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Building Large Space Bases in Low Earth Orbit

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Abstract

Opening the space frontier to human settlement and enterprise requires that a basic infrastructure be developed that will provide the necessary services to support these human activities. One of the first steps in establishing this basic infrastructure is to build large space bases in low earth orbit that will serve as the terminus for the reusable launch vehicles or planetary shuttles now under development. This paper discusses a proposed approach for building such large space bases using the current Space Shuttle's technology base.

Introduction

In the companion paper, "Space Infrastructure Planning," a basic operational need for the first phase of the human settlement of space was proposed:[1]

> *Phase 1 (2000-2040) will design, develop, build, deploy, and operate a space operations and transportation network extending from the earth's surface to the surface of the moon and the surface of Mars. This network will support exploratory, research, civil governmental and commercial human and robotic activities in circumterrestrial space, in circumlunar space and on the lunar surface. This network will support routine human exploration of Mars and the near-earth asteroids.*

A preliminary systems engineering functional analysis of the space infrastructure architecture required to support this Phase 1 need was undertaken. This resulted in a definition of the basic functions required to be performed by the infrastructure (Figure 1) and a basic Transportation and Operations Infrastructure Functional Architecture that links these functions (Figure 2). Examination of this functional architecture indicates that the starting point for its implementation is with the H-7 earth surface base, T-4 planetary shuttle, and H-4 space base in low earth orbit (LEO).

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[2] Views expressed in this paper are those of the author and may not represent those of the U.S. Air Force or U.S. Government.

