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Requirements for Space Settlements on the Moon and Mars

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When large space settlements are finally built on Earth's Moon and eventually Mars, inevitably the customers who pay for them will start the process by specifying requirements with a Request for Proposal (RFP). Although we are decades away from seeing the first of these documents, some of their contents can be anticipated now, and provide insight into the variety of elements that must be researched and developed before large settlements in these hostile environments can happen. Space Settlement Design Competitions for High School students present design challenges in the form of RFPs, which predict basic requirements for space settlement attributes in the future, including structural features, infrastructure, living conveniences, computers, business areas, and safety. The requirements are generically summarized for lunar and Mars scenarios.

I. Introduction

BY any reasonable estimates, humans are many decades away from beginning construction of the first large settlement on Earth's Moon or Mars. Design efforts to this point have been studies resulting in conceptual designs. Such studies certainly play an important part in engineering development; they identify problem areas, and form a basis of experience on which to draw when the formal design process commences. Designers participating in a study, however, have the luxury of focusing on isolated aspects of the design or ignoring details. Ref. 1 notes that design omissions in studies "are a matter of prioritization in the study process; they are causes of failure when committed by industry contractors."

When a customer initiates design development intended to lead to construction of a major project, the contract process begins by establishing requirements. This most basic of System Engineering principles is the essential first step toward assuring successful completion of a complex project, yet it has been largely ignored in prior studies of large lunar and Mars settlements. Requirements for contract performance are typically specified in a Request for Proposal (RFP), which includes a Statement of Work (SOW) describing design elements on which the competing contractors will be judged. Although there may be implied requirements (e.g., office areas must have desks and chairs, whether or not they are noted in the SOW), the SOWs for future lunar and Mars settlements will touch on every feature and process that must be designed into the system to keep it safe, functional, and a tolerable place to live. A customer requesting development of a future lunar or Mars settlement—and the contractors that develop it—must consider the settlement as an entire system, rather than a collection of research pieces. The intent of this paper is to summarize requirements likely to appear in SOWs for future settlements on Earth's Moon and Mars.

II. A Generic Lunar or Mars Settlement RFP

In the course of conducting Space Settlement Design Competitions for high school students, the authors have chosen to go well beyond the technical detail necessary to get one, two, or five people into a small community. The logical growth of such a community would come with experience gained in this very new environment. We made a leap of faith to the far distant future where it would be possible to plan a large community. The macro problems of dealing with the environment and distance from Earth combined with designing a unique community are now the challenges with which the students must contend. We also endeavor to create a work environment as similar as possible to what engineers and managers encounter in industry; as a consequence, instead of merely telling student teams to design what they think is right for a particular scenario (essentially replicating the experience of a study group), each Competition employs an RFP to define exactly what the customer wants in the design. Through use in 59 Competitions over 21 years, these documents have become standardized summaries of basic requirements for large space settlement designs in various on-orbit, lunar, and Mars scenarios, and are used here as the source for a

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model SOW. The authors suggest that future space settlement studies can use this model SOW as a “sanity check” for basic completeness of design. It is further suggested, however, that RFPs and designs for smaller surface bases and other habitations can benefit from the experience that has gone into this document, and consider incorporating some of the same factors.

Design Competition SOWs begin with a short introductory paragraph, followed by design requirements for four broad technical areas. The SOW continues with a request to define schedule and cost, and concludes with a description of business areas unique to the particular settlement that will have bearing on its individual design. Competition SOWs specify “minimum requirements” for proposals, which are addressed here in comments following examples of SOW text. As in a real SOW, Space Settlement Design Competition SOWs request consideration of system use after the design and construction process (Table 1), although the Competition format requires brevity.

Table 1. Section 1 of the Model SOW. *An Executive Summary identifies the overall contract expectation.*

Sec.	Topic	SOW Text Describing Requirement
1.	Executive Summary	The contractor will describe the design, development, and construction of the [first or second] space settlement on the surface of [Earth’s Moon or the planet Mars], and develop plans for operations required to maintain the community.

Section 1 generally identifies the Competition scenario, defined by the general type of location (i.e., lunar/Mars surface) and the number of prior settlements in that location. Subsequent sections get into specifics.

