

MILESTONES TO SPACE SETTLEMENT

AN NSS ROADMAP





"Moon, Mars, and Beyond" (Bill Wright, NSS)

Milestones to Space Settlement: An NSS Roadmap

Part I: INTRODUCTION

The National Space Society ("NSS") is a nonprofit educational organization whose Vision 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 embraces *both* space as a future second home for humanity *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 all of us on the Earth. These two elements of the Vision are intertwined: development of space products and services for the people of Earth will both require human presence in space and will enable and motivate expansion of our species away from the home planet.

This Roadmap has been prepared to lay out for the public the major Milestones that will likely have to be passed and the major Barriers that will have to be surmounted in order for humankind to achieve that Vision.

While the Roadmap to some extent highlights what can, should and will 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 of the world. Eventually the entire world will participate in achieving the Vision and reaping its fruits.

NSS has identified 20 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 at any time breakthroughs may enable us to shatter Barriers and leapfrog Milestones.

Of the Milestones currently identified, the first six must be passed en route to the settlement of all destinations — the Moon, Mars, asteroids, orbital space settlements, and, eventually, the stars. Specific Milestones then follow for each of these destinations. These Milestones are presented here, with commentary on their current status, along with changes and developments necessary to reach them.

These Milestones will be reached by a combination of governmental and nongovernmental efforts. Having their people in space and utilizing the resources of space will be goals pursued by many governments on behalf of their people. A major function of government is to do what is societally important that cannot be done by individual citizens or cannot be done by them economically or, in some governments' view, what should not be done by them individually. Accordingly, steps toward these Milestones will be made to the extent (i) that various governments actually commit to achieving them and (ii) that governments permit and encourage nongovernmental space activities.

OUTLINE OF THE ROADMAP

Part II: MILESTONES TO ALL DESTINATIONS

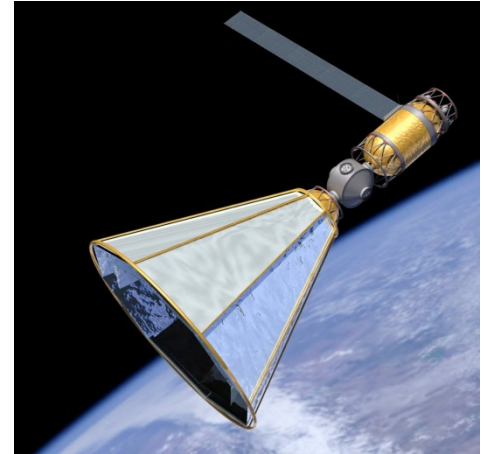
GENERAL BARRIERS TO SPACE SETTLEMENT:

- *Psychological*
- *Social*
- *Economic*

MILESTONE 1: Continuous Occupancy in Low Earth Orbit. Construction of continuously occupied structures in Low Earth Orbit (LEO).

MILESTONE 2: Higher Commercial Launch Rates and Lower Cost to Orbit. The emergence of a sufficiently large launch market, with more efficient and reliable vehicles with faster turnaround times, or technical and operational improvements such as re-usable vehicles, or both, significantly lowering the cost of access to space. Both higher launch rates and lower vehicle and operational costs will be required.

- *Flight Test Demonstrations*
- *Government Contracting*
- *Progress in Launch Technology*
- *Space Tourism*
- *Commercial Facilities in Orbit*
- *Space Solar Power*
- *Other Commercial Space Applications*
- *Governmental Policies*



Cryogenic orbital propellant depot with sunshade (NASA)

MILESTONE 3: An Integrated Cislunar Space Transportation System. In addition to Earth-to-orbit launch systems, the creation of transportation systems and infrastructure in “cislunar space,” i.e., the space between the Earth and the Moon, resulting in regular commerce in cislunar space.

MILESTONE 4: Legal Protection of Property Rights. Legal protection of property rights enacted to provide prospective off-Earth investors and settlers with the security to take financial risks.

MILESTONE 5: Land Grants or Other Economic Incentives. Economic incentives, such as “land grants,” to encourage private investment in off-Earth settlements.

MILESTONE 6: Technology for Adequate Self-Sufficiency. People leaving Earth with the technology and tools needed to settle, survive and prosper without needing constant resupply from Earth.

- *Enabling Technologies*
- *Precursor Missions*

Part III: UTILIZATION OF SPACE TECHNOLOGY AND RESOURCES

MILESTONE 7: Applications of Space Technology on and for Earth. The technologies and techniques developed on the road to space settlement applied widely and benefiting all on Earth.

- *In General - Direct Benefits*
- *In General – Indirect Benefits*
- *Later: Extra-Terrestrial Raw Materials*
- *Later: Sunlight from Orbit*

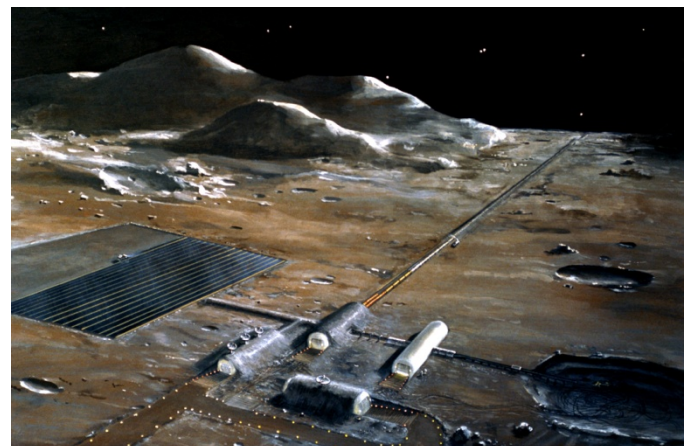
MILESTONE 8: Space Solar Power System (SSP). Establishment of an operational space-based solar power system transmitting the Sun’s energy to Earth.

MILESTONE 9: A Workable Asteroid Protection System. A system capable of detecting and defending against Earth-approaching asteroids or comets built and standing by to launch on short notice.

Part IV: TO THE MOON

PARTICULAR BARRIERS:

- *Political and Psychological*
- *Goal Definition*
- *Biological*
- *Uniquely Lunar*



Lunar Base with shielded habitats and mass driver (NASA)

MILESTONE 10: Robotic Confirmation of Lunar Resources. Satellites orbiting the Moon and possibly robotic landers determining the nature and extent of lunar ice and volatile deposits and providing the information necessary to guide the choice of the best sites for a lunar outpost.

- *Water and Lunar Volatiles*
- *Sites for Lunar Outposts*

MILESTONE 11: A Lunar Research Facility. A lunar research facility established to study human habitation, test various equipment and techniques, and conduct lunar investigations.

MILESTONE 12: A Government / Industry Lunar Base. The initial research facility evolving into a permanently occupied, ever-expanding lunar base, or such a base created at another site using what has been learned from the initial facility, and increasingly performing commercial functions.

- *Noncommercial Functions*
- *Commercial Functions*

MILESTONE 13: A True Lunar Settlement. The lunar base evolving into a permanent settlement, increasingly self-sufficient and increasingly focused on commercial activities.

Part V: TO MARS

PARTICULAR BARRIERS:

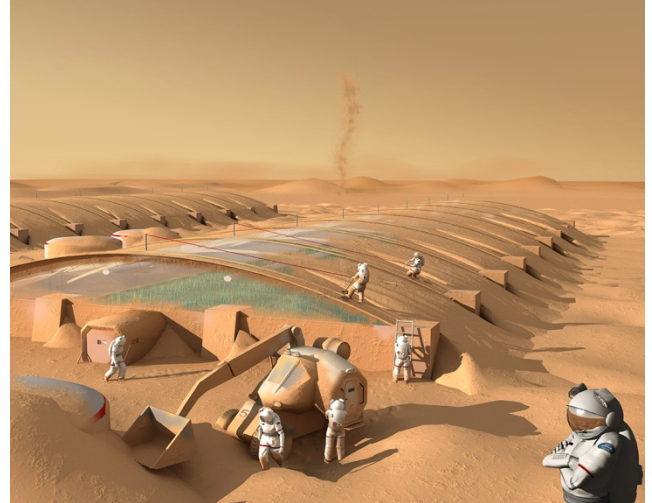
- *Psychological and Political*
- *Biological*
- *Goal Definition*
- *Uniquely Martian*

MILESTONE 14: Robotic Exploration of Mars for Local (In Situ) Resources. Satellites orbiting Mars and robotic landers determining the nature and extent of Martian resources, especially ice, guiding the choice of the best sites for follow-on human missions.

- *Scientific Knowledge*
- *Data for Human Exploration and Outposts*

MILESTONE 15: Creation of a Logistics System for Transporting Humans and Cargo to the Martian Surface. An integrated sustainable system designed and built for transporting humans and cargo from space to the Martian surface, maintaining the crew on the surface, and returning crew and payload safely back to Earth.

- *Earth to Mars Transit Transportation Systems*
- *Earth Orbit to Mars Orbit on a "Cycler"*
- *Mars Landing Systems*
- *Earth Return Systems*



Mars settlement (Raymond Cassel, NSS)

- *Martian "Ferries"*
- *Orbital Propellant Depot*
- *Habitation Systems*

MILESTONE 16: A Continuously Occupied Multi-Purpose Base. Following initial crewed missions to identify a suitable location and the particular infrastructure and equipment needed there, establishment of a continuously occupied multi-purpose Mars base.

MILESTONE 17: A True Martian Settlement. The Martian base evolving into a permanent settlement, increasingly self-sufficient and increasingly focused on commercial activities.

Part VI: TO THE ASTEROIDS

MILESTONE 18: Exploration, Utilization and Settlement of Asteroids. After robotic identification of suitable asteroids, robotic and human crews following to establish mining bases and habitats for transients, and, eventually, carving out and building permanent human settlements.