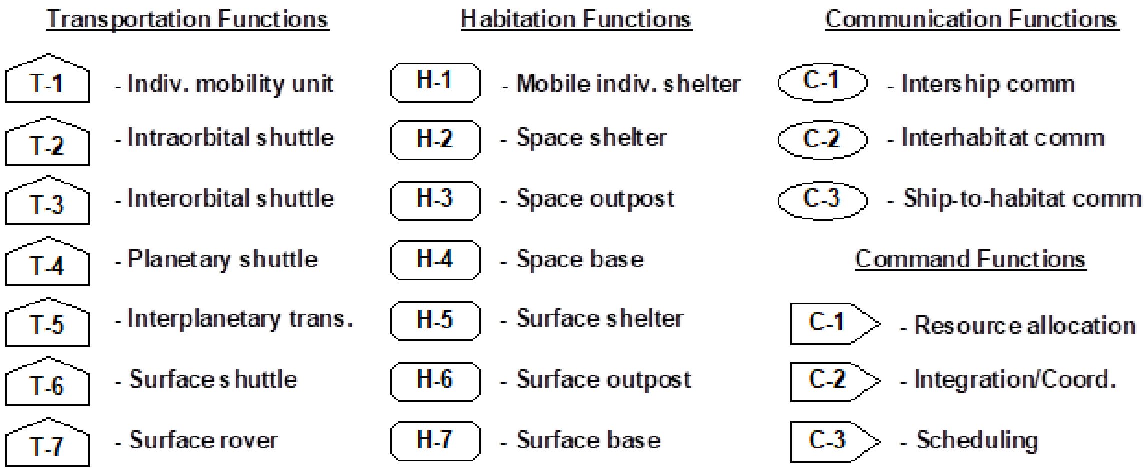

Figure 1 – Phase 1 Basic Infrastructure Functions

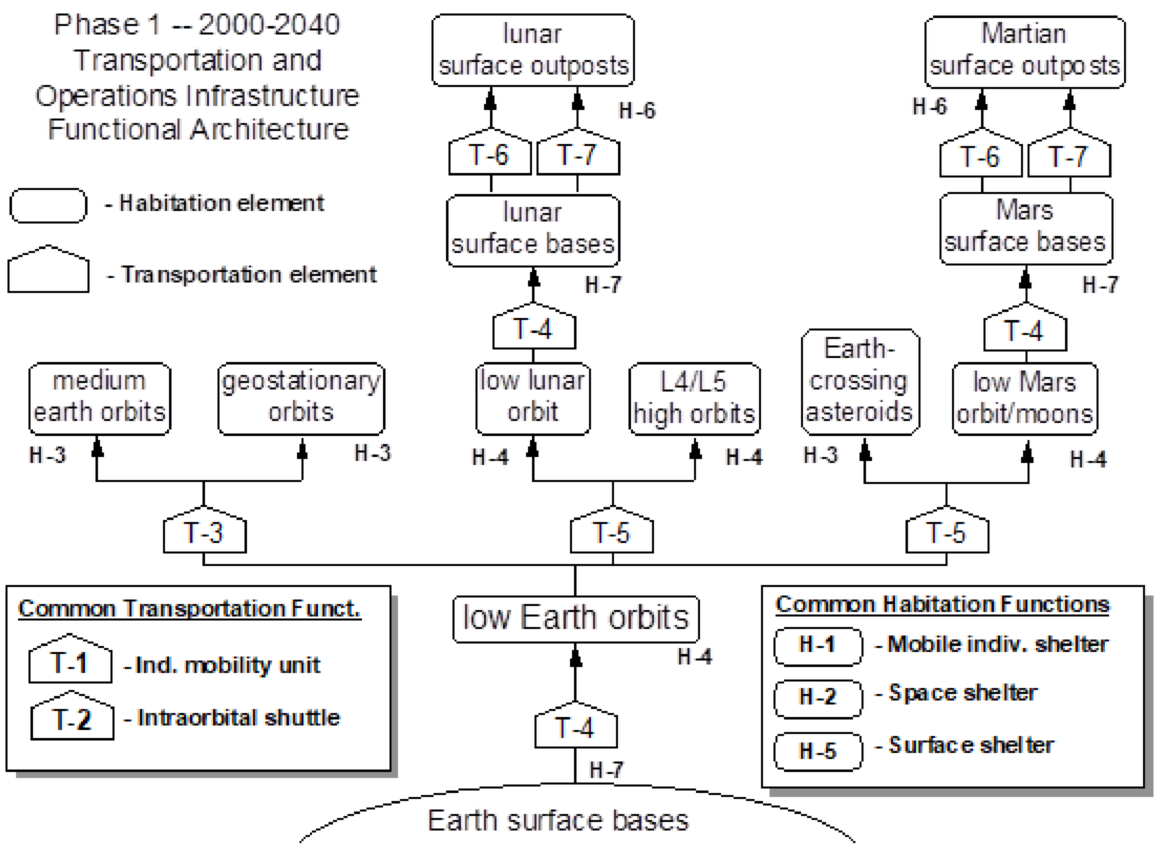

Figure 2 – Phase 1 Functional Architecture

Development of the H-7 earth surface base and the T-4 planetary shuttle is underway in several countries, most notably with the United States' Reusable Launch Vehicle or RLV Program being run by NASA. It is expected that this second-generation planetary shuttle will take the place of the existing NASA Space Shuttle providing enhanced safety and increased flight frequency at substantially reduced costs.

Now that the H-7 Earth surface base and T-4 planetary shuttle development is underway, attention can be turned to planning space bases in LEO that can serve as the primary destination for these shuttles. This paper discusses the basic requirements for these LEO space bases and proposes one method for their design and fabrication that draws extensively upon the existing Space Shuttle technology base and infrastructure.

- Transportation system node servicing the:
  - T-3 Interorbital Shuttle
  - T-4 Planetary Shuttle
  - T-5 Interplanetary Transport
- Command & control center
- Communications center
- Logistics center (repair, replenishment, modification, maintenance, and spare parts warehouse)
- Final assembly & checkout facility
- Space training facility
- Recreational/physical conditioning facility
- Farm
- Medical support facility
- Space rescue team base
- Fuel depot
- Crew/transient quarters
- Crew/guest mess

Figure 3 – LEO Space Base Primary Functions

H-4 LEO Space Base Size

The diversity of functions required to be performed indicates that the H-4 LEO space bases will be substantial in size. One measure of the need for large space bases can be seen from an assessment of the payload capability of the T-4 planetary shuttles now in development.

Published information regarding the NASA RLV program indicates that the payload capability will be approximately 10,000 kg to a low earth orbit of 460 km, the typical altitude of a LEO space base. Table 1 shows the total potential payload placed in such an orbital altitude based upon the number of vehicle flights per week. This reflects the capability of a modest RLV fleet of five vehicles that begins commercial operations with one flight per week for the fleet and grows to four flights per week for the fleet as the RLV matures over several years of use.

