ares I Launch Opportunity #4
Ares I Launch Opportunity #5
Ares I Launch Opportunity #6
Ares I Launch Opportunity #7
Ares I Launch Opportunity #8
Day 0 +1 +2 +3 +4 +10 +11 +12 +13 +14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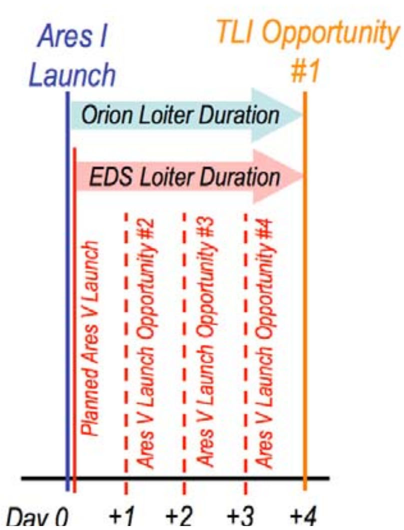
Ares I Launch Opportunity #3
Ares I Launch Opportunity #4
Ares I Launch Opportunity #5
Ares I Launch Opportunity #6
Ares I Launch Opportunity #7
Ares I Launch Opportunity #8
Day 0 +1 +2 +3 +4 +5 +11 +12 +13 +14 +15


Ares I Launch
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Ares V Launch Opportunity #3
Ares V Launch Opportunity #4
Day 0 +1 +2 +3 +4

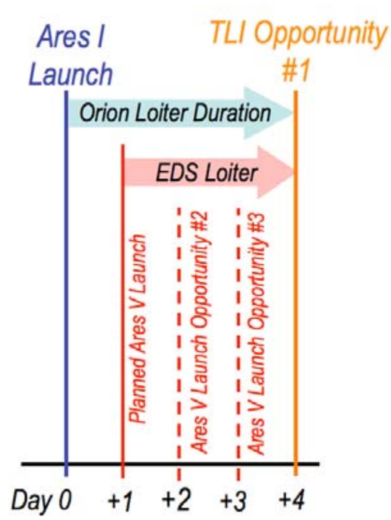
Ares I Launch
TLI Opportunity #1
Orion Loiter Duration
EDS Loiter
Planned Ares V Launch
Ares V Launch Opportunity #2
Ares V Launch Opportunity #3
Day 0 +1 +2 +3 +4

Table 1. 1½-Launch Options

Launch Order	Launch Separation	Orion LEO Loiter	EDS LEO Loiter	Launch Opportunities for Second Vehicle
V-I	24-Hour	1 Day	2 Days	1
		2 Days	3 Days	2
		3 Days	4 Days	3
		4 Days	5 Days	4
		4 Days	15 Days	8
		4 Days	25 Days	12
	90-Minute	1 Day	1 Day	1
		2 Days	2 Days	2
		3 Days	3 Days	3
		4 Days	4 Days	4
		4 Days	14 Days	8
		4 Days	24 Days	12
I-V	24-Hour	2 Days	1 Day	1
		3 Days	2 Days	2
		4 Days	3 Days	3
	90-Minute	1 Day	1 Day	1
		2 Days	2 Days	2
		3 Days	3 Days	3
		4 Days	4 Days	4

For all of the cases that were evaluated as part of this study, the assumption was made that both launch vehicles would be fully prepped and ready to fly on separate launch pads before the first vehicle would be launched. In addition, the assumption was made that the weather and sea state forecasts would support the launch of both vehicles. If either vehicle suffered a technical problem or if weather or sea state forecasts did not support the launch of both vehicles, then the entire launch process would be delayed until a later opportunity.

4. PREDICTION OF PNSL

PnSL was determined by using a discrete event simulation model called Constellation-Requirement Assessment Simulation Technique (C-RAST), which was built using Rockwell Automation's Arena simulation software. C-RAST models the launch countdown for the integrated Ares I–Orion vehicle and the integrated Ares V–Altair vehicle. C-RAST is an updated version of the Constellation-Manifest Assessment Simulation Technique [3].

The C-RAST model begins at the point in time at which both vehicles are ready to begin launch countdown on their respective launch pads. C-RAST progresses through an approximate two to three day countdown with the possibility of launch delays occurring at discrete points along the countdown. These discrete points were identified based on the points at which launch vehicles such as the space shuttle and the Delta II experience launch countdown delays. These points include management reviews at two days prior to launch and one day prior to launch, at a decision point on whether or not to commit to loading the cryogenic propellants, at the propellant loading phase, at post-propellant loading operations including crew insertion, at the final management decision to commit to launch, and at terminal countdown operations.

The probabilities of a launch delay occurring at these discrete points was determined after reviewing space shuttle and Delta II historical data and then filtering that data based on the differences between those launch vehicles and the Constellation vehicles. Sources of potential delays include vehicle malfunctions, weather, and sea state. Subject matter experts provided information that was also considered in developing the delay probabilities. The duration of a delay is modeled as a probability distribution by using a combination of space shuttle and Delta II historical data. Separate distributions were created to correspond to the type of delay. For example, weather delays tend to be one day in duration, whereas flight hardware delays tend to be longer.

Table 2 shows the PnSL values for the V-I launch order with 90-minute and 24-hour separation for 4, 5, 14, and 15 days of EDS LEO loiter capacity, respectively. Maximum Orion loiter capacity was assumed to be fixed at approximately four days.

Table 2. PnSL in V-I Launch Order

Launch Separation	Orion LEO Loiter	EDS LEO Loiter	PnSL
24-Hour	1 Day	2 Days	26.9%
	2 Days	3 Days	22.9%
	3 Days	4 Days	16.9%
	4 Days	5 Days	14.1%
	4 Days	15 Days	5.5%
	4 Days	25 Days	4.0%
90-Minute	1 Day	1 Day	8.7%
	2 Days	2 Days	6.8%
	3 Days	3 Days	5.9%
	4 Days	4 Days	4.7%
	4 Days	14 Days	1.9%
	4 Days	24 Days	1.2%

Similarly, Table 3 shows the PnSL data for the I-V launch order with 90-minute and 24-hour separation. Due to the 4-day loiter limitation of the Orion, cases with greater loiter duration for the EDS are not applicable because the Orion is placed in orbit first.

