40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit
11-14 July 2004, Fort Lauderdale, Florida

AIAA 2004-4068

Architecting Rapid Growth in Space Logistics Capabilities

James Michael Snead[*]
Beavercreek, Ohio 45430

This paper describes how the United States can develop, deploy, and operate an integrated, commercial-based, space logistics infrastructure to undertake its transition into a true spacefaring nation. The paper first addresses historical examples and the benefits arising from building new logistics infrastructure. It relates this experience to the advantages that building an integrated space logistics infrastructure would have on human space operations and the growth of other Government and commercial space enterprises. The paper continues with a description of an example space logistics architecture and its logistics functions that would provide basic spacefaring capabilities. The paper then describes example systems, comprising this architecture, which would provide safe and routine access to and from space for passengers and cargo, mobility within the Earth-Moon system for passengers and cargo, and in-space logistical facilities and services. Special attention is given to achieving near-term reusable space access. The paper concludes with a discussion of how the commercial space logistics services and suppliers could be established and organized through a new federal space logistics corporation that would contract for commercial logistical services for Government space operations while also supporting commercial space operations.

Acronyms

ELV = Expendable Launch Vehicle
EELV = Evolved Expendable Launch Vehicle
LH = Liquid hydrogen
LEO = Low Earth Orbit
LOX = Liquid oxygen
NTR = Nuclear Thermal Rocket
RLV = Reusable Launch Vehicle
ROM = Rough Order of Magnitude
SHS = Super Heavy Spacelifter
SLV = Space Logistics Vehicle
USSLA = United States Space Logistics Authority

I. Introduction

FOR those who share the dream of becoming a true spacefaring civilization, the last three decades have been tough. The first decade of the 21st century has not turned out even remotely similar to that which was envisioned in the 1950s and 1960s as the nation charged into space. The dream is fading; it is time to fix this.

Let us turn back the clock over five decades to a time that was closer to the Wright Brothers' first powered flight than to today. Its 1947 and the crack of the passage of a sonic boom from a high-flying supersonic aircraft (Fig. 1) punctuates the silence of the Mojave Desert for the first time, thus signaling the

Figure 1: XS-1 in flight.

---

[*] P.E.; chair, AIAA Space Logistics Technical Committee; AIAA Senior Member, jamesmsnead@aol.com

beginning of routine flight faster than the speed of sound—an accomplishment then generally believed by the public to be impossible due to the existence of a "sound barrier" to supersonic flight. Following this milestone, aerospace capabilities rapidly progressed through three spirals of research and development. The first was applying jet power to subsonic aircraft to produce such capable aircraft as the B-52 and KC-135. The second was advancing aircraft design to supersonic and low hypersonic flight culminating with the famed SR-71, XB-70, and X-15. And, the third was building the first generations of space launch systems and spacecraft capable of orbiting the Earth and transporting astronauts to the Moon and returning them safely to the Earth. All of this was accomplished in only 22 years; just the time needed for someone born the year the sound barrier was "broken" to grow up, complete college, and start to work. Becoming a true spacefaring nation by the early 21st century was a "given" in the 1960s as the space dream firmly took hold and the American aerospace industry exhibited a very strong "can do" spirit pushing the edges of the envelope and then delivering on its promises.

In planning the future of American space activities, it is important to recognize that *human space exploration is but one element of what a true spacefaring nation will undertake in space*. Space, being a true frontier, will first be explored and then settled by undertaking a wide range of human enterprises. While human space exploration will certainly be an important and leading part of these enterprises, it will quickly be dwarfed in magnitude by the other human enterprises undertaken in space once the barriers to routine and safe travel to, and living in, space are overcome. This may sound like a fanciful dream, but consider this: At any moment, hundreds of thousands of humans are living not on the Earth but in habitats self-powering their way through atmospheric conditions that cannot support human life. We call it flying and take air travel for granted because it has become quite safe and comfortable. With comparable advancements in astronautics, within the next hundred years or less, hundreds of thousands of humans can be living temporarily in self-powered habitats—called spacecraft—transiting the inhospitable environment of space without giving space travel a second thought. Where might they be going? To wherever human enterprises exists in space: perhaps to the Moon, to Mars, or to human-built space colonies orbiting the sun, or even to a different star system. Considering the advances in technology since the Wright Brothers first flew, it is difficult to project human accomplishments in space travel in the next century. However, we can be certain that, given the means, human civilization will expand beyond this planet of its birth.

This dream of becoming a spacefaring nation is very important to many Americans and, especially, to many American aerospace professionals. Therefore, it is very important that we fully explore the potential to realize this dream as American space policy is being reassessed and, potentially, redirected. *The purpose of this paper is to provide an overview of how America's aerospace industry could undertake the development and construction of a new national space logistics infrastructure—an infrastructure suitable for moving America beyond being only a human space exploration nation to becoming the first true human spacefaring nation.* This space logistics emphasis would move America boldly forward into the 21st century with new civil, commercial, national security, and scientific exploration capabilities. These capabilities would enable America to lead the world in the development and application of astronautics technologies and commerce, just as America rapidly advanced and applied aeronautics capabilities in the later half of the 20th century for significant economic benefit and enhanced national security.

Please note that each section of the paper begins with an overview and a list of key points discussed in that section. This paper is organized into the following sections:

I. Introduction
II. Background Information
III. Near-Term Space Logistics Architecture Example
IV. Near-Term Reusable Space Access
V. Shuttle-Derived Super Heavy Spacelifter
VI. Near-Term Orbiting Logistics Facilities
VII. Near-Term Space Mobility Systems
VIII. Organization and Funding
IX. Conclusion

II. Background Information

A. Overview and Key Points

Space is a new frontier in which human enterprises do not yet occur routinely. What is lacking is the existence of a suitable space logistics infrastructure. Opening new frontiers through building new logistics infrastructure has been one of the keys to American economic growth and enhanced national security. This history provides valuable insights into why *building space logistics capabilities is an enabling step in becoming a true spacefaring nation*. Key points discussed in this section are:

1) The importance of becoming a true spacefaring nation is well recognized by prominent Americans as documented by two recent congressionally directed aerospace commissions.
2) Becoming spacefaring means to develop the technical and operational experience, skills, capabilities, and industrial base needed to master operations in space to support not only scientific discovery, but also the equally important areas of national and planetary security, economic benefit, and human settlement.
3) American history demonstrates that building new logistics infrastructure is an important and proven means of developing mastery of operations in new frontiers and that such infrastructure building has been an important element enabling economic and social development in the United States for over 200 years.
4) Space logistics is defined as the science of planning and carrying out the movement of humans and materiel to, from, and within space combined with the ability to maintain human and robotics operations within space. This definition is derived from the common definition of military logistics.
5) Space logistics was recognized as an important element of the American space program when the program's implementation strategy was developed in the 1950s. Abandonment of the space logistics elements of the initial space exploration scenario, during the shift to the timeline of the Apollo program, did not foster the orderly development of spaceflight capabilities and transition to a broader human space enterprise.
6) Defining the top American human space program goals and objectives only in terms of scientific exploration has previously failed to garner sufficient political support, as seen from the Space Exploration Initiative experience. It is possible that this was due to a lack of planning focus on establishing the enabling space logistics capabilities that would permit the space exploration objectives to be achieved as part of an expansion of human space enterprises including space commercialization.

B. The Importance of Becoming a True Spacefaring Nation

In 2002, the Commission on the Future of the United States Aerospace Industry (referred to herein as the Aerospace Commission) was chartered by Congress to "study the issues associated with the future of the U.S. aerospace industry in the global economy, and the industry's future importance to the economic and national security of the United States."[1] This commission reported its findings and recommendations in November 2002. It emphasized the importance of America being a spacefaring nation:

> The Commission concludes that the nation will have to *be a spacefaring 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*.[2] (Emphasis added)

But what exactly should being a "spacefaring nation" mean? How should this guide space policy formulation? The American Heritage Dictionary of the English Language defines spacefaring as "the launching of vehicles into outer space." With this definition, America already meets the Aerospace Commission's standard for success in the 21st century and has since the late 1950s. Yet, within the context of the purpose of the Aerospace Commission and its conclusion—America becoming a "spacefaring nation" in order to "be a global leader in the 21st century"—the commission's finding clearly implies more than just launching vehicles into space or simply leading in space exploration. It also emphasized leadership in space-derived security and economic benefit.

In 2001, the Commission to Assess United States National Security Space Management and Organization (referred to herein as the Space Commission) also addressed this point when it noted:

> The first era of the space age was one of experimentation and discovery. Telstar, Mercury and Apollo, Voyager and Hubble, and the Space Shuttle taught Americans how to journey into space and allowed them to take the first tentative steps toward operating in space while enlarging their knowledge of the universe. We are *now on the threshold of a new era of the space age, devoted to mastering operations in space*.[3] (Emphasis added)
>
> Mastering near-earth space operation is still in its early stages. *As mastery over operating in space is achieved, the value of activity in space will grow*. Commercial space activity will become increasingly important to the global economy. Civil activity will involve more nations, international consortia and non-state actors. U.S. defense and intelligence activities in space will become increasingly important to the pursuit of U.S. national security interests.[4] (Emphasis added)

These important findings clarify that being a spacefaring nation is far more than simply launching vehicles into space, and it is more than undertaking only a reinvigorated human space exploration program to the Moon and Mars. *To become a 21st century spacefaring leader, America must develop the technical and operational experience, skills, capabilities, and industrial base needed to master operations in space—and not just for scientific discovery, but also for the equally important areas of national and planetary security, economic benefit, and human settlement.* While America's current spacefaring capabilities have not achieved this level of mastery, with appropriate investment in space logistics capabilities, this objective can be achieved—and, as discussed in this paper, could be achieved surprisingly soon.

C. The Importance of Building Logistics Infrastructure

In 2004, America is celebrating one of its most prominent Government-sponsored scientific explorations with the 200th anniversary of Lewis and Clark's *Corps of Discovery*. American passion for new knowledge and scientific exploration remains a key driving force in establishing national priorities and policy.

Figure 2: National Road built from Cumberland, Maryland (1815) to Vandalia, Illinois (1840s).

In 1802, just prior to the start of the Lewis and Clark expedition, the Government initiated another important precedent—building national logistics infrastructure. That year, U.S. Secretary of the Treasury Gallatin succeeded in having a provision added to the bill authorizing the formation of the State of Ohio for funding road construction in the new state. This led to Congress approving, in 1806, building the first national highway across 1,300 km (800 miles) of wilderness to connect Cumberland, Maryland[*] with the Mississippi River (Fig. 2). *This legislation established the precedent for all later federal infrastructure development programs.*[†] After the completion of route surveys, the initial construction contracts for what we now refer to as the "National Road" were released in 1811. The first important link across the Allegany Mountains to the Ohio River was completed in 1818, following a delay due to the War of 1812. Building the road "formally" stopped near Vandalia, Illinois, in 1841. By that time, railroads were fast becoming the preferred form of transportation. Yet, during its primary years of operation through the 1850s, the National Road was the central artery of America moving new settlers west to the newly opened territories and moving goods and produce to the metropolitan markets of the east to sustain their burgeoning populations. In the late 1870s, one old timer recalled, "The wagons were so numerous that the leaders of one team had their noses in the trough at the end of the next wagon ahead and the coaches, drawn by four or six horses, dashed along at a speed of which a modern limited express might not feel ashamed."[5] As a recent news report noted, one could travel from the Atlantic Ocean to the Mississippi River without getting lost—a remarkable achievement across what had been the wilderness of a new frontier only a generation earlier.

The pending completion of the first leg of the National Road in 1818 may have prompted the building of the next great infrastructure project—the Erie Canal linking Lake Erie with the Hudson River near Albany. Initiated by New York Governor Dewitt Clinton in 1817, following up on his initial proposals as mayor of New York City[‡], the nearly 580 km (363 mile) long canal was to provide an important transportation link between the upper Ohio Valley and

---

[*] Cumberland, Maryland, was selected because an existing private road ran from Baltimore to Cumberland. This approach leveraged existing private investment and did not place the Government in a position of competing with private enterprise.

[†] Determining an acceptable funding method for building the National Road was a major political accomplishment. In Ohio, Indiana, and Illinois, funding for construction of this road was stipulated in the enabling legislation granting statehood with funds being raised through the sale of federal lands in these new states. Later legislation permitted the states to establish tolls on the road to support its maintenance and repair.

[‡] The initial idea of the Erie Canal was made by surveyor Cadwallader Colden in 1724. In 1805, Jesse Hawley wrote essays advocating building the canal. In 1808, Judge James Geddes of Syracuse, New York, conducted what is today called a technology demonstration program to show how the canal could be built.

northern New York State with the port at New York City and, from there, Europe. Seven million dollars in funding was secured through the state government. The canal was completed in 1825.[*] [†] [‡]

Building the canal was a significant engineering accomplishment involving 83 locks and 18 aqueducts over rivers and ravines. It rose 172 m (568 ft) from the Hudson River to Lake Erie and was capable of transporting boats carrying 27 metric tons (30 tons) of cargo.[6] [§] A very rough estimate is that 3,500-7,000 workers were employed each year during the construction of the canal.[**] When the canal was completed, the cost of shipping bulk cargo from Buffalo to New York dropped to five percent of the cost of shipping by land.[7] This spurred an increase in shipments of wheat, for example, from 3,600 bushels to over 1 million bushels within 15 years, helping New York City to become the busiest U.S. port.[8] Ohio followed New York's lead and built nearly 1,600 km (1,000 miles) of canals to interconnect Ohio commerce with Lake Erie, the Erie Canal, and the Ohio River.

The financial and economic growth successes of these early infrastructure programs fostered further Federal Government-led efforts from the railroads of the 1860s through the Internet and Global Positioning System of the 1980s. In 1985, President Reagan issued a proclamation addressing national transportation systems. It began, "Our Nation's history can be traced through the development and growth of transportation in America. Our country has grown as transportation has given us access to new geographic, economic, and technical frontiers." Hence, as American history unmistakably illustrates, *building new logistics infrastructure, especially transportation, is a successful means of applying or exploiting new technology, creating industrial knowledge and capabilities, and providing for and encouraging economic growth—all vital to opening new frontiers. The United States can use these successes, with confidence, to guide its national investments in space logistics infrastructure and related astronautical technologies and enterprises—investments required to become truly spacefaring.*

D. Defining Space Logistics

A useful working definition of space logistics can be taken from the following generally accepted definition of military logistics:

> The science of planning and carrying out the movement and maintenance of forces. In its most comprehensive sense, those aspects of military operations that deal with:
> 1) Design and development, acquisition, storage, movement, distribution, maintenance, evacuation, and disposition of materiel;
> 2) Movement, evacuation, and hospitalization of personnel;
> 3) Acquisition or construction, maintenance, operation, and disposition of facilities; and,
> 4) Acquisition or furnishing of services.[9]

Adapting this definition for logistics in support of space operations and looking to the future expansion of human activities into the central solar system, the following definition of space logistics has been developed by the AIAA Space Logistics Technical Committee:

> Space logistics is the science of planning and carrying out the movement of humans and materiel to, from, and within space combined with the ability to maintain human and robotics operations within space. In its most comprehensive sense, space logistics addresses the aspects of space operations both on the Earth and in space that deal with:

---

[*] The Federal Government would not support the proposed Erie Canal. Thomas Jefferson called it a "folly," perhaps leading to the well-known name of "Clinton's Folly" used by its detractors.

[†] To provide some perspective on the relative cost of the Erie Canal, recall that the Louisiana Purchase, undertaken in 1803 by President Jefferson, was made for fifteen million dollars using funds borrowed from Great Britain.

[‡] The Erie Canal, which cost 10 percent more than was originally budgeted, paid for itself within 9 years. Through 1882, when tolls were ceased, New York collected $121 million.

[§] The first rebuilding of the Erie Canal, from 1836 to 1862, increased the barge capacity to 218 metric tons (240 tons) of cargo. The next upgrading starting in 1905, overseen by New York Governor Teddy Roosevelt, increased the barge capacity to 2,700 metric tons (3,000 tons). The second rebuilding utilized new steam-powered earth-moving and construction technologies and created the industrial base used five years later, through President Teddy Roosevelt's initiative, to build the Panama Canal.

[**] With an average worker's pay of between $0.50 and $1.00 per day, this yields an annual workforce of approximately 3,500 to 7,000, without taking into account any seasonal adjustments.

1) Design and development, acquisition, storage, movement, distribution, maintenance, evacuation, and disposition of space materiel;
2) Movement, evacuation, and hospitalization of people in space;
3) Acquisition or construction, maintenance, operation, and disposition of facilities on the earth and in space to support human and robotics space operations; and,
4) Acquisition or furnishing of services to support human and robotics space operations.

