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DELTA IV LAUNCH VEHICLE GROWTH OPTIONS TO SUPPORT NASA'S SPACE EXPLORATION VISION

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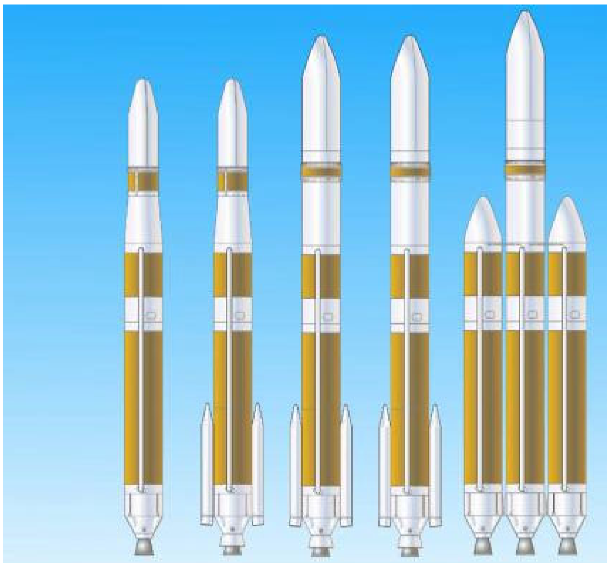
ABSTRACT

One of the defining attributes of the Vision for Space Exploration is its emphasis on affordability, which is also linked to another key attribute—long-term sustainability. As applied to space-lift requirements, this overriding constraint may argue for system choices not optimized for architectural elegance but, rather, for lowest development or recurring cost. Affordability constrains most projects and, second only to safety, may be the most important factor in the success of the Vision for Space Exploration. Finding the most affordable space launch approach and designing the architecture for cost may be the key to shaping the overall exploration architecture for success.

THE NEED TO DEVELOP AFFORDABLE AND SUSTAINABLE LAUNCH INFRASTRUCTURE REQUIREMENTS

To optimize the exploration architecture for affordability, it is helpful to identify the family of modifications to existing space launch systems that have minimal cost, schedule, and risk impact and to identify the growth cost breakpoints (i.e., those modifications that significantly increase costs). With two U.S. Evolved Expendable Launch Vehicle (EELV) systems already in existence, it may be most cost effective to consider EELV-based spiral development to achieve the near-term objectives of the Exploration architecture by identifying the most affordable growth paths. If the Vision for Space Exploration can be accommodated within the lowest cost growth paths of the existing EELV launch systems, this will avoid the potentially high non-recurring and recurring development costs of a dedicated heavy-lift system.

The Delta IV launch system has the potential to be a major contributor to the Exploration launch infrastructure due to its inherent affordability and sustainability (Figure 1). Delta IV currently has 14 launches on contract for U.S. government customers through 2010, assuring that this system will be



	Medium	Medium+ (4,2)	Medium+ (5,2)	Medium+ (5,4)	Heavy
GTO (kg)	4,231	5,941	4,869	6,822	12,757
LEO (kg)	9,106	12,305	10,616	13,864	21,892
GEO (kg)	1,138	2,036	1,686	2,786	6,276

GTO: 185 x 35,786 km at 27.0 deg Delta IV
LEO: 407 km circular at 28.7 deg
GEO: 35,786 km circular at 0 deg

Figure 1. The Delta IV Family of Launch Vehicles

available to support the exploration initiative with no development costs to the program. Further, Delta IV has numerous growth options to meet emerging exploration requirements, and affordability can be used as a driving requirement when deciding on an optimal exploration growth spiral development path.

In this paper, we examine the benefits of spiral development based on the operational Delta IV launch system, with emphasis on identifying the affordability and sustainability benefits achieved by leveraging the substantial existing and inherent features of this launch system.

DELTA IV OVERVIEW

Delta IV represents the newest generation of space transportation systems. With the full backing of The Boeing Company, Delta IV has been designed and developed to provide inherent efficiencies in manufacturing, integration, and launch processes.

Delta IV represents a family of related launch vehicles, as illustrated in Figure 1. The simplest and smallest is the Delta IV Medium, which has a launch capability of placing more than 4,000 kg into a standard geosynchronous transfer orbit (GTO). This configuration of Delta IV has a 4-m-diameter fairing.

