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Space Settlements

A Design Study

Edited by

- Richard D. Johnson, NASA Ames Research Center
- Charles Holbrow, Colgate University

Authored by the participants of

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Foreword

SPACE SETTLEMENTS: A DESIGN STUDY

The question, "What is feasible?" can be finally answered only by future historians. If in the 14th and l5th Centuries when new technology first made transoceanic voyages possible, European rulers had inquired what they should do with this new capability, no man could have been long-headed enough to perceive all the possibilities, nor persuasive enough to communicate his vision to others. We now realize that technology is but a part of any broad stride taken by man. A perception of advantage to be gained, resolve, organization, and a continuity of effort - some of the elements that must combine with technology to effect a major human advance - is indeed vital

Space exploration, an active pursuit for less than two decades, has already displayed an extraordinary power to alter our viewpoints and stretch our minds. The concept of spacecraft Earth, a sphere of finite resources and ominous pollution, became pervasive and powerful at the same time we first received good photographs of our planetary home. The study summarized in this volume is another mind-stretcher. As explained on the following page, settlement in space is not an authorized program, and no man can now say if or when such a dazzling venture may be formally undertaken. But by their efforts to put numbers on an idea, to assess the human and economic implications as well as technical feasibility, the participants in this effort have provided us with a vision that will engage our imagination and stretch our minds

James C Fletcher
Administrator
National Aeronautics and Space Administration
October 1, 1976

Preface

The following report grew out of a 10 week program in engineering systems design held at Stanford University and the Ames Research Center of the National Aeronautics and Space Administration during the summer of 1975. This program, sponsored jointly by NASA and the American Society for Engineering Education, brought together nineteen professors of engineering, physical science, social science, and architecture, three volunteers, six students, a technical director, and two co-directors. This group worked for ten weeks to construct a convincing picture of how people might permanently sustain life in space on a large scale.

This report, like the design itself, is intended to be as technologically complete and sound as it could be made in ten weeks, but it is also meant for a readership beyond that of the aerospace community. Because the idea of colonizing space has awakened strong public interest, the report is written to be understood by the educated public and specialists in other fields. It also includes considerable background material. A table of units and conversion factors is included to aid the reader in interpreting the units of the metric system used in the report.

The goal of the summer study was to design a system for the colonization of space. The study group

was largely self-organized; it specified important subsidiary goals, set up work groups, and elected its project managers and committee heads. There were three project managers; each served for three weeks during which he assigned tasks, coordinated activities and developed the outline of the final report. As a consequence of this organization, the report represents as nearly as is possible the views of the entire study group. The conclusions and recommendations are the responsibility of the participants and should not be ascribed to any of the sponsoring organizations; NASA, ASEE, or Stanford University .

An effort of the magnitude of this design study could not have been possible without major contributions by many individuals. The co-directors, Richard Johnson of NASA and William Verplank of Stanford, made available to and guided participants in the use of the resources of the Ames Research Center and Stanford University. Their continuing helpfulness and timely assistance were important contributions to the successful conclusion of the project.

The technical director, Gerard K. O'Neill of Princeton University, made essential contributions by providing information based on his notes and calculations from six years of prior work on space colonization and by carefully reviewing the technical aspects of the study.

So many able and interesting visitors contributed to the study participants' understanding of the problem of designing a workable system for colonizing space that it is not feasible to thank them all here. Nevertheless, it is appropriate to acknowledge those from whom the study group drew especially heavily in the final design. In particular Roger Arno, Gene Austin, John Billingham, Philip Chapman, Hubert P. Davis, Jerry Driggers, Peter Glaser, Albert Hibbs, Arthur Kantrowitz, Ken Nishioka, Jesco von Putkammer, and Gordon Woodcock are thanked for their help and ideas.

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LIST OF PARTICIPANTS
IN THE NASA-ASEE ENGINEERING SYSTEMS DESIGN SUMMER PROGRAM
June-August 1975

Faculty Fellows

ABO-EL-ATA, MAMDOUH
Division of Engineering
San Francisco State University
San Francisco, California 94132

FOX, JOEL
Mechanical Engineering
University of Hawaii
Honolulu, Hawaii 96822

GIESBRECHT, MARTIN
Department of Economics and Administration
Wilmington College
Wilmington, Ohio 45177

HANNAH, ERIC
Physics Department
Princeton University
Princeton, New Jersey 08540

HEPPENHEIMER, THOMAS
Division of Geological and Planetary Sciences
California Institute of Technology
Pasadena, California 91125

HILL, PATRICK
Archietecture & Environmental Design
California Polytechnic State University
San Luis Obispo, California 93401

HOLBROW, CHARLES
Department of Physics & Astronomy
Colgate University
Hamilton, New York 13346

HUBBARD, MONT
Mechanical Engineering
University of California
Davis, California 95616

HUDDLESTON, JR., TED
Chemical Engineering
University of Mississippi
University, Mississippi 38677

JEBENS, HAROLD
Civil Engineering
University of Wisconsin-Platteville
Platteville, Wisconsin 53818

LOPEZ, DAVID
Dept. of Management & Organization
University of Washington
Seattle, Washington 98195

MARUYAMA, MAGOROH
Systems Science
Portland State University
Portland, Oregon 97207

MORGAN, DONALD
Industrial Engineering Department
California Polytechnic State University
San Luis Obispo, California 93407

OWEN, GORDON
Division of Engineering

San Francisco State University
San Francisco, California 94132

POLLACK, BARY
Dept. of Electrical Engineering and Computer Sciences
University of California
Berkeley, California 94720

RICHARDS, JR., ROWLAND
Civil Engineering
University of Delaware
Newark, Delaware 19711

RUSSELL, ALLAN
Department of Physics
Hobart and Wm Smith Colleges
Geneva, New York 14456

SUTTON, GORDON
Department of Sociology
University of Massachusetts
Amherst, Massachusetts 01002

VOLTMER, DAVID
121 Electrical Engineering East
Pennsylvania State University
University Park, Pennsylvania 16802

Students

BRODY, STEVEN
54-620
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

BUGOS, BEVERLY (Hazelton)
Aeronautics & Astronautics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

DREXLER, ERIC
Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

HOPKINS, MARK
Department of Economics
Harvard University
Cambridge, Massachusetts 02138

SPERBER, B. RAY
Department of Physics
Massachusetts Institute of Technology

Cambridge, Massachusetts 02139

WINKLER, LAWRENCE H.
Aeronautics & Astronautics; Life Sciences
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Visitors

MACHOL, ROBERT
Management Science
Northwestern University
Evanston, lllinois 60201

SKLAREW, RALPH
Xonics
963 Dunlin Circle
Westlake Village, California 91361

JONES, ROBERT T.
Code D
Ames Research Center
Moffett Field, California 94035

Technical Director

O'NEILL, GERARD K.
Department of Physics
Princeton University
P.O. Box 708
Princeton, New Jersey 08540

Co-Directors

JOHNSON, RICHARD D.
Chief, Biosystems Division
Ames Research Center
Moffett Field, California 94035

VERPLANK, WILLIAM
Mechanical Engineenng
Stanford University
Stanford, California 94305

1. The Colonization of Space

We have put men on the Moon. Can people live in space? Can permanent communities be built and inhabited off the Earth? Not long ago these questions would have been dismissed as science fiction, as fantasy or, at best as the wishful thinking of men ahead of their times Now they are asked seriously not only out of human curiosity, but also because circumstances of the times stimulate the thought that

space colonization offers large potential benefits and hopes to an increasingly enclosed and circumscribed humanity.

Permanent communities can be built and inhabited off the Earth. The following chapters present a detailed description of a system for the colonization of space. It is not the best system that can be devised; nor is it complete. Not all the important questions about how and why to colonize space have been posed. Of those that have, not all have been answered satisfactorily. Nevertheless, the 10-week summer study is the most thorough and comprehensive one made to date. On its basis space colonization appears to be technically feasible, while the obstacles to further expansion of human frontiers in this way are principally philosophical, political, and social rather than technological.