Part VII: TO ORBITAL SPACE SETTLEMENTS

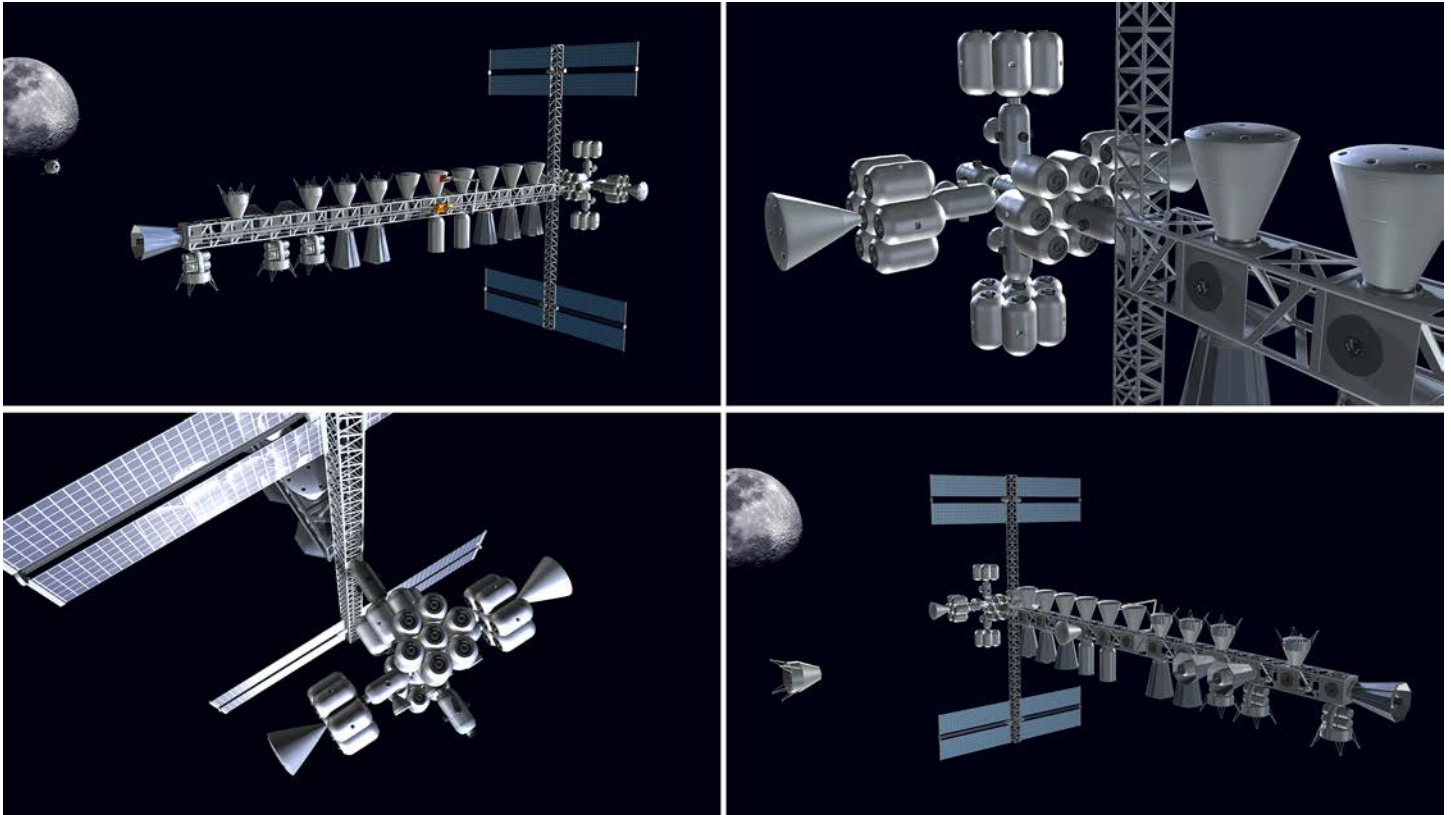
MILESTONE 19: Construction of Orbital Space Settlements. Orbital "cities in space" built from asteroid or lunar materials.

Part VIII: TO THE STARS

MILESTONE 20: Development of Interstellar Travel. Eventually, methods developed to enable humans to travel to other stars.



Settlement construction from asteroid material (Bryan Versteeg, spacehabs.com)



“Fill ‘er up!” Four views of a cislunar way station at L1 with shielded crew modules and multiple standardized docking ports for propellant depots and re-usable lunar and Mars ferries (anna.j.nesterova@gmail.com)

Part II: MILESTONES TO ALL DESTINATIONS

GENERAL BARRIERS TO SPACE SETTLEMENT:

At every stage, certain Barriers will be encountered.

Psychological. For many, the pace of space development is frustratingly slow, especially when compared to the fast pace of computer revolutions. Government agencies and even the media tend to report and explain space activities in a boring manner, if not ignoring them altogether. Space development would be furthered by greater education of the public and by stimulating and sustaining public interest over long periods of time. In retrospect, it is amazing the extent to which space is now integrated into every aspect of our civilization without people even being much aware of it.

Social. For alleged “safety” reasons, governments are tempted to limit the ability of private individuals to organize and undertake space ventures or to voluntarily accept the risks of travel into space. If there had been such societal restraints two hundred years ago, the frontier of the American West would not have been settled then. Space development requires the freedom to voluntarily take risks and, consequently, societal aversion to risk-taking is a barrier to be resisted and countered.

Economic. Space development requires long lead times, which means long-term funding. Economics, or at least perceived economics, will always be a Barrier, both to governmental and private efforts.

(1) Governments, unfortunately, have inherent pressure to think in the short-term and perhaps just to the next election. Even if they authorize long-term programs, they are unlikely to simultaneously provide long-term funding, even if long-term funding would also result in significant savings over the life of the program.

(2) In the private sector, investors also tend to look to immediate rather than long-term profits. To encourage private investment in space activities, governments need to provide an encouraging environment, for example, by reducing or eliminating unneeded regulations, by legislating limits to liability in the case of space-related accidents, by allowing space travelers to take voluntary risks, or by providing rewards for or tax relief from space ventures.

MILESTONE 1: Continuous Occupancy in Low Earth Orbit.

Construction of continuously occupied structures in Low Earth Orbit (LEO).

The attainment of this Milestone is ongoing now. No permanent space settlement can be constructed without first accumulating (i) the technical knowledge, industrial tools, unique materials and techniques necessary to create such a novel habitat, as well as (ii) biological data about the ability of terrestrial life to survive and thrive for long periods of time outside Earth's atmosphere and gravity.

That knowledge and expertise has been and will be acquired by the launching or construction of large structures in Low Earth Orbit (LEO). LEO is the closest place in which research can occur and techniques can be practiced, and from which escape in an emergency is most feasible.

From the U.S. Skylab, to the Soviet Mir, to the International Space Station (ISS), such crewed structures have been placed in orbit, and space stations of other countries have been long anticipated. These space stations are essentially tools, rather than ends in themselves — laboratories in which we learn how to construct in space, live and work in space, gather biological data, avoid or survive space debris, and explore scientific principles and

technologies that can be developed only in space. Over time, newer equipment will be added and critical new experiments will be conducted onboard, e.g., with a variable gravity centrifuge to determine the effects of living in lunar or Martian gravity, with space solar power transmitters and receivers, with Closed or Controlled Ecological Life Support Systems, or with new power systems.

The queue for workspace and experimental time aboard the ISS is a long one. The time any space station can remain in LEO is limited by atmospheric drag and by wear and tear, but every month in which a space station is in orbit provides a wealth of new data and experience.

The International Space Station will be followed in orbit by other human-occupied facilities, such as hotels, laboratories, factories and depots. These would support space tourism and recreation, scientific research, low-gravity manufacturing, space solar power infrastructure, and refueling and repair operations, and the like. The lessons learned will be applied to later space settlements.

MILESTONE 2: Higher Commercial Launch Rates and Lower Cost to Orbit

The emergence of a sufficiently large launch market, with more efficient and reliable vehicles with faster turnaround times, or technical and operational improvements such as re-usable vehicles, or both, significantly lowering the cost of access to space. Both higher launch rates and lower vehicle and operational costs will be required.

This Milestone will be reached in several ways:

Flight Test Demonstrations. NASA and other government-funded space agencies continue their roles in developing space transportation technology specific to achieving operational cost reduction through flight test demonstrations of technology. Examples are such U.S. test vehicles as the X-34 and X-37. These activities create “on the shelf” technology for industrial or commercial uses. This government role has proven beneficial in the aviation industry and more recently in the private space industry.

Government Contracting Practices. Government contracting practices evolve to emulate more commercially reasonable practices, which will likely dramatically lower the cost of government-funded efforts. Such practices include continuing to move from direct responsibility for

managing the development of launchers and other hardware to just purchasing hardware and launch services for crew and cargo from commercial sources. With the government as a stable customer, a market is expected to be created which will encourage competition among many enterprises, existing and new, which will inevitably further reduce the unit cost of each space flight.

Progress in Launch Technology. Launch rates alone cannot be counted on to reduce launch costs (for example, if labor costs for construction and launch are too high). Improvements will occur in 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 cost. One significant example is the use of reusable vehicles.

Space Tourism. Space tourism develops into an industry requiring numerous launches that will lower the cost of each launch to commercially sustainable levels. Hundreds, perhaps thousands, have already made deposits on private suborbital flights. These journeys will later extend into Earth orbit and then into orbits around the Moon and back.

Commercial Facilities in Orbit. With the development of reliable and affordable space transportation, private enterprises create commercially profitable orbital facilities, e.g., hotels and factories. These facilities will be large enough to allow travelers to enjoy the feel and unique opportunities of zero gravity for extended periods, but small enough to be able to move to avoid known space debris. It is likely that transportation and facilities will evolve together, in that the availability of one will serve as a commercially justifiable rationale for the other.

Space Solar Power. A different path to achieving high launch rates and lower costs to orbit might be forged by the world's need for power. In this case, human travel to destinations in and beyond Earth orbit would be an incidental benefit rather than a primary goal. If and when it becomes apparent to governments that all available conventional sources of power — e.g., coal, natural gas, wind, hydroelectric, geothermal, nuclear, and ground-based solar — will be either inadequate to meet the needs of their people or that the side-effects of their use are unacceptable, they inevitably will look more closely at space solar power, or SSP (sometimes referred to as space-based solar power, or SBSP, since it involves satellites in

space transmitting the Sun's energy down to Earth.) The SSP systems that emerge could be built by private enterprises on their own or by governments, or by some sort of partnership. Either way, those systems require and therefore will result in the high frequency of launches that drives costs down.