Table 1 – Projected RLV Fleet Cargo Capability

Flights/ Week	Payload/ Week (kg)	Flights/Yr. (1)	Payload/Yr. (kg)	Pay. Vol./Yr. (m^3) (2)
1	10,000	50	500,000	2,500
2	20,000	100	1,000,000	5,000
3	30,000	150	1,500,000	7,500
4	40,000	200	2,000,000	10,000

Notes:

(1) Assumes approximately a 96 percent mission success rate.

(2) Payload density assumed at an average of 200 kg/m^3.

At a modest flight rate of two flights per week, the potential payload delivered to orbit will mass 1000 metric tons with a corresponding payload volume of approximately 5,000 m^3. For comparison purposes, the support for the International Space Station (ISS) has been estimated at approximately 50 metric tons per year.

Another measure of the required size can be taken from an estimate of the number of permanent crew members required to provide the capabilities listed in Figure 3. This estimate is shown in Table 2.

The ISS has an internal volume of 1200 m^3 to support a permanent crew size of six.[2] Using this ISS ratio of approximately 200 m^3/crew member, the space base volume requirement to support the initial crew size of 33 would be approximately 6,600 m^3.

Table 2 – Estimated IOC Crew Complement

Functional Area	***Crew Size***
Command & Control	7
Communications	4
Transportation System Support	3
Logistics/Maintenance Support	7
Final Assembly & Checkout	2
Space Training	2
Recreational/Physical conditioning	1
Farm	1
Medical Support	2
Quarters Management	2
Crew/Guest Mess	2
Total	***33***

An estimate of the total base volume requirement can then be arrived at by combining this personnel volume requirement (6,600 m^3) with a cargo storage requirement (5,000 m^3) based on the modest flight rate of two flights per week. This yields an initial estimate of the LEO space base volume of the order of 12,000 m^3– ten times the size of the ISS.

Artificial Gravity Requirement

While orbital conditions yield a weightless condition as a byproduct, this has both advantages and disadvantages from the perspective of designing an orbital space base. Figure 4 lists the basic space base functions and indicates the perceived benefit brought by performing these functions in either a zero gravity or an artificial partial gravity environment.

Functions which involve extravehicular activities or logistical support activities tend to benefit from being performed under zero gravity. Certain functions such as extravehicular and zero-g operations training can only be done in a zero-g environment. On the other hand, functions which involve crew support—physical conditioning, eating, medical support, food production—benefit from being performed in a partial gravity environment. Certain mechanical functions also benefit from being performed in a partial gravity environment primarily because of the simplicity that gravity introduces into the design. Convective cooling, fresh air circulation, and bio-waste disposal are three examples.

Functional Area	***Benefits from Zero Gravity***	***No Particular Benefit***	***Benefits from Partical Gravity***
Transportation system support	■		
Command & control		■	
Communications		■	
Logistics support	■		
Final assembly & checkout	■		
Space training	■		
Recreational/physical conditioning			■
Farm			■
Medical support			■
Crew/transient quarters			■
Crew/guest mess			■
Fuel deport	■		

Figure 4 – LEO Space Base Gravity Requirements

H-4 LEO Space Base Timeline

Construction of a large space base in LEO requires the capability to transport construction crews, supplies, and, finally, the operations crew to the base. The current Space Shuttle averages six to seven missions per year. Starting in the late 1990s, three to five of these missions each year will be dedicated to building and, then, supporting the ISS. Even if the Space Shuttle was affordable, its limited availability precludes its use for supporting the construction of a large space base.

Under these circumstances, the construction of this base must await the arrival of the second-generation planetary shuttle discussed earlier. With a targeted first flight of the RLV in 2005, it may be expected that its initial operational capability will be achieved in 2008, following three years of flight and operational testing. The RLV would then be available to support the construction of a large LEO space base starting in the 2009 time frame. A 2009 space base construction start would be consistent with a desire to complete the deployment of the Phase 1 space architecture in the 2030-2040 time frame.

H-4 LEO Space Base Requirements Summary

The LEO space base design should incorporate these features:

- Internal volume of the order of 12,000 m^3.
- Crew size of 33 permanent personnel plus allowance for transient personnel.
- Provide both zero gravity and partial gravity environments.
- Utilize a technology base that can support initiation of on-orbit construction starting in 2009.

LEO Space Base Design Approach

Designing the space base can take one of three approaches. First, the base can be built from small modules transported into orbit via the RLV in much the same way the

ISS is planned to be built. Second, it can be built in orbit from raw materials lifted into orbit with the RLV or an expendable launch vehicle. Or, third, the base can be built from large prefabricated modules launched into orbit using a super heavy lift expendable launch vehicle--an extension of the method used to launch the U.S. Skylab space station in the early 1970's.