E. Space Logistics Lessons-Learned

When the American space program began in the 1950s, as explained recently by Dr. Roger Launius,[*] it was viewed as an "integrated space exploration scenario centered on human movement beyond this planet and involving these basic ingredients accomplished in essentially this order:

1) Earth orbital satellites to learn about the requirements for space technology that must operate in a hostile environment.
2) Earth orbital flights by humans to determine whether or not it was really possible for humanity to explore and settle other places.
3) Develop a reusable spacecraft for travel to and from Earth orbit, thereby extending the principles of atmospheric flight into space and making routine space operations.
4) Build a permanently inhabited space station as a place both to observe the Earth and from which to launch future expeditions to the Moon and planets.
5) Undertake human exploration of the Moon with the intention of creating Moon bases and eventually permanent colonies.
6) Undertake human expeditions to Mars and eventually colonize the planet."[10]

Steps 3 and 4 of this scenario identified the core space logistics aspects of the scenario, probably reflecting a logistically oriented space program popularized by Dr. Werhner Von Braun in the early 1950s.[†] If executed in a deliberate manner, this effort would have led to an initial reusable space access system and permanently manned space station in the mid-1970s and the initial lunar landings in the late 1970s or early 1980s with—one might speculate—subsequent initial Mars human exploration in the 1990s. However, as Dr. Launius discusses, this logistics-centered scenario was abandoned with President Kennedy's decision in 1961 to bypass steps 3 and 4 and proceed directly to the lunar exploration part of Step 5. The logistics foundation for progressively building on success to move from exploration to settlement of the Moon and Mars was not created. Dr. Launius addressed this point:

> Not long after the first lunar landing in July 1969, President Richard Nixon told an assembled audience that the flight of Apollo 11 represented the most significant week in the history of Earth since the creation. Clearly, at least at that time, the President viewed the endeavor as both path-breaking and permanent, a legacy of accomplishment on which future generations would reflect as they plied intergalactic space and colonized planets throughout the galaxy. Dr. Hans Mark, director of NASA's Ames Research Center during the 1960s, recently voiced a less positive result for Apollo. "President Kennedy's objective was duly accomplished, but we paid a price," he wrote in 1987, "the Apollo program has no logical legacy.' *Mark suggested that the result of Apollo was essentially a technological dead end for the space program. It did not, in his view, foster an orderly development of spaceflight capabilities beyond the lunar missions.*[11] (Emphasis added)

With the growing war in Vietnam and the new, federally-funded social programs of the 1960s, one will never know if the original space exploration scenario would have led to an actual lunar landing or whether changing political priorities would have diverted the funding elsewhere. The especially turbulent 1960s and early 1970s make it difficult to say what would "most likely" have happened. What we can conclude with some certainty is:

---

[*] Chair of the Division of Space History at the Smithsonian Institute's National Air and Space Museum and previously the chief historian of the National Aeronautics and Space Administration from 1990-2002.

[†] The 1952-54 publication of Dr. Von Braun's concepts for a future American space program in Collier's Magazine, followed by television shows by Walt Disney, transformed the public's view of space travel from science fiction to achievable science fact. Dr. Von Braun's technical credentials as a world-leading rocket engineer were recognized by the American public and aerospace community.

1) The Apollo lunar landings, Skylab, the Space Shuttle, and the International Space Station have demonstrated the technical feasibility of becoming a true spacefaring nation. Humans living and working in space and on other planets is not just the realm of science fiction as it was in the 1950s when the initial American push into space started. We can anticipate improved spacefaring capabilities resulting from appropriate national emphasis and political support.
2) The Space Shuttle and International Space Station programs have, at a minimum, sustained an American industrial base for large launch systems and human spaceflight. This can now be exploited to initiate the next era of the space age. However, this situation is not static, as the aging of the aerospace workforce and recent industry consolidation are significantly diminishing the industrial base. Each year sees a significant loss in capability and confidence.
3) The impact of not building a sustaining space logistics infrastructure is very clear; the space program has not realized the national benefits, beyond scientific returns, that are necessary to sustain and grow human and robotics operations in space.

One final part of the history of space logistics, relevant to this discussion, was the Space Exploration Initiative proposed in 1989 *largely as a response to the loss of the Space Shuttle Challenger in 1986*. The central theme of this initiative was described as "…back to the Moon, back to the future. And this time, back to stay. And…a journey into tomorrow…a manned mission to Mars."[12] These initiating remarks by President George H. W. Bush led to the preparation and publication of an extensive series of implementing recommendations built around the continued use of the Space Shuttle and the late-1980s version of the Space Station Freedom. The only new near-Earth logistics capability discussed was an unmanned, heavy lift vehicle. This heavy lift vehicle was recommended because "it will require fewer launches to support any architecture, and offers more operational flexibility when launching cargo and piloted missions [presumably the Space Shuttle] in the same year."[13] With an estimated price tag of $700B,[14] substantially influenced by the continued use of the Space Shuttle, and no clear direct benefits outside of the scientific community, the Space Exploration Initiative did not gain political support even among many of the space program's most ardent Congressional supporters.

The important conclusion drawn from the Space Exploration Initiative is that defining the space program's vision and implementation strategy too narrowly, by focusing tightly on just human space exploration, does not provide an economically and politically-viable implementation scenario. The space scientist's natural focus on identifying and resolving underlying scientific questions and communicating new knowledge to the public and political supporters (e.g., Hubble Space Telescope photos and photos from the new Mars rovers and orbiters) is an important element of space program planning. However, it is also important to address the aerospace engineer's focus on developing and deploying beneficial new capabilities, the space logistician's focus on identifying the means to support all space missions practicably, the manager's focus on industrial base utilization, the space entrepreneur's focus on commercialization and wealth/job generation, and the space pioneer's focus on opening space to human settlement and enterprise. Thus, a politically and economically sustainable space program also needs to encourage and enable the early and robust initiation of non-scientific human space enterprises, such as building near-term space logistics capabilities.

III. Near-Term Space Logistics Architecture Example

A. Overview and Key Points

Becoming a spacefaring nation is the vision to be achieved; defining how is a combination of systems architecting and systems engineering. Systems architecting provides the macro view of how the vision can be achieved through the coordinated use of technologically feasible system solutions. Systems engineering adds definition to further define how the architect's solutions can be technically and operationally implemented. Systems architecting and engineering also address the coordinated use of the industrial base to ensure the effective and affordable development, production, and operation of the new capabilities. Key points discussed in the section are:

1) The near-term space logistics systems discussed are those that would enable a significant expansion of human and robotic spacefaring operations.
2) Through the use of available technologies, subsystems, and components, the initial space logistics infrastructure elements could begin initial operation within approximately six years.
3) The infrastructure functions identified address transportation and logistics support for civil, scientific exploration, commercial, and national security operations within the Earth-Moon system and, then, throughout the central solar system.

4) These space logistics capabilities could be developed and operated through a Government–private industry partnership that is primarily, but not entirely, Government-owned and private industry-operated.
5) Systems selection guidelines are defined that emphasize innovation, competition, the early deployment of the new capabilities, the generation of public support for the building of the space infrastructure, and the use of building the infrastructure to encourage and sustain the development of the future aerospace workforce.

B. “Third Best” Objective Used to Guide the Selection of the Space Logistics Examples

In the 1930s, Sir Robert Watson Watt, the British “father” of radar, characterized the type of system he was attempting to develop and deploy to meet Britain’s critical need for air defense. He coined what he called the “Law of the Third Best,” paraphrased as the following: “The best never comes. Second best takes too much time. Design a product that works – the third best – and build it. The third best design is what can be validated and deployed without unacceptable cost or delay.”[15]

The systems architecture objective, used to guide the selection of the example infrastructure architecture and system elements discussed in this paper, was to identify an approach for opening the space frontier for significantly expanded human and robotics spacefaring operations that could be accomplished without unacceptable cost or delay – a third best approach. To be clear, the objective is to quickly deploy capability, not develop technology.

C. Defining “Near-Term”

The development and initial production cycle for aerospace systems typically takes five to ten years to reach an initial operational capability (IOC). The shorter period corresponds to those programs that have adequate funding, good industrial capability, and generally mature technologies—in other words, a “third best” approach. This is accomplished using subsystem and component technologies in production today or nearing production status. Hence, the “near-term” solutions discussed in this paper are those whose development could be initiated almost immediately and whose starting technology maturity should enable their development to proceed in an orderly manner such that flight operations could be initiated within approximately six years of the start of their development.

D. Logistics Functionality Selected

Responding to the space logistics definition discussed earlier, this example space logistics architecture has the following functional capabilities:

1) Transportation of:
    a) Passengers and medium-class payloads to and from low Earth orbit (LEO).
    b) Heavy and oversize cargo to LEO.
    c) Passengers and cargo within the central solar system.
2) Logistics facilities in space for:
    a) Housing for travelers and assigned personnel.
    b) Medical care.
    c) Recreation.
    d) Assembly, maintenance, and repair.
    e) Materiel handling and storage.
    f) Offices and research and development work areas.
    g) Operations control centers.
3) Logistics services in space providing:
    a) Assembly, maintenance, and repair.
    b) Facility and service management.
    c) Miscellaneous services, including: emergency personnel evacuation and medical support; communications; recreation; security; administration; navigation; propellant storage and handling; etc.[*]

E. Government-Industry Collaboration

Large Government infrastructure projects are generally undertaken as collaborative efforts with private industry. Using this approach, the relationship between Government and private industry for establishing and operating the example space logistics infrastructure is depicted in Fig. 3.

A general list of logistics systems, facilities, and services is shown in the middle column of Fig. 3. On the left, Government activities and responsibilities and their linkages to the elements of the middle column are identified. On

---

[*] These areas of space logistics services are not addressed in this paper.

the right, private industry activities and responsibilities and their linkages to the elements of the middle column are identified. The goal of this strategy is to minimize Government operational involvement while maximizing commercial involvement and opportunity.

The Government's responsibilities are divided into three categories. First, is the acquisition of capital equipment such as reusable mobility systems and in-space facilities. Next, is the purchase of reusable and expendable spacelift, in-space mobility, in-space logistics support, in-space facility operations, and terrestrial spaceport services. These include contracting with private industry to operate and maintain the purchased capital equipment. Finally, the Government provides direct services in the form of safety assurance, emergency services, infrastructure oversight, and capital investment funding.

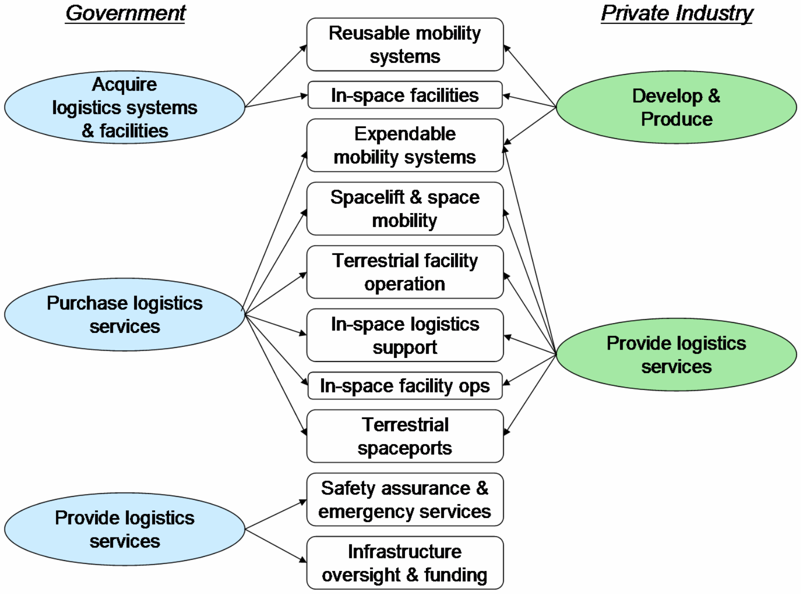

Figure 3: Functional organization of Government and private industry responsibilities to acquire and provide systems, facilities, and services.

Private industry would develop and produce the capital equipment and provide the Government-purchased logistics services. The broad range of private industry involvement—covering design, fabrication, assembly, transportation, operations, servicing, training, and commercial use of the new space logistics capabilities—provides substantial opportunity for creating new businesses and fostering competition.

It is worth noting that the reason why the Government would directly acquire the capital equipment and facilities in this example is that, as with most large Government infrastructure projects, these space infrastructure capital investments will require special government-backed financing. Government ownership is appropriate to ensure fair and competitive access to the space logistics services and facilities enabled by these investments. The Government may also be expected to maintain ownership to ensure that it has assured access to the space logistics capabilities necessary to support critical Government space operations. Further details of this approach, including funding mechanisms, are discussed in Section VIII.

F. Systems Selection Guidelines

Transforming the space logistics architectural capability needs into illustrative space logistics systems was undertaken, using the following guidelines, to implement the "Law of the Third Best:"

1) Provide systems that embrace or can provide the key characteristics of safety, affordability, and operability inherent in terrestrial systems used by or in the proximity of humans.
2) Make effective use of the existing aerospace industrial base capabilities such as adaptations of existing subsystems and components and the use of existing manufacturing and operational capabilities.
3) Ensure that the integrated space logistics capabilities have broad application to civil, commercial, national security, and space exploration missions.
4) Focus on rapidly developing and deploying the new capabilities and then introducing new, enhancing technologies through spiral development.
5) Foster the creation of new competitive commercial suppliers and service providers.
6) Identify and adopt appropriate standards for safety, security, and functional interoperability.
7) Foster public support for the space logistics infrastructure.
8) Encourage the development of the future aerospace workforce.

G. Example Space Logistics Systems

The example or notional space logistics systems, providing the logistics function defined above, are:

1) Reusable launch vehicles (RLV) for routine passenger and cargo transport to and from LEO.
2) An expendable Shuttle-derived super heavy spacelifter for transporting heavy and oversize payloads to LEO.

3) Space logistics bases in LEO from which logistics services are undertaken and at which space mobility systems are based.
4) Modular, mission-transformable space logistics vehicles (SLV) to transport passengers and cargo in space and provide maintenance support for satellites and other space platforms.
5) Space hotel in LEO to provide housing, office space, medical, administrative, and recreational support for people in space.
6) Large manned spacecraft to transport passengers and cargo and provide logistics support services within the Earth-Moon system and, eventually, within the central solar system.

IV. Near-Term Reusable Space Access

A. Overview and Key Points

This section addresses the reasons why reusable, aircraft-like space access is needed and why this is believed to be achievable with near-term systems. Key points discussed in this section are:

1) The Government's forecast of future commercial space launch demand has been trending downward for several years and now does not forecast any growth for the next decade.
2) The Air Force Scientific Advisory Board stated the conclusion, in 2000, that reusable launch vehicles (RLVs) offer "great promise" for growth in both commercial and Government space operations and will be necessary to make space operations affordable.
3) The Government's need for assured space access would appear to require that a minimum of two types of RLVs be fielded.
4) Key near-term RLV design guidelines are defined that emphasize innovation and aircraft-like safety, operability, and utility.
5) Recent Government near-term RLV conceptual design studies have identified example two-stage RLVs that provide suitable cargo and passenger transport to and from Earth orbit and would support building and operating the initial in-space logistics capabilities.
6) The early start of RLV flight operations would stimulate the market demand for improved space access capabilities, leading to Government and private investment in follow-on, second-generation space access technologies.
7) A reasonable RLV fleet would have an annual launch capacity capable of supporting expanded civil, commercial, national security, and space exploration operations in space.
8) Very preliminary recurring cost estimates for these near-term RLVs supports the proposition that aircraft-like RLVs should yield a substantial reduction in the annual cost of Government spacelift.

B. Rationale for the Selection of RLVs

A core belief used in defining this illustrative space logistics architecture is that it should embrace reusable systems and critical subsystems for most elements. A primary area of consideration is defining the systems that will be used to transport passengers and medium-class cargo to and from LEO. To date, all human space transport systems have been fully or partially reusable.[*] If the national space policy is to continue with only limited and extra-ordinary human space operations, then continuing this expendable approach is a candidate for selection for future space mission planning. However, if the primary emphasis is to enable a broad expansion of human operations in space, including the commercial transport of humans to open new market opportunities, then fully reusable approaches should be the preferred choice. Three important considerations help to justify this conclusion: 1) the stagnation of the ELV-based commercial launch market, 2) the predominate terrestrial use of reusable systems , and 3) Air Force Scientific Advisory Board conclusions identifying the need to move to reusable space access systems for meeting future national space launch needs.

1. Improving the Potential for Space Commercialization Growth

Since the early 1960s, with the demonstration of the capabilities and advantages of space-based global communications, space commercialization has become an important element of the U.S. economy. In 2002, "U.S.

---

[*] Some refer to the Space Shuttle as a reusable launch vehicle. However, while the orbiter is reusable, following extensive maintenance and checkout, the external tank and solid rocket boosters constitute significant new and rebuilt components for every mission. Hence, the Space Shuttle is referred to in this paper as a partially reusable system.

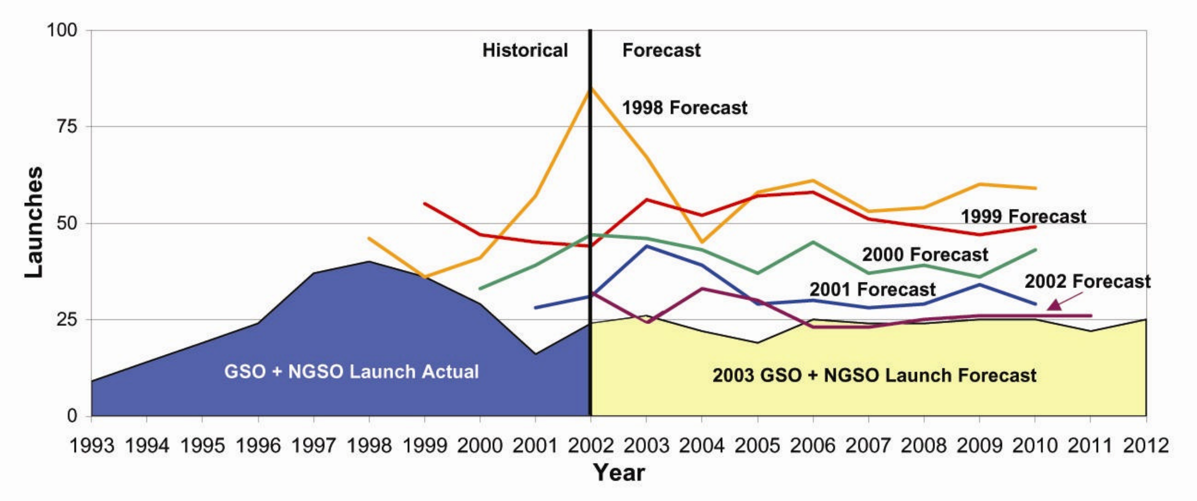

Figure 4: Historical FAA commercial worldwide space transportation forecasts showing the trend of decreasing forecasts for future commercial launch needs.

economic activity linked to commercial space industry totaled over $95 billion and contributed $23.5 billion in employee earnings throughout the United States."[16] This is about one percent of the U.S. Gross Domestic product.

