

Depot-Centric Human Spaceflight:

Strengthening American Industry, Creating a Robust Beyond-LEO Exploration Program, and Enabling the Commercial Development of Space

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Executive Summary

On-orbit storage and transfer of propellants are key capabilities that enable innovative transportation methods for multiple destinations beyond earth orbit, stimulate the commercial spaceflight industry, and allow for sustainable and affordable manned exploration beyond LEO using existing commercial launch vehicles. We find reason to believe that a depot-centric transportation approach will allow NASA's manned space program to operate in a manner that is exceptionally responsive to the objectives given the Augustine Committee.

We would like to suggest an architecture combining existing medium-lift vehicles with small, simple orbital propellant depots. We believe this architecture will provide for manned operations beyond LEO, including to the lunar surface, in a shorter time-frame, at lower federal expense, and with lower planning or mission risk than any architecture relying on heavy-lift boosters. We believe this architecture provides for greater commercial participation than any heavy-lift alternative, and enables flexibility in planning and operations both short and long term.

Depots allow NASA to use existing launch vehicles, allowing it to focus its efforts on actual exploration. Depots make heavy lift vehicles purely optional for manned spaceflight to the Moon, Near-Earth Objects, and possibly Mars as well.

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Depots are a Realistic Near-Term Transportation Option

Historically, solutions to transportation logistics problems like those faced by space travel beyond LEO, have always involved the caching of propellants or supplies. Orbital propellant depots continue the historical trend embodied in supply caches for early Antarctic expeditions, naval coaling stations during the age of steam warships, and forts and way stations during the Mormon pioneer migration to Utah and the settling of the American West.

Most of the technologies required for first-generation propellant depots have already reached a high level of maturity. Many of the technologies needed for depots, such as propellant settling and pressure control, are related to those of cryogenic upper stages. Over the past several decades, various commercial and government entities working on upper stages, like the Centaur, Saturn S-IVB, and Delta III/IV upper stages, have matured these technologies in order to extend the capabilities of their own systems. This places most of the technologies needed for implementing first-generation propellant depots at a high readiness level². In order to mature the few remaining pieces of the puzzle, ULA and NASA are building a cryogenic orbital test bed (CRYOTE) that can fly as a secondary payload on Atlas V. A version of the same apparatus, suitable for flight on suborbital vehicles, is also being investigated by Masten Space Systems. There are also synergistic programs being funded by DARPA and other defense entities, such as the recently completed Orbital Express program, investigating autonomous rendezvous and propellant transfer.

The intriguing reality is that depots are actually more technologically mature today than orbital rendezvous was at the time of the Apollo mission-mode decision. At the time, NASA made the difficult and audacious (but ultimately vindicated) decision to accept the risk of the Lunar Orbit Rendezvous mode, years before anyone had successfully performed an orbital rendezvous. In the end, the decision to use a riskier but more innovative mode, and then to aggressively pursue and retire the technical risks, enabled NASA to avoid the budgetary, schedule, and programmatic risks of building the super heavy Nova launch vehicle. Had they not taken this calculated risk, the program probably would have been unsuccessful. All programs have risks, but it is important to make sure that the risks NASA takes are enabling risks—risks that, when retired, enable safer, more capable, more affordable, missions.

While the decision to use Lunar Orbit Rendezvous enabled NASA to forego at least the development of super-heavy launch vehicles, LOR still required the development of a Saturn-V class HLV. The lack of sustainability of the HLV approach was illustrated by the fact that the program was already starting to wind down before Neil Armstrong's boots touched the lunar surface. Pursuing orbital propellant depots is an enabling risk that avoids this sustainability trap, and eliminates the need for NASA to build and operate its own launch vehicles at all, allowing it to use existing commercial launch vehicles instead.

² Kutter et al. *Settled Cryogenic Propellant Transfer*. AIAA 2006-4436.

Depots are Responsive to the Committee’s Objectives

While HLV-centric architectures provide shuttle workforce retention, depot-centric architectures are significantly more responsive to the objectives of the Augustine Committee:

Objective	Depot-Centric Architectures	HLV-Centric Architectures
Expedite a new U.S. capability to support utilization of the International Space Station	<ul style="list-style-type: none"> • No launch vehicle development on critical path for sending crew/cargo to ISS • Synergistic with commercial ISS resupply needs—uses the same launch vehicles 	<ul style="list-style-type: none"> • Requires significant launch vehicle development before ISS crew capability is ready • EELV work for crew access and COTS do not synergize with beyond-LEO elements
Support missions to the Moon and other destinations beyond Low-Earth Orbit	<ul style="list-style-type: none"> • Support lunar, NEO, and Mars/Venus orbital missions with existing boosters and payload fairings • Inherently multi-destinational • Enables both commercial and international partners to participate in beyond LEO activity 	<ul style="list-style-type: none"> • Capable of supporting NASA-run lunar, NEO, and Mars surface missions
	<ul style="list-style-type: none"> • Mars and Venus surface missions are possible but may require more EDL work or larger fairings. 	
Stimulate commercial spaceflight capability	<ul style="list-style-type: none"> • Provides large, elastic markets for launchers • Can benefit from improvements in launch vehicle technology • Incentivizes RLV development 	<ul style="list-style-type: none"> • Does not stimulate commercial spaceflight other than via COTS • Cannot as easily benefit from improvements in launch vehicle technology.
Fit within the current budget profile for NASA exploration activities	<ul style="list-style-type: none"> • No HLV development means expedited lunar hardware development and earlier lunar surface missions • Low fixed cost gives more flexibility in balancing operations and developing new capabilities • Enables COTS-like efforts for crew/cargo delivery beyond LEO 	<ul style="list-style-type: none"> • Current architecture is estimating first lunar landing in 2028 if constrained to current budget • Other HLV architectures more affordable, but still push lunar hardware development out • High fixed-costs result in low lunar mission rate, and hard to balance lunar efforts vs. Mars hardware development