Table 3. PnSL in I-V Launch Order

Launch Separation	Orion LEO Loiter	EDS LEO Loiter	PnSL
24-Hour	2 Days	1 Day	20.8%
	3 Days	2 Days	15.3%
	4 Days	3 Days	13.0%
90-Minute	1 Day	1 Day	10.8%
	2 Days	2 Days	8.1%
	3 Days	3 Days	7.0%
	4 Days	4 Days	5.4%

5. VEHICLE AND ELEMENT COSTS

A major factor that was considered in the analysis of the 1½-launch operational concepts is the relative cost of the transportation elements. If a significant disparity exists between the costs of an Ares I stack and an Ares V stack, then the total risks should be evaluated rather than just focusing on the probability of failure.

Costs estimates were developed for each of the relevant transportation elements based on data provided from the project offices. For the Ares I, the Ares V, and the Orion service module, the marginal unit costs were used as an estimate for the per-unit replacement cost. Because a large number of these elements will be used over the course of the ISS and lunar programs, these elements were assumed to be assembly-line-type items. If a replacement unit were needed, the next unit off of the line could be used. No significant added fixed costs were assumed for acquiring an additional unit. For the Ares V, cost estimates were developed for two different options. The baseline architecture assumes that the 51.0.48 option [4] is used for the Ares V. This option represents the current baseline Ares V configuration for the Constellation Program. However, this option is limited to a 71.1 t capability to LEO. Certain launch options may require increased Ares V capability, which would dictate an upgrade to the 51.0.47 option with a capability of 74.7 t to LEO.

For the Orion crew module, the marginal cost of refurbishment was used. Again, no added fixed costs were assumed to be necessary to refurbish an additional unit.

For the Altair lunar lander, both fixed and marginal costs per unit were used for the analysis. Because the number of Altair landers is expected to be relatively limited and many components may be procured as fixed unit purchases up front, the production of an additional lander may require a substantial fraction of the fixed costs to be incurred in order to resume production. However, the total fraction of the fixed costs that would be incurred is unclear. For the purposes of comparing the 1½-launch options, the full fixed and marginal costs were used. However, a sensitivity analysis was also completed over a range of Altair costs with the marginal cost only representing the low end and the full cost representing the high end.

For presentation in this report, all cost data has been normalized to the cost of Ares I stack equivalents. Actual cost estimates were used in the comparison of options for the decision makers. However, because the primary cost issue reflects the relative difference in cost between the Ares I and the Ares V stacks, the normalization of the cost data does not impact the analysis or the results presented in this paper. All costs were normalized by the cost of an Ares I stack, which included the cost of the Ares I crew launch vehicle, the Orion service module, the Launch Escape System, and the refurbishment of the Orion crew module. All costs are, therefore, presented as Ares I stack equivalents, or AI. These figures reflect the relative cost of each transportation element as compared with the cost of an Ares I stack. Table 4 details the cost data used for this analysis.

Table 4. Replacement Cost Estimates for Transportation Elements

Element	Per Unit Cost (Ares I Stack Equiv.)
Ares I – Marginal Cost	0.40 AI
Orion SM & CM Refurbishment – Marginal Cost	0.60 AI
Ares V (51.0.48) – Marginal Cost	0.90 AI
Ares V (51.0.47) – Marginal Cost	1.13 AI
Altair – Fixed Cost	1.19 AI
Altair - Marginal Cost	0.79 AI
Altair - Total	1.98 AI

6. PROBABILITY OF LOSS OF CREW

The initial selection of a V-I launch order was predicated on two factors. The first was the ability to add substantial loiter time to the EDS if the Ares V was launched first. The other factor, which is also potentially significant, is the added risk to the crew if the Ares I were to be launched first. In that option, the crew would be placed into LEO prior to the launch attempt of the Ares V. If the Ares V were not able to launch in the available four-day window, then the crew would have to return to Earth. If the mission were to be re-attempted later, then a crew would again have to be placed in LEO. This, in effect, exposes a crew to an additional launch, LEO operations, and entry, descent, and landing (EDL).

For the V-I launch order, no additional risk to the crew would result from the 1½-launch operations. However, with 90-minute separation, other potential risks to the crew for a

V-I launch order must be considered. In this case, NASA has determined that inserting the Orion crew into the capsule and preparing for launch in the 90-minutes between launches would be difficult. Therefore, the crew would most likely have to be on the pad, in the capsule, when the Ares V launches. If an incident were to occur on the pad or in the initial stages of launch that resulted in a catastrophic loss of the Ares V, then the crew would be in some potential danger. This represents an added crew risk for the V-I launch order if a 90-minute separation were used. In the 24-hour case, the crew would not be exposed to this type of risk.

In order to accurately compare the risks to the crew due to launch order between cases, both the added launch risk for I-V options and the range safety issues for V-I options need to be considered.

For an Ares I flight that is forced to return to Earth with no TLI, the total PLOC for the crew is the sum of the risks of the Ares I launch, four days of Orion LEO operations, and an EDL from LEO. Based upon the current risk estimates for the Ares I and Orion designs, the PLOC for a LEO mission is estimated to be approximately 0.00253 or 1 in 396. As the designs for the Ares I and the Orion mature and risk is "bought out" of the systems, these risk estimates are likely to improve. For reference, the requirement for crew risk for the orbital mission, derived from the Constellation Architecture Requirements Document (CARD) is 0.00036, or 1 in 2,793. However, in order to be as conservative as possible in relation to crew safety, the current risk value was used. Table 5 details the breakdown of the PLOC for both the current and CARD estimates.