Other Commercial Space Applications. Other potential commercial space applications may lead to increased launch rates and decreased costs. Examples are robust communication satellite architectures, orbital servicing infrastructures, or 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, as a national policy choice, may commit to the building of large space outposts in Earth orbit or on the Moon which will require a number of launchers over a sustained period large enough to reduce the per-launch cost to financially practicable levels. Such governmental initiatives may be created by a desire for prestige or not to be left behind by the space initiatives of other countries, by a concern for protection from asteroids and comets, by the need for a space-based solar power system to transmit solar power to Earth, or by government uses of space for security, environmental surveillance, improved communications, or many other uses, as well as by the traditional philosophical, political and economic policy rationales long articulated by NSS and others in the space community. Such initiatives will increase launch rates and reduce unit costs.

MILESTONE 3: An Integrated Cislunar Space Transportation System

In addition to Earth-to-orbit launch systems, the creation of transportation systems and infrastructure in “cislunar space,” i.e., the space between the Earth and the Moon, resulting in regular commerce in cislunar space.

Whether developed by government agencies or private entrepreneurs, either separately or in partnership, cislunar development will likely include:

- Reusable space vehicles carrying people and cargo between Earth orbit and lunar orbit.
- In-space way-stations in lunar orbit or at the gravitationally balanced Earth-Moon L-1 or L-2 LaGrange Points, or all three, that each include a depot to refuel spaceships bound to the Moon or

Mars or back to Earth. It is likely that the way-stations will come to have attached habitats for crews either permanently based or as a temporary refuge while en route to other destinations.

- Reusable space vehicles to ferry people and cargo from such way-stations to the lunar surface and back.

As with sustainable Earth-to-orbit launch costs, primary keys to the development of cislunar space will be both

reducing the cost of cislunar transportation and infrastructure to affordable levels and having enough of a lunar presence — i.e., enough people and enough cargo traversing cislunar space to reasonably amortize or justify the costs. To be significant enough, that lunar presence will almost certainly involve surface operations and probably a permanent presence, but a regular supply of tourists and scientists journeying just to lunar orbit and back may be a sufficient catalyst.

MILESTONE 4: Legal Protection of Property Rights

Legal protection of property rights to provide prospective off-Earth investors and settlers with the security to take financial risks.

Successful settlement of space would be impeded if the settlers are not permitted to own real property (i.e., 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 their businesses in extraterrestrial locations. Private individuals and groups who are considering investing their own resources to settle and develop the space frontier will need to know in advance that, if they succeed, they will be rewarded by 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 (although some nations have claimed ownership of the portions of the geosynchronous orbit arc over their territories). Therefore, it may be that nations or other terrestrial entities cannot grant 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 wherein reasonable claims on extraterrestrial lands, based on beneficial occupancy and development, could be recognized by terrestrial governments.

MILESTONE 5: Land Grants or Other Economic Incentives

Economic incentives, such as “land grants,” to encourage private investment in off-Earth settlements.

Claims of title to off-Earth land will be recognized on the basis of beneficial occupancy and development. Most likely they will also require that the occupancy be intended to be permanent.

Claims could plausibly be broadened to include additional tracts large enough to make feasible subdivision and resale. Such extraterrestrial “land grants,” akin to those granted as incentives to railroads by the U.S. after the Civil War,

Even if cislunar infrastructures were initially sponsored or run by governments, cislunar operations and on-board personnel increasingly will come from an ever more skilled 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 anywhere in the solar system.

Aspects of a legal regime for property rights in space include:

- Incorporating the usual protections for individuals, businesses, and the natural environment, while also ensuring fair competition for use or ownership of property. These protections include 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, and protection of settlers’ rights and space resources.
- Evolving gradually, so as not to strangle a young and growing off-world presence in over-bureaucratization and over-regulation.

Note that no individual or company currently has the power to issue “titles” to uninhabited extraterrestrial real estate. NSS regards any past and contemporary offers of “title” to such lands which are not clearly denoted as symbolic and unofficial, as being unethical and deceptive.

appear to be a likely way to foster privately funded space settlements. Such measures would increase the potential for private investment in affordable space transportation and facilities and could be the difference in making settlement economically feasible. To that end, governments and the space community will be likely to develop acceptable legal mechanisms and methods of offering such land grants as an incentive for developing permanent off-Earth settlements.

MILESTONE 6: Technology for Adequate Self-Sufficiency

People leaving Earth with the technology and tools needed to settle, survive and prosper without needing constant resupply from Earth.

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

(a) to meet their basic needs for air, water, power, shelter, basic foodstuffs, and the like by using local materials — e.g., soil, metals, ice and other volatiles, sunlight, and, in the case of Mars, atmosphere – such methods collectively often referred to as “in situ resource utilization” or “ISRU,” and

(b) to maintain, repair, reuse, recycle and to some extent replicate the materials and tools that constitute the daily-living amenities that are the hallmarks of modern life, such as medicines, electronics and clothing.

In building towards that goal, off-Earth settlements will initially receive regular infusions of initial infrastructures and supplies (e.g., habitats, power generating equipment, medicines, tools and electronics) until a critical mass has been assembled. That initial assemblage will enable the community to achieve adequate self-sufficiency, with a need for only occasional imports of non-critical items for which the community has not yet been able to develop its own manufacturing base. At that stage regular two-way commerce, of both people and materials, will develop between the community and Earth and other off-Earth settlements. Such a development is often characterized as the essence of a “spacefaring civilization.” Much later, as the community matures it may achieve a level of complete self-sufficiency, which, if necessary, could allow it to survive without any further imports from Earth or any other world.

Achievement of this Milestone involves two basic and contemporaneous processes:

Enabling Technologies. Substantial investments in a broad spectrum of enabling technologies and techniques.

These include, among many others: materials (e.g., metals, ceramics, fabrics) and materials acquisition; structural design (e.g., using metals, soils, inflatables); manufacturing and miniaturization; nanotechnology; robotics; bioengineering; in-space food production; energy systems; recycling of air and organic materials (sometimes referred to as Controlled or Closed Ecological Life Support Systems, or “CELSS”); microgravity and in-vacuum manufacturing techniques.

Precursor Missions. Robotic precursor missions (followed by crewed missions) to land and test, among other things:

- a wide variety of materials exposed to the off-Earth environment for long periods of time, just as the Earth-orbiting Long Duration Exposure Facility (LDEF) once tested the durability of such materials.
- methods and equipment for digging to expose and retrieve various raw materials.
- methods and equipment for converting such soil and other materials into useful structural elements.
- mechanisms to convert local soil (or atmosphere) to water and rocket fuel.
- transportation systems for surface operations.
- methods of radiation shielding.
- methods of dealing with the effects of dust and electrostatics on equipment.
- various power sources (e.g., solar, nuclear).
- communication techniques (both local and to Earth).
- manufacturing processes in vacuum and near-vacuum.
- manufacturing processes in microgravity and low-gravity conditions.
- methods of agriculture and food production in microgravity and low-gravity conditions.

These missions will become increasingly complex, as initially promising technologies and techniques are tested on ever larger scales.



Space Solar Power concepts, clockwise from top: SPS ALPHA (Artemis Innovation); Sun Tower (NASA); DOE/NASA 1980s Reference Design (Mark Maxwell); SERT Sandwich Concept (NASA); Integrated Symmetrical Concentrator (Pat Rawlings, NASA)

Part III. UTILIZATION OF SPACE TECHNOLOGY AND RESOURCES

MILESTONE 7: Applications of Space Technology on and for Earth

The technologies and techniques developed on the road to space settlement applied widely and benefiting all on Earth.

The technologies and techniques developed for space settlement will not be limited to space settlements. Rather, as has always been the case, both directly and indirectly they will provide widespread benefits to Earth economies and lifestyles, as well as providing humans with a substantially enhanced ability to protect this planet from the impacts of comets and asteroids.

Some benefits will be realized almost immediately. Others will materialize over longer periods of time.

In General — Direct Benefits. Anticipated benefits from that 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 TV, 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 proliferate.
- Satellites for Remote Sensing. Improved use of space-borne sensors, in orbit or on the Moon, will increasingly be used for such purposes as: better weather monitoring and prediction; location of buried mineral deposits; keeping abreast of crop, fresh water and sea conditions; understanding

geological conditions; and, eventually, detecting imminent earthquakes.

- Commercial Use of the Space Environment. New products and knowledge will come from orbital research and manufacturing facilities utilizing the vacuum and weightlessness available only in space.
- Biomedical Knowledge from the Space Environment. Observations and experiments in weightlessness have provided crucial medical insights and breakthroughs, as well as revolutions in medical monitoring. Continued breakthroughs are to be expected, especially with respect to the conditions of 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 living on Earth.

In General — Indirect Benefits. What is designed for space application will challenge and inspire thousands of young minds and will find thousands of new applications on Earth. That has always been the case with the investment in space. After building spacecraft, scientists and engineers looked at the thousands of specialized small parts they created, that would not have

existed but for the focused goal of space exploration (and the need to preserve priceless human cargo), and then found new on-Earth uses for them. In that process they created dozens of new industries and thousands of new jobs on Earth. Those benefits were in addition to benefits in the space industry itself and in addition to the ordinary multiplied effects of any government or industry spending. Similar benefits will continue to arise from future space development.

Later: Extra-Terrestrial Raw Materials. The Moon and the asteroids contain metals and other materials that are rare on Earth, e.g. platinum. 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 their use in space.

Later: Sunlight from Orbit. As orbital infrastructures become more sophisticated, new capabilities may emerge, including the ability to use giant space mirrors to modify the Earth's weather, for example, to increase the food supply (by increasing growing hours) or fresh water (by influencing rainfall patterns) or to provide illumination in dark areas. While world cooperation and unintended consequences will be significant barriers to such uses, the technology should be feasible.

MILESTONE 8: Space Solar Power System (SSP)

Establishment of an operational space-based solar power system transmitting the Sun's energy to Earth

Space solar power can potentially supply all the electrical needs of our planet. SSP will transmit from orbit energy from the Sun that is clean and reliable and, most significantly, inexhaustible.

Many of the world's greatest problems will be greatly alleviated by accessible energy or cheap energy, or both, which can be provided by SSP. For example, SSP can provide energy to replace fossil fuels, energy to light and heat homes and factories in remote areas, energy for farming, energy for transportation, and energy to desalinate sea water.

SSP can reduce or eliminate the need to burn fossil and nuclear fuels to generate electricity. This use alone currently represents about one-third of all the world's energy demands. The capacity of SSP is so large that it should have an immense effect in reducing production of greenhouse gasses and their effect on global climate.