The first approach is feasible but impractical. It is estimated that approximately 140 modules, capable of being carried within the RLV payload bay (approximately 90 m^3 in size), would be required to provide sufficient internal volume. Further, the design of a base involving over 100 interconnected modules would be highly complex from a structural integrity and subsystem (air, power, water, etc.) basis. The large number of modules would also significantly increase the time and complexity of the on-orbit assembly. Finally, it is also likely that such a design, modeled after the ISS, would preclude rotation of the base to generate the partial gravity environments that are desirable for certain base functions.

The second approach builds the base from partially assembled components brought up from the earth. While this approach offers the greatest design flexibility, it requires a substantial orbital infrastructure to support the construction, especially to support a large construction crew. Robotic approaches to on-orbit fabrication may be feasible but lack the demonstrated maturity to consider for this base fabrication approach. This approach essentially adds additional difficulty and complexity to the first approach described above, may not be technically feasible in the 2009 time frame, and, hence, is not practical.

The third approach, the one proposed in this paper, is to fabricate the base using specially modified Space Shuttle external tanks transported into orbit via an unmanned launch vehicle derived from the Space Shuttle. With this approach, described in greater detail below, a large space base meeting the requirements outlined above can be built.

Utilization of Space Shuttle Technologies and Facilities

The current investment in the Space Shuttle technology development and facilities probably exceeds $20 billion. With the transition to the RLV, most of this investment and technology base will be discarded, much as the Saturn V technology base fell by the wayside as the Space Shuttle was being developed.

Rather than abandoning this substantial technology and launch infrastructure investment, the Space Shuttle could be transitioned from an manned system to an unmanned system by transforming it into a super-heavy lift, Saturn V-class launch vehicle. This is not a new idea. It has been studied several times by NASA and the aerospace industry under the name Shuttle-C.

Examination of this Shuttle-C concept indicated that to effectively use it to build large space bases, its design required further optimization. This refined design is referred to as Shuttle-S and is shown in Figure 5 at the same scale as the Saturn V.

Shuttle-S Design

Shuttle-S is shown in Figures 5 and 6. Rather that the side-by-side arrangement of the propellant tanks and payload module as typically depicted in Shuttle-C configurations, Shuttle-S uses the traditional vertical stacked arrangement.

The core vehicle is comprised of two Shuttle solar rocket boosters attached to a modified Shuttle liquid oxygen tank mounted on top of a Shuttle liquid hydrogen tank. The liquid hydrogen/oxygen rocket engines are mounted on the bottom of the liquid hydrogen tank.

The Shuttle-S payload module mounts on top of the liquid oxygen tank of the core vehicle. This permits a wide variety of payload sizes and diameters to be accommodated without impacting the configuration of the core vehicle. This feature is one advantage of the vertical Shuttle-S design over the Shuttle-C side-by-side design. The total payload capability of Shuttle-S would be approximately 100 metric tons.

The Shuttle-S core vehicle would eb fabricated in existing Space Shuttle facilities, assembled in the Vehicle Assembly Building at Kennedy Space Center, and launched from the existing Shuttle launch facilities. Some modification to the launch facilities and the crawler would be required to accommodate the stacked Shuttle-S configuration.