THE OVERALL SYSTEM

The focus of the system is a space habitat where 10,000 people work, raise families, and live out normal human lives. Figure 1-1.shows the wheel-like structure in which they live. This structure orbits the Earth in the same orbit as the Moon in a stable position that is equidistant from both Earth and Moon. This is called the Lagrangian libration point, L5. The habitat consists of a tube 130 m (427 ft) in diametral cross section bent into a wheel 1790 m (over 1 mi) in diameter. The people live in the ring-shaped tube which is connected by six large access routes (spokes) to a central hub where incoming spacecraft dock. These spokes are 15 m (48 ft) in diameter and provide entry and exit to the living and agricultural areas in the tubular region. To simulate Earth's normal gravity the entire habitat rotates at one revolution per minute about the central hub.

Much of the interior of the habitat is illuminated with natural sunshine. The Sun's rays in space are deflected by a large stationary mirror suspended directly over the hub. This mirror is inclined at 45 degrees to the axis of rotation and directs the light onto another set of mirrors which, in turn, reflect it into the interior of the habitat's tube through a set of louvered mirrors designed to admit light to the colony while acting as a baffle to stop cosmic radiation. With the help of abundant natural sunshine and controlled agriculture, the colonists are able to raise enough food for themselves on only 63 ha (156 acres). The large paddle-like structure below the hub is a radiator by which waste heat is carried away from the habitat.

Abundant solar energy and large amounts of matter from the Moon are keys to successfully establishing a community in space. Not only does the sunshine foster agriculture of unusual productivity, but also it provides energy for industries needed by the colony. Using solar energy to generate electricity and to power solar furnaces the colonists refine aluminum, titanium, and silicon from lunar ores shipped inexpensively into space. With these materials they are able to manufacture satellite solar power stations and new colonies. The power stations are placed in orbit around the Earth to which they deliver copious and valuable electrical energy. The economic value of these power stations will go far to justify the existence of the colony and the construction of more colonies.

Principal components of the overall space colonization system and their interrelations are shown schematically in figure 1-2.

DESIGN GOALS

This system is intended to meet a set of specific design goals established to guide the choice of the principal elements of a practicable colony in space. The main goal is to design a permanent community in space that is sufficiently productive to maintain itself, and to exploit actively the environment of

space to an extent that permits growth, replication, and the eventual creation of much larger communities. This initial community is to be a first step in an expanding colonization of space.

To effect this main goal, the following subsidiary goals must be met using existing technology and at minimum cost:

1. Design a habitat to meet all the physiological requirements of a permanent population and to foster a viable social community.
2. Obtain an adequate supply of raw materials and provide the capability to process them.
3. Provide an adequate transport system to carry people, raw materials, and items of trade.
4. Develop commercial activity sufficient to attract capital and to produce goods and services for trade with Earth.

Fortunately, the design study could draw on substantial earlier work. Active interest in space colonization as a practical possibility began in 1969 when Gerard O'Neill and students at Princeton University undertook a detailed assessment of space colonization. They aimed at a model to show the feasibility of a space colony rather than an optimum configuration and they selected as a test case a rotating habitat in satellite orbit around the Earth at the distance of the Moon, using solar energy to sustain a closed ecological system. They proposed a habitat constructed of processed lunar ore delivered by an electromagnetic accelerator and located at either the Lagrangian point L4 or L5 in order to make delivery of the ore as simple as possible. (The Lagrangian points are described in ch. 2.) The habitat was configured as a l-km long cylinder with hemispherical end-caps. It was to have an Earth-like internal environment on the inner surface and be supplied with sunlight reflected from mirrors (ref. 1).

Subsequently, the Princeton group suggested that the L5 colony could construct solar power stations from lunar material. They concluded that this would improve the economics of both the satellite solar power stations and the colony itself (ref. 2).

The concept of satellite solar power stations has received increasing attention since its introduction by Peter Glaser in 1968 (ref. 3). These ideas were further considered and developed by a conference "Space Manufacturing Facilities" which took place at Princeton University on May 7-9, 1975 and focused more attention on O'Neill's test case.

This report presents a rationale for the design choices of the Ames-Stanford study group and it details how the various parts of the system interrelate and support each other. The next three chapters discuss successively how the properties of space specify the criteria that a successful design must satisfy, what human needs must be met if people are to live in space, and the characteristics of various alternative components of the design. Some readers may wish to skip directly to chapter 5 where the details of the operation of the system are described. Chapter 6 provides a detailed analysis of the sequence of events needed for the colony to be built. Timetables, manpower requirements, and levels of funding are presented for the construction of the main parts of the overall system. This chapter also looks at long-term benefits from solar power stations in space and some possible ways to structure economics so as to initiate the establishment and growth of many colonies over the long term. Chapter 7 looks at the future development of colonization of space, and finally chapter 8 discusses why space colonization may be desirable and provides some conclusions and recommendations for further activities and research.

THE HISTORY OF AN IDEA

The history of the idea of space colonization extends back into myths and legends of ancient times, but the first account of an actual space colony appeared in 1869 when Edward Everett Hale's novel, Brick Moon, described how a colony in space happened by accident.

A brick sphere, intended for guiding maritime navigators, was to be catapulted into Earth orbit by rotating wheels. When it rolled onto the catapult too soon, still containing many workers inside, the first space colony was launched. Fortunately, the workers had ample food and supplies (even a few hens), and they decided to live the good life permanently in space, maintaining contact with the Earth only by a Morse code signalled by making small and large jumps from the external surface of their tiny spherical brick colony (ref. 4).

The following quotation on the history of the idea of space colonization is taken with permission directly from "Space Colonization Now?" by Robert Salkeld, Astronautics and Aeronautics, September,1975.

"Precursors of the notion of small self-contained worlds in space appeared in novels by Jules Verne in 1878 and Kurd Lasswitz in 1897 (refs.5, 6).

"In 1895 the space-station concept was noted from a more technical viewpoint in a science-fiction story by Konstantin Tsiolkovsky (ref. 7). In 1903 Tsiolkovsky expanded his description of the manned space station to include rotation for artificial gravity, use of solar energy, and even a space "greenhouse" with a closed ecological system (ref. 8). Thus, at the turn of the Twentieth Century, the idea of the space habitat was defined in terms of some of its basic elements. The idea progressed slowly over the next fifty years, then accelerated. In 1923 Hermann Oberth elaborated on potential uses of space stations, noting that they could serve as platforms for scientific research, astronomical observations, and Earth-watch (ref. 9). In 1928 Guido von Pirquet considered a system of three stations, one in a near orbit, one more distant, and a transit station in an intermediate elliptical orbit to link the other two; he suggested that they might serve as refueling depots for deep space flights (ref. 10). The concept of a rotating wheel-shaped station was introduced in 1929 by Potocnik, writing as Hermann Noordung. He called his 30-m-diam station "Wohnrad" (living wheel) (1) and suggested that it be placed in geosynchronous (2) orbit (ref. 11). During World War II, space stations received some military study in Germany (ref. 12), and after the war the idea surfaced again in technical circles as a geosynchronous rotating-boom concept (3) proposed by H. E. Ross in 1949 (ref. 13).

"The space-station idea was popularized in the United States by Wernher von Braun. In 1952 he updated Noordung's wheel, increased the diameter to 76 m, and suggested a 1730-km orbit (ref. 14). At about the same time, Arthur C. Clarke published "Islands in the Sky," a novel involving larger stations (ref. 15), and in 1961 Clarke (in another novel) suggested placing large stations at the Lagrangian libration points where they would maintain a fixed position relative to both the Earth and the Moon (ref. 16). In 1956 Darrell Romick advanced a more ambitious proposal for a cylinder I km long and 300 m in diameter with hemispherical end-caps having a 500-m-diam rotating disc at one end to be inhabited by 20,000 people (ref. 17).