For current space businesses, expendable launch systems have met the space access needs with acceptable cost and risk. However, declining projections of future launch rates and satellite production contracts signify a stagnating technology base and the need to undertake a new approach for encouraging growth.[17, 18] (See Fig. 4 for a depiction of how the Government's projections of future demand for commercial space launches have decreased in recent years.)

Two similar terrestrial analogs of growth stagnation were microwave and landline analog telecommunications and broadcast television. Intentional Government intervention to break up monopolies, open new bands of the radio frequency spectrum to commercialization, and support the creation of cable and wireless digital communication infrastructure created the opportunity for private industry to introduce new technologies and competing services. This initiated the transition to the next era of communications—cable- and wireless-based communications—creating the opportunity for substantial economic growth and rapid technology advancement.

An important lesson learned from the communications industry is that timely and carefully crafted Government intervention to create circumstances for greater competition and new services can jump-start a stagnating industry, yielding substantial public, private, and Government benefit. Applying this model to space commercialization by working with industry to establish substantially improved space logistics capabilities, founded on assured space access for passengers and cargo, should also serve to jump-start this stagnating industry.

2. *Expendables in a world of reusables*

Expendable launch systems are a rare exception in a world generally built on reusability for safety-critical, mission-critical, and economically costly operations. The fact that expendable launch systems exist today may be attributed to President Kennedy's decision, as discussed earlier in this paper, to bypass the slower-to-be-developed reusable space access system in order to accelerate the manned space program. In the late 1950s, expendable launch systems were generally derivatives of ballistic missiles. First with the Soviet Union, and then with the United States, these missiles were adapted to the new role of launching satellites and then humans into space. Had the original space exploration scenario been pursued, fully reusable space launch systems would have been developed in the 1960s and early 1970s and the use of expendable launch vehicles for launching satellites and humans may have been abandoned.

Single-mission expendable systems and key subsystems have generally not been found to be safer and more economical to operate than comparable fully reusable systems. Across a very broad range of applications and technologies, multi-mission, reusable systems are preferred to expendable systems for safety and economy. This is especially true in transportation where virtually everything from shoes to climbing ropes to parachutes to aircraft are fully reusable, with the obvious exceptions of expendable launch vehicles and the partially-reusable Space Shuttle. One reason for this preference for reusables is that it may not be possible to produce a complex expendable item with sufficient quality and adequate protection of public safety while at the same time yielding a sufficient cost advantage over the competing reusable system. Expendable systems require additional manufacturing, transportation, storage, and sales costs per cycle of customer use compared with a quality reusable system. This places expendables at an economic and convenience disadvantage unless no reusable alternative exists, as is the situation today with space access. One would expect that had expendables offered a superior solution in safety- and operationally-critical areas, competition would have identified and introduced these expendable solutions into the marketplace. Yet, the marketplace is almost devoid of such expendable examples.

3. *Air Force Scientific Advisory Board assessment*

In 2000, the Air Force Scientific Advisory Board addressed the reusable launch vehicle vs. expendable launch vehicle debate in the report “Why and Whither Hypersonics Research in the US Air Force:”

> The Air Force published “Vision 2020: Global Vigilance, Reach and Power” stating a desire for “controlling and exploiting the full aerospace continuum.” If that vision implies frequent, routine, on-demand operations into and within space, the enabler for this vision is an affordable, responsive, reliable, robust space launch capability. Getting to orbit requires Mach 25 flight—and all speeds between 0 and Mach 25. This interpretation of the vision cannot be fulfilled within the likely Air Force investment program using expendable launch vehicles (ELVs); *reusable launch vehicles (RLVs) will be necessary to make routine space operations affordable. Airbreathing hypersonic systems are one of the two concepts that show promise of allowing the realization of these capabilities—the other being rocket systems.* On the other hand, if the vision simply implies doing more of the same things done today, the Air Force can probably live with ELVs indefinitely.[19] (Emphasis added)

Later in their report, the Board drew the following conclusions while discussing potential military utility:

> We envision that a TSTO [two-stage-to-orbit] launch system [discussing an airbreathing first stage and rocket-powered second stage] would lift substantial payload weight to LEO at a cost per pound of an order of magnitude or more lower than current or next-generation ELVs ($800 to $100 per pound depending on design and launch frequency). Such a system would be designed to be launched, recovered, and prepped for the next mission using procedures as much like current aircraft operations as possible, thereby providing affordable, reliable, responsive space launch to enable on-demand military space operations. Such a system would not only provide for affordable, reliable military space launch, but would also enable many more space and near-space missions (military, civil, and commercial) that today are made unaffordable by the high cost of access to space. *Probably no other single technology offers such great promise of enabling the future of military space operations and civil space activities.*[20] (Emphasis added)

In summary, three arguments have been advanced as to why the development of near-term RLVs should be pursued. First, an integrated space logistics infrastructure, including reusable space access for passengers and cargo, should help to revitalize the stagnating space commercial industry by offering new opportunities for competition and services. Second, in the highly competitive terrestrial marketplace, expendable systems, especially transportation systems, have not found a sustainable market advantage over quality reusable systems. Finally, qualified experts on the Air Force Scientific Advisory Board assess RLVs as offering “great promise” for enabling future, affordable advances in military, civil, and commercial space operations.

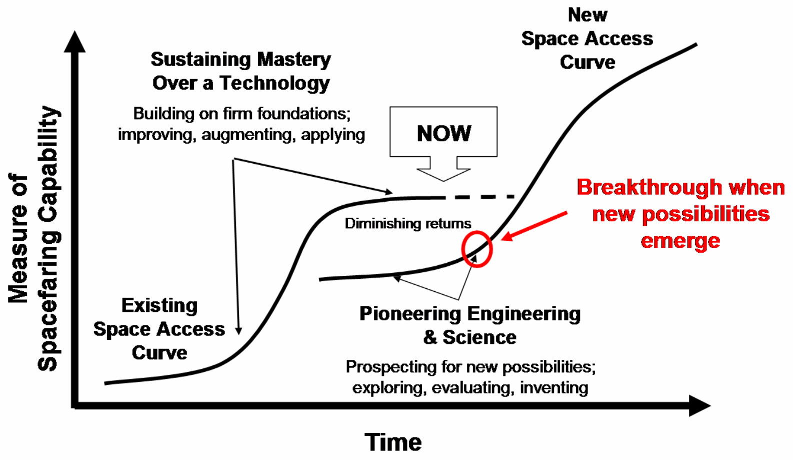

Figure 5: Technology “S” curves depicting the needed transition from the current to a new space access paradigm.

Figure 5, adapted from Ref. 21, depicts the fact that a choice now exists to continue with the current space launch paradigm built around ELVs and the Space Shuttle or to “jump” to a new, RLV-based, greater promise paradigm. The key question is whether the requisite “breakthrough” exists with the new space access paradigm enabling the transition to be undertaken. This is addressed in the next section of the paper.

One final note is needed on the future

of space access and the issue of whether ELVs or RLVs offer the better choice for the immediate future. While this author argues that RLVs offer the greater promise for the future, some argue that new ELVs are preferred based on the economics of developing, producing and operating these systems. One recent RLV vs. ELV economics paper concludes that: "Economics, rather than philosophy, should be the major driver in how new launch vehicles are designed and built."[22] This author would include safety in this statement and would point to previously discussed terrestrial experience with the predominance of reusable systems for critical and costly missions to counter-argue that significant safety and economic advantages of new ELVs over RLVs are likely not to emerge. Yet, when the competition for the development of the new space access launch systems begins, ELV proponents should have the opportunity to demonstrate how they can achieve comparable or better levels of aircraft-like safety, operability, affordability, and future market-growth opportunity.

C. Near-Term RLVs

The successful development and deployment of RLVs is a critical step in becoming a spacefaring nation. This subsection of the paper will address these areas:

1) The need for the development of multiple RLV types to meet the nation's requirement for assured space access.
2) Key near-term RLV design characteristics.
3) RLV design requirements.
4) Achieving aircraft-like safety and operability.
5) The results of recent Government near-term RLV conceptual design studies.
6) Initial fleet size and flight capacity.
7) A ROM estimate of recurring RLV mission costs.
8) Concluding remarks.

1. *Assured space access requirement*

In May 2003, a joint task force of the Defense Science Board and Air Force Scientific Advisory Board reported their findings and recommendations with respect to the Acquisition of National Security Space Programs. One key element of this study addressed the issue of assured access to space using the Evolved Expendable Launch Vehicles (EELVs). EELVs resulted from the Air Force's implementation of national space policy in the 1990s where the development of two expendable launch systems, the Atlas 5 and the Delta IV, was undertaken to provide improved unmanned space access capabilities for national security needs and to improve the industrial base and enhance American commercial space access competitiveness. With respect to the EELVs, the task force found, "National security space is critically dependent upon assured access to space. Assured access to space at a minimum requires sustaining both contractors until mature performance has been demonstrated."[23]

This finding reflects two important assured space access issues. First, redundancy in payload launch capabilities is necessary for assuring the ability to launch vital Government payloads. And, second, there is a clear need to maintain competition in launch services to both improve today's capabilities and preserve future launch development competition and innovation. Both of these assured access issues will continue to be important as the transition is made from ELVs to RLVs. Hence, a decision to transition to RLVs for future space access will necessarily involve a commitment to build and operate *a minimum* of two design-independent RLV flight systems.

A likely acquisition scenario, to encourage innovation and provide opportunity for expanded competition, would start with the conceptual design of up to five different/competing systems. The number of competing designs would be reduced to three at the preliminary design review. Finally, the first two to successfully complete the technical risk reduction and design verification milestones leading up to a decision to build prototypes would proceed.

This approach of developing multiple RLV types will raise concerns about the expense of this approach. Yet, not only is this necessary for achieving assured space access and opening the space frontier, it is important for creating the conditions for competition that will further decrease operating costs and increase safety. Recall the Space Shuttle and the recognition, early in its flight history, that it would not achieve the routine and operable space access outlined as program objectives when its development was initiated. One may speculate that had competing Space Shuttle designs been developed—at least taken to the beginning of prototype fabrication and testing—than the total life cycle cost to date would have been lower—perhaps significantly lower—as competition would have stimulated improvements and clearly inferior designs would have been abandoned. The higher up-front cost required to develop and produce at least two design-independent reusable launch vehicles is simply part of the price of entry into the next era of the space age; part of building a robust and economically useful space logistics infrastructure, addressing the needs of national security, reinvigorating the industrial base, and encouraging the future aerospace workforce.

2. *Key near-term RLV design guidelines*

In 1956, Colonel William O. Davis, PhD, assigned to the Air Force Office of Scientific Research, wrote the following with respect to establishing design requirements for reusable manned space access. Note that the timing of this was consistent with the 1950s-era integrated space exploration scenario discussed in Section II of this paper.

> Let us forget for the moment that we ever heard of the rocket and guided missile. Let us assume that we will start from scratch with the science that is available to us and a knowledge of our objectives and design a space flight system from here. The basic requirements for a manned space flight system can be determined from knowledge of human limitations, human physiology, engineering, economics, and common sense. If we were to list these basic requirements in order of their priority, they should be as follows:
>
> - The space flight system should be so designed and operated that there is a high probability that the human beings will be able to return to earth safely, either in case of a normal flight or in the case of an emergency.
> - The space flight system should be so designed and operated that there is a high probability that all equipment will survive the flight in workable conditions.
> - There should be a high probability for flight success in the system.
> - The manned space flight system should be compatible with the physical, biological, and mental limitations of human beings. There should be low acceleration but no zero gravity. Tolerable temperatures should be maintained in the system at all times. Flight times should be short, not over several weeks in duration. The entry profile for the return to the earth should be reasonable with low accelerations, low heating, constant control, and ability to select the landing point.
> - The manned space flight system should perform in an economical manner.

Updating this emphasis on safety, reusability, and passenger transport comfort, the following guidelines for near-term RLVs are proposed:

a) Select two-stage or comparable RLV designs that are capable of being developed, produced, demonstrated, and introduced into operation without unreasonable delay or cost. Do not organize nor characterize the RLV programs as generic technology development and demonstration programs.
b) Integrate the RLV into the overall space logistics architecture by identifying and addressing key interfaces such as: payload size and mass; the means of passenger transport; orbital performance in terms of achievable orbital altitudes, inclinations, and mission duration; on-orbit payload handling and passenger transfer; and, on-orbit safety "flight" inspections prior to the return of the orbital component(s) to the Earth.
c) Provide common minimum performance and payload handling requirements and interfaces to enable assured access for Government and commercial payloads.
d) Provide for passenger safety, comfort, and in-space emergency rescue appropriate for commercial passenger transport.
e) Select RLV designs that accommodate future "stretching" of the RLV; to enable the economical replacement of key subsystems and components to increase safety, performance, operability, and affordability.
f) Emphasize design innovation and flexibility, not only for improving the RLV's performance and operability, but also for enhancing the operation of the overall space logistics infrastructure.
g) Anticipate and proactively address Murphy's Law.
h) Protect public safety to establish and maintain public acceptance and support.

The importance of the first point is worth emphasizing and discussing. The near-term RLV acquisition program needs to be a developmental engineering program focused on designing and validating the contractors' preferred configuration. Hence, Government-led generic RLV technology programs, like the NASP/X-30, should not form the basis or jumping-off point for near-term RLV acquisition programs. This does not necessarily mean that technology development will not be required. Undoubtedly, some design-specific issues will arise—they always do—that are prudently solved through tightly focused technology projects. However, the decision on new technology solutions should be under the control of contractors' systems engineers. They are in the best position to assess the advantages and disadvantages of available and proposed alternatives and to determine acceptable fallback paths should the new technology solution not progress as expected.

Let's look at an example. Assume that a near-term RLV design with a projected recurring operating cost of $2,200 per kg ($1,000 per lb) has been defined as the preferred configuration. If the design payload mass is 16,780 kg (37,000 lb)—representative of the near-term RLVs discussed later in this paper—the recurring mission cost would be $37M. Should this system become operational and replace the current space transportation systems, launch costs will be reduced by approximately 80 per cent from the current value of around $11,000 per kg ($5,000 per lb).[24] With current Government launch expenditures of approximately $4.5B[*], this reduction equates to a savings of approximately $3.6B annually.

Now assume that a one-year delay in the start of RLV operations is proposed to incorporate a new technology that will reduce the projected recurring operating cost 10 percent to $1,980 per kg ($900 per lb). The corresponding reduced mission cost would be $31.5M. However, the proposed delay will "cost" the Government an additional $3.6B. At a savings of $3.5M per mission, approximately 1,000 missions would be needed to break even in terms of total Government expenditures.[†]

Such a proposal to incorporate a new technology would be an example of a "second best" design that takes too long compared with an acceptable "third best" design for the initial RLV capability. The appropriate way to accommodate new technology is through spiral development. This is where new technology is inserted into later production systems or introduced through the modification of an existing production system. For RLVs, examples of spiral development would be the incorporation of lighter propellant tanks, improved engines, or improved thermal protection systems.

An interesting and unrecognized argument for aggressively pursuing a "third best" design is that rapid progress towards developing and fielding the initial elements of the space logistics infrastructure, e.g., space hotels, will promote significant near-term investment—both Government and private—in the enabling technologies for the follow-on second-generation RLVs. Once the initial infrastructure is operating, entrepreneurial energy will strive to exploit the first in-space logistics capabilities and opportunities they enable. With these initial capabilities, the true opening of the space frontier will begin, especially for commercial human operations in space. This will create new market "demand" for improved and more affordable space access capabilities; demand that will probably require a new generation of space access technology solutions. Thus, *by focusing on the "third-best" RLV solution initially, conditions will be created that should foster significant investment in the next-generation RLV research and development. No other approach for creating sufficient future demand for improved space access, absent a substantial Government investment in new military capabilities, appears to warrant the substantial research and development required to enable next-generation RLVs.*

3. *Example RLV performance, cargo handling, and passenger transport requirements.*

In addition to the general RLV design guidelines, the conceptual design of the RLVs starts with a set of design and performance requirements to be satisfied. The following are the requirements used to size the near-term RLVs described later in the paper.

a) Ascent performance requirements:
   1) RLV Mission 1: 185 km (100 n.m.) circular at 28.5 deg. inclination.[‡] In this mission, the RLV second stage releases the payload once circular orbit is achieved and then returns to the Earth for landing at the earliest opportunity. The payload may consist of a satellite and booster, a cargo container for logistical support of in-space operations, or a small passenger spaceplane carried as an external payload. This mission typically establishes a maximum payload mass requirement. Only RLV second stage configurations with external cargo carriage would be expected to be capable of carrying a passenger spaceplane.
   2) RLV Mission 2: 500 km (270 n.m.) circular at 28.5 deg. inclination. In this mission, the RLV second stage directly delivers the payload to the space logistics base or space hotel located at this orbital altitude and inclination. The RLV second stage first circularizes its orbit at 185 km (100 n.m.) and then

---

[*] This is the author's estimate based on requested Space Shuttle appropriations for FY05-09 averaging $4.0B per year and Government ELV launch costs that are believed to be in the range of $0.5B per year. While the former expenditure is published as part of the proposed federal budget, the latter ELV launch service expenditures are not separately identifiable in available budget information. The $0.5B would purchase, for example, two Atlas 2AS and six Delta 2 ELVs based on 2002 cost data published by the Futron Corp.