As the initial system is augmented and improved, increasing percentages of terrestrial power needs will be supplied from space. Even before the system is completed, the realization of the pending availability of so much energy could promote world peace by substantially reducing the need for nations to fight for control of fossil fuels.

Most of the system will provide continuous base load power, notwithstanding night or weather conditions, but some of it can be for intermittent or emergency use. With an ability to be directed to multiple locations, even isolated settlements, SSP increasingly will obviate the need for expensive, delicate, and politically sensitive long-distance re-transmission networks between power plants and all the places of end use.

The scientific feasibility of SSP has been established, and the search is underway for a consensus as to the best designs and needed infrastructure.

MILESTONE 9: A Workable Asteroid Protection System

A system capable of detecting and defending against Earth-approaching asteroids or comets built and standing by to launch on short notice.

It is widely recognized that the extinction of the dinosaurs was largely a result of an asteroid smashing into the Earth. That such impacts can still occur was demonstrated by the cataclysmic impacts of Comet Shoemaker-Levy 9 fragments on Jupiter in 1994 which were witnessed by hundreds of millions around the world. Dinosaurs could do nothing to protect themselves; humans can.

In time, just as their citizens buy home fire insurance that almost never will be used, governments will come together to create the capability to better detect threatened collisions and then design and build a defense against them.

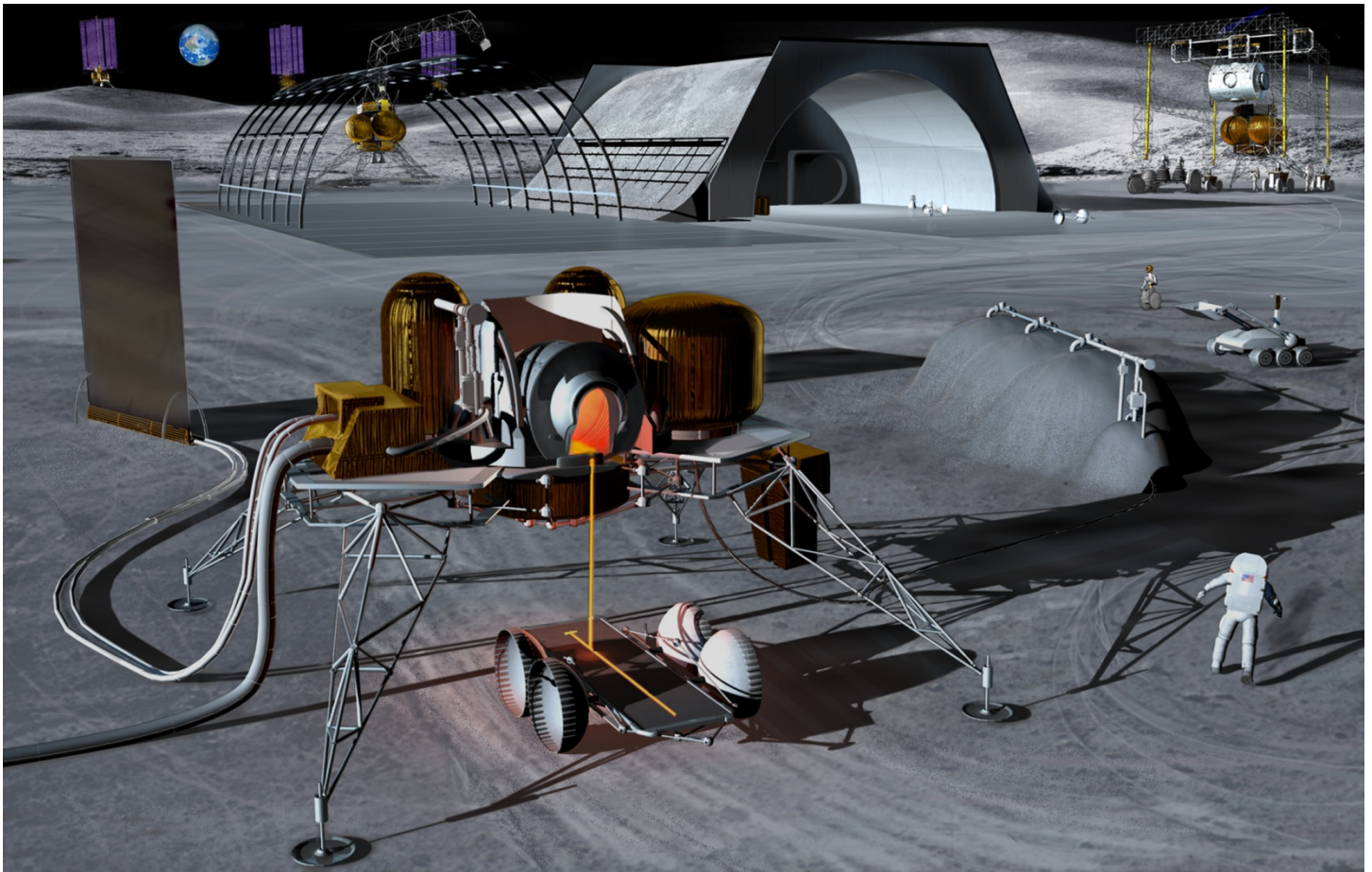
As to detection, telescope sky scans have located and calculated the orbits of thousands of asteroids and comets, but so far have identified none likely to be large enough or close enough to dramatically impact Earth. However, large parts of the sky, especially outside the ecliptic, remain unsearched and our telescopes are still not sensitive enough to identify smaller but still dangerous objects. Every year large objects pass Earth just inside or outside the orbit of the Moon without being discovered until very close or even until after they passed.

As to defense, the scientific know-how exists to divert smaller asteroids still far from Earth. However, adequate knowledge of the composition and internal structure of the larger objects is still lacking. Consequently, the knowledge about the best way to deflect or destroy them is likewise lacking. Future missions to asteroids and comets should help fill in that knowledge gap. With that information, whatever launch systems, weapons systems and in-space infrastructures are necessary to protect the Earth can and will be built, and will remain on standby for launch on short notice against a threatening celestial object that is late being discovered.

Reduction of launch costs from other space activities would make their creation more feasible and attractive to governments, and therefore more likely to be achieved sooner. And, if the world should see a need for urgency in creating such a defense system, that priority could itself be a driver for the higher launch rates and accompanying reductions in launch costs that would spur realization of other space benefits.



(Raymond Cassel, NSS)



ISRU operations on lunar base (Mark Maxwell, courtesy Dennis Wingo and Skycorp Incorporated)

Part IV: TO THE MOON

The Moon, only a quarter of a million miles away, passing overhead every night, beckons as a visible and obvious destination for human settlement.

PARTICULAR BARRIERS:

Major Barriers specific to the Moon will have to be overcome to reach the Milestones en route to that settlement. Those Barriers include:

Psychological and Political. Scientific investigation of the Moon is currently being, and will continue to be, undertaken by or with the support of various governments, but only on a project by project basis. Until a firm, final, irreversible and financially supported commitment is made to create a permanent — and the operative word is “permanent” — settlement on the Moon, it will not happen. That commitment could occur early, in the event of a national political decision, or only after successive phases of lunar exploration and development have shown a likelihood of cost effectiveness and sustainability. Either way, obtaining that commitment might even be viewed as a Milestone in its own right.

Architecture Definition. Early Lunar bases run the risk of being abandoned if reusable transportation systems are not used from the beginning. This risk will be lessened to the extent that, from the start, mission architectures are designed as a sustainable, reusable, integrated system that pursues ISRU and self-sufficiency technologies as a very early goal.

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

(1) Lethal ionizing radiation comes from the sun and even more powerful cosmic rays originate from outside the solar system. Habitats will have to be shielded, probably by being covered with thick layers of local regolith or built underground. More difficult will be

finding a way to shield humans while operating on the surface.

(2) Gravity is the true unknown. Humans (as well as other animals and plants) are the product of some 500 million years of terrestrial evolution, all that time being adapted to live in a one-gravity environment. We already know of problems from long duration space flight, such as bone loss and vision degradation. No one knows whether or not humans can live long-term in the low lunar gravity, nor whether offspring can be safely born and raised. This barrier will be tested either by the placement in orbit of a

variable gravity centrifuge (something that was omitted from the International Space Station) or the hard way, by real-life experience by people living on the Moon.

Uniquely Lunar. Each body orbiting the Sun has its own characteristics. The Moon presents some unique challenges which will have to be overcome — e.g., its half-month days followed by half-month nights, its pervasive and abrasive dust, its cratered and mountainous terrains, its possible lack of usable water, and its most useful resources (including what water exists) not being conveniently located.

MILESTONE 10: Robotic Confirmation of Lunar Resources

Satellites orbiting the Moon and possibly robotic landers determining the nature and extent of lunar ice and volatile deposits and providing the information necessary to guide the choice of the best sites for a lunar outpost.

The Apollo missions chose landing sites primarily on the basis of safety on landing and then on the basis of general scientific interest to learn about the history and composition of the Moon. Successor lunar missions have emphasized and will continue to emphasize discovering what lunar resources can best support future long-duration human operations there.

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 in certain areas near the lunar poles, notably in deep permanently shadowed craters. Knowing exactly what these volatiles are and how extensive are the deposits, and especially how much of them are water, will be crucial to understanding their availability to make rocket fuel and breathing oxygen and provide other support for human habitation. Every kilogram of water that does not need to be imported from Earth represents a significant step toward self-sufficiency and immensely eases the logistical requirements for supporting humans on the Moon. Thus, this knowledge about lunar volatiles will provide the basis for designing all subsequent lunar habitats.

Sites for Lunar Outposts. While attention has been focused on volatiles at the lunar poles, as well as the possible advantages of a deep crater for lunar optical and

radio astronomy, there are obvious difficulties of establishing the first habitats at those sites — e.g.,

- fuel requirements greater than for landing closer to the lunar equator,
- higher risks in landing inside a crater near a shadowed crater wall,
- difficulties in communication with Earth when it is not in line of sight — establishing a network of lunar relay satellites will ease that problem but will add to the infrastructure cost and complexity,
- the lack of sunlight for solar power,
- limitations on where ground vehicles can travel for further research.

