National Space Society

Roadmap to Space Settlement

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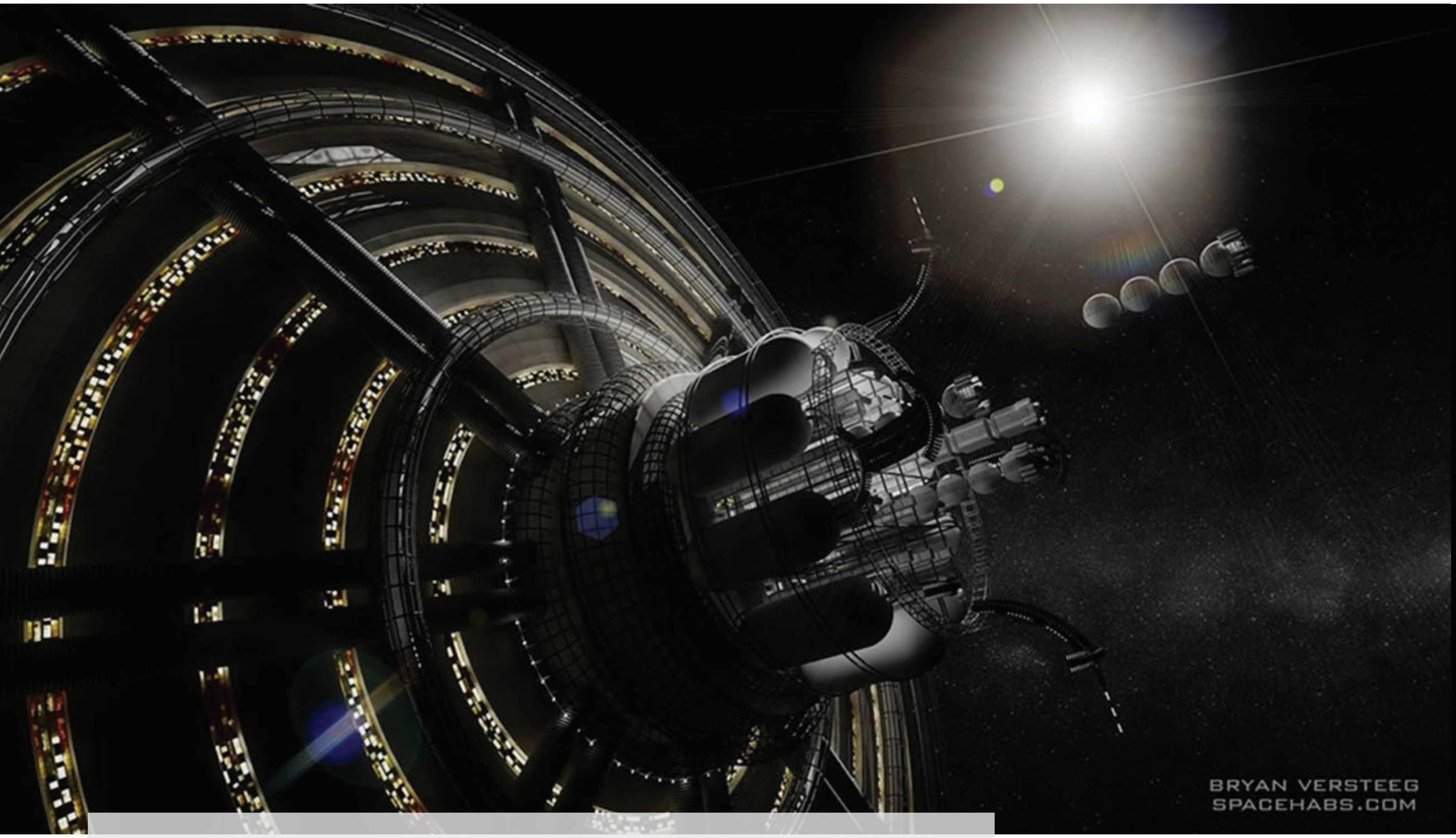


Kalpana 1 orbital space settlement for 3,000 people. Credit: Bryan Versteeg, spacehabs.com

The National Space Society (NSS) is a nonprofit educational organization whose Vision Statement is: *"People living and working in thriving communities beyond the Earth and the use of the vast resources of space for the dramatic betterment of humanity."*

This vision of space settlement embraces both space as a future second home for humanity in the form of a free, spacefaring civilization, and the resources of space (such as the sun's energy for space-based solar power, extra-terrestrial minerals for raw materials, and low-gravity for manufacturing) being used for the benefit of everyone on Earth. These two elements of the vision are intertwined. The development of space-based products and services for the people of Earth will require a human presence in space, and this presence will enable and motivate the expansion of our species away from our planet.

NSS believes that space development and settlement will occur most efficiently, and humanity's prosperity will be best ensured, if the free market drivers of competition and profit are central to these efforts, and every individual is given full freedom of thought and action.

Interior of Kalpana 1 orbital space settlement. Credit: Bryan Versteeg, spacehabs.com

GENERAL DRIVERS FOR SPACE SETTLEMENT

There are a multitude of forces pushing for space settlement. Some of the most important reasons, rationales, and goals are:

- Improving the quality of life on Earth.
- Providing space-based services via satellites to Earth, such as improved communications, remote sensing, navigation, and weather prediction.
- Greatly enhancing the chances for the long-term survival of humanity and other Earth species by ending the "all of the eggs in one basket" problem. In the words of poet Leslie Fish, "If you would not perish then grow."
- Developing and using space resources to reduce humanity's reliance on Earth-based resources and industry.
- Protecting Earth and its environment from asteroid impacts and climate change.

A future that includes the expansion of humanity into space is vastly preferable to one in which we are limited to the resources of Earth.

This roadmap describes the major milestones to be met, and the primary barriers to be overcome, to achieve the NSS Vision. In this context, a milestone is an accomplishment or event that significantly promotes or advances any of the reasons, rationales, or goals listed above. These milestones should not be thought of as arranged along a single route, but instead marking major nodes along the branches of different possibilities.

While the roadmap to some extent highlights what can and should be done by the United States, which to date has been the leader in off-Earth space exploration and development, it is equally applicable to all countries. Eventually, all nations may participate in achieving this vision and reaping its fruits.

NSS has defined 31 major milestones based on our current knowledge and perspective. These can be achieved with incremental advances in current technologies. However, researchers around the world are pushing the frontiers of science in many fields, and new breakthroughs may enable us to leapfrog currently accepted milestones at any time.

Some of these milestones must be reached prior to the settlement of cislunar space, the Moon, Mars, asteroids, and eventually, other star systems. Specific milestones then follow for each of these destinations. These milestones are presented here, with commentary on their current status, along with the changes and developments necessary to reach them.

Surpassing these milestones will require a combination of governmental and nongovernmental efforts. The goals of populating space and utilizing its resources must be pursued by multiple governments and a variety of private groups, and while political and economic factors will drive much of this activity, the settlement of space will ultimately be driven by the basic human need to survive and thrive.

GENERAL BARRIERS TO SPACE SETTLEMENT

Barriers will be encountered at each stage of space settlement. A barrier is defined as a substantial obstacle to achieving a milestone, and it must be overcome before that milestone can be accomplished.

Technical. There are technical barriers to providing safe, reliable, efficient, and inexpensive transport to, from, and between locations in space. There are also technical difficulties in creating the needed infrastructure, human habitats, and industrial sites in space. The creation of reliable reusable rocket boosters remains a technical barrier, though this is changing rapidly. Another significant barrier is the lack of mitigation of debris in Earth orbit.

Biological. Physiological barriers to human space settlement include human responses to microgravity in non-rotating space habitats (e.g., those not generating a form of artificial gravity), long-term exposure to radiation in space, and lower gravity levels and other conditions on other planetary bodies.

Cultural. Many people feel that the pace of space development has been extremely slow, especially when compared to the rapid development of computer technology. While there is more information about space activities available to the public than ever before, mainstream media outlets often cover only larger, more headline-generating events, frequently overlooking or performing minimal coverage of other critically important, but less sensational, stories that would benefit general audiences. Space development would be furthered by continuously stimulating and sustaining public interest via improved outreach and education over extended periods of time. It is also important to provide context for the many benefits that space-related technology currently provides—most people are unaware of how deeply space-related activities are already integrated into their daily lives.

Psychological. Psychological issues include:

- Claustrophobic responses to enclosed and confined space habitats, triggered by the knowledge that one cannot leave the habitat at any time (unless wearing a pressure suit), and a constant awareness of a possible loss of air pressure.
- Isolation from others due to communication delays to and from Earth.
- Lack of exposure to a “natural” (Earth-like) environment (“nature-deficit disorder”).
- Challenges inherent in social interactions within a population that is initially limited in size.

Social. For alleged safety reasons, governments may be tempted to limit the ability of private individuals to organize and undertake space ventures or to voluntarily accept the risks involved in spaceflight. If there had been such societal restraints two hundred years ago, the frontier of the American West would never have been settled. Space development requires the freedom to voluntarily accept risk. The current governmental aversion to risk, along with the associated legal issues, must be overcome.

Economic. Space development requires long lead times, and therefore needs stable, long-term funding. Economic issues, both actual and perceived, are often major barriers to both governmental and private efforts. Some of these issues include:

- The very high cost of access to Earth orbit and space, which has prevented the frequent transport of passengers and cargo to, from, and through space. Such transport operations must ultimately resemble how commercial airlines function today.
- Short-term thinking within government, often linked to political and election concerns. Often when long-term programs are ultimately authorized, ongoing funding at consistent levels is not forthcoming, even if it would result in significant savings over the life of the program.
- Private sector investors seeking immediate gains rather than long term profits. In order to encourage private investment in space activities, governments need to provide an environment that encourages growth. Examples include: the reduction or elimination of unneeded regulations, legislating limits to liability in the case of space-related accidents, allowing individuals to take voluntary risks in spaceflight, and providing rewards for, or tax relief from, space ventures.

MILESTONE 1

Dramatically Lower Launch Costs to Orbit

Development of reusable boosters and spacecraft leading to dramatically lower launch and space transport costs.

DESCRIPTION

The emergence of partially and fully reusable rocket boosters and other efficient means of reaching orbit will result in increased efficiency as well as faster turnaround times and higher launch rates. These improvements should significantly lower the cost of access to space, allowing an expanded launch market. This would lead to further reductions in launch costs due to higher demand. These improvements will also enable new uses of space which are currently too expensive for practical use. These include space solar power, space tourism, and other commercial uses of orbital space.

Progress on this milestone will be demonstrated as such activities become increasingly affordable. This milestone is likely to be passed within a few years.

COMPONENTS

Methods of fully reaching this milestone include:

Private Launch Companies. The emergence of private launch companies who provide launch services for both government and private customers is revolutionizing the launch industry. The focus on reusable rockets by companies in the U.S. and China should reduce launch costs to a fraction of current rates and allow high-mass and high-frequency space operations.

Government programs. Technology development and other programs by the United States and other governments may assist in reducing launch costs.

Flight Test Demonstrations. NASA, other government-funded agencies, and private companies will continue their roles in developing space transportation technology specific to achieving lower costs through flight test demonstrations. These activities create “on the shelf” technology for industrial and commercial uses.

Government Contracting Practices. Government contracting practices and policies that encourage the design, construction, and use of newer spaceflight technologies are needed. These policies should emulate accepted commercial practices, which should dramatically lower the cost of government-funded efforts. Such practices include the continuing move by NASA and the U.S. Air Force away from direct responsibility for managing the development of launchers and other hardware. Government entities would engage in simpler (and more efficient) purchases of hardware and launch services for both crew and cargo from commercial sources. Having government as a stable customer should result in an environment that will encourage competition, further reducing launch costs.

Progress in Launch Technology. Launch rates alone cannot be counted on to reduce costs (for example, if labor costs for construction, launch and refurbishment remain too high). Improvements should occur in the methods used for the design and physical construction of boosters, testing and preparing them for launch, and operating them before and during launch, which will speed and automate operations and thereby reduce costs. One significant example is the use of reusable launch vehicles. In addition, non-rocket launch methods may be developed, such as magnetic acceleration with linear motors, for certain cargo. Other examples include standardized payload containers and test procedures to minimize launch preparation costs. Launch costs can also be reduced with large rockets that fly routinely so that multiple customers may share launch costs; smaller launch vehicles are also being developed that will serve a wide range of customers at lower cost.

Space Tourism. Space tourism is a developing industry that may soon launch with great frequency, lowering the cost of each launch to commercially sustainable levels. Hundreds of prospective passengers have already made deposits on private suborbital flights. These journeys may later extend into Earth orbit and then orbits around the Moon and back, and ultimately to Mars.

Commercial Facilities in Orbit. With the development of reliable and affordable space transportation, private enterprise will likely develop commercially profitable orbital facilities such as hotels that would be large enough to allow travelers to enjoy the experience of zero gravity for extended periods, but small enough to be able to move to avoid known space debris. Orbital manufacturing facilities are also being planned for the near future. It is likely that transportation and facilities will evolve in a mutually supporting fashion, and that the availability of one will serve as a commercial justification for the other.

Space Solar Power. Global energy requirements may also serve to drive high launch rates and lower costs to facilitate the launching of large solar power generating stations into orbit. In this case, human travel to destinations in and beyond Earth orbit would be an incidental benefit rather than a primary goal. A number of nations are investigating the promise of space solar power as a practical energy source, since conventional sources of power (coal, natural gas, wind, hydroelectric, geothermal, nuclear, and ground-based solar) may be inadequate to meet the ever-increasing needs of Earth’s population, can be too expensive for some markets, or have unacceptable side effects. The systems that emerge could be built by private enterprises on their own, by governments, or in a partnership of the two. These systems will require a higher frequency of launches that should drive costs down.

Twin boosters from the 2018 launch of the Falcon Heavy return to the launch complex to be refurbished. Credit: SpaceX

MILESTONE 1.
Dramatically Lower Launch Costs to Orbit - *continued*

Other Commercial Space Applications. Other potential commercial space applications may lead to increased launch rates and decreased costs. Examples include robust communication satellite architectures, low-Earth orbit (LEO) data switching and storage networks, orbital servicing infrastructures, and robust global surveillance constellations.

Governmental Policies. Whether or not governments believe in or are willing to wait for private enterprise to lead the way, they may commit to the building of large space outposts in Earth orbit, on the Moon, or elsewhere, which will require many launches over a sustained period sufficient to reduce the per-launch cost to financially practicable levels. Such governmental initiatives may be created by a desire for national prestige (to keep up or exceed the space initiatives of other countries), a concern for protection from asteroids and comets, the need for a space-based solar power system to transmit power to Earth, or government uses of space for security, environmental surveillance, improved communications, or other uses. Such initiatives should increase launch rates and reduce unit costs. To be effective, the policies should use launch costs as one of the primary criteria for selecting a launcher and not unfairly penalize or impede the use of reusable vehicles.

BARRIERS

- Continued government reliance on and support for expendable launch systems and in-space vehicles.
- Bias toward pro-expendable policies by government employees, private contractors, and venture capitalists resulting in a reluctance to work openly and aggressively on other technologies.

COMPLETION

This milestone will be achieved when launch prices to low-Earth orbit are no longer a major barrier to space operations. This will occur when prices drop by a factor of ten or more below the average 2017 global price of about $5,000 per kilogram.

MILESTONE 2

Continuous Human Occupancy in Low-Earth Orbit

Construction of continuously occupied pressurized structures in low-Earth orbit.

DESCRIPTION

From the U.S. Skylab, to the Soviet Salyut and Mir, to the International Space Station (ISS), and China's Tiangong orbital stations, crewed structures have been placed in orbit and, in the case of the ISS, continuously occupied for almost twenty years. These space stations are essentially tools, rather than ends in themselves—laboratories where we learn how to construct large structures in orbit, live and work in space, gather biological data, avoid or survive collisions with space debris, and explore scientific principles and technologies that can be developed only in space.

The International Space Station will be followed in orbit by other human-occupied facilities, which will likely include hotels, laboratories, factories, and storage depots, with many of them commercially owned and operated. These would support space tourism and recreation, scientific research, low-gravity manufacturing, space solar power infrastructure, refueling and repair operations, and the like. The lessons learned can then be applied to eventual human space settlements.

COMPONENTS (needed to create a habitat in space)

No permanent space settlement can be constructed without first accumulating the technical knowledge, industrial tools, unique materials, and techniques necessary to create such a novel habitat, as well as biological data about the ability of humans to survive and thrive for long periods of time outside Earth's atmosphere and without gravity.

The required knowledge and expertise has been and will continue to be acquired by the launching and assembly of large structures in low-Earth orbit. This is the closest location in which research can occur and techniques can be practiced, and from which rapid escape in an emergency is most feasible.

Over time, newer equipment will be added and critical new experiments conducted onboard these stations. A variable gravity centrifuge, large enough for small mammals, is needed to determine the effects of living in partial gravity environments such as those found on the Moon and Mars. Tests with space solar power wireless energy transmitters and receivers, closed or controlled ecological life support systems, and larger, more efficient electrical power systems are also required.

BARRIERS

- High launch cost to LEO.
- Insufficient focus on non-pressurized docking, external logistics, and robotic cargo handling for LEO operations.
- Insufficiently developed economic justification for ongoing LEO activities.
- Man-made space debris accumulating in LEO that pose a hazard to life and property so long as effective international mitigation efforts are lacking.

COMPLETION

The attainment of this milestone will be recognized gradually as inhabited orbital infrastructures become permanent, are supported by sustainable economic activity, and include at least one commercially owned and operated LEO station.

Private companies such as Bigelow Aerospace are in the forefront of the development of privately-owned orbital habitat modules. Credit: Bigelow Aerospace

MILESTONE 3

Development of a Space Tourism Industry

Design for a privately-backed space station. Credit: Axiom Space

Growth and development of a robust space tourist industry, including frequent orbital and suborbital flights and a growing number of, and sophistication of, space hotels.

BACKGROUND

As of 2017, the space tourism industry has completed nine flights to the ISS, while existing companies are building suborbital tourist vehicles, envisioning trips to private space stations, and planning a trip around the Moon. Space tourism is price sensitive, and reducing costs for passengers will significantly expand the market. Thus, tourism can drive launch vehicle and habitat development by generously rewarding reduction in cost. Expansion of this market can lead to economies of scale which should further lower the price and stimulate more market demand. In addition, reusable rocket engines and new large reusable boosters are under development, which should enable the transport of much larger and more massive single payloads to orbit. Such high-mass space operations should allow the industry to create larger, safer, and more luxurious designs for orbital passenger vehicles and space hotels.

COMPONENTS

Passenger-rated launch systems and space hotels.

BARRIERS

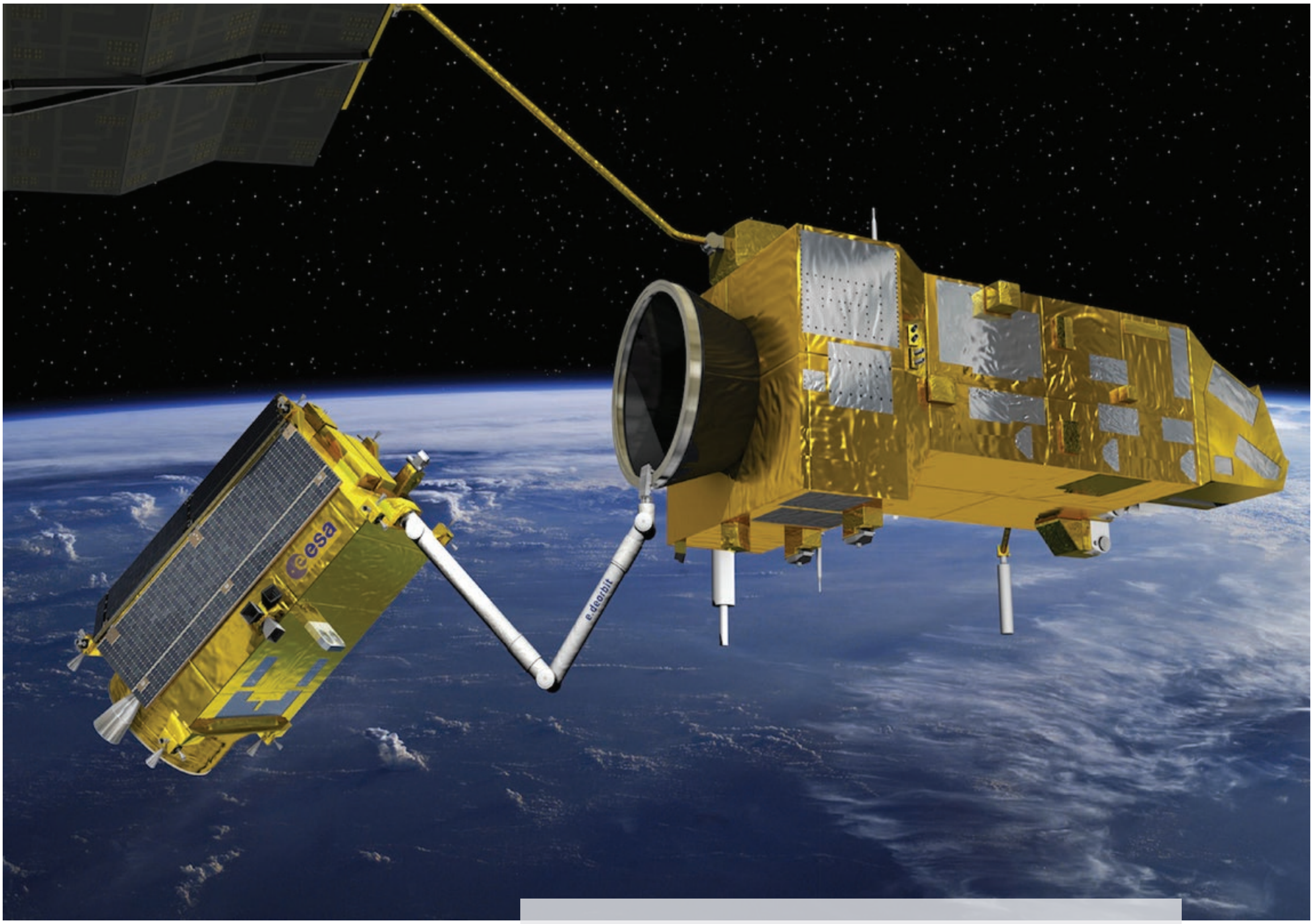
- Cost, safety, and reliability of launch and passenger carrying vehicles and operations.
- Cost of building and operating space hotels.
- Excessive regulation and premature safety standards.

COMPLETION

This milestone can be considered achieved when at least one facility in space allows regular bookings for tourism or orbital spaceflights for tourists that are scheduled at least several times per year.

MILESTONE 4

Establishment of In-Space Commerce by Private Companies



Satellite servicing could allow for much greater longevity and lower costs for orbital infrastructure. Credit: NASA

Establishment of commerce in or between locations in space by one or more companies.

DESCRIPTION

In-space commerce involves operations such as the delivery of goods from one location in space to another location in space, or the performance of services for any facility in space. The delivery of propellants from LEO to a propellant depot at the Earth-Moon L1 (Lagrange) point and the production of propellants on the Moon are good examples. Some forms of space commerce (as distinct from in-space commerce) already exist in the form of the delivery of goods from Earth to LEO. In-space commerce also includes the manufacturing of products on space stations for later use on Earth or in space.

COMPONENTS

These enterprises would need to be profitable and operate primarily without subsidies or special governmental protection from failure.

The companies would provide products or services to locations in space which could include tourism (note the overlap with space tourism in Milestone 3).

BARRIERS

Uncertainty about what activities will be profitable and what customers will exist due to rapidly changing space transportation costs and interests of government agencies.

COMPLETION

This milestone can be considered achieved when a company has made a profit on its in-space operations for at least five years.

MILESTONE 5

Crew Habitats for Use Beyond Low-Earth Orbit

Safe habitats for crews operating well beyond LEO and outside Earth's protective magnetosphere.

DESCRIPTION

Crew habitats are one of the most critical parts of space infrastructure. Crews operating well beyond low-Earth orbit and outside of Earth's protective magnetosphere are exposed to about 600 times the constant cosmic radiation and much more solar radiation, including dangerous but intermittent solar mass ejections, than we are on Earth.

Crews in locations beyond LEO are also farther away from assistance and cannot return to Earth quickly in an emergency. Providing artificial gravity via the use of rotating or tethered modules may be necessary to maintain better long-term crew health for long durations spent in microgravity. Note that this milestone refers primarily to smaller crew habitats launched from Earth for trips beyond LEO and as logistics bases, and does not include the much larger residential settlement habitats that would be constructed in space and on other worlds.

COMPONENTS (required capacities)

Crew habitats beyond low-Earth orbit must be able to:

- Provide redundant life support systems that will last 50 percent longer than the designated mission length, or long enough for a rescue mission to reach the crew.
- Carry sufficient food and water for the crew, or recycle water and grow food, with a comfortable margin for safety.
- Protect against constant cosmic radiation (heavy, fast nuclei from outside the solar system).
- Protect against regular levels of solar radiation as well as intermittent large bursts in the form of solar mass ejections.
- Support possible designs for creating artificial (centrifugal) gravity with rotating habitats.
- Assist in support of the crew's physical and mental health. For long trips and stays beyond cislunar space, this includes making the habitats sufficiently large for continuous habitation.