There are three other Delta IV configurations that share the designation Delta IV Medium Plus: the M+ (4,2), the M+ (5,2), and the M+ (5,4). (These are referred to as the "Medium Plus 4-2," and so on.) The M+ (4,2) also uses a 4-m-diameter fairing and two graphite-epoxy motors (GEMs, the solid rocket motor boosters)—thus the (4,2) designation. Similarly, the M+ (5,4) uses a 5-m fairing and four GEMs. All Delta IV launch vehicles share a common first stage, designated the Common Booster Core (CBC), and very closely related second stages.

The fifth configuration of Delta IV is the Delta IV Heavy, formed with a first stage consisting of three CBCs, plus the 5-m upper stage and a larger 5-m fairing. The Delta IV Heavy is capable of placing more than 13,000 kg into a standard GTO and 22,000 kg into an International Space Station (ISS)-compatible low Earth orbit (LEO).

Elements of the Delta IV

The heart of the Delta IV family is an entirely new first stage, powered by the world's largest hydrogen-burning engine, the new Boeing Rocketdyne-developed RS-68 (Figure 2). The RS-68 exemplifies the design approach undertaken for this new generation of Delta launch vehicles: compared to the Space Shuttle main engine, the RS-68 has 93% fewer parts. It is inherently simple in its design, manufacture, and operation and operates at a lower chamber pressure than the SSME—in effect, the engine is designed for production efficiency and inherently reliable operation.

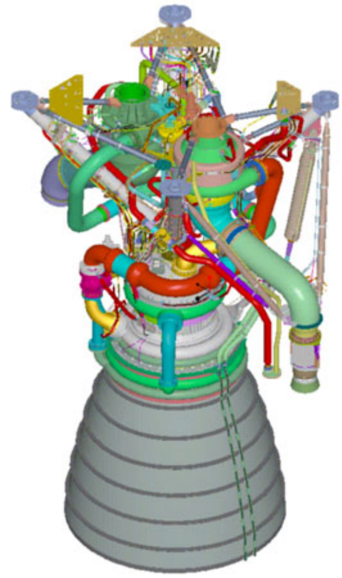


Figure 2. The Delta IV First-Stage Engine, the RS-68

The Delta IV upper stage uses a high-performance cryogenic Pratt and Whitney RL10B-2 engine. Like the Delta family of rockets, the RL10 engine also has a long heritage of more than four decades of use.

The CBC and upper stages are manufactured and integrated at the new Boeing facility in Decatur, Alabama. This dedicated factory is unique in the world of launch vehicle manufacturing. Based on lean-manufacturing principles, first stages are manufactured from raw stock under one roof and in a fraction of the time traditionally required to manufacture stages (Figure 3).

In addition to the new facility in Decatur, Boeing has made major infrastructure commitments in the new launch complexes at Cape Canaveral Air Force Station in Florida, and Vandenberg Air Force Base in California. These combined facilities, plus the simplified integration processes put in place for Delta IV, will enable

Figure 3. The 1.5-M-ft² State-of-the-Art Delta Manufacturing Facility in Decatur, Alabama

high launch rates capable of satisfying present and emerging Exploration schedule requirements.

Central to the Delta IV family of launch vehicles is its design for producibility and reliability. As a consequence, the Delta IV is an inherently robust launch system, able to accommodate performance upgrades and grow to meet evolving requirements, as may be forthcoming in the definition of the Exploration initiative.

AFFORDABILITY-DRIVEN EARTH-TO-ORBIT PERFORMANCE UPGRADES

Utilizing the existing Delta IV could lead to the lowest Exploration design, development, test, and evaluation (DDT&E) costs among the current launch options. However, the current Delta IV Heavy lift capability barely meets a low-end 25-metric-ton-to-LEO requirement using the existing 5-m fairing. Obviously, a 25-metric-ton launch vehicle carries the requirement of significantly more on-orbit operations than the larger launch vehicle options, while higher payload capability enables reduced on-orbit integration and aggregate launch risk.

Based on growth studies conducted under independent research and development (IR&D) funding, Boeing has identified several mutually compatible, relatively low-risk performance upgrades which, collectively, have the potential to double the performance of the current Delta IV Heavy vehicle to meet the needs of Exploration architecture (Figure 4).

