Pathways To Colonization

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Abstract. The steps required for space colonization are many to grow from our current 3-person *International Space Station*, now under construction, to an infrastructure that can support hundreds and eventually thousands of people in space. This paper will summarize the author's findings from numerous studies and workshops on related subjects and identify some of the critical next steps toward space colonization. Findings will be drawn from the author's previous work on space colony design, space infrastructure workshops, and various studies that addressed space policy. In conclusion, this paper will note that significant progress has been made on space facility construction through the *International Space Station* program, and that significant efforts are needed in the development of new reusable Earth to Orbit transportation systems. The next key steps will include reusable in space transportation systems supported by in space propellant depots, the continued development of inflatable habitat and space elevator technologies, and the resolution of policy issues that will establish a future vision for space development.

A PATH TO SPACE COLONIZATION

In 1993, as part of the author's duties as a space program planner at the NASA Marshall Space Flight Center, a lengthy timeline was begun to determine the approximate length of time it might take for humans to eventually leave this solar system and travel to the stars. The thought was that we would soon discover a blue planet around another star and would eventually seek to send a colony to explore and expand our presence in this galaxy. The notional steps required took about 200 years, and required basic advances in space technology such as reusable transportation systems, space elevators, large colony construction techniques, and space resources development. At about 100 years into the plan is when the first large scale space colonies began to develop, and at 200 years into the plan, 3 of these colonies, along with a fleet of industries and asteroid resources, are launched to a neighboring star system where a hypothetical blue planet has been discovered. Since 1993, the plan has been updated periodically to incorporate NASA's 25-year plans, and many advanced concepts from future thinkers around the world. It recognizes a reasonable progression in technology and has no technology leaps like the warp drives and transporters from science fiction. Figure 1 is a reduced, unreadable graphic of this plan, which full size measures 9-feet in length. An internet-accessible version is planned.

Purpose

Such a vision establishes a framework where goals can be set that span many decades. In 2002, NASA in partnership with the Foresight and Governance Project at the Woodrow Wilson Center in Washington, D.C, organized a "Global Foresight Workshop" (2002) to explore with other Federal agencies broad challenges and goals for the 21st century. Many long-range goals for the nation and worldwide were discussed and selected, among them were space related goals of interest to NASA. During much of the Agency's history, NASA advanced studies have focused consistently on the challenges of science-driven space exploration and operations. However, workshop findings indicated little interest in these goals unless they can also solve national and global issues. Many technologies and space development studies indicate great potential to enable new, important commercial markets in space that could address the many global challenges facing America in this century. But communication of these ideas are lacking.

This 9-foot poster is a notional 200-year timeline for sending colonies to the next star. It is organized into 50-year blocks of time beginning with the past 50 years of space flight history. The timeline rows are organized by our solar systems planets beginning with our sun, Mercury, etc., to Pluto and interstellar space. Major events seen in the center rows are primarily in Earth-orbit, at Earth's moon Luna, and Mars.

FIGURE 1. Development Of Space: A Path To The Stars.

Goal Setting

Prior to the Global Foresight Workshop, organizers solicited goals from key agencies and organizations across the country, and internationally through solicitations from the United Nations University, via "The Millennium Project" (2002). Over one hundred goals were submitted, which were then combined and condensed to 46 for consideration at the workshop. The top five goals based on high ranking for overall global importance were as follows.

1. Provide clean water and food
2. Provide clean and abundant energy
3. Eliminate all major diseases
4. End slavery globally
5. Provide universal health care

These goals were deemed most important because they address the human condition, the root cause of wars, conflicts, poverty and starvation. In contrast, it is interesting to note that the five least favored goals included space.

- Improve human intelligence 50 points in 50 years
- Create permanent ocean habitats
- Establish several habitats throughout the solar system
- Move much of the industrial economy into space
- Develop means for allowing individuals to triple their life span

So how can space exploration and development demonstrate its importance to society? An example might be to consider addressing the 2nd cited goal above, "provide clean and abundant energy," through pursuit of space solar power satellite development to supplement energy sources on Earth. Forecasts cited at the workshop indicate that by 2050 an additional 3 billion people will be added to the world's population, and 5-7 billion of the 9 billion will live in high urban concentrations. At present, the increasing use of fossil fuels will continue until signs of depletion, or more severe environmental impacts occur.

Benefits

Space colonization is a grand plan, a vision that could be accomplished. But, why should we ever do such a thing? In general, it is believed that space development will accelerate technology development that will improve life on earth. This has been the trend throughout our nearly 50-years in space so far. Specifically, space exploration and development programs focused on colonization of space could reap tremendous long-term benefits.