A. Structural Design

The overall structural design of the lunar or Mars settlement establishes the limitations on which every other design aspect is based. Larger designs require more materials and longer construction schedules. Smaller designs constrain the amount of area available for residential communities and agriculture, and limit the ability to isolate incompatible land uses. Proximities of areas for various activities in the settlement influence requirements for transportation, communication, and utilities distribution. Reduced gravity on the Moon or Mars influences details like ceiling heights in buildings and structural strength of containment structures. Requirements for these attributes are identified in Section 2 of the Competition SOW (Table 2). Some requirements are intentionally vague, to encourage contractor trade studies that may optimize designs in ways not envisioned by the customer.

Table 2. Section 2 of the Model SOW. *The “Structural Design” section identifies attributes of the overall structure.*

Sec.	Topic	SOW Text Describing Requirement
2.	Structural Design	The settlement must provide a safe and pleasant living and working environment for a community of [between 10,000 and 25,000] full-time residents, plus an additional transient population, not to exceed [between 500 and 2500] at any time, of business and official visitors, guests of residents, and vacationers. The design must enable use of natural light, and views of surrounding terrain.
2.1	External Configuration	Exterior design drawings must identify all volumes and their uses, must illustrate the local terrain and compatibility with it, and must clearly show dimensions of major structural components. Identify construction materials utilized for major structural components. The design and materials must be capable of retaining their functionality and appearance in the [lunar or Mars] environment, without requiring significant expenditures of settlement resources for maintenance and repair. The proposal will specify means for providing protection from radiation and debris penetration.
2.2	Internal Arrangement	The settlement design must specify utilization of interior space, with areas designated and drawings clearly labeled and dimensioned to show residential, industrial, commercial, agricultural, and other uses. The proposal must provide justifications for facility sizes and locations.
2.3	Construction Sequence	The proposal is expected to describe the process required to construct the settlement, by showing the sequence in which major structural components will be assembled.

Most Competition SOWs emphasize the requirement for safety with a request for plans to mitigate two disaster scenarios: penetration by a natural object or debris, and an explosion involving a hazardous chemical. In Mars scenarios, the request to retain “functionality and appearance” addresses the sand-blasting effects of Martian dust storms, which can propel soil at high speeds and cover surfaces with grit. A strong implied requirement for this section is a very high priority on keeping lunar and Martian dust from getting inside the settlement; soils on both the Moon and Mars are extremely fine and have abrasive qualities that are harmful to machinery.

The population defined in the SOW for each Space Settlement Design Competition is selected almost arbitrarily, although only rarely less than 10,000 or more than 25,000 residents. There is usually additional clarification about visitors, with statements like “some of the visitors will be scientists studying Luna”, or “scientists studying Mars, its environment, and indigenous ecosystems.” Given recent improved understanding about the Martian environment, recent Mars scenario RFPs include the requirement that “the site must avoid ice-rich soils, which provide an unstable foundation.”

The primary discriminator in this section is that the structural design must be clearly illustrated. Proposals are expected to show an overall exterior view of the settlement (indicating where launch/landing sites, agricultural areas, residences, and other functions are located), a map or layout of interior land areas, and a drawing showing several intermediate steps of settlement assembly. The judges are especially attentive to assure that the settlement residents have ample opportunities to see views outside the settlement.

B. Operations and Infrastructure

The ability for humans to live and work in a lunar or Mars settlement—essentially for a lifetime—is profoundly affected by the details of infrastructure that they encounter every day. The factors identified by the model SOW are consistent with other research[2]. Section 3 of the Competition SOW assures that contractors will provide basic infrastructure to meet human needs (Table 3).

Table 3. Section 3 of the Model SOW. *The “Operations and Infrastructure” section identifies systems required for basic operation of the settlement.*