These difficulties will motivate the continued search for sites that may lack volatiles but will have the advantages for a first outpost that a polar site lacks. Other advantages may include the existence of caves, or different soils that can be better utilized in the construction and maintenance of a habitat, or higher concentrations of particular metals.

When all the new data is evaluated, and all the variables balanced, including initial and ongoing costs, a choice will be made for where to site the first permanent outpost — i.e., where structures will be landed or built which will be the site for more than a single visit.

MILESTONE 11: A Lunar Research Facility

A lunar research facility established to study human habitation, test various equipment and techniques, and conduct lunar investigations.

The first outpost will be designed to support successive missions, each building on the knowledge gained and infrastructure built by its predecessors. This facility may be government sponsored and funded, or could be established by private enterprises. The outpost may consist of a single module visited and used over and over or of 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. Other deliveries, either before or after a habitation module, could be rovers, bulldozers and tractors, building cranes, mining 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 outpost could be either vacated between missions or be continuously occupied. If the latter, the outpost will be exceptionally useful in determining the ability of Earth life to thrive for long periods in the one-sixth gravity environment, and in the case of plants and other animals, to reproduce successfully.

This first outpost will be mainly a research facility. Over time and as it grows, it will test, among other things,

- life support and recycling systems,
- health maintenance regimens (much as the International Space Station has tried various methods for keeping astronauts in good condition in zero gravity),
- cooking in one-sixth gravity,
- spacesuits,
- lunar transportation vehicles,
- alternate power sources (e.g., battery, solar, nuclear),

- if volatiles are nearby, techniques for extracting water and making rocket fuel,
- construction techniques (such as digging, moving, shaping lunar regolith),
- creating at a distance a storage site for rocket fuel,
- various kinds of radiation shielding,
- mining and smelting techniques,
- manufacturing and fabrication techniques unique to one-sixth gravity and/or vacuum,
- crew psychology in a new environment,
- gardening and animal husbandry in that unique environment.

Surface explorations will also continue contributing to our scientific knowledge about the Moon generally.

In addition, if the public relation possibilities are maximized, regular broadcasts from the Moon will 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. That will mean (1) having always available in case of emergency a means to return to Earth, whether by a vehicle capable of returning directly to Earth or a vehicle capable of reaching a second vehicle in lunar orbit that can return them to Earth, and (2) having a crew refuge which can sustain the crew against sudden burst of solar or cosmic radiation for a specified length of time (and is also a crew habitat during normal operations). The exposure to sudden radiation bursts was an inherent risk accepted by the Apollo missions, but will probably not be accepted where long duration stays are involved.

MILESTONE 12: A Government / Industry Lunar Base

The initial research facility evolving into a permanently occupied, ever-expanding lunar base, or such a base created at another site using what has been learned from the initial facility, and increasingly performing commercial functions.

Once the initial lessons have been learned from the lunar research facility, a growing lunar base will turn its attention to maximizing its usefulness to other space operations and achieving some commercial profitability.

The base will encourage early industry investment and involvement. Some separate modules could be privately financed, as could the visits by various researchers.

Noncommercial Functions. The lunar base will continue the basic scientific and technological research begun by the research facility, probably with government funding and direction. It will also be used to provide government services for use on Earth, such as environmental sensing, including “space weather,” and tracking objects orbiting the Earth. The techniques learned during the Research Facility phase — e.g. utilization of lunar volatiles to produce rocket fuel — will increasingly be incorporated into the Base phase.

In addition, with the experience gained from operating in the lunar environment, the base very likely will be used as a test-bed for developing and checking out the many technologies and hardware that will be needed for Mars missions. While Mars has a slight atmosphere, different dust, seasons, and gravity twice that of the Moon (although still only one-third that of Earth) conditions on the Moon provide a much more rigorous environment for thorough testing. Even entire modules intended for Mars could be field-tested on the Moon.

MILESTONE 13: A True Lunar Settlement

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

As the lunar base grows, in volume, in area, in the number of modules connected and nearby, and, especially, in population, at some point people will look back and realize that people are on the Moon for good. 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 government employees,
- children being brought to the Moon, and, gravity permitting, being born there,
- schools and chapel spaces,
- no requirement that enough vehicles be standing by to evacuate the entire population at once (though there would be provisions for evacuating people from individual modules in the event of emergency),
- surgical facilities,
- Closed or Controlled Ecological Life Support Systems that recycle enough to minimize the need for imports for daily living,
- ability to make repairs using local materials,
- facilities for visitors, whether scientists, tourists, or others,

Commercial Functions. Both by design and happenstance, commercial uses of the lunar base will increasingly arise. As the technology gets increasingly proved, so that the risk from innovation uncertainty is substantially reduced, private companies will be better able to evaluate the risks and potential profits of investment in the lunar infrastructure. At that point, they are likely to invest in (i.e., fund) lunar enterprises more substantially. Possible commercial opportunities include, e.g.,

- if the base is located near extractable volatiles, providing rocket propellant for cislunar operations which could be one of the base’s primary and most commercially valuable uses,
- the gathering and sale of research data,
- the production and sale of lunar entertainment,
- tourism, with a nearby bare-bones hotel module and lunar excursions.

- use as a staging point and support facility for the development of other lunar settlements.

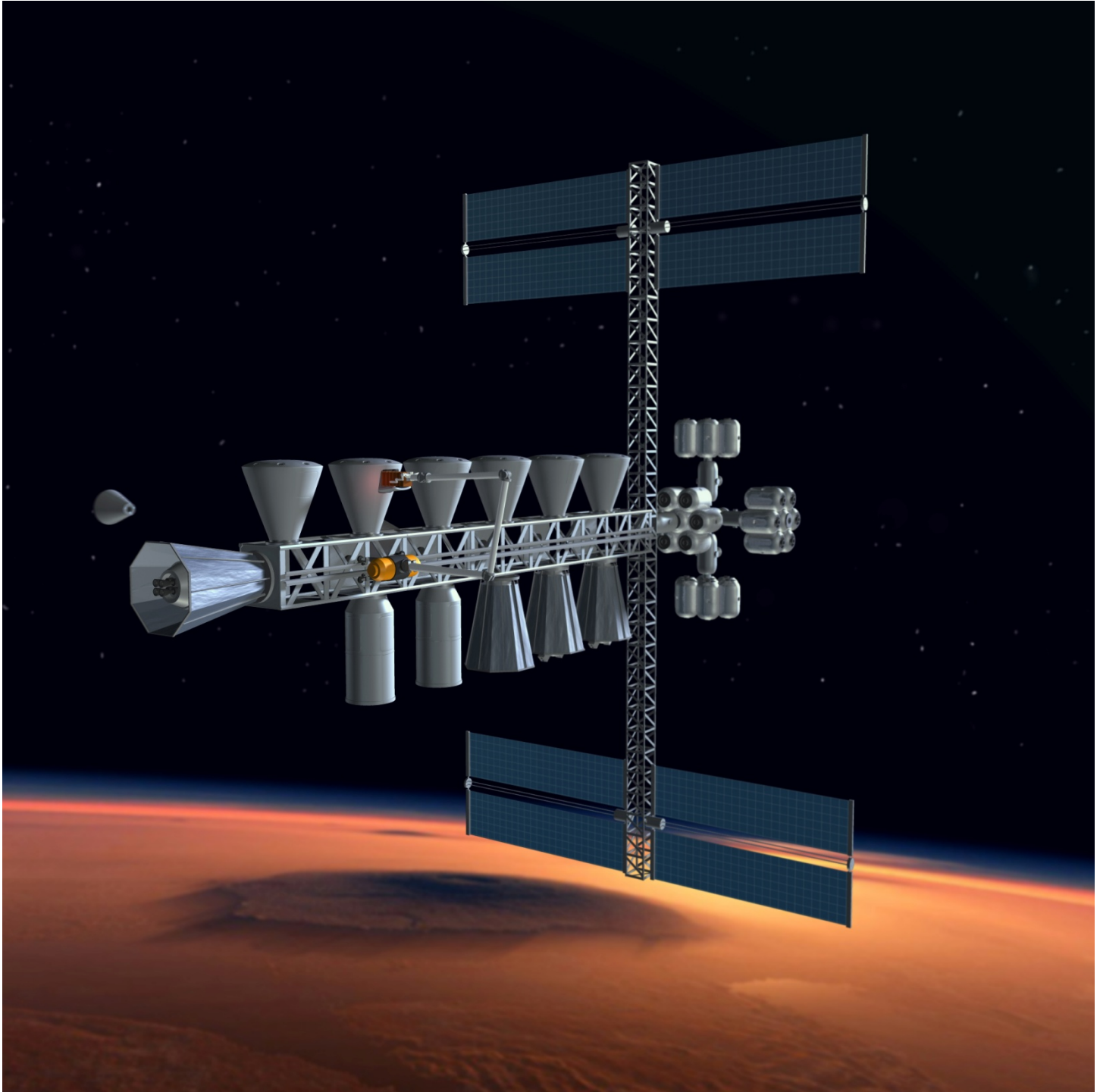
While the settlement’s facilities are reasonably predictable, the composition of its population is not. That will depend on what are the biological effects of living in the low lunar gravity for long periods, even a lifetime, and on fetal development and later growth. It may be that people and their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

As the cost of space transportation drops and the cost of the settlement is amortized or written off, the commercial activities that were initiated and experimented within the base phase will be expanded, especially tourism and development of products and services for use on Earth. Lunar hotels may be among the structures most frequently added to the settlement. 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 in routine maintenance.