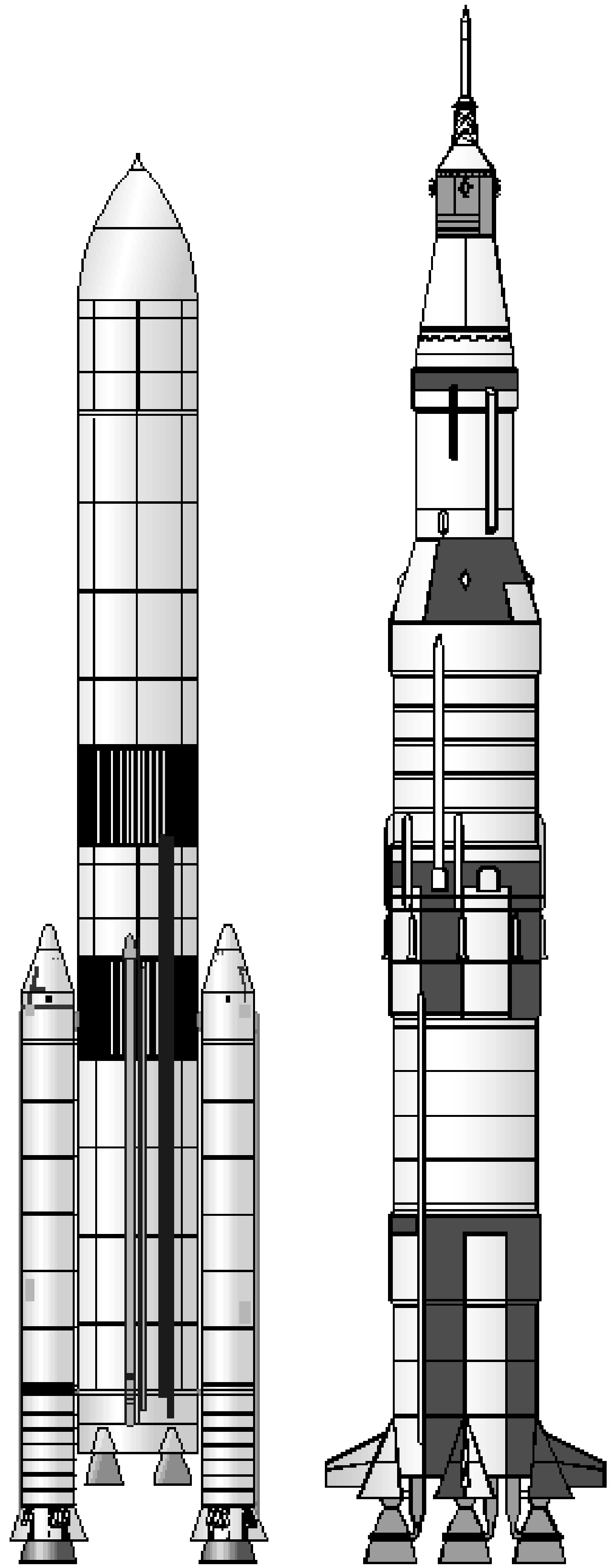

Figure 5 – Shuttle-S and Saturn V

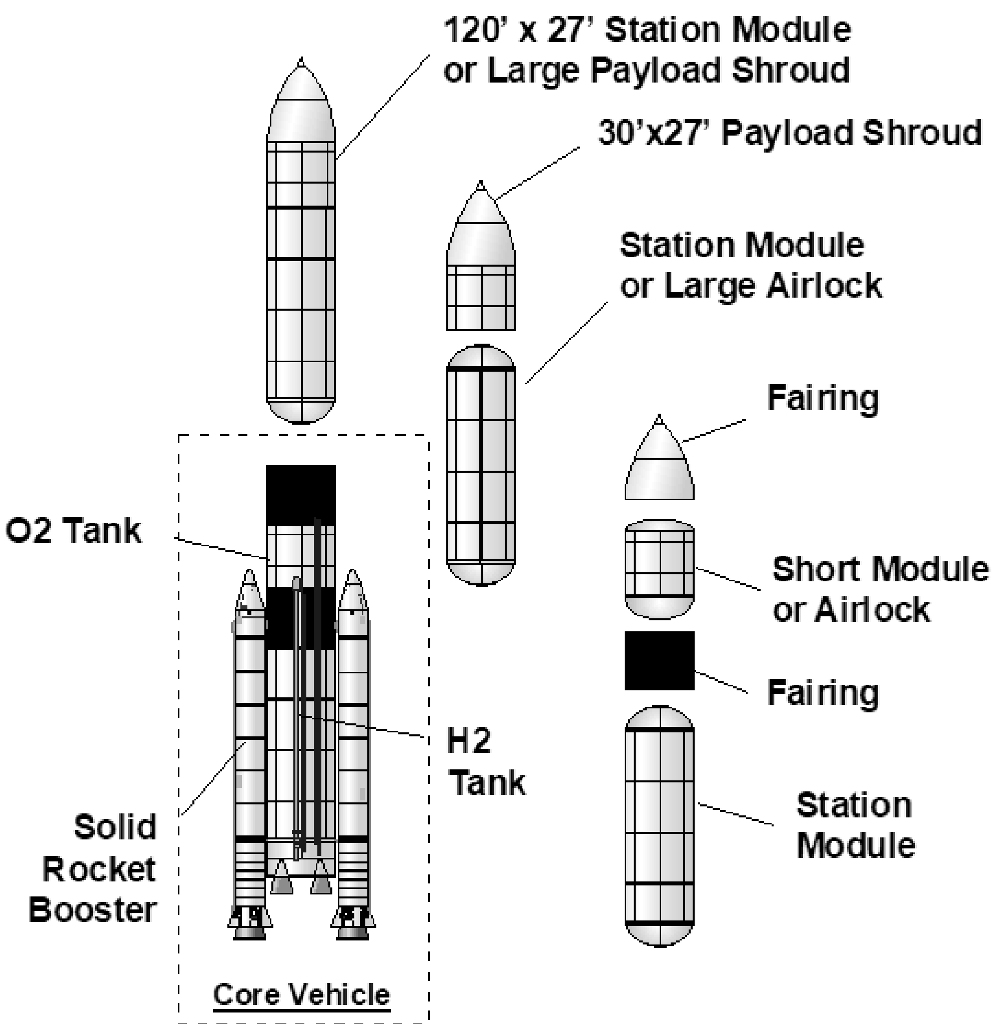

Figure 6 – Shuttle-S Core Vehicle with Several Payload Modules

Space Base 1

Using Shuttle-S, large space base modules can be fully fabricated on the Earth and launched directly into orbit. One possible configuration of a large space base assembled in orbit from these modules is shown in Figure 7. This is referred to as Space Base 1.[3]

This large space base meets the general design criteria for a H-4 space base outlined above. The gross internal volume is approximately 20,000 m^3—approximately 16 times larger than the ISS. The space base has a continuous power availability of 300 kW_e with a peak power of 700 kW_e.

The base can be designed to rotate about the hub. This provides a variable artificial gravity environment in the spokes while maintaining a quasi-zero g environment in the hub. With this approach, each spoke becomes effectively a 22-story tall building. At approximately 2 rpm, the ends of the spokes experience a gravity level of 0.4 g, approximately that of Mars. Subdivided into floors, the four spokes shown in this configuration have, in total, approximately 4,000 m^2 of useable floor area and 11,000 m^3 of useable volume. For comparison purposes, this is approximately equal to 20 four-bedroom homes.

