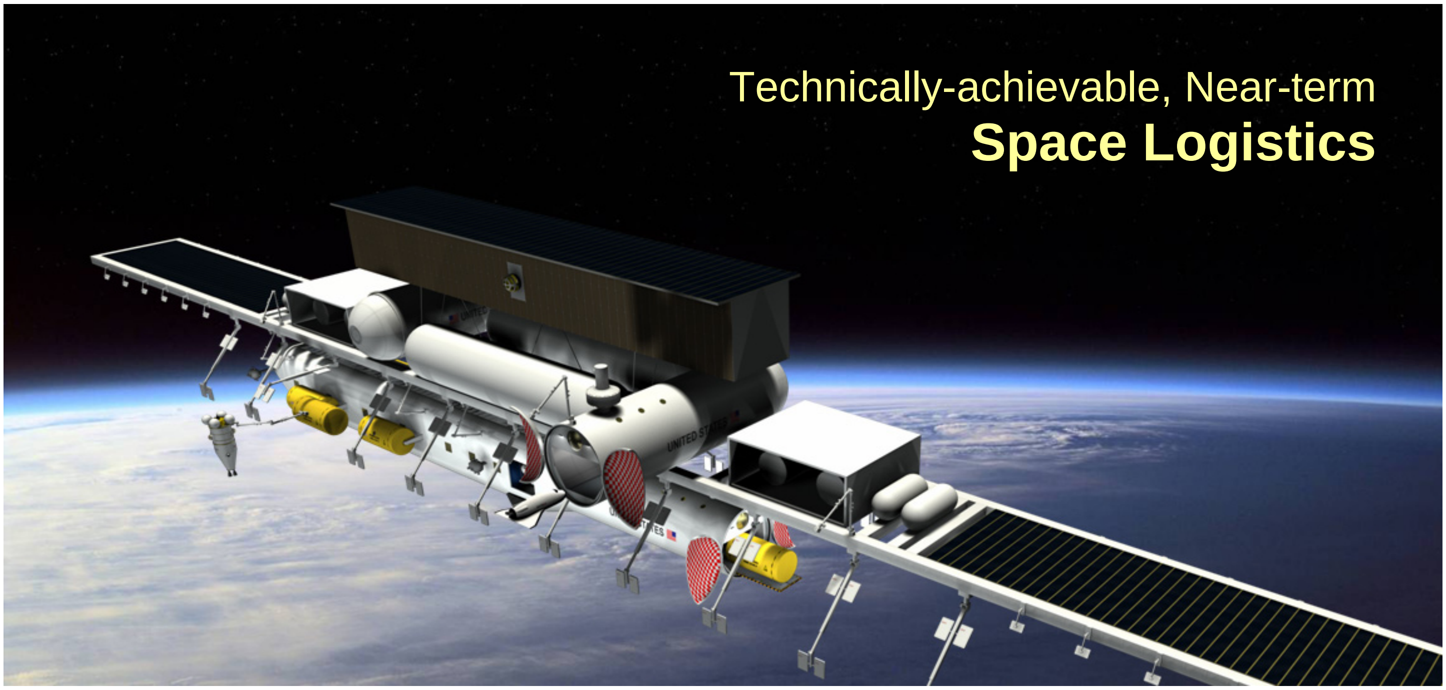

James Michael Snead, P.E.

Throughout human history, the drive to explore new frontiers has been quickly followed by the equally powerful drive to settle the new frontier. Thriving societies establish integrated logistics networks to enable people to move and settle new lands; to supply them with needed food, supplies, and tools not locally available; to create new economic wealth through trade, to maintain family, cultural, and political ties; to enhance security; and to undertake further exploration and discovery.

The expansion of human activities into space will follow this proven path. From terrestrial spaceports, new spaceways to and within the Earth-Moon system and new off-world logistics bases will be established to enable practical human and robotic space exploration, enhance national and planetary security, enable new commercial enterprises, and, sooner than we today expect, establish permanent human settlements in space.

Role of logistics

In any enterprise, logistics is the foundation upon which all other operations are based. Logistics operations conduct research and development; acquire systems; procure commercial capabilities and services; provide materiel, energy, communications, security, trained operators and maintainers; provide on-site habitat, sustenance, recreation, and medical support; transport materiel and personnel; supply and maintain on-going customer operations; and, in the end, recover materiel and personnel. All governmental and commercial operations share a common need for safe, operable, affordable, and sustainable logistics executed within an integrated logistics infrastructure.

Importance of space logistics

Today, it is evident that U.S. governmental and commercial space operations share a common need to improve their ability to operate safely, effectively, and affordably in space. In 2001, the Congressionally-chartered *Commission to Assess United States National Security Space Management and Organization* identified this as their primary finding. “The Commission unanimously concluded that the security and well being of the United States, its allies and friends depend on the nation’s ability to operate in space.” The following year a second Congressionally-chartered commission also emphasized the need for improved logistics. The *Commission on the Future of the United States Aerospace Industry* concluded: “The nation will have to be a space-faring nation in order to be the global leader in the 21st century—our freedom, mobility, and quality of life will depend on it. America must exploit and explore space to assure national and planetary security, economic benefit and scientific discovery. At the same time, the United States must overcome the obstacles that jeopardize its ability to sustain leadership in space.”