BARRIERS

- Lack of incentives and resources to construct, maintain, and operate habitats outside of LEO that provide the additional protections needed for continuous occupation by humans.
- Lack of consensus over the difficulty of and need for creating artificial (centrifugal) gravity for long-duration space flight.
- Lack of consensus over how to best protect crews against space radiation and what level of protection is needed.

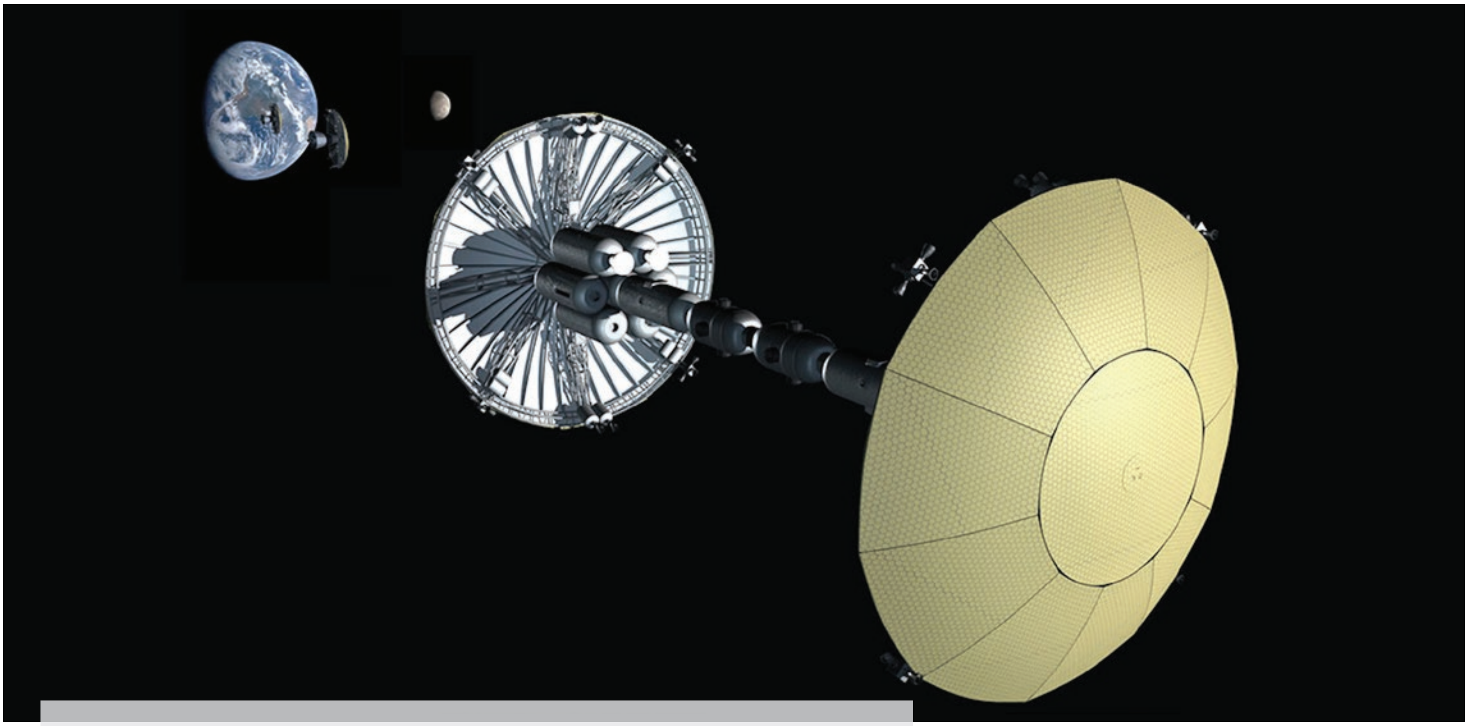
COMPLETION

This milestone can be considered achieved when a crew module or habitat can support a crew for a minimum of six month periods, with effective radiation protection (equal to or less than radiation exposure levels to crews in LEO), and is in geosynchronous Earth orbit or any cislunar orbit or location.

Proposed Nautilus-X Extended Duration Multi-Mission Space Exploration Vehicle. Credit: NASA/Mark Holderman

MILESTONE 6

Use of Rotational Artificial Gravity for Habitats and Industry



Two temporarily connected rotating habitats (with surrounding storage modules for shielding) with aerocapture shields for use at Mars. Credit: Anna Nesterova

The creation and use of rotating structures in space that can produce artificial gravity of the desired strength.

DESCRIPTION

The creation of artificial gravity is currently possible only by rotating structures that utilize centrifugal force. The simplest form of artificial gravity consists of two habitats rotating around each other connected by a cable. Larger, more permanent systems such as a torus (ring-shaped) habitat require more extensive construction efforts. In such a structure, "down" is away from the center of rotation.

COMPONENTS (types of uses)

There are at least three uses for artificial gravity in space:

- Vehicles or habitats intended for lengthy human occupancy.
- Transferring cryogenic propellants from one craft to another (gravity-forced fuel transfer)
- Mining and smelting facilities for harvesting and using materials from asteroids.

BACKGROUND AND RATIONALE

Artificial gravity produced via acceleration can last only for a few minutes, that is, for the duration of a rocket engine firing. However, there seems to be no insurmountable barriers to using rotation to create artificial gravity. The problems are bureaucratic, economic, and physical. Rotating environments need to be designed to avoid damage from collisions and the threat of fire from the convection of hot air, which does not occur in a microgravity environment. Such environments should also be large enough to be well tolerated by the occupants.

BARRIERS

- Perceived difficulties in creating rotating environments versus microgravity (e.g., "weightless") environments.
- Risk of collision between spacecraft and parts of rotating environments.
- Greater threat of fire inside rotating environments.
- Greater economic cost for building large rotating environments with lower rotation rates (lower rotation rates means larger size, therefore higher mass, therefore higher cost).
- Belief by many, especially in government, that there is no requirement for artificial gravity in order to achieve their limited goals in space.

COMPLETION

This milestone can be considered achieved when rotational gravity is used in a human-inhabited module in space during routine operations.

MILESTONE 7

Legal Protection of Property and Other Rights

The enactment of legal protection for property rights that will provide prospective off-Earth investors and settlers with the security to take financial risks.

DESCRIPTION

The successful settlement of space will be impeded if the settlers are not permitted to own real property (e.g., interest in real estate) as well as personal property, and if business enterprises are not permitted to own and run the facilities necessary to operate in off-Earth locations. Private individuals and groups who are considering an investment in the settlement and development of space will need to know in advance that they will be rewarded financially via legally enforceable recognition and protection of their claims of private ownership.

Current treaties among the nations of Earth prohibit national claims of sovereignty over bodies in space, though some nations have claimed ownership of the portions of the geosynchronous orbit that crosses over their territories. Therefore, nations and other terrestrial entities may not be capable of granting ownership of property in space. However, even in the absence of modifications to such treaties, it is possible to expect that a legal regime could be established in which reasonable claims on extraterrestrial bodies, based on beneficial occupancy and development, could be recognized by terrestrial governments.

COMPONENTS

Aspects and developments regarding a legal regime for property rights in space include:

- Incorporating widely accepted protections for individuals, businesses, and the natural environment, while also ensuring fair competition for use or ownership of property. These protections include the prevention of monopolistic ownership of scarce and valuable resources, as well as sensible zoning.
- Striving for the creation of economic incentives for human expansion into space, access to space for all users, and protection of settlers' rights and space resources.
- Evolving regulation and protections gradually, so as not to strangle a young and growing off-world presence in excessive bureaucratization and over-regulation.

As has occurred with international trade, companies may be able to define and enforce property rights and contracts without using the power of states to act as single-source enforcers. International traders regularly respect the property rights defined in voluntary contracts, where there is no single state with authority over all sides.

An example of the development of in-space property rights is the 2015 U.S. Commercial Space Launch Competitiveness Act (CSLCA), which states:

> "51303. Asteroid resource and space resource rights: A United States citizen engaged in commercial recovery of an asteroid resource or a space resource under this chapter shall be entitled to any asteroid resource or space resource obtained, including to possess, own, transport, use, and sell the asteroid resource or space resource obtained in accordance with applicable law, including the international obligations of the United States."

Other relevant examples exist. In 2016, the U.S. Federal Aviation Administration issued an official permit for a private company to land on the Moon and use local resources. In 2017, legislation similar to the CSLCA was adopted in Luxembourg. Both bills accept that there can be no claims of sovereignty in space, but that resources can be removed, processed, and sold.

These developments may mark the beginning of a new legal regime, but their significance is yet to be determined. Hopefully a legal means by which a settlement in space can be recognized as sovereign over an area of space or a celestial body will be developed as an international agreement. Space mining companies have indicated that they could mine minerals from the Moon or asteroids, but so far have not demonstrated any intent to gain formal claim to the mining sites.

Note that no individual or company currently has internationally recognized authority to issue titles to uninhabited extraterrestrial real estate. Therefore, any past and contemporary offers of title to such lands which are not clearly denoted as symbolic and unofficial are unethical and deceptive.

COMPLETION

This milestone can be considered complete when either multiple companies are mining celestial bodies and selling the output on Earth or in space, with majority recognition among nations of their right to do so; or at least one space settlement exists on a planet or moon, with recognition of the right of the settlers to own and benefit from the area they occupy.

MILESTONE 8

Land Grants or Other Economic Incentives for Space Settlement

Effective economic incentives, such as land grants or prizes, to encourage private investment in off-Earth settlement and any supporting ancillary development.

DESCRIPTION

Market economics provide an incentive for space settlements, but other economic incentives such as land grants (territory on any rocky body) or prizes can also be created. Claims of title to off-Earth land could be recognized on the basis of beneficial occupancy and development. The granting of most such claims would also require that the occupancy be intended to be permanent. These claims could plausibly be broadened to include additional tracts large enough to make feasible subdivision and resale. Extraterrestrial land grants, akin to those granted as incentives to railroads by the United States after the Civil War, may foster privately funded space settlements.

Such measures would increase the potential for private investment in affordable space transportation and facilities, and could enable economically feasible settlement. To that end, governments and the space community will likely develop legal mechanisms and methods of offering such land grants as an incentive for developing permanent off-Earth settlements.

Prizes similar to the Google Lunar XPrize could be established to challenge and inspire engineers, entrepreneurs, and innovators from around the world to develop low cost methods for constructing space settlements and life support systems, and to utilize in-situ (on-site) resources.

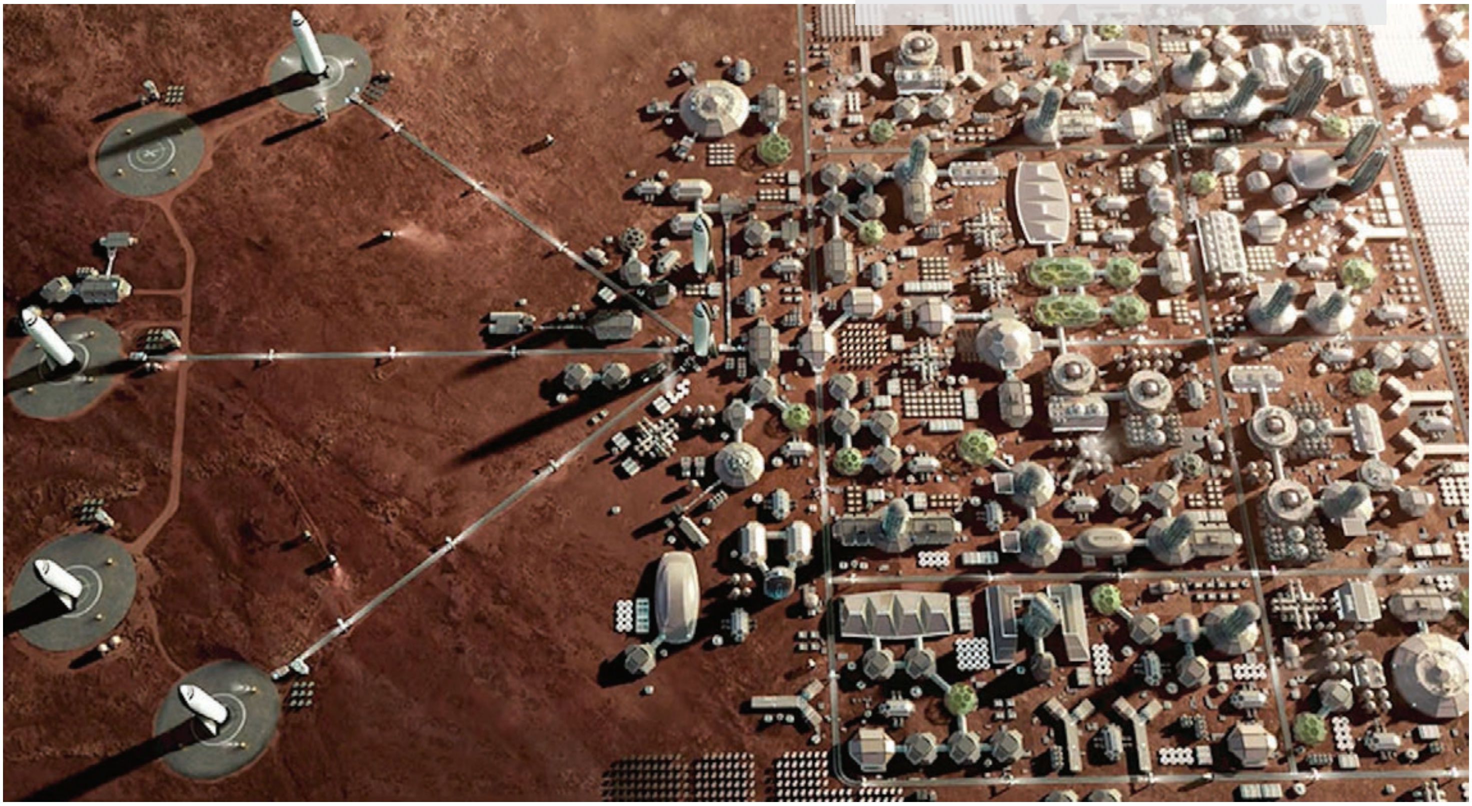
BARRIERS

- Existing space treaties do not allow ownership of celestial bodies by individual countries.
- Shortage of existing prizes to encourage the development of technologies for permanent settlements off-Earth.

COMPLETION

This milestone can be considered achieved when a land grant or other economic incentive has been offered and a space facility has been built that meets the conditions of the land grant or other economic incentive.

Land grants could speed up the settlement of Mars or other locations. Credit: SpaceX



MILESTONE 9

Technology for Adequate Self-Sufficiency

People leaving Earth with the technology and tools needed to settle, survive, and prosper without the requirement of ongoing resupply of survival essentials from Earth.

DESCRIPTION

For a community off-Earth to thrive, it cannot be dependent on a constant resupply of critical resources from Earth. Adequate self-sufficiency will be achieved by the development of technologies and techniques that enable the settlers to:

- Meet their basic needs for survival essentials such as air, water, power, shelter, basic foodstuffs, and the like using local materials such as soil, metals, ice (and other volatiles), sunlight, and, in the case of Mars, the atmosphere. Such methods are often collectively referred to as in-situ resource utilization (ISRU).
- Maintain, repair, reuse, recycle, and to some extent replicate the materials and tools that constitute the amenities of daily living in modern life, such as medicines, electronics, and clothing.

Off-Earth settlements will initially receive regular infusions of infrastructure and supplies, such as habitats, power generating equipment, medicines, tools, and electronics, until a critical mass has been reached. This will enable the community to achieve adequate self-sufficiency, with a need for only occasional imports of items for which they have not yet been able to develop a manufacturing base. At that stage regular commerce, in terms of both people and materials, will develop between the community, Earth, and other off-Earth settlements. Such a development is often characterized as the essence of a spacefaring civilization.

As a community matures, it may achieve a level of self-sufficiency that would allow it to survive indefinitely without further imports from Earth. It would be difficult for any community to become entirely self-sufficient—most communities on Earth are not to this day. But trade in commodities between individual settlements in space may replace most imports from Earth.

COMPONENTS: Required capacities, processes, and steps

Precursor Missions. Robotic precursor and test missions (followed by crewed missions) to accomplish the following:

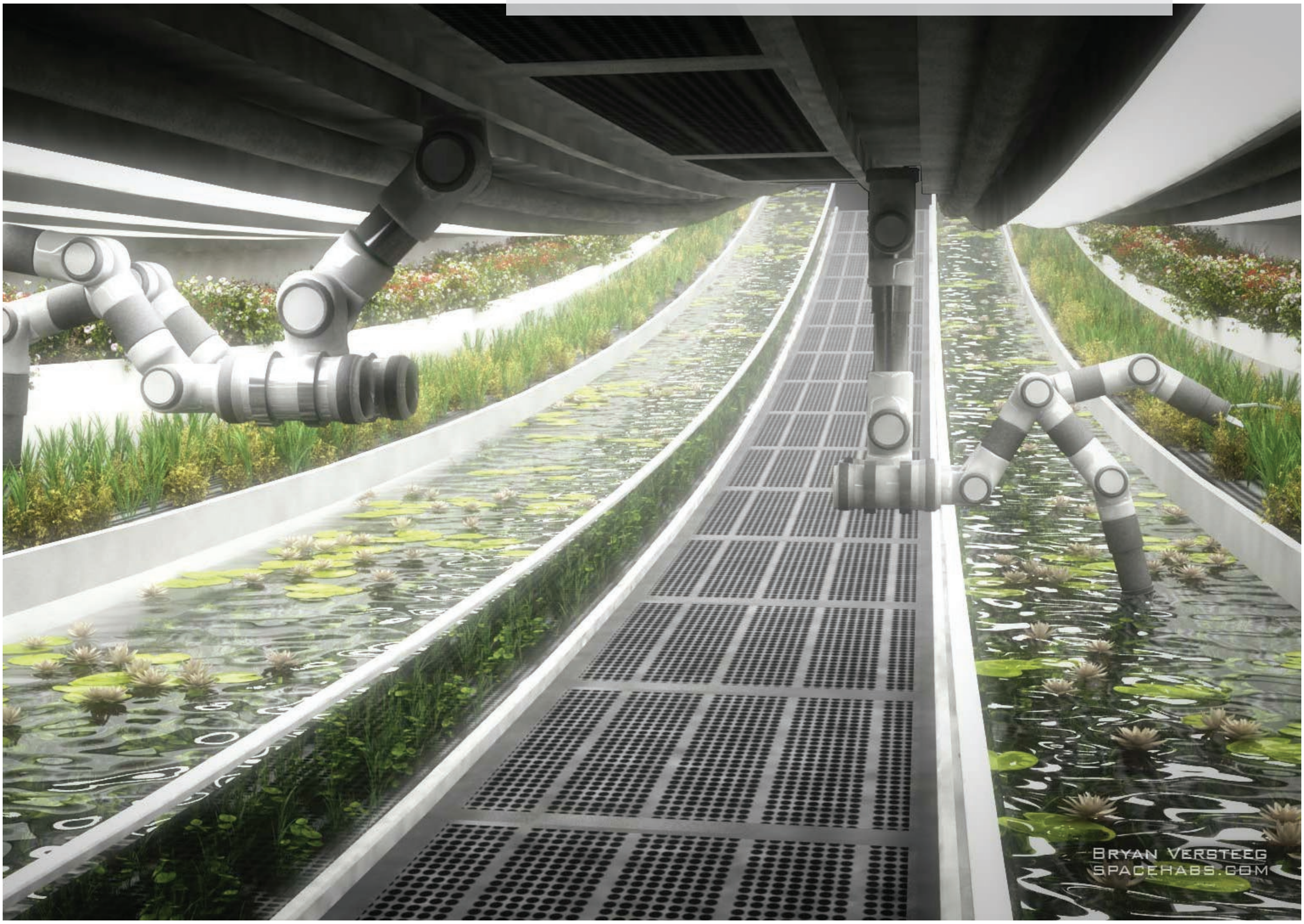
- Test a wide variety of synthetic materials for durability, toxicity, outgassing characteristics, and exposure to off-Earth environments for long periods of time.
- Land or rendezvous and verify the existence of usable raw materials at mining sites on asteroids, moons and planets.
- Characterize the environment for possible settlement and mining sites.

Enabling Technologies. Substantial investments in a broad spectrum of enabling technologies and techniques, including methods and equipment for digging and drilling to expose and retrieve various raw materials (materials acquisition) in asteroids and planetary bodies. This should be followed by the ability to convert volatile materials into pure volatiles for life support and propellants, and rock and soil into structural elements, both on planetary surfaces and in space (in microgravity). Desired outcomes include:

- The use of local soil and solid minerals, combined with some volatiles, to create useful materials, such as metals, plastics and polymers, composites, ceramics, fabrics, and soils.
- Methods to convert the materials into useful structural elements.
- Mechanisms to convert ice or atmospheric gases (volatiles) to potable and pure water, oxygen, plant growth media, and rocket fuel.
- Other relevant technologies including: manufacturing, miniaturization, nanotechnology, robotics, materials fabrication, energy use, and structural design (hard shell habitats vs. inflatables).
- Transportation systems for operations on planetary surfaces and in space between orbiting settlements and other locations.
- Materials for and methods of effective radiation shielding.
- Methods of dealing with the effects of lunar and Martian dust and electrostatics on equipment.
- Various power and energy sources (solar, nuclear, and others), and energy storage systems.
- Communication techniques (both local and to Earth or other locations).
- Manufacturing processes in vacuum, microgravity, and low-gravity conditions.
- Methods of agriculture and food production in microgravity and low-gravity conditions.
- Bioengineering and in-space food production.
- Recycling of air and organic materials (sometimes referred to as Controlled or Closed Ecological Life Support Systems, or “CELSS”).

continued >>

Cross-section of a rotating aquaculture area. Credit: Bryan Versteeg



MILESTONE 9. Technology for Adequate Self-Sufficiency *- continued*

Pilot-Scale Operations. Pilot-scale operations could prove out the processes that will be used at full-scale, before the full-scale equipment is built and moved to where it will be used.

Full-Scale Operations. Full-scale operations would be used on-site to build, maintain, and operate the settlements, including any local industries.

The ultimate goal is to develop the full set of technologies needed to be able to turn “dead” asteroidal or surface rocks and minerals into “living,” maintainable, sustainable, and adequately self-sufficient space habitats. These operations will become increasingly complex, as initially promising technologies and techniques (for example, additive manufacturing) are tested on ever larger scales.

COMPLETION

This milestone can be considered achieved when a space settlement exists with an amount of goods exchanged comparable to a city in a technically advanced country.

MILESTONE 10

Demonstration of Multi-Generational Human Survival off Earth

Human reproduction and raising children to adulthood over several generations in space.

DESCRIPTION

Factors which could affect human reproduction may be different from those needed merely for survival. Adult humans can survive periods of both lunar gravity and microgravity, reduced air pressure and oxygen levels, and some varying habitat rotation rates (for artificial gravity generation) and background radiation rates. The limits for viable multi-generation human survival may differ, and should be investigated in other mammals and primates before committing to a major settlement in any proposed location. Other environmental factors may also need to be considered.

Demonstration of normal development of the mammalian life cycle is essential before attempting to raise children in large numbers in a given off-Earth location. This would prove that there would be no significant developmental abnormalities which could prevent the normal operation and growth of a human settlement. There are multiple conditions, including gravity levels, that could possibly cause developmental and health problems, and some of these conditions are difficult or impossible to reproduce on Earth.

Even if a rotating space settlement has an artificial gravity field at the rim, there are still potential developmental abnormalities (resulting from the varying gravity levels toward the hub, the rotation itself, or the chemical and radiation environmental differences within the habitat) that need to be resolved to protect children's health. This means that the full range of conditions needs to be tested when they vary from those on Earth. This applies to conditions on a terraformed planet as well as on a rotating space settlement.

The completion of this milestone for a single location does not necessarily remove a need for other locations which have different conditions to go through the same test sequence. However, once normal development has been demonstrated at a given gravity level or rotation rate, it can be assumed that development will also be normal at higher gravity levels up to that of Earth and also with slower rotation rates at settlements with artificial gravity.

continued >>

A child is born and raised in space. Credit: Adrianna Allen

MILESTONE 10. Demonstration of Multi-Generational Human Survival off Earth *- continued*

COMPONENTS

Verification of mammalian conception, gestation, live birth, and growth to adulthood for at least three generations at any proposed settlement site, first with rodents such as mice or rats, followed by small primates such as marmosets. The settlement site could be occupied by humans during the animal tests, but ideally no children would be conceived there until the animal tests are complete and successful. These tests would be followed by the conception, birth, and raising to adulthood of a limited number of children in the settlement environment.

Below is a list of conditions that could possibly cause human developmental abnormalities or health problems that require further investigation before humans settle in various off-Earth locations:

- Gravity levels above or below that of Earth could pose developmental problems. Gravity levels on planets and moons cannot be controlled, but people can decide not to settle on objects where the gravity is below or above a level determined to be safe for human development. In our solar system, the gravity level issue is primarily related to settlements on worlds with low gravity levels, such as on the Moon or Mars.
- Artificial gravity on orbiting space settlements would be created by rotation. Past experiments with adult humans suggest that settlement rotation rates should be limited to no more than two to four rotations per minute, although it has not been possible to test rates with a large rotational radius, which would allow for lower rotation rates at the same gravity level. Future tests in space will determine the appropriate rate of rotation and the desirable radius of the structure.
- Cosmic, solar, and background radiation levels within a settlement habitat should be no more than those existing on Earth, where somewhat higher than average natural levels are shown to cause little or no increase in developmental or health problems.
- Air pressure should be maintained by a majority component of nitrogen at a level sufficient to prevent an increased danger of flammability. As oxygen levels increase compared to nitrogen levels, the danger of flammability increases, except at air pressures too low to sustain life.
- Oxygen levels might be somewhat less than those experienced by people in a high-altitude city such as Quito, Ecuador. People give birth and grow to adulthood at even higher altitudes, but the small populations there can mask uncommon medical problems. Some human populations have adapted over thousands of years to living at extreme altitudes. However, many individuals have problems with altitude sickness at even lower elevations.