The upgrades illustrated in Figure 4 offer the promise of substantially increasing the capabilities of the Delta IV—without necessitating a new launch pad—and reducing the number of launches to support Exploration architecture, greatly reducing on-orbit assembly operations. Affordability is improved through lower development costs and, potentially, lower life-cycle costs because of the ability to share manufacturing, integration, and launch facilities with other Delta IV users. These upgrades form the basis for additional potential future growth options (Figure 5).

Each of these upgrades is based on existing operational vehicles and elements, including:

RS-68 Upgrades. The RS-68 main engine has ample margin for performance upgrades. An RS-68 with a regeneratively cooled nozzle is a low-cost/low-risk upgrade offering significant I_{sp} and weight benefits. A second engine operation upgrade is the utilization of densified propellants, the use of propellants cooled below normal operating temperature, yielding denser fluids. Densified propellants have the advantage of allowing increased propellant loading, while taking advantage of the regeneratively cooled nozzle for added efficiency. Boeing demonstrated its ability to work with densified liquid hydrogen as part of the X-33 technology development program (Figure 6).

GEMs on the Delta IV Heavy. Adding up to six strap-on GEMs to the Heavy vehicle offers a significant boost in performance with a potentially low DDT&E cost. The use of a GEM-augmented Delta IV Heavy could provide additional low-cost lift for cargo delivery. As illustrated in Figure 7, six GEMs added to the