[†] The total "cost" of delay would also need to address the impact on potential RLV customers that would be waiting for the lower cost of the RLVs to expand current space operations or start new space enterprises.

[‡] This corresponds to a launch due east from Kennedy Space Center. Other United States or global spaceports could also be used. This condition is simply a standard mission allowing comparison of performance with other published data.

conducts an optimum orbit transfer to the higher orbit to rendezvous with the space facility. Following delivery, the second stage returns to the Earth for landing. This mission typically establishes a mission duration requirement and an on-orbit Delta-V requirement.

Discussion: Unlike ELVs, which can be configured to provide a range of performance with strap-on boosters and different upper stages, an RLV's performance will be defined by achievable total mission Delta-V vs. payload mass—comparable to how the performance of a conventional transport aircraft is defined. These two RLV missions illustrate logistical support missions to support on-orbit operations in LEO. The lower orbital altitude (at 185 km) maximizes the payload mass delivered into this orbital inclination while the higher orbital altitude (500 km) would be used to predict the payload mass that could be delivered directly to a space logistics base.

Once the Mission 1 and 2 performance capabilities are established, determining the RLVs performance to other inclinations and orbital parameters can be readily calculated. One additional set of such missions may be the resupply of the International Space Station while another may be launching satellites into high-inclination or polar orbits.

b) Cargo carriage requirements: The following requirements were used in the development of the example space logistics infrastructure:
   1) Minimum cargo mass, excluding any external cargo container and cargo restraint system if used, delivered to RLV Mission 1 is 6,800 kg (15,000 lb).
   2) Minimum spaceplane mass delivered to RLV Mission 1 is 15,900 kg (35,000 lb).
   3) Payload cargo dimensions up to 4.6 m (15 ft) diameter by 9.2 m (30 ft) long delivered to RLV Mission 2.

Discussion: Today's EELVs are designed to accommodate payloads with a diameter up to approximately 4.6 m. To replace EELVs for medium-class payloads, the RLVs should also be able to carry these payloads. The diameter and length of the cargo dimensions, whether carried internally in a second stage cargo bay or carried externally in a cargo container, are intended to support the transition of EELV payloads to the RLVs and meet on-orbit logistics support needs. For instance, in the conceptual design of the LEO space facilities and spacecraft discussed later, these dimensions were used to size space facility and spacecraft components transported to orbit using the RLVs and to size the dimensions of the space hangars.

c) Passenger carriage requirements: Transport a minimum of 10 passengers plus flight crew, with a combined mass of 1,475 kg (3,250 lb), to and from the space logistics facilities in LEO.

Discussion: Safe passenger transport is a primary RLV mission, reflecting its importance in achieving the desired transformation to a true spacefaring nation and opening the space frontier to routine human space enterprises. Options for passenger transport include: (a) a small spaceplane carried as a third stage and released in a low circular orbit; (b) a second stage designed to transport the passengers internally in a specially-configured payload canister carried in the internal payload bay; (c) an external cargo module configured as a passenger compartment; and (d) a specially configured second stage that has a permanent passenger compartment and is designed to only transport passengers. While option (a) is used in this example near-term space logistics infrastructure for reasons discussed later, it is expected that second-generation RLVs may use one of the other options to achieve lower per-passenger transportation costs.

4. *Achieving "aircraft-like" safety and operability*

Recall the movie *2001: A Space Odyssey*, where the vision of the future of routine and safe travel to orbit—of a sleeping passenger on a future spaceplane approaching an orbiting space station—helped to establish the public's expectation of what the future of human space transportation should bring. Developing RLV designs that accomplish human space transportation elegantly will be very important in gaining public support for building an integrated space logistics infrastructure and opening space to expanded human enterprises. The early systems architecting and conceptual designs of the RLVs must establish public confidence that space travel will follow the lead of commercial air travel in becoming increasingly safe and routine.

Interestingly, how this could be achieved was identified by the previously quoted remarks by the Air Force Scientific Advisory Board. An RLV "would be designed to be launched, recovered, and prepped for the next mission using procedures as much like current aircraft operations as possible…" Nearly a century of aircraft design, testing, and operational experience has produced a robust set of systems engineering procedures and processes for developing, fielding, and operating flight systems with remarkable safety and operability. These systems engineering processes are highly adaptable. With the appropriate infusion of systems engineering experience and expertise from expendable launch vehicles and the Space Shuttle, they should yield RLVs with acceptable safety and operability. *The key to success is to establish an RLV systems engineering philosophy that approaches the RLV development from the point of view of developing an advanced aircraft capable of achieving orbit rather than developing a reusable version of an expendable launch vehicle. The former requires primarily an improvement in performance while the latter requires a fundamental change in the basic design of the system.*

5. Recent Government near-term RLV conceptual design studies

The Air Force Research Laboratory and the Air Force Aeronautical System Center's Engineering Directorate (ASC/EN) at Wright-Patterson Air Force Base, Ohio, have jointly developed an RLV modeling environment that utilizes "parametric geometry-based methods that enable immediate performance, aerodynamic, structural, and thermodynamic analyses" to be rapidly performed.[25] During 2003-2004, the ASC/EN Aerospace Systems Design and Analysis group undertook a near-term RLV conceptual design analysis.[26] The purpose of this study was to determine if "third-best," two-stage RLV designs could be defined with reasonable performance and a practical design. For this study, the following study requirements and constraints were used:

a) System configuration: The RLVs were two-stage, vertically-launched, horizontal landing systems with either internal payload carriage, in a payload bay similar to the Shuttle orbiter, or an external cargo module. A small spaceplane for passenger transport could be carried in place of the external cargo module. The first stage used fly-back, airbreathing engines to return to the launch site after stage separation. The second stage used an unpowered landing. Each of the four systems sized was a point design for a specific payload configuration and total mission Delta-V. Both stages, in all four systems, used LOX/kerosene propellants. These systems were unmanned for the cargo delivery mission.

b) Technology maturity: The RLV weight estimation relationships used current technologies consistent with the near-term definition used in this paper. Four RD-180 engines were used for the first stage and four RD-120 engines for the second stage. The airframe and propellant tanks used aluminum or aluminum-lithium metallic structures. The TPS used the most recent versions of the leading edge, surface tiles, and surface blankets used on the Shuttle orbiter. Other subsystem weights, including the fly-back jet engines on the first stage, used current technology weight estimation relationships. Shuttle-based weight estimation relationships were used for the structure, propellant tanks, TPS, orbital maneuvering system, reaction control system, auxiliary power units, etc.

c) Sizing assumptions: Both stages were designed to enable orbit to be achieved in the case of an engine-out during ascent. The first stage thrust-to-weight ratio was 1.35 with the engines throttled to 0.92 at takeoff. The second stage thrust-to-weight ratio was 1.27 with engines throttled to 0.92 at stage separation. The total ideal Delta-V, to achieve a 92.6 km (50 n.m.) by 185 km (100 n.m.) orbit, was 8,960 m/s (29,400 ft/s). The main propellant reserves were 1.0 percent on the second stage and the trapped main propellants were 0.5 percent on both stages. The Isp of the orbital maneuvering system (OMS) and reaction control system was 320 Sec. These engines were used for orbit circularization, orbit transfers, and deorbit maneuvering. The first stage fly-back engines had an installed thrust-to-weight ratio of 4.0 with a stage thrust-to-weight ratio of 0.3. The first stage return cruise Mach number was 0.5. Both stages had a subsonic lift-to-drag ratio of 5.0. The wings on both stages were sized for a wing loading of 366 kg/m^2 (75 lb/ft^2) with a touch down velocity of 352 km/hr (190 knots). The landing gear weight was 4.0 percent of the landing weight. A 15 percent margin was applied to all empty weights except the engine weights.[*] The published weight, thrust, and Isp for the RD-180 first stage engines were used. The published Isp of the RD-120 second stage engine was used while the weight was increased by 17 percent to include an engine gimballing capability to provide engine out capabilities. A recent reported 15 per cent increase in the maximum thrust of the RD-120 engine was not incorporated into the sizing analysis.

---

[*] The Space Shuttle orbiter experienced a weight growth during its development of approximately 25 percent. This weight growth is captured in the Shuttle-based weight estimation relationships used in these conceptual design studies. The 15 percent weight growth margin used in this study was over and above the current Shuttle-based estimated weights. This combines conservative predicted subsystem weights with an appropriate margin to address two-stage RLV unique design issues, should they arise.

d) Sizing cases. Note that each of these is a point design. For example, while Case 1 will include an OMS system sized to reach the 500 km orbital altitude, in Case 2 the OMS would only be sized for the 185 km orbital altitude. Similarly, in Case 3 the second stage is sized to land with the payload while in Case 4 it is not sized to land with a payload.

Case 1 - RLV Mission 2: Internal payload bay carriage of a 4.6 m (15 ft) diameter x 9.2 m (30 ft) cylindrical cargo to a 500 km (270 n.m.) circular orbit at an inclination of 28.5 deg. The second stage is sized to return with the cargo.* This mission is designed to drop off the cargo at an orbiting space facility. An internal payload bay was used to quantify the performance impact for this internal cargo carriage mode vs. that of the external cargo carriage in the Case 3 configuration.

Case 2 - RLV Mission 1: Internal payload bay carriage of a 4.6 m (15 ft) diameter x 9.2 m (30 ft) cylindrical cargo to a 185 km (100 n.m.) circular orbit at an inclination of 28.5 deg. The second stage is sized to return with the cargo. This mission is designed to drop off the cargo in a low orbit where the cargo would be retrieved and ferried to the orbiting space facility in the higher orbit.

Case 3 - RLV Mission 1: External payload carriage of a 3.7 m (12 ft) diameter x 9.2 m (30 ft) cylindrical cargo to a 185 km (100 n.m.) circular orbit at an inclination of 28.5 deg. The second stage is sized to return with the cargo. This mission is designed to drop off the cargo in a low orbit where the cargo would be retrieved and ferried to the orbiting space facility in the higher orbit. This RLV could also carry a passenger spaceplane but could not land with the spaceplane.[†]

Case 4 - RLV Mission 1: External payload carriage of a 3.7 m (12 ft) diameter x 9.2 m (30 ft) cylindrical cargo to a 185 km (100 n.m.) circular orbit at an inclination of 28.5 deg. The second stage is not sized to return with the cargo. This vehicle would be a point design for delivering a non-returnable cargo module or a passenger spaceplane to orbit.

e) Study results. Note that in all four cases the gross weight of the RLV system at lift off is 1,063,648 kg (2,345,344 lb). (Figure 6 contains illustrations of two-stage RLVs taken from Ref. 27.)

Case 1 - Weight empty = 124,210 kg (273,882 lb); first stage fuselage length = 36.9 m (121 ft); internal payload = 4,300 kg (9,500 lb) delivered to 500 km (270 n.m.); payload percentage of gross weight = 0.4%.‡

Case 2 - Weight empty = 124,463 kg (274,442 lb); first stage fuselage length = 39 m (128 ft); internal payload = 8,400 kg (18,550 lb) delivered to 185 km (100 n.m.; payload percentage of gross weight = 0.8%.

Case 3 - Weight empty = 116,132 kg (256,070 lb); first stage fuselage length = 39 m (128 ft); external payload = 16,800 kg (36,970 lb) delivered to 185 km (100 n.m.); payload percentage of gross weight = 1.6%.

Case 4 - Weight empty = 112,612 kg (248,310 lb); first stage fuselage length = 39 m (128 ft); external payload = 20,600 kg (45,340 lb) delivered to 185 km (100 n.m.); payload percentage of gross weight = 1.9%.

Discussion: *It is appropriate to reemphasize that these four cases reflect estimates of the performance of near-term RLVs. In all four cases, with the specified 15 percent empty weight margin included and using Shuttle-based weight estimating relationships, the conceptual designs produce useful performance at reasonable weights. In all cases, the system was capable of engine-out at any point in the mission and able to complete the mission.*

In Case 1, the RLV directly delivers the large cargo container to an orbiting space facility, such as the LEO space logistics base discussed later in the paper. The lower cargo weight, compared with Case 2, is a result of the second stage delivering the cargo directly to the space base. This approach, while simplifying cargo delivery,

---

[*] This means that the wing and landing gear weights have been adjusted to reflect a higher landing weight that includes the maximum payload weight. This provides a mission abort capability without causing damage to the second stage. In no case is the second stage designed to land with a spaceplane attached. Aerodynamic and stability and control considerations, rather than weight, would be the reason for this restriction.

[†] In no case would the second stage be expected to land with a spaceplane attached. Aerodynamic and stability and control considerations, rather than weight, would be the reason for this restriction.

[‡] The fineness ratio of the Case 1 configuration was slightly different from that for the other three cases. This resulted in a slightly shorter vehicle length.

requires greater OMS propellant mass to provide the additional Delta-V to raise the orbital altitude of the entire RLV second stage and cargo to the space base and then to deorbit for landing. With a fixed gross weight established by the use of a fixed number of existing first stage engines, the increased mission Delta-V is achieved at the expense of a decrease in delivered payload mass. This is very similar to cargo aircraft where the payload decreases as a function of increasing mission range once the maximum takeoff weight is reached.

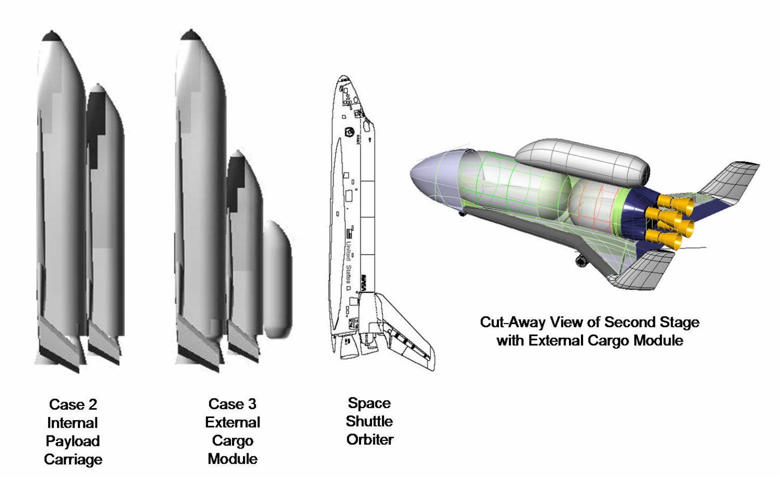

Figure 6: Illustrations of conceptually sized near-term, two-stage RLVs (Ref. 27).

In Case 2, the RLV is sized to delivery the cargo container to a low circular orbit. A small booster engine attached to the rear of the container would ferry it to the higher orbit where the space base is located. The weight of this booster is expected to be approximately 10 percent of the total released cargo weight. Instead of an attached booster, a Space Logistics Vehicle based at the space logistics base could retrieve the container and return it to the base. The important result of this case is that dropping the cargo off at the lower orbital altitude approximately doubles the cargo weight delivered to the space base per RLV mission. This indicates that the space logistics architecture should accommodate this mode of cargo delivery.

In Case 3, the vehicle does not have an internal payload bay but carries the cargo externally. The increase in payload weight over Case 2 is the result of the reduction in the second stage weight due to the removal of the payload bay and doors. However, the delivered weight now includes the external cargo module in addition to the cargo carried inside the module. The weight of the cargo module is expected to range from 25-40 percent of the total delivered cargo weight. This would indicate that the delivered cargo weight would range from 10,000 kg (22,200 lb) to 12,600 kg (27,700 lb). As with Case 2, a booster engine or a tug would transport the cargo to the space base. Another point to note is that the maximum practical diameter of the cargo was believed to be about 3.7 m (12 ft.) vs. the 4.6 m (15 ft) for the internal payload bay configuration.[*]

In Case 4, the payload delivered to orbit increases because the second stage of the RLV would not be designed to return the cargo module to the Earth. Hence, the added wing and landing gear weight in Case 3 required to return with the payload—about 3,800 kg (8,400 lb)—translates into an increase in the delivered cargo or spaceplane payload weight.

The external cargo module carriage of Cases 3 and 4 permit a small passenger spaceplane to be carried in place of the module. Once the low circular orbit is achieved, the spaceplane would separate from the RLV second stage and complete the transportation of the passengers to the orbiting space facilities. After the spaceplanes have separated, the RLV second stage would reenter and land at the next opportunity. The spaceplanes, after delivering the passengers and picking up returning passengers, would reenter and land much as the Space Shuttle does today.

From these conceptual design study results, the Case 3 RLV configuration was selected for this example space logistics infrastructure. This provides the ability to transport cargo to orbit or carry a small spaceplane for passenger transport.

6. *Initial RLV Fleet Size and Flight Capacity*

A key architecture decision is sizing the flight capacity of the initial fleet of RLVs. Should the initial fleet be sized just to meet the current Government and U.S. commercial launch needs or should it be sized to provide capacity for growth in American spacefaring operations? Key infrastructure capabilities, such as transportation and energy production, are costly and must remain economically productive for prolonged periods to recoup the

---

[*] This was a result of the point optimization of the RLV second stage for this case. When the length of the second stage of the RLV was shortened from Case 2 by removing the internal payload bay, the optimization process also decreased the diameter of the second stage's propellant tanks to maintain a target fuselage fineness ratio for subsonic performance. Further design analysis would be required to determine if the targeted 4.6 m (15 ft) diameter cargo envelope could be achieved.

substantial investment in their building. Hence, it is quite common to oversize the capacity of these infrastructure capabilities to ensure adequate future capacity to support economic growth resulting from the new infrastructure.