Table 5. PLOC Estimates for 4-Day Orion LEO Mission

Phase	Current PLOC	CARD Requirement
Ares I Launch	0.00077 ($^1/_{1300}$)	0.00011 ($^1/_{9168}$)
LEO Loiter (4-Days)	0.00071 ($^1/_{1400}$)	0.00010 ($^1/_{9873}$)
EDL from LEO	0.00104 ($^1/_{960}$)	0.00015 ($^1/_{6770}$)
Total	**0.00253 ($^1/_{396}$)**	**0.00036 ($^1/_{2793}$)**

The added risk to the crew in the I-V option can be calculated as the total Probability of loss of Crew (PLOC) for an orbital mission multiplied by the probability that the crew will be required to refly the flight for a given mission, which is equal to the probability that the Ares V does not launch at all (PnSL) plus the probability that the Ares V launches (Probability of Second Launch (PSL)) but fails to reach LEO.

$$\textit{Added crew risk for I-V launch order} = PLOC_{LEO} * (PnSL + PSL * P_{Ares\ V\ Ascent\ Failure}) \quad (1)$$
where
$$PSL = 1 - PnSL$$
$$P_{Ares\ V\ Ascent\ Failure} = 0.0115.$$

Using the PnSL of 5.4% for the I-V launch order with a 90-minute separation and four days of loiter, the added risk to the crew per mission is equal to 0.000164, or 1 in 6,092.

$$\textit{Added crew risk for I-V launch order} = 0.00253 * (0.054 + 0.946 * 0.0115) = 0.000164 \quad (2)$$

Quantitatively assessing the risks that the crew faces because the are within the Flight Hazard Area for the V-I launch order with a 90-minute separation is not currently possible. However, based on the opinion of subject-matter experts, this risk is not considered to be insignificant. The crew faces no significant added risk for a V-I launch order with a 24-hour separation because they would not be loaded into the Orion until after the launch of the Ares V.

7. Figures of Merit

The goal of the launch order analysis was to evaluate the identified operational concepts and then produce a series of relevant figures of merit (FOM) for each one. The most basic metric that was considered was the probability that each concept would result in a failure to launch the second vehicle. The FOMs for the study had to cover a number of areas that were significant to decision makers on selecting a concept.

Probability of No Second Launch

This metric not only contributes to expected losses but also stands alone as an important measurement of success or failure. Because any failure to launch the second flight in a timely manner will result in the loss of a vehicle and would force the flight to be reflown, some adverse public and political reaction is likely, even if such a loss is anticipated by NASA.

Cost of Failure

The primary direct impact on NASA of a failed second launch would be the cost to replace hardware and attempt to refly the mission. Although other options may ultimately be pursued by NASA if such an event did occur, such as cancelling the mission, the replacement cost remains an indicator of the value of the hardware that is lost.

In this analysis, the metric that was selected is the expected cost of replacement hardware. The expected cost is calculated as the product of the PnSL for each option and the cost of the hardware that is lost for that option. This value is not the actual replacement cost per mission if a second launch failure did occur. It is a probabilistic amortization of those costs. These costs would effectively be imposed on every human lunar mission resulting in a large added cost over the program.

In the case of the V-I launch order, the cost of lost hardware is the sum of the costs for the Ares V booster, the EDS, and the Altair lander. In reality, some cost would also be incurred to replace lost cargo on the lander. However, for this study these costs were considered to be negligible.

For the I-V launch order, the cost of lost hardware is the sum of the costs for replacement of the Ares I and the Orion service module, as well as the cost of refurbishment for the Orion command module.

Loss of Delivery Capability to the Surface

This metric captures the negative impacts of increasing the loiter period for the Ares V. In the V-I launch order, as the loiter period is increased, the total cargo delivery capacity of the transportation system to the lunar surface decreases. This penalty, unlike the replacement cost, is not probabilistic but is incurred on every lunar mission.

Additional Risk to the Crew

The additional risk to the crew for each option was considered as a primary metric by decision makers. As described, the quantitative added risk for the I-V launch option was calculated as a metric. For the V-I 90-minute option, the added risk was treated qualitatively.

Additional Costs or Complexities

Aside from the four basic FOMs described above, additional complexities had to be considered for certain launch options. The most significant of these complexities was the total launch vehicle capability. In certain cases, the additional EDS propellant load was so great that, with the baseline Ares V option, there would not be enough cargo delivery capacity to LEO to support a viable lunar lander. In these cases, the application of that launch option would require an upgrade to the capacity of the Ares V. This would lead to a significant increase in both Design, Development, Test, and Evaluation (DDT&E) costs and production costs for every flight.

8. SELECTION OF FINAL LAUNCH OPTIONS

An initial evaluation of the full set of 1½-launch options was evaluated across the described FOMs. The goal of this initial analysis was to select a subset of options for final analysis and comparison that would represent the best performance across all of the FOMs.

90-Minute versus 24-Hour Separation

Before investigating launch order or loiter duration in detail, basic results comparing the PnSL for 90-minute and 24-hour launch separation were provided to decision makers. Table 6 summarizes the PnSL values for each of these cases.

Table 6. Comparison of PnSL for 90-Minute and 24-Hour Separation Cases

90-Minute Separation	PnSL	24-Hour Separation	PnSL
I-V 4-Day Orion 4-Day EDS	5.4%	I-V 4-Day Orion 3-Day EDS	13.0%
V-I 4-Day Orion 4-Day EDS	4.7%	V-I 4-Day Orion 5-Day EDS	14.1%
V-I 4-Day Orion 14-Day EDS	1.9%	V-I 4-Day Orion 15-Day EDS	5.5%

The PnSL for the 24-hour cases are significantly worse than those for the respective 90-minute counterparts. A number of factors cause the 24-hour PnSL results to be so relatively poor. First, the 24-hour separation allows one less launch attempt than for the 90-minute case. Second, the 24-hour separation introduces a greater probability that the weather or sea state could change and fall outside the limits between launches. Finally, the increased time between launches increases the probability that a failure will occur in the second launch vehicle as a result of the longer period for such a failure to manifest.