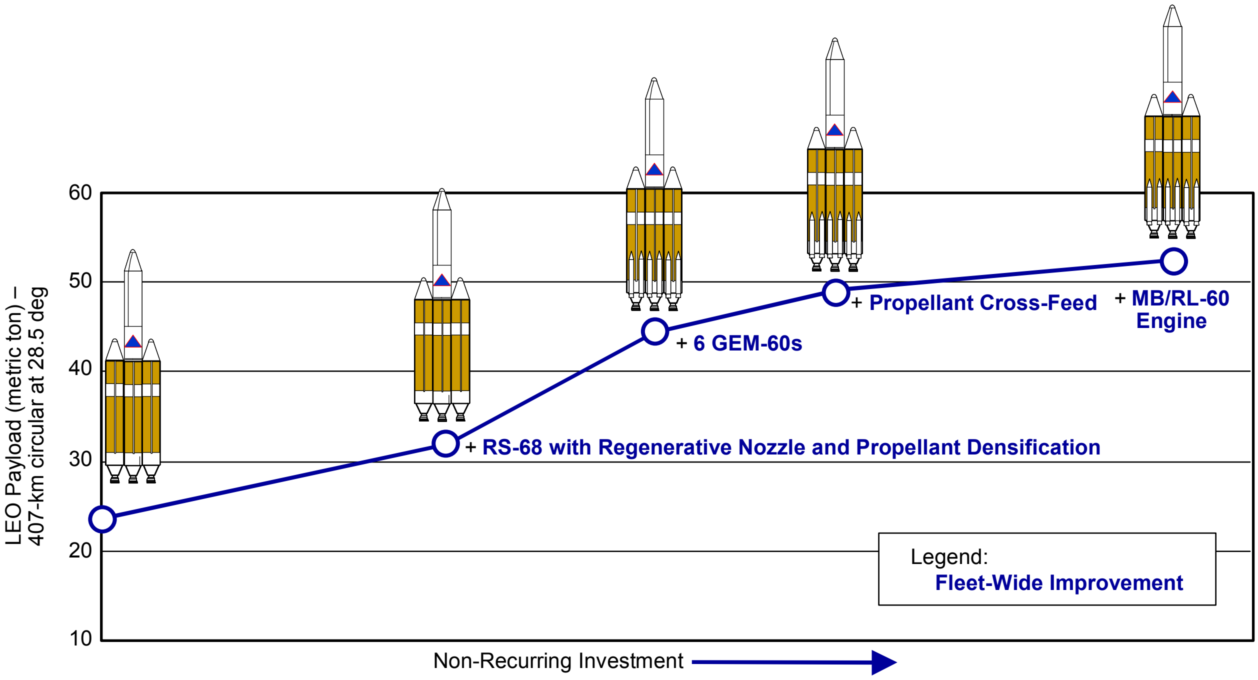


Figure 4. Low-Risk Delta IV Growth Path Affordably Doubles Current Performance

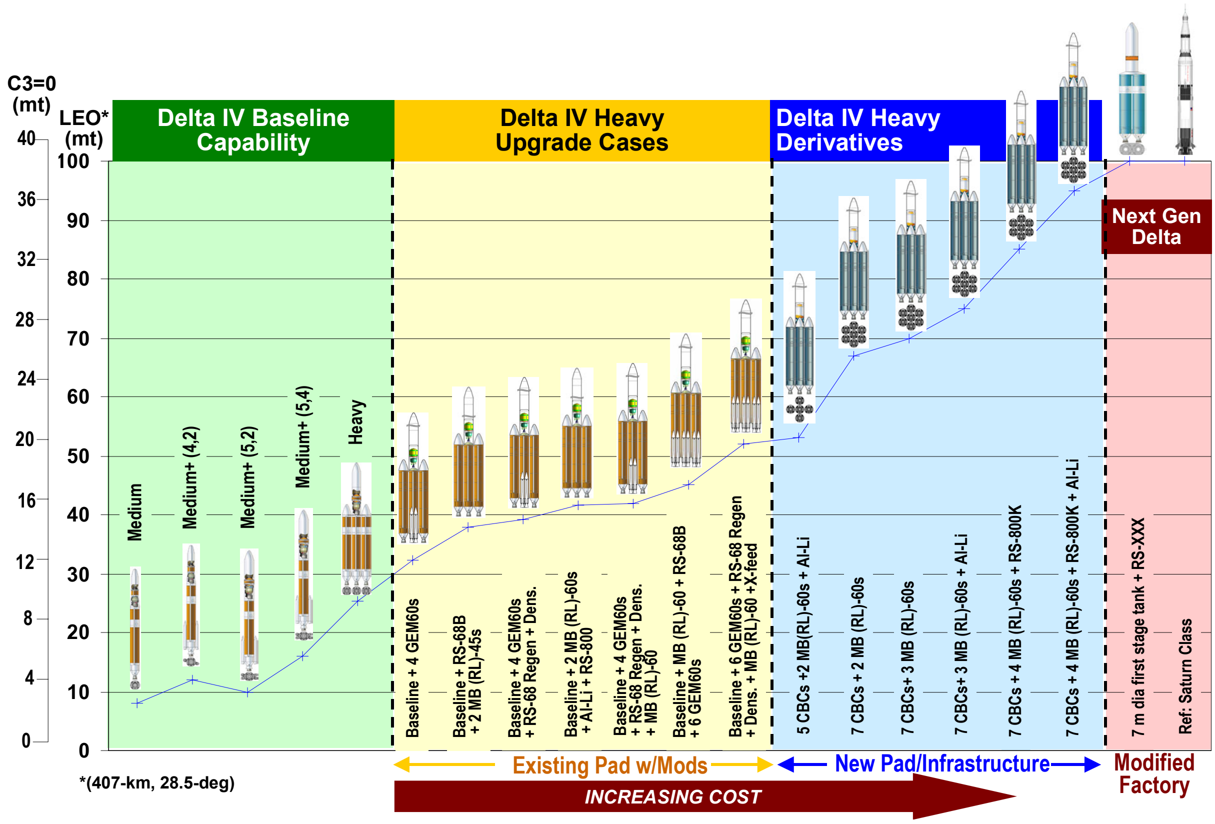


Figure 5. Delta IV Growth Options to Support Exploration

Figure 6. Boeing Liquid Hydrogen Densifier, Developed as Part of the X-33 Program

Delta IV Heavy provides an increase of more than 11,000 kg payload delivery to LEO.

Positioning the GEMs on a single (south) side of the Delta IV Heavy enables the enhanced vehicle to use the existing launch pad. While modifications to the launch pad (such as plume deflectors) would be required, substantial new infrastructure costs would be avoided.