Clearly, to maintain U.S. leadership in space, effective and affordable space logistics capabilities need to be established. This article describes how the U.S. can respond to this challenge using current technologies to establish an integrated space logistics infrastructure, operating throughout the Earth-Moon system, to significantly expand government and commercial

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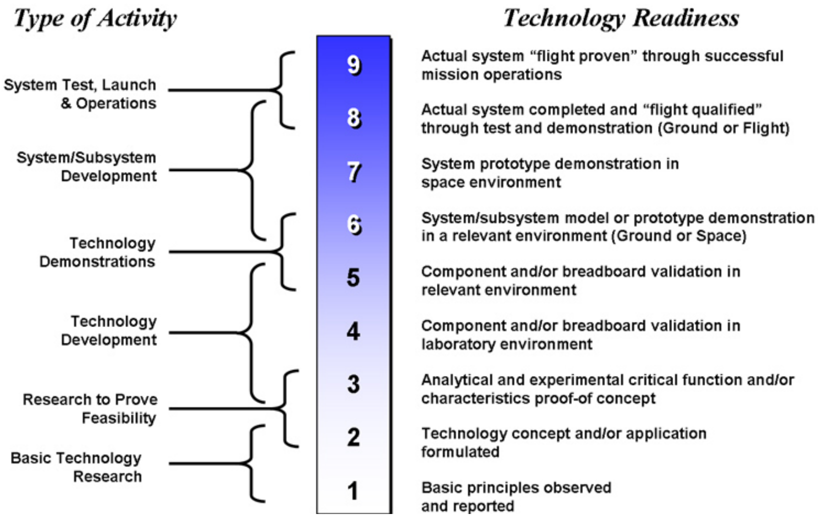


Technology Readiness Scale used to assess the maturity of technologies to be applied to new development programs.

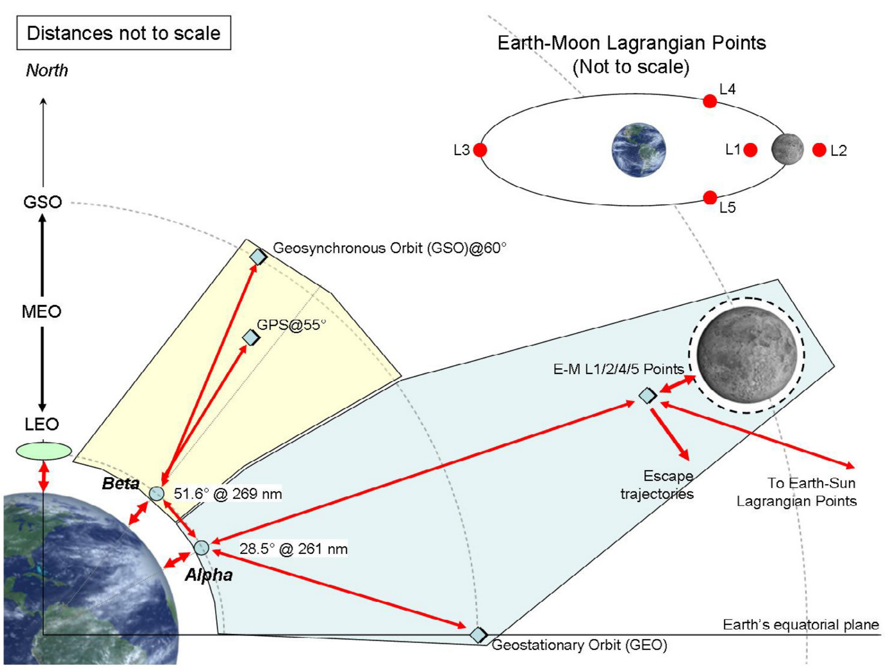
space operations and revitalize the U.S. aerospace industrial base.

Near-term solutions

In the late 1930s, Sir Robert Watson Watt, was charged with developing an early warning system that could be integrated with fighters and anti-aircraft guns to defend Great Britain from bomber attack. A new technology solution—what became radar—was needed, as the old methods of ground-based observers did not always give sufficient warning to permit the fighters to scramble and climb to the altitude and location necessary to intercept the incoming bombers.

Sir Watson Watt applied his "Law of the Third Best." He argued that when responding to critical near-term needs that cannot be satisfied through available systems, the "best" solution never comes and the "second best" solution takes too much time. Instead, he argued, identify the "third best" solution—"the one that can be validated and deployed without unacceptable cost or delay."[1] The third best solution is not a retreat to past technical solutions. Rather, it is a pragmatic application of near-term technologies to achieve affordable solutions.

In applying this Law of the Third Best to identifying a solution to overcome the obstacle of the lack of an integrated space logistics infrastructure, the approach discussed in this article focuses on the use of mature technologies as identified by their Technology Readiness Level (TRL). The TRL scale, commonly used in the aerospace industry, ranges from a minimum value of 1 for basic principles observed and reported to a maximum value of 9 for the actual system operations. Within the aerospace industry, it is generally accepted that when the enabling technologies reach a TRL of 6—"system/subsystem model or prototype demonstration in a relevant environment (ground or space)"—the technologies are sufficiently mature to support a decision to initiate system development. Using this TRL 6 criterion, a pragmatic, but forward-looking, selection of currently available aerospace technologies can enable an integrated space logistics infrastructure to be established throughout the Earth-Moon system.



Spaceways within the Earth-Moon system accessible with near-term reusable space access and in-space mobility systems

Earth-Moon system spaceways

The spaceways route map, shown at the left, covers the Earth-Moon system. Using TRL 6-9 space access and in-space mobility systems described below, terrestrial spaceports can be linked with orbiting space logistics facilities in low Earth orbit (LEO) to provide access to most destinations of interest within the Earth-Moon system.