Certain operational complexities would be incurred for a 90-minute launch separation, as compared with the baseline 24-hour separation. Final countdown for both vehicles would overlap and, as described earlier, in a I-V launch order, the crew would be in the flight hazard area of the Ares V. However, NASA has investigated operational concepts for a 90-minute separation and has found no major barriers.

Based upon this PnSL data, it was determined that the added probability of mission failure for a 24-hour separation for any given launch option was simply too large to be tolerated. The added launch complexity and flight hazard risk of the 90-minute case did not justify the added probability of mission failure. The political and public perception of these types of failures, especially multiple similar failures, is likely to be poor. In the case of a V-I launch order, a high-cost asset (2.88–3.11 AI) is being lost. In the case of a I-V launch order, the appearance would be that the crew was launched for no reason, in addition to an Ares I stack loss.

For these reasons, the decision was made to not investigate further the 24-hour separation cases. Therefore, the point-of-departure architecture was changed to a 90-minute separation.

Loiter Duration

For each of the 1½-launch order options, cases were evaluated with varying loiter durations in LEO in order to select loiter periods that would be optimal for each launch sequence.

Table 7. Comparison of FOMs Across Loiter Period Options for V-I Launch Order (90-Minute Launch Separation)

Ares V Loiter, Days	**PnSL**	**Cost of No Second Launch** (Ares I Stack Equiv.)	**Expected Vehicle Replacement Cost, per Crewed Mission** (Ares I Stack Equiv.)	**Change in Propellant Mass, kg**	**Cost to Provide Added Loiter**
1	8.7% ($^{1}/_{11.5}$)	2.88 AI	0.25 AI	-119	0
2	6.8% ($^{1}/_{14.7}$)	2.88 AI	0.20 AI	-79	0
3	5.9% ($^{1}/_{16.9}$)	2.88 AI	0.17 AI	-40	0
4	4.7% ($^{1}/_{21.3}$)	2.88 AI	0.14 AI	0	0
14	1.9% ($^{1}/_{52.6}$)	3.11+ AI	0.06 AI	395	>$1B+
24	1.2% ($^{1}/_{83.3}$)	N/A	N/A	834	N/A

Table 8. Comparison of FOMs Across Loiter Period Options for I-V Launch Order (90-Minute Launch Separation)

Ares I Loiter, Days	**PnSL**	**Cost of No Second Launch** (Ares I Stack Equiv.)	**Expected Vehicle Replacement Cost, per Crewed Mission** (Ares I Stack Equiv.)	**Added Loiter Mass**	**Added PLOC**
1	10.8% ($^{1}/_{9.2}$)	1.00 AI	0.11 AI	-119	0.00030
2	8.1% ($^{1}/_{12.3}$)	1.00 AI	0.08 AI	-79	0.00023
3	7.0% ($^{1}/_{14.3}$)	1.00 AI	0.07 AI	-40	0.00020
4	5.4% ($^{1}/_{18.5}$)	1.00 AI	0.05 AI	0	0.00016

For the V-I launch order, EDS loiter durations of 1, 2, 3, 4, 14, and 24 days were investigated. For the 4-, 14-, and 24-day EDS loiter periods, an Orion loiter of 4 days (the design maximum) was used. For the 1-, 2-, and 3-day EDS loiter cases, the Orion loiter period would match the EDS loiter, although no mass changes were made to the Orion design. Table 7 shows the PnSL and cost results for each V-I case.

In these results shown in Table 7, the cost of No Second Launch was 2.88 AI for each of the cases up to a 4-day EDS loiter. This replacement cost estimate corresponds to the 51.0.48 Ares V design. For the 14-day loiter case, the amount of excess propellant that is required for boil-off increases by 395 kg from the 4-day baseline amount. An additional mass increase would also be required to account for the additional required tankage, photovoltaic arrays, MMOD protection, and reboost. The 51.0.48 Ares V design would not be viable with that amount of additional mass. For a 14-day loiter period, in order to produce a viable architecture, the Ares V would have to be switched to the 51.0.47 design option, which includes composite solid rocket booster (SRB) casings and hydroxyl-terminated polybutadiene (HTPB) SRB propellant. The 51.0.47 has a greater marginal cost than the 51.0.48, which increases the cost of No Second Launch from 2.88 to 3.11 AI. In addition, there would be added costs that were not calculated as part of this study for the added EDS complexity.

A 24-day loiter period, which would require an additional 439 kg of propellant beyond the 14-day case and additional tankage mass, was not considered to be a viable option even with the 51.0.47 Ares V. The reduction in PnSL between 14 and 24 days was relatively small (0.019 and 0.012, respectively) compared with the added mass that would be required.

The 4-day EDS loiter case provides 1000 kg delivery capability to the lunar surface. Reducing the loiter period below four days would only provide a small marginal increase in surface delivery capability. Because the PnSL and the expected vehicle replacement costs grow substantially worse as the loiter period is reduced below four days, the 1-, 2-, and 3-day loiter periods were determined to be suboptimal. For the V-I launch order, the 4-day EDS loiter with the 51.0.48 Ares V and the 14-day EDS loiter with the 51.0.47 Ares V were selected as candidate cases for final comparison.

For the I-V launch order, the EDS and Orion loiter periods of one, two, three, and four days were considered. Again, the Orion mass was not varied for shorter LEO durations.

Table 8 shows the PnSL, cost, and PLOC data for each of these options.

As can be seen from the data in Table 8, both the PnSL and the expected vehicle replacement cost increase rapidly as the loiter period decreases below 4 days. In addition, because the PnSL increases, the added PLOC also increases substantially as the loiter duration is shortened. As with the V-I case, the reduction in loiter mass that can be achieved by shortening the loiter period below 4 days is relatively small. For the I-V launch order, loiter periods for the EDS and Orion of less than 4 days were considered to be sub-optimal. Only the four-day loiter period was considered for the I-V launch order in the final comparison of cases.