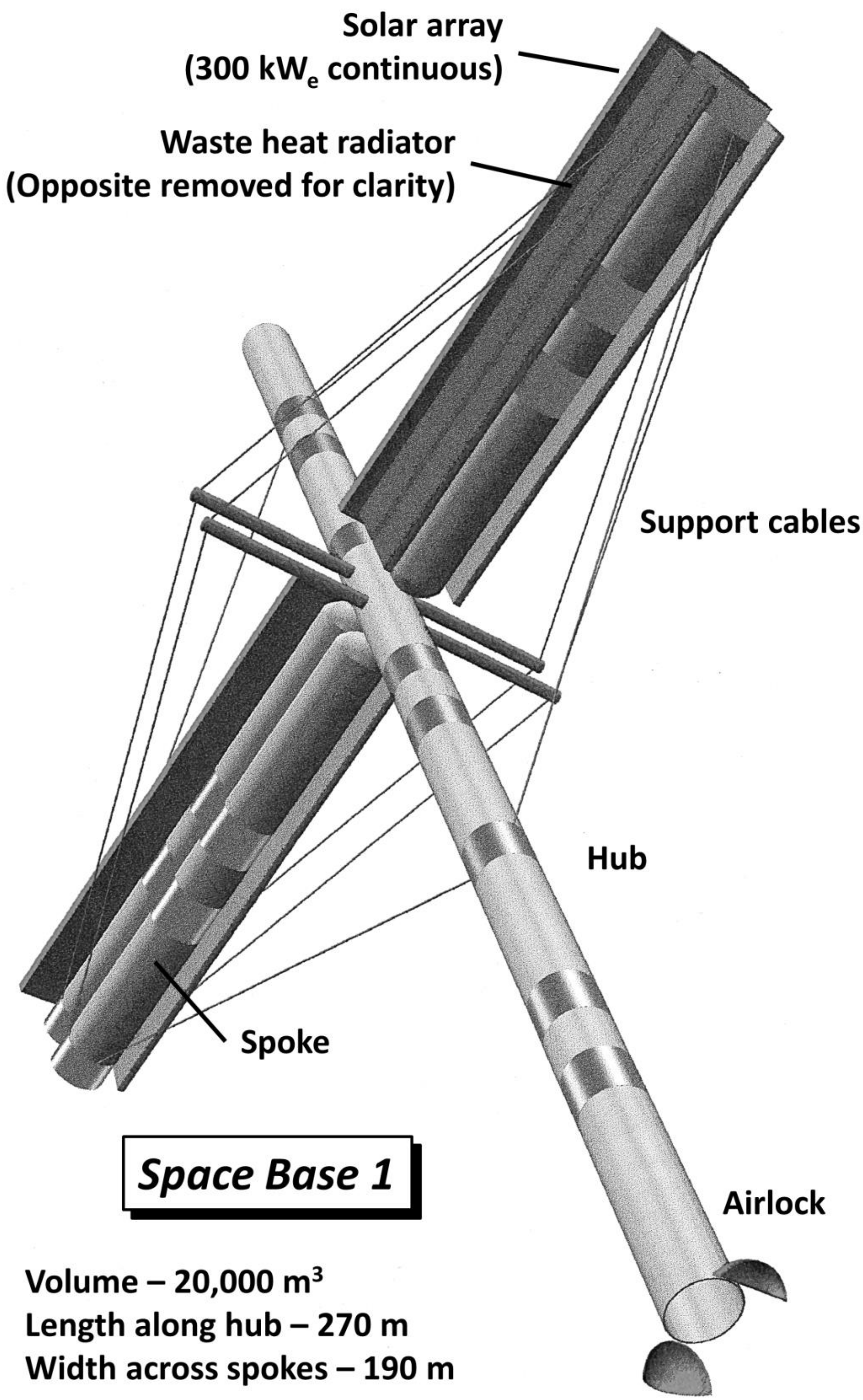

Figure 7 – Space Base 1: Large H-4 LEO Space Base

Enhanced Utilization of Shuttle-S

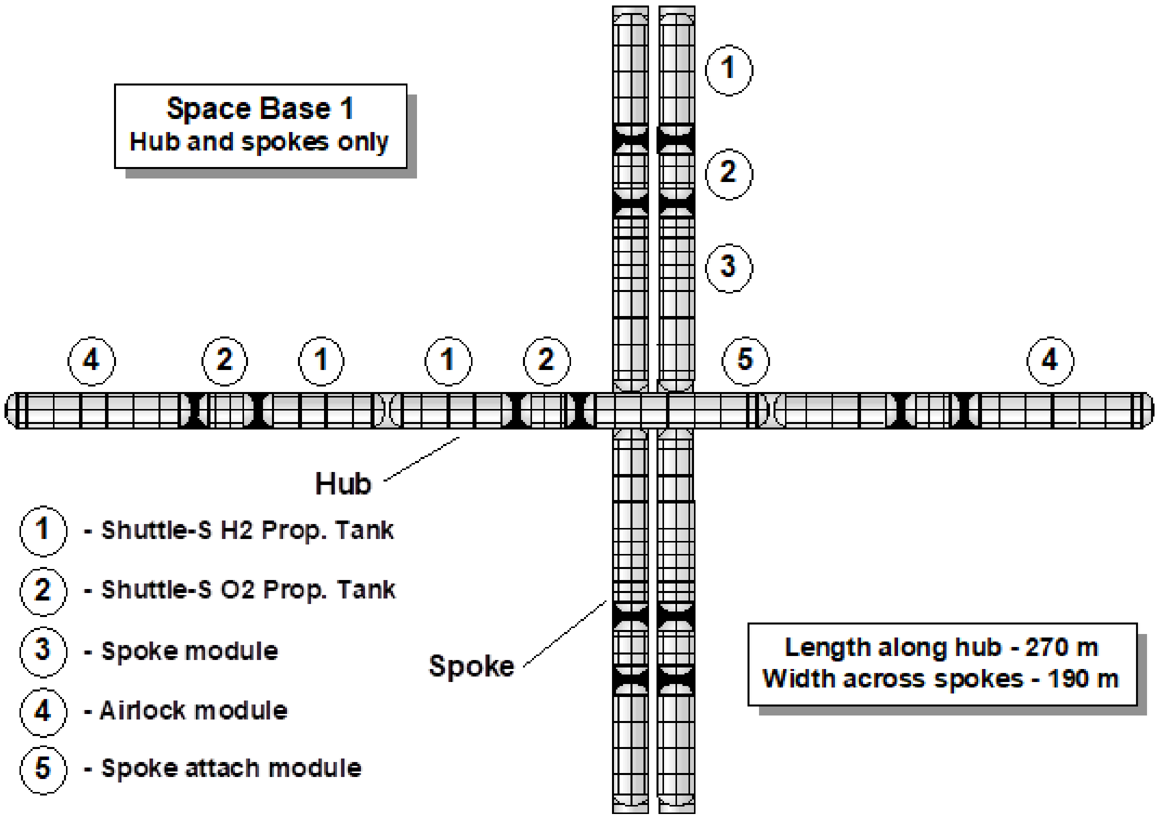

Figure 8 – Details of Hub and Spoke Desgin

Examination of the base design shown in Figure 8 shows that, through careful planning and design, the entire Shuttle-S can be directly integrated or "recycled" into the fabrication of the base.. Essentially, the entire Shuttle-S, less the Solid Rocket Boosters which are jettisoned early in the ascent trajectory, is placed into orbit. The core vehicle, comprised of the main hydrogen and oxygen tank, remains attached to the payload module instead of being jettison just short of orbital velocity as is done with the Shuttle's external tank.

With this approach, the entire Space Base 1 shown in Figure 8 can be placed into orbit with only seven Shuttle-S launches plus one Shuttle-S launch carrying oversized cargo such as solar arrays and thermal waste heat radiators. As shown in Figure 8, each spoke is an entire Shuttle-S launch vehicle: a liquid hydrogen tank, a liquid oxygen tank and a spoke payload module. Thus, four launches place all of the spokes into orbit. In a similar manner, the hub is comprised of three Shuttle-S launch vehicles. Two of these are used for the end airlock modules and one for the center spoke attach module.

The key design feature of this approach to using the entire Shuttle-S launch vehicle in the assembly of Space Base 1 is that the complex modules of the base are completely fabricated and tested on the Earth and then attached to a standard core vehicle and launched into orbit. These complex modules would include the command and control centers, communications stations, medical facility, labs, large airlocks and the hub's spoke attachment module. The core vehicle's hydrogen and oxygen tanks would have been designed to permit easy on-orbit retrofitting into general-purpose base modules such as crew quarters, storage areas, and recreational facilities using prefabricated modules and equipment carried in the payload modules.

This design approach transforms the Shuttle-S into a cost-effective launch vehicle because everything can be reused. It also minimizes the amount of on-orbit extravehicular assembly through using a few large modules instead of a large number of small modules.