Sec.	Topic	SOW Text Describing Requirement
3.	Operations & Infrastructure	Describe facilities and infrastructure necessary for operating the community, including conduct of businesses and accommodating incoming and outgoing spacecraft and surface vehicles.
3.1	Construction Materials Sources	The proposal will identify a recommended location on the [lunar or Mars] surface, and the reasons for its selection. Identify sources of materials and equipment that will be used in construction and operations (Earth, asteroids, existing on-orbit facilities, Luna, Mars, or elsewhere), and means for transporting those materials to the settlement location.
3.2	Community Infrastructure	The proposed settlement design will show elements of basic infrastructure required for the activities of the settlement's residents, including (but not limited to): • food production (including growing, harvesting, storing, packaging, delivering, selling), • electrical power generation and distribution, • internal and external communication systems, • internal and [lunar or Mars] surface transportation systems, • atmosphere/climate/weather control, • household and industrial solid waste management, • water management (including fresh water distribution and sewer routing), and • day/night cycle provisions. Define transportation corridors and means of access throughout and between facilities, including designs of transportation vehicles for use in and around the settlement. Include a diagram and/or map to show movement of imports from port facilities to point of use. Drawings of transportation systems vehicles and rights-of-way must show dimensions. Define storage facilities required to protect against interruption in food production (e.g., contamination or blight) or production of commodities needed for daily life; supply lines for imports may be interrupted for [weeks on Moon or months on Mars].
3.3	Space Infrastructure	Identify existing or new on-orbit infrastructure required to develop or sustain settlement operations (e.g., launch or on-orbit vehicles, satellites, and power plants). Vehicle requirements will specify desired payload weights and sizes, mission durations, flights per year, fleet sizes, turnaround time between missions, and ground-based and/or space-based support facilities. The customer encourages commercial development and operations of new space vehicle(s), which will not be included in settlement construction costs.

Although SOW Section 1 identifies whether the settlement is on the Moon or Mars, this section requests that a specific location be identified, either by proximity to a named terrain feature or with latitude and longitude. Important discriminators in this section include a chart or table showing where materials and equipment are acquired, drawings showing locations and routing of utilities, and a chart or table identifying vehicles and other infrastructure outside the settlement (e.g., solar power satellites) which will be required for effective operations of the settlement. Many of the requirements identified in Paragraph 3.2 influence the internal design elements identified in Section 2; agricultural areas will occupy a significant portion of internal areas, power generation facilities will be large and detectable in the external view of the settlement, and roads may appear on external views or internal maps. It is significant that the SOW allows proposals to identify specifics of the atmosphere; lower atmospheric pressure is acceptable for humans, and can enable cost savings in containment construction.

Access to water is a major discriminator for the Competition judges. On Mars, water in the polar caps and presumed aquifers in low-lying terrain are expected to be relatively straightforward to harvest[3]. On the Moon, although it is tempting to assume that the Clementine and Lunar Prospector missions found abundant water at the lunar poles, more recent research[4] suggests that the hydrogen signatures from those regions belong to very low concentrations of various hydrogen compounds (including water) created by solar wind bombardment and mixed several meters deep into the regolith. The authors of Ref. 4 note that "a great deal of hydrogen and oxygen is available at lower latitudes, too, where it would probably be more accessible to lunar colonists than at the poles."

The length of local days and nights on the Moon requires some consideration of providing artificial days and nights for settlement residents, and the long periods without sun complicate use of solar energy for electrical power at locations other than the poles.

C. Human Factors

The Design Competition organizers are very sensitive to the importance of general habitability to the long-term (perhaps lifelong) residents of a space settlement. The common term "island fever" describes a general penned-in feeling that residents of isolated locations can feel, even if they live in a place that can generally be considered a paradise (e.g., Hawaii). Hence, the requirement from Section 2 that the residents have views of the terrain outside the settlement is reiterated here, and emphasized with a requirement that natural sunlight be provided in living areas. Indeed, site selection may be influenced by aesthetics of surrounding terrain features. The Human Factors section of the SOW has a significant quantity of implied requirements (e.g., houses need furniture, workers need offices, communities need a police station and government facilities), and invites the most creativity from Design Competition participants (Table 4).

Table 4. Section 4 of the Model SOW. *The "Human Factors" section identifies habitability factors.*

Sec.	Topic	SOW Text Describing Requirement
4.	Human Factors	Quality of life is important to customer members, who plan to maintain traditional comforts of Earth without the sacrifices normally associated with a frontier environment. Residents expect traditional community attributes that citizens of Earth's major cities might enjoy (e.g., comfortable houses, fine food, access to world-class entertainment). Assure that natural sunlight and views of the [lunar or Mars] surface are readily available to residents.
4.1	Community Design	Settlement communities will provide facilities for services that residents could expect in a comfortable suburban environment (e.g., housing, education, entertainment, medical, parks and recreation, etc.), variety and quantity of consumables and other supplies, and public areas designed with open space and consideration of psychological factors. The proposal must depict or specify means of distributing consumables to settlement residents.
4.2	Residential Design	Include designs of typical residential homes, clearly showing room sizes. Full-time inhabitants will be customer members who are involved with the settlement's business interests, who operate independent business ventures in the settlement or elsewhere on [Luna or Mars], who manage settlement maintenance and operations, and who produce products and provide services as needed by the community and for trade. Anticipated demographics of the original population are: married adults 50%, single men 26%, single women 22%, children 2%.
4.3	Work Environments	Designs of systems, devices, and vehicles intended for use by humans will consider enhancement of productivity (i.e., efficient use of people's time) in the [lunar or Mars] environment, both inside and outside the settlement. Drawings of these items must clearly indicate their sizes. Spacesuit designs will be required for work and recreation on the surface.