9. COMPARISON OF LAUNCH OPTIONS

Based on the results that are described earlier, three cases were evaluated and compared in the final definition of a 1½-launch point operational concept. Table 9 describes the three cases.

Table 9. Downselected Launch Options

Case	Launch Order	EDS Loiter	Orion Loiter	Separation
1	I-V	4-Days	4-Days	90-Minute
2	V-I	4-Days	4-Days	90-Minute
3	V-I	14-Days	4-Days	90-Minute

The three final options were compared for each identified FOM. The option(s) that maximized performance for each FOM were identified. Finally, the results were subjectively compared across all of the FOMs.

PnSL and Cost of Failure

Table 10 summarizes the PnSL and replacement cost metrics for each of the three final options.

The data in Table 10 shows that a V-I launch order with a 14-day loiter provides the lowest possible PnSL at 1.9%. The 4-day loiter cases for the V-I and I-V launch order are similar at 4.7% and 5.4%, respectively. For the expected vehicle replacement cost, the I-V 4-day case provides the lowest cost, at 0.05 AI per mission. The V-I 14-day loiter, even with its small PnSL, has a larger expected cost of 0.06 AI. The expected vehicle replacement cost of the 4-day V-I case is significantly higher at 0.14 AI because of the higher stack replacement cost.

Table 10. Comparison of PnSL and Cost of Failure

Case	PnSL	**Cost of No Second Launch** (Ares I Stack Equiv.)	**Expected Vehicle Replacement Cost, per Crewed Mission** (Ares I Stack Equiv.)
I-V 4-Day Loiter	5.4%	1.00 AI	0.05 AI
V-I 4-Day Loiter	4.7%	2.88 AI	0.14 AI
V-I 14-Day Loiter	1.9%	3.11+ AI	0.06 AI

Added Probability of Loss of Crew

It is not possible to quantitatively compare the added probability of loss of crew as a result of the 1½-launch operations between the I-V and V-I launch orders. While the PLOC that is added due the possibility of reflying a mission can be determined for the I-V order, it is not possible at this time to determine the added PLOC for the crew in the Ares V flight hazard area in the V-I order. However, the cases can be compared subjectively, to determine if added PLOC supports the selection of one option over another. Table 11 summarizes the added PLOC for each case.

Table 11. Comparison of Added PLOC

Case	Added PLOC
I-V 4-Day Loiter	$^{1}/_{6,092}$
V-I 4-Day Loiter	Crew within Ares V Flight Hazard Area
V-I 14-Day Loiter	Crew within Ares V Flight Hazard Area

Other Considerations

Aside from the primary metrics described above, several other issues were taken into consideration for these cases. Table 12 summarizes these issues for each option.

The primary consideration was the additional requirements that are imposed by a 14-day loiter. In order to support a 14-day loiter, the EDS is essentially transformed from a stage to an independent vehicle. This transformation would require significant added mass for increased MMOD protection, photovoltaic arrays, and additional propellant, beyond the boil-off, for reboost and attitude control. The net effect is a substantial increase in both the mass and complexity for the EDS. As discussed previously, this mass increase, along with the added mass for boil-off, results in the 51.0.48 Ares V option not being viable. The 51.0.47 Ares V option would, therefore, be required to support an EDS with a 14-day loiter. The change in the Ares V and EDS designs not only increases the unit cost of the vehicle, as described above, but will also increase the DDT&E costs of the elements by a minimum estimated value of $1B. The total increase could be substantially greater.

Two other considerations apply to both of the V-I cases. The first issue involves Ares I flight rules. In a V-I launch order, where the Ares V and the Altair have been placed in LEO prior to the crew launch, as the launch opportunities expires, pressure could be placed on launch controllers to relax the Ares I launch rules in order to avoid the loss of the Ares V stack in orbit.

Table 12. Comparison of Other Considerations

Case	Cost to Provide Added Loiter	Other Considerations for a "No Second Launch" Event
I-V 4-Day Loiter	0	
V-I 4-Day Loiter	0	• Replacement of Ares V stack could involve significant Program delays • Potential pressure to relax Ares I flight rules to avoid the loss of Ares V stack
V-I 14-Day Loiter	>$1B+	In addition to previous case: • Ares V EDS complexity and mass increases as a function of loiter – MMOD Protection – PV Arrays – Additional propellant for re-boost and attitude control

Table 13. Summary Comparison of Final Cases

Case	PnSL	**Expected Vehicle Replacement Cost, per Crewed Mission** (Ares I Stack Equiv.)	Cost to Provide Added Loiter	Added PLOC	Other Considerations for a "No Second Launch" Event
I-V 4-Day Loiter	5.4%	0.05 AI	0	$^{1}/_{6,092}$	
V-I 4-Day Loiter	4.7%	0.14 AI	0	Crew within Ares V Flight Hazard Area	• Replacement of Ares V stack could involve significant Program delays • Potential pressure to relax Ares I flight rules to avoid the loss of Ares V stack
V-I 14-Day Loiter	1.9%	0.06 AI	>$1B+	Crew within Ares V Flight Hazard Area	In addition to previous case: • Ares V EDS complexity and mass increases as a function of loiter

Second, differences exist in the programmatic consequences between the loss of an Ares I stack and an Ares V stack, beyond the replacement cost. Ares I and Orion flight rates could be relatively high to support ISS and lunar missions. Replacing one of these stacks would be a matter of accelerating the next launch vehicle in the pipeline. For the Ares V and Altair, however, the replacement could involve more significant delays. The Ares V itself would be a more expensive and more complex vehicle to replace. The Altair lander presents the greatest complexities. A limited number of landers will be produced for the lunar campaign. Acquiring an additional replacement lander could involve the reopening of production lines. In addition, each Altair will be unique to some degree because of the mission objectives and the cargo that it carries. Finally, the cargo itself would need to be replaced in the event of a loss.

Summary Comparison

Table 13 summarizes the comparison of the three launch options. In this table, the cells that indicate potential negative aspects for each case are highlighted.