CBC Propellant Cross-Feed. By adding cross-feed lines to route propellants from the strap-on CBCs to the core CBC, propellant is depleted from the strap-ons earlier and they are thus jettisoned earlier than the basic Heavy vehicle, which operates without cross-feed (Figure 8). With propellant cross-feed, the core CBC is still fully loaded at the time of strap-on jettison and the core engine runs at full throttle. A significant

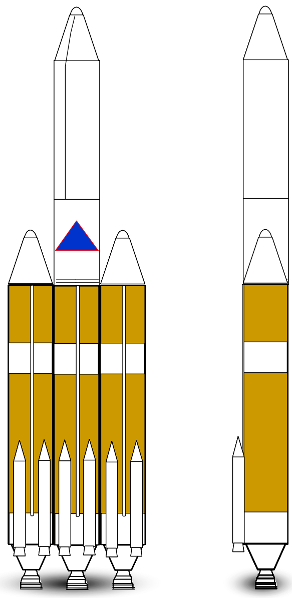


Figure 7. A GEM-Enhanced Delta IV Heavy Provides up to an 11,000-kg Increase in ETO Lift Capability

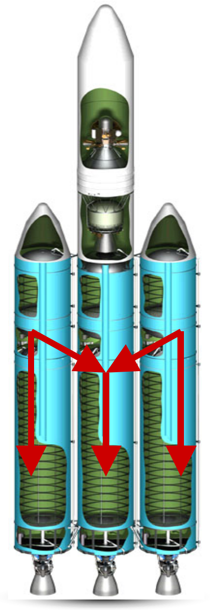


Figure 8. Propellant Cross-Feed Increases Delta IV Heavy Efficiency by Allowing Earlier Jettison of Strap-on CBC Boosters

performance increase is realized with the strap-on CBCs jettisoned earlier, yet the calculated reliability impact due to cross-feed is offset by the reduced engine run times.

Upper-Stage Engine Upgrade. The Delta IV upper stage is the first all-new cryogenic upper stage developed in the United States since the 1960s. The Delta IV upper stage utilizes the RL10B-2 25-klb thrust engine and is available in either a 4-m or 5-m-diameter configuration. The engine has multiple-restart capability as well as the capability of completing extended duration direct geostationary orbit insertion missions lasting up to 7 hr.

Because the current stage has been optimized for GTO missions, LEO applications would benefit from increasing the thrust level available to the stage. Enhancing the current 5-m upper stage with a new, higher thrust engine or by using two or more RL10s on the second stage offers a significant performance increase as well as providing affordability benefits due to its applicability for other missions.

One approach would be to incorporate an increased-thrust upper-stage engine. Candidates include the Boeing-Mitsubisihi Heavy Industries MB-60, or the Pratt & Whitney RL-60. Both of these engines, currently under development, provide 60 klbf vacuum thrust, with a similar high I_{sp}, and would increase the Delta IV Heavy Earth-to-Orbit (ETO) performance on the order of 3,000 kg, while also providing critical added capability for operations beyond LEO.

The existing Delta IV upper stage can be further upgraded to provide additional potentially important capabilities that enable an affordable and sustainable implementation of the Vision for Space Exploration (Figure 9). Boeing is currently evaluating modifications to the Delta IV upper stage for use as a Trans-Lunar Injection (TLI) or In-Space Transportation (IST) stage, either as an upper stage or as an on-orbit asset, as described in the following section.

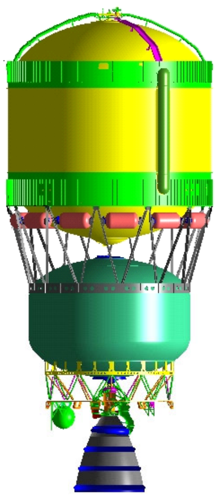


Figure 9. An Advanced Upper Stage, Based on the Delta IV Heavy Upper Stage, Could Incorporate a Higher Performance Engine such as the MB-60 or the RL-60

Aluminum-Lithium Structure. Replacing the standard aluminum alloy of either the upper stage, or both upper stage and CBCs with aluminum-lithium (Al-Li) alloy provides another low-risk performance upgrade available to the Delta IV vehicles. Using Al-Li for the upper stage would provide over 300 kg of performance benefit to the Delta IV Heavy, while application to both stages would provide a further performance gain of ~1,000 kg.

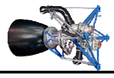
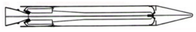
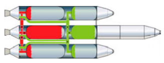
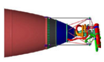
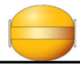
The upgrades identified above illustrate the principle of obtaining significant performance gains through upgrades to the inherently robust Delta IV family of launch vehicles. The estimated risks and approximate performance impacts on Delta IV Heavy delivery to LEO are summarized in Table 1.