Two orbiting space logistics nodes, accessed initially from the primary U.S. terrestrial spaceport in Florida, will be established in LEO to provide a "common" destination to regularize space access. The first of these at 28.5 degrees inclination (Alpha node) will link Florida to destinations in geostationary orbit (GEO), the Earth-Moon Lagrangian points, and low lunar orbit. This will enable:

- Enable new GEO operations, such as high-power communications and observation satellites, to be assembled and logistically supported;
- Enable a logistics node to be established at the L1 Lagrangian point to support lunar surface explorations anywhere on the Moon's surface;

- Enable a new space telescope to be assembled and logistically supported at the L2 point;
- Enable inner and outer solar system missions to be initiated from L1; and,
- Enable the return of lunar resources, such as lunar-derived oxygen, from the Moon to be established via the L1 or L4/5 points.

The second LEO space logistics node will be located at 51.6 degrees inclination (Beta node). Initially this will provide support for the International Space Station (ISS) in the 51.6 degree inclination orbit and support for Global Positioning System satellites in their 55 degree inclination orbit. It will also enable support for national security and earth observation satellites in a variety of high inclination orbits and it may provide a preferred location for a space tourism hotel as its higher inclination orbit enables a larger percentage of the Earth's surface to be observed.

Establishing aircraft-like space access

Fundamental to deploying a useful space logistics infrastructure is achieving aircraft-like space access for passengers and cargo. The objective is safe, operable, and increasingly less expensive space access—what "aircraft-like" means in this context.

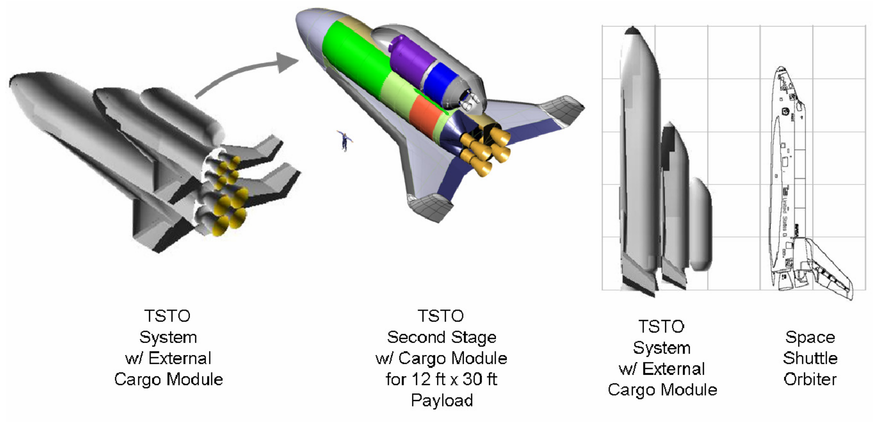
Accomplishing this objective requires new, fully-reusable space access systems developed, produced, tested, and operated using aircraft-style systems engineering principles and practices. Only such fully-reusable space access systems will meet a fundamental threshold of aircraft-like operations where each *production* flight system can been demonstrated, through acceptance flight testing, to be operationally safe and suitable before it is placed into service to routinely carry cargo and passengers.

The first generation fully-reusable systems will not be single-stage solutions, such as the National Aerospace Plane/X-30 or VentureStar/X-33. These represent the "first best" solution that is not yet technologically achievable (TRL 2-3). Nor will the solutions be two-stage systems incorporating advanced scramjet air-breathing or hybrid rocket propulsion systems, as these represent the "second best" solutions that would take too long to develop (TRL 3-5). The desired third best solution is a rocket-powered, two-stage, vertical-takeoff system for which sufficient technical information and understanding exists to enable reasonable conceptual designs to be defined *and* for which acceptable cost, schedule, and technical risk assessments can be made (TRL 6-9).

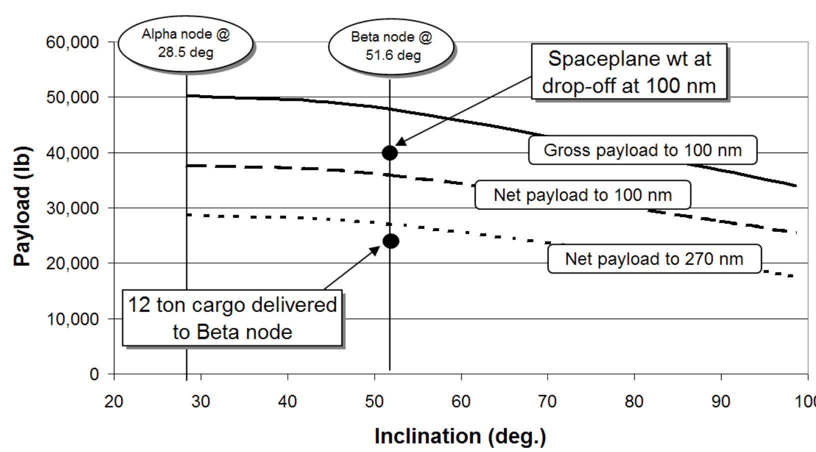
Conceptual design studies, undertaken by the Air Force Aeronautical Systems Center and Air Force Research Laboratory at Wright-Patterson Air Force Base and closely correlated with similar design studies undertaken by industry, show that the development of TRL 6-9, two-stage-to-orbit (TSTO), fully-reusable space access systems can now be undertaken. A representation of the design and performance of the types of systems addressed in these studies is seen in the figures above and below, respectively.