I-V 4-Day EDS Loiter 4-Day Orion Loiter—The I-V launch order case resulted in the highest PnSL of the three final cases, with a probability of a missed second launch of 5.4% per mission. However, because of the low cost of failure for this case, it also had the lowest expected vehicle replacement cost at 0.05 AI per mission.

V-I 4-Day EDS Loiter 4-Day Orion Loiter—The V-I option with 4-day EDS and Orion loiter has a PnSL that is similar to that for the I-V option at 4.7%. The PnSL for this case was somewhat lower due to the lower complexity of the second launch vehicle. This case, however, resulted in the greatest expected cost of failure at 0.14 AI. In addition, the V-I launch order includes the additional considerations that involve the pressure to relax flight rules and the difficulty in replacing an Ares V stack.

V-I 14-Day EDS Loiter 4-Day Orion Loiter— Of the three options, the V-I 14-day EDS loiter case presented the best PnSL value. The 1.9% PnSL was less than half the PnSL for either of the 4-day loiter cases. However, because of the high cost of failure, the overall expected vehicle replacement cost per mission was similar to that of the I-V 4-day case.

In evaluating this case, the primary concern, however, was over the other required costs. Because of the added boil-off propellant and other described EDS complexities required to support this duration, the baseline 51.0.48 Ares V option was no longer viable. The 51.0.47 Ares V option, with an upgraded capacity, would be required. The DDT&E costs for this upgrade would be large. The cost difference for the Ares V upgrade alone is estimated to be greater than $1B. In addition, the costs to upgrade the EDS, including photovoltaic arrays and MMOD protection, would be added. Although these are one-time DDT&E costs rather than recurring costs, they occur in a phase of the program where the budget is most restricted.

In addition, the 51.0.47 design for the Ares V has been reserved as an option in case it is needed because of mass growth or performance uncertainty for the transportation system. If the upgraded design is adopted in the baseline to support a 14-day loiter and a more complex EDS, then no current options are available to provide a hedge against mass growth or performance uncertainty in the transportation system. While further upgrades to the EDS are possible, these upgrades were not considered desirable when the 51.0.48 and 51.0.47 options were down-selected for further consideration by the Constellation Program.

Because of the requirement to upgrade the Ares V to the 51.0.47 option, as well as the added complexity of the EDS stage, the V-I 14-day loiter case was removed from consideration for the 1½-launch launch operational concept. While this option offers a significantly lesser PnSL than the other two options at 1.9% versus 4.7% - 5.4%, the added costs and risks associated with this option, particularly costs during the crucial DDT&E period, were determined to be unacceptable. This opinion was reinforced by the results for total expected replacement cost. While the V-I 14-day loiter case has a low PnSL, because of the high consequence of failure, the total expected replacement cost was actually somewhat greater than for the I-V 4-day loiter case.

10. Selection of $1^1/_2$-Launch Point-of-Departure Operational Concept

As described previously, the V-I 14-day loiter case was determined by decision makers to involve too much added cost and risk to justify the resultant improvement in PnSL. The decision was reinforced by the fact that the second primary metric, the expected cost of failure, was not improved by the V-I case with a longer loiter period.

The two final cases, the I-V 4-day loiter and the V-I 4-day loiter, were compared; the I-V launch order was selected for the baseline point-of-departure architecture.

The PnSL values, which represent the probability of a failure event during the dual launch phase, were similar for the I-V and V-I cases, at 5.4% and 4.7%, respectively. The expected replacement cost per mission was significantly lower for the I-V case, however. Even with the cost uncertainty, the I-V case clearly would likely always result in a lower total cost.

Crew safety was a major consideration in selecting between the two cases. A clear, quantifiable added risk to the crew exists in selecting the I-V launch order. The crew would be required to endure an additional set of launch, loiter, and EDL events in the case of a missed second launch.

However, because the probability of loss of crew is conditional to the PnSL, the overall added risk of 1 in 6,092 is considered to be quite small. This is particularly true when the added risk is compared with the overall risks to the crew that are anticipated for a human lunar mission.

In addition, although they could not be quantified at this point in time, additional crew risks are associated with the V-I launch order. Although no determination can be made at this point whether these range safety risks may be similar in magnitude to the added risks in the I-V case, they certainly cannot be totally discounted.

The selected I-V case with a 4-day loiter and 90-minute separation offered the most balanced results across the FOMs that were used in this study. The PnSL of 5.4% was larger than other cases but similar to the PnSL that could be achieved in any case if the Ares V was limited to the 51.0.48 option. The consequence of failure in this case was much less than for the V-I case, which resulted in an expected cost of less than half of that for the V-I launch order.

In addition, the other complexities that were associated with the V-I launch order–potential pressure to relax flight rules and the disruptions caused by having to replace an Ares V–also trended toward the selection of the I-V launch order.

11. Point-of-Departure and Uncertainty

Note that the selected 1½-launch operational concept represents only a point-of-departure architecture to be used as a baseline for ongoing lunar architecture studies. It does not represent a final selection of launch order, separation, or loiter period, and NASA is taking no steps to preclude a change in the operational concept in the future.

In fact, because of the uncertainty that is involved in the initial design and costing, the possibility exists that, upon further refinement, the parameters that drive this study could change to a degree that would cause the operational concept to be reconsidered.

In addition, significant uncertainty exists in the data that were used to generate the PnSL results in C-RAST. Because the Ares V is still in the early stages of design, large amount of uncertainty still exists as to the launch reliability for the vehicle. As the design matures and more accurate estimates of reliability become available, the operations concept could also be reconsidered.

In fact, it may ultimately be desirable to develop a 1½-launch system that allows for launch in either order. For the purposes of this study, the Ares V reliability and, therefore, the PnSL were treated as constant values. Because there is a limited test program for the Ares V before the crewed lunar mission begins, there is liable to be significant growth in reliability for the Ares V over a number of missions. If the initial reliability is low, then the desire would be to launch the Ares V first so that the crew is not launched unnecessarily. Because the values used in this analysis represent the mature steady-state estimates, the PnSL for the I-V options could be worse than predicted in this analysis for some number of early missions. If the initial reliability is significantly lower, then it may be desirable to launch initial missions in a V-I order and then switch to I-V as reliability improves.