- Advanced space life support technologies will improve health, prevent diseases, resolve disabilities, and extend our life span.

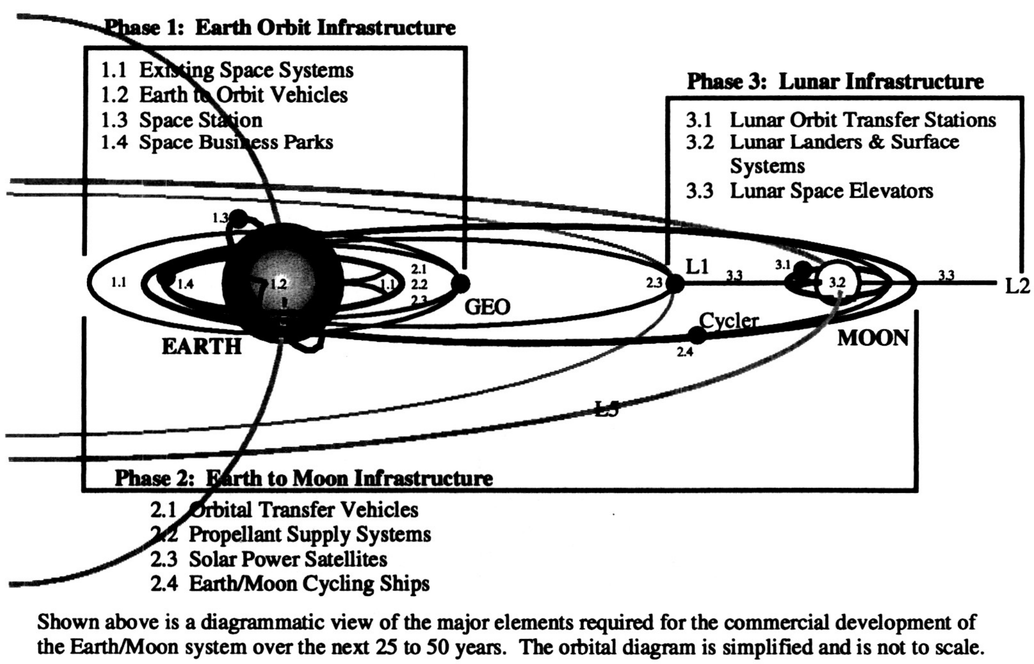
- Advanced space agriculture will generate new agricultural methods in draught areas, improve crop monitoring, and produce healthier food products.
- Space solar power beamed to earth could supplement terrestrial power sources and help produce abundant energy globally with insignificant impact to the earth's environment.
- Space infrastructure development will make it possible to do planetary defense from potential asteroid strikes on earth.
- Expanding our civilization into space implies a potential for unlimited growth and unlimited wealth for all people.

It is interesting to note that many of the problems addressed above are related to the national and global goals cited at the Global Foresight Workshop. They address the root causes of war, conflict, poverty, and starvation. Space development leading to eventual colonization will provide alternative ways to address the problems of humanity worldwide. The challenge will be to develop a consistent coordinated effort among the many industries, agencies and governments that should be involved in opening this new frontier.

Planning

What is needed are national plans to build up our space infrastructure similar to the way government and industry has cooperated in the air traffic system, interstate highways, railroads, port authorities, housing, and electric, water & waste utility systems. Such an endeavor would ultimately lead to international cooperation as has occurred in the *International Space Station* program. Figure 2 provides a notional diagram of how one can envision and organize such a plan for development of the entire Earth / Moon system. Clearly, such a plan would lay the foundation for eventual colonization of space.

Phase 1: Earth Orbit Infrastructure; is representative of where we are today. Critical to the success of the remaining phases are the development of reusable transportation systems for Earth to obit, and in-space operations. Today, no space transportation systems are completely reusable, even our Space Shuttle has major expendable and refurbished units as part of its first stage. A critical near-term goal is to develop a completely reusable earth to orbit transportation system, which could mean developing a reusable first stage for our current Shuttle. Such a system at high launch rates will lower the cost of space access and enable the development of new industries in space like tourism and commercial space stations called space business parks. Such multipurpose facilities in orbit could open up many new markets not yet imaginable today.



Shown above is a diagrammatic view of the major elements required for the commercial development of the Earth/Moon system over the next 25 to 50 years. The orbital diagram is simplified and is not to scale.