Depots Enable Cheap and Reliable Access to Space

Large-scale utilization of outer space will never happen without significant improvements in the cost, reliability, and maturity of space transportation. Non-depot, HLV-centric architectures do little or nothing to address these problems. Depots, however, by their very nature, enable and encourage continual improvements in the affordability and safety of space transportation.

Propellant depots allow a lunar transportation network to immediately take advantage of new advances in low-cost earth-to-orbit transportation: Advances like RLVs and inexpensive ELVs like the SpaceX Falcon series of launchers. This allows the cost of lunar and other missions to decrease over time. Depot architectures allow NASA to avoid being trapped with high fixed-cost transportation modes that do not benefit as much from improvements in launch costs.

Not only can depots take advantage of lower launch cost developments when they occur, but they actually help drive launch cost innovation. At low flight-rates, fixed-costs dominate the per-launch cost of any launch system. By requiring high flight-rates, depots can help significantly lower the cost of propellant on-orbit, while also lowering the cost of launches for other purposes, including science, national defense, and commercial missions.

Launch vehicle reusability is one of the keys to lowering the cost of delivering people and material to orbit. However, the solution to developing such systems has proven elusive because RLV development involves both technical and market challenges. Depots can help provide markets for RLVs; because propellant is infinitely divisible, and even a minimalist depot-centric lunar architecture could provide enough demand to justify the development of small RLVs. While providing price-elastic demand for low-cost orbital delivery doesn't guarantee that RLVs will immediately appear, it would make it substantially easier for companies to privately raise the money needed to try. NASA can thus help promote private investment in launch technology improvements by merely buying the services it needs from existing providers.

Depots enable the reuse of in-space assets such as transfer stages, tugs, and landers. The ability to get multiple uses out of in-space hardware can greatly increase the affordability of lunar transportation. As a corollary, by making it substantially easier to field tugs, depots also enable tugs to offer repair, life-extension, and hardware upgrade services for satellites and space telescopes.

Depots are also critical to effectively utilizing propellants produced in-situ on the Moon, Mars, or elsewhere. Without depots, such propellants can only refuel an ascent stage. With depots, descent, earth-return, and interplanetary stages can be refueled as well. This will drastically reduce the amount of mass needed to deliver a payload or person to planetary surfaces and other destinations beyond LEO—possibly by as much as half. This combination of depots and ISRU enable transportation beyond LEO to reach commercially useful price points, thus making the system more sustainable.

Depots Help Reinvigorate America's Space Industry

Depots allow America to begin to regain its intellectual, technical, and manufacturing preeminence, by allowing organic business growth independent of federal budget and procurement cycles. By allowing for a more open and modular transportation architecture, depots enable the creation of new businesses and wealth along the way. By separating the launch and in-space segments of transportation, it is easier for small companies to compete in providing various elements of a transportation network. An HLV-centric program funnels funding and procurement decisions through a monolithic federal process at direct taxpayer expense, and fails to provide the benefits of small and medium business creation. Due to the cost of development, HLVs inherently tend toward fragile, inflexible point-design *architectures*, instead of inherently robust and continuously evolving transportation *networks*.

Depots help provide the launch demand needed to make the US launch industry healthy, innovative, and internationally competitive again. Providing enough demand to allow for a healthy launch industry will help attract private investment in launch development, leveraging and enhancing NASA's investments in those technologies. This increased demand will also enable the investment environment needed for successfully fielding privately-developed reusable launch vehicles. Providing a healthy and growing domestic launch capability also ensures the access to space the US needs for national security purposes.

A depot-centric transportation network enables and encourages the development of an open architecture—one that multiple commercial and international entities can easily interact with and that is not tied to any one specific destination. Doing so provides unprecedented opportunities for small and medium business, by breaking space transportation into niches small enough that smaller groups can meaningfully participate. It is worth noting that the success of the personal computer and the phenomenal growth of the Internet relied on these same benefits of open architectures and small, modular components. We can further multiply this effect through the use of prizes and COTS-like programs, as well as more traditional SBIR and Broad Area Announcement solicitations. An HLV-centric architecture, on the other hand, provides, at best, only limited opportunities for the vast majority of American businesses to participate. Those who do participate do so only as providers of specialized components to a single prime contractor.

An open architecture greatly improves international cooperation in space as well. International partners can carry propellant to depots on available boosters, greatly reducing single-partner mission risk. Given that depots lend themselves well to commercial operation, it is reasonable to expect that, as in any other mature industry, international engagement will manifest itself as a rich variety of business-to-business commercial interactions, rather than the more limited government-to-government interaction exemplified by previous international space projects. Moving near-Earth operations onto this diverse commercial footing will enable American business to more readily participate as we expand our economic sphere into this new territory.