The flight capacity of the RLV fleet will be dependent on: (a) the turn around time between flights for each flight system; (b) the number of flight systems in the fleet; and, (c) and the percentage of time a flight system spends in depot for scheduled maintenance. In this example, the turn around time between flights, for the same flight system, is assumed to be one month at the initial operational capability (IOC) and one week at the Full Operational Capability (FOC). Just to be clear, this means that at IOC, the same flight system would be ready for launching one month after it lands from the previous mission. At FOC, it would be ready one week later. FOC is assumed to occur 3-5 years after the system achieves IOC. Each new production flight system would undergo about one year of acceptance flight and ground testing prior to entering flight operations. The production delivery rate for each flight system would be one per year with a total of three production flight systems per type. It is also assumed that one of these three flight systems would be in the depot for inspection and maintenance at any given time, during the early years of operation, to ensure continued flight safety and to support health monitoring of key RLV subsystems under actual usage conditions. This data collection will be very important in gaining the confidence necessary to reduce the frequency of post-flight inspections and permit the flight rate to increase from once per month at IOC to once per week at FOC.

Figure 7 depicts the growth in annual RLV fleet flight capacity under these assumptions. *It is clear that for the early years of an integrated space logistics infrastructure, highly rapid turn-around times of 1-2 days, often cited as a near-term RLV requirement, does not appear to provide any clear advantage warranting a delay in deploying near-term RLVs.* This is because the need for assured access requires at least two types of RLVs to be built and common sense indicates that a moderate number of at least three systems of each type should be produced. At a modest flight rate of once per week—extremely rapid for ELVs and quite slow for commercial aircraft—the initial RLV fleet will have a substantial annual flight capacity of over 200 missions per year at FOC. This will easily meet the current Government needs for about 12-20 missions per year and have substantial excess capacity, including human transport capacity, to support new civil, commercial, national security, and space exploration operations in space.

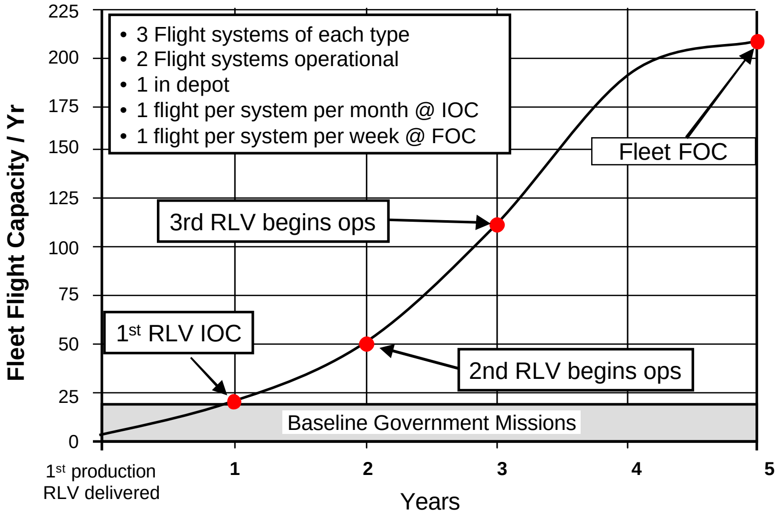

Figure 7: Near-term RLV fleet flight capacity (total available flights per year).

7. Estimates of recurring RLV mission costs

Previously, a target recurring RLV mission cost of $2,200 per kg ($1,000 per lb) was discussed. With a Case 3 design payload of approximately 16,800 kg (37,000 lb), the recurring mission cost target would be approximately $37M. Twenty annual Government missions at this recurring cost would total approximately $740M. This would yield an annual savings to the Government of approximately $3.8B. An obvious question is just how realistic is such a recurring cost reduction. Using the Case 3 two-stage RLV, a rough-order-of-magnitude (ROM) assessment of the recurring costs can be made.

The starting point is to make assumptions of the number of missions between replacement for the first and second stage rocket engines at IOC. For this ROM recurring cost assessment, assume the engines are capable of 10 missions between replacement at IOC.[*] Assume the replacement costs are $30M for each RD-180 and $15M for

---

[*] The RD-180 engine, used in the example near-term RLV design, is believed to have some degree of reusability based on its lineage to the reusable RD-170 engine. Further, the application of jet engine-style durability and damage tolerance improvements, which have been used successful to adapt existing jet engines to new usages, provides a methodology for achieving this goal.

each RD-120.* At IOC, the mission amortized replacement costs for the engines would be (4 x $30M + 4 x $15M) / 10 = $18M ($1,070 per kg or $487 per lb). The balance of the recurring mission cost, $37M - $18M = $19M, is for direct and indirect support. The average annual worker salary, for aerospace system support, is assumed to be $225,000 for 1,500 hours of labor per year. The available number of support hours per mission can be estimated as $19M / $0.225M x 1,500 hours = 126,667 hours. Ref. 26, the recent Government near-term RLV study, provides a very preliminary estimate of 54,200 hours of direct support per mission. This represents approximately 40 percent of the total hours available or about $8M of the recurring mission cost ($476 per kg or $216 per lb). The balance, approximately $11M per mission, would be used for in-direct support, non-engine spares, propellants, and other expendables.

At FOC, with assumptions of 25 missions between engine replacement and a 50 percent reduction in the direct and indirect support per mission attributed to increased system maturity and increased flight frequency, the mission costs reduce to (4 x $30M + 4 x $15M) / 25 + .5 x ($8M + $11M) = $16.7M ($1000 per kg or $450 per lb). This ROM analysis, while certainly very preliminary, provides support for the contention that achieving a substantially reduced recurring cost with near-term RLVs may be achievable.

Both commercial and military flight systems typically establish operational cost objectives early in the program development cycle. For commercial airlines, such metrics are essential for establishing and achieving profitable operation. Near-term RLVs would be treated in a similar manner with development, production, and recurring cost objectives established early in the concept development phase and tracked throughout the program. *Hence, near-term RLVs that do make it through the competitive down-selects and become operational will most likely achieve substantial recurring cost reductions.* Innovation and competition during all phases of RLV development will help to ensure that realistic cost objectives are established and achieved. They will also help to ensure that the cost reductions expected as the systems move from IOC to FOC are also realized.

8. RLV concluding remarks

Achieving aircraft-like reusable space access is widely viewed as the bridge to a new era of the space age. However, many also believe that this bridge has yet to be reached; that new technology breakthroughs are required to accomplish this goal. The purpose of this section has been to identify how a class of “third-best” RLV designs exists that can be readily and rapidly exploited to cross this bridge. Hence, *the breakthrough in reusable space access, shown in Fig. 5, is understanding that the answer does not lie in yet-to-be-invented technologies but in the determined application of two-stage RLV system designs that can be executed today.*

V. Shuttle-Derived Super Heavy Spacelifter

A. Overview and Key Points

This section briefly discusses the role of a Shuttle-derived super heavy spacelifter (SHS) in this example integrated space logistics architecture. Key points discussed in the section are:

1) The concept of a Shuttle-derived super heavy spacelift system has been studied extensively for over a quarter century.
2) This system provides the ability to launch heavy and oversize components for orbiting vehicles and facilities that would not be practical to configure as smaller components, as was done with the International Space Station, or fabricated in space at this time.
3) This approach makes effective use of the existing Space Shuttle industrial base and launch capabilities and it provides for continuity of political support among this important space community.
4) The utility of this system is enhanced by designing its core propellant tanks to be reused in orbit as pressurized habitat compartments thereby making the near-term assembly of large orbiting space facilities more practicable.

B. Brief History

The development of unmanned version of the Space Shuttle to provide a Saturn V-class cargo launch capability has been studied since the mid-1970s. The initial attractiveness of a Shuttle-derived launch vehicle resulted from its ability to launch large, fully assembled components that were not limited to the payload size and weight capacity of

---

* Multiple news articles on the Internet state that the current cost of the RD-180 is approximately $10M. This is for the engine assembled in Russia and used on the Atlas 5. For this ROM cost estimate, an arbitrary 3X multiplier was applied to provide an upper bound estimate of the cost of a reusable version of this engine. The estimated cost of the reusable version of the RD-120 engine was assumed to be 50 percent of the estimated cost of the reusable RD-180.

the Space Shuttle orbiter or the Titan IV ELV. This approach also used the Shuttle industrial base and launch infrastructure to minimize development and operational costs through cost sharing with the Space Shuttle program. The development of such a launch system was a primary recommendation of the Space Exploration Initiative in the early 1990s, the most recent study to determine how a renewed human space exploration program of the Moon and Mars could be undertaken. It was also evaluated as part of the launch architecture of early versions of the International Space Station.

C. Use in an Integrated Space Logistics Infrastructure

While it is certainly possible to develop an entirely new heavy space launch system, perhaps even one that is fully reusable in the classic sense, the “third best” approach of using a Shuttle-derived system is used in this example. This approach is also attractive from a political point of view in that it continues and updates a significant part of the existing Space Shuttle manufacturing base and launch operations rather than having these end with the planned completion of the Space Shuttle operations in 2010.

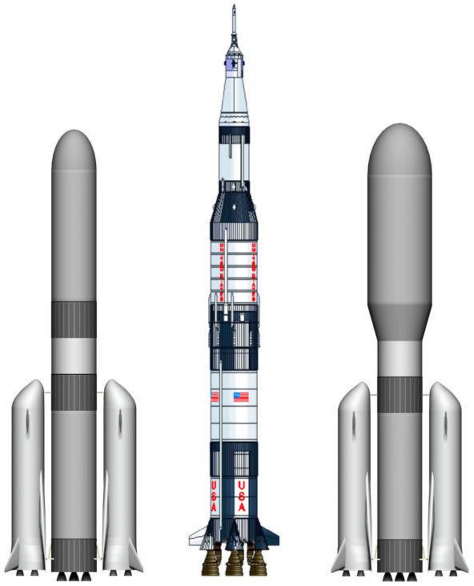

Figure 8: Shuttle-derived super heavy spacelifter with two payloads sizes shown in comparison with the Saturn V—a mission module (left) and a large payload shroud (right).

As shown in Fig. 8, the example SHS uses a vertically stacked configuration. The system would be capable of launching payloads with weights up to approximately 84,000 kg (180,000 lb) and sizes up to 12 m (40 ft) in diameter into a 500 km (270 n.m.) circular orbit east from Kennedy Space Center. The vehicle configuration would be a central propellant tank core with either solid rocket boosters, as used on the Space Shuttle, or new reusable fly-back boosters similar to the RLV’s first-stage (as shown in Fig. 8). Based on Space Shuttle experience, the flight capacity of the SHS may be expected to be 3-5 missions per year.

An important infrastructure architectural feature is designing the SHS’s core propellant tanks for reuse in orbit for “free” pressurized habitat volume. This is an updated, and more practical, approach to the 1970s-era idea of reusing the Space Shuttle’s external tank in space. As will be described later in the two examples of orbiting space facilities, the ability to functionally “recycle” the SHS propellant tanks substantially increases the size of the orbiting facilities that can be assembled without increasing the number of required launches.* When the core propellant tanks are reused in this manner, the SHS becomes a “reused” launch system. The payload and core propellant tanks become part of the orbiting space facility while the fly-back boosters, reusable core engines, and avionics package—the latter two returned via the RLVs—are reused on future SHS missions. Even on traditional payload launch missions, the SHS’s core propellant tanks could be stockpiled in orbit for reuse on other space construction programs.

VI. Near-Term Orbiting Space Facilities

A. Overview and Key Points

The first permanent footholds in a new frontier are the logistics facilities. These support the initial human operations in the frontier—homesteading, business operations, conducting research and trade, extracting natural resources, etc. This section provides examples of two orbiting space logistics facility—space logistics bases and space hotels. To reinforce the near-term technical feasibility of the example space logistics infrastructure described in this paper, this section also describes how their design and on-orbit assembly could be undertaken using current industrial capabilities with the support of the near-term RLVs and SHS. Key points discussed in this section are:

1) The 1970s use of the Saturn V to launch the large Skylab space station provides a useful model for establishing the architecture for building the first generation of orbiting space logistics facilities.

---

* This approach would only be cost-effective when the needed on-orbit reconfiguration of the SHS’s propellant tanks is modest in scope, such as their use for crew quarters and storage. This limitation has been used in the examples used in this paper.

2) The SHS enables a modular construction architecture to be used for assembling the large space logistics facilities needed to support a significant expansion of human space operations.
3) These orbiting space facilities could incorporate large pressurized space hangars enabling traditional logistics support operations, such as inspection and maintenance, to be conducted in a pressurized work environment.
4) The LEO space logistics base could incorporate a large space dock making possible the on-orbit assembly and maintenance of large space facilities, space platforms, and spacecraft.
5) The same modular construction approach used to build the space logistics base could also be used to build the first space hotels to provide housing for the increasing numbers of people traveling to space associated with growing human space operations.
6) The first space hotel would substantially increase the demand for passenger transport resulting in the need to concurrently introduce second-generation RLVs with lower mission costs per passenger and increased flight rates.
7) In order to be operational when needed, the research and enabling technology demonstration for second-generation RLVs should start at approximately the same time as detailed design begins for the first-generation RLVs.

B. Modular Design Approach

At the end of the Apollo program, the Government elected to use an extra Saturn V to launch the United States first space station called Skylab. The technical feasibility of replacing the third stage of the Saturn V with a space station of comparable size and then launching this into orbit, using just the first two stages, was explored early in the Saturn V development program. At the end of the Apollo program, this concept was the “third best” approach for building a large space station at an acceptable cost and schedule.

The SHS system enables a similar approach to be used for designing and assembling large orbiting space facilities. Three basic payload configurations would be developed for the SHS. The first would be a general-purpose space logistics facility mission module similar in size to the SHS’s LH propellant tank—approximately 8.4 m (27.5 ft) in diameter and 30.4 m (100 ft) in length. The second is a large space hangar approximately 10 m (33 ft) in diameter and 36.6 m (120 ft in length). The final configuration is a family of payload shrouds designed to carry payloads up to 12.2 m (40 ft) in diameter. The mission module, space hangar outer shell, and payload shrouds could be produced, along with the SHS’s core propellant tanks, at the current Space Shuttle external tank manufacturing facility.

C. Example Orbiting Space Logistics Base

As listed previously, the space logistics base’s functions are: (1) housing for travelers and operating crews; (2) emergency care; (3) in-space assembly, maintenance, and repair; and (4) materiel handling and storage. The example space logistics base is shown in Fig 9 and an exploded view is shown in Fig 10.

The example space logistics base consists of four elements. At the top in Fig. 10 is the mission module providing the primary base control facility, emergency medical support, and crew and visitor quarters. The personnel quarters are located inside core propellant tanks that are retained from the SHS used to launch the mission module. The overall length of the mission module and propellant tanks is approximately 76 m (250 ft). Solar arrays and waste heat radiators (shown cut-away in Fig. 10) are mounted on a framework surrounding the mission module to provide additional radiation and micrometeoroid protection.

The second element consists of twin space hangars. These serve as airlocks for receiving spaceplanes and

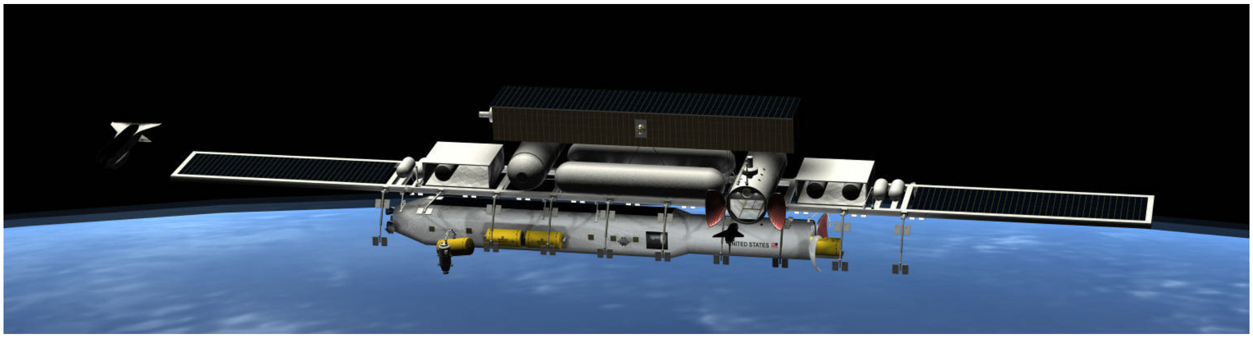

Figure 9: Conceptual LEO space logistics base supporting a large manned spacecraft docked at the base’s space dock.