"The companion idea of a nuclear-propelled space ark carrying civilization from a dying solar system toward another star for a new beginning was envisioned in 1918 by Robert Goddard. Possibly concerned about professional criticism, he placed his manuscript in a sealed envelope for posterity and it did not see print for over half a century (ref. 18). In 1929 the concepts of artificial planets and self-contained worlds appeared in the works of 1. D. Bernal and Olaf

Stapledon, and by 1941 the interstellar ark concept had been fully expanded by Robert A. Heinlein and others, many appearing in the science-fiction publications of Hugo Gernsback and others (refs. 19-24). In 1952 the concept was outlined in more technical detail by L. R. Shepherd (ref. 25), who envisioned a nuclear-propelled million-ton interstellar colony shaped as an oblate spheroid, which he called a "Noah's Ark."

"A related idea, the use of extraterrestrial resources to manufacture propellants and structure, was suggested by Goddard in 1920. It became a common theme in science fiction and reappeared in technical literature after World War 11. In 1950 A. C. Clarke noted the possibility of mining the Moon and of launching lunar material to space by an electromagnetic accelerator along a track on its surface (ref. 26).

"In 1948 Fritz Zwicky suggested use of extraterrestrial resources to reconstruct the entire universe, beginning with making the planets, satellites, and asteroids habitable by changing them intrinsically and changing their positions relative to the Sun (ref. 27). A scheme to make Venus habitable by injecting colonies of algae to reduce atmospheric CO_2 concentration was proposed in 1961 by Carl Sagan (ref. 28). In 1963 Dandridge Cole suggested hollowing out an ellipsoidal asteroid about 30 km long, rotating it about the major axis to simulate gravity, reflecting sunlight inside with mirrors, and creating on the inner shell a pastoral setting as a permanent habitat for a colony (ref. 29).

"In 1960 Freeman Dyson suggested an ultimate result of such planetary engineering (ref. 30); processing the materials of uninhabited planets and satellites to fashion many habitats in heliocentric orbits. A shell-like accumulation of myriads of such habitats in their orbits has been called a Dyson sphere."

On July 20, 1969 Astronauts Neil A. Armstrong and Edwin E. Aldrin, Jr., walked on the Moon. In the context of history just reviewed the ". . . one small step for a man, one giant leap for mankind" appears quite natural and unsurprising. And if the first step is to be followed by others, space colonization may well be those succeeding steps. Perhaps mankind will make the purpose of the next century in space what Hermann Oberth proposed several decades ago:

"To make available for life every place where life is possible. To make inhabitable all worlds as yet uninhabitable, and all life purposeful."

2. Physical Properties of Space

The physical properties of space are rich in paradoxes. Space seems empty but contains valuable resources of energy and matter and dangerous fluxes of radiation. Space seems featureless but has hills and valleys of gravitation. Space is harsh and lifeless but offers opportunities for life beyond those of Earth. In space, travel is sometimes easier between places far apart than between places close together.

The purpose of this chapter is to explore and understand these properties of space and the apparent paradoxes to derive a set of basic design criteria for meeting the goals for space colonization set out in chapter 1. Together with considerations of the physiological and psychological needs of humans in space, these basic criteria compose the quantitative and qualitative standards on which the design of the space colonization system is based. These criteria also serve as the basis for a discussion and comparison of various alternative ways to locate, organize and construct, and interconnect the mines,

factories, farms, homes, markets, and businesses of a colony in space.

THE TOPOGRAPHY OF SPACE

For the resources of space to be tapped safely, conveniently and with minimum drain on the productive capabilities of the colonists and Earth, the peculiarities of the configuration of space must be understood.

Planets and Moons: Deep Gravity Valleys

Gravitation gives a shape to apparently featureless space; it produces hills and valleys as important to prospective settlers in space as any shape of earthly terrain was to terrestrial settlers. In terms of the work that must be done to escape into space from its surface, each massive body, such as the Earth and the Moon, sits at the bottom of a completely encircled gravitational valley. The more massive the body, the deeper is this valley or well. The Earth's well is 22 times deeper than that of the Moon. Matter can be more easily lifted into space from the Moon than from the Earth, and this fact will be of considerable importance to colonists in deciding from where to get their resources.

Libration Points: Shallow Gravity Wells

There are other shapings of space by gravity more subtle than the deep wells surrounding each planetary object. For example, in the space of the Earth-Moon system there are shallow valleys around what are known as Lagrangian libration points (refs. 1, 2). There are five of these points as show in figure 2-1, and they arise from a balancing of the gravitational attractions of the Earth and Moon with the centrifugal force that an observer in the rotating coordinate system of the Earth and Moon would feel. The principal feature of these locations in space is that a material body placed there will maintain a fixed relation with respect to the Earth and Moon as the entire system revolves about the Sun.

The points labeled Ll, L2, and L3 in figure 2-1 are saddle-shaped valleys such that if a body is displaced perpendicularly to the Earth-Moon axis it slides back toward the axis, but if it is displaced along the axis it moves away from the libration point indefinitely. For this reason these are known as points of unstable equilibrium. L4 and L5 on the other hand represent bowl-shaped valleys, and a body displaced in any direction returns toward the point. Hence, these are known as points of stable equilibrium. They are located on the moon's orbit at equal distances from both the Earth and Moon.

The foregoing picture is somewhat oversimplified; it neglects the effect of the Sun. When this is taken into consideration (refs. 3, 4), stable equilibrium is shown to be possible only in particular orbits around L4 and L5, as indicated by the dashed lines in figure 2-1. The shape of The shape of space around L4 and L5 is discussed in detail in reference 4. The basic conclusion is that massive objects placed in the vicinity of L4 and L5 would orbit these points with a period of about one month while accompanying the Earth and Moon around the Sun. At the price of the expenditure of some propulsive mass, objects could be maintained near the other libration points rather easily (ref. 5). The cost of such station keeping needs to be better understood before the usefulness of these other points for space colonies can be evaluated.

Two Kinds of Separation in Space: Metric Distance vs Total Velocity Change (Δv)

The availability of resources for use by colonists is closely related to the properties of space. The colony should be located where station-keeping costs are low, where resources can be shipped in and out with little expenditure of propulsion mass, and where the time required to transport resources and people is short. These three criteria, minimum station-keeping, minimum propulsion cost, and

minimum transportation time cannot be satisfied together. Some balance among them is necessary. In particular, time and effort of transportation are inversely related.

Figure 2-1 shows the distances between points in the vicinity of Earth of importance to space colonization. The diagram is to scale, and the distances are roughly in proportion to time required to travel between any two points. However, in space travel the important measure of propulsive effort required to get from one point to another is the total change in velocity required (Δv). Thus the Δv to go from low Earth orbit (an orbit just above the atmosphere) to lunar orbit is 4100 m/s, which is only 300 m/s more than to go to geosynchronous orbit (note that these numbers are not additive). Figure 2-2 shows a schematic diagram of the Δv's required to move from one point to another. It is drawn to scale with respect to Δv, and shows that most of the effort of space travel near the Earth is spent in getting 100 km or so off the Earth, that is, into low Earth orbit. Note, this orbit is so close to the Earth's surface that it does not show on the scale of figure 2-1. Thus travel time to low Earth orbit is a few minutes, but the effort required to obtain this orbit is very large. Or, again revealing the inverse relation between travel time and effort, to go from low Earth orbit to lunar orbit takes about 5 days, but requires less than half the effort needed to go from the Earth's surface to low orbit. Figure 2-2 also shows that certain points that are far apart in distance (and time) are quite close together in terms of the propulsive effort required to move from one to the other; for example, geosynchronous orbit, L5, and lunar orbit.

The three primary criteria for choosing sites for the various parts of the colony - mines, factories, farms, homes, markets - are ease of access to needed resources, rapidity of communication and transportation and low cost. The topography of space can be exploited to achieve satisfactory balances among them.