Achieving assured space access is an important systems architecting requirement for an integrated space logistics infrastructure. This will be accomplished by deploying (at least) two design- and manufacturing-independent fully-reusable TSTO space access systems. The initial fleet will consist of six operational flight systems with three of each design. With each flying on average once per month, the initial fleet flight *capacity* will be approximately 50 flights per year. As turn-around time decreases as the system matures—consistent with aircraft-like operations—the fleet flight capacity will increase to about 100 flights per year. Assuming an 80/20 split of cargo to passenger missions, this fleet could transport approximately 12 tons per mission x 80 missions or 960 tons of cargo and 20 missions x 10 passengers or 200 passengers to LEO each year.

To emphasize this key point, *building fully-reusable, aircraft-like TSTO space access systems can now be undertaken to transport pas-*



Two-stage-to-orbit (TSTO) fully-reusable space access concept developed by the Air Force Aeronautical Systems Center and the Air Force Research Laboratory, Wright-Patterson AFB, OH. The unmanned cargo configuration is shown carrying a Space Logistics Vehicle tug. For passenger transport, a small spaceplane is carried in place of the external cargo module.



TSTO reusable space access system estimated gross payload delivery performance to Alpha and Beta space logistics nodes and high inclination orbits.

sengers and cargo to LEO. This critically needed revolution in space access will:

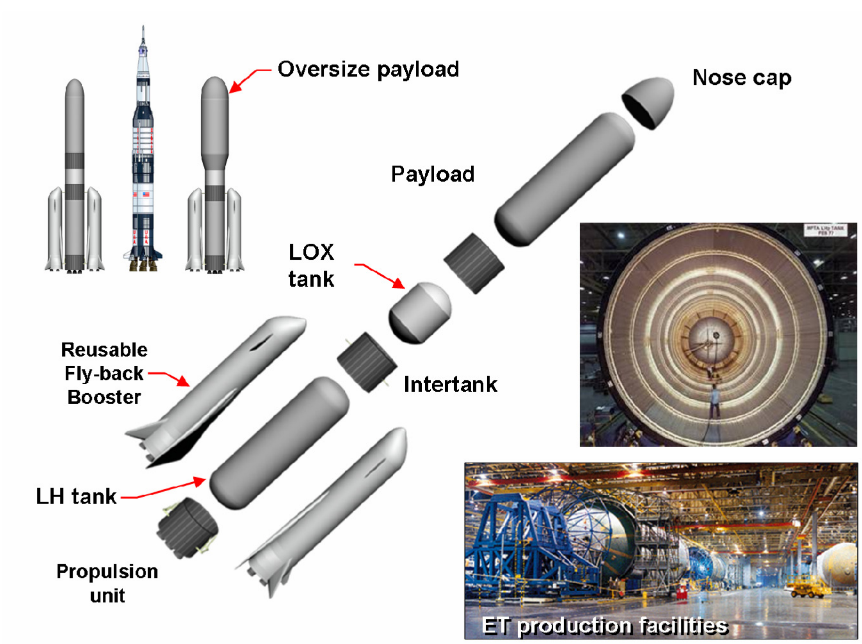
- Provide assured space access with improved aircraft-like safety and operability to support critical government space launch needs;
- Provide extra capacity to support increasing commercial and government space launch demand consistent with lower costs and increased safety and operability;
- Provide sufficient capacity to establish the initial LEO logistics nodes and services described below; and,
- Strengthen the U.S. aerospace industrial base to prepare for the competitive follow-on development of second- and third-generation reusable space access systems.

Shuttle-derived heavy spacelift

All forms of terrestrial mobility include unique systems to transport heavy and oversize components, e.g., the C-5 Galaxy aircraft. Establishing the capability to launch heavy and oversize payloads to the LEO space logistics nodes will be critical to creating an integrated space infrastructure serving a broad customer base. The "third best" solution is to develop a Shuttle-derived system that can launch large government and commercial payloads and also be used to launch the large orbiting facility and spacecraft assemblies necessary to establish permanent in-space logistics support capabilities.

The concept of a Shuttle-derived system to create a system comparable to a Saturn-V stretches back to the 1970s. The general idea has been to replace the Shuttle's orbiter with a cargo carrier, but otherwise reuse the remaining Shuttle system elements. As we enter the 21st century, this approach is now outdated. Improved manufacturing capabilities for the large propellant tanks, the use of reusable boosters in place of the Solid Rocket Boosters; the sizing of the vehicle to meet the specific payload performance needs of the space infrastructure; the benefits of a vertically-stacked arrangement; and, the potential to reuse the core propellant tanks in space indicate that an updated launch system will be needed.

An important part of this conversion is updating the current manufacturing and launch operational support facilities. The External Tank manufacturing facilities in Louisiana will need to be modernized to incorporate new propellant tank production technologies, e.g., spin forming, and expanded to enable the design and production of customized large space assemblies such as the space hangars, space hotel, and large spacecraft modules described below. The Vehicle Assembly Building and associated launch system support infrastructure at the Kennedy Space Center will also need to be updated to conduct the final assembly and checkout the new launch system and payloads. Finally, the Shuttle launch pads will need to be configured to support the new launch system's design.



Shuttle-derived heavy space launch system uses a vertically-stacked arrangement to provide flexibility in carrying oversize payload and enhance the ability to reuse the core propellant tanks in building large orbiting facilities. This configuration uses fully-reusable "fly-back" boosters based on the design of the first stage of the fully-reusable, TSTO space access systems.

LEO space logistics node facilities

Four types of initial facilities will be initially deployed to each of the LEO space logistics nodes: space construction shacks, space logistics base, space hotel, and space propellant depot. The first three are described below.