Important discriminators in this section are maps and illustrations of the community design. Proposals are expected to show locations of amenities that people need and use, including grocery stores, churches, restaurants, and shops. Numbers, sizes, and locations of schools and hospitals are expected to be identified. Ceiling heights and long lines of sight in public areas are important factors for psychological health.

Housing designs represent significant trade studies for space settlement development. Space can be conserved and construction costs can be reduced by creating densely populated communities, but the judges consider apartment complexes with small units to be "rabbit warrens" unsuitable for the relatively prosperous and well-educated people expected to form the bulk of space settlement populations. Alternatively, although acreage and large homes would be appreciated by the residents, every acre made habitable comes at a very high cost. Section 4.2 implies a population of professional workers who will appreciate a high standard of living. Demographics are arbitrarily selected (with some expectation that the high cost of transportation will limit the initial population of children), but are provided as a guideline for how many housing units will need to be planned in the initial design. Competition participants are encouraged to recognize that the demographics do portend addition of children to the population.

An expectation associated with Section 4.3 is that proposals identify the types of work that people will do in the settlement, which can be addressed with a chart or table listing tools needed to perform tasks. The judges are looking for tools appropriate to various work environments, vehicles that can be entered and exited quickly, and spacesuits that can be donned and doffed easily.

It is recognized that people either living on or visiting the Moon and Mars will want to "play outside"; they may not need "industrial grade" or custom-fitted spacesuits required for daily use by people who will make a living outside, but the requirement must be addressed. Similarly, residents and visitors will expect access to vehicles for longer excursions on the lunar or Mars surface. An implied requirement for all vehicles and spacesuits used outdoors is that they be designed in a manner that will not bring lunar or Mars dust inside the settlement, which may require some integration with the structural design of doors and/or airlocks to the outside surface.

Yet another implied requirement for human habitation on the Moon and Mars is the need to mitigate effects of long-term residency in reduced natural gravity environments. This is rarely addressed well by students, and occasionally (especially for the lower lunar gravity) inspires designs of colossal spinning rings mounted on inadequately defined spindles or levitated in unquantified electromagnetic fields—which invariably fail to impress the judges.

D. Automation Design and Services

The emphasis in the Human Factors section on a population of professional people residing in space settlements implies that routine, dangerous, and menial tasks will not be done by people. Design Competition scenarios—especially for lunar and Mars locations—are presumed to occur at least two decades in the future, by which time it is expected that significant advancements will be achieved in computing and especially robotics technology. The SOW therefore presents "automation" as a significant and separate technical area, with implications affecting all other design areas (Table 5).

Table 5. Section 5 of the Model SOW. *The "Automation Design and Services" section addresses the use of computers and robots.*

Sec.	Topic	SOW Text Describing Requirement
5.	Automation Design and Services	Contractors' proposals must specify number and types of computers, software, network planning, and robotics applications required for the settlement's facility, community, and business operations. Computer system descriptions will include types and capacities of data storage media, data collection, data distribution, and access of users to computer networks. Show robot designs, clearly indicating their dimensions. Identify locations and sizes of repair, maintenance, and storage facilities, and special transportation corridors for robots.
5.1	Automation of Processes	Describe use of automation for construction. Consider automation for transportation and delivery of materials and equipment, assembly of the settlement, and finishing of the interior.
5.2	Facility Automation	Specify automation systems for settlement maintenance, repair, and safety functions, including backup systems and contingency plans for failures. Define physical locations of computers and robots for critical functions. Robots that operate outdoors must be capable of retaining their functionality and appearance in the [lunar or Mars] environment. Describe means for authorized personnel to access critical data and command computer and robot systems; include descriptions of security measures to assure that only authorized personnel have access, and only for authorized purposes.
5.3	Habitability and Community Automation	Specify automation systems to enhance livability in the community, productivity in work environments, and convenience in residences. Emphasize use of automation to perform maintenance and routine tasks, and reduce requirements for manual labor. Provide for privacy of personal data and control of systems in private spaces. Describe access to community computing and robot resources from individuals' homes and workspaces.