SOLAR RADIATION: AN ABUNDANT AND ESSENTIAL SOURCE OF ENERGY

Although apparently empty, space is in fact filled with radiant energy. Beyond Earth's atmosphere this energy flows more steadily and more intensely from the Sun than that which penetrates to the surface of the Earth. Through one square meter of space facing the Sun pass 1390 W of sunlight; this is nearly twice the maximum of 747 W striking a square meter normal to the Sun at the Earth's surface. Since the Earth does not view the Sun perpendicularly and is dark for half of each day, a square meter of space receives almost 7.5 times the sunlight received by an average square meter on the whole of the Earth. Figure 2-3 compares the wavelength distribution of the Sun's energy as seen from above the Earth's atmosphere with that seen at the surface of the Earth and shows that not only is the intensity of sunlight greater in space, but also there are available in space many wavelengths that are filtered out by the Earth's atmosphere.

To live in space humans must be protected from the fierce intensity and penetrating wavelengths of unattenuated sunlight, but this same energy is one of the primary resources of space. If this steady, ceaseless flux of solar energy is tapped its value may be very large. If the Sun's energy is converted with 10 percent efficiency to electrical power which is sold at a rate of $.012/kW-hr, a square kilometer of space would return more than $14,000,000 each year.

It is important for the colonization of space that an effective way be found to use this solar energy.

MATTER IN SPACE: A MAJOR RESOURCE

Space is extraordinarily empty of matter. The vacuum of space is better than any obtainable with the

most refined laboratory equipment on Earth. This vacuum may be a resource in its own right, permitting industrial processes impossible on Earth. Nevertheless, there is matter in space and it is of great interest to space colonization.

Matter in space comes in a broad spectrum of sizes great masses that are the planets and their satellites, smaller masses that are the asteroids, even smaller meteoroids, and interplanetary dust and submicroscopic particles of ionizing radiation. The entire range is of interest to space colonization because the principal material resources must come from the great masses while meteoroids and ionizing radiation may be dangerous to the colony's inhabitants.

Sources of Matter in Space

The principal material resources of space are the planets, their moons, and asteroids. Their accessibility is determined by distance from possible users of the material and by the depth of the gravitational wells through which the matter must be lifted.

The planets of the solar system are major loci of material resources, but they are mostly very distant from prospective colonies, and all sit at the bottoms of deep gravitational wells. The effort to haul material off the planets is so great as to make the other sources seem more attractive. Of course, if a planet is nearby and is rich in resources, a colony might find the effort justified. Consequently, the Earth could be an important source of material to a colony in its vicinity, especially of the elements hydrogen, carbon, and nitrogen that are not available in sufficient amounts elsewhere near Earth.

The moons of planets, with their usually shallow gravitational wells, offer an attractive source of needed matter. The moons of Mars have very shallow wells, but they are too distant from any likely initial site for a colony to be useful The same argument applies even more strongly to the more distant satellites of the outer planets. It is the Earth's natural satellite, the Moon, that offers an attractive prospect. The Moon is near the likely initial sites for a space colony; its gravitational well is only 1/22 as deep as that of the Earth. Moreover, as figure 2-4 shows, the Moon can be a source of light metals, aluminum, titanium, and iron for construction, oxygen for respiration and rocket fuel, and silicon for glass (ref. 6). There are also trace amounts of hydrogen (40 ppm) and carbon on the Moon, but not enough to supply a colony. Certainly the Moon's resources, supplemented with small amounts of particular elements from Earth, can supply all the elements necessary to sustain human life and technology in a space colony.

Asteroids offer some interesting possibilities. They have very shallow gravitational wells; some come closer to Earth than Mars; and some asteroids may contain appreciable amounts of hydrogen, carbon, and nitrogen as well as other useful minerals (refs. 7-14). Moving in well determined orbits which could be reached relatively easily, the asteroids may become exceptionally valuable resources, especially those that contain appreciable amounts of water ice and carbonaceous chondrite.

Comets may also be included in this inventory of material resources of space. Like many meteoroids, comets are thought to be "dirty snowballs," a conglomerate of dust bound together with frozen gases and ice. Comets are not suitable resources because of their high velocity and their infrequent penetration of the inner Solar System.

Meteoroids: An Insignificant Danger

Measurements made on Earth, in space, and on the Moon (refs. 8,10,11,13) have provided a fairly complete picture of the composition, distribution, and frequency of meteoroids in space. Near the Earth most of these travel relative to the Sun with a velocity of about 40 km/s. Figure 2-5 plots the frequency of meteoroids exceeding a given mass versus the mass, that is, it gives an integral flux. This graph

shows that on the average a given square kilometer of space will be traversed by a meteoroid with a mass of 1 g or greater about once every 10 years, and by one with mass of 100 g or greater about once in 5000 years. A 10-kg meteoroid might be expected once every 100,000 years.

Danger of collision of a large meteoroid with a space habitat seems remote. But meteoroids occur frequently in clusters or showers, so that when one collision is likely, so are several more. There is a possibility of a correlated sequence of collisions with attendant damage more serious and complicated than from a single collision. This form of risk would only occur on a time scale of hundreds of years, which is the time scale characteristic of the occurrence of showers of meteoroids.

Although the probability of severe structural damage from impact of a meteoroid is negligible, blast effects of even a small meteoroid could be serious. Impact of a meteoroid with a closed vessel, for example, a spaceship or habitat, will produce a pressure wave which although quite localized will be dangerous to anyone near its origin. A one gram meteoroid, if it lost all its energy by striking a vessel, might kill or seriously harm someone standing close to the point of collision, but would be harmless to anyone more than a few meters away. Clearly it is desirable to shield a space colony against such collisions, and as is discussed subsequently, extensive shielding is also required for protection against ionizing radiation. This radiation shield would also protect against meteoroids.

Loss of atmosphere because of puncture by meteoroids is not a serious threat. In habitats of the size considered in this study, at least a day would be required to lose 60 percent of the atmosphere through a hole one meter in diameter - the size of hole that would be blasted by a meteoroid only once in 10,000,000 years. Smaller meteoroids might be responsible for small leaks, but the requirement for safe habitation under these circumstances is simply a regular (*e.g.*, monthly) program for detecting and repairing such leaks. A more detailed analysis of the meteoroid hazard is given in appendix A.

Ionizing Radiation: Major Threat

Both the Sun and the Galaxy contribute fluxes of ionizing particles. The quiescent Sun constantly emits a solar wind (ref. 15) of about 5 to 10 protons, electrons, and particles per cubic centimeter traveling at speeds of about 500 km/s. These particles do not possess penetrating energies and therefore offer no threat to humans. However, the solar wind may indirectly affect humans because it neutralizes any separation of electric charge that might occur in space and produces a small variable interplanetary magnetic field (~5 nT at the distance of the Earth (lAU) from the Sun). Consequently, space contains essentially no electric field, whereas on Earth the electric field is 100 V/m near the surface. Given that the human body is a good electrical conductor and forms an equipotential surface in the Earth's field, and that humans live a good portion of their lives in electrostatically shielded buildings, it seems unlikely that living for prolonged times in the absence of an electric field would cause harm, but this is not definitely known. Similarly, although there is evidence that living in magnetic fields thousands of times more intense than the Earth's will harm people, the consequences of living in a magnetic field that is both 10,000 times weaker and variable with time are not known (refs. 16,17).

Solar flares and galactic cosmic rays on the other hand are direct and serious threats to life in space. In sporadic violent eruptions the Sun emits blasts of high energy protons capable of delivering dangerous doses of radiation. Figure 2-6 shows the integral flux of solar flare particles at the Earth's distance from the Sun and compares it with the galactic flux. For these moderate sized events the galactic flux is the dominant source of particles above 1 GeV/nucleon. Also shown in figure 2-6 is the most intense flare ever recorded (a class 4 solar flare) which occurred on February 23, 1956. This flare illustrates the worst known radiation conditions to be expected in space. Without a space habitat having extensive protection against extremely energetic protons such a flare would contribute many tens of rem of dose

in less than an hour to moderately shielded personnel, and many times the fatal dose to the unprotected human being. (For an explanation of the "rem" see appendix B.)

The frequency of dangerous cosmic-ray flares is once in several years during a solar maximum, and once in a few decades for a flare as large as the class 4 flare. Because a significant portion of the protons originating from a large flare are relativistic (i.e., traveling at speeds approaching that of light), there is only a few minutes between optical and radio indications of an outburst and the arrival of the peak of the proton flux. People not in a sheltered place have very little time to get to one. Once a flare has begun, fluxes of energetic particles persist for a day or so in all directions.