BARRIERS

- Lack of facilities to test plants and animals (especially mammals) in artificial gravity at different levels than that of Earth.
- Assumed difficulty of providing sufficient radiation shielding for rotating space settlements.
- Potential difficulty in testing the effects of the settlement location's chemical environment, such as outgassing, lunar dust, and Martian soil chemistry (e.g., perchlorates).

COMPLETION

This milestone can be considered achieved for a particular settlement site and design when the first third-generation human is conceived there by parents who were also both conceived at the same settlement. The third-generation individual should be born and raised to biological maturity with normal health.

MILESTONE 11

An Effective Asteroid Protection System

An asteroid could threaten Earth at any time. A defensive capability is crucial. Credit: David A. Hardy, www.astroart.org

A system capable of detecting and defending against Earth-approaching asteroids and comets built and standing by for a deflection mission on short notice.

DESCRIPTION

It is widely recognized that the extinction of the dinosaurs was largely a result of an asteroid smashing into Earth. Proof that such collisions can still occur was demonstrated by the cataclysmic impacts of Comet Shoemaker-Levy 9 fragments on Jupiter in 1994, which were witnessed by millions around the world. The 1908 Tunguska event and the 2013 near-miss meteor airburst over Chelyabinsk are potent reminders that similar "city-killer"-sized asteroids are much more frequent than catastrophic climate-changing impacts.

We have the engineering know-how to protect ourselves from such species-endangering events. In time, just as their citizens buy home fire insurance that is almost never used, governments should join to create the capability to better detect threatened collisions and then design and build a defense against them.

Astronomers have located and calculated the orbits of thousands of asteroids and comets, but so far have not identified any likely to be large enough or close enough to cause widespread devastation. However, large parts of the sky, especially outside the ecliptic, remain unsearched and current telescopes are not sensitive enough to identify smaller but still dangerous objects. Every year large objects pass by the Earth in trajectories that are close to, and sometimes inside of, the orbit of the Moon. Many are not discovered until very close or even after they have passed. Additionally, some large comets come into the inner solar system from the Oort Cloud and would be much more difficult to detect in time to successfully deflect them.

Theoretically, we know how to divert smaller asteroids that are still far away from Earth. However, adequate knowledge of the composition and internal structure of larger objects is still lacking, and we need to be able to detect which asteroids are solid and which are "rubble piles," collections of loose rock and ice that would take different methodologies to interdict than solid objects. Since different deflection and destruction methods work best on different asteroid compositions and densities, that knowledge is necessary to choose methods suited to individual asteroids. Future missions to asteroids and comets should help fill in that knowledge gap. With that information, whatever launch systems, in-space infrastructures, and deflection or removal systems are necessary to protect Earth can and should be built and remain on standby for a deflection mission on short notice against any threatening celestial objects. The emphasis would likely be on early detection and propulsive diversion, but higher energy or explosive methods should not be ruled out since asteroid threats need to be dealt with on a case by case basis.

continued >>

NASA'S DART mission will be a first step toward understanding how to interdict and deflect threats to Earth. Credit: NASA

MILESTONE 11. An Effective Asteroid Protection System - *continued*

As the price of launches and other space activities is reduced, asteroid defense will become more feasible and attractive to governments, and is therefore likely to be achieved more quickly. Since the Chelyabinsk event, the media are taking the asteroid risk more seriously, while NASA, FEMA, and some international agencies are starting to take responsibility for asteroid detection, deflection, and disaster planning. However, some deflection methods may not be deemed acceptable because they could be used as weapons against people on Earth.

COMPONENTS

- Optical and infrared telescopic asteroid detection systems (note that infrared telescopes must be located in space, and in some cases inside the orbit of Venus looking away from the sun).
- Methods of characterizing asteroids (see Milestone 26) sufficient to design an adequate defense system.
- An interplanetary mission system capable of sending an interceptor, possibly on short notice, that can deflect an asteroid far enough in advance that it does not hit Earth.

BARRIERS

- Lack of commitment to an effective asteroid defense system.
- Lack of agreement on the most effective defense method.
- Lack of agreement on politically acceptable defense methods.

COMPLETION

This milestone can be considered achieved when a detection system is operational that can detect all asteroids and comets down to 10 meters in diameter that will approach Earth within one million miles in time to defend against them. Additionally, a sufficiently fast reaction method must be in place to intercept any threatening asteroid or comet in time for a defense system to be deployed.

MILESTONE 12

In-Space Fabrication and Construction of Large Pressurized and Unpressurized Single-Piece Structures

Microgravity construction methods developed to fabricate structures that are too large to be launched intact from Earth.

DESCRIPTION

This milestone covers large space structures that, rather than being assembled in space like the modular International Space Station, are instead fabricated in space as a single piece (using methods such as friction-stir welding). Large structures assembled from smaller components have already been built, as in the case of the ISS, but the maximum size of the individual components limits what can be achieved. Launchable pre-assembled structure diameters are limited to the diameter of the launch vehicle (or those with a wider payload fairing), though a larger expandable structure could be launched if it fits the payload fairing when uninflated.

For example, a typical Stanford Torus (a large, donut-shaped habitable space structure) could have a minor diameter of 200 meters and a major diameter of 2,000 meters. This would obviously be far too large to be launched from the ground. In-space structure fabrication and construction can also be applied to fabricating the unpressurized parts of such structures, as well as very large unpressurized space structures such as jig factories (a jig factory is a large industrial jig—a framework that keeps things from moving while they are being worked on—in which the entire factory is the jig). This capability would enable the construction of rotating space settlements, and the eventual construction of massive spacecraft.

COMPONENTS (requirements)

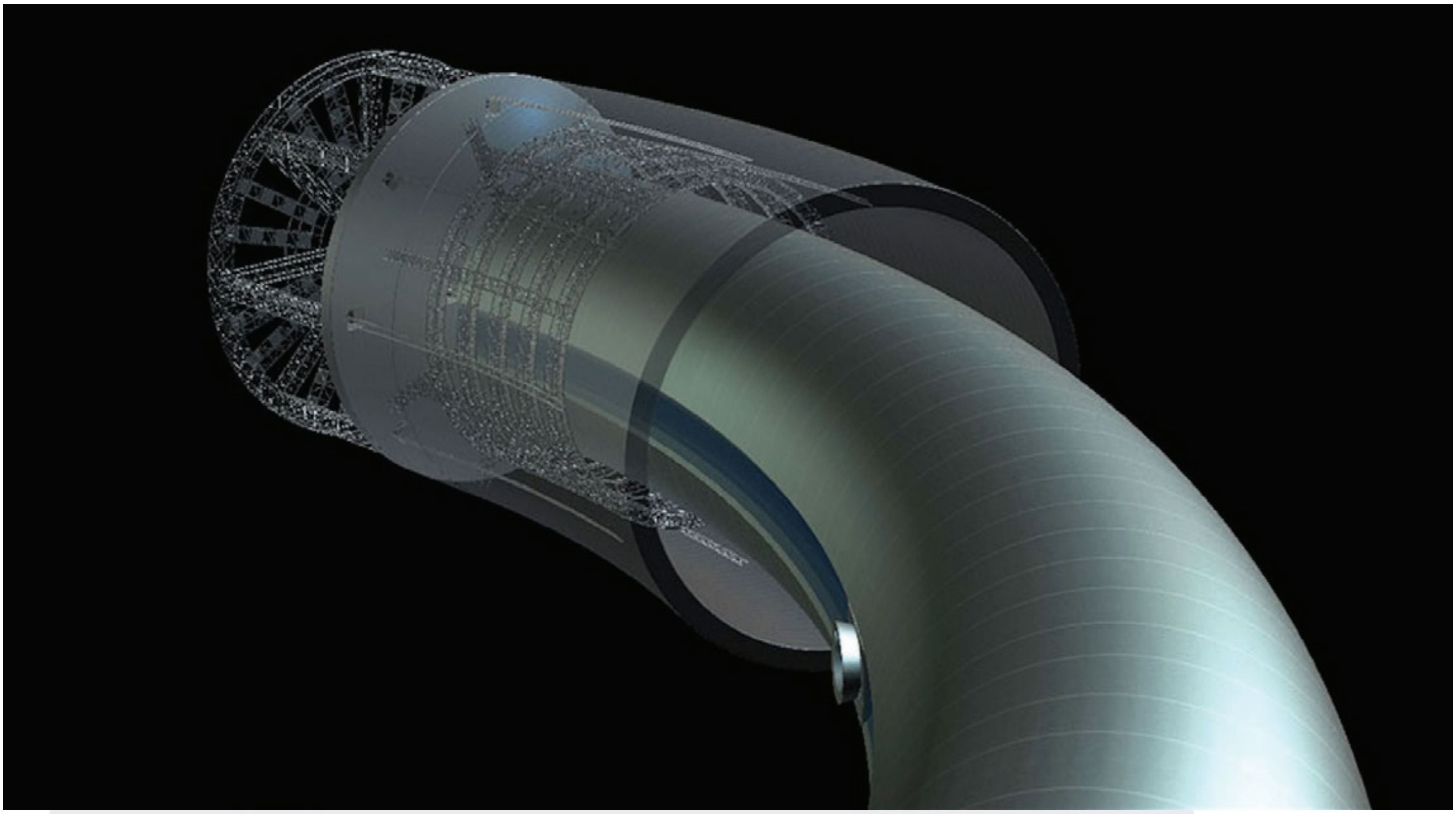
- Very large robotic jig factories and additive manufacturing factories in orbit.
- A large supply of construction parts made from material from asteroids or moons.

BARRIERS

- Lack of methods to mine asteroids or moons and turn the derived materials and minerals into structural components.
- Lack of efficient in-space transport to move heavy materials to the desired sites in space.
- Lack of advanced robotic factory designs, construction methods, software, and equipment.
- The difficulty of operating in a vacuum and microgravity with a minimum of personnel.

COMPLETION

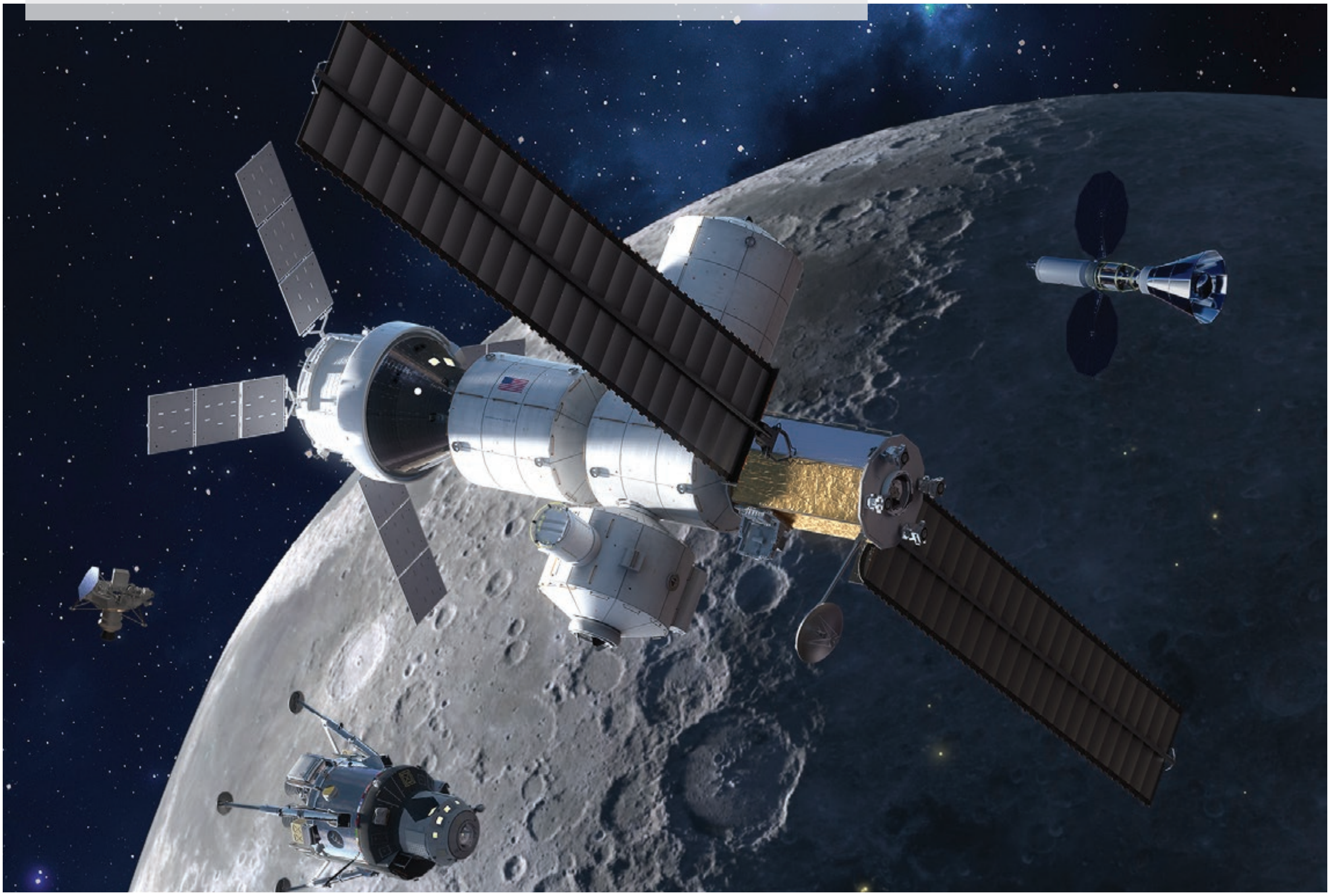
This milestone can be considered achieved when the first space manufacturing facility is built that can create single-piece structures that are too large to be launched from Earth.



A jig factory fabricating the curving habitation tube for a Stanford Torus settlement. Credit: Anna Nesterova

PART TWO:
Utilization and Development of Cislunar Space

The cislunar economy could include a variety of hardware architectures. Credit: NASA



MILESTONE 13
Use of Space Technology and Resources on and for Earth

Space technologies, techniques, and resources used widely and benefitting everyone on Earth.

DESCRIPTION

The technologies and techniques developed for space settlement will not be limited to space settlements. Rather, they will provide widespread benefits to Earth economies and lifestyles, as well as a substantially enhanced ability to protect our planet from potential impacts of comets and asteroids. Some benefits will be realized almost immediately, while others will materialize over longer periods of time.

COMPONENTS (list of benefits)

Anticipated benefits from continued investment in space activities include:

Satellites for Communication. As space platforms increase in size, power, capability, and numbers, existing public and private applications (such as direct-to-user-from-orbit television, radio, and data) will be augmented by more and increasingly sophisticated communications services.

Satellites for Global Positioning, Navigation, and Timing. The establishment of such resources in space has already revolutionized life on Earth, as entire economies have begun to blossom around location-based services. These uses will continue to proliferate.

Satellites for Remote Sensing. Improved use of space-borne sensors, in orbit and on the Moon, will increasingly be used for such purposes as: better weather monitoring and prediction; locating buried mineral deposits, water, and archaeological sites; tracking agricultural, freshwater, and sea conditions; understanding geological conditions; and eventually detecting imminent earthquakes.

Humanity already benefits greatly from satellites such as the GOES weather satellites and COSPAS-SARSAT search and rescue satellites. Credit: NOAA/Lockheed Martin

MILESTONE 13. Use of Space Technology and Resources on and for Earth - *continued*

Commercial Use of the Space Environment. New products and knowledge will come from orbital research and manufacturing facilities utilizing the vacuum and microgravity conditions available only in space. Production of unique pharmaceutical and biological materials in space has already been demonstrated by several companies.

Biomedical Knowledge from the Space Environment. Observations and experiments in microgravity have provided crucial medical insights and breakthroughs, as well as revolutions in medical monitoring. Continued breakthroughs are to be expected, especially with respect to conditions relating to human aging.

Ecology. People living in space and on other worlds will need to conserve and recycle resources to a greater extent than we do on Earth. The technologies and system improvements developed should have widespread applicability to those living on Earth.

Agriculture. Space settlements will help drive the development of more efficient and productive agricultural methods that can be applied on Earth to ease hunger and increase the local production of food in urban areas.

Spin-offs. Things that are designed for application in space will challenge and inspire thousands of young minds and find many new applications on Earth. This has always been the case with investment in space. After building spacecraft, scientists and engineers look at the engineering and systems they have created that would not exist but for the focused goal of space exploration (and the need to preserve precious human cargo), and have then found new uses for them on Earth. This process has created new industries and thousands of new jobs.

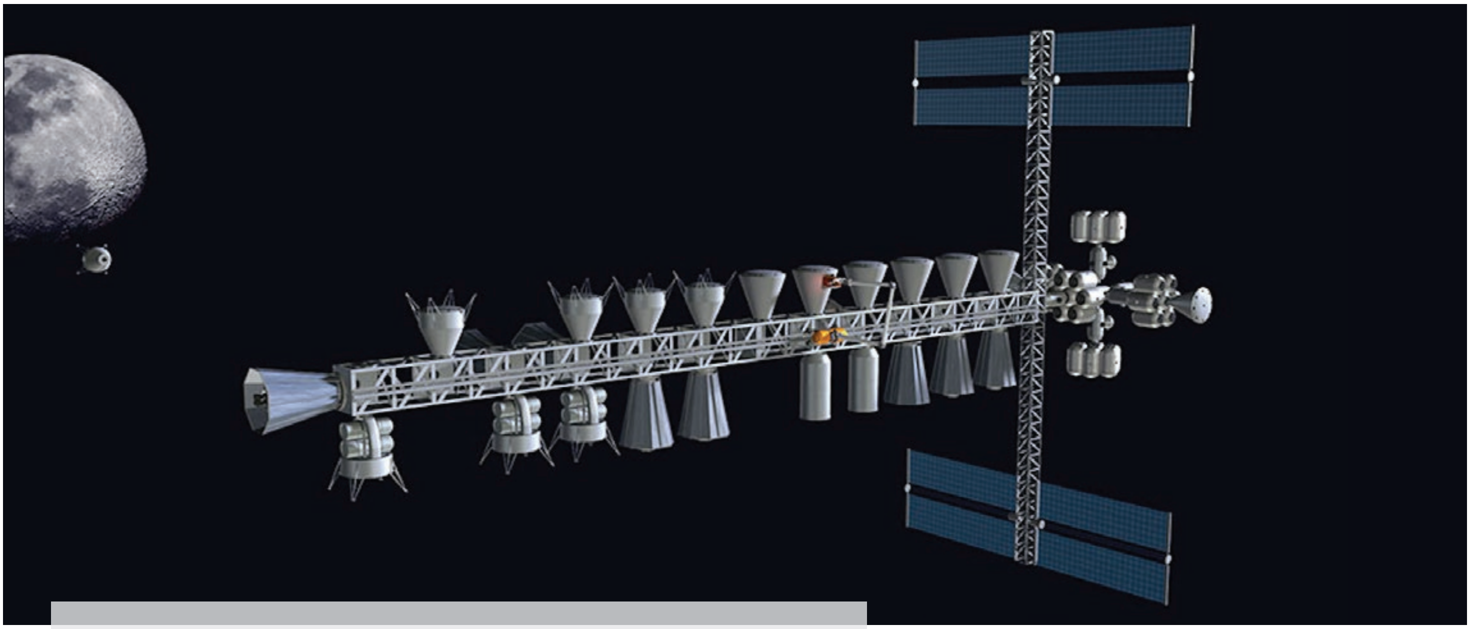
Extra-Terrestrial Raw Materials. The Moon and asteroids contain metals and other materials that are rare on Earth; platinum and certain rare earth elements are two examples. As space technologies are developed and the human presence increases beyond Earth orbit, transportation costs will come down and allow the harvesting of these resources and their return to Earth or use in space. Asteroid mining companies have been founded via private investment, and various countries have shown interest in the concept.

Power from Orbit. Building a system of solar power satellites in geosynchronous Earth orbit could supply clean power to the Earth's population (covered in more extensive detail in Milestone 17).

Sunlight from Orbit. It may be possible to use giant mirrors in orbit to, for example, increase the food supply and provide illumination in dark areas.

MILESTONE 14

An Integrated Cislunar Space Transportation and Logistics System



A logistics base at L1 with habitat modules (at right) and multiple docking ports for vehicles and propellant depots. Credit: Anna Nesterova

Infrastructure and transportation systems providing regular movement of people, cargo, and propellant between locations in cislunar space.

DESCRIPTION

In addition to Earth-to-orbit launch systems, the creation of transportation systems and infrastructure in cislunar space (the space between Earth and the Moon) should result in regular commerce within that region. Cislunar space is considered to include all space near and within the Moon's orbit, including low-Earth orbit, geosynchronous orbits, any lunar orbits, the lunar surface, and the five Earth-Moon Lagrange points.

COMPONENTS

- Reusable space vehicles carrying people, cargo, and propellant between various locations in cislunar space.
- In-space logistics bases located in lunar orbit, at the gravitationally balanced Earth-Moon L-1 or L-2 Lagrange points, or other locations for transferring and storing propellant and cargo.
- Crew habitats attached to the logistics bases for either permanent bases or as temporary refuges while en route to other destinations.

BARRIERS

- Continued reliance on and support for expendable crew-carrying spacecraft.
- Little attention paid to logistics operations in space that support human operations.
- Little focus or progress on propellant depots in space and reusable in-space vehicles.

BACKGROUND

As with sustainable Earth-to-orbit launch costs, the keys to the development of cislunar space will be the reduction in cost of cislunar transportation and infrastructure to affordable levels, as well as the development of a lunar presence and sufficient numbers of people and amounts of cargo traversing cislunar space, to reasonably justify the costs. To reach significance, that presence will almost certainly involve lunar surface operations and probably a permanent lunar presence, but a regular supply of tourists and scientists journeying to lunar orbit may be a sufficient catalyst. The Moon appears to have substantial water reserves in the surface deposits of frozen volatiles at its poles. Some of this water could be used to create rocket fuel for base operations and refueling in space via orbiting depots and tankers.

Even if cislunar infrastructures are initially sponsored or run by governments, cislunar operations and on-board personnel may come from an increasingly capable private sector. The transportation systems and infrastructure developed for cislunar operations, especially if integrated with each other, will prove applicable to other in-space operations elsewhere in the solar system and can provide material support, such as propellant, for such operations.

COMPLETION

This milestone can be considered achieved when regularly scheduled transfers of crew, cargo, or propellant occur between three or more locations in cislunar space.

Robust Space Infrastructure for Human and Robotic Operations

DESCRIPTION

Robust space infrastructure includes not only crew habitats and the life support and power needed to operate them, but also equipment to support the work that the crew is doing. This includes science, spacecraft, and logistical operations, and support for the construction of additional bases in space and on the Moon, Mars, and asteroids. Space presents major challenges for the operation and use of electronics, computers, and communications and data transmission systems, but it also offers some major opportunities. Improvements are needed in a variety of areas specific to space applications.