To address this uncertainty, an additional set of analyses was completed. In this uncertainty analysis, calculations were made to determine how much each major input parameter would have to change in order to cause the launch option decision to change, if that decision were made on expected replacement cost alone. The analysis was conducted by comparing the final two options: the I-V 4-day loiter and the V-I 4-day loiter cases.

The results of the uncertainty analysis are shown in Table 14. In this table, the current estimate used for each major parameter is listed. Then, the value for each parameter at which the launch order decision (based on the expected cost of failure) would switch is listed. Generally, the required shifts are large, although the required changes in Table 14 are for single variables only. Simultaneous changes of multiple parameters that are lower in magnitude could also cause a change in the launch order decision.

The greatest level of uncertainty in the current analysis involves the transportation element replacement costs. Because of the uncertainty involving fixed and marginal costs for Altair and because of the uncertain nature of cost estimates in early design large shifts could potentially occur in the cost data for all elements as the designs mature.

Table 14. Sensitivity of Launch Order Decision to Major Parameters

Parameter	Current Estimate	Value at Which Launch Order Would Switch (if all other values remain constant)
PnSL I-V (4-day loiter)	5.4%	13.5%
PnSL V-I (14-day loiter)	4.7%	1.9%
Cost of Ares I Stack	1.00 AI	2.5 AI
Cost of Ares V Stack	2.88 AI	1.15 AI

In order to represent the impact of uncertainty in the cost data, a “breakeven” cost ratio was determined. The important factor in comparing expected costs for the I-V

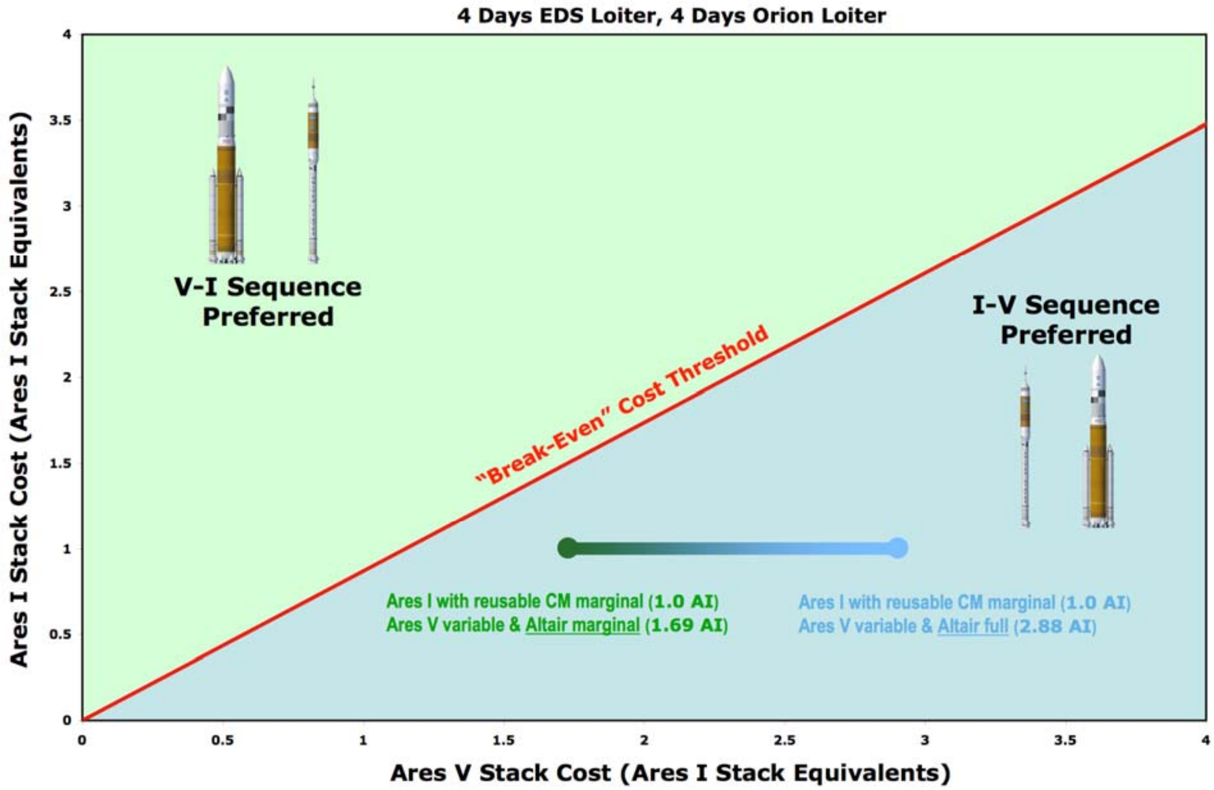

Figure 6 – Relative Ares I and Ares V Stack Costs

and V-I launch orders is not the absolute costs of the Ares I and Ares V stacks but rather the relative costs between the two. Given the predicted PnSL values for the I-V and V-I cases, any set of cost data in which the cost of the Ares V is greater than 115% of the cost of the Ares I will result in the expected replacement cost per mission for the I-V option being lower. This relationship is depicted graphically in Figure 6.

Figure 6 can be used to determine the resultant optimal launch order for any set of Ares I and Ares V stack replacement costs, based on minimizing the expected cost of failure. The cost of the Ares V stack is specified on the horizontal axis, and the cost of the Ares I stack is specified on the vertical axis. The sloping red line in the center of the figure represents the break-even cost boundary. If the set of costs is below this line in the light-blue region, then the I-V launch order is preferable. If the set of costs are above the red line in the light-green region, then the V-I launch order is preferable.