DELTA IV-DERIVED EXPLORATION IN-SPACE TRANSPORTATION CAPABILITY

Delta IV Cyrogenic Upper Stage Applicability to Exploration

The Delta IV cryogenic upper stage (DC US) has the potential to address Exploration system needs, both as an In-Space Transportation (IST)/Trans-Lunar Injection (TLI) stage and as a first step to developing advanced thermal control and propellant management techniques in a low-gravity environment. Because it is an existing stage, reliability is higher and development costs are reduced—development begins with a configuration that

Table 1. Development Risk Assessment for Potential Delta IV Upgrades to Address Exploration Requirements

Enhancement Option		Estimated Technology Readiness Level	Estimated total risk*	Approximate Performance Impact (t)
RS-68K (Regenerative Nozzle + Densification) 		4-8**	Low-Med Low	+7
GEM-60 Augmentation 	4 GEM-60s	6		+8
	6 GEM-60s	5	Low-Med	+11.5
Propellant Cross-feed 		3	Med	+5
MB-60 or RL-60  		5	Low	+3.5
Al-Li Tankage 		5	Low	+1.3

* *System development (technical, cost, schedule)*
** *Engine is TRL 7-8, Densification is TRL 4-5*

has a proven flight heritage, thus reducing development risk. The spiral development approach to meet in-space transportation requirements based on the existing DC US is analogous to the ETO approach described in the previous section.

Both the current DC US and an upgraded upper stage potentially can be used for IST as well as for in-space propellant storage, either as an upper stage or as a payload. In either case, the use of a high-performance O_2/H_2 chemical stage offers improved payload capability, relative to an Earth-storable (NTO/MMH) stage, for moderate-duration (weeks to months) missions. The conservative design of the DC US accommodates upgrades: the structurally stable separated tanks minimize heat leak between the tanks for long-duration missions and provide maximum ground and flight safety in case of propellant leak.

The Delta IV upper stage is a stepping stone to a TLI stage, and the TLI stage is a potential stepping stone to an array of other Exploration applications, including cryo depot, lunar landers, and even habitat modules. Further, Delta IV upper stages offer a low-risk, high-fidelity platform for demonstrating the required technology.

Developing an advanced upper stage (AUS) (as illustrated in Figure 9) based on the existing DC US, to meet emerging requirements of the Exploration initiative, employs modifications in three primary categories:

1. Use of a higher thrust engine such as the MB-60 or RL-60.

2. Cryogenic propellant storage technology to accommodate long-duration missions.

3. Propellant tank sizing to optimize engine with mission trajectory requirements.

Each of these modifications provides analogous benefits of affordability and sustainability by leveraging existing elements with limited development to meet demanding Exploration requirements beyond low Earth orbit. As with the modifications described previously to expand ETO performance, each upper-stage upgrade can be combined to achieve specific mission or architecture requirements.

The upper-stage engine upgrade for Delta IV has application both to reaching LEO, as described in the previous section, and to operations in LEO and beyond.

Long Term Cryogen Storage

As part of an ongoing IR&D effort, Boeing has initiated an analysis of the applicability of the Delta IV upper stage for on-orbit propellant storage and assessed the modifications to the stage that would be necessary to accommodate operations lasting up to 1 year or longer.

Development of an optimum design for a cryogenic application depends on the specific use, particularly the mission duration, propellant-use profile, and available power. Short-duration missions (hours), such as the current DC US application, require minimal thermal control technologies. In many cases, foam insulation is adequate with no tank pressure-control system required.

Subcooled (densified) propellants also provide increased storage duration with minimal impact to the flight vehicle. Boeing has extensive experience in the production and use of these subcooled propellants.

As storage durations increase, additional thermal control techniques can be utilized, including application of multi-layer insulation (MLI), a thermodynamic vent system, and vapor-cooled shields. Propellant mixing is also normally required to reduce thermal stratification and pressure rise rate. Propellant boil-off rates as low as 6% per year have been demonstrated in a 1-g environment. For very long duration missions, most of these techniques are used to some extent to provide very low propellant boil-off rates. Our analysis to date indicates that, depending on the mission scenario selected, these nearly passive thermal control methods may be adequate to meet cryogenic storage requirements for missions up to a 1-year duration.