COMPONENTS (types of infrastructure)

Infrastructure to support extended and cost-effective human operations in space requires the design, deployment, and operational use of multiple components, including:

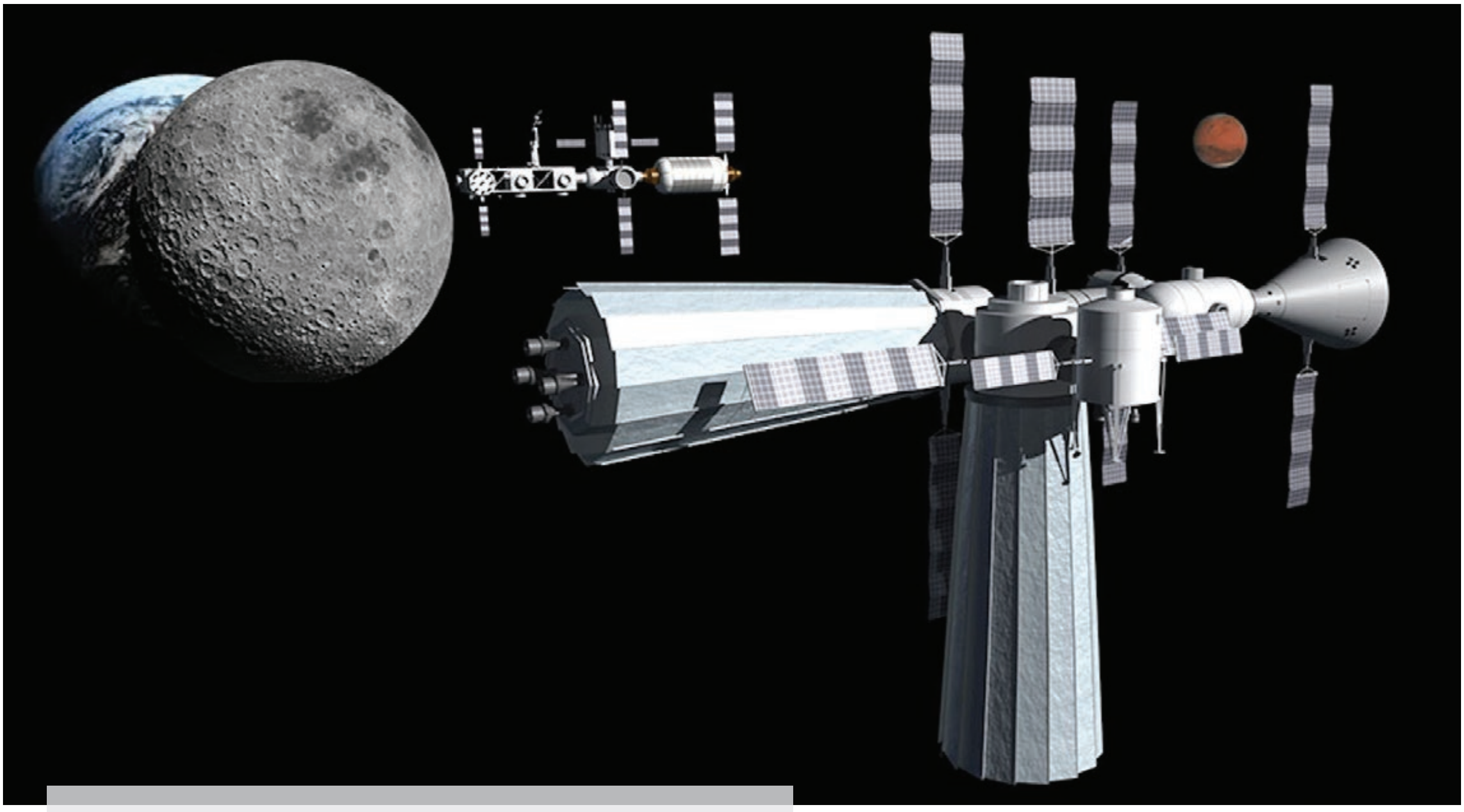
- Reusable spacecraft (such as space tugs) that are operated and refueled in space.
- Propellant depots that will allow spacecraft to be reused and refueled in space.
- A cryocooler, sunshade, and propellant insulation system that can achieve zero boil-off conditions for large cryogenic propellant depots.
- Automated and teleoperated robotic systems for the construction, operation (including logistics), and maintenance of infrastructure and habitats.
- Power transfer via wireless power transmission from one location in space to another.
- High-bandwidth interplanetary communications systems.

BARRIERS

- Current lack of large, proven cryo-cooler systems for cryogenic propellant depots in microgravity.
- Current lack of proven technology to transfer cryogenic liquids between non-accelerating and non-rotating objects in space (both acceleration and centrifugal forces aid in the transfer of fuel).
- Lack of software needed to safely operate external robotic systems in a manner similar to assembly line robots.
- Lack of sophisticated telepresence systems to allow direct human operation of external robots as needed for construction and logistics.

COMPLETION

This milestone can be considered achieved when a logistics base demonstrates the ability to dock several pressurized and non-pressurized space vehicles, move cargo from one vehicle to another robotically, and store and transfer sufficient cryogenic propellants for the operation of space transport vehicles.



A logistics base and propellant depot at L2. Credit: Anna Nesterrova

MILESTONE 16

Development of the First Equatorial Low-Earth Orbit Settlement

A small (about 100-meter diameter), rotating habitat for permanent residents, providing an approximation of Earth gravity in equatorial low-Earth orbit below approximately 500 kilometers.

BACKGROUND

A rotating settlement (for example, with a diameter of 100 meters, a mass of 8,500 tons, and housing about 500 people) could evolve from large space stations or space hotels. If located in equatorial low-Earth orbit, such settlements would not need radiation shielding because they would be protected by Earth and its magnetic field, and will avoid the higher radiation environment of the South Atlantic Anomaly that affects non-equatorial orbits. Without the need for radiation shielding, the mass of such settlements can be drastically reduced compared with orbital settlements located elsewhere in space. Combined with proximity to Earth, this lowers cost and simplifies both logistics and integration with Earth's economy. It therefore seems feasible for all of the building and resupply materials to be launched from Earth with a reasonable number of launches using projected future launchers. Precautions to avoid uncontrolled de-orbiting would also be needed.

COMPONENTS

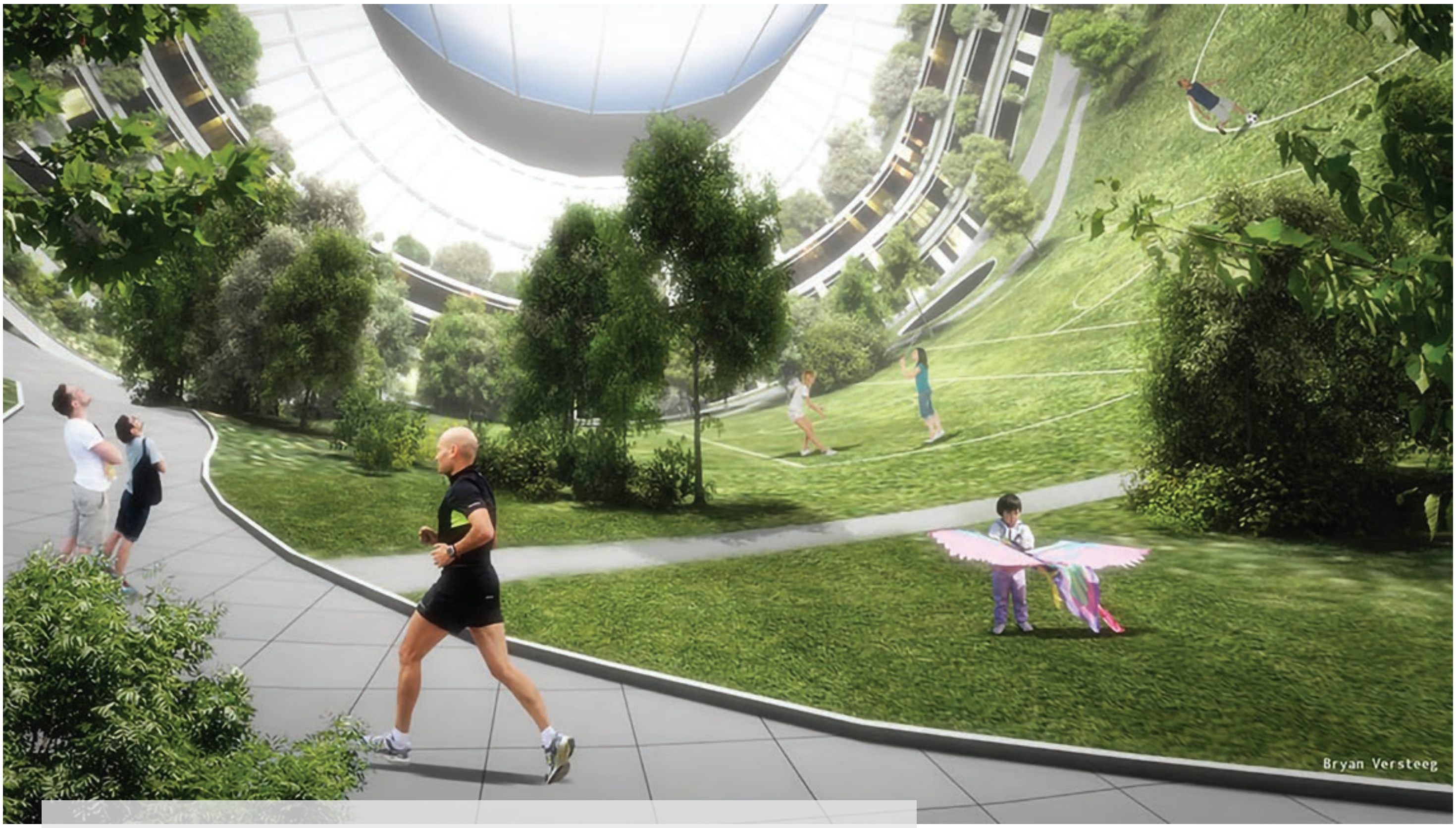
- Habitat intended for permanent residency.
- Transportation system to equatorial LEO.

BARRIERS

- Lack of construction technology.
- Lack of life support technology.
- Questionable economic return.
- Presence of LEO debris.

COMPLETION

This milestone can be considered completed when an equatorial low-Earth orbit settlement is in regular operation.



An equatorial low Earth orbit space settlement Kalpana 2. Credit: Bryan Versteeg

Space Solar Power System

Establishment of an operational space-based solar power system harvesting solar energy in space and transmitting that energy to markets on Earth.

DESCRIPTION

Space solar power can potentially supply a majority of the electrical needs of our planet by transmitting energy produced from sunlight from orbiting facilities. This promises to be clean, reliable, and affordable, and more significantly, it would be renewable and inexhaustible. Many of the world's current problems would be greatly alleviated by accessible and cheap energy, which can be provided by space solar power. Unlike Earth-based solar power, it can provide almost continuous baseload power (the minimum amount of electrical power needed during any 24-hour period), as well as peak load power, to replace fossil fuels. It can be used to light and heat homes, to power factories, to power farming and transportation, to desalinate seawater, and to provide energy in remote areas.

Space solar power can reduce or eliminate the need to burn fossil fuels or utilize nuclear fuels to generate baseload electricity. Baseload use alone currently represents about one-third of the world's energy demand. The capacity of space solar power is so large that it should have an immense impact on reducing the production of greenhouse gases and their effect on global climate. Even before a space solar power system is completed, the pending availability of so much energy could promote global peace by substantially reducing the need for nations to compete for control of fossil fuels.

A major advantage of space solar power for baseload power utilities is that it requires almost zero energy storage, because sunlight is continuously available in space in a geostationary or geosynchronous Earth orbit. Space solar power platforms located in such orbits could provide power to receivers on Earth more than 99.5 percent of the time. Ground-based intermittent alternatives such as solar and wind cannot be used directly for baseload power, since that would require massive amounts of expensive energy storage. Large amounts of the solar and wind energy currently produced is wasted when there is an excess of production due to a lack of energy storage facilities. By avoiding expensive storage technologies, space solar power is projected to be much cheaper than environmentally sound ground-based energy alternatives.

Although a space solar power system would primarily be used to provide continuous baseload power, some of the power can be used for intermittent or emergency use as needed due to its ability to be redirected from one receiver to another in less than a few seconds. Multiple locations, even isolated settlements, could increasingly be served by space solar power, reducing the need for expensive, delicate, and politically sensitive long-distance re-transmission networks between power plants and consumers. It would also greatly reduce the need for fossil fuel delivery systems, such as pipelines, tanker ships, trains, and trucks.

Space solar power for baseload power markets should be much more economical in its use of building materials and efficient in its use of land area than ground-based solar or hydroelectric power plants. For example, the Three Gorges Dam project in China required the inundation of over 100 square miles of valuable farmland to produce on average 10 gigawatts of electrical power. A similar 10 gigawatts delivered by space solar power would require about 36 square miles, and the land underneath the receiver could be simultaneously used for agriculture or other purposes (unlike the land at the bottom of a reservoir). By comparison, 10 gigawatts of baseload power delivered by ground-based solar power would require a solar array covering about 360 square miles, after accounting for nighttime and seasonal variations in solar intensity, spacing of the solar collectors, and the effects of clouds and other weather conditions. This is 10 times as much area as the space solar power requirement.

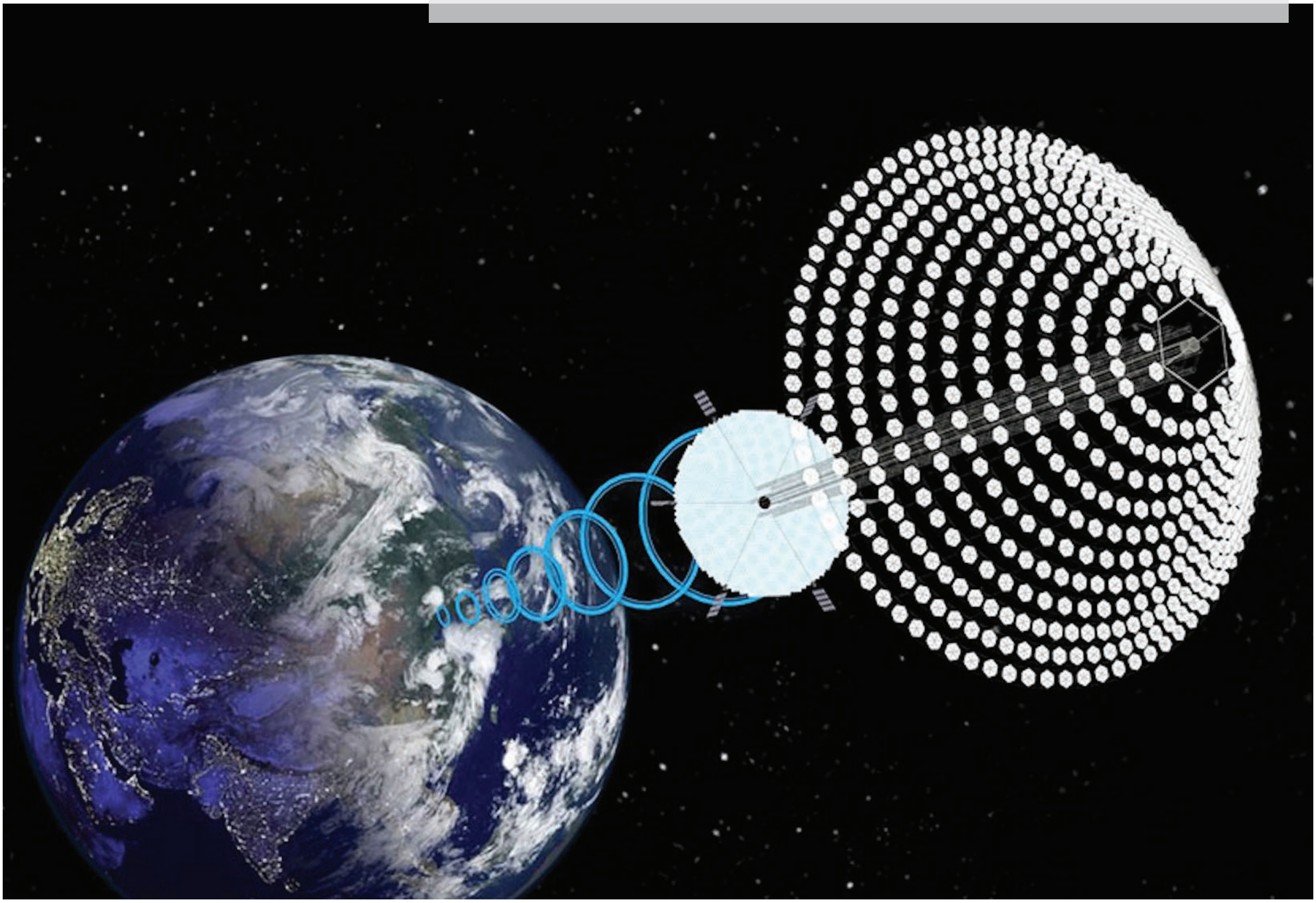
Space solar power has the potential to be transformational for a wide range of missions and markets in space. As of 2017, the cost of electricity in space (for example, at the International Space Station) is approximately $50 to $100 per kilowatt-hour, as opposed to a retail price of about 10 cents to 25 cents in most markets in North America. The development of space solar power, with costs of electricity competitive with terrestrial markets (less than 5 cents to 15 cents per kilowatt-hour), would radically transform prospects for a variety of in-space markets, including space resources development, manufacturing in space, and space settlement.

COMPONENTS (necessary components)

- Valid business case.
- Economical surface-to-geosynchronous Earth orbit transport.
- Effective design for, and development and construction of, the space component (the solar power satellite).
- Effective design for, and development and construction of, the ground component consisting of a receiving antenna (rectenna) and related systems.

continued >>

A space solar power satellite, SPS Alpha. Image: John Mankins, Mankins Space Technology



MILESTONE 17. Space Solar Power System - *continued*

BARRIERS

- Opposition to and misconceptions about wireless power transmission, which is essential to transmit solar power from space to the ground.
- Lack of consensus that space based solar power can be more economical than alternate ground-based electrical power.
- Insufficiently reduced launch costs.
- Lack of a detailed, economically buildable design.
- Lack of agreement on the choice of microwave frequencies to use for power transmission, primarily to avoid conflict with existing frequency allocations.
- Concerns that the system could be used for powering weapons.

COMPLETION

This milestone can be considered achieved when space solar power systems have become operational in multiple locations, with more in the construction pipeline, and a consensus has been reached that space solar power needs to be a major component of future power supplies.

The Moon, only a quarter of a million miles distant from Earth, is a visible and obvious destination for human settlement.

PARTICULAR BARRIERS

Major barriers specific to settlement of the Moon will have to be overcome to reach the settlement milestones. These barriers include:

Psychological and Political Commitment. Until successive phases of lunar exploration have shown a likelihood of affordability and sustainability, no country or private entity is likely to make a firm commitment to a permanent human settlement on the Moon. To date, there is no such commitment.

Goal Definition. There is a lack of consensus on a clear set of lunar goals that would move beyond the expeditionary model, also known as "flags and footprints."

Architecture Definition. There is a lack of information and consensus on the infrastructure needed and the order in which it should be built.

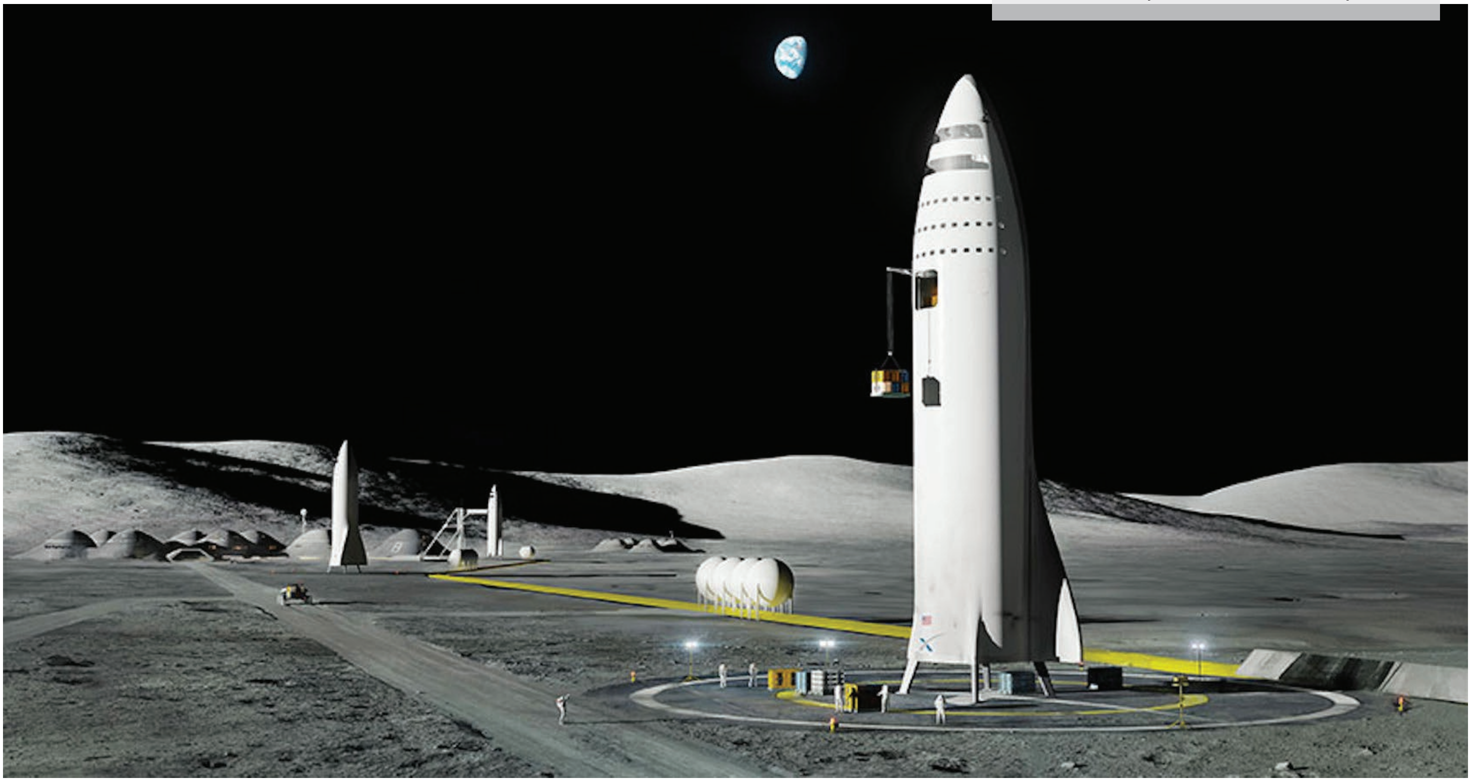
Economics. Supporting human lunar operations will be expensive, and there is no agreement on how to financially underwrite these efforts.

Biological. There are two major potential barriers to a permanent human settlement on the Moon: radiation, and gravity that is only one-sixth that of Earth.

- Lethal ionizing radiation from the sun and even more powerful cosmic rays from outside the solar system pose serious threats to humans on the Moon. Habitats must be shielded, probably by being covered with thick layers of local regolith or built underground. More difficult will be finding a way to shield people while operating on the surface.
- Gravity is the true unknown. Humans (as well as other animals and plants) are the product of some 500 million years of terrestrial evolution, and all terrestrial life has evolved to live in a one-gravity environment. We already know about the dangers of long duration space flight, such as bone loss and vision degradation. No one knows whether humans can successfully live over the long-term in low lunar gravity, nor whether children can be safely born and raised under these conditions.

Certain Lunar Characteristics. Each body orbiting the sun has its own characteristics. The Moon presents some unique challenges which must be overcome, such as half-month days followed by half-month nights creating a 500 degree temperature swing in most areas; pervasive and abrasive dust; a lack of easily recoverable water (except in probable ice deposits close to the poles); and the unknown usability of those deposits should they be recoverable.

Moon base operations. Credit: SpaceX



MILESTONE 18

Robotic Confirmation of Lunar Resources

Orbiters and robotic landers to determine the nature and extent of lunar ice, volatile deposits, and other lunar resources, and to provide the information necessary to choose the best site for a lunar outpost or mining base.

DESCRIPTION

The Apollo lunar landing missions chose landing sites primarily on the basis of safety and general scientific interest to learn about the history and composition of the Moon. Future lunar robotic missions should emphasize the discovery of what lunar resources can best be utilized for human benefit. Sites for future lunar outposts and bases will probably be determined by the findings of those robotic missions.

Water and Lunar Volatiles. Robotic probes from several countries have determined that water and other valuable volatile elements are present in significant percentages in lunar soil at four volatile deposit zones (near the current and ancient lunar pole locations), notably in deep, permanently shadowed craters. The pole positions were probably shifted by an asteroid collision at some time in the distant past; the previous polar locations are a few degrees away from the current ones. We need to know what volatiles are present at each location, and how extensive and deeply buried they are. Knowing the proportion of the deposits consisting of water ice will be crucial to understanding their availability for the manufacture of rocket fuel and oxygen, and to provide other support for human habitation. Every kilogram of water that does not need to be imported from Earth or other locations represents a significant step toward self-sufficiency and immensely eases the logistical requirements for supporting humans on the Moon.

Non-Volatile Resources. Other major resources on the Moon include oxygen, silicon, titanium, iron, magnesium, aluminum, and calcium. Most of these resources are mixed into the regolith (lunar soil). Concentrations change significantly from highland to mare sites, but these minerals can be found essentially at any location on the Moon.