Cosmic rays from the galaxy are a continuous source of highly penetrating ionizing radiation. Figure 2-7 shows the galactic cosmic ray spectrum and chemical abundances. The lower-energy portions of the curves show the modulating effect of the solar wind which with varying effectiveness over the 11-year solar cycle sweeps away from the Sun the less penetrating particles of the galactic cosmic rays. In the absence of any shielding the galactic cosmic radiation would deliver an annual dose of about 10 rem.

An important feature of note in figure 2-7 is the presence of heavy nuclei such as iron. In fact, heavy cosmic ray nuclei range up to heavy transuranium elements but quite noticeably peaking in abundance around iron. When a fully ionized iron nucleus is traveling below about half the speed of light its ionizing power is several thousand times that of minimally ionizing protons. (See appendix B for a brief discussion of the behavior of charged particles in matter.) At this level of ionizing power the passage of a single iron nucleus through the human body destroys an entire column of cells along its trajectory. The total amount of energy dumped in the body is small, but it is concentrated intensively over localized regions.

It is not yet known how bad this form of radiation is in terms of such things as increased rates of cancer. However, the loss of nonreproducing cells, such as spinal-column nerve cells, that any given exposure will cause can be calculated, Comstock *et al*. (ref. 18) estimate that the Apollo 12 astronauts during their two week voyage lost between 10-^7 and 10-^4 of their nonreplaceable cells. Such losses, although negligible in adults, might be very serious in developing organisms such as children.

The phenomenon of secondary particle production is important. When high-energy particles collide with matter, in a shield for example, they produce a great spray of particles, which in turn may produce even more particles. Consequently, the addition of a little shielding may, in the presence of highly energetic particles like those at the upper end of the cosmic ray spectrum, give rise to an even larger radiation dosage than if no shielding were used. There is also the possibility that a little shielding will slow down the rapidly moving heavy ions and make them more effective in the damage they do to tissue. Thus, for shielding that has a mass of a few tonnes (1) for each square meter of surface protected the effect will be to increase the annual dosage from cosmic rays from about 10 rem to as much as 20 rem.

But what is an acceptable radiation dose? For the terrestrial environment the U.S. Federal Government sets two standards (refs. 19-21). For radiation workers, adults over the age of eighteen working in industries where exposure to radiation is apt to occur, the standard is 5 rem/yr. For the general population, and especially children and developing fetuses, the standard is less than 0.5 rem/yr. Arguments can be sustained that these limits are conservative. There is evidence that exposures to steady levels of radiation that produce up to 50 rem/yr will result in no detectable damage (refs. 20,21), but the evidence is not fully understood nor are the consequences known of long-term exposure at these levels. For comparison, most places on Earth have a background of about 0.1 rem/yr.

3. Human Needs in Space

Elementary essentials such as air, water, food, and even the sensation of weight all have to be provided to the space colony. Engineering criteria to assure physiological safety and comfort are essential, but equally important is to provide for psychological and esthetic needs of the colonists.

The structure, mass, and shape of the habitat are sensitive to the choice of design criteria. Rather substantial savings in structural mass, and hence in cost and construction time, can be obtained by deviating from Earthlike conditions. Because the physiological effects of appreciable deviations from some of the terrestrial conditions are unknown, the living conditions in space are designed to be similar to those on Earth despite additional costs. The treatment of weightlessness is an example of this conservative approach.

WEIGHTLESSNESS: PSEUDOGRAVITY IS NEEDED

An outstanding feature of space is the absence of the sensation of weight. In vessels moving freely in orbit objects exhibit weightlessness; they are said to be in "free fall," or subject to "zero gravity" or "zero g." Weightlessness is a major potential resource of space, for it means humans can perform tasks impossible on Earth. Large masses do not require support, and their movement is restricted only by inertia. Structures can be designed without provision for support against the forces of gravity; in free space there is no such thing as a static load. Although these opportunities are only beginning to be explored, it seems likely that weightlessness will permit novel industrial processes (refs. 1, 2). Moreover, in free space, levels of pseudogravity can be produced and controlled over a wide range of values. This capability should foster the development of manufacturing processes not possible on Earth. Despite these potentially important commercial advantages of life in free fall, possible physiological consequences are of concern.

On Earth, gravity subjects everyone continuously and uniformly to the sensation of weight. Evolution occurred in its presence and all physiology is attuned to it. What happens to human physiology in the absence of gravity is not well understood, but experience with zero g is not reassuring. In all space flights decalcification occurred at a rate of 1 to 2 percent per month (ref. 3), resulting in decreased bone mass and density (ref. 4). There is no evidence to suggest that the rate of calcium resorption diminishes even in the longest Skylab mission of 89 days (ref. 5). Longer exposures could lead to osteoporosis and greatly reduced resistance to fracture of bones on minor impact. Moreover, because the body presumably draws calcium from the bones to correct electrolyte imbalances (ref. 4), it is clear that in zero g over many weeks and months a new equilibrium in the cellular fluid and electrolyte balance is not achieved. Furthermore, hormone imbalances also persist. In the later stages of some missions suppression of steroid and other hormone excretions were noted, together with reduction of norepinephrine output (ref. 3), unstable protein and carbohydrate states (ref. 5), indications of hypoglycemia, and unusual increases in secondary hormone levels with corresponding increases in primary hormones (private communication from J. V. Danellis, NASA/Ames Research Center). The medical problems on returning to Earth from zero g are also significant. Readaptation to 1 g has been almost as troublesome as the initial changes due to weightlessness. Following even the relatively short missions that have been flown to date astronauts have experienced increases of 10-20 beats/min in heart rate, decreased cardiac silhouette, changes in muscle reflexes, venous pooling, and leucocytosis (refs. 3-5). Although changes in physiology have been reversible, it is not known whether this will be

so after prolonged weightlessness. Vascular changes, such as reduction in the effectiveness of veins or variations in the pattern of response of mechano-receptors in the walls of blood vessels, or changes such as decrease in the effectiveness of the immune system, or the manifestation of differences in fetal development (especially possible inhibitions of the development of the balance mechanism of the inner ear), may become irreversible.

From present knowledge of the effects of weightlessness on physiology it seems appropriate to have at least some level of gravity acting on humans in space most of the time. Levels below the Earth normal (1 g) are not considered because there is no data on the effects of long-term exposure to levels of gravity between zero and one. Consequently because short term excursions into weightlessness reveal the complexity of the resulting physiological phenomena, and because the study group decided to be cautious in the absence of specific information, a criterion for safe permanent habitation is adapted - that the residents should live with the same sensation of weight that they would have on the Earth's surface, namely 1 g. Some variation about this figure is inevitable and so it is specified that humans permanently in space should live between 0.9 g and 1 g. This choice of a 10 percent variation is arbitrary, but also maintains conditions as Earth-like as possible.

The decision to provide 1 g to the colonists means they must reside in a rotating environment; the most feasible way to generate artificial gravity. However, in a rotating system there are forces acting other than the centrifugal force which supplies the pseudogravity. Thus, although the inhabitant at rest in the rotating system feels only the sensation of weight, when he or she moves, another force, called the "Coriolis force," is felt. The Coriolis force depends upon both the speed of motion and its direction relative to the axis of rotation. The direction of the force is perpendicular to both the velocity and the axis of rotation. Thus if the person in figure 3-1 jumps off the mid-deck level of the rotating torus to a height of 0.55 m (21.5 in.), because of Coriolis force he would not come straight down, but would land about 5.3 cm (more than 2 in.) to one side. At low velocities or low rotation rates the effects of the Coriolis force are negligible, as on Earth, but in a habitat rotating at several rpm, there can be disconcerting effects. Simple movements become complex and the eyes play tricks: turning the head can make stationary objects appear to gyrate and continue to move once the head has stopped turning (ref. 6).