Space construction shack

The space construction shack concept is modeled after the Skylab space station. These will be the first units deployed to the LEO space logistics nodes. Launched as a single unit by the Shuttle-derived system, these shacks will provide living quarters for the assembly crew; provide power, life support, and orbit station-keeping to the facility modules during assembly; and, provide direct pressurized access to the space logistics base's modules during on-orbit assembly to minimize extravehicular activity. Two construction shacks will be used at each node to provide redundant habitats for the assembly crews and to maintain positive control of the base modules as it is being assembled.

Space logistics base

The initial primary orbiting facility at each LEO node will be a space logistics base. It will support and enable support and reusable mobility operations to be undertaken throughout the Earth-Moon system. The five primary components of the base will be the operations module, the twin pressurized space hangars, the air storage system, and the space dock.

The operations module straddles the twin hangars. It will provide the command and control facilities for the base, emergency medical facilities, crew and visitor quarters, recreational facilities, and internal storage. Like the other large modules for the base, the operations module is launched using the Shuttle-derived launch system with the core oxygen and hydrogen propellant tanks remaining attached to the payload to be reused as part of this module.

Twin space hangars, facing in opposite directions, sit below the operations module. Comparable in size to the first stage of the Saturn V, the hangars are 33 feet in diameter and 120 feet in length. This large size will enable on-orbit servicing to be shifted from extravehicular operations, as has been done on the Hubble Space Telescope, to shirt-sleeve maintenance within a pressurized environment. Entire satellites, smaller spacecraft, or large assemblies will be serviced within either the main hangar deck or the aft spherical work bay. Bench level support for smaller components, e.g., avionics, will be undertaken within the upper work compartments.

For depressurizing the hangar, air will be pumped into the two sets of storage tanks located between the two hangars. These tanks will be the recycled core propellant tanks from the two Shuttle-derived systems used to launch the two hangars.

A structural truss sits below the hangars and air storage tanks. It provides the structural foundation for the base, supports part of the base's solar arrays and waste heat radiators, and provides attachment points for the robotic arms and lights that constitute the space dock. This space dock will be used to assemble large space facilities and spacecraft, to externally store construction materiel, and to secure spacecraft between missions.

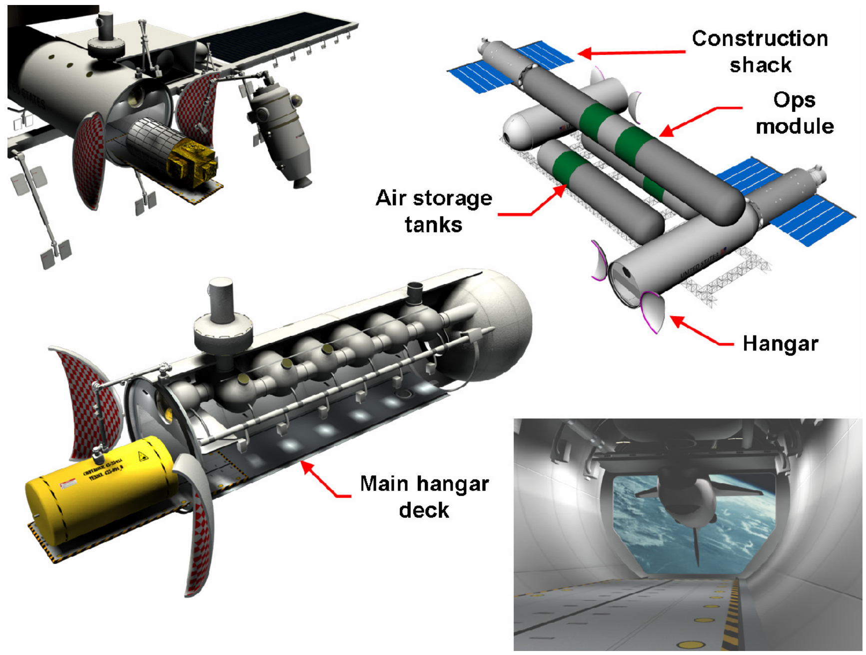
Space hotel

The improved safety and regularization of passenger space access provided by the first generation fully-reusable space access systems will enable more people to travel to LEO and create a demand for increased living space in LEO. To meet this need, a 100-person space hotel will house government and civilian travelers to augment the crew and visitor quarters available at the space logistics base. It will also provide facilities for on-orbit government and business operations and enable commercial space tourism operations to begin.