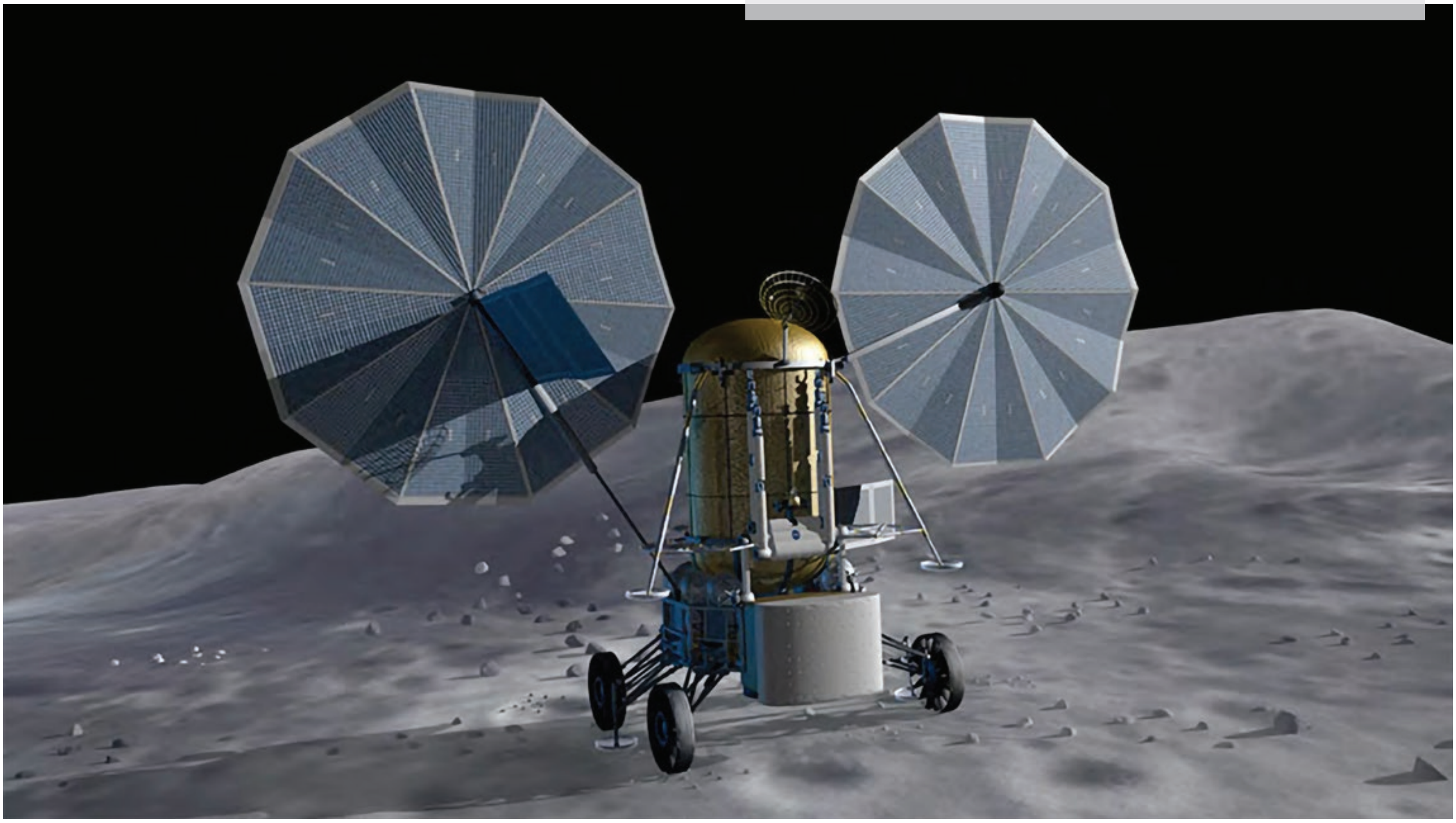
BARRIER

Delay or lack of commitment for lunar orbiter and rover missions that could characterize and verify the location, depth, thickness, and concentration level of ice, volatile deposits, and other resources.

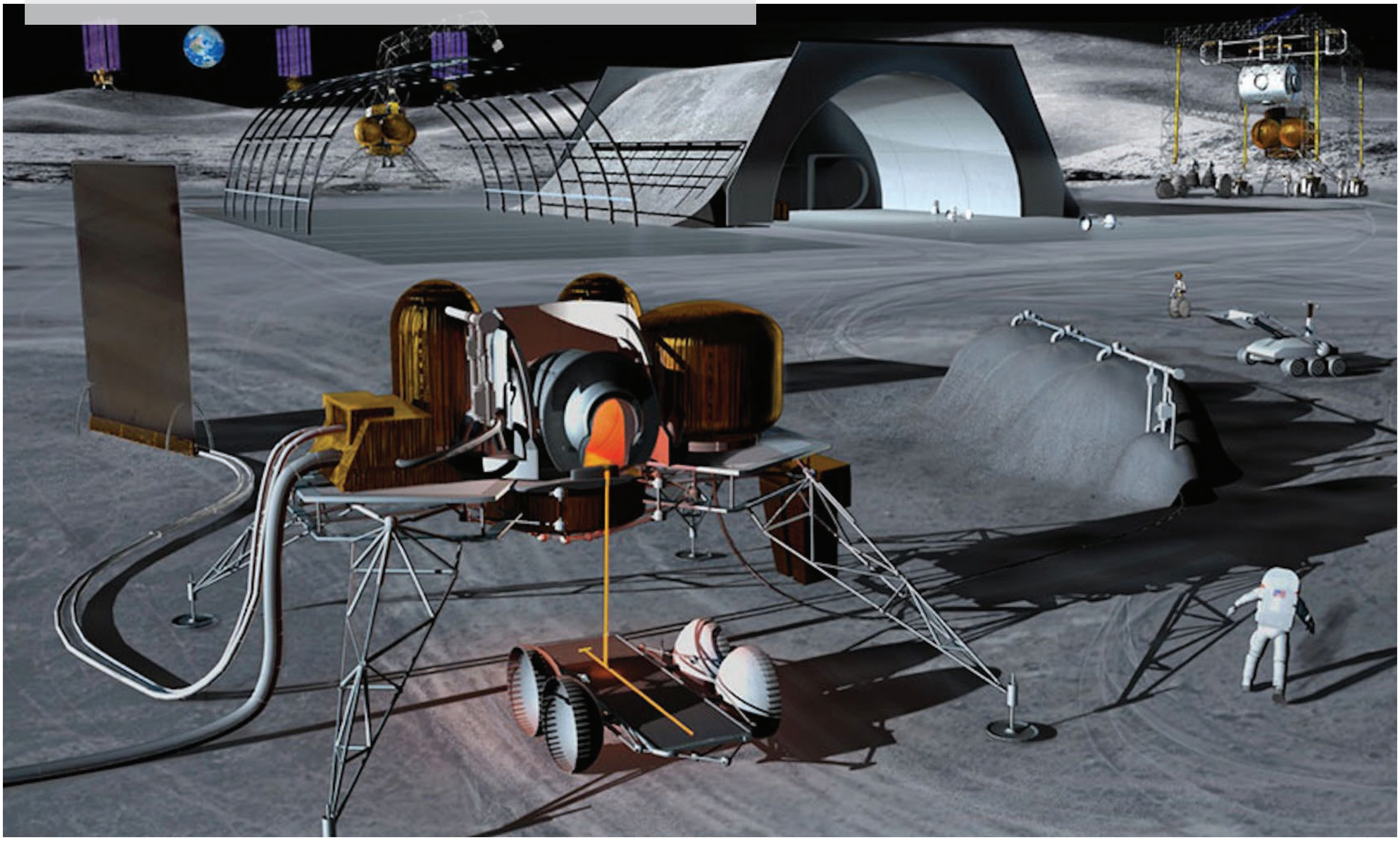
COMPLETION

This milestone can be considered achieved when enough data, including the locations of water deposits and other resources, has been gathered to intelligently pick one or more lunar sites for outposts and bases.

An ISRU water processing demonstration mission. Credit: NASA



An ISRU Lunar Base. Credit: Mark Maxwell/Dennis Wingo/Skycorp Inc.



A crewed lunar research facility established to study human habitation, test various equipment and techniques (including mining of lunar resources), and conduct lunar science investigations.

DESCRIPTION

A choice must be made regarding the location of the first lunar outpost. Habitation structures will need to be delivered or built at the site for use during multiple visits.

Finding, selecting, and validating sites for lunar outposts: Some of the most critical site characteristics may be detected by orbiters and surface rovers. Various lunar sites should be considered for early outposts, each with advantages and disadvantages. Lunar polar sites have the advantage of less extreme temperature fluctuations, and do not have two-week long night periods. They appear to have valuable resources in deep craters at four locations that are directly around and adjacent to the polar zones. Other site characteristics should be included in the selection process, such as: mineral abundance levels in the regolith, geological features like lava tubes, the nearby availability of sunlight, proximity to good locations for radio astronomy, terrain roughness (which affects the ability of rovers and humans to navigate around the site), and limitations to equipment use due to extremely low temperatures in permanently shadowed zones.

- Polar sites in general have areas with about 20 percent more sunlight (for power) than non-polar sites, with some having up to 80 percent more sunlight. The total lack of sunlight for solar power in shadowed polar areas is compensated by the fact that areas with more continuous sunlight access are nearby.
- There are slightly higher risks in landing inside a crater near a shadowed crater wall, or on the narrow rim of a fully shadowed crater.
- Maintaining communication with Earth is a challenge when a base is not in line-of-sight with terrestrial antennas. Establishing a network of lunar relay satellites would ease that problem but will also add to the cost and complexity of lunar infrastructure supporting polar locations.

Lunar base sites outside the polar areas could be established if the polar volatiles prove to be difficult to extract, which may motivate a continued search for sites that lack volatiles but have advantages for a first outpost that a polar site lacks. All sites outside the immediate polar zones have a two-week long lunar night, which makes additional reliable power sources mandatory.

continued >>

MILESTONE 19. A Lunar Research and Development Facility - *continued*

Facility design and operation: The first lunar outpost should be designed to support successive missions, each building on the knowledge gained and infrastructure built by its predecessors. This facility could be government sponsored and funded, or alternatively established by private enterprises. The outpost may consist of a single module or multiple modules landed or constructed in later missions; the latter is likely to be the most cost-effective and productive. An early module could be a habitation module, allowing extended crew stays. Power supply modules will need to be delivered before human crews arrive. Other deliveries, either before or after a habitation module, could include rovers, excavators, tractors, unloading and construction equipment, pilot-scale mining and smelting equipment, kilns for metallurgy, telescopes for astronomy, medical labs and other scientific modules, and more habitation modules. This staging would allow for both short visits by scientific specialists and the gradual building of a larger facility at the initial site.

The initial outpost could be either vacated between missions or continuously occupied by a small, rotating crew. If the latter, the outpost will be exceptionally useful in determining the ability of humans to survive and be productive for long periods in the one-sixth gravity environment, and in the case of plants and animals, to reproduce and complete life cycles successfully.

This first outpost will probably be a combined research facility and mining base, possibly at a polar location. The crew habitat module will have to be shielded from space radiation and temperature extremes. This can be done by burying the habitat underground or covering it with several meters of regolith. If sufficient equipment is available, and a large lunar lava tube is found in a suitable location, the tube might be used for shelter. Over time and as it grows, the outpost may be able to test, among other things:

- life support and recycling systems,
- effective means of keeping abrasive lunar dust out of the habitation modules,
- health maintenance regimens for the low-gravity environment,
- cooking in one-sixth gravity,
- spacesuits,
- lunar transportation vehicles,
- alternate power sources and backup power supply systems (battery, solar, and nuclear),
- techniques for extracting water for direct use and for rocket fuel synthesis (if volatiles are found nearby),
- construction and fabrication techniques using local materials,
- construction of a storage site for rocket fuel at a distance from the habitat,
- various methods and materials for providing radiation shielding,
- pilot-scale, then later full-scale, mining and smelting techniques,
- manufacturing and fabrication techniques unique to one-sixth gravity and vacuum,
- crew psychology in a new environment,
- indoor plant growth for food production,
- animal life cycle tests with small mammals in the low-gravity lunar environment.

A high priority should be placed on testing pilot-scale production of water and rocket fuel from the polar deposits. If prototype equipment is delivered early in the program, the pilot-scale can transition to full-scale production sooner.

Surface explorations based from the facility will continue contributing to our scientific knowledge about the Moon. In addition, regular broadcasts from the Moon could be carried in popular media venues and would serve to educate the public and increase support for further human space activities. Entertainment companies in particular may find a way to finance and profit from such activities.

The first outpost or outposts are likely to conform to current astronaut safety standards. This will mean always having available a means for emergency evacuation to Earth or another safe location, and having a shielded crew refuge which can protect the crew from sudden bursts of solar or cosmic radiation for a specified length of time (and which can also serve as a crew habitat during later normal operations). Apollo-mission level risks will probably not be accepted where long duration stays and routine lunar flight operations are involved.

COMPLETION

This milestone can be considered achieved when significant scientific results are returned and (depending on the amounts of volatile deposits found) a commercially significant amount of lunar water has been extracted and processed.

MILESTONE 20

A Continuously Occupied Multi-Purpose Lunar Base

An initial lunar facility evolving into a permanently occupied, ever-expanding lunar base (or an additional base created at another site), using what has been learned from the initial research and development facility, and increasingly performing commercial functions such as the production of rocket fuel from volatile deposits and the shipment of fuel to orbit.

DESCRIPTION

Scientific research, use of resources, and preparation for possible future lunar settlements are some of the main rationales for a lunar base. The goals of the scientific community may be paired with in-situ resource utilization (ISRU) to share the cost of the base. Both activities can also be conducted with a rotating crew, avoiding the possible long-term problems associated with low gravity and other issues inherent in long-term occupancy.

Early lunar bases run the risk of being abandoned if affordable space transportation systems are not used from the beginning and the order and composition of critical base infrastructure is not agreed on. The risk of abandonment of an early lunar base may be lessened if mission architectures are designed as a sustainable, modular, reusable and, therefore, affordable, integrated system that pursues ISRU and self-sufficiency technologies as a very early goal. Creating an economic rationale for the base, such as a commercial ISRU operation that produces propellant for lunar, cislunar, and Mars operations, could greatly enhance the probability that the lunar base would continue to be supported.

Once the initial lessons have been learned from the lunar research and development facility, a growing lunar base will turn its attention to maximizing its usefulness to other space operations and achieving some commercial viability. Success of such a base should encourage early industry investment and involvement. Some modules could be privately financed, as could visits by various researchers.

Noncommercial Functions. The lunar base will continue the basic scientific and technological research begun by the research facility, possibly with government funding and direction. The techniques learned during the research facility phase, including the utilization of lunar volatiles to produce rocket fuel, will increasingly be incorporated into the operations of the continually occupied lunar base.

In addition, with the experience gained from operating in the lunar environment, the base may be used as a test-bed for developing the many technologies and hardware that will be needed to colonize Mars. While Mars has a slight atmosphere, seasons, very different kinds of dust, and gravity twice that of the Moon (but still only about one-third that of Earth), conditions on the Moon provide a much more rigorous environment for thorough testing. Entire modules intended for Mars could be field-tested on the Moon. It is a valid test site with the advantages of being close enough to Earth for easier and faster resupply, with the result that any rescue operations would be much faster than those involving Mars (i.e., a travel time of days instead of months).

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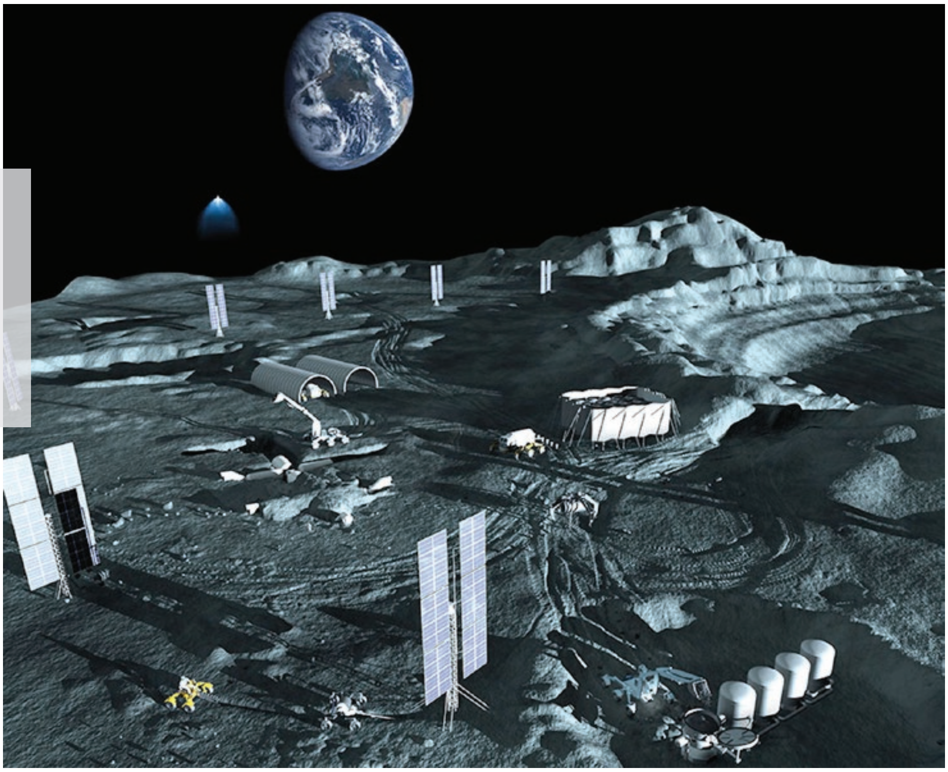


Lunar polar mining base with buried crew habitats, widely spaced solar power panels, propellant production plant and depot tank farm. Credit: Anna Nesterova

MILESTONE 20

A Continuously Occupied Multi-Purpose Lunar Base - *continued*

The European Space Agency's design study for a lunar base. Credit: ESA/Foster+Partners

MILESTONE 20. A Continuously Occupied Multi-Purpose Lunar Base - *continued*

Commercial Functions. Commercial uses of the lunar base should gradually increase. As the technology improves and the risk from innovation uncertainty is substantially reduced, risks and potential profits of investment in lunar infrastructure can be better evaluated. At that point, it is likely that investments in lunar enterprises will be more substantial. Possible commercial opportunities include:

- if located near extractable volatiles, providing rocket propellant for cislunar and Mars operations could be one of the base's primary and most commercially valuable uses,
- generation and sale of research data,
- production and sale of lunar entertainment media for Earth,
- tourism, with a possible inclusion of a bare-bones hotel module near the base for lunar excursions.

BARRIERS

- Lack of proof of commercially valuable volatile and mineral deposits on the Moon.
- Difficulty coping with lunar dust.
- Lack of agreement on radiation shielding levels, methods, and technology, including whether the base will be above ground and covered by regolith, dug into the ground, or in a lava tube.
- Continuing funding conflicts between multiple, seemingly divergent government space goals.

COMPLETION

This milestone can be considered achieved when a true lunar settlement is established or the multi-purpose base has been continuously occupied for at least a decade.

MILESTONE 21
A Permanent Lunar Settlement

A lunar base or other lunar habitations evolving into a permanent settlement, which is increasingly self-sufficient and focused on commercial activities.

DESCRIPTION

As lunar habitation grows in volume, area, the number of modules connected and emplaced nearby, and especially population, lunar settlements will eventually reach a point of permanence. While it is hard to define a permanent settlement, some aspects that might be present include:

- people moving to the Moon with no intention of ever returning to Earth,
- residents other than employees,
- children being brought to the Moon and, gravity and other conditions permitting, being born and raised there,
- commercial businesses including manufacturing and markets,
- schools, churches, and other gathering spaces,
- surgical and medical facilities,
- closed or controlled ecological life support systems (CELSS) that recycle sufficiently to minimize the amount of imports needed for daily living (including food),
- some form of local governance,
- the ability to make most repairs using local materials,
- facilities for visitors, whether scientists, tourists, or others,
- use as a staging point and support facility for the development of other lunar settlements.

While the settlement's facilities are reasonably predictable, the composition of its population is not. That will depend on the biological effects of both living in the low lunar gravity for long periods, even a lifetime, and on fetal development and later growth. It may be that people and their families will be able to move to the Moon and live there for generations, or the permanent settlement might be occupied by a constantly changing population shuttling to and from one-gravity environments.

As the costs of space transportation and settlement decrease, the incipient commercial activities that were initiated in the base phase will be expanded. This includes tourism, the development of products and services for use at other locations, and the production of components to support services for Earth such as space solar power. Lunar hotels may be the most frequently added businesses. The low lunar gravity might even make the Moon a retirement destination of choice. An increasing proportion of lunar settlers will be involved in these commercial activities, rather than routine maintenance.

One significant commercial activity that could be sustained by a growing lunar settlement would be the creation of a system of electromagnetic mass drivers or coil guns (similar to rail guns) for transporting commodities. These devices would precisely hurl mined lunar materials or lunar-derived rocket fuel directly from the lunar surface into trajectories where they would be captured in space. They could then be used to construct orbital space habitats or refuel outbound spacecraft substantially more economically than could be done if those resources needed to be brought up from Earth or the lunar surface by rocket power. Another activity that could be supported by a growing settlement would be the establishment and maintenance of permanent observatories at various locations.

BARRIERS

- A possible lack of volatiles on the Moon except at the poles.
- A possible lack of light elements and metals.
- A possible lack of concentrated metallic ore bodies.
- Cost of importing volatiles to non-polar lunar locations.
- Lack of consensus on economic models for early lunar commerce.
- Lack of proof that humans can complete a normal life cycle in an environment with one-sixth the gravity of Earth and the impracticality of creating sufficiently high artificial gravity on the lunar surface.

COMPLETION

This milestone can be considered achieved when the lunar settlement has been occupied for several decades, with a population that is stable or growing.

"Lunar Lights." Image: Raymond Cassel

PART 4:
On to Mars

With gravity about one-third that of Earth and twice that of the Moon, an atmosphere averaging one percent of the density of Earth's, an axial tilt and a day length very similar to Earth's, and vital deposits of volatiles like water, Mars beckons to provide another home for humanity.

PARTICULAR BARRIERS

Major barriers specific to Mars will have to be overcome to reach the milestones en route to the settlement of Mars. These barriers include:

Psychological. Mars is a long way from Earth. With current technology it is more than a six-month journey each way and, due to orbital mechanics, pragmatically accessible from Earth for only a short launch window every two years. A single round trip would last either about 500 days, allowing only a short 30- to 60-day stay on the surface before the launch window for return to Earth would close (opposition mission), or 900 to 1,050 days, allowing 500 days for on-surface operations (conjunction mission). This great distance could create a feeling of isolation for crew members or settlers.

Governmental. A lack of any definitive and ongoing government decision to support a practical human Mars expedition, or allow a private Mars expedition.

Political. The lack of political support to create a permanent and growing human presence on Mars. With trips so infrequent, lasting so long, and relatively few or exciting on-surface events, public interest is likely to be inconsistent. When public interest wanes, a decline in political support usually follows.

Goal Definition. Early government-led human Mars exploration runs the risk of resulting in expeditionary "flags and footprints" or "grab (rocks) and go" missions followed by the "been there, done that" lethargy that ended the Apollo lunar program. This risk will be lessened if the goal is a continued human presence and settlement on Mars by private or government efforts (or a combination of the two), and mission architectures are designed from the very beginning as a sustainable, reusable, integrated system that pursues ISRU and other technologies for self-sufficiency.

Biological. As with the Moon, there are two major potential barriers to the permanent human settlement of Mars: radiation and gravity.

- While solar radiation is diminished due to Mars' distance from the sun and thin atmosphere, it can be lethal for unprotected life on the surface. Extra-solar cosmic radiation is somewhat diminished by the Martian atmosphere compared to the lunar surface, but it still a hazard to humans located there. Methods to shield habitats and people operating on the surface will need to be developed.
- Though Martian gravity is twice that of the Moon, it is still only one-third that of Earth. Whether complex terrestrial life can thrive and reproduce under such conditions is unknown. This barrier can be tested using in-space variable-gravity centrifuges or on-planet experience.

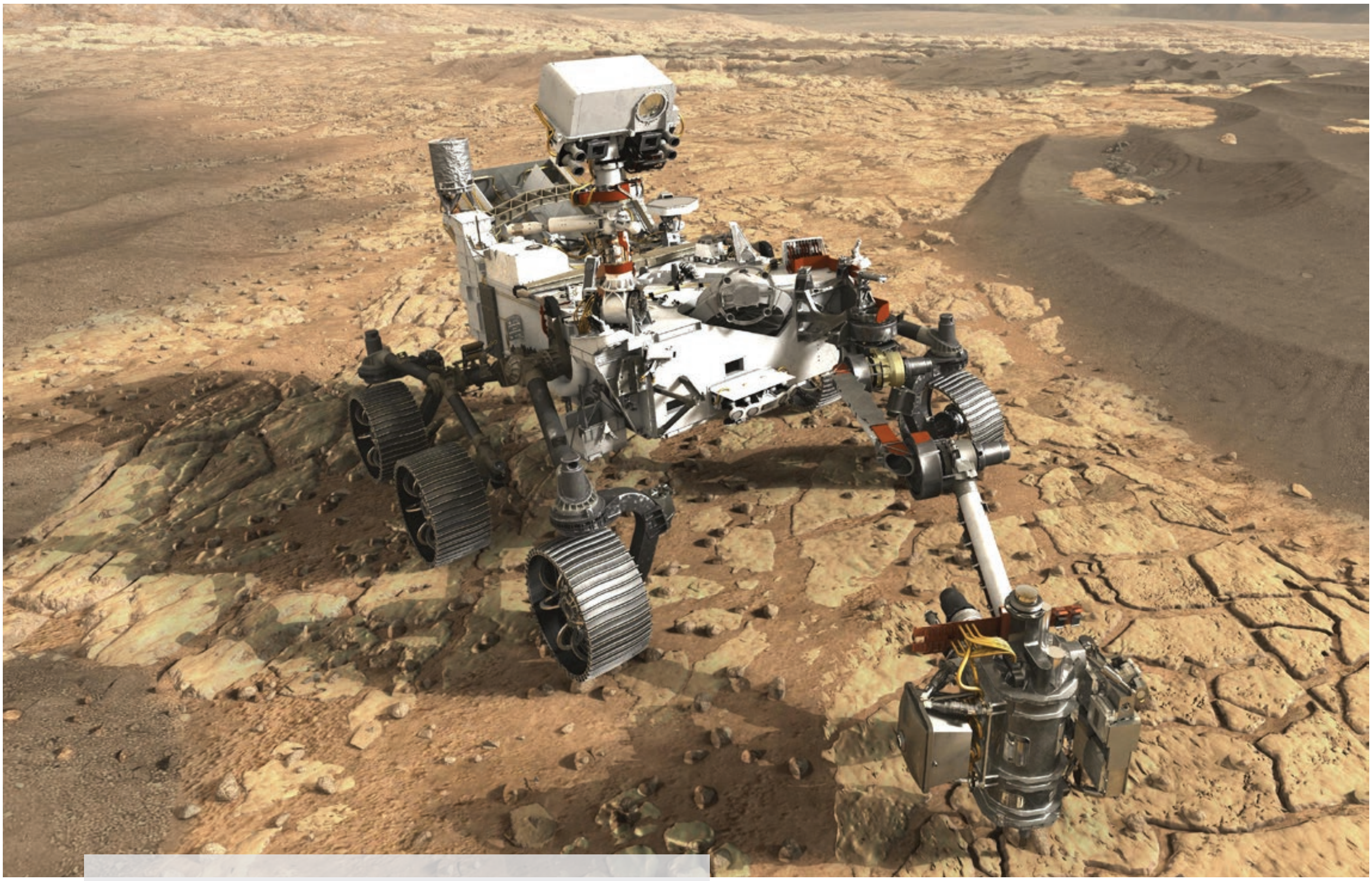
Certain Martian Characteristics. Challenges unique to the Martian environment will have to be overcome, such as dust storms, hazardous soil chemistry, accessibility to water, vehicle-trapping sand, low night temperatures, and acclimation to slightly longer days.