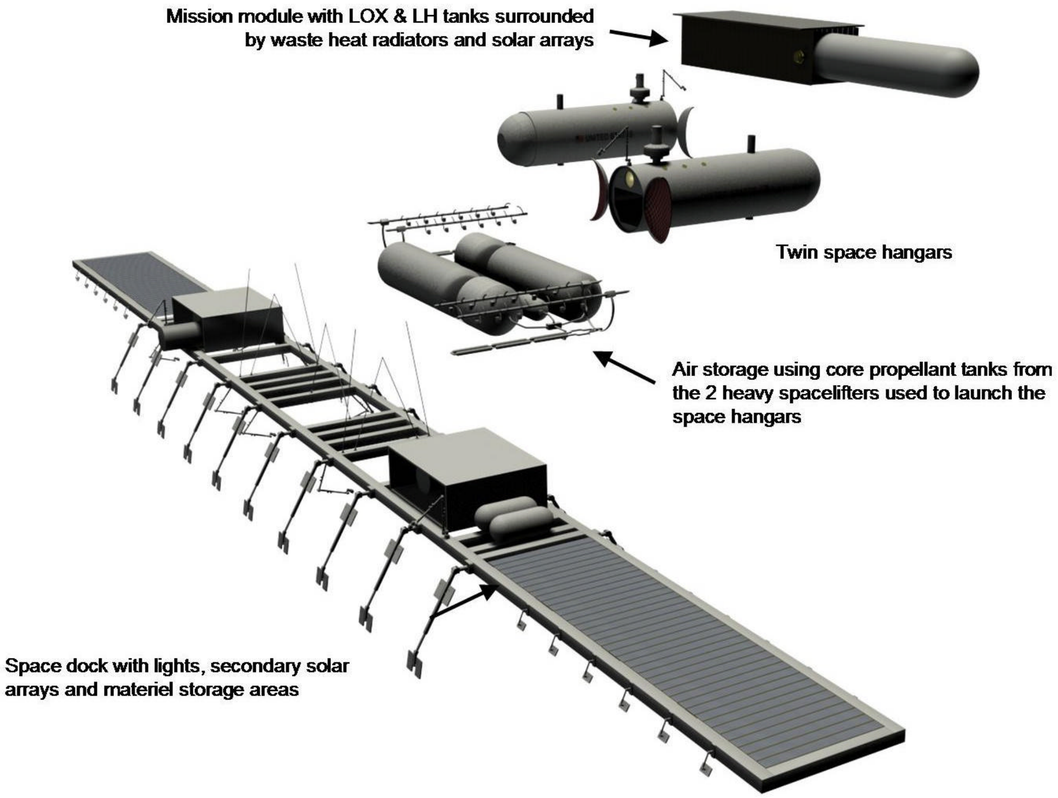

Figure 10: Exploded view of the space logistics base.

provide a pressurized work bay for conducting on-orbit maintenance of satellites and space platforms. As shown in Fig. 11, the space hangar consists of a structural cylindrical shell 10 m (33 ft) in diameter, a forward pressure bulkhead containing the primary pressure doors, and an aft spherical work bay. These elements, which define the primary structure, would be manufactured as a single unit and launched as the payload of an SHS. The large, non-pressurized, space debris protection doors would be temporarily mounted inside the hangar for launch and then demounted and installed during the final assembly of the hangar at the LEO construction site. All of the other hangar components would be sized for transport to orbit in the cargo module of the RLVs and then taken through the hangar's primary pressure doors for installation.

Future logistics supportability is a key feature of this hangar design. The size, weight, location, and access of the internal hangar components enables them to be inspected, repaired, and replaced without affecting the primary structural / pressure integrity of the hangar. With the exception of the space debris protection doors, this would be done inside the hangar when it is pressurized. The ISS-type airlock and space debris protection doors, although mounted externally, would be demounted and brought into the hangar for inspection, maintenance, and repair. For the repair of the primary pressure doors, they would be demounted and taken into the spherical work bay or the other hangar for servicing.

The hangar's design enables both pressurized and unpressurized hangar

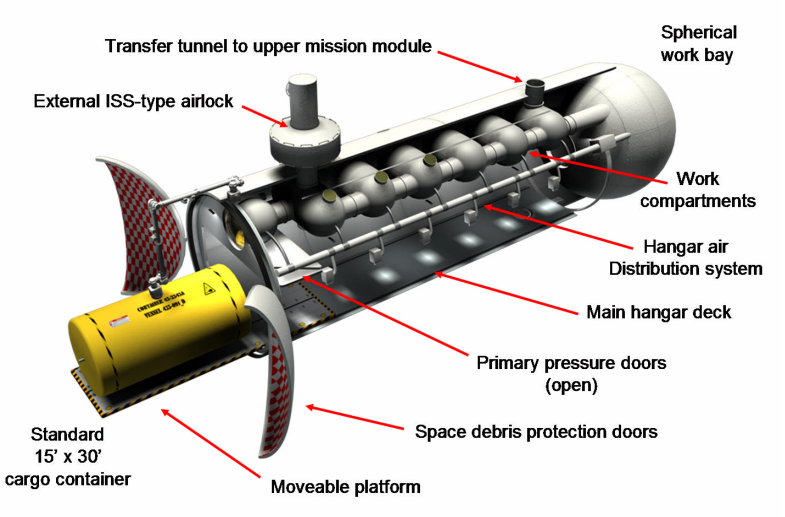

Figure 11: Cut-away view of the space logistics base's hangar.

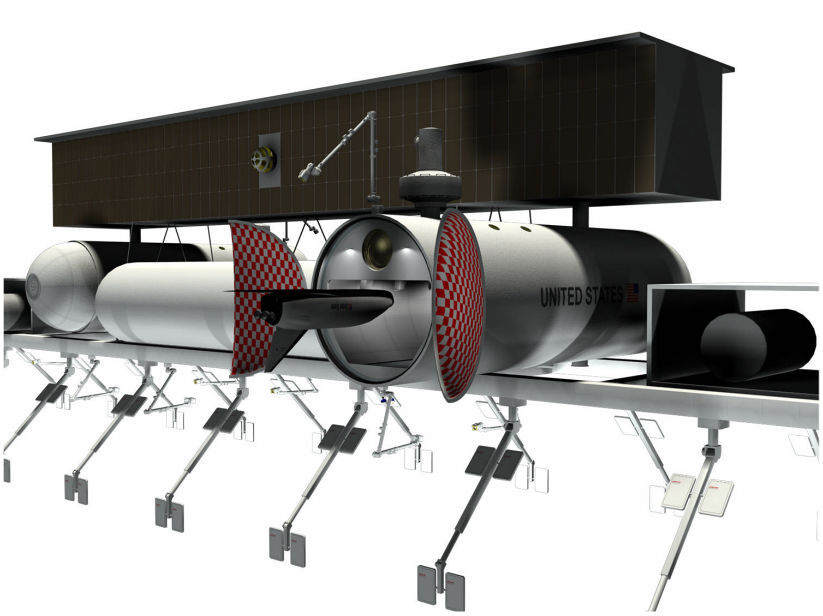

Figure 12: Inverted passenger spaceplane entering space hangar.

operations to be undertaken simultaneously. When the main hangar deck is depressurized to receive cargo or spaceplanes, for example, pressurized maintenance operations would continue inside the 9.8 m (32 ft) diameter spherical work bay and the 2.8 m (9 ft) diameter x 4.3 m (14 ft) work compartments arranged along the top of the hangar.

Hangar operations in support of the passenger spaceplanes, as shown in Fig. 12, highlight the improvement in on-orbit logistics support enabled by the large hangars. After entry into and repressurization of the hangar, the passengers would disembark from the spaceplane. Support technicians, working in the hangar's shirtsleeve environment, would inspect the spaceplane and, in particular, the thermal protection system for any damage to ensure that it is ready for its return to the Earth. While at the space base, the spaceplane would remain in the hangar to protect it from micrometeoroid or space debris damage. Minor repairs to the spaceplane could also be undertaken to ensure flight safety.

The third element is the air storage system. The prominent parts of this system are the large air storage tanks that are the reused core propellant tanks from the two SHS used to launch the twin space hangars. Besides storing air from the hangars, this system also: manages the oxygen, carbon dioxide, and moisture levels; removes toxic gases, vapors, and particulates; and, controls the temperature and circulation of the air within the hangar and its compartments.

The fourth and final element is the space dock. It would be constructed from structural truss segments assembled within the space hangars using components transported to orbit in the RLVs. The space dock would provide the ability to assembly and support large space logistics facilities, such as the space hotels and large manned spacecraft described in the following. It could also used to store materiel and as a mount for additional solar arrays.

The space hangars and space dock would enable traditional logistics operations of maintenance, assembly, and resupply to be routinely conducted in Earth orbit. This is an enabling capability necessary to become spacefaring and achieve mastery of operations in space.

The space logistics base would have approximately 20 personnel assigned. The tour of duty would be 90 days with half of the crew rotating every 45 days. Crew rotation and base resupply would require approximately 32 RLV missions per year per base with 8 spaceplane missions and 24 cargo missions. This would provide approximately 12,000 kg (26,000 lb) of expendables and spares per person per year. At $37M per mission, a ROM estimate of the annual transportation support cost per base would be approximately $1.2B.

D. Space Hotel

While the LEO space logistics base would have sufficient housing capacity to support the 20 assigned personnel and a modest number of transient visitors, it would not be a primary housing facility. Since people cannot simply pitch a tent and "camp out" in space, establishing early permanent housing facilities is an important and enabling element of opening the space frontier to expanded human operations. The architecture of the Shuttle-derived heavy spacelifter and the LEO space logistics base was selected so that the first large space housing complexes, referred to as space hotels, could be constructed using the same space logistics base modules.

A composite illustration of the design, assembly, and deployment of the example space hotel is shown in Fig. 13. This hotel design is configured as a hub and spoke design with a long central hub and opposing sets of spokes attached to the central hub module. This configuration makes it possible to use variants of the space base's mission modules and space hangars as the primary elements of the space hotel's design.

Element 1, in Fig. 13, shows the start of the hotel assembly sequence. The central hub module, shown with the SHS's core propellant tanks still attached, is being positioned at the space logistics base's space dock. The central

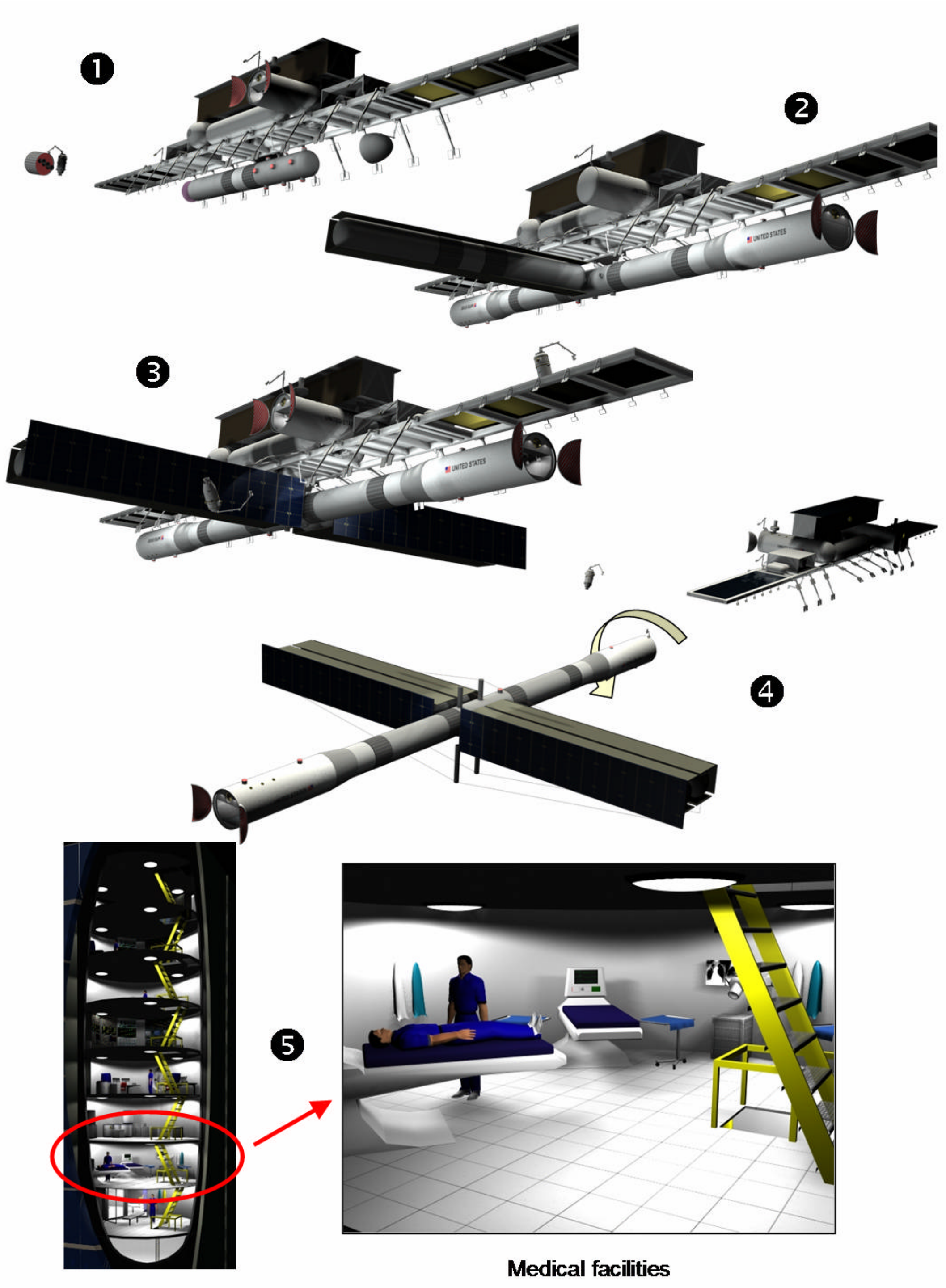

Figure 13: Assembly and internal arrangement of the example space hotel.

hub module would be a version of the mission module used in the space logistics base. Its design would include 12 docking ports around its circumference for attaching the spokes.

Element 2 shows the completed hub and one attached spoke. Two space hangars are located at the ends of the hub and the first spoke is shown attached to the central hub module. In assembling the hub, the core propellant tanks from the two SHS missions used to launch the hangars would be incorporated into the hub to provide additional pressurized volume. This approach would be also used for the spokes. Each spoke would consist of a general-purpose mission module with the SHS's core propellant tanks reused for additional pressurized volume. As with the mission module on the space logistics base, the spokes would be surrounded by solar arrays and waste heat radiators. This is what provides their "boxy" appearance.

Element 3 shows the completed 100-person space hotel with two pairs of spokes on opposing sides of the hub. This is the baseline space hotel configuration. Seven SHS missions would be required to launch the hub and spoke modules for the baseline hotel. One additional SHS cargo mission would be used for the solar arrays and waste heat radiators.

This design enables the hotel to be expanded to 6, 8, 10, or 12 spokes. Each spoke would require one additional SHS mission. The 12-spoke configuration would accommodate up to approximately 300 people. Each additional spoke would be tailored to provide a specific capability, such as research and development facilities, tourist quarters, office space, retail space, etc.

Element 4 shows the completed space hotel after being released from the space dock. It also shows how the hotel would rotate about the long axis of the hub to produce modest levels of artificial gravity in the spokes. At about two revolutions per minute, a Mars gravity level is achieved at the ends of the spokes. This use of artificial gravity enables the spokes to be organized into floors (Element 5 in Fig. 13). Each spoke would contain 18 floors with 14 of these available for general use and the remaining 4 floors used for storage and equipment. The spokes would be 8.4 m (27.5 ft) in diameter. This would provide a useful floor area of approximately 42 m^2 (450 ft^2) per floor. The total available floor area in the baseline configuration would be 2,340 m^2 (25,200 ft^2). The 12-spoke configuration, having 192 floors total, would have 3 times this floor area—7,026 m^2 (75,600 ft^2) or about 23 m^2 (250 ft^2) per person.

An estimate can be made of the number of guests visiting the hotel each year. Assuming a 3:1 ratio of guests to staff, approximately 76 guests would be staying each night in the baseline configuration and 228 guests in the full configuration. With one third of the useful floors configured as guest cabins, two cabins to a floor, each cabin would have a useful area of approximately 21 m^2 (225 ft^2).[*] With an average stay of one week, approximately 4,000 guests and 12,000 guests would visit the 4- and 12-spoke hotels each year, respectively.

If each passenger spaceplane carries 10 guests, approximately 400 and 1,200 RLV flights would be required each year. With an additional 25% required for staff transport and resupply, the 4-spoke hotel would require about 10 flights per week and the 12-spoke hotel would require about 30 flights per week. If the RLVs could achieve a one-week turnaround time, and allowing for one in five RLVs being in depot for maintenance, 12 RLVs would be required to support the 4-spoke hotel and 36 RLVs for the 12-spoke hotel.[†]

At the $37M per flight cost discussed previously for first generation RLVs, the per passenger transportation cost would be approximately $3.7M. With this transportation cost structure, a sustainable space tourism or space business market may not be possible. However, if a second generation RLV could reduce this cost by a factor of 10 to $0.37M per passenger, as an example, then an initial market demand for the baseline hotel may develop and be sustainable. In such case, the annual transportation revenue for the baseline hotel would be $3.7M x 500 = $1.9B and the 12-spoke hotel would be $5.6B.[‡] This improvement in transportation costs would also yield a savings of 90%—approximately $1B per year—in the transportation costs to support the LEO space logistics bases. Human space exploration missions would also realize a significant cost reduction.

While developing a conceptual design of a space hotel would appear premature at this early stage of considering the architecture of an initial space logistics infrastructure, several important conclusions emerge that indicate otherwise:

1) Careful selection of the initial space logistics architecture can also establish the industrial capability to build the first space hotels necessary to enable the expansion of human enterprises in space.
2) A commercially successful space hotel will require second generation RLVs to lower further the cost of transportation to orbit.

---

[*] A standard cabin on the new Queen Mary 2 cruise ship has an area of 18 m^2 (194 ft^2). A premium cabin has an area of 23 m^2 (248 ft^2).