This is because Coriolis forces not only influence locomotion but also create cross-coupled angular accelerations in the semicircular canals of the ear when the head is turned out of the plane of rotation. Consequently motion sickness can result even at low rotation rates although people can eventually adapt to rates below 3 rpm after prolonged exposure (ref. 6).

Again a design parameter must be set in the absence of experimental data on human tolerance of rotation rates. Although there has been considerable investigation (refs. 7-20) of the effects of rotating systems on humans the data gathered on Earth do not seem relevant to living in space. Earth-based experiments are not a good approximation of rotation effects in space because most tests conducted on Earth orient the long axis of the body parallel to the axis of rotation. In space these axes would be mutually perpendicular. Also on Earth a spinning laboratory subject still has Earth-normal gravity acting as a constant reference for the mechanism of the inner ear.

Although most people can adapt to rotation rates of about 3 rpm, there is reason to believe that such adaptation will be inhibited by frequent, repeated changes of the rate of rotation. This point is important because colonists living in a rotating system may also have to work in a non-rotating environment at zero g to exploit the potential benefits of weightlessness. For a large general population, many of whom must commute between zero g and a rotating environment, it seems desirable to minimize the rotation

rate. There is a lack of consensus in the literature and among experts who have studied the problem on the appropriate upper limit for the rotation rate (refs. 21-28). For the conditions of the space colony a general consensus is that not more than several rpm is acceptable, and for general population rates significantly greater than 1 rpm should be avoided. Therefore, 1 rpm is set as the upper limit of permissible rotation rate for the principal living quarters of the colonists, again reflecting the conservative design criteria.

ATMOSPHERE: LESS IS ENOUGH

To maintain life processes adequately the human organism requires an atmosphere of acceptable composition and pressure. The atmosphere of the space habitat must contain a partial pressure of oxygen (pO_2) sufficient to provide high enough partial pressure within the alveoli of the lungs (~13.4 kPa or ~100 mm Hg) for good respiration yet low enough to avert losses in blood cell mass and large changes in the number and distribution of micro-organisms, such as the growth of "opportunistic" bacteria (refs. 4, 29). The value of pO_2 at sea level on Earth is 22.7 kPa (170 mm Hg) which sustains the needed oxygen in the blood. The range of tolerable variation is large and not well defined, but for general populations deviations of more than 9 kPa (70 mm Hg) in either direction seem unwise (ref. 30).

The presence of an inert gas in the colony's atmosphere is desirable since it would prevent an unusual form of decompression from occurring in the body's chambers and sinuses, while providing a greater safety margin during either accidental pressure drops or oxygen dilution by inert gases (ref. 31). Although several other gases have been used for this purpose, there are several reasons why nitrogen appears the most reasonable candidate for the colony. For example, since nitrogen constitutes almost 80 percent of the Earth's atmosphere, it is not surprising to find that some organisms require the gas for normal development (ref. 31). Further, with time, denitrifying bacteria will release nitrogen gas into the atmosphere, thereby resulting in the eventual accumulation of significant quantities. Finally, the inclusion of nitrogen-fixing plants in the colony's life support system means that the gas level can be biologically maintained by the conversion of nitrogen gas into protein. Thus the inevitable presence and the various benefits of nitrogen gas dictate its inclusion in the atmosphere, perhaps at a level of 26.7 kPa (~200 mm Hg).

The level of carbon dioxide should be maintained below the OSHA standard (ref. 32), which specifies that pCO_2 be less than 0.4 kPa (3 mm Hg). At the same time the CO_2 levels will be high enough to permit maximum rates of photosynthesis by crop plants. Trace contaminants should be monitored and controlled to very low levels.

Finally, it is desirable to maintain a comfortable relative humidity and temperature. Various sources (ref. 30) suggest a range of temperatures around 22 degrees C and a relative humidity of about 40 percent. This criterion implies a partial pressure of water vapor (pH_2O) of 1.0 +/- 0.33 kPa (7.5 +/- 2.5 mm Hg).

A major consequence of these various criteria is that human life can be safely and comfortably supported at a pressure well below that of a normal Earth atmosphere (ref. 31). The grounds for choosing a particular value are discussed in chapter 4.

FOOD AND WATER

Humans living in space must have an adequate diet; and food must be nutritious, sufficiently abundant,

and attractive. There must be enough water to sustain life and to maintain sanitation. A diet adequate for a reasonable environmental stress and a heavy workload requires about 3000 Cal/day. It should consist of 2000 g of water, 470 g dry weight of various carbohydrates and fats, 60 to 70 g dry weight of proteins, and adequate quantities of various minerals and vitamins(1) .The importance of the psychological aspects of food should not be neglected. The variety and types of food should reflect the cultural background and preferences of the colonists.

COMBINED ENVIRONMENTAL STRESSES: PROBABLY NOT SERIOUS

While very little is known about physiological response to individual environmental stresses, even less is known about combined effects. The long-term, cumulative, interactive effects of biodynamic factors (hypogravity, Coriolis forces), atmospheric factors (composition, pressure, temperature), radiation and electromagnetic factors (illumination quality and periodicity, magnetic field strength), temporo-spatial factors, and other environmental factors could be additive. (ref.33)

$$(E_{total} = \sum_{i=1}^{n} E_i), \text{ synergistic } (E_{total} > \sum_{i=1}^{n} E_i), \text{ or}$$

$$\text{antagonistic } (E_{total} < \sum_{i=1}^{n} E_i), \text{ (ref. 33).}$$

It seems probable that if a substantial effort is made to provide reinforcing stimuli for maintaining biological rhythm (solar spectral and intensity distribution) (ref. 34) and diurnal periodicity (ref. 35), adequate nutrition, and a pleasant living environment, the problems of combined environmental stress would prove minimal.

ENVIRONMENTAL DESIGN TO REDUCE STRESS

To satisfy the physical needs of people in a way consistent with the goals described in chapter 1, habitable environments have to be created with maximum efficiency and minimum mass. Unless design criteria are carefully set, such environments may be so artificial or so crowded as to exert damaging psychological stresses on the inhabitants. The psychological needs are discussed more fully in appendix A. Moreover, the extreme novelty of the surroundings or the sense of isolation of living in space may be stressful. It is the task of the architectural (ref. 36) and environmental designer to reduce such stresses by shaping and interrelating structures and surroundings to meet the psychological, social, cultural and esthetic needs of the colony's inhabitants while also satisfying their vital physiological needs.

Diversity and Variability

Environmental psychologists and behavioral scientists (refs. 37-39) have pointed out that variety, diversity, flexibility and motivation can make apparently deficient environments quite satisfactory to their inhabitants. It is important that space colonists become meaningfully involved in their environment. This can result from there being a planned complexity and ambiguity (ref. 38), that is, the design of the habitat must not be so complete as to be sterile; it must avoid motel banality. The ideal is to build a setting that provides individuals and groups alternate ways of satisfying their goals, thus giving them freedom of choice. Attaining such an ideal is greatly facilitated by the large size of the habitat which frees from limitations planned for in the small interiors of space stations.

In particular the interior should have a general plan so that the finishing and details can be left to the choice of the colonists themselves. Emphasis in the design of living area of a space colony should not be on specifics, but on the range of options. Colonists need access to both large and small, private and community spaces, to long vistas and short ones, but with a flexible, manipulatable architecture. They need to be able to exploit and to change these spaces according to individual wants. The initial design must permit the colonists to reshape the interior by developing and altering the spaces.

To these ends a building system must be developed which is fairly flexible, light weight, easily mass produced, capable of fast efficient erection, and yet allows a variety of spaces to evolve. It must also provide a sufficient esthetic quality, both materially and spatially. These criteria suggest a system that is built from modular components; that is, panels and structural elements that are uniform in size but when stacked or laid horizontally allow any combinations of shapes to be achieved.