For still longer duration missions, or when propellant conservation requirements are severe, active refrigerators (i.e., cryogenic coolers), when combined with other techniques, can provide a zero propellant boil-off capability but require a significant amount of power. For a nuclear-based stage, power availability may not be an issue.

While most of these thermal control techniques have been demonstrated to some extent in a 1-g environment, an in-space development effort will be required to verify operation in the operational (i.e., low-g) environment.

Propellant Tank Sizing

The existing Delta IV 5-m-diameter upper stage uses a propellant loading of 60,000 lb and is designed to meet the requirements of delivery to LEO, GTO, and direct insertion to GEO with the present RL10B-2 upper-stage engine.

Adding a higher-performance upper-stage engine, or using the upper stage to enter a TLI or other higher energy orbit can be best achieved by matching propellant loading to engine and mission requirements. In the case of Delta IV, the upper-stage basic design is preserved, as the modular tanks are stretched to meet lunar or even interplanetary trajectory requirements. Preliminary analyses suggest that an evolved Delta IV upper stage using an MB-60, RL-60, or three RL10 engines and matched increased propellant upper stage would be an optimized combination for a TLI stage, as shown in Figure 9.

TLI Stage Mission Scenarios

A human lunar-landing architecture approach (i.e., number of payloads, mass, geometry) has not yet been selected as an element of the Exploration initiative. Some payloads may be launched directly to a TLI trajectory; some may transition to a lunar polar orbit from L-1; while others may be launched to LEO, assembled into a larger system, and then injected on a TLI trajectory using a dedicated stage, illustrated conceptually in Figure 10.

The Delta IV upper stage or the DC US-derived TLI stage could be used as a conventional multi-burn upper stage. This could support a scenario for lunar robotic missions or for more elaborate missions to pre-position hardware in lunar orbit or at L-1—instead of LEO—prior to in-space integration and checkout, (illustrated conceptually in Figure 10).

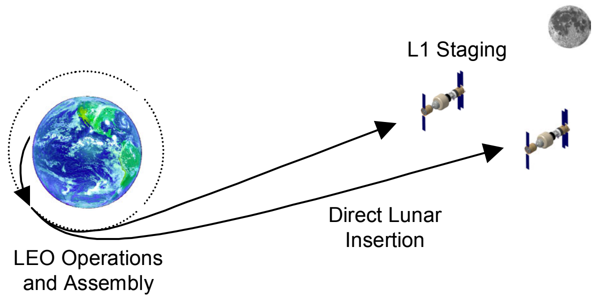


Figure 10. A Delta IV-Derived Upper Stage can Provide Versatile Support for a Range of In-Space Transportation Requirements

Payloads can be delivered to a TLI trajectory using two main engine burns: the first burn to reach LEO, followed by a coast to optimum position, then a second burn to inject into the TLI trajectory.

As long as the spacecraft payload includes orbital insertion capability, mission duration is envisioned to be similar to the current stage operation and no extended-duration kits would be required.

An alternative scenario could be to provide for longer duration cryogenic storage and use of the stage to place the spacecraft at L-1 or in lunar orbit. Reusability of the long-duration stage could provide significant system cost benefits. In such an architecture, additional propellant would be supplied to a refueling site at L-1 or in LEO to enable stage reuse.

The Delta IV upper stage could also be launched as a payload. In this scenario, a fully fueled DC US would be delivered to LEO in standby mode (duration TBD based on mission architecture) waiting for all other elements to be integrated in preparation for sending the integrated stack to the Moon or beyond. An adapter, similar to the current interstage structure, would be required to connect the payload to the launch vehicle. The fueled upper stage would remain in LEO while the lunar stack is being assembled. The TLI injection burn(s) would then be accomplished at the end of this standby/assembly phase. The optimum design of the propellant and thermal control systems depends on the duration of this standby/assembly period.