Planetary Protection. The possibility of life on Mars currently seems remote, but cannot be totally excluded. It is unlikely that the existence of life on Mars can be definitively proven or disproven by robotic probes alone. There are those who feel that until some definitive result is obtained, all spacecraft must undergo the most strenuous sterilization processes at great cost, and that no humans should walk on Mars due to the microbial residue they will inevitably carry onto the surface. This viewpoint could prevent the settlement of Mars for centuries if it is strictly implemented. In addition, unreasonably strict sterilization regulations, which cannot entirely eliminate microbes carried by humans, could make human trips to Mars prohibitively expensive or impossible.

Credit: Javier Arizabalo

MILESTONE 22

Robotic Exploration of Mars for Local (In Situ) Resources



NASA's Mars 2020 rover at work. Credit: NASA/JPL-Caltech

Satellites orbiting Mars and robotic landers, supplemented if needed by rovers teleoperated by an orbiting crew, determining the location, nature, and extent of Martian resources—especially water ice—and guiding the choice of the best sites for follow-on human missions.

DESCRIPTION

Robotic missions to Mars, both orbiters and landers, have provided and are currently providing tantalizing hints about Martian geological history. Continuing missions, utilizing the favorable launch windows that occur about every 26 months, may be entirely robotic or supplemented by crewed missions to a Martian moon or even low-Mars orbit. From these locations the crew could teleoperate Mars landers without the long delay in radio transmissions to and from Earth, and test equipment that later could be used on the Martian surface. In the event that a clearly superior landing site for the initial human surface base cannot be identified in advance, such a crewed orbital mission could be used to teleoperate rovers to determine which site is best.

There are two fundamental objectives of such missions:

Scientific Knowledge. One fundamental objective of these missions will be to continue learning more about the planet's geological history, both to understand it for its own scientific value and to ascertain if there are any implications for Earth. In particular, these missions would be searching for:

- The existence of Martian life or evidence of past life.
- The location, purity, and amounts of surface and buried water ice or liquid water, especially near the surface and the equator.
- Locations with thick layers of exposed rock to provide an accurate geological history.
- Geological implications from diverse soil and rock samples that help us compare Earth to Mars.
- Locations and amounts of valuable minerals and metal ores such as hematite.
- An understanding of Martian weather, seasons, and atmosphere.
- Indications of any biological or other contaminants that could be harmful if returned to Earth.
- Rates of loss of the Martian atmosphere and water from solar wind stripping and photolysis (the decomposition of molecules by ultra-violet light).

continued >>

MILESTONE 22. Robotic Exploration of Mars for Local (In Situ) Resources *- continued*

Data for Human Exploration and Outposts. The other fundamental objective of these robotic Mars missions will be to ascertain existing conditions that are favorable to human exploration and settlement on the planet, especially near the Martian equator where less fuel is required to land and return to orbit. In particular, these missions would:

- Search for the best sites for follow-on human activities.
- Search for ice or water sources that will be the most accessible.
- Search for any deep brine layers and concentrations of other minerals that might be useful.
- Test a wide variety of materials and machines in the Martian environment to determine how well they continue to function over long periods of time while exposed to wind, dust, radiation, daily temperature fluctuations, and seasonal changes.
- Test various robotic rover designs in ever longer traverses over varied Martian terrain.
- Test prototypes of in situ resource utilization equipment to convert carbon dioxide and excavated ice to fuels (including rocket propellants) and oxygen, and eventually convert solid minerals into structural materials.
- Test a variety of energy supply and backup systems.
- Test automatic and teleoperated equipment designed to excavate and transport ice to a fuel production plant.
- Test automatic construction techniques both in, and using, Martian soil.
- Determine the best methods for growing food on Mars, on the surface or below ground.

With favorable launch windows existing only about every 26 months, determining the tradeoffs as to which measuring instruments, test equipment, and rovers will be sent on any particular mission, and in what order, will provide challenges for policy makers.

COMPLETION

The first objective of this milestone (scientific knowledge) may never be fully completed, as scientific investigation is open-ended. The second objective (exploration and outpost data) can be considered achieved when there is agreement on at least three viable surface sites for future human development, all of which have a source of water ice nearby.

Proposed Mars robotic sample return vehicle. Credit: NASA/JPL-Caltech

An Integrated Martian Space Transportation and Logistics System

An integrated and sustainable system capable of safely transporting humans and cargo from Earth or cislunar space to the Martian surface, maintaining the crew on the surface, and returning the crew back to Earth or cislunar space.

DESCRIPTION

Initial Mars bases will depend on a transport and logistics connection to Earth or cislunar space. Three critical factors in creating a safe transportation and logistics system are: reliability and redundancy in vehicles, equipment, and supplies; adequate radiation shielding; and having one or more well-trained medical crew members.

Reaching and returning from Mars will be significantly more difficult than similar operations on the Moon. Due to the great distance between Earth and Mars, equipment or supplies that fail on Mars cannot be easily replaced. An unexpected failure that might be surmountable on the Moon, only a few days away from Earth, could be fatal on Mars. Consequently, materials and equipment destined for use on Mars should be especially well designed, manufactured, and tested for high reliability.

Due to the distance and years-long rescue time, it is extremely important that all human Mars journeys utilize the principle of redundancy. It is especially important to have more than one crew habitat vehicle which can support the entire crew and more than one main propulsion vehicle which can propel the entire system in case of accident or equipment failures. This would allow the crew to perform self-rescue and significantly reduce the problem of distance from Earth as a major crew safety issue.

Unless we are discussing one-way trips to Mars, decisions must be made about whether to undertake a 500-day stay (conjunction mission) or a 30- to 45-day stay (opposition mission) after a six- to eight-month journey. That decision will drive the planning for the transportation, landing, habitation, supply, and Earth return systems. For an ongoing series of Mars expeditions, opposition missions are much less desirable than conjunction missions. The opposition mission type requires leaving Mars orbit within about six weeks of arrival, leaving little time to accomplish desired objectives, including repairs if necessary.

Earth to Mars Transportation Systems. Systems proposed to travel between Earth orbit and Mars orbit include vehicles in which the crew will be in microgravity during transit and vehicles using tethers or other methods to create artificial gravity by rotation. Most systems that have been proposed use chemical propellants of one kind or another. Other proposed propulsion systems include nuclear-thermal propulsion and electric propulsion (ion and plasma). Electric propulsion is currently better suited for cargo than for human transport, and may become more important as both solar cells and electric thrusters are improved and scaled-up. While the preferred goals and payload ought to determine the appropriate transportation system, the sequence may be just the opposite, with the choice of transportation system determining the length or the type of trip and the tonnage that can be transported. The choice of architecture will be influenced by the strength of the desire to have humans on Mars, tempered by the state and the cost of then-available technology.

Reusable transit vehicles that can return to Earth orbit or a logistics base at a cislunar location would greatly reduce costs for repeated Mars flights. Many concepts propose leaving from a cislunar location such as the Earth-Moon L1 point (EM-L1) and using lunar-derived propellant to reduce the mass of propellant that otherwise would need to be lifted from Earth.

Earth Orbit to Mars Orbit on a Cycler. A large cycling spacecraft, sometimes called an Aldrin Cycler (named for Buzz Aldrin, who has refined the concept), that moves between Earth and Mars without actually entering into either planet's orbit, would require less fuel and, since it can be very massive, can provide much more radiation protection for passengers. Such a spacecraft would require very high reliability and redundant transfer (taxi) vehicles at each end of the trip, since the cycler cannot wait for launch delays. Due to the requirement for multiple transfer vehicles at each end of the trip, the cycler system might not be used extensively until later in the development of civilian transport to Mars.

Mars Surface Landing Systems. Many transportation concepts have been proposed for landing methods, including:

- Earth (or Earth orbit) directly to the Martian surface (direct entry). Variations in landing systems include aero-braking (either with direct insertion from Earth or using multiple orbital passes), parachutes, and braking rockets. Such methods could be used by systems which have very high landing accuracy and do not depend on a prepositioned orbital base or propellant depot.
- Earth (or Earth orbit) to a Martian moon and then in a separate spacecraft to the surface of Mars. This creates an additional delta-V (propulsion) penalty of about one kilometer per second for a round trip ending back at the Martian moon.
- Earth (or Earth orbit) to a Mars orbital facility or an Earth return vehicle orbiting Mars and then to the surface of Mars (entry from orbit). Such concepts generally will use a separate lander and one of the landing techniques considered for direct entry.

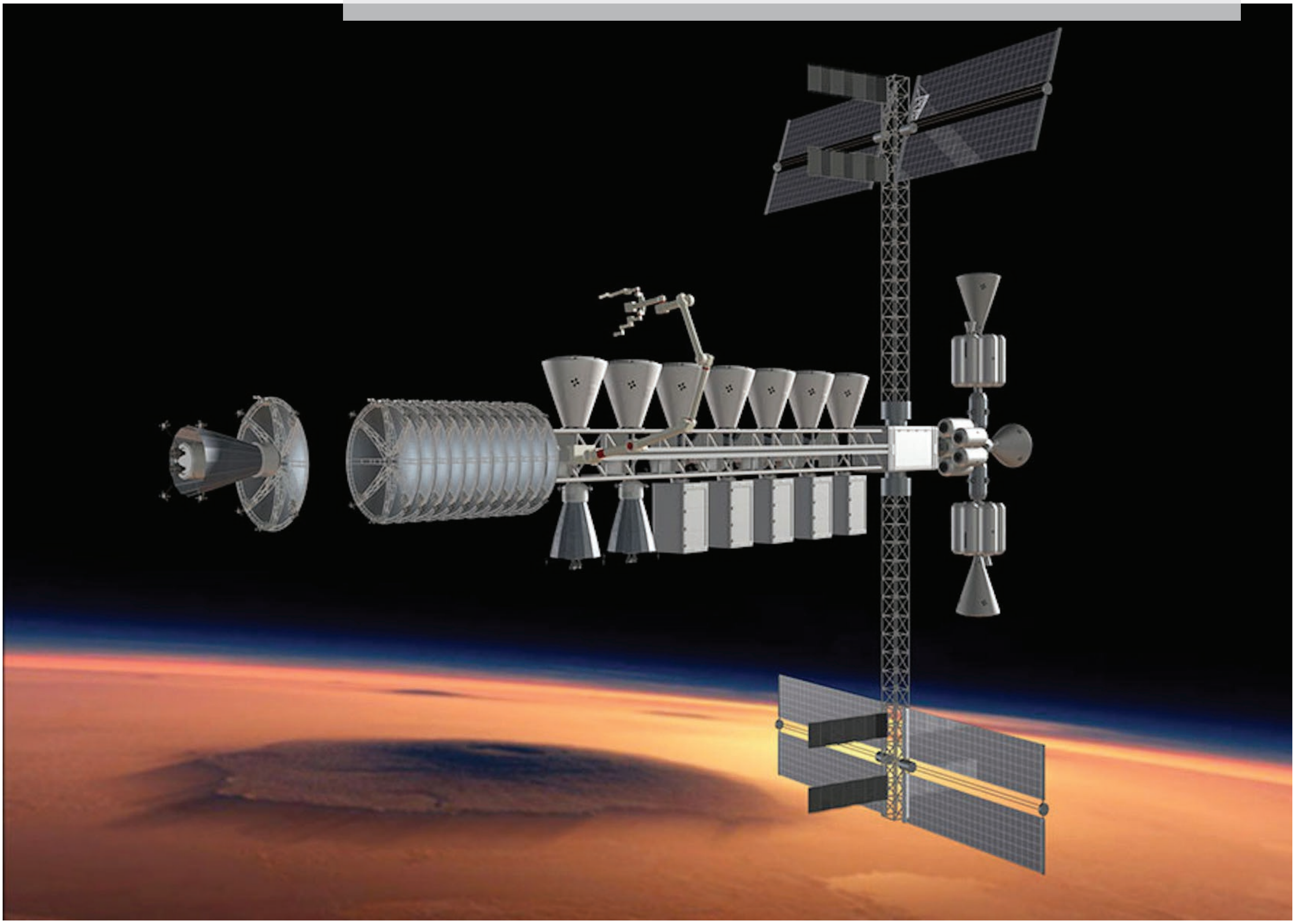
continued >>

MILESTONE 23. An Integrated Martian Space Transportation and Logistics System - *continued*

Entry, Descent and Landing Techniques. Landing methods for human-sized Mars vehicles will be different from those used for Apollo or the Mars rovers and landers due to the thin atmosphere and low gravity. By 2004, NASA scientists realized that no one knew how to land large crewed vehicles on Mars efficiently. Landing on Mars takes about one-third or less of the propulsive deceleration than is needed for a lunar landing due to the braking effects of an atmosphere, even though Mars gravity is about twice that of the Moon. Although the landing trajectory can be complicated by short-term variations in atmospheric pressure, the thin Mars atmosphere serves as an excellent air brake for a vehicle landing at high speeds (over about Mach 2.5) and can reduce over two-thirds of the total entry velocity from orbit. However, for final descent and landing at speeds below about Mach 2.5, the air is too thin to slow large vehicles sufficiently, even with very large parachutes.

A likely solution to this problem is supersonic retro-propulsion, the use of rocket engines firing toward the vehicle's direction of motion, a technique that was first demonstrated by the successful re-entry and subsequent landing of SpaceX's Falcon 9 rocket first stages in 2015. A team of NASA scientists analyzed the Falcon 9 rocket entry plume videos and concluded that this technique would work for other types of re-entry vehicles. The large parachute systems for human-sized Mars vehicles were deemed impractical and development efforts have been put on hold.

A logistics base in orbit around Mars, with habitat modules (at right) and multiple docking ports for vehicles, propellant depots, and aerocapture shields. Credit: Anna Nesterova



MILESTONE 23. An Integrated Martian Space Transportation and Logistics System *- continued*

Earth Return Systems. Various architectures have been proposed for a return to Earth, such as:

- Direct return from the Martian surface to Earth (or Earth orbit) using the original landing vehicle. This is the transportation model SpaceX has proposed, where the transit vehicle is also the lander, making it very large.
- Direct return from the Martian surface to Earth (or Earth orbit) using a separate return vehicle (called a Mars Ascent Vehicle or MAV), either attached to the original landing vehicle or pre-positioned during a previous uncrewed mission.
- The original crew transit vehicle stays in a circular low-Mars orbit, possibly docked at an orbiting base. The crew returns to Mars orbit in a reusable ferry to rendezvous with the transit vehicle, which subsequently returns to Earth, Earth orbit, or Earth-Moon L1.
- The Earth return vehicles (including habitat modules) are left in a high elliptical Mars orbit, which preserves much of the needed departure velocity, while the crew is operating surface missions from low-Mars orbit. The crew can be transferred between orbiting base habitats and the Earth return habitats in small ferry vehicles using a very small amount of fuel.
- Rendezvous from Mars orbit with an Aldrin cycler on its way past Mars for a return to Earth orbit. The main issue here is that the cycler cannot wait for a launch delay, so at least two ferries could be used simultaneously during a flight to a cycler, so that if one ferry has a propulsion failure, passengers can transfer to the other one. A cycler may eventually play a significant role in moving large numbers of civilian passengers to Mars.

Orbital Propellant Depot. Mars landing vehicles need to bring some propellant from Earth for the initial landings of fuel production equipment ("bootstrapping" propellant). Insulated tanks of fuel brought to Mars could remain in Mars orbit as cryogenic propellant depots. These depots would also be available to store propellant made on Mars from in-situ resources and brought up by reusable ferries. This stored fuel could then be used for future trips to the surface, Phobos, and Deimos, or for Earth return vehicles. The depots could be berthed at an orbiting base.

Orbital Logistics Base. A low-Mars orbit base would provide the easiest location to reach the Martian surface, and could provide a crew refuge and orbital habitation before landing, logistics capacity to load cargo, places to berth propellant depots and dock Mars ferries and cargo vehicles from Earth, and additional science capacity for base site selection, surface monitoring, and rover control. A near-equatorial orbit at 400 kilometers allows the lowest transport fuel requirements for round trips to the surface and back.

Martian Ferries. Producing fuel on Mars can facilitate continued use of reusable vehicles that return directly to Earth or reusable ferries that go to Mars orbit, rather than single-use "land and abandon" vehicles. This would greatly reduce the tonnage required to be launched from Earth for transportation purposes during construction of an expanded Mars base. Initial missions would land propellant production facilities that could be assembled on the Martian surface. Observations from orbit have shown vast deposits of subsurface water ice in many parts of Mars, and even subsurface deposits of liquid water. Situating a base near a proven ice or liquid water deposit would allow in-situ production of liquid oxygen-hydrogen and oxygen-methane propellants.

Some combinations of these propellants are energetic enough to allow a ferry on the surface to perform a direct Earth return or reach orbit, and return to the Martian surface with a large payload on the same load of propellant. Ultra-light structural engineering may also allow liquid methane and oxygen propellants to be used by Mars ferries without orbital refueling. Nearby subsurface water ice would be even more advantageous if confirmed near the equator, where it is believed to exist, because it requires less fuel to reach orbit and land near the equator. For this reason, verifying that a landing site has a water ice supply has been considered by NASA to be a critical issue prior to human landing missions.

Surface Habitation Systems. The technological and logistical requirements for orbital and surface crew habitats will depend on whether a short or long stay on Mars is planned. The longer the stay, the greater the mass of supplies required, and the fewer crew that can be supported. For a short, month-long opposition stay, the surface habitat may be the lander itself or a pre-positioned habitat. For a long, 500-day conjunction stay, a pre-positioned surface habitat is likely, possibly supplemented by a supply of oxygen or rocket fuel extracted from the Martian environment. Site location will probably be determined by the availability of large deposits of water ice nearby as a source of water, oxygen, and propellants. A conjunction mission will require a shielded or buried surface habitat. An important piece of equipment is an earthmover that can move the Martian soil to cover habitat modules with regolith to provide shielding from radiation and excavate buried ice. Even if a subsurface lava tube or cave is utilized, earthmoving equipment will likely be needed for excavating regolith and ice.

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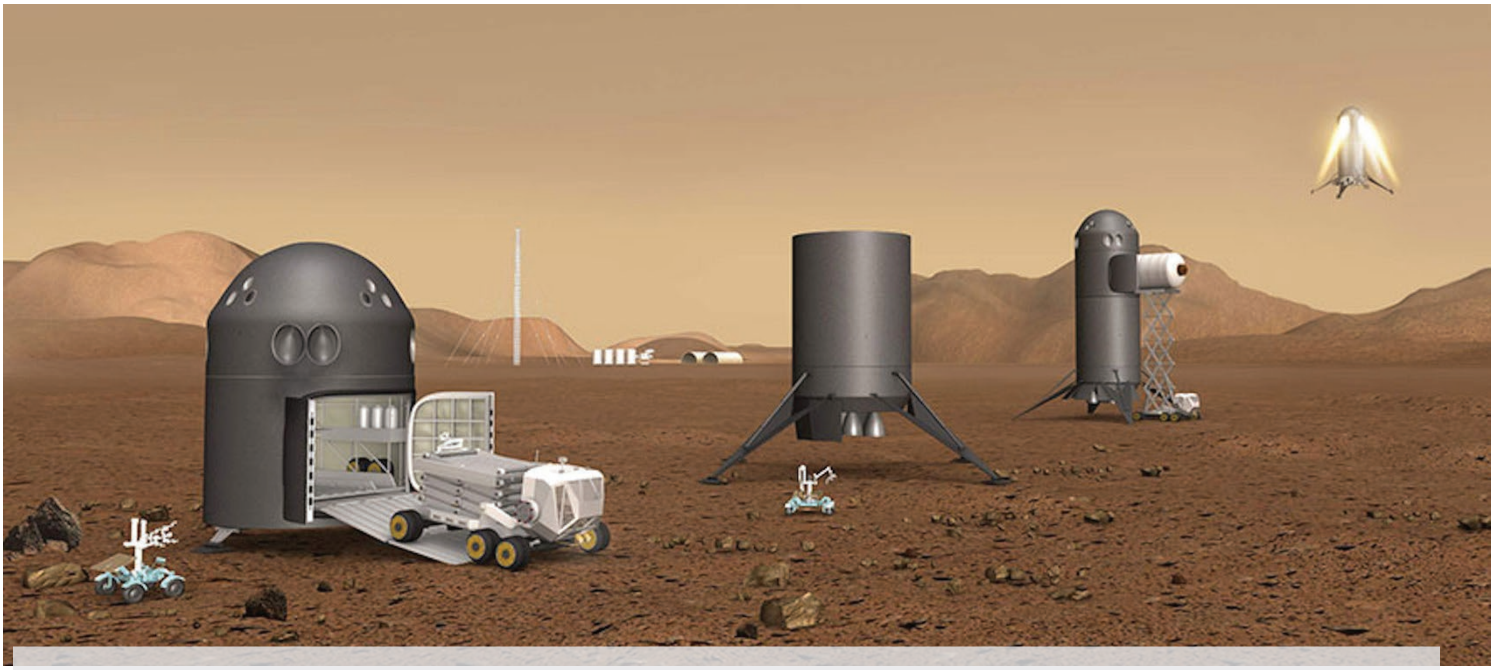


The Langley Hercules reusable Mars ferry concept. First lander carries a loader and is expendable, but subsequent landers are reusable. Credit: Anna Nesterova

MILESTONE 23. An Integrated Martian Space Transportation and Logistics System - *continued*

Orbital Crew Habitats. Orbital habitats would be an integral part of an orbital logistics base. Their extent and supply requirements depend heavily on what kind of mission is planned. For a short surface mission, the orbital habitat could serve as a crew refuge. If a long, orbit-only mission is planned so a crew can help locate a suitable surface base site, the habitat would need extensive supplies and the same level of radiation shielding as during an interplanetary transit. The habitat also might need the ability to generate artificial gravity. If Earth return vehicles are left in low Mars orbit for a short mission, those vehicles can serve as the habitats.

To the extent the entire Mars transportation system is based on reusable vehicles, rather than ones thrown away after a single use, the cost of the exploration, development, and settlement of Mars will be greatly reduced. Fewer vehicles would be needed, extra vehicles may be available for redundancy, more cargo can be delivered to the surface, and crew risks may be reduced by not having to use a new and untested vehicle each time.

BARRIERS

- Continued reliance by some parties on all-expendable spacecraft designs for Mars mission planning.
- Continued focus by some parties on "flags and footprint" type missions with no infrastructure left behind.
- Perception that Mars missions must be very high cost.
- Insistence that due to high costs, Mars missions must be minimalist with only one vehicle of each type, resulting in a lack of vehicle redundancy and greatly increasing risk to the crew.
- Lack of a cislunar transport and logistics system to L1, L2, or other locations near the Moon.
- Lack of a lunar polar mining base to provide fuel for routine Mars transits.
- Lack of governmental adoption of designs for fully re-usable Mars ferries.

COMPLETION

This milestone can be considered achieved when

1. cargo and crews can be moved from Earth or cislunar space to Mars orbit or surface, and
2. move between Mars orbit and surface (back and forth local transport),
3. be sustained on the Martian surface safely during at least an approximately 500-day stay,
4. the crews can safely leave the Martian surface, and
5. return to Earth.
6. The transportation system has been used to safely move at least three successive crews over seven years between Mars orbit and surface and return them to Earth safely, and
7. steps 2, 4, and 5 use locally produced propellant.

MILESTONE 24

A Continuously Occupied Multi-Purpose Mars Surface Base

Following the identification of a suitable base location and the selection of the particular infrastructure and equipment needed there, the establishment of a continuously occupied multi-purpose Mars surface (or sub-surface) base.

DESCRIPTION

Crews landing on Mars will continue the exploratory work begun by satellites and robotic landers. The ability of humans to efficiently use tools, travel faster and over greater distances, recognize and investigate features faster than robots, and adapt to new circumstances will greatly accelerate the accumulation of knowledge, especially that necessary to build a permanent outpost. The first crews will experiment with ISRU technology and test alternative power sources, habitats, propellant manufacturing techniques, oxygen extraction processes, gardening methods, mining equipment, ground and air transport, construction techniques, and other equipment. These crews should give special attention to the extraction and utilization of ice from nearby deposits to produce water, oxygen, and rocket fuel, to enable their vehicles to return to Earth or Mars orbit.