There are ways to offset the undesirable effects of artificiality other than by facilitating individual variation. One is to provide large-scale vistas, that is, to make the habitat large enough to lessen the sense of its being manmade. To this end it may be desirable to limit a colonist's view so that the entire structure cannot be seen in a single scan by designing it so that some parts are always out of sight of others. Natural objects might also be simulated, but such simulation is usually recognized as being false. It then exaggerates the sense of artificiality, although it is possible to represent the natural environment by miniature design with a high degree of perfection and satisfaction, as in Japanese gardens. A better idea is to provide contact with the actual environment of space. Convenient access to regions of zero gravity and to views of the Earth, the Moon, and stars would provide stimuli taking full advantage of life in space; it also would provide panoramic vistas, long lines of sight, and awareness of reality beyond the human scale.

On a smaller scale the artificiality of the interior would be reduced by the presence of live, growing things such as vegetation for eating or for decoration, children playing and exhibiting the chaos of youth, or animals such as pets or livestock. Living things should be provided as an integral part of the interior architecture of the colony. The desire here is to have an environment that is not completely regimented. To that end, it might be desirable to have some random variation in the climate, but the politics of producing fluctuations in temperature and humidity are probably best left to the colonists themselves.

Space Needs Within the Colony

To design a human habitation in space, a criterion must be set for area available, most conveniently expressed in terms of area per person. The amount of area allocated per person has two important consequences: it determines the population density of habitation on which depends the sense of crowding; it limits services and facilities provided to the inhabitants.

A brief survey of the literature (refs. 40-43) indicates that there should be at least 40 m^2 of projected area per inhabitant. Projected area means area projected onto the largest plane perpendicular to the direction of the pseudogravity. Thus a three-story house with 60 m^2 of floor space occupies only 20 m^2 of projected area. Actual usable area can be made larger than projected area by constructing levels within a habitat, or several stories within a building. As table 3-1 shows, 40 m^2 per person is rather less than the area per person in most U.S. cities, although it is more than in some small French villages. It is an important task of space colony architects to organize this space to minimize the sense of crowding, while still providing needed services.

TABLE 3-1 (gif format)

TABLE 3-1.- AVAILABLE LAND PER CAPITA IN SELECTED CITIES AND TOWNS

Location	Per capita area, m^2 /person
Boston, Mass	185.8
Chicago,Ill	171.2
El Paso,Tex.	950.5
Jersey City, N.J.	150.1
New York, N.Y.	98.3
Manhattan Borough, N.Y.	38.2
San Francisco, Calif.	164.3
St.Paul, France	27
Vence, France	46.2
Rome, Italy	40.0
Columbia, Md.	503
Soleri's Babel IIB	15.1
Space Colony	>= 40

Based upon experience with Earth cities, the needs of a community of 10,000 for living area and volume are categorized and a land-use plan is developed together with quantitative estimates of the volumes and areas needed. Some of the major spaces that must be provided are:

1. Residential - dwelling units, private exterior space, pedestrian access space
2. Commercial business - shops, offices
3. Public and semipublic enclosed space - government offices, hospitals, schools (with community multimedia center), churches (which may also serve as community and assembly halls), recreation, and entertainment
4. Public open space - parks, outdoor recreation (swimming, golf, playgrounds), zoo
5. Light service industry - personal goods, furniture, handicrafts, etc.
6. Wholesaling and storage
7. Space for mechanical subsystems - electrical distribution and transformer substations, communication and telephone distribution, air movement and distribution, water treatment (supply, return, recycling), sewage treatment
8. Transportation
9. Agriculture

To estimate the area and volume required for these various purposes, it is helpful to consider the organization and distribution of space within cities on Earth. Environmental psychologists and planners have long realized that sufficient area must be provided so that an individual can escape at least temporarily from the pressure of crowds. Parks and open spaces near high density neighborhoods are as important in space as on Earth (ref. 43). Space offers some possibilities for reducing apparent population density that are not easily available on Earth, such as by stacking areas in widely spaced levels or having within the same habitat different communities working and sleeping on different schedules so that their inhabitants could use the same recreational area but at different times (ref. 44).

Less unusual would be to use certain areas for more than one purpose; for example, churches could also serve as assembly halls, and orchards could double as parks. In appendix B a detailed examination is made of areas and volumes required for these various functions, assuming some multipurpose usage. The results of this study are summarized in table 3-2.

TABLE 3-2 (gif format)

TABLE 3-2.- SUMMARY OF COMMUNITY SPACE AND AREA ALLOCATIONS

Space use	Surface area required, m^2/person	No. of levels	Projected area, m^2	Estimated height, m	Volume, m^3
Residential	49	4	12	3	147
Business: Shops Offices	2.3 1	2 3	1.0 .33	4 4	9.2 4.0
Public and semipublic; Schools Hospital	1 .3	3 1	.3 .3	3.8 5	3.8 1.5
Assembly (churches, community halls	1.5	1	1.5	10	15
Recreation and entertainment	1	1	1	3	3
Public open space	10	1	10	50	500
Service industry	4	2	2	6	24
Storage	5	4	1	3.2	16
Transportation	12	1	12	6	72
Mech. subsystem Communication distr. switching equipment for 2800 families	0.5	1	0.5	4	.2
Waste and water treatment and recycling	4	1	4	4	16
Electrical supply and distribution	.1	1	.1	4	.4
Miscellaneous	2.9	3	1	3.8	11.2
Subtotals	94.2	-	46.6	-	823.3
Agricultural space requirements (a) Plant growing areas	44	3	14.7	15	660
Animal areas	5	3	1.7	15	75
Food processing	4	3	1.3	15	60

collection, storage, etc.					
Agricultural drying area	8	3	2.7	15	120
Totals	155.2	-	67.0	-	1738.3

(a) Agricultural space requirements are provided for completeness and convenience. The details are explained in the succeeding chapters.

NOTE: the areas and volumes arrived at are approximations for use in establishing mass estimates and aiding in the structural design of the entire habitat enclosure.

They suggest that, to meet community needs, 47 m^2 of projected area and 823 m^3 of volume are needed for each inhabitant. Agriculture requires an additional 20 m^2/person and 915 m^3/person. The justification of these last two numbers depends on how the design criterion of providing sufficient quantities of nutritious food is met; a topic discussed further in the next two chapters.

SMALL SIZE AND ISOLATION

The vastness of space and the smallness of the colony strongly affect the social, physical and governmental organization of the colony. Like any other human community, the colony has to specialize in exploitation of peculiar features of its environment to optimize its productivity. The fruits of this exploitation must be exchanged for the products of other specialized communities; trade with Earth is essential. The importance of trade is magnified by the small size of the colony which forces it to depend on Earth for many services and goods which are essential to modern society but often taken for granted. Furthermore, given that travel times among the components of the colony and to Earth may be of several days and also very expensive, it is clear that the transportation system is exceedingly important and that unusual emphasis must be placed on electronic communications and on trade in intangible goods and services.

Trade is Essential

It has been empirically demonstrated that selfs Efficiency grows with size in modern high-energy societies. For communities of 10,000 people there is little hope of achieving self-sufficiency as measured by lack or absence of trade. There have been studies of sociology, economics, and geography which indicate the degree to which various specialities can be sustained. Colin Clark, one of the world's distinguished students of economic organizations, reports (ref. 45) that cities need populations of 100,000 to 200,000 in order to provide "an adequate range of commercial services....". Moreover, populations of 200,000 to 500,000 are required to support broadly-based manufacturing activity.

A small settlement in space, of less than 100,000 people, would necessarily require continuing support from Earth. There is little possibility that such a settlement can be sustained without a steady and sizable movement of materials and information between Earth and the colony. Because of high demands on material productivity, ordinary business services such as banking, insurance, bookkeeping, inventory control, and purchasing would very likely remain on Earth. Management of the transportation system, and sales and delivery of products would be Earth based. The highly technological and specialized services of medicine, higher education and even of those branches of science and engineering not used in the day-to-day life of the colony would come from Earth. A community of 10,000 cannot conceivably support a large research university or a large medical center. Communities of this size on Earth do not encompass much social and cultural variety, and their major

productive activities are usually limited in kind and number. To point up the lack of diversity that may reasonably be expected, consider how many and what variety of religious organizations and sects might be expected in a space colony of size 10,000.