FIGURE 2. Earth / Moon Infrastructure Development

Phase 2: Earth to Moon Infrastructure; focuses on infrastructures that will be important for transportation to the moon and eventual utilization of its resources. Key to the success of this phase again is a reusable transportation system supported by a propellant supply system. Today all our upper stages are expendable. A reusable system would replace these upper stages for all transfers from low-Earth-orbit (LEO) to geosynchronous-Earth-orbit (GEO) and would lay the foundation for a reusable transport to the Moon and back. The combination of all the preceding systems would then make it possible to consider the development of cycling ships between the Earth and Moon for tourism and regular transportation to and from the Lunar surface for exploration and development. In addition, at this stage in the space infrastructure development it would be possible to give serious consideration to the development of large power satellite platforms for collection of solar energy for use in space and on Earth.

Phase 3: Lunar Infrastructure; sets the stage for the development of large-scale space colonization. It includes the development of reusable transportation systems to the surface and new surface systems for life support and lunar recourses development. Perhaps the most critical new system to be developed is a lunar space elevator. A test system would first be deployed on the far side of the moon with its center of mass at L2. A second elevator would later be deployed through L1 and serve as the primary transportation hub to the surface. These systems would set the stage for eventual development of Earth to GEO space elevators (Smitherman, 2000) that could enable economical mass transportation of the materials, equipment, and people needed to build large-scale colonies in space.

SPACE COLONIZATION CONCEPTS

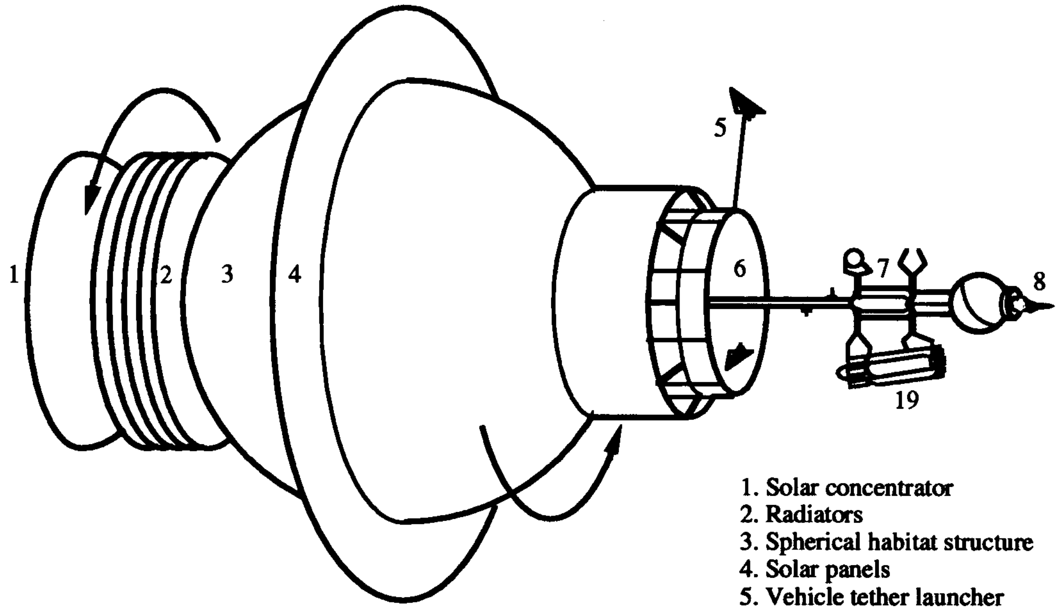
The idea of space colonization has been around for many years, primarily in science fiction materials. In 1977 NASA recognized this possibility officially through the publication of "Space Settlements: A Design Study," (Johnson, Holbrow, 1977). Included, are a variety of innovative colony concepts designed to house thousands of people in city-like complexes orbiting the Earth. Their designs take on the circular shapes of toroids, spheres, and cylinders so they can rotate to produce an artificial gravity. Other concepts have included colonies on the surface of the moon and Mars, and inside large asteroids.

Spherical Colony Concept

In 1980 the author explored a spherical design for a colony that might be one of the first types on the scale of a small town in space. Figure 3 shows two illustrations from this concept, which was originally conceived as an Earth/Moon cycling ship built from massive quantities of lunar materials. Later analysis indicates that an inflatable system would be more practical with a double outer wall filled with water, probably frozen, to form a rigid structure with radiation protection equivalent to the Earth's. The sphere is about 600 meters in diameter, which is about as small as a colony could be built to obtain a 1-g environment and rotate at no more than 2 revolutions per minute. That was the goal, to create an earth-like gravity with minimal rotational forces. It is believed that this size structure could comfortably accommodate at least 3000 people.