If the transportation architecture results in landings on a Martian moon, crews stationed there will complete similar tests on that moon. They also will probably give special attention to locating craters or other areas suitable for permanent underground quarters shielded from radiation.

Any surface base that is designed or intended to be temporary could be a dead end. Such a base would waste crucial logistics resources such as the fuel production plant needed to support the base and the ascent vehicles, or would require the use of all expendable vehicles, making such Mars expeditions too expensive to accomplish or maintain. If possible, the first surface base should be intended to be permanent unless or until surface investigations and experience demonstrate that it is not a good site for a permanent base.

At some point a decision must be made to concentrate efforts on a primary base location, either the site of a previous landing or a newly selected site. Most likely the site chosen will be near shallow deposits of ice and surface mineral deposits such as iron oxide and sulfur compounds, which can provide many of the essential elements needed for long-term habitation and reduce substantially the re-supply tonnage needed. If possible, the site should be located near a geological boundary which could provide access to multiple critical mineral deposits. That primary site may grow into the first continuously occupied human base.

As with a base on the Moon, this base will likely be occupied by a rotating group of inhabitants as well as some who remain permanently. The crew will be housed underground in standardized habitation modules that are partly buried under several meters of regolith for radiation protection. It also may be housed in a suitable cave or lava tube. The base will probably be powered by a combination of solar power and buried nuclear reactors, since there are no fossil fuels on Mars. It should have stores of food for at least three years. The base should among other things:

- Continue scientific research and exploration of Mars by crew members on the surface.
- Start or expand fuel production from Martian water ice and atmospheric carbon dioxide, and create fuel storage facilities.
- Start or expand mining activities and develop techniques for locating and making use of in-situ resources such as iron oxide, feldspar in basalt, and sulfides.
- Initiate deep drilling to attempt to find any brine layers below the permafrost layer (or cryosphere), where microorganisms (existing or extinct) and useful dissolved mineral salts are most likely to be found.
- Use Martian minerals to create structural materials to build and shield habitats.
- Eventually cater to visiting scientists and tourists in increasing numbers.
- Private commercial services may be established near the base, and over time the focus of the base may shift towards commercial uses. Alternatively, the initial base could be established by a commercial entity and rent space or services to governments.

BARRIERS

- Lack of orbiting radar units precise enough to locate ice deposits at proposed base sites.
- Uncertainty on the amount and location of important minerals such as iron oxide and sulfides.
- Concerns about and lack of agreement on planetary protection protocols for human bases on Mars.
- Lack of planning for and implementation of time-saving measures so that the crew can perform work beyond the management of life support and equipment maintenance.
- Development of habitats, materials, and machines that can survive and function within the dusty Martian environment.

COMPLETION

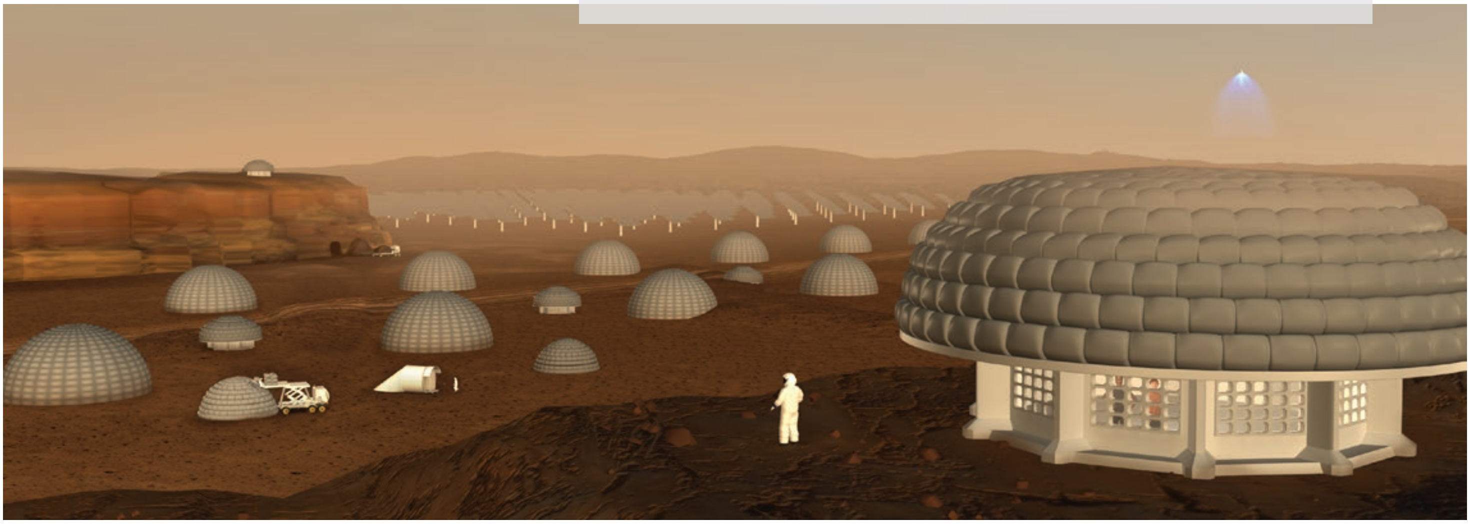
This milestone can be considered achieved when a Mars surface base has been continuously occupied for one decade.

See page 57 for illustration of a Mars base.

MILESTONE 25

A True Martian Settlement

Early Mars city partially underground with shielded buildings and cupolas.



The Martian base evolving into a permanent settlement, increasingly self-sufficient and focused on commercial activities.

DESCRIPTION

The Martian base will continue to evolve, growing in volume, area, the number of habitat modules connected or nearby, and, especially, population. At some point the decision will be made that the site should be a permanent settlement if it has sufficient resources. The distinguishing characteristics of that settlement may include:

- people emigrating to Mars with no intention of ever returning to Earth,
- children being brought to Mars, and being born there,
- reasonable self-sufficiency, including basic life support, stable food production, and the ability to construct additional habitation spaces from local materials with on-site equipment,
- recognition that in the event of an emergency it will be impossible to evacuate the entire population, willingness to bear that risk, and consequently no requirement that enough vehicles be standing by for that purpose,
- enough habitat space to house all of the inhabitants in an emergency if part of the settlement is damaged,
- reasonably adequate medical and surgical facilities, comparable to a rural hospital on Earth,
- a local economy, with the inhabitants serving each other's needs, as in small isolated villages on Earth,
- facilities for visitors, whether scientists, tourists, or others.

Whether humans and other mammals can survive and thrive for long periods of time, and reproduce and grow to adulthood successfully in the low gravity of Mars, remains to be determined, with or without advanced biomedical intervention.

As the costs of space transportation and settlement decrease, emigrants from Earth should be able to pay for at least part of the cost of their relocation. On Mars, commercial activities and experiments that were initiated in the initial base phase may be expanded, including tourism. Hotels may be among the structures added to the settlement and an increasing proportion of Martian settlers may be involved in such commercial activities.

The majority of initial Mars settlements and buildings will likely be below ground so that the civilian population is not exposed to radiation. Underground pedestrian and vehicular tunnels will probably connect most of the habitats in each community. Some buildings may be partly on the surface but, if they are intended for extended human use, will be shielded with regolith. Some separate communities may be connected by subways. Psychological pressure for a view of the outdoors may result in the creation of above-ground domes or glass-walled structures with fully shielded roofs to allow anyone, even children, to see outdoors without significant radiation exposure.

BARRIERS

- Lack of a developed and affordable commercial transportation system to get large numbers of civilians to Mars.
- The ability to build pressurized structures from local materials, such as steel from hematite, since millions of tons of habitats cannot be economically imported from Earth.
- The need to develop sufficiently large power sources on a world totally devoid of fossil fuels.
- Concerns about and lack of agreement on planetary protection protocols for human settlement on Mars.

COMPLETION

This milestone can be considered achieved when a growing settlement of at least 1,000 adults has been on Mars long enough for one generation to be born there who in turn have produced viable children.

MILESTONE 26

Robotic Characterization of Asteroids

Remote or robotic characterization of near-Earth (and other) asteroid orbits, compositions, and structures.

DESCRIPTION

Telescopic observations will initially identify asteroids as near-Earth objects (NEOs), Earth-threatening NEOs, main-belt asteroids, and other orbital groupings. Initial robotic missions to near-Earth asteroids of commercial interest can confirm the size of these bodies, the composition (e.g., rocky, metallic, or carbonaceous), and identify the actual abundance of minerals contained within. Metallic asteroids contain iron, nickel, and platinum group metals, and carbonaceous asteroids contain carbon compounds and water. Robotic probes can also estimate the structure of asteroids, differentiating between apparent “rubble piles” of loose fragments and solid, non-fractured rock and metal bodies. Some missions will bring back indicative samples of asteroid material for analysis. All of this information will assist governments in planning planetary defense against threatening NEOs, and will further enable mining companies to decide which asteroids to focus their efforts on. Earth-threatening NEOs composed of useful minerals could be put on a list of objects to be mined to extinction so there is no remaining body to pose a risk. Radio beacons may also be placed on NEOs to make tracking them easier.

BARRIERS

- Lack of information on the composition and physical structure of asteroids.
- Lack of telescopes dedicated to spectral analysis of asteroid composition.
- Lack of telescopes dedicated to finding and tracking Earth-threatening asteroids.
- Lack of inexpensive robotic probes that can rendezvous with and analyze asteroids.

COMPLETION

The investigation of asteroids will be ongoing as activity expands into the asteroid belt, which contains thousands of objects. Partial completion can be considered achieved when sufficient knowledge of asteroids exists that allows governments to plan planetary defense, or when mining of surveyed asteroids begins.

NASA’s Osiris Rex asteroid sample return mission, which launched in September, 2016. Credit: NASA

MILESTONE 27
Utilization of Asteroids

After the identification of suitable asteroids, robotic and human crews following to establish mining bases and habitats for temporary occupation, and eventually building permanent human settlements nearby.

DESCRIPTION

Asteroids contain huge mineral wealth, but this is meaningless unless these resources can be accessed. These include iron, nickel, platinum group metals, other non-volatile materials, and also volatiles like water ice. There are different classes of asteroids with varying amounts of these materials that would be useful, lowering operational costs in space and improving life on Earth. That potential value may be the primary driver for asteroid exploration and mining.

As on the Moon and Mars, deposits of volatiles can be converted to rocket fuel and oxygen, enabling further space operations. The metals in asteroids can be refined and turned into construction materials for building large structures in space. Smelting and fabrication of parts from asteroids will require either the development of new techniques for working in microgravity, or the use of rotating structures to provide gravity so that existing methods can be used. The practicality of returning asteroidal materials to Earth or other locations would depend on transport costs, the value of the materials, and the extent to which those materials can be separated and purified to reduce the total mass before transport. The return of materials to Earth is expected to involve the use of fuel obtained from asteroid mining.

In time, asteroids may be utilized to create permanent rotating habitats made of asteroid-derived materials and using unprocessed asteroid materials for radiation shielding. These habitats could house either visiting crews or, if there is sufficient mining to be done, permanent occupants. With appropriate asteroids, these mining stations may go through the same processes of growth as settlements on the Moon and Mars, and might evolve into permanent settlements where people will raise their children and live out their lives. Proposals have also been made for hollowing out an asteroid and building a rotating space settlement inside it.

The eventual construction and location of rotating space settlements in the orbits of minable asteroids would reduce the transport costs of asteroid resources and derived materials for the construction of such settlements. This would create a synergy which should accelerate the asteroid mining industry.

BARRIERS

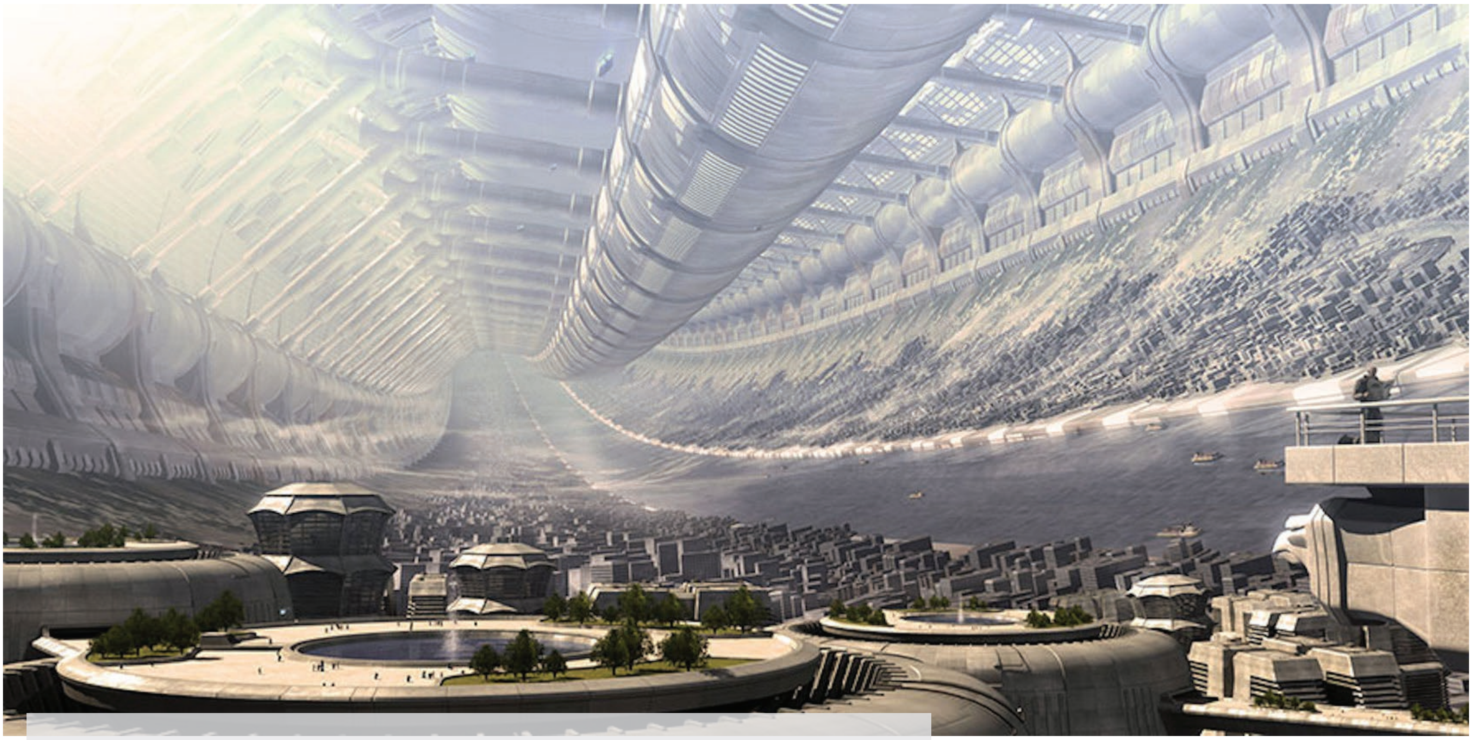
- Economic barriers (transport costs) to moving asteroidal products to space settlement construction sites, as well as Earth and its vicinity.
- Lack of knowledge of methods for mining, refining, and fabricating asteroidal products into building materials in microgravity.
- Lack of detailed planning and design for the use of fabricated materials to build large space structures.

COMPLETION

This milestone can be considered achieved when asteroid mines and smelters are regularly sending ores or refined products to Earth, the Moon, or Mars, or contributing substantial structural mass to the construction of rotating space settlements.

The eventual construction of rotating space settlements from minable asteroids. Credit: Bryan Versteeg

Development of Orbital Space Settlements



An orbital settlement built from resources found in space. Credit: Alexander Pruess

Orbital cities in space built from asteroid or lunar materials.

DESCRIPTION

Orbital space settlements are large pressurized structures that constitute cities or villages with residential, commercial, and governmental functions, and are built in space from asteroid or lunar materials. The settlements would rotate to provide artificial gravity.

Princeton physicist Gerard O'Neill proposed the construction of orbital space settlements in 1974. An orbital settlement (sometimes called an "O'Neill Settlement") is a giant rotating space structure, large enough and rotating fast enough so that people standing on the inner surface experience a centrifugal force equivalent to gravity on the surface of Earth. Thus, children on orbital space settlements would be raised in Earth-equivalent gravity, which appears to be important for normal bone and muscle development. Three proposed types of orbital settlements are: Bernal Spheres (and a variation called Kalpana), the Stanford Torus, and O'Neill Cylinders.

Shapes

Since orbital space settlements must rotate, only a few basic shapes work well: a sphere, torus, cylinder, disk, or some combination of these shapes. Current materials are strong enough for habitats many kilometers in length, which is big enough for a moderately large city. The inner surface of the hull provides the real estate on which crops could be grown and homes and businesses could be constructed. While the interior surface of the outermost hull will experience gravity similar to that of Earth, interior structures (located at levels closer to the axis of rotation) might be positioned for fractional gravity, and zero gravity is available at the axis of rotation. People and their families could live in such a settlement indefinitely, in communities ranging in size from villages to cities which have their own internal economies as well as external imports and exports.

Radiation Shielding

The Equatorial Low Earth Orbit (ELEO) settlements discussed in Milestone 16, which could act as precursors for later orbital settlements, use the Earth's geomagnetic field to shield them from space radiation. All other settlements would need to use extensive radiation shielding. Unlike lunar or Martian surface settlements, radiation shielding is required all the way around an orbital settlement, so roughly twice as much shielding mass is necessary. Shielding can consist of a substantial mass of asteroidal rubble, water, waste material, or some other mass.

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MILESTONE 28. Development of Orbital Space Settlements - *continued*

Location Options

Orbital settlements could be built in or moved to a variety of orbits, including Earth, solar, and others, as well as locations such as Lagrange points. Most of these orbits would be selected to have continuous solar energy available. The choice of orbit may be driven by access to materials, such as sites co-orbiting near an asteroid mine. For use in cislunar space, lunar material could be launched using electromagnetic launchers (mass drivers). Material mined from an asteroid could be utilized either in an orbit close to the asteroid or moved to some other desired location. There are thousands of candidate asteroids among the near-Earth objects, some requiring less energy to reach than the Moon.

Eventually such cities in space could be located throughout the solar system, orbiting planets or moons, co-orbiting with asteroids, at Lagrange points, or in solar orbit. These settlements may be very different from each other, each reflecting the particular tastes, cultures, and needs of those who build, finance, and settle them. Such diversity could provide a new flowering of human creativity. These diverse settlements would also disperse humanity throughout the solar system, enabling the survival of our species in the event that some disaster were to befall Earth.

Economic Considerations

Orbital settlements may be built by private companies, governments, or consortiums. It will be financially possible to build them only when the cost of construction and support is less than the expected value of the settlement, financial or otherwise.

The Potential Scale of Orbital Settlement

Orbital settlements could be built in virtually unlimited numbers. NASA Publication SP-413 (*Space Settlements: A Design Study*) states: "If the asteroids are ultimately used as the material resource for the building of new colonies, and… assuming 13 [kilometers] of total area per person, it appears that space habitats might be constructed that would provide new lands with a total area some 3,000 times that of the Earth."

COMPONENTS (required capacities)

Habitats in space beyond low-Earth orbit designed as space settlements must be able to:

- Provide redundant life support systems for residents that will last for many decades.
- Store sufficient reserves of food and water for residents, and optimally, recycle water and grow food.
- Provide a high level of protection and redundancy against loss of air pressure.
- Protect against constant cosmic radiation, intermittent radiation from solar mass ejections, and general solar radiation to a level that is safe for children and pregnant women.
- Provide sufficient artificial (centrifugal) gravity to maintain healthy living conditions.
- Provide for permanent residency by making the habitats suitable for comfortable living.
- Provide employment and recreation opportunities for residents.

BARRIERS

- Lack of asteroidal or lunar-derived materials for the construction of orbital settlements.
- Lack of detailed planning, design, and methods for the creation of orbital space settlements, including the use of materials to build large, pressurized, rotating structures in space.
- Lack of immediate economic incentives to work toward orbital settlement construction.
- Inadequate understanding of human physical adaptation and the psychology of individuals and large groups of people living in space.
- Lack of information on the cost to construct orbital space settlements.
- "Planetary chauvinism," the idea that people should only live on planetary surfaces.

COMPLETION

This milestone can be considered achieved when a rotating space settlement built primarily from non-terrestrial materials has a population of at least 1,000, including families and children. Another milestone will be achieved when the total population in orbital space settlements exceeds the population of Earth.

MILESTONE 29

Terraforming and Para-Terraforming

Modification of other planets or moons to support human, animal, and plant life in a manner similar to Earth.

DESCRIPTION

Terraforming (literally "Earth-shaping") of a planet, moon, or other body is the hypothetical process of deliberately modifying its atmosphere, volatile components, temperature, surface topography, or ecology to be similar to the environment of Earth, making it habitable for human life.

Three levels or types of terraforming are:

- Para-terraforming: very large-scale pressurized habitats and agricultural zones on the surface without requiring substantial atmospheric modifications. This assumes that the cosmic radiation present on a surface without a dense atmosphere can be dealt with in some way.
- Partial terraforming: adequately blocking cosmic radiation, allowing some plants to grow on the surface and humans to walk there without pressure suits and radiation protection but with air-breathing equipment, and at an ambient pressure of about one-third Earth sea level.
- Full terraforming: extensive modification of a world's surface to provide an Earth-like atmosphere and "aquasphere" (open bodies of water), allowing the survival of humans, animals, and plants without special protective equipment.

Terraforming of a cold, dry planet similar to Mars would include four main phases:

- Warming the planet so that water is not frozen.
- Importing or liberating (by warming the planet) enough atmospheric mass to stop galactic radiation from reaching the surface.
- Importing and/or liberating (by melting crustal permafrost and polar water ice) enough water to provide large areas of water surface which in turn allows significant humidity and rainfall. Frozen water reserves on Mars are estimated to be at least 5 million cubic kilometers, sufficient to cover the entire planet in about 35 meters of water if melted. Much more deep water is likely to be detected, allowing the creation of sufficient oxygen in the atmosphere from in-situ resources.

An additional long-term step may be the creation of an artificial magnetosphere around the planet, to prevent solar winds from stripping away the new atmosphere.

Mars is the most obvious example of a terraformable planet in our solar system, but different types of planets would require different kinds of terraforming operations. A planet with an atmosphere that is too dense to breathe could, with great effort and significant time, have the excess atmosphere removed, if the atmospheric mass is not too large. If the planet is not too hot and has water, oxygen-producing algae could be introduced early on to start oxygen production.

COMPONENTS (types of terraforming modifications)

- Preventing cosmic radiation from reaching the surface.
- Adjusting the average planetary temperature.
- Adding atmospheric mass to allow water on the surface.
- Adjusting the amount of water surface area and depth.
- Adjusting the amount of oxygen and nitrogen.
- Removing toxic substances from the atmosphere.
- Creating a biosphere on the planet's surface.
- Creating areas of arable land.

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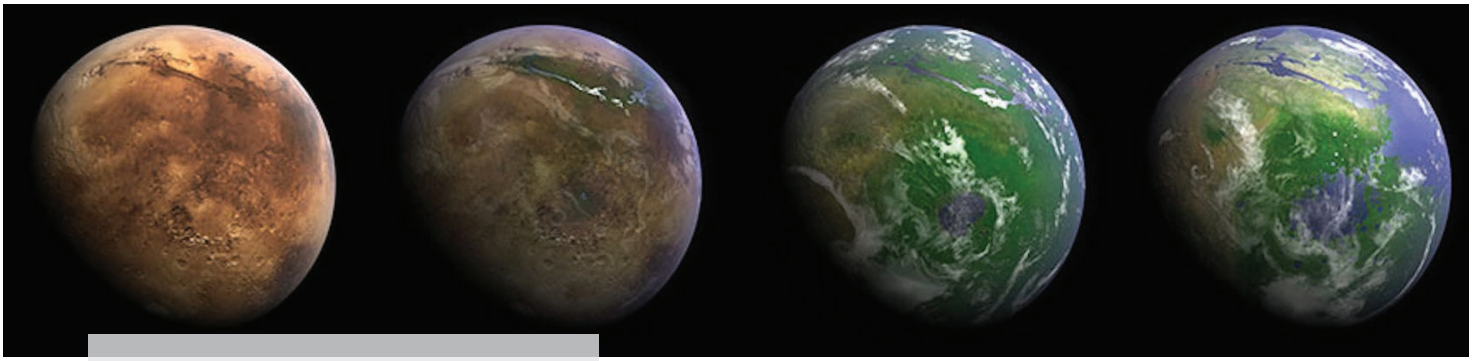


Steps to terraforming Mars. Credit: Kevin Gill

MILESTONE 29. Terraforming and Para-Terraforming - *continued*

BARRIERS (general)

- Opposition to terraforming by those who claim that "rocks have rights" which are more important than bringing life to another world.
- Opposition by people who think that large-scale human projects are morally wrong or reduce the intrinsic beauty of a planet.
- If it is decided that only totally sterile planets may be terraformed, then we will need a valid and publicly acceptable means of effectively demonstrating that a planet meets the established criteria of sterility before terraforming efforts begin.
- The need to establish a set of criteria to allow for the terraforming of planets which are known to harbor life of some kind.