The intent of Figure 6 is to provide a visual indication of how much change could occur in the cost estimates before the launch order decision would be reconsidered. The current cost estimates are represented as a vertical bar on the chart. The Ares I cost is fixed at 1.00 AI. The Ares V cost is represented as a range of 1.65 to 2.88 AI, which represents the full range that is produced by the possible inclusion of fixed costs.

Across the range of current cost estimates, a large margin still exists before the break-even point is reached. Even with no fixed costs included for the Ares V, the Ares V cost would have to decrease by 32%, or the Ares I cost would have to increase by 47% for the cost of failure to be equal for the two cases. These changes seem to be outside the current range of cost uncertainty.

The Constellation Program has initiated an action to monitor the key parameters identified in this analysis as the transportation element designs continue to mature. If the designs reach a state at which the selected point-of-departure operational concept is called into question, then this baseline may be updated.

12. SUMMARY

The initial specification of an operational concept for the 1½-launch solution was largely based on three assumptions. First, there was a "gut reaction" that one would not want to risk launching a crew until the EDS and lander were safely in orbit. Second, the assumption was made that the probability of missing the second launch could be substantially reduced by providing a long loiter period for the EDS. Finally, with long EDS loiter periods, the assumption was made that a 24-hour launch separation would have no significant impact on mission success.

More detailed analysis indicated that all three of these assumptions were not entirely accurate. The added risk to the crew, dictated by the conditional probability of enduring a second launch and encountering a loss-of-crew event, was quite small, especially as compared with the total risk for a human lunar mission.

The ability to use added loiter to reduce PnSL was largely limited by the Ares V capabilities. Loiter periods of more than four days would require a change to the selected Ares V option (significantly increasing DDT&E and unit cost) and would substantially increase the complexity of the EDS.

Finally, with shorter loiter periods, the 24-hour launch separation significantly increased the probability of no second launch. The increase in PnSL outweighed the advantages of having a long separation between the launches.

Taking these limitations into account, the assumed launch order, launch separation, and loiter duration were called into question. A structured methodology to evaluate the probability of failure, the cost of failure, and the risk to the crew allowed NASA decision makers to methodically compare the options and to select a point-of-departure for 1½-launch operations that would result in the best expected mission performance.

Loiter durations of greater than four days were determined to be nonviable. The added cost and complexity of the Ares V and the EDS, particularly during the DDT&E period, would impose significant affordability issues. Although the PnSL could be substantially reduced by increasing the loiter, these improvements did not justify the added complexity.

With loiter periods limited to four days or less, the 24-hour launch separation was also determined to be nonviable. Although switching to a 90-minute separation would impose some operational complexity at launch and could impose some additional risk to the crew in a V-I launch order, these factors were outweighed by the significant penalty to PnSL.

Finally, the launch order itself was evaluated. With a 4-day loiter, both launch orders resulted in similar values for PnSL. The I-V order would result in some added crew risk in the event of a missed launch, but the magnitude of the added risk was determined to be quite small, especially because the crew would face some indeterminate added flight hazard risk in the V-I option as well. The major discriminator between launch orders was in the expected cost of failure. Because a 1½-launch failure in the V-I order would result in the loss of an Ares V, the EDS, and the Altair lander, the consequence of failure is quite high. A failure in the I-V launch order would result in substantially lower costs to replace the Ares I and an Orion service module and refurbish an Orion crew module. The result of the large difference in relative costs is that the expected cost of failure is substantially lower for the I-V launch order.

The results of the study allowed decision makers to select a I-V launch order, with a 90-minute separation and a 4-day EDS/Orion LEO loiter period as the point-of-departure operational concept. This concept will serve as the baseline for ongoing lunar mission development. However, as designs mature and the major parameters used in this analysis are refined, the operational concept for the 1½-launch solution will be further evaluated.

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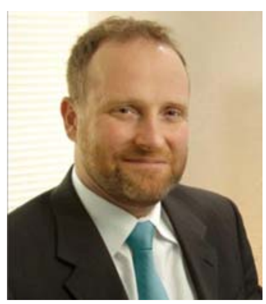
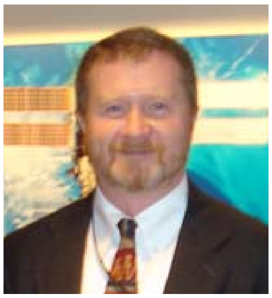
BIOGRAPHY



Chel Stromgren currently serves as the Chief Scientist of the Center for Strategic Analytics at Science Application International Corporation (SAIC). In this role, Mr. Stromgren leads the development of probability and risk-based strategic models and strategic analysis of complex system development. Mr. Stromgren has supported NASA in the analysis of Space Shuttle and International Space Station operations in the post-Columbia environment and has led the development of strategic campaign models for the lunar exploration initiatives. He holds a Bachelor of Science degree in Marine Engineering and Naval Architecture from the Webb Institute and a Master of Science degree in Systems Management from the Massachusetts Institute of Technology.

Grant Cates is a Senior Operations Research Analyst at SAIC. He retired from NASA in 2006 after 25 combined years in federal service, including 7 years on active duty in the Air Force. At NASA he served in varying capacities on the Space Shuttle Program, including Space Shuttle Columbia Vehicle Manager and Flow Director. He received a Ph.D. in Industrial Engineering from the University of Central Florida in 2004.



William Cirillo currently serves as a Senior Researcher at NASA Langley Research Center in Hampton, Virginia, where he has worked for past 20 years in the area of Human Space Flight Systems Analysis. This has included studies of Space Shuttle, International Space Station, and Human Exploration beyond low Earth orbit. In 2005, Mr. Cirillo served at NASA Headquarters as a core member of the Exploration Systems Architecture Study (ESAS) team, where he was responsible for studying the use of Ares I/Orion in meeting future ISS crew and logistics transportation needs. Mr. Cirillo currently leads a team of analysts within the NASA Constellation Program in assessing at a strategic and tactical level the manifesting of assembly and logistics flights for establishing permanent human presence on the Moon.