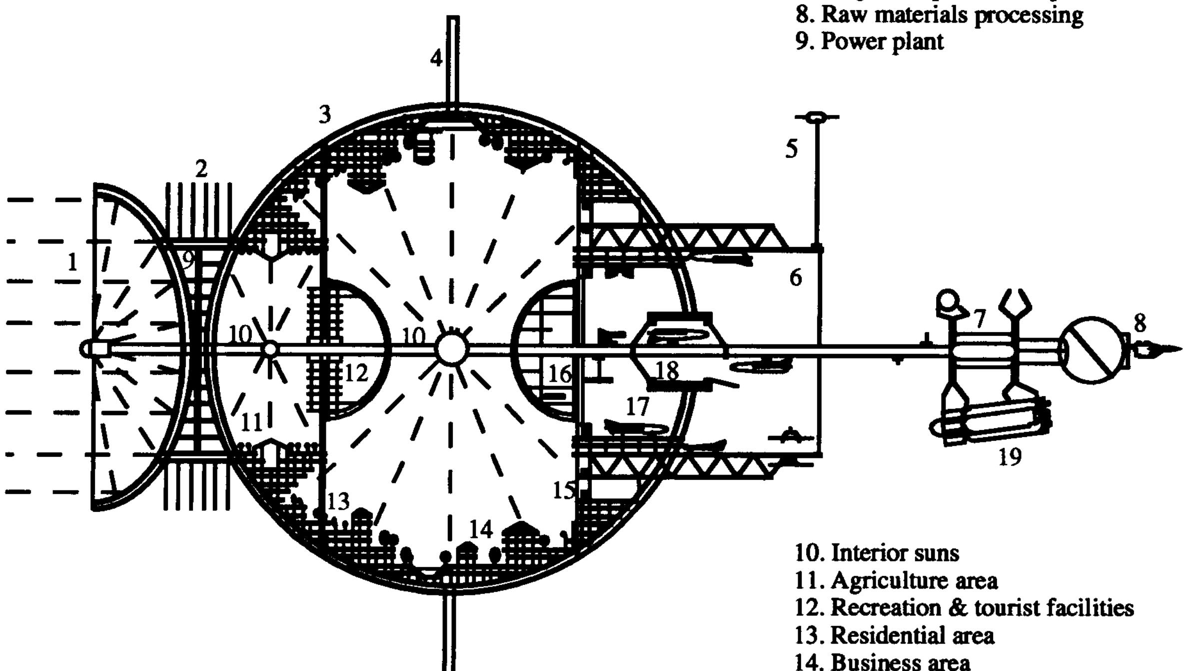
Figure 3-A illustrates an overall exterior view of the colony identifying its major features as: 1) a solar concentrator that collects sunlight and transfers it to the interior of the colony structure to form two interior suns (10) for the agricultural, and urban habitat areas respectively; 2) radiator structures to pull waste heat from the interior maintaining a comfortable living environment; 3) spherical habitat, as previously mentioned, constructed from a large inflatable structural shell system; 4) solar arrays around the perimeter that always face the sun as does the solar concentrator; 5) a momentum exchange launch concept for spacecraft leaving the colony; 6) a landing platform that would enable aircraft-like landings on a 1/2-g platform level; and 7) and 8), industrial area for processing raw materials into propellants and other materials.

Figure 3-B illustrates an overall cross-section view of the colony interior along the axis of rotation. Area 9 outside of the main sphere is for power production utilizing solar energy and possibly nuclear sources. Area 11 is a 1/2-g environment for agricultural production. Areas 13 and 14 are the main open space environments for living, working and recreational activities. The bright interior sun at the center provides the appearance of a sky and prevents direct observation of the other half of the colony directly above. Area 12 is a near 0-g recreational area, and areas 15-18 accommodate the industrial and transportation operations for the colony.



1. Solar concentrator
2. Radiators
3. Spherical habitat structure
4. Solar panels
5. Vehicle tether launcher
6. Landing platform
7. Propellant production plant
8. Raw materials processing
9. Power plant

A. Exterior View: Overall structure measures approximately 840 m x 1320 m.



10. Interior suns
11. Agriculture area
12. Recreation & tourist facilities
13. Residential area
14. Business area
15. Industrial area
16. Microgravity processing area
17. Vehicle assembly & servicing
18. Airlock
19. Large vehicle assembly & servicing

B. Cross-section View of Interior: The interior diamerter of the presurized sphere measures approximately 600 m. When rotated at about 2 rpm the lower levels have a simulated 1 g earth-like gravity and 1/2 g at the landing platform. The vertical scale of the lower floor levels is exagerated for clairity.