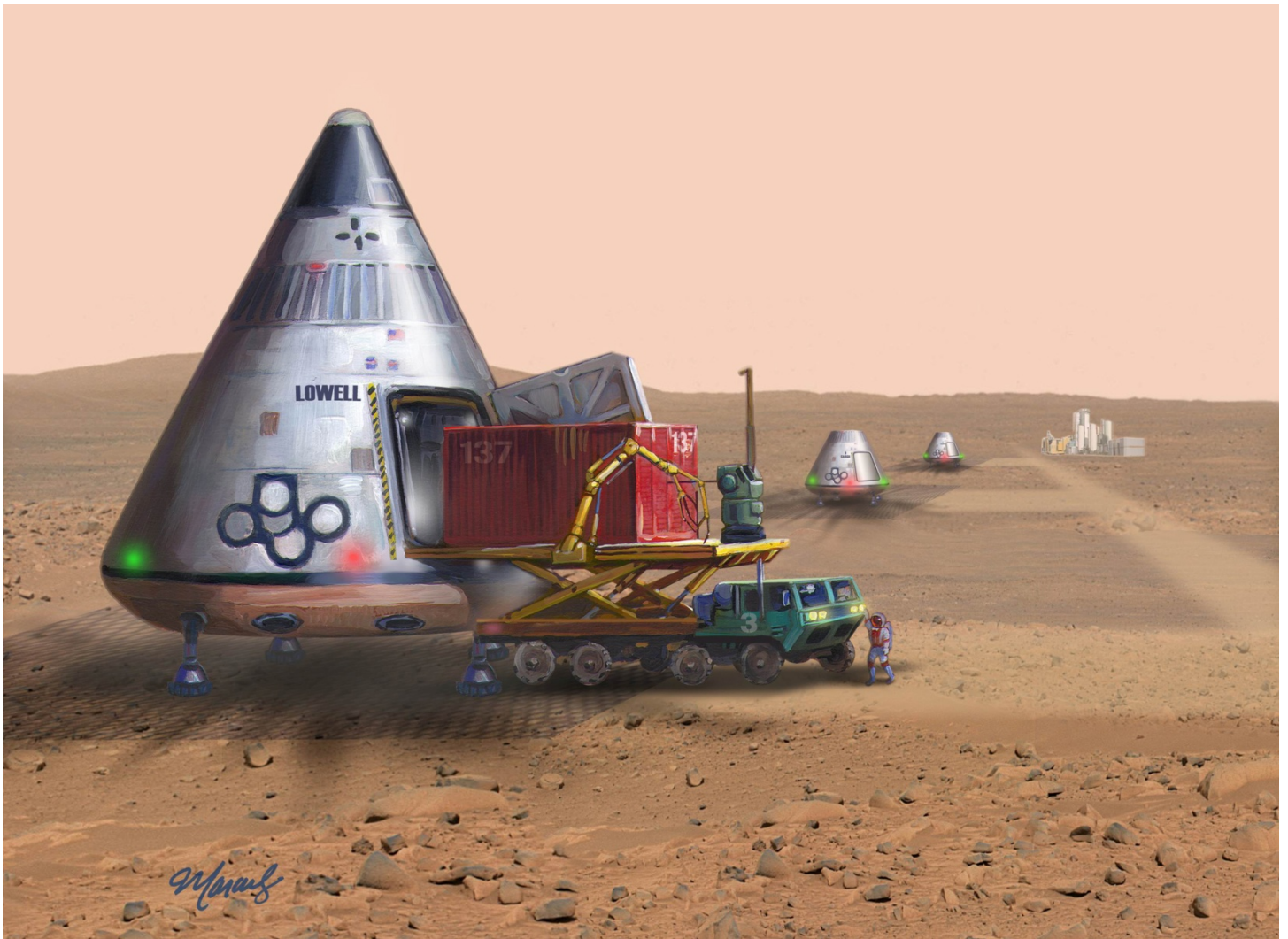
One significant commercial activity that could be sustained by a growing permanent settlement would be the creation

of a system of mass drivers. These would electromagnetically hurl mined lunar materials or lunar-derived rocket fuel into orbits where they could be used to construct orbital space habitats or to refuel outbound spacecraft substantially more economically than could be done if those resources needed to be brought up from the bottom of Earth's gravity well.

Another activity that could be supported by a growing settlement would be the establishment and maintenance of permanent observatories at various locations, including on the far side of the Moon for astronomy, and on the near side of the Moon for continuous surveillance of cislunar space and the Earth.



Mars way station with docking ports for propellant depots and crew and cargo ferries (anna.j.nesterova@gmail.com)



Reusable Martian ferries with propellant production and storage facility in the background (Marcus Mashburn)

Part V: TO MARS

With a gravity one-third that of Earth's and twice that of the Moon, an atmosphere 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, Mars uniquely beckons to provide another world for humankind.

PARTICULAR BARRIERS:

However, major Barriers specific to Mars will have to be overcome to reach the Milestones en route to the settlement of that planet. Those Barriers include:

Psychological and Political. Mars is a long way from Earth. With current technology it is more than a 6-month journey each way and, on account of 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 30-60 day stay on the surface before the launch window for return to Earth would close (opposition mission), or about 900-1050 days, allowing 500 days for on-surface operations (conjunction mission). With trips so infrequent,

lasting so long, and with relatively few or exciting on-surface events, public interest is likely to wane. Where public interest wanes, a decline in political support usually follows suit shortly thereafter. Therefore, any political decision to create a permanent and growing human presence on Mars will be almost a Milestone in itself.

Goal Definition. Early Mars exploration runs the risk of ending up as “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 to the extent that, from the start, mission architectures are designed as a sustainable, reusable, integrated system that pursues ISRU and self-sufficiency

technologies as the earliest goal, with ultimate settlement in mind.

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

(1) While solar radiation is diminished on account of Mars' distance from the Sun and Mars' whisper-thin atmosphere, it still can be lethal to life on the surface. Extra-solar cosmic radiation would be undiminished. Methods to shield habitats and humans on the surface will have to be developed.

MILESTONE 14: Robotic Exploration of Mars for Local (In Situ) Resources

Satellites orbiting Mars and robotic landers determining the nature and extent of Martian resources, especially ice, guiding the choice of the best sites for follow-on human missions.

Robotic missions to Mars, both orbiters and landers, have provided tantalizing hints about Martian history and Martian geology. Continuing missions, utilizing the favorable launch windows that occur about every two years, may be entirely robotic or may be crewed missions to a Martian moon, from which the crew would (a) teleoperate Martian landers without the long delay in radio transmissions to and from Earth, (b) explore that moon, and (c) test equipment that later could be used on Mars.

There are two fundamental objectives of these missions.

Scientific Knowledge. One fundamental objective of these missions will be to continue to learn more and more about Martian history and geology, both to understand it for its own scientific value and to ascertain if there are any implications as to Earth's own history and future. In particular, these missions will be searching for:

- Existing Martian life of any kind.
- Evidence of past Martian life, now extinct.
- Ice or buried liquid water, especially near the surface.
- Geological implications from diverse soil and rock samples.
- An understanding of Martian weather and seasons.
- Indications of any biological or other contaminants that could be harmful if returned to Earth.
- The best sites for follow-on human activities.

Data for Human Exploration and Outposts. The other fundamental objective of these robotic Mars missions will be to be ascertain existing conditions that are favorable and unfavorable to human exploration and

(2) Martian gravity, although twice that of the Moon, is still only one-third that of Earth. Whether terrestrial life can thrive and reproduce under such conditions is unknown. This Barrier can be tested by in-space variable-gravity centrifuges or by actual on-planet experience.

Uniquely Martian. Unique challenges of the Martian environment will have to be overcome — e.g., Martian dust, soil chemistry, shifting wind-blown dunes, accessibility of water, vehicle-trapping sand, acclimation to somewhat longer days.

settlement, especially near the Martian equator where less fuel is required to land and return to orbit. In particular, these missions will:

- Search for ice or water sources that will be the most accessible to humans.
- Search for brine and concentrations of other minerals that might be useful to humans.
- Test materials and machines against the Martian environment. For example they will want to learn whether and how — over long periods of time exposed to wind, dust, daily temperature changes, and seasonal changes — a wide variety of test materials will remain sturdy and machines workable. They will test how various mechanical equipment perform and hold up in that environment.
- Test various rover designs in ever longer traverses over varied Martian terrain.
- Test various in situ resource utilization (ISRU) equipment to automatically convert Martian air to rocket fuel.
- Test various energy supply systems.
- Test automatic digging equipment to automatically dig up and collect ice.
- Test automatic construction techniques both in and using Martian soil.
- Include mini-garden bubbles to test the ability of terrestrial plants to grow there.

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

MILESTONE 15: Creation of a Logistics System for Transporting Humans and Cargo to the Martian Surface

An integrated sustainable system designed and built for transporting humans and cargo from space to the Martian surface, maintaining the crew on the surface, and returning crew and payload safely back to Earth.

Reaching, landing on and returning from Mars, with its great distance from Earth, an atmosphere and a gravity twice that of the Moon's, will be significantly more difficult than similar operations on the airless Moon. On account of that distance, equipment or supplies that fail on Mars cannot be easily replaced. An unexpected failure that might be recoverable from on the Moon, only a few days away from Earth, could be fatal on Mars. Consequently, materials destined for Mars should be especially well tested.

Decisions will have to be made as to which duration mission to undertake — a 500-day stay after a 6-month journey or just a 30-60 day stay — and that decision will drive the design of the transportation, landing, habitation and return systems.

Earth to Mars Transit Transportation Systems. Architectures proposed for the transportation systems needed to transit between Earth orbit and Mars orbit include single-launch systems or multiply launched vehicles, and includes vehicles assuming weightlessness during transit or vehicles using tether systems to create “artificial gravity.” Most systems contemplate using chemical propellants of one kind or another. Other proposed propulsion systems include nuclear-thermal propulsion and electric propulsion (e.g., ion, magneto-plasma-dynamic, arcjet). While the preferred goals and payload ought to be the determinants of the appropriate transportation system, the sequence may be just the opposite, with the choice of a transportation system determining the length of the trip, the resulting stay options at Mars, and the tonnage that can be brought. The choice of architecture will be influenced by the strength of the desire to have humans on Mars, tempered by the state and cost of then available technology. Reusable transit vehicles that can return to Earth orbit would reduce mission costs.

Earth Orbit to Mars Orbit on a “Cycler.” A cycling spacecraft that moves between the two planets in a regular period, without actually entering into orbit around Mars or Earth, would require less fuel and provide more protection for crews.

Mars Landing Systems. Many architectures have been proposed for such landings, such as:

- 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, braking rockets, or combinations of them.
- Earth (or Earth orbit) to orbit around Mars, and then to the surface of Mars (entry from orbit). Such systems generally will use a separate lander using one of the landing techniques considered for direct entry, with the mother ship remaining in orbit (crewed or not).
- Earth (or Earth orbit) to a landing on a Martian moon, and then to the surface of Mars with a separate lander.