[†] Launch sites for these RLVs would be distributed around the world. This would allow operations at the space hotel to run 24 hours per day since there is no day and night in LEO.

[‡] This further reduction could come about through the introduction of a spiral version of the first-generation RLVs where improvements to the high maintenance cost subsystems, e.g., engines, could substantially reduce the recurring costs. Another approach would be development of entirely new RLV configurations—perhaps a single-stage configuration—that would also result in a substantial reduction in recurring costs per passenger through subsystem design improvements and the ability to carry more passengers per trip. A key issue in both approaches is the amortization of the development and production costs. High flight rates, probably dependent on space tourism, would be required to yield an overall transportation cost sufficiently low to enable profitable commercial operations.

3) In order for these second generation RLVs to be ready when the first space hotel is completed, the technology research investment would need to begin concurrently with the start of the detailed design of the initial space logistics systems. Conversely, for private investment to seriously consider building the first hotels, significant science and technology progress in developing the second generation RLVs must be demonstrated by the time the initial hotel construction contracts are made.
4) The benefits of reduced space transportation costs will also substantially lower the cost of operation of the initial elements of the space logistics infrastructure, leading to a likely increase in demand for more in-space logistics services.
5) Space hotels and second-generation RLVs may become an important new aerospace product for the American aerospace industry, establishing American leadership in this new and growing field of human astronautical technologies.
6) It is not unrealistic to expect, with the building of an integrated space logistics infrastructure, that hundreds of people could be living and working in space by 2020, growing to thousands of people by 2040 with many of these living in the first permanent orbiting space settlements.

VII. Near-Term Space Mobility Systems

A. Overview and Key Points

The expansion of human and robotics space operations will require improved space transportation within the central solar system. With the establishment of logistics bases and hotels in LEO, the deployment and operation of new reusable space mobility systems will be needed to support expanded human space operations. This section describes two example mobility systems: a space logistics vehicle and a large manned spacecraft. Key points discussed in this section are:

1) Medium-class space logistics vehicles, transportable to orbit in the RLVs, could provide cargo handling and cargo delivery within the Earth-Moon system.
2) Large manned spacecraft, built using the same modules and technologies used to build space logistics bases and space hotels, could be assembled and based at the space logistics bases.
3) With nuclear thermal rockets (NTR), these large manned spacecraft could transport passengers and cargo anywhere within the Earth-Moon system.
4) With improved propulsion, such as advanced fusion systems, these large manned spacecraft could transport passengers and cargo anywhere within the central solar system.

B. Space Logistics Vehicle

In-space logistics support vehicles, such as the Automated Transfer Vehicle being developed to support the International Space Station, are intended to provide for the routine movement of satellites and delivery of supplies in Earth orbit. In this example space logistics architecture, this concept has been expanded to a family of modular reusable spaceflight systems referred to as space logistics vehicles (SLV). As shown in Fig. 14, these provide local, intermediate, and extended range mobility.

Element 1, in Fig. 14, is the tug version consisting of a lower propulsion module, a middle crew module, and an upper robotic arm module. The robotic arm is shown connected to a 4.6 m (15 ft) diameter x 9.2 m (30 ft) standard cargo container conforming to the size of the RLV payloads discussed previously. This tug version was sized, excluding the robotic arm, to fit within the 3.7 m (12 ft) diameter x 9.2 m (30 ft) long cargo module of the example Case 3 RLV described earlier. Once transported to orbit and mated to a robotic arm, this tug is used to support the assembly of the LEO space logistics base and provide materiel handling at the base. The tug can be taken inside the space hangars for routine maintenance, servicing, and mission reconfiguration. Its performance was sized to retrieve the 11,400 kg (25,000 lb) cargo containers delivered to the 185 km (100 n.m.) circular orbits and transfer these containers to the space logistics base or space hotel.

Elements 2 and 3 show other tug configurations with a passenger module and a satellite refueling module. Element 4 is an intermediate range version of the SLV that has sufficient Delta-V to conduct significant plane change and orbital altitude maneuvers in LEO.

The largest version of the SLV is the Element 5 extended range configuration. While retaining common crew and mission modules, the propulsion module is increased in size to fill the payload envelope of a 4.6 m (15 ft) diameter x 9.2 m (30 ft) long RLV cargo module in order to maximize the SLV's performance. After delivery to the space logistics base, the extend range propulsion module would be mated inside one of the space hangars with the engines and the crew and mission modules. Two of these extended range SLVs, as shown in Element 6 of the illustration, have sufficient performance to deliver approximately 18,100 kg (40,000 lb) to geostationary orbit or

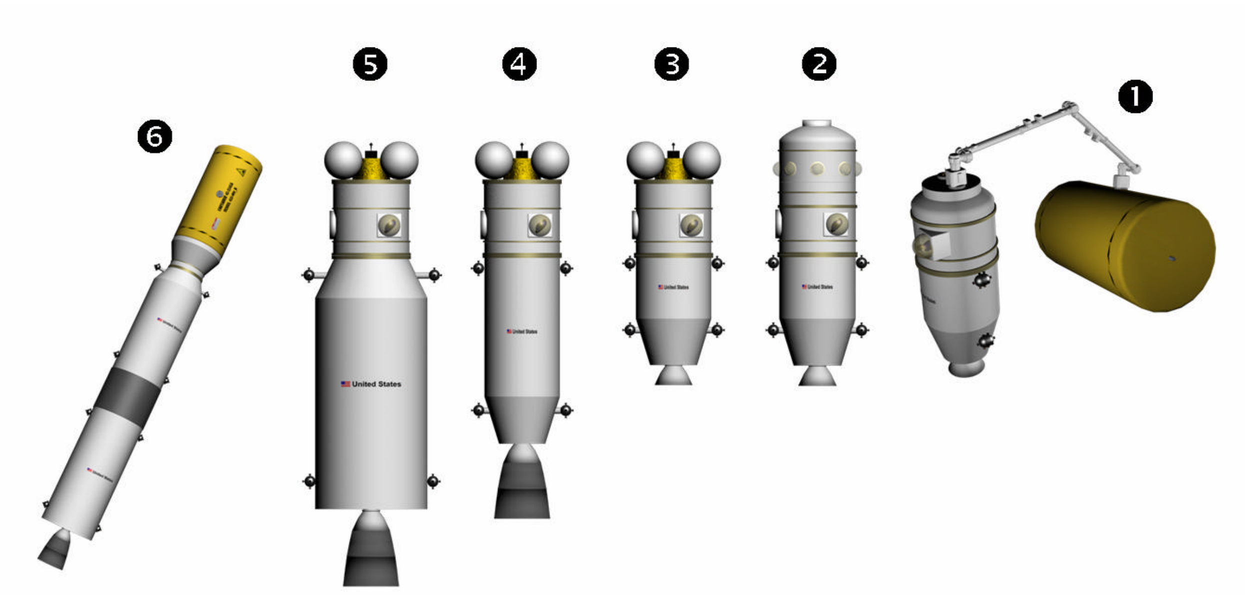

Figure 14: Space Logistics Vehicles: (1) Human crewed tug version of the SLV with robotic arm for payload handling; (2) Passenger transport; (3) General human crewed SLV figuration for local mobility; (4) Intermediate range human crewed SLV; (5) Extended range human crewed SLV; (6) Pair of extended range unmanned SLVs for transporting payloads to geostationary orbit or to lunar orbit

lunar orbit and return to the LEO space logistics base. A single extended range SLV, operated as an unmanned vehicle, has sufficient performance to fly to geostationary orbit or lunar orbit, perform inspections or black box replacements, and return to LEO.

The SLVs were designed as LH/LOX propulsion systems using mature expander cycle engines, such as the RL-10 family used for many years in upper stages and the newer Rl-60 engines now under development. This provides the maximum performance for chemical propulsion enabling the twin configuration of extended range SLVs to provide mobility throughout the Earth-Moon system.

C. Large Manned Spacecraft

While SLVs are essentially a utility transport designed for short mission durations of 2-3 days, expanded human operations within the central solar system will require mobility/logistics systems with greater endurance and capacity for transporting both passengers and cargo as well as providing needed “road-side” logistics support. Figures 9, 15, and 16 illustrate such an example large manned spacecraft that, as a starting point, is designed to

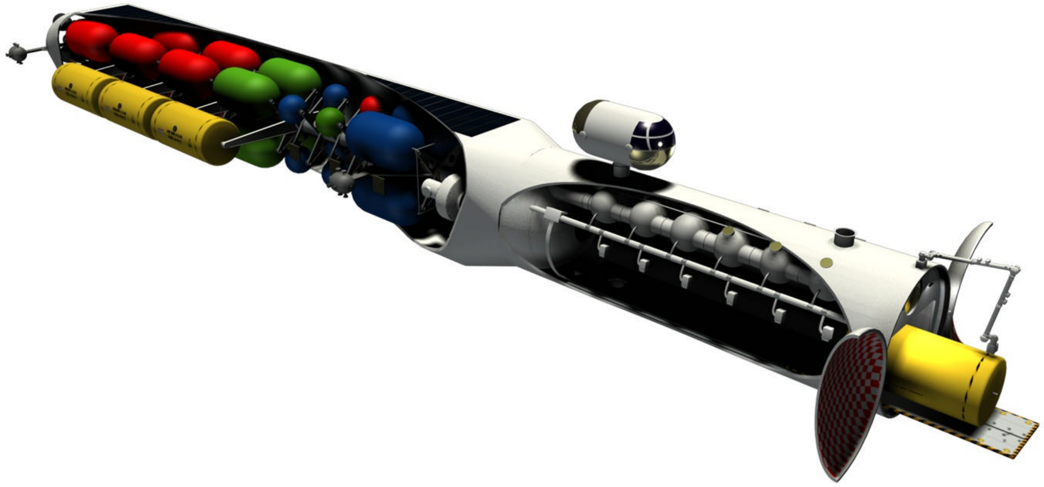

Figure 15: Cut-away view of a large manned spacecraft

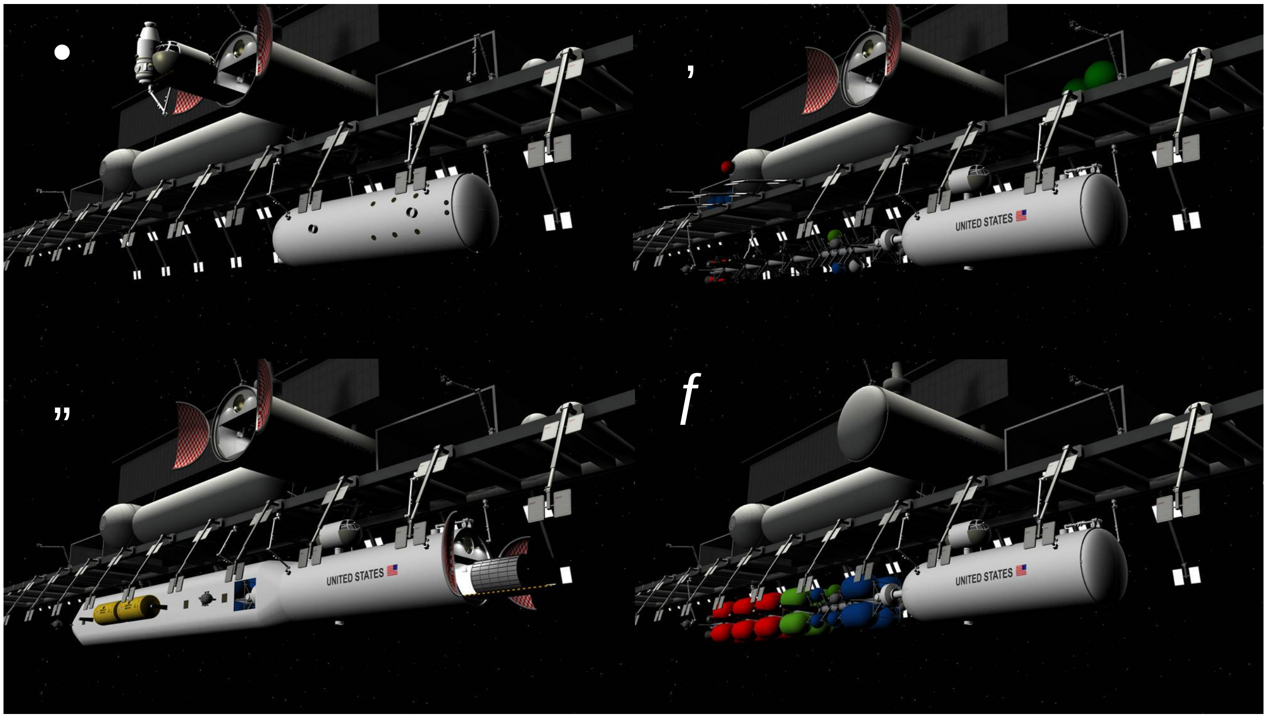

Figure 16: Assembly of a large manned spacecraft in the LEO space logistics base’s space dock.

provide mobility and logistics support within the Earth-Moon system.

This example spacecraft design uses the modular construction architecture used in building the space logistics base and the space hotel. Fundamentally, it is a self-powered space hangar. While the spacecraft would also transport cargo and passengers, the incorporation of a space hangar enables the logistics support processes developed for the LEO space logistics bases to be conducted anywhere within the Earth-Moon system. This provides critical logistics support to space operators, anywhere in the Earth-Moon system, using the same logistics processes—system designs for space servicing, trained technicians, tools, equipment, spares, etc.—developed and demonstrated at the LEO space logistics bases. In addition, the availability of the pressurized hangar enables these logistics services to be conducted in a pressurized shirtsleeve environment, just as they would be done in the space logistics base’s hangar in LEO. Therefore, as human space operations move away from LEO to geostationary orbit, the LaGrangian Points, or lunar orbit, mission planners can have confidence that demonstrated logistics support capabilities available in LEO would also be available wherever needed in the Earth-Moon system. This should significantly reduce program risk.

Elements 1-4 of Fig. 16 show the assembly of the example spacecraft. In Element 1 the spacecraft’s hangar module, following launch with an SHS and separation from the SHS’s core propellant tanks, is positioned at the space dock using several robotic arms. Once the hangar is in place, other components for the spacecraft, ferried to orbit using the RLV and stockpiled at the space logistics base, would be installed. In Element 1, for example, the spacecraft’s flight deck is shown being removed by an SLV tug from the space logistics base’s space hangar in preparation for being attached to the spacecraft hangar module. This modular design approach provides a logistically supportable spacecraft design that can be repaired and updated by replacing appropriate internal and external components.

In Elements 2 and 3, the flight deck has been attached, the hangar module rotated into an upright orientation, the aft keel beam has been attached, and the air and propellant storage tanks have been attached to the keel beam. Like the flight deck, the storage tanks would be sized to fit within the RLV payload envelope. Finally, in Element 4, the solar thermal and micrometeoroid barrier have been installed over the aft fuselage structure and the spacecraft is nearing readiness for first flight.

Once the spacecraft assembly and final preparations for flight are completed, the space dock would be used as its base of operations. In Fig. 9, cargo modules are shown being loaded onto the aft cargo pylons in preparation for a cargo delivery mission.

The example spacecraft is designed to achieve Delta-Vs of between 7,600-8,800 m/s (25,000-29,000 ft/s) with 68,000 kg (150,000 lb) of cargo. The lower performance reflects the use of LH/LOX chemical propulsion using standard expander cycle rocket engines. The higher performance reflects the use of NTR with LOX augmentation, as proposed in Ref. 27. With NTR/LOX, the spacecraft would be capable of delivering the design payload to either geostationary orbit or lunar orbit and returning to LEO. In addition to carrying cargo, the spacecraft could carry SLV tugs configured to ferry cargo and passengers to the lunar surface. Hence, the spacecraft and the SLVs would provide a means to open the entire Earth-Moon system to expanded human space operations.

Of all of the technologies needed to build the example space logistics systems, only the NTR/LOX propulsion system represents technology not yet at or in the final stages of flight readiness demonstration. With sufficient development effort, given that the NTR part of this system has been previously demonstrated, such a propulsion system should be capable of being brought to operational status in 12-15 years, suitable for initiation of spacecraft operations throughout the Earth-Moon system by 2020. This would be followed by upgrades to more advanced nuclear propulsion systems—perhaps fusion based—permitting these large spacecraft to provide transport and logistics support anywhere within the central solar system. For these advanced propulsion development programs, the space logistics infrastructure would enable developmental and operational testing of nuclear propulsion systems to be undertaken in space, while also providing a safe means of transporting these propulsion systems to orbit.

VIII. Organization and Funding

A. Overview and Key Points

This section proposes the formation of a Federal Government Corporation to function as a space logistics authority to lead and organize Government and industry resources. Key points discussed in this section are:

1) Approximately 60 Federal Government Corporations have been created under the Necessary and Proper clause of the Constitution.
2) The proposed United States Space Logistics Authority would be a new Federal Government Corporation functioning as a port authority for space logistics capabilities to meet Government needs throughout the central solar system.
3) Near-, mid-, and far-term objectives for the USSLA and associated possible Government and industry activities are described.
4) Required capital funding for building and operating a near-term space logistics infrastructure, over the next 25 years, would be a very small percentage of the total U.S. funding expended, at all levels of government, for public infrastructure building and operation.

B. United States Space Logistics Commission

Achieving specific goals or objectives is best done by a team of carefully selected, dedicated people focused on a specific task and sharing common and well-understood success criteria. To build new infrastructure, a governing authority is typically created to establish the tightly focused, information-sharing, problem-solving environment necessary for complex infrastructure projects to be successfully organized and executed.