SPIRAL DEVELOPMENT OF THE DELTA IV-BASED LAUNCH SYSTEM: ADDITIONAL BENEFITS

In addition to a spiral-development upgrade of the Delta IV as a cost-effective means of meeting emerging NASA Exploration requirements, the use of the existing Delta IV system and infrastructure will provide additional cost benefits and synergies to Exploration requirements. There are three independent synergies that are available to NASA and the Exploration initiative through the use of the already operational Delta IV launch system:

- Potential reduction in demonstration launches and costs.
- Utilization of existing ETO infrastructure in the definition of an Exploration architecture.
- Benefits in shared crewed/non-crewed launch systems or elements.

The benefits to Exploration in these area can be summarized as follows.

Improving Flight Demonstration Affordability. Current NASA ground rules require contractors to include the cost of three demonstration launches in new vehicle development programs. This has the potential of incurring increased demonstration costs that are a significant element of the total development effort. Undoubtedly, crewed systems will require extra flight validation, but for larger cargo vehicles with the largest per-flight cost, this leads to potentially excessive costs. In the EELV program, the Air Force is performing only one heavy demonstration flight before flying high-value U.S. government payloads. For the inaugural Delta IV mission (M+ 4,2), Boeing flew an actual commercial payload, as did Lockheed Martin's Atlas 5. By reducing the number of demonstration flights of the unmanned cargo vehicle to a single mission, while retaining a larger number of demonstration missions for the presumably smaller and lower cost human-rated launch vehicle, NASA could achieve substantial cost benefits, while maintaining demonstrated reliability. Alternatively, as with Apollo (where Pegasus micrometeoroid detection satellites were launched on early Saturn Vs), NASA could identify low-risk payloads suitable for launch on the demonstration launches.

ETO Launch Potential Drivers. It is worthwhile noting that, in most cases, payload size directly corresponds to payload cost. NASA has had good success in executing a robust interplanetary, space science, and Earth science program using the constraints of the Delta II to keep payloads affordable—Exploration may benefit from similar sizing discipline in developing the key Exploration architecture elements. Identifying the lowest cost path for heavy-lift growth is a worthwhile exercise at this stage in the Exploration Vision, and it would be beneficial to understand the most cost-effective spiral development approach for launch vehicles to facilitate near-term, cost-constrained Exploration element sizing. This approach may prove especially valuable in the early years of the exploration program, possibly through its lunar phase, where resources are especially tight and lift requirements are likely to be more modest.

Human/Non-Human Potential Synergies. Although affordability would seem to be in conflict with prioritizing crew safety, this is not necessarily the case. A crewed vehicle based closely on an existing expendable launch vehicle could tie into its operational tempo benefits: historically, vehicles that launch often tend to have higher reliability. Moreover, a crewed vehicle based on an already existing launcher can benefit from the detailed flight history and operational insights gained well in advance of the first crewed flight. To accomplish this, it is recommended that changes between crewed and uncrewed vehicles be minimized—an approach that also leads to lower development costs.

The option of using a three-CBC launch vehicle sharing the existing EELV launch infrastructure with the Air Force and other users may offer the lowest DDT&E and, possibly, the lowest life-cycle cost of any option, while providing higher demonstrated reliability.

SUMMARY

We have illustrated the potential of gaining significant new space transportation capability to meet the emerging requirements of the Exploration initiative, based on affordability-driven enhancements to the existing and operational Delta IV launch system. As applied to Earth-to orbit performance, we have described a set of enhancements that could effectively double the lift capability of the Delta IV Heavy launch vehicle. These performance upgrades minimize non-recurring development cost, and schedule and safety risks by leveraging the substantial development already achieved in bringing the Delta IV family to its current operational status.

We have described additional potential affordability benefits available to the development of in-space transportation systems based on enhancing the existing Delta IV upper stage. The DC US, with modifications for longer mission durations, offers the potential to provide a major enabling element (TLI/IST stage) required for future exploration missions.

Finally, we have described synergistic benefits to the Exploration initiative that relate to using a launch system such as Delta IV with its substantial infrastructure capacity, thus providing reliability and cost benefits from increased utilization across multiple programs (USAF and NASA/civil space), and across multiple missions (cargo delivery and human transportation).

Delta IV spiral development growth decisions should be made through concept feasibility and development studies in conjunction with the overall Exploration architecture to establish specific benefits and identify risks. Boeing is continuing to evaluate the options for growth described herein through its IR&D program and in coordination with NASA.

Defining and implementing an affordable space launch and transportation approach may be the key to shaping the overall exploration architecture for success.