Earth Return Systems. Similarly, various architectures have been proposed for the return to Earth, such as:

- Direct return from the Martian surface to Earth (or Earth orbit) using the original landing vehicle.
- Direct return from the Martian surface to Earth (or Earth orbit) using a separate return vehicle either attached to the original landing vehicle or pre-positioned in a previous uncrewed mission.
- Rendezvous either in orbit or on a moon with the original crew transit vehicle or in a separate return vehicle that either accompanied the original vehicle or was pre-positioned there, and return to Earth (or Earth orbit).
- Rendezvous with a “cycler” for its return to Earth orbit.

Orbital Propellant Depot. Mars landing vehicles need to bring their propellant for the initial landings from Earth. A fuel container brought to Mars could remain in Mars orbit as a cryogenic propellant depot. That depot would be available to store propellant made on Mars from in situ resources and brought up by reusable Martian “ferries.” This stored fuel could then be used for future trips to the surface, for trips to Phobos and Deimos, or for Earth return vehicles.

Martian “Ferries.” Having fuel produced on Mars can facilitate continued use of reusable ferries, rather than single-use “land and abandon” vehicles (Mars landers) and thus greatly reduce the tonnage needed from Earth for

transportation purposes during construction of an expanded Mars base and thereafter. Initial missions could land propellant production facilities that could be assembled on the Martian surface. Situating a base near subsurface water ice would allow in situ production of liquid hydrogen and oxygen propellants, which are energetic enough to allow ferries to reach orbit, return to the Martian surface with a large payload, and even leave extra fuel in an orbital depot. 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 from, and to land near, the equator.

Habitation Systems. The technological and logistical requirements for the crew habitat while on Mars will depend on whether a short or long stay is planned. The longer the stay, more supplies will be required and/or fewer crew will be possible. For a short stay the habitat may be the lander itself or a pre-positioned habitat. For a long stay, a pre-positioned habitat is likely, possibly

supplemented by a supply of oxygen or rocket fuel extracted out of the Martian environment by contemporaneously pre-positioned ISRU equipment. Site location may be determined by availability of large deposits of water ice nearby as a source of water, oxygen, and propellants. An important piece of equipment is an earthmover that can move the Martian soil to provide shielding from radiation and to excavate buried ice.

To the extent the system is based on reusable vehicles, rather than ones thrown away after a single use, the exploration and settlement of Mars will be greatly facilitated. For example, fewer vehicles will be needed, extra vehicles may be available for redundancy, and crew risks may be reduced by not having to use a new untested vehicle each time.

Balancing all the variables, settling on an integrated and expandable system, and then actually building it will be a true Milestone.

MILESTONE 16: A Continuously Occupied Multi-Purpose Base.

Following initial crewed missions to identify a suitable location and the particular infrastructure and equipment needed there, establishment of a continuously occupied multi-purpose Mars base.

Initial crews landing on Mars will continue the exploratory work begun by satellites and robotic landers. The ability of humans to use tools, travel greater distances (whether on foot or by rover) and adapt to new circumstances will greatly accelerate the accumulation of knowledge, especially that necessary to build a permanent outpost.

In particular, these first crews will experiment with ISRU technology, testing, among other things, alternative power sources, habitats, propellant manufacturing techniques, oxygen extraction processes, gardening, mining equipment, ground transport, air transport (e.g., balloons, Mars planes, and even rocket “hoppers”), construction techniques and equipment and medical equipment. The crews will give special attention to extracting and using ice from deposits in the landing area or, if none, to searching for them.

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

At some point a decision will be made to concentrate efforts in a primary 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 brine, which can

provide many of the essential elements needed for long-term habitation and which will reduce substantially the re-supply tonnage needed. That primary site will 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 by some who stay permanently. It will, among other things,

- Continue scientific research and exploration.
- Expand fuel production and fuel storage facilities.
- Expand mining activities,
- Initiate deep drilling to attempt to find brine layers below the permafrost, where micro-organisms (existing or extinct) and useful dissolved minerals are most likely to be found.
- Use Martian materials to build future habitats.
- Cater to visiting scientists and tourists in increasing numbers.
- Develop techniques for making increased use of in situ resources.

As with the Moon, commercial opportunities will increasingly arise and over time the focus of the base will shift towards commercial uses.

MILESTONE 17: A True Martian Settlement.

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

The Martian base will continue to evolve, growing in volume, in area, in the number of modules connected and nearby, and, especially, in population. At some point the decision will be made that the site is to be a permanent settlement.

The distinguishing characteristics of that settlement will include:

- people emigrating to Mars with no intention of ever returning to Earth,
- children being brought to Mars, and, gravity permitting, being born there,
- reasonable self-sufficiency having been demonstrated, including basic life support, stable food production, ability to construct additional habitation spaces from local materials with on-site equipment,
- a recognition that in case of emergency it will be impossible to evacuate the entire population and a willingness to bear that risk (as was the case on terrestrial frontiers), and, consequently, no requirement that enough vehicles be standing by for that purpose,
- reasonably adequate medical surgical facilities,
- 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,
- a science center for the continued study of the planet
- use as a staging point and support facility for the development of other bodies in the solar system.

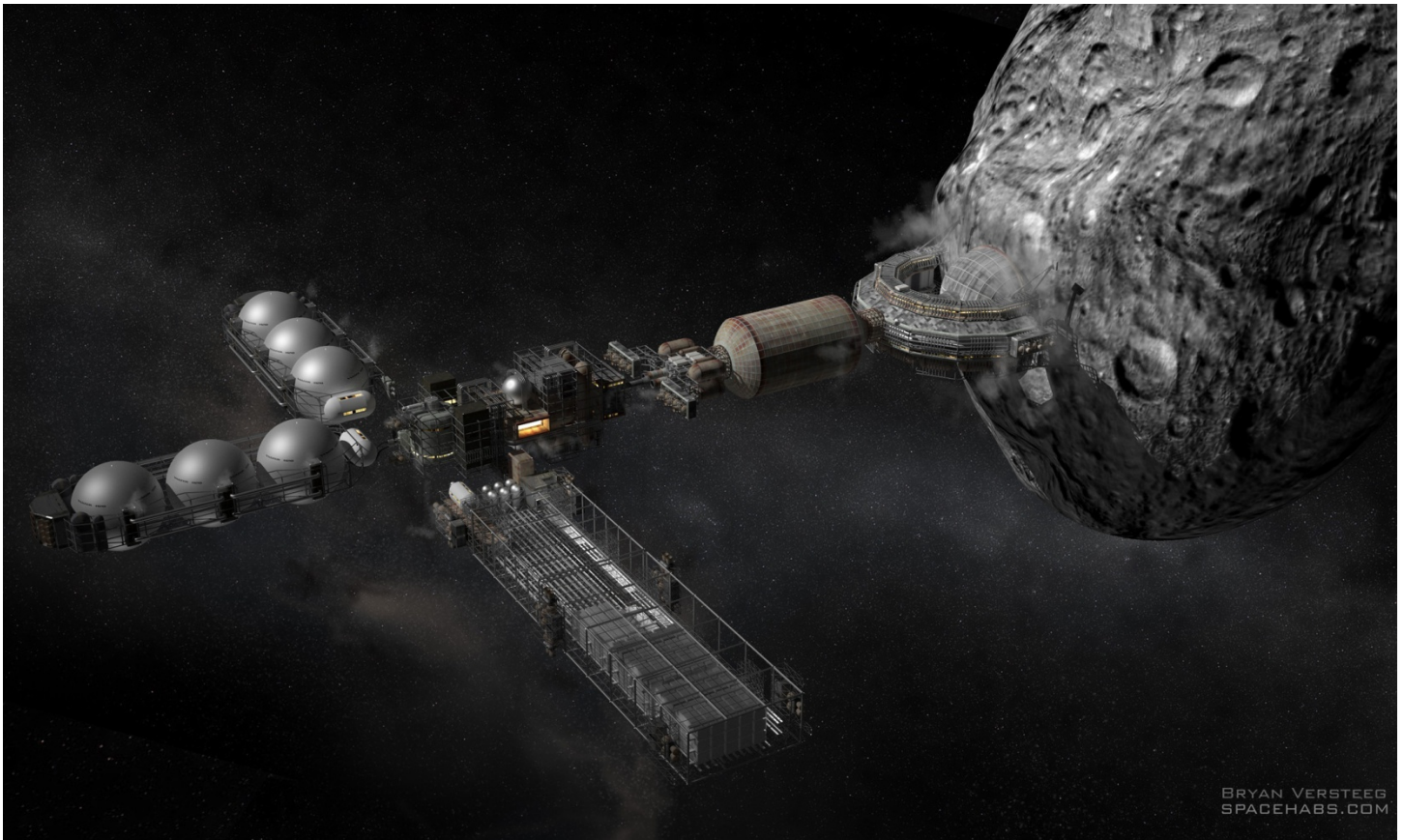
Whether Earth life can survive and thrive for long periods of time, and reproduce successfully and grow normally, in the one-third gravity of Mars remains to be determined. It may be that people and their families will be able to move to Mars, be born there, and live there for generations, or it may be that the permanent settlement is filled by a constantly changing population. But either way, the settlement should thrive.

As the cost of space transportation drops and the cost of the settlement is amortized or written off, emigrants from Earth will be able to pay all or at least part of the cost of their relocation. On Mars, the commercial activities and experiments that were initiated in the base phase will be expanded, especially tourism. Hotels may be among the structures most frequently added to the settlement. An increasing proportion of Martian settlers will be involved in these commercial activities.

Eventually, terraforming will be considered.



Mars settlement construction (Bryan Versteeg, spacehabs.com)



Asteroid smelter (Bryan Versteeg, spacehabs.com)

Part VI: TO THE ASTEROIDS

MILESTONE 18: Exploration, Utilization and Settlement of Asteroids.

After robotic identification of suitable asteroids, robotic and human crews following to establish mining bases and habitats for transients, and, eventually, carving out and building permanent human settlements.

Asteroids have huge mineral wealth, if it can be accessed. There are different classes of asteroids with varying amounts of metals, nonmetals and volatiles that would be useful both on Earth and in space. That potential value may be the primary driver for asteroid exploration and mining.