Important discriminators in this section include charts or tables describing automated devices used for settlement construction, and listing automation requirements (specific computers and robots) for operating the settlement.

Drawings of robots, computers, and networks that will be used by the residents serve as a "reality check": the judges look for innovative applications of automation technologies, tempered with the reality that some automated systems we can imagine will take much longer to develop than we would like. The requirement that outdoor robots retain "functionality and appearance" is related, of course, to the abrasive lunar or Martian dust, which is expected to eventually grind to a halt any machinery it invades.

Requirements often overlooked in the Automation section are related to physical sizes and locations of computers, maintenance and repair facilities, and dedicated operating areas that safely separate some robot operations from people and vehicles. Implied requirements include personnel responsible for administering computer systems and maintaining robots, which are also rarely (if ever) addressed.

E. Schedule and Cost

One factor that cannot be avoided in a simulation of industry practices is that the business of business is business—and that means getting paid to deliver products on time. As in real proposals, the most difficult part of the process is to accurately predict the schedule and amount of money that will be required to accomplish development and construction of a space settlement (Table 6).

Table 6. Section 6 of the Model SOW. *The "Schedule and Cost" section defines the construction process.*

Sec.	Topic	SOW Text Describing Requirement
6.	Schedule and Cost	The proposal will include a schedule for completion and occupation of the settlement, and costs for design through construction phases of the schedule.
6.1	Design and Construction Schedule	The schedule must describe contractor tasks from the time of contract award until the customer assumes responsibility for operations of the completed settlement. Show schedule dates when customer members may begin moving into their new homes, and when the entire original population will be established in the community.
6.2	Cost	Specify the costs associated with settlement design through construction in U.S. dollars, without consideration for economic inflation. Include estimates of numbers of employees associated with each phase of design and construction in the justification for contract costs to design and build the settlement.

Because space settlement development will not be a straightforward undertaking, and it can be anticipated that some pitfalls will happen during the design, testing, and construction processes, the primary discriminator for this section of the proposals is the reasonableness of schedule and cost estimates. Schedules must allow time for "back to the drawing board" episodes that may occur during analysis, testing, and construction. It will not be possible to have a completed space settlement operating only five years after contract award; a customer will not be interested in waiting 25 years to have a space settlement completed. It is not possible to find enough people to pay and goods to buy in order to spend a trillion dollars a year on a new commercial project; it is not reasonable to expect that a space settlement can be built with expenditures less than a billion dollars a year.

III. Business Areas

There is no point to building a space settlement—or any community, for that matter—unless it has a purpose. In short, it must enable the customer to make money. How the customer defines the way a settlement is expected to make its living can affect where it is located, and major features of its design (Table 7).

Table 7. Section 7 of the Model SOW. *The "Business Development" section identifies the primary bases of each settlement's economy.*

Sec.	Topic	SOW Text Describing Requirement
7.	Business Requirements	The settlement will host a variety of commercial and industrial ventures, which may change with time. Trade will be conducted with Earth and other space facilities. The basic design must include sufficient flexibility to accommodate development of additional compatible business types with little configuration change. The original configuration must, however, accommodate three major business pursuits:

The Space Settlement Design Competition SOWs typically define three primary business pursuits for initial operations; these vary from one Competition to the next in order to provide variety and challenge for the students. This is an artificial limit because of the Competition format, but is instructive for future space settlement planners: economic success will be more likely if the settlement is optimized for a few business areas. Other capabilities may emerge with time, but initial operations should focus on excelling at a limited number of specialties rather than doing many things poorly.