For building an integrated space infrastructure, a new Federal Government Corporation, possibly named the United States Space Logistics Authority (USSLA), could be created through an act of Congress and executed as an independent Government agency. The authority to "create government corporations comes from the Necessary and Proper clause of the Constitution, Article I, Section 8, paragraph 18, which states:"[28]

> To make all laws which shall be necessary and proper for carrying into execution the foregoing powers and all other powers vested by this Constitution in the Government of the United States or in any Department or Officer thereof.

In 1933, President Franklin D. Roosevelt called on Congress to establish the Tennessee Valley Authority as "a corporation clothed with the power of government but possessed of the flexibility and initiative of a private enterprise."[29] Since that time, more than 60 such Federal Government Corporations have been created to execute unique government functions that were best undertaken outside of the normal Government departments and existing agencies. An appropriate USSLA charter, modeled after that of the Tennessee Valley Authority, would be:

> To provide safe and assured access to, from, and throughout space for people and cargo; to provide for in-space logistical support; to normalize and expand space operations throughout the central solar system for civil, commercial, and national security operations in space; to provide for space industrial development; to

> provide for the human settlement of space by the creation of a corporation for the development and operation of terrestrial and in-space Government properties and equipment and the establishment of an integrated infrastructure of commercial space services to provide assured access to space and the support of the in-space Government properties and Government space operations and for other purposes.

One important characteristic of the USSLA is that it would *not* be an operating agency in the sense that USSLA employees would operate the U.S. Government properties or directly provide the space access and logistical support services. Rather, the USSLA would be organized to acquire Government-owned systems and facilities from U.S industry and to contract for and provide management oversight of the U.S. commercial space service providers supporting Government space operations.

In its early phase of operation, the USSLA would be an executive agent, functioning much as Government system program offices do, to implement and manage contracts with industry to develop, build, and deploy the new infrastructure capabilities and services. Each of the system management teams would be modest in size—50 to 200 people—to achieve the correct balance between required expertise, experience, flexibility, responsiveness, and decision authority necessary for successful program organization and execution. The size of each team and its composition would change as each program progresses from program initiation through deployment or service implementation. It is expected that six to ten such project teams would be created, during the initial ten-year phase of building the space infrastructure, to address the scope of space logistics operations described in this paper. In its later phase of existence, once the initial space infrastructure becomes operational, the USSLA would function as a contract administrator ensuring that the Government has access to the needed competitive space logistics services necessary to support growing Government operations in space.

C. USSLA Implementation Objectives and Related Government and Industry Spacefaring Actions

The following outline of USSLA objectives and related Government and industry spacefaring actions helps to portray not only how the establishment of an integrated space logistics infrastructure can be achieved, but it also helps to describe what being "spacefaring" will mean in terms of expanded U.S. operations in space.*

1. Near-term Objectives (1-5 years)

Establishing a clear public understanding of the spacefaring vision of America, the purpose of the USSLA, and the organization of the U.S. industrial base to achieve this vision would be the initial objectives of the USSLA. Other related USSLA actions could include:

- Establishing the initial infrastructure architecture.
- Defining commercial service roles and functions.
- Establishing a space infrastructure development fund.
- Contracting for the development and preparing to deploy the initial infrastructure capabilities.
- Interfacing these capabilities with mid- and long-term plans for Government operations in space.
- Fostering future commercial use of the space infrastructure.

Associated activities of other Government departments and agencies could include:

- Establishing updated human space flight and in-space operations rules and regulations.
- Integrating mid- and long-term space infrastructure capabilities into the planning for renewed human exploration of the Moon, Mars, and near-Earth objects.
- Conducting research and development to support second-generation reusable space access systems.
- Integrating mid- and long-term space infrastructure capabilities into the planning for expanded military and national security operations in space.
- Fostering the development of new space business operations for tourism and space resource development that would utilize the space logistics infrastructure capabilities.
- Preparing to deploy and operate a space flight traffic control system.
- Preparing to deploy and operate an upgraded space hazard detection and avoidance system.
- Expanding in-space research and development for technologies that would enhance or exploit the space infrastructure capabilities.

---

* These objectives and related actions were first listed in a paper by the author, "Visions of a 21st Century Spacefaring America," published as a poster paper at the AIAA International Air and Space Symposium and Exposition: The Next 100 Years, Dayton, Ohio, July 2003.

- Establishing space "in situ" research and development capabilities, enabled by the space infrastructure, which would support the expansion of civil, commercial, and national security space research and development.
- Using the renewed emphasis on human space activities to reinvigorate American student interest in science and engineering to support the development of the future American aerospace workforce.
- Developing and implementing a strategy for expanding the U.S. industrial base for supporting a 21st century spacefaring nation.
- Preparing to establish U.S. "Space Guard" emergency services for the protection of human safety and American-owned property in space.
- Preparing and enacting legislation to foster commercial enterprise activities in space.
- Preparing and enacting legislation to define property rights in space, especially with respect to orbital locations accessible by and supported by the space logistics infrastructure.
- Preparing and enacting legislation to create a U.S. National Space University with facilities located both terrestrially and in-space—the first "space grant" university.

Commercial and private interests could:

- Prepare business strategies and ventures to provide the new commercial space service needs of the USSLA and Federal Government.
- Undertake privately funded research and development to bring new products and capabilities to the space services marketplace as well as products and services that exploit the new infrastructure capabilities.
- Invest in new facilities and human resources to prepare for new opportunities in space.
- Transition commercial space satellite designs to approaches that can make use of the space launch and on-orbit servicing capabilities offered by the new space infrastructure.

2. *Mid-Term Objectives (5-15 years)*

In the mid-term, the USSLA would focus on deploying and initiating the initial infrastructure capabilities. These activities would include:

- Deploying and initiating operations of the initial space transportation and in-space logistical support space flight systems, facilities, and services.
- Contracting for commercial space service providers to operate the USSLA-owned space flight systems and facilities.
- Contracting with the commercial space service providers for core Government space service needs, e.g., space launch and satellite servicing.
- Leasing USSLA-owned space flight systems and facilities, on an "excess capacity" basis, to the contracted commercial space service providers to increase the nation's benefits from these new infrastructure capabilities.
- Developing and deploying the second phase of space infrastructure space flight systems and facilities including space hotels in Earth orbit and spacecraft capable of transporting people and cargo within the Earth-Moon system.

Associated activities of other Government departments and agencies could include:

- Operating a space flight traffic control system combined with a space hazard warning and avoidance system.
- Operating the U.S. Space Guard.
- Executing in-space human space exploration activities (e.g., training and equipment development) in preparation for a return to the Moon and the exploration of Mars and near-Earth objects.
- Conducting expanded research and development for next-generation commercial space infrastructure capabilities as well as high-risk and long-lead space-based research and development.
- Deploying and operating an expanded terrestrial civil observation system for environmental protection and the protection of human life and private property.
- Building the first "space grant" university facilities in space as part of the creation of the U.S. National Space University.
- Offering the first "astronaut" student scholarships for students to attend the National Space University.
- Graduating the first accredited astronauts.
- Preparing to provide for planetary defense.
- Undertaking Government-industry partnerships to exploit space natural resources for energy, engineering materials, and consumables (e.g., oxygen, water, and propellants), and space manufacturing and construction.

- Undertaking research and development in support of unique Government needs such as advanced nuclear propulsion and asteroid defense.

Commercial and private activities could include:

- Providing contracted transportation and logistical support services to the USSLA, Government, and commercial businesses.
- Augmenting the baseline infrastructure services with additional services targeted at existing or new Government and commercial customers.
- Establishing a space tourism industry.
- Establishing a space power industry to provide electrical power and propellants for space operators.
- Establishing a space hotel and resort industry.
- Establishing a space construction and assembly industry.
- Establishing a to-space and in-space transportation industry that would take over the transportation responsibilities, initiated under the USSLA, for passenger and cargo transport to and from Earth orbit and within Earth orbit.
- Building private space research and development centers in space.
- Developing next generation space technologies.
- Undertaking research and development to commercialize space natural resources and space manufacturing and construction.

3. *Far-Term USSLA Goals (12-25 years)*

While the USSLA would retain ownership and operational control of key Earth orbiting facilities and spaceflight systems, it would transition the contracted space transportation and logistical support services for Government space operations to commercial suppliers. The USSLA would then turn its focus on the following:

- Expanding the orbiting logistical support facilities, as may be needed, to meet growing Government needs.
- Establishing routine transportation to and from the Moon.
- Building the first permanent logistical support base in lunar orbit and on the Moon to support renewed lunar exploration, scientific research, and natural resource recovery.
- Establishing a logistical support facility in geostationary orbit to support the increased use of geostationary satellites including, possibly, solar power satellites and direct broadcast personal communication services.
- Establishing a logistical support facility at a LaGrangian Points to support exploration and logistical support operations throughout the central solar system and natural resource recovery from the Moon.
- Developing and deploying upgraded manned spacecraft utilizing advanced nuclear propulsion.
- Providing interplanetary transportation to Mars and near-Earth objects, perhaps using LEO space hotels employed as Earth-Mars cycling spacecraft.
- Developing and building the first prototype space colony at a LaGrangian point.
- Preparing to support the extraction and delivery of non-terrestrial materials.
- Logistically supporting the first human exploration missions to Mars and near-Earth objects.

D. Space Infrastructure Capital Funding

A key element of this example "third best" strategy has been to minimize technical and program execution risks through the use of existing industrial capabilities. With this strategy, building the infrastructure changes from a Government-sponsored high technology program, such as the supersonic transport or a pure space exploration program, to a Government-sponsored infrastructure program that is fundamentally no different from building a new canal, bridge, seaport, or major airport. Like these examples, it is undertaking a construction program using demonstrated industrial capabilities. With this change, and with the Government's intent and clear need to be a consumer of the space logistics services brought into being by the new space logistics infrastructure, development and production funding should be able to be raised using conventional Government-backed bonds.

As with all substantial infrastructure programs, this funding approach avoids the necessity of paying for the infrastructure's development and construction using annual appropriations. The key question then becomes—how to pay back the bonds? Earlier in the paper, a ROM estimate of the recurring costs of near-term RLVs was discussed. A conclusion was drawn from this ROM estimate that the potential annual savings in Government space launch costs could approach \$3.6B. Over a 25-year time period of the operational life of the initial fleet of RLVs, this provides a cost savings of roughly \$90B that could be used to pay off these bonds. Obviously, further Government savings through improved space operations, decreased space access costs for expanded Government space operations, and the economic benefits of a resurgent aerospace industrial base would add to the inherent worth of this space logistics infrastructure investment.

Another way to assess the wisdom of this investment in building a space logistics infrastructure is to consider how much investment American makes in public works. Various Internet sources indicate that approximately 2.5 percent of the Gross Domestic Product is spent annually on building and operating just the transportation and water public works. With a current Gross Domestic Product of approximately \$11,000B, approximately \$275B is spent annually, by all levels of government, on just these two segments of public infrastructure. Over the next 25 years, the total expenditures will be approximately \$7,000B.

In 2002, "U.S. economic activity linked to the commercial space industry totaled over \$95 billion and contributed to \$23.5 billion in employee earnings throughout the United States."[30] If this level of economic activity is thought of as a "space domestic product," the total over the next 25 years, without any projected increases or infrastructure investment, would be approximately \$2,400B. Hence, an investment of \$90B in projected savings from improved space access coupled with another \$60B in additional building and operations expenditures (2.5 percent of the \$2,400B space domestic product) *may* yield a 2X-5X increase in the space domestic product, generating an additional \$2,400B-\$9,600B in U.S. economic activity. All the way back to the National Road and Erie Canal, history has demonstrated that prudent infrastructure investment substantially increases benefiting economic activity. The \$60B would equate to less than one percent of the total U.S. public infrastructure building and operating expenses during this same period.

IX. Conclusion

In *The Art of Systems Architecting*, Rechtin and Maier state the following with respect to nature of classical architecting. "In the earliest stages of a project it is a structuring of an unstructured mix of dreams, hopes, needs, and technical possibilities when what is most needed has been called an inspired synthesizing of feasible technologies."[31] The purpose of this paper was to move the debate on a spacefaring future beyond wishful musings to discussions of how a "synthesizing of feasible technologies" could be undertaken to initiate the important transition of the United States into a true spacefaring nation. To help advance the debate to what actions could be undertaken now, the focus of this paper has been on near-term, "third best" approaches that make use of existing capabilities of the American industrial base. As the example near-term space logistics architecture and constitutive systems discussed in this paper hopefully demonstrate, the spacefaring future of our dreams, hopes, and needs can be achieved within the next twenty years through a prudent strategy for near-term space logistics investments.

Acknowledgments

The author wishes to thank Alicia Hartong, John Livingston, and Brendan Rooney of the Air Force Aeronautical Systems Center for their conceptual design analysis of near-term RLVs. The author also wishes to thank Isiah Davenport of the General Dynamics Corp. for his assistance in preparing many of the 3-D models and illustrations used in this paper.

Author's Notes

The views and opinions expressed in this paper are those of the author. All errors and omission are the responsibility of the author. The illustrations of the example space logistics infrastructure are in the public domain. This update to the original paper includes corrections of typographical errors and minor changes to align the paper with the presentation. Additional estimates of the development, production, and recurring cost of operations of the near-term RLVs are contained in the author's presentation based on this paper.

References

---

[1] "Final report of the Commission on the Future of the United States Aerospace Industry," 2002, p. xxi.

[2] "Final report of the Commission on the Future of the United States Aerospace Industry, 2002, pp.3-11.

[3] "Final Report of the Commission to Assess United States National Security Space Management and Organization," 2001, p. xi.

[4] "Final Report of the Commission to Assess United States National Security Space Management and Organization," 2001, p. xii.

[5] Harper's Monthly, 1879.

[6] http://www.eriecanal.org.

[7] http://www.archives.nysed.gov/projects/eriecanal/ErieEssay/ecf.html

---

[8] http://www.canals.state.ny.us/cculture/history/

[9] http:// www.logisticsworld.com/logistics.

[10] Roger D. Launius, “Kennedy’s Space Policy Reconsidered: A Post-Cold War Perspective,” Air Power History, Winter 2003, p. 22.

[11] Roger D. Launius, “Kennedy’s Space Policy Reconsidered: A Post-Cold War Perspective,” Air Power History, Winter 2003, p. 26.

[12] “America at the Threshold: Report of the Synthesis Group on America’s Space Exploration Initiative,” Superintendent of Documents, U.S. Government Printing Office, 1991, p. iv.

[13] “America at the Threshold: Report of the Synthesis Group on America’s Space Exploration Initiative,” Superintendent of Documents, U.S. Government Printing Office, 1991, p.31.

[14] Roger D. Launius, “Kennedy’s Space Policy Reconsidered: A Post-Cold War Perspective,” Air Power History, Winter 2003, p. 24.

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

[16] “The Economic Impact of Commercial Space Transportation on the U.S. Economy: 2002 Results and Outlook for 2010,” Associate Administrator for Commercial Space Transportation, Federal Aviation Administration, March 2004, p. 1.

[17] “The Economic Impact of Commercial Space Transportation on the U.S. Economy: 2002 Results and Outlook for 2010,” Associate Administrator for Commercial Space Transportation, Federal Aviation Administration, March 2004, p. 2.

[18] 2003 Commercial Space Transportation Forecasts, Federal Aviation Administration’s Associate Administrator for Commercial Space Transportation and the Commercial Space Transportation Advisory Committee, May 2003, p.6.

[19] “Why and Whither Hypersonics Research in the US Air Force,” United States Air Force Scientific Advisory Board, SAB-TR-00-03, December 2000, p. vi.

[20] “Why and Whither Hypersonics Research in the US Air Force,” United States Air Force Scientific Advisory Board, SAB-TR-00-03, December 2000, p. 58.

[21] http://www.grc.nasa.gov/WWW/PAO/html/warp/brakthru.htm

[22] James R. Wertz, “Economic Model of Reusable vs. Expendable Launch Vehicles,” IAF Congress, October 2-6, 2000, p. 14.

[23] “Acquisition of National Security Space Programs,” Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, May 2003, p. 7.

[24] “Space Transportation Costs: Trends in Price Per Pound to Orbit 1990-2000,” Futron Corporation, September 6, 2002, http://www.futron.com.

[25] Greg Moster, “Reusable Military Launch System Team,” AFRL Technology Horizons, April 2004, p. 38.

[26] Alicia Hartong, “Near-Term RLVs,” AIAA 29th Annual Dayton-Cincinnati Aerospace Sciences Symposium, March 2004, United States Air Force Aeronautical Systems Center, Wright-Patterson Air Force Base, OH, ASC 04-0609.

[27] Stanley K. Borowski and Leonard A. Dudzinski, “`2001: A Space Odyssey’ Revisited—The Feasibility of 24 Hour Commuter Flights to the Moon Using NTR Propulsion with LUNOX Afterburners,” NASA/TM—1998-208830/REV1, December 2001.

[28] “Seeking Nontraditional Approaches to Collaborating and Partnering with Industry,” RAND, Arroyo Center, 2002, page 57. Available on the web at http://www.rand.org/publications/MR/MR1401/.

[29] http://www.fdrlibrary.marist.edu/odtvacon.html

[30] “The Economic Impact of Commercial Space Transportation on the U.S. Economy: 2002 Results and Outlook for 2010,” Associate Administrator for Commercial Space Transportation, Federal Aviation Administration, March 2004, p. 1.

[31] Eberhardt Rechtin and Mark W. Maier, “The Art of Systems Architecting,” CRC Press, 1997, p. 5.