FIGURE 3. Spherical Colony.

Construction Technology

One of the latest possible scenarios for large-scale colony construction is through the use of a space elevator. If the plans for Earth / Moon Infrastructure development can be done as indicated in Figure 2, then space elevator and colony construction should be a possible next step. The colony construction site for the concept shown in Figure 3 would be at GEO either attached to the space elevator or in orbit in the vicinity of a space elevator. Construction would begin with a large inflatable that can expand to the volume shown. The intent would be to first fabricate and inflate the shell as a pressure vessel, and attach the power systems, air locks and utility cores to maintain a habitable environment inside. Once the shell is in place, and a work environment established, then interior construction would begin in a more conventional way, except that the gravity level inside could be adjusted up or down by adjusting the rotational rate of the colony structure. Perhaps the most critical technology to be developed here is the large inflatable shell structure. Some work has been done on inflatable habitation modules at the NASA Johnson Space Center, but continued development and demonstration in space is needed.

All these systems could be brought up from Earth on the space elevator and assembled in space using automated, robotic and human systems. The large volume of massive materials required for such a project would seem impractical to construct by single flights of spacecraft from the Earth, or to even manufacture in space given the wide variety of materials required. A space elevator would resolve that problem by functioning like a railway, connecting the colony's construction site to the resources on Earth. Details on the feasibility and possible construction techniques for a space elevator are outlined in a NASA publication (Smitherman 2000), along with details on the critical technologies required.

POLICY

Key to these initiatives is not technology development or large spending bills. It is a simple matter of good policy that establishes a clear goal with incentives to move government and industry investments in a direction towards space infrastructure development. Industry and policy makers have proposed many ideas for expanding markets into space, but any initiative stated by the government must be backed up with appropriate regulations and incentives. The Public Space Travel Workshop (1997), New Space Industries Workshop (1998) and the National Forum on the Future Development of Space (1999) all identified policy issues that were critical to the successful future development of space. Key policy issues discussed repeatedly in these and other workshops and studies included the following.

- Promote private investments in space development through government anchor tenancy, tax credits, consortiums, trade promotion, education, and endorsement.
- Promote the creation of innovative financing opportunities, such as a space development bank, limited liability insurance, and government guaranteed loans to reduce risk and cost of new space investments.
- Consider promoting tax policy that will leverage tax revenues from mature and profitable space commerce to fund space infrastructure development initiatives.
- Promote technology development and demonstration of new x-vehicles that will lower the cost of space transportation and enable public space travel.

Implementation of these kinds of polices is the only way to simultaneously open new markets and spur industry to develop the required infrastructures.

CONCLUSIONS

In conclusion, it is important to utilize our existing space systems to build on the next step. The Space Shuttle represents a huge technology advancement that should not be lost. It can be upgraded and improved, and other vehicles can be built to compliment its capabilities. The *International Space Station* is a similar great achievement whose technology can be utilized to build many other capabilities in space. Transfer of these technologies and systems into the private sector, and continued use and expansion of these capabilities is important or we will loose them completely.

Space colonization on a large scale may still be many decades away. But proper planning now can lead to that goal toward the latter part of this century. The critical path to reaching the goal of space colonization includes the following.

- Development of national plans to build up our space transportation infrastructure similar to the way government and industry has cooperated in air traffic system, interstate highways, railroads, port authorities, and electric, water & waste utilities
- Continued technology development for reusable launch vehicles including a completely reusable first stage for the current Space Shuttle.
- Development of reusable transfer vehicles and in-space propellant depots.
- Reinstatement of inflatable module development for large volume habitats.
- Investment in carbon nanotube development for structural applications and future space elevators.
- Promotion of private investments in space development through government anchor tenancy, tax credits, consortiums, trade promotion, education, and endorsement.
- Creation of innovative financing opportunities, such as a space development bank, limited liability insurance, and government guaranteed loans to reduce risk and cost of new space investments.
- Tax policy that will leverage tax revenues from mature and profitable space commerce to fund space infrastructure development initiatives.

It may not yet be possible to set space colonization as a major national goal. But, it is certainly possible to establish plans and policies that will develop space infrastructures for commercial markets that could eventually lead to a colonization capability. And in the end, space development leading to eventual colonization will provide alternative ways to address many problems facing humanity worldwide.

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