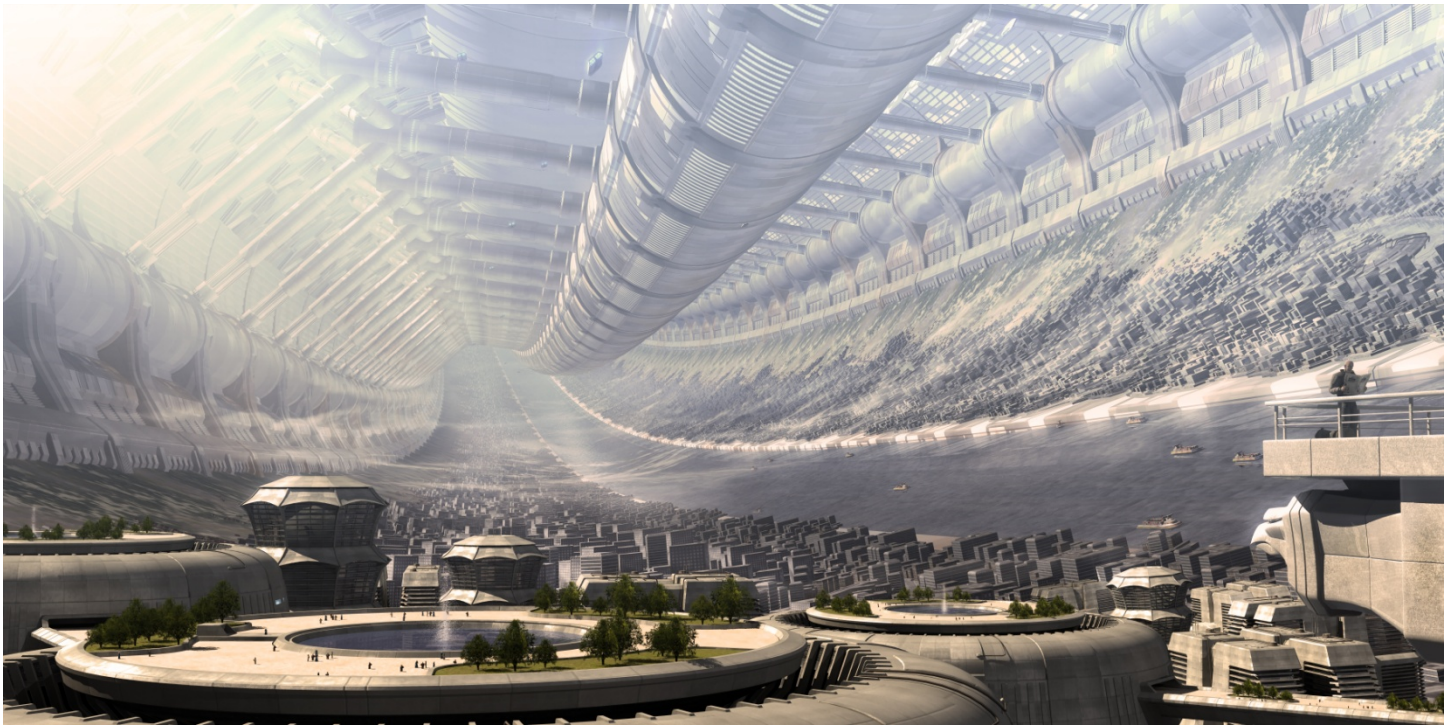
Robotic missions will confirm the composition of different types of asteroids. As space transportation systems become more robust, long-duration crewed follow-up missions will confirm earlier discoveries and begin the process of mining and harvesting these materials and returning them to Earth. As is expected to be the case on Mars, crews will convert deposits of volatiles to rocket fuel and oxygen, thus enabling further exploration before returning home.

In time, these asteroids will see more permanent habitats created, probably dug into the interior for radiation

shielding. These habitats will house either visiting crews or, if there is sufficient mining to be done, permanent occupants, or at least occupants staying for long times.

To the extent the lack of gravity turns out to be an unacceptable condition or insurmountable barrier, colonies using centrifugal force to create artificial gravity may be built in caverns inside the most valuable solid asteroids. Alternatively, in a rubble-pile asteroid, a rotating settlement with a non-rotating shell could be buried just below the surface for radiation protection.

With an appropriate asteroid, these mining stations may go through the same processes of growth as settlements on the Moon and Mars and evolve into permanent settlements, where people will raise their children and live out their lives, as on any far frontier.



A torus orbital space settlement (Alexander Preuss, NSS)

Part VII: TO ORBITAL SPACE SETTLEMENTS

MILESTONE 19: Construction of Orbital Space Settlements

Orbital “cities in space” built from asteroid or lunar materials.

In 1974, Princeton physicist Gerard O’Neill proposed the construction of orbital space settlements. An orbital settlement (sometimes called an “O’Neill Colony”) is a giant rotating spacecraft, large enough and rotating fast enough so that people standing on the inner surface would experience a centrifugal force equivalent to gravity on the surface of the Earth. Thus, children on orbital space settlements would be raised in Earth-normal gravity, which is important for normal bone and muscle development.

Since orbital space settlements must rotate, only a few basic shapes work well: sphere, torus, cylinder, or some combination. Current materials are strong enough for habitats many kilometers in extent, big enough for a moderately large city. The inner surface of the hull is real estate, i.e., land on which crops could be grown and homes constructed. While the outer hull will experience one gravity, interior structures can be positioned for fractional gravity, and even zero gravity at the axis of rotation. People and their families can live there indefinitely, in communities ranging in size from villages to cities which have their own internal economies as well as external imports and exports.

The International Space Station and other space stations are today's small precursors of later large orbital settlements. Tourism hotels in space may be the next step, followed by low-gravity retirement homes. These activities would develop much of the technology and infrastructure for people to live well and work effectively in space.

As with any space settlement, radiation shielding will be required. Unlike Lunar or Martian surface settlements, radiation shielding is required on all sides, so roughly twice as much shielding mass is necessary.

Habitats could be built in, or moved to, a variety of orbits. Most of these orbits would be selected to have 24/7 solar energy available. The choice of orbit may be driven by access to materials. Lunar material could be launched into space using electromagnetic launchers (mass drivers). Asteroid material 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.

The first flourishing orbital habitat would mark another Milestone in humankind's development, growth, and expansion into the universe.

Eventually such cities in space could be located throughout the solar system, orbiting around 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 and cultures of those who built, financed and settled it. Such diversity could provide a new flowering of human creativity. The result would also be to disperse humankind throughout the solar system, enabling survival even if some disaster were to befall the Earth.

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 km 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."

Another Milestone in space settlement will eventually be reached when the population in space exceeds that on Earth.

ORBITAL SPACE SETTLEMENT DESIGNS:

Kalpana One

Diameter: 1/3 mile

Population: 3,000

(*Bryan Versteeg, spacehabs.com*)

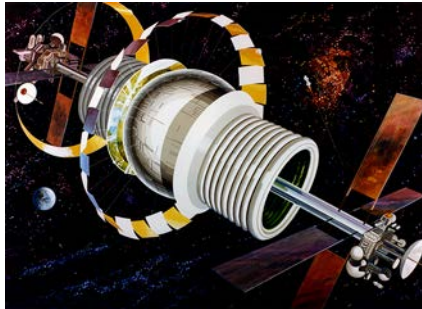


Bernal Sphere

Diameter: 1/3 mile

Population: 10,000

(*Rick Guidice, NASA*)

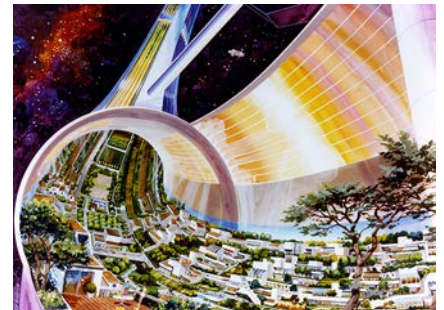


Stanford Torus

Diameter: 1 mile

Population: 10,000

(*Don Davis, Rick Guidice, NASA*)

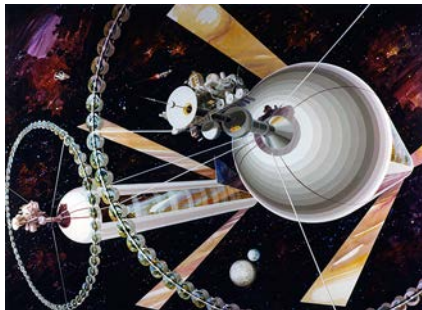


O'Neill Cylinder

Diameter: 4 miles

Population: over a million

(*Rick Guidice, NASA*)





(Hubble Space Telescope)

Part VIII: TO THE STARS

MILESTONE 20. Development of Interstellar Travel

Eventually, methods developed to enable humans to travel to other stars.

The stars are far away, the nearest being more than four light years away, and totally unreachable by any propulsion system currently in existence. However, it remains a dream for humanity to expand into the universe and live among the stars. We know that planets are commonplace and Earth-like planets are expected to be found somewhere among the nearer stars. While Earth-like (or similar) planets may be a primary destination, it is also known that planets are not needed for human habitation of another solar system because asteroids are likely to be available to support populations in orbital settlements in numbers larger than what planetary surfaces could support.

Scientific and technological breakthroughs may hasten the time when interstellar travel is possible. For example, breakthroughs in the biological sciences may enable us to modify humans to be better star travelers. Also, NASA has supported modest programs seeking scientific breakthroughs in propulsion physics. Any such breakthrough could accelerate settlement of our own solar system in addition to helping to reach the stars. A “breakthrough” by definition is unpredictable. However, it

seems very unlikely that any such breakthrough would be sufficiently dramatic that it would allow travel back and forth between stars in a meaningful time-frame. It is more likely that the best technology would only allow colony ships to make one-way trips to plant the first human homes in another solar system.

Such colony ships could take several forms. They could be “generation ships” in which the descendants of the original crew will be the ones who reach the final destination – or in which a “generation” is much longer than ours if life spans are greatly extended in the future. Or they could use some form of suspended animation which would allow the crew to travel for decades or centuries and be revived at their destination. Or they could be fully self-sufficient orbital settlements with relatively large populations; a space city that orbits the Sun could also orbit another star.

Once a solar system around another star is reached, human inhabitants could spread out and build a civilization there, and then repeat the process around other, more distant stars.

Once established throughout the solar system, humans will be truly out of their cradle, and the risk of extinction will be much reduced. When established around multiple stars, the future of humanity will be virtually unbounded. *Ad Astra!*

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MILESTONES TO SPACE SETTLEMENT

AN NSS ROADMAP



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