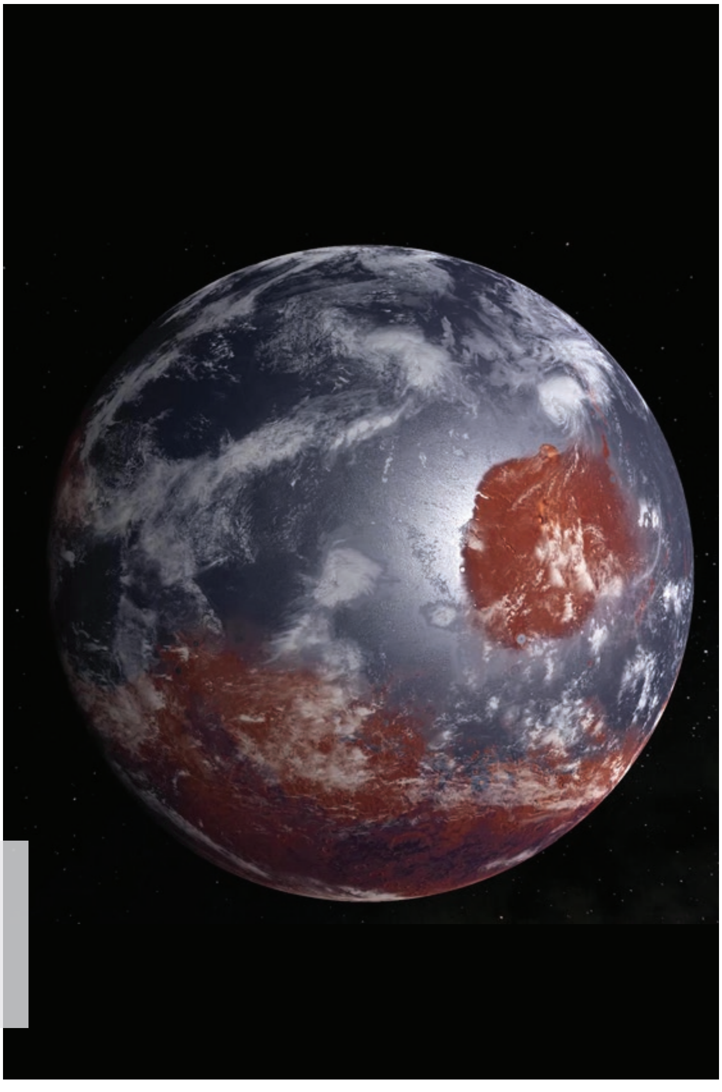
BARRIERS (items lacking)

- Engineering and construction methods to cover large areas of land with pressurized enclosures for para-terraforming efforts.
- A means of creating perfluorocarbon (super-greenhouse) gases on some planets from carbon and fluorine, including finding large sources of fluorine in Mars minerals.
- A means of creating (and keeping in position) giant, low-mass parasols or mirrors used for thermal control at some planets.
- A means of moving large masses of volatiles such as frozen nitrogen, carbon dioxide, or water ice to planets where they are needed with very large space tugs or other forms of propulsion.
- A fusion or other advanced propulsion system to power space tugs to allow the movement of large masses of volatiles.
- Replicator systems to build a fleet of very large fusion-powered space tugs for mining volatiles.
- Secure software to safely operate this fleet and prevent malevolent parties from taking control of it to cause mass destruction.
- Software to simulate the climatological effects of the proposed terraforming efforts.

COMPLETION

The partial terraforming milestone (which covers several different situations) can be considered achieved when the climate and atmosphere of at least a substantial portion of a planet has been changed enough to achieve one or more of the following: preventing harmful levels of radiation from reaching the surface, water flowing on a substantial portion of the surface of a previously frozen planet, rain falling on the surface of a previously dry planet, and plant life germinating and growing on the surface or in the waters of a previously sterile planet.

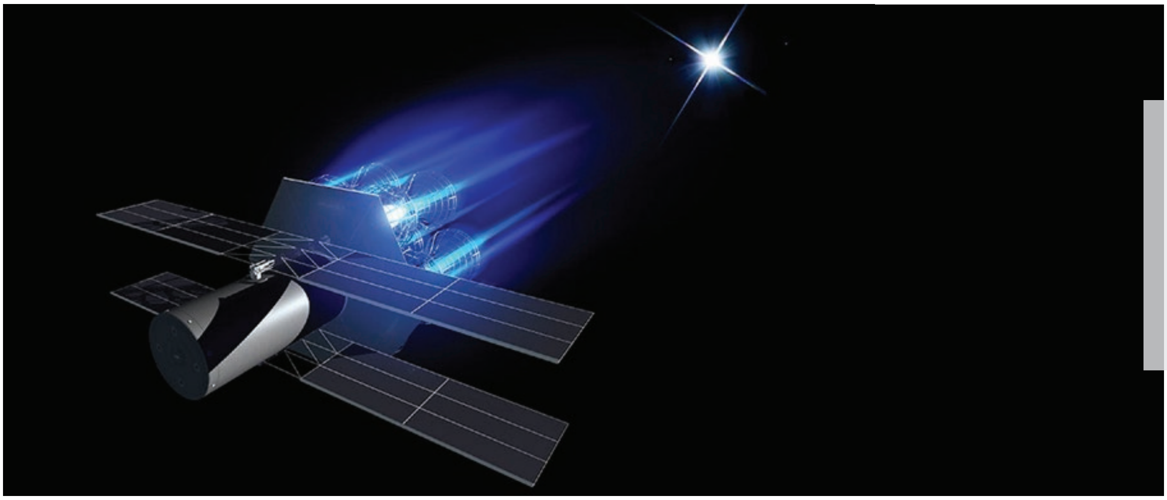
The full terraforming milestone will be achieved when humans, plants, and animals can directly breathe the air and work on the surface of a previously oxygen-free planet without pressure suits, oxygen supplies, or radiation protection.



A terraformed Mars showing the Elysium volcanic area as a large island in the Boral Ocean which will cover much of northern Mars. Credit: NASA

MILESTONE 30

Development of Interstellar Travel and Settlement



An interstellar generation ship performing a deceleration while approaching another star system. The body of the vessel is a cylinder three kilometers in diameter. Credit: Anna Nesterova

Human travel to other solar systems and the establishment of settlements in other star systems or on extrasolar planets in these star systems.

DESCRIPTION

Interstellar travel spans distances that are hard for humans to visualize. The stars are very far away, with the nearest being more than four light years distant (or about 38 trillion kilometers), distances that are unreachable by any propulsion system currently in existence. However, the expansion of humanity into the universe to live among the stars remains a central dream for many. Interstellar travel would allow human civilization and Earth's biosphere to spread beyond our solar system, ensuring the long-term survival of our species.

It is now known that planets are commonplace and some Earth-like planets are expected to be found somewhere among the nearer stars. Planets, however, are not needed for human habitation of another star system because asteroids are likely to be available that can support populations in orbital settlements in numbers much larger than what planetary surfaces could support. Thus, detection of habitable or terraformable planets in a star system in advance of a voyage is not required, but may be desirable, whereas the presence of either terrestrial-type planets or asteroids as a material source is required. It is possible that on arrival in a target planetary system, orbital space settlements and industrial infrastructure would be constructed using local resources before any settlement is attempted on a planet.

In the absence of an Earth-like planet, the vessels will need to carry with them the equipment to build pressurized surface settlements or mine asteroids and build rotating space settlements. As the population and industrial base is built up, settlers may eventually terraform any suitable planets. In addition to crew and passengers, interstellar vessels may carry frozen embryos or other forms of genetic data which can be reconverted to living organisms for genetic diversity.

Successful interstellar voyages by humans would mark a new phase in our species' history, where humans would be living in more than one star system.

COMPONENTS (types of interstellar missions)

- Generation ship: A very large rotating space settlement with its own propulsion and energy source which can maintain an artificial biosphere for hundreds of years. Passengers and crew would remain awake during the entire trip and the people arriving at the destination would be the descendants of the original voyagers.
- Single generation ship: A ship where the occupants have extended life spans such that most are expected to live long enough to reach the destination.
- Hibernation ship: Spacecraft in which occupants would be placed in long-term hibernation or cryogenic suspension during the trip, while some may remain awake to protect the ship and occupants and ensure the operation of critical systems.
- Seed ship: A ship controlled by artificial intelligence systems, containing frozen embryos or DNA data which is then used at the destination to artificially gestate and rear humans. Automated systems would need to produce habitats for humans to live in from asteroidal or planetary resources.
- Interstellar probe: A scientific craft containing no crew or genetic material, but that can serve as a technological step toward crewed missions. If a laser and light sail system is used, this vehicle could have a relatively small mass. Ideas also exist for much smaller probes that could be sent in swarms to multiple star systems. If they are practical, these "star wisps" (so named by Dr. Robert Forward) would become invaluable interstellar scouting agents for humanity.

continued >>

MILESTONE 30
Development of Interstellar Travel and Settlement - *continued*

MILESTONE 30. Development of Interstellar Travel and Settlement - *continued*

COMPONENTS (types of human settlement operations)

Once a settlement ship has reached another star system, a variety of operations could begin in order to expand the human population and provide multiple places for them to live. There are at least six major types of such human operations in a given star system:

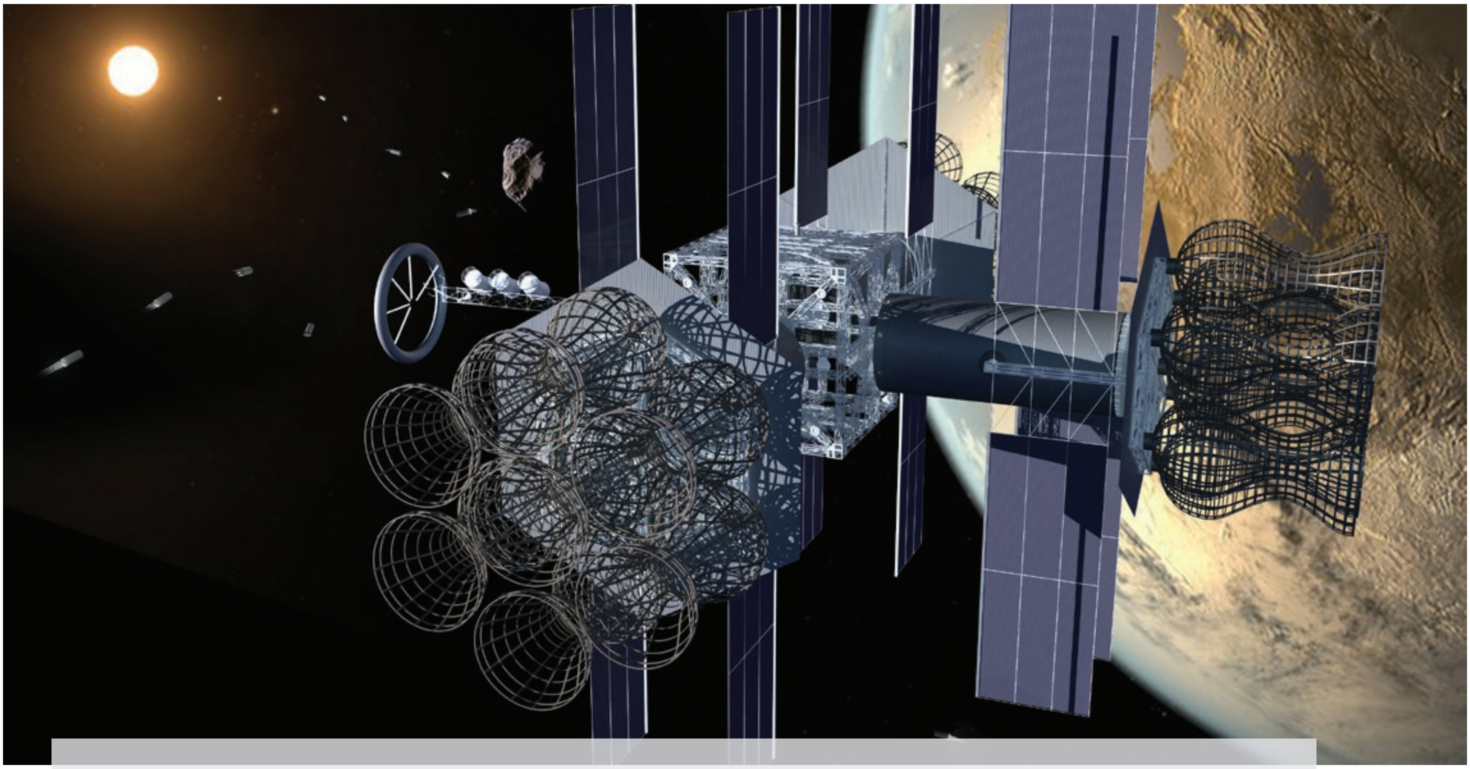
- Mining, transfer, and use of space resources.
- Building rotating space settlements.
- Establishment and growth of pressurized surface settlements.
- Para-terraforming, the creation of very large pressurized environments on planetary surfaces.
- Terraforming planets to allow human settlements and plant and animal life to survive outside of pressurized environments.
- Construction of interstellar settlement vessels.

BARRIERS

- Lack of propulsion methods needed to reach speeds of at least one percent of the speed of light, or about 3,000 kilometers per second.
- Lack of energy sources such as fusion that can support a ship for a century or more.
- Lack of a means of protecting the ship from collision with interstellar debris and passengers from particulate radiation caused by the ship's high velocity.
- Lack of methods to sustain a generation ship's closed ecology, and the motivation, and technological expertise to ensure its viability across many decades.
- Lack of ability to build in-space settlements from local asteroidal resources.
- Lack of consensus that sterility of a planet is necessary and a means of effectively proving that a planet is sterile before it can be used for settlement.
- Lack of a means of terraforming chosen planets.
- Lack of multi-decade hibernation or cryogenic suspension methods that are reliable and safe.
- Lack of sufficient resources and political will to undertake the necessary research and construction.
- Belief that interstellar voyages are impossible.
- Political opposition to the expansion of human civilization across the galaxy.

COMPLETION

This milestone can be considered achieved when a human settlement is established and growing in at least one solar system besides our own.



Interstellar generation ships arrive in another solar system and start constructing torus space settlements out of local asteroid material. Credit: Anna Nesterova

MILESTONE 31

Survival of Humanity via Space Settlement

The general expansion of space settlement increases the likelihood that humanity will survive in the long term, particularly through the development of specific, isolated settlements designed to survive.

DESCRIPTION

One of the major goals of space settlement is to ensure the survival of humanity; if our species does not survive, then the value of millennia of human effort is lost.

Space settlements may ensure the survival of humanity from two categories of existential risks: those caused naturally, and those caused by advanced human technology. Commonly recognized natural risks include asteroid impacts, supervolcanoes, and gamma ray bursts. Technological causes include biotechnology, self-replicating chemicals, nanotechnology, and artificial intelligence. Human activity resulting in catastrophic climate change or global warfare are also potential concerns. According to the Future of Humanity Institute, human extinction is more likely to result from technological rather than natural causes.

There are two categories of space settlement which could result in humanity surviving existential risks:

- The general, longer-term growth and redundancy of space settlement becomes so large that settlements (or a network of settlements) could survive despite being cut off from Earth even without taking specific efforts to prepare for existential risks. This is the sort of self-sufficiency that could ensure against risks in the long-term but not the near-term.
- Alternatively, in the nearer-term, settlements specifically designed for survival could focus their development on providing for the requirements of the settlement using local resources (without engaging in trade) and seeking isolation from risks of extinction. They would need to produce all of the equipment that is necessary for these goals from local resources.

COMPONENTS (those necessary for the survival of settlements)

- Identification of the needs for survival and production of equipment to provide for those needs.
- Development and demonstration of these systems in analogue bases and short-term space settlements.
- Stress-testing of these settlements by isolation (not supplying them from Earth) in order to prove that they could survive indefinitely if necessary.
- Supplying a means of relocation for some of the population of the settlement to another survivable location.

BARRIERS

- Lack of understanding of the minimum number of humans needed to maintain a civilization.
- Lack of identifiable economic incentives to create settlements that can survive over the long term.
- Long time frame to achieve sufficient redundancy in space settlements.

COMPLETION

This milestone can be considered achieved when careful analysis concludes that at least some settlements would likely survive recognized existential risks from Earth or elsewhere.

Credit: Richard Bizely, bizleyart.com

CONCLUDING REMARKS

Mark M. Hopkins, *Chair of the NSS Executive Committee*

Bruce Pittman, *NSS Senior Operating Officer*

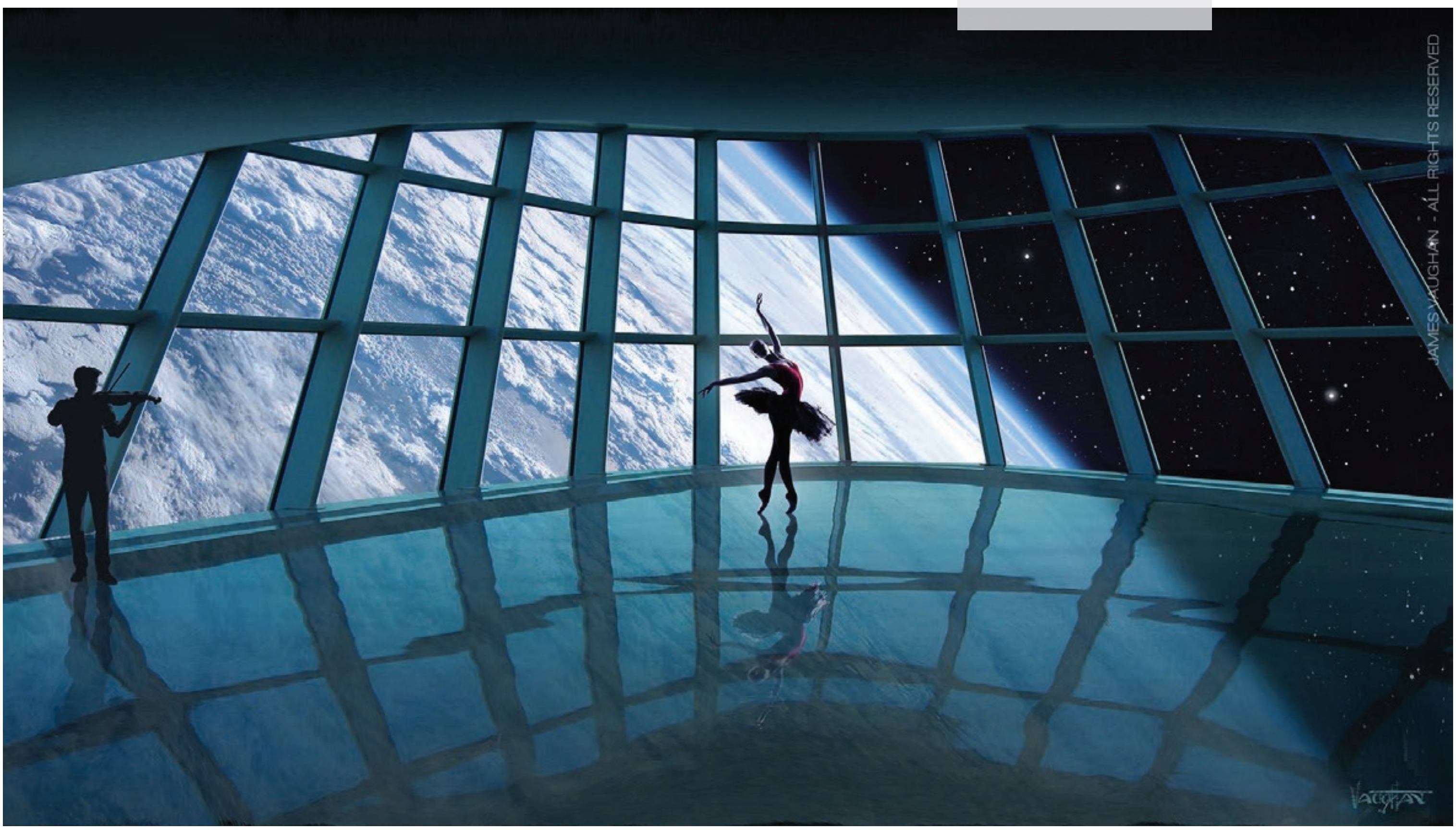
Dale Skran, *NSS Executive Vice President and Chair of the Policy Committee*

The National Space Society **Roadmap to Space Settlement** attempts to provide a guide to the future of human expansion into space based on our current understanding of the technologies and motivations required for humanity to not only survive but thrive, both on Earth and throughout the solar system. Since predicting the future is a perilous undertaking, it is likely that significant aspects of this expansion, when it happens, will differ from what is offered here. However, this Roadmap provides a strong starting point for a larger, meaningful discussion of how our expansion beyond the confines of our planet may be accomplished.

While this discussion has taken us all the way from low Earth orbit to settlements in other star systems, the growth of our species and its endeavors is potentially limitless. But it must begin somewhere, and it must begin soon. We stand on the threshold of a new space age, one with a thriving space economy and routine and affordable access to space, and where living off the Earth will not only be possible but for many desirable. What is needed is the motivation to proceed, and the investment in the research and development necessary to take the first meaningful steps away from Earth. These first steps are achievable in the 21st century with enough drive and commitment by global governments and private enterprise, and will likely be accomplished through the intelligent blending of the two.

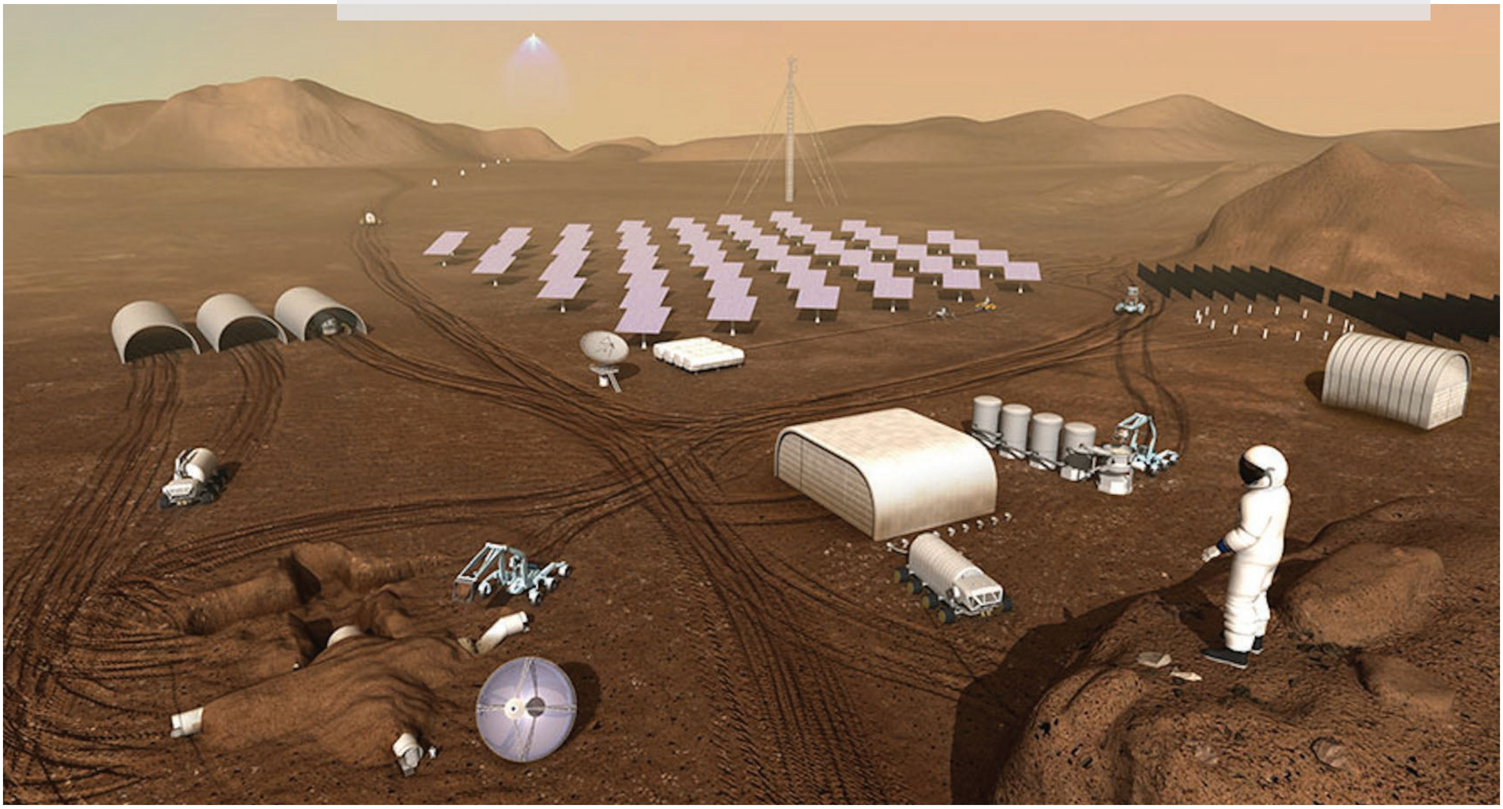
The time to begin is now, and the National Space Society stands ready to lend its expertise and energies to those who are ready to begin this amazing journey outward.

Credit: James Vaughan



Asteroid mining (Milestone 27). Credit: Bryan Versteeg, spacehabs.com

A Mars base (Milestone 24) with buried crew habitats, solar and nuclear power production, ice mining, propellant production and storage, and distant launch and landing site. Credit: Anna Nesterova

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