Although the business areas that will create profit for future space settlements can only be guessed at this time, the diversity described for various lunar and Mars Competition scenarios provides some insight into the activities that will occupy residents. Examples include:

- Exploration, surveying/mapping[2], and research of lunar and Mars surfaces
    - Base for exploration vehicles and mobile laboratories (Ref. 5 provides examples); a significant percentage of settlement population may be "out" at any one time
    - On Mars, base for aerial robot explorers (Ref. 6 provides examples)
    - Base for robot explorers
    - Laboratories for detailed study of samples brought back from the field
    - On the lunar far side, optical and radio astronomy telescopes
- Search for Martian life
    - Laboratories for specialized study of samples that may include life forms
    - Quarantine capability if life is found
- Harvesting/mining of lunar and Martian resources
    - Logistics support for operations in multiple remote locations
    - Manufacture of specialized equipment and vehicles for harvesting local resources
    - Maintenance and repair facilities for equipment to harvest resources
- Lunar or Mars ores refining and manufacturing
    - Capability to produce useful things from local materials for settlement use (e.g., vehicles, robots, computers, construction equipment, construction materials, consumable goods)
    - Production of both raw and refined materials for export
    - Production of goods for export
- Export/Import center for lunar / Martian commerce
    - Transportation system(s) for distributing imports and getting exports to landing/launch site
    - Cargo handling systems to unload, warehouse, and load
    - Major lunar exports: helium-3[7], materials for on-orbit manufacturing, chemicals and products for human activities in Earth orbit
    - Major Mars exports: deuterium[8], provisions for ships near Mars orbit (water, air, fuel, agricultural products, consumable goods)
- Base for development of infrastructure on the Moon and Mars
    - System for safe navigation of remote areas and/or undeveloped travel routes
    - Surveying to identify locations for future settlements and other operations
    - Road and/or rail construction for travel between major destinations
    - Construction of additional large settlements and other habitations
    - Maintenance and repair of construction equipment
    - On the Moon, construction and operation of mass driver(s)[9] for inexpensive and less polluting launch services (on Mars, mass drivers would be feasible on any of four major extinct volcanoes, which rise above the atmosphere)
- Tourist destination and resort
    - Passenger terminal for disembarkation from transport ships
    - Lodging, restaurants, and things for visitors to buy
    - Access to places visitors want to see and things they want to do
    - Lunar- and Mars-unique sports and amusement park experiences
- On Mars, base for terraforming
    - Construction of space-based terraforming aids (e.g., super-soletta to warm the planet)
    - Development and deployment of surface-based terraforming aids (e.g., mine and release nitrogen and oxygen into the atmosphere, bring water to the surface, develop new life forms)

Consideration of the infrastructure required for some of these various businesses illustrates that there are opportunities for compatibilities, and risks of incompatibilities, which would lead to design compromises. An example of compatible services is an export/import center with tourist facilities that serves as a base for exploration, research, and infrastructure development; some synergy could accrue between excursions for exploration, tourism, and deployment of construction equipment. An example of less compatible services that could lead to design compromises and inefficiencies is a large strip-mining operation with raw materials refining and manufacturing, combined with agricultural production for export and a tourist facility; this scenario combines large installations that could compete with each other for resources and personnel, and may limit visitor entertainment options or even jeopardize visitor safety. The developers of early space settlements will be well advised to plan different communities for different purposes.

IV. Unique Requirements for Specific Lunar and Mars Settlement Scenarios

Ref. 2 differentiates between “Scientific Exploration & Research” and “Commercial Exploration” on Mars, and this distinction will also be true for Luna. The early small settlements on the Moon and Mars are expected to focus primarily on scientific study. As research from these installations identifies profit-making opportunities, missions for exploration equipment—both existing and new—will evolve to support the studies most interesting for commercial development.

Tourist experiences will be different on Luna and Mars; a lunar vacation may be accomplished in two weeks, but a journey to Mars involves a far greater commitment of time and treasure. Whereas lunar tourists may be satisfied with excursions to a few historical sites and scenic areas, a day of “play” in 1/6 g (both indoors and outdoors), and shopping for unique souvenirs, visitors to Mars will want to “see it all” after spending months to get there. It will behoove planners of Mars settlement tourist facilities to map out itineraries that will keep visitors entertained for a month or more before they return to Earth.