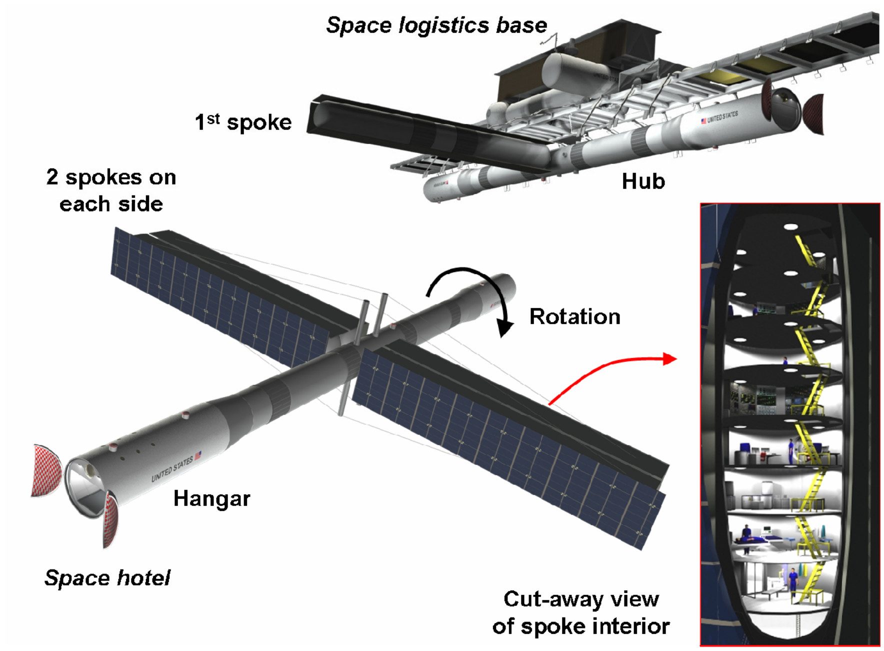
One configuration for such a hotel is to rearrange the components used to assemble the space logistics base into a hub and spoke configuration. The space hangars are incorporated into the hub while the operations module becomes a spoke. In both the hub and the spokes, the core propellant tanks from the Shuttle-derived launch system are recycled into the structural design. In this manner, only seven launches of the Shuttle-derived system will be needed to launch the necessary modules to provide a four-spoke space hotel with approximately 25,000 sq. ft of floor space in the four spokes.

This particular configuration—one of several that could be developed—enables artificial gravity to be produced in the spokes by rotating the hotel about the hub's longitudinal axis. The maximum gravity level will be about 0.3 g at the end of the spokes. This artificial gravity will assist in providing comfortable and safe living accommodations for guests while the "zero-g" experience will be provided in special, safety-designed facilities in the hub.

The space hotel will be assembled using the space logistic base's space dock to receive,



The space logistics base's hangar will have three maintenance areas: the main hangar deck, the aft spherical work bay, and the upper work compartments. A small passenger spaceplane is seen entering the main hangar deck for on-orbit inspection before returning to the Earth.



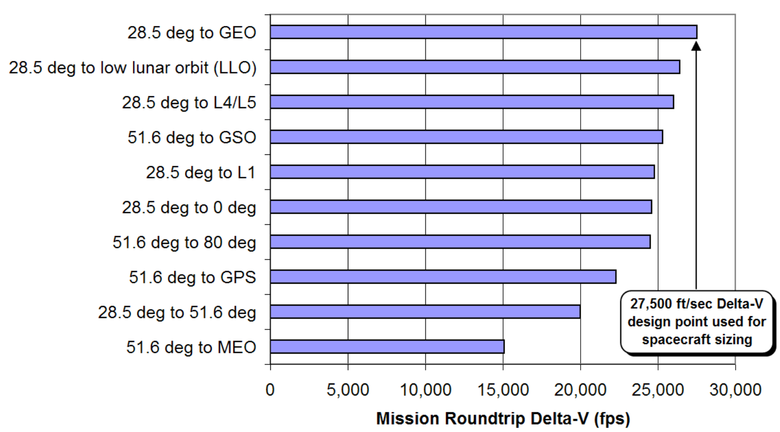
Hub and spoke configuration space hotel rotates about the hub to produce artificial gravity in the spokes. This enables the spokes to be arranged with floors.

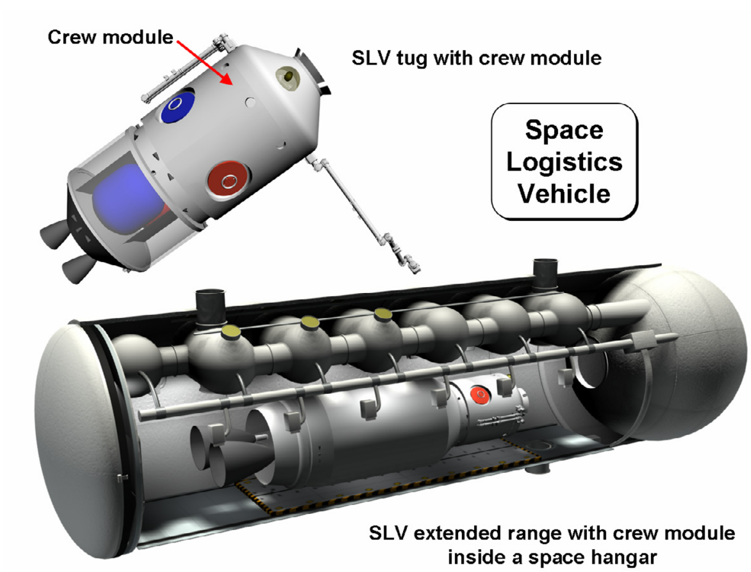
position, and hold the components during assembly. The space construction shacks will again be used to house the assembly crews and provide access to the hub and spoke modules during the final on-orbit preparations for mating.

The potential impact of even a modest 100 person space hotel on the requirements for passenger transport will be significant. With 75 guests per night, the space hotel will host about 4,000 guests per year, assuming a one week average stay. This will create the demand for about 500 additional passenger and cargo missions each year. The potential transport revenue of $5 billion per year, at $10 million per mission for example, may be sufficient to stimulate private investment in developing second-generation reusable space access systems tailored to passenger transport.

This space hotel configuration is expandable, allowing twelve spokes to be attached to the hub. This will provide about 75,000 sq. ft. of floor space and accommodate about 300 people. Spokes specifically configured to meet research, educational, hotel, and business needs can be designed and added to the baseline four-spoke hotel to meet demands for increased on-orbit capabilities. For example, spokes specifically configured with research labs at the Moon and Mars artificial gravity levels would enable research, development, testing, and training of human extraterrestrial surface exploration systems to be undertaken with greater confidence.