Rough Order of Magnitude Cost Estimate

A preliminary cost estimate for building a large LEO space base can now be made. With eight required Shuttle-S launches and assuming each launch costs $1 billion (two to three times the cost of a current Space Shuttle mission), a rough order of magnitude direct cost for the base would be $8 billion. Research and development costs and the required supporting RLV flights would add another $4 billion, making the total cost $12 billion. Reductions in this preliminary cost estimate may be possible through cost-based design optimization and the elimination of many of the extraneous costs now associated with the Space Shuttle orbiter processing. The fact that the Shuttle-S is not manned, that the orbiter is not used, and that substantially different individual mission planning, as now required for Shuttle missions, would not be required, should help to reduce this cost. A recurring cost for additional space bases may be of the order of $4 billion each.

Summary

Building a space infrastructure to support the human settlement of space is an engineering challenge whose time has arrived. Not only is our expanding technology base enabling affordable transportation into low earth orbit with the second-generation planetary shuttles now in development, but our existing Space Shuttle technology base offers the opportunity to build large space bases in low earth orbit to best utilize this new transportation capability.

By proposing an approach for building large space bases in low earth orbit that appears to be both practical and affordable, this paper has also attempted to demonstrate that building the entire space infrastructure may not be as impossible as it at first appears.

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[1] J.M. Snead, "Space Infrastructure Planning," Proceedings of Space 96: The Fifth International Conference and Exposition on Engineering, Construction, and Operations in Space, Albuquerque, New Mexico, June 1-6, 1996.

[2] "Space station: The next iteration," Theresa M. Foley, Aerospace America, January 1995, p. 22

[3] J.M. Snead, "Space Base 1: Building a Large Space Station Using External Tank Technologies," Proceedings of the AIAA/Space Studies Institute Conference on Space Manufacturing 8: Energy and Materials From Space, May 1991, p. 233