By the time humans are ready to establish a major presence on Mars, other enterprises will have created regular (if infrequent) destinations in more distant parts of the solar system. These may include asteroid mining operations, or exploration missions to the outer planets. The numbers and types of ships engaged in these voyages will depend on what humans find in these far-flung locations, and what they decide to do about the assets they find. The existence of this traffic is, however, likely to create both commercial and humanitarian missions for a Mars settlement. The commercial opportunities will arise from the need for all ships traversing distant areas to occasionally take on provisions, just as seafaring exploration missions did in earlier centuries. Whether or not those ships have capability to land on Mars, they will be able to enter Mars orbit or request rendezvous from a supply ship, and will be eager to take on water, food, air, fuel, and consumable commodities produced on Mars. Crews on long-term missions may be allowed extended stays at a Mars settlement for “R & R”. Regularly-scheduled cargo and passenger missions between Earth and Mars will also plan to take on supplies at Mars, instead of storing enough for round trips from/to Earth. Humanitarian missions will be requested when these long-distance ships experience medical emergencies, damage, equipment failures, or any other incident that merits a request for a rescue mission.

Finally, although it is tempting to think of the Moon and Mars as lifeless, desolate landscapes that present themselves for exploitation by humans to relieve the ills of home planet Earth, eventually these places will be homes for people, too. The Moon especially has no natural mechanisms for erasing the scars that humans leave, and space settlers will be wise to consider future uses of the land in their planning for initial operations in each new location. Mass driver technology represents an opportunity to launch materials and vehicles without producing a lunar atmosphere of rocket exhaust or causing smog on Mars. When inspired to include these considerations in their designs, Space Settlement Design Competition participants occasionally suggest innovations that may not be obvious to the rest of us: one young man suggested that a “reverse mass driver” could enable a ship to land on the Moon or Mars without emitting chemical exhaust.

V. Conclusion

When the real RFPs for the first lunar and Mars settlements are actually issued, decades in the future, they will be both significantly different from and eerily similar to the documents described here. The differences will arise from advances in technology and understanding of space settlement requirements; the similarities will be due to the priority to satisfy the basic needs of human existence. Although the RFPs developed for Space Settlement Design Competitions serve a primary function as educational tools for young people, they can also have value for the technical community as indicators of the breadth of research and system development that must occur before space settlements can be considered feasible. All of the elements described here must be worked in order for settlements on the Moon and Mars to happen.

Acknowledgments

The authors thank the thousands of students and hundreds of volunteers who have inspired us to continue improving the materials we develop for Space Settlement Design Competitions. Somewhere along the line, we realized that what we produce for them goes beyond what we have found in the technical literature, so we now write papers to share these insights with the technical community. Indeed, this paper will be made available to future participants in Competitions with lunar and Mars scenarios, to help them better understand what we look for in winning proposals.

References

[1]Gale, A. E., and Edwards, R. P., "Requirements for Space Settlement Design," *Space Technology and Applications International Forum-STAIF 2004* [CD-ROM], American Institute of Physics c/o Springer-Verlag, New York, 2004, pp. 1067-1074.

[2]Gustafson, R. J., Rice, E. E., Gramer, D. J., and White, B. C., "A View of Future Human Colonies on Mars," *Space Technology and Applications International Forum - STAIF 2003* [CD-ROM], American Institute of Physics c/o Springer-Verlag, New York, 2003, pp. 1250-1257.

[3]Powell, J., Maise, G., and Paniagua, J., "Xanadu: A Polar Base for Manufacturing Supplies on Mars," *Space Technology and Applications International Forum-STAIF 2004* [CD-ROM], American Institute of Physics c/o Springer-Verlag, New York, 2004, pp. 951-958.

[4]Vondrak, R. R., and Crider, D. H., "Ice at the Lunar Poles," *American Scientist*, Vol. 91, No. 4, July-August 2003, pp. 322-329.

[5]Cohen, M. M., "Mobile Lunar and Planetary Bases," *Space 2003 Proceedings* [CD-ROM], AIAA, Reston, VA, 2003.

[6]Pankine, A. A., et al., "Mars Exploration with Directed Aerial Robot Explorers," *Space Technology and Applications International Forum-STAIF 2004* [CD-ROM], American Institute of Physics c/o Springer-Verlag, New York, 2004, pp. 1019-1026.

[7]Schrunk, D., Sharpe, B., Cooper, B., Thangavelu, M., *The Moon – Resources, Future Development and Colonization*, Wiley-Praxis Series in Space Science and Technology, Praxis Publishing Ltd, Chichester, England, 1999, pp. 301-303.

[8]Zubrin, R., *The Case for Mars*, The Free Press, Simon & Schuster Inc., New York, 1996, pp. 224-225, 245-246.

[9]Heppenheimer, T.A., *Colonies in Space*, Stackpole Books, Harrisburg, Pennsylvania, 1977, pp. 82-90.