Round-trip Delta-Vs within the Earth-Moon system using only rocket propulsion show that most destinations of interest are achievable with reusable spacecraft having performance of approximately 27,500 ft/sec Delta-V.





In-space mobility

In 1950, Robert A. Heinlein, noted science fiction author, wrote, "*Get to low-earth orbit and you're half way to anywhere in the solar system.*" One of the primary functions of the LEO space logistics facilities is to support routine mobility within the Earth-Moon system for passengers and cargo. Assessing the mission Delta-V requirements to provide this mobility indicates that a design requirement for appropriately 27,500 ft/sec, plus an allowance for mid-course corrections, rendezvous, and docking, will enable LEO-based spacecraft to reach and return from most destinations of interest.

Of particular interest is the overlap in mission performance requirements between those within geostationary orbit—missions of primary interest to commercial and national security operations—and missions beyond geostationary orbit. *A class of fully-reusable spacecraft designed to access geostationary orbit (GEO) from the Alpha node will also have sufficient performance to support space operations to the Lagrangian points or low lunar orbit. Hence, spacecraft designed to deploy or service satellites in geostationary orbit will have a dual mission capability to provide transportation to support human space exploration missions to the Moon.*

Space Logistics Vehicle

The first fully-reusable, space-based spacecraft will the Space Logistics Vehicle (SLV). These are medium-size, conventional, rocket-powered systems that, by employing a modular design, range in size from a tug to an extended range version.

The SLV tug will support LEO space logistics node operations. Initially deployed with the space construction shacks, it is sized such that, with the crew module attached, it fits within the cargo module of the full-reusable space access system. Based at the construction shack and then at the space logistics base, it will ferry cargo between a 100 nm drop-off orbit and the higher 270 nm altitude of the LEO space logistics nodes. The SLV tug will also support materiel handling associated with assembling large space structures and undertake space search and rescue missions.

The SLV extended range (SLV/ER) configuration will establish the first fully-reusable space mobility capability throughout the Earth-

Moon system enabling routine satellite deployment and the beginning of onsite satellite servicing. While initially the SLV/ER will be sized to perform unmanned missions to GEO for satellite delivery or onsite servicing, later versions will be upgraded to provide passenger transport capabilities between LEO Alpha and Beta nodes and throughout the Earth-Moon system.

Space Logistics Transport

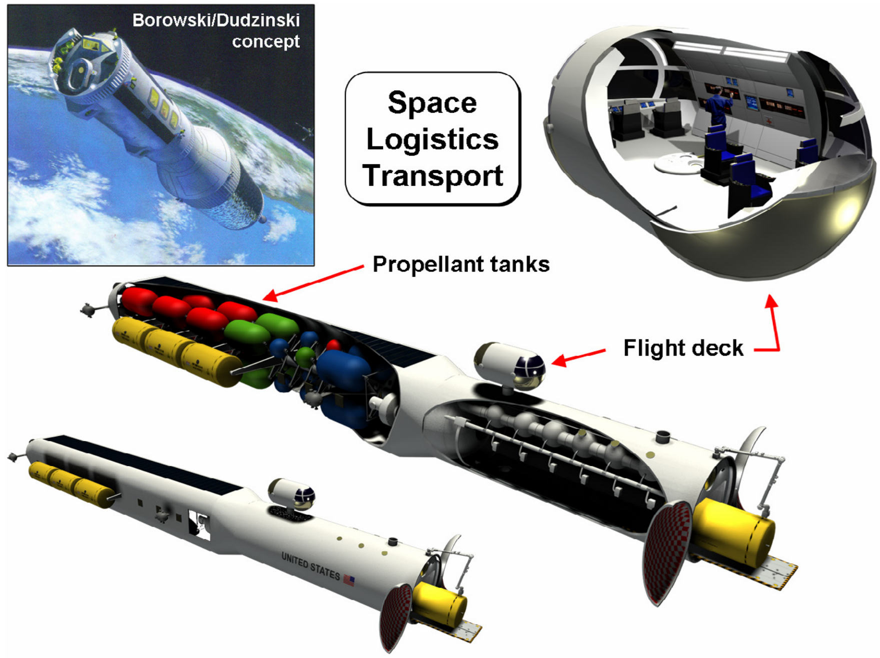
In the mid-term, space logistics operations will grow to enable and support expanded human and robotic operations within the Earth-Moon system. An important element of this growth will be expanding the ability to conduct on-site logistics support operations—inspection, servicing, repair, assembly, replenishment, and upgrade—where needed within the Earth-Moon system.

Early logistics support operations—equipment maintenance, training, component replacement, upgrades, test, and inspection—within this integrated space logistics infrastructure will be designed to use the LEO space logistics bases' pressurized hangars. As human and robotic space operations move beyond LEO, the ability to reuse existing subsystem designs and associated logistics support capabilities will make such operations more attractive and affordable. Hence, the need for space hangar-based maintenance and support anywhere within the Earth-Moon system may be expected to emerge in the mid-term. For example, the design of a lunar shuttle to ferry passengers and cargo between the L1 point and the lunar surface may be based on the SLV/ER. Since the SLV/ER would be designed for in-hangar maintenance and support, it may be expected that a lunar shuttle would also require in-hangar maintenance and support.

This need for mobile, on-site logistics servicing support will be provided with the Space Logistics Transport (SLT). This will be a large manned spacecraft, assembled at the LEO space logistics base's space dock, which incorporates a modified space hangar. It is an expanded version of a similar spacecraft concept proposed by Stanley Borowski and Leonard Dudzinski of NASA Glenn Research Center in 1997. Like their concept, the SLT will incorporate liquid oxygen-augmented nuclear thermal propulsion to enable round-trip missions within the Earth-Moon system without the use of aerobraking.

An example mission of the SLT would be to support the deployment of a new class of GEO satellites that require final on-site assembly of such elements as large solar arrays or large aperture antennas. The SLT would be parked in GEO to serve as a temporary operations base. An SLV tug would be taken along to provide on-site handling and positioning of satellite components while the SLT itself would serve as the temporary "space dock" tp position and controll the satellite as it is assembled. SLV/ERs would be used to ferry satellite components to GEO and rotate SLT crew members. The SLT's space hangar would be used to prepare the satellite components for installation, to service the SLV tug, and to support emergency rescue and assembly "glitch" recovery operations. Once assembly and checkout is complete, the SLT would return to its LEO space logistics base for maintenance and replenishment.

A similar mission to support human exploration operations on the Moon would be to position the SLT at the L1 point or in low lunar orbit. SLV/ERss would ferry passengers, cargo, and propellants to the SLT where these would be loaded onto SLV-derived lunar shuttles to ferry these to the lunar surface bases. To support initial permanent human operations on the Moon, SLTs could be kept permanently stationed at the L1 point with individual SLTs rotating back to the LEO space logistics base for maintenance and replenishment. Eventually, these SLTs would be replaced by a permanent space logistics base stationed at L1.



Space Logistics Transport combines a large space hangar with a liquid oxygen-augmented nuclear thermal rocket to provide mobility and on-site servicing support within the Earth-Moon system.

Organization and Funding

The space logistics infrastructure systems architecture described in this article emphasizes the use of TRL 6-9 technologies, especially for improved fully-reusable space access systems. This is in contrast with other recent efforts, such as the National Aerospace Plane/X-30 and VentureStar/X-33, where TRL 2-5 technology approaches were unsuccessfully used to attempt to achieve significant performance improvements. *The critical importance of this distinction in the TRL of the enabling technologies is that by us-*

ing TRL 6-9 technologies, uncertainties associated with performance, cost, and schedule will be minimized. This, in turn, enables these new space logistics capabilities to be acquired with an organizational and funding approach in line with building infrastructure rather than a traditional government approach using annually-appropriated funds for development and production.

Space Logistics Authority

Complex public infrastructure projects are generally undertaken through special government organizations. These may be referred to as commissions, as in the Panama Canal Commission, or authorities, as in the Tennessee Valley Authority. Through legislative action, these not-for-profit organizations are created and vested with the authority to raise funds and initiate public works. They also manage the collection of fees and tolls; retire debt; direct the operation, maintenance, and improvement of the new infrastructure; and, contract with private enterprises to use the new capabilities.

By using mature technologies, building the much needed space logistics infrastructure can be undertaken as a public infrastructure project. This permits necessary funds for the design and production phase to be raised by a newly-created space logistics authority selling government-backed bonds rather than relying on annual federal appropriations. This combination of increased technology maturity and yearly funding assurance will translate into a development effort that is significantly lower in cost and of shorter duration than an effort undertaken through more traditional government aerospace system development approaches.

Establishing a new government-industry partnership that emphasizes the use of competitive commercial capabilities and service providers is a vital element of this approach. The space logistics authority will direct the overall effort, select and approve specific approaches through competitive bidding, take ownership of the key capital equipment and facilities, manage the contractors that operate the infrastructure, and raise and disburse the funds. This approach will create substantial new opportunities for U.S. aerospace companies of all sizes—many expected to be new—as they compete to develop and operate the many elements of the initial infrastructure.

Funding

While modern logistics infrastructure is a crucial foundation of a technological civilization, it is also an element of a nation's economy that generally requires government financial underwriting through monopolies, tax subsidies, debt forgiveness, grants, or direct ownership and operation. Space access and, increasingly, the other elements of space logistics are important to the U.S. economy and critical to its national security. Recognizing this, Congress has consistently sustained funding to ensure space access to support national security needs and maintain a human space program.

Current federal government annual appropriations for space access operations total $5-6 billion each year. Over a period of 25 years, this would provide a financial pool of $125-150 billion that could be used to pay for the recurring operating costs of the two modest fleets of reusable space access systems and to retire the public debt incurred for their development and production. By emphasizing the use of mature technologies, the cost of development and production could be debt financed like most government infrastructure programs. Once operations begin and the old launch systems are retired, the same level of annual federal appropriations—$5-6 billion per year—would then be applied to meet the new recurring operational costs for government space launches and to retire the debt. This means that the development of two fully-reusable space access systems—as the first elements of an integrated space logistics infrastructure—could be undertaken without requiring increases in current annual appropriations.

Conclusion

In the early days of supersonic jet fighter design, the area-ruled or wasp-waist fuselage design concept provided an innovative solution to overcoming the large drag coefficient rise at sonic velocities. It enabled many new supersonic military fighter aircraft to be built that were otherwise not possible with the then available jet engine performance. One of these aircraft, the Air Force T-38 supersonic trainer, is still in operation.

The United States has an analogous situation with finding an affordable solution to the clear need for improved space logistics. The innovative use of today's technologies, combined with a port authority-type government-industry partnership, can provide the needed logistics bridge to a true spacefaring future. This approach is worthy of serious consideration by government and industry.

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[1] Arthur M. Squires, *The Tender Ship: Governmental Management of Technological Change*, Birkhäuser, 1986, p. 122.