Economies of scale for communities suggest an optimal size well above that of the early settlement in space.

Isolation: Offset by Transportation and Communications

While the small size of the colony exaggerates its dependence on Earth, the vastness of space and the long times and expense of travel tend to isolate the colonists from the home planet. A good design must attempt to anticipate and offset the effects of such isolation.

Travel from the colony to Earth is expensive, and takes a number of days. Given the need for trade and for the importation of many items of high technology that a small community cannot supply itself, the transportation system is exceedingly important. It seems essential to provide for "return migration" of persons and families to Earth who strongly wish for it, although it might be necessary to devise ways to discourage commuting.

The difficulty of physically transporting goods or people leads to a strong emphasis on electronic communication. Direct lines of sight from the colony to the Earth make radio, television, and facsimile transmission easy. Many of the special services mentioned earlier could be supplied remotely, for example, accounting, education, and even many medical diagnostic services can be performed electronically. Consequently a colony in space is expected to have highly developed electronic communications for commerce, education, entertainment and community activities. These should be designed to be easily accessible to the members of the colony, probably with two-way capability and linked to computers. The network is of such importance that it should have a high degree of redundancy for reliability, and be designed to assure privacy. It is likely that both the physical and social organization of the community will be shaped around the communications system.

Governance and Social Order

Distance and isolation also affect the governance and social order. Whether space colonization is a unilateral effort on the part of the United States or a cross-national enterprise, it will most likely be sponsored by a public or quasipublic organization with a bureaucratic structure which permeates the early settlement. The sense of isolation may stimulate the organizational development of communities away from the organizational form of the sponsor as the interests and life circumstances of a rapidly growing population change and develop. The form of governance depends very much on the preferences of the settlers, in much the same way as allowances for individual choice have been emphasized in other considerations of life in space.

Maintenance of order and of internal as well as external security initially falls to the Earth-based sponsoring organizations and then to the organized community which is expected to rise early in the colony's history. The small size of the settlement, combined with a rather precarious manufactured environment, may emphasize a concern for internal security. Any individual or small group could, in prospect, undertake to destroy the entire colony by opening the habitat to surrounding space, by disrupting the power supply, or by other actions which have few corresponding forms in Earth-based settings. Whatever organizational form the colonists evolve, it must be able to assure the physical security of the habitat and its supporting systems, and this need for security may infringe upon other desirable features of the colony and its operation.

SUMMARY OF DESIGN CRITERIA

The following physiological, environmental design, and organizational criteria must be met by a successful space habitat for the colonization of space.

Physiological Criteria

The basic physiological criteria are summarized in table 3-3.

TABLE 3-3 (gif format)

TABLE 3-3.- SUMMARY OF PHYSIOLOGICAL CRITERIA

Psuedogravity	0.95 +/- 0.5 g
Rotation rate	<= 1 rpm
Radiation exposure for the general population	<= 0.5 rem/yr
Magnetic field density	≤ 100 μ T <
Temperature	23 +/- 8 degrees C
Atmospheric composition pO_2	22.7 +/- 9 kPa (170 +/- 10 mm Hg)
p(inert gas; most likely N_2)	26.7 kPa 2 <78.9 kPa (200 < pN_2 < 590 mm Hg)
pCO_2	< 0.4 kPa
pH_2O	1.00 +/- 0.33 kPa (7.5 +/- 2.5 mm Hg)

Environmental Design Criteria

The criteria for environmental design are both quantitative and qualitative. Quantitative criteria are summarized in table 3-4.

TABLE3-4 (gif format)

TABLE 3-4.- SUMMARY OF QUANTITATIVE ENVIRONMENTAL DESIGN CRITERIA

Population: men, women, children	10,000
Community and residential projected area per person,m^2	47
Agriculture, projected area per person, m^2	20
Community and residential, volume per person, m^3	823
Agriculture, volume per person, m^3	915

Desirable qualitative criteria are summarized in table 3-5.

TABLE 3-5 (gif format)

TABLE 3-5.- SUMMARY OF QUALITATIVE CRITERIA OF ENVIRONMENTAL DESIGN

Long lines of sight
Large overhead clearance
Noncontrollable unpredictable parts of the environment; for example, plants, animals, children, weather
External views of large natural objects
Parts of interior out of sight of others
Natural light
Contact with the external environment
Availability of privacy
Good internal communications
Capability of physically isolating segments of the habitat from each other
Modular Construction of the habitat of the structures within the habitat
Flexible internal organization
Details of interior design left to inhabitants

Organizational Criteria

The organizational criteria have to do with both physical organization and social and managerial organization. In the first category is the criterion that the components of the colony be located so that the resources of space can be effectively exploited: solar energy, matter in the Moon or asteroids and on Earth, high vacuum of space and possibilities of pseudogravity variable from 0 g to more than 1 g. The colony must be provided with a transportation system that is capable of sustaining close contact with Earth, and with extensive electronic communications.

The organization of the governance of the colony is less restrained by specific criteria than are other aspects of life in space. Nevertheless, the organization must be such as to permit comfortable life under crowded conditions far from other human communities. Moreover, the organization must facilitate a high degree of productivity, foster a desirable degree of diversity and heterogeneity, and maintain the physical security of the habitat.

The next chapter considers a number of alternative ways of meeting these criteria. From the various alternatives the particular design is then selected and justified.

4. Choosing Among Alternatives

A few years after people move into the first colony, the system should settle down and operate as described in chapter 1. But why is the colony shaped as a torus and located at L5 with ore supplies from the Moon? Why is it not a sphere out at the asteroids or near a moon of Mars, or a cylinder in geosynchronous orbit around the Earth, or some other combination of alternatives? What are these alternatives, and why were they rejected? The purpose of this chapter is to answer these questions by evaluating reasonable alternatives in terms of the goals of the design study (ch. 1) and the criteria laid out in chapters 2 and 3.

A successful systems design combines subsystems satisfying various conflicting criteria to produce a unified working entity. The parts of the space colony- transportation, mining, the habitat, manufacturing, agriculture, and so on - must interact and interrelate in such a way that the demands of each for energy, raw materials, manpower, transport, and waste removal can be met by the overall system. In turn this system must satisfy the physiological, cultural, architectural, and physical criteria necessary to maintain a permanent human community in space using near-term technology and at a minimum cost.

In 10 weeks the study group was able to assemble only one reasonably consistent picture of life in space; there was no time to go back through the system and attempt to find optimal combinations of the subsystems. Moreover, again because time was short, many of the comparisons among alternative subsystems were more qualitative than study group members would have liked.

Effort devoted to alternatives depended upon the particular subject. A great deal of time was spent considering different forms for the habitat, how to handle the shielding and how to process lunar material. Less time was given to considering alternative patterns of siting the colony and its parts, of different ways to achieve life support, or of various possible transportation systems. In some cases much effort was expended but few alternatives were generated; an example is the system for moving large amounts of matter cheaply from the Moon to the colony. No alternative at all was found to the manufacture of solar satellite power plants as the major commercial enterprise of the colony.

It is important to realize that the alternatives described in this chapter constitute a major resource for improving the proposed design and for constructing new designs that meet other criteria. Rejection of any concept for the current "baseline system" does not mean that concept is fundamentally flawed. Some alternatives were rejected because they failed to meet the criteria, which were deliberately chosen conservatively and might well be changed on the basis of future experience or under different assumptions. Others were rejected simply because information about them was incomplete. Yet others were not chosen because their virtues were recognized too late in the study to incorporate them into a unified overall picture.

The alternatives might also be useful for designing systems with other goals than permanent human settlement in space; for example, space factories with temporary crews, or laboratories in space. Alternatively, new knowledge or advances in technology, such as the advent of laser propulsion or active shielding against ionizing radiation, might make rejected subsystems very desirable.

THE SHAPE OF THE HABITAT

What shape is most suitable to house this colony of 10,000 people? The question is particularly interesting for several reasons. The appearance and arrangement of the habitat are most obvious and understandable by everyone, being the most direct exhibition of the reality of the idea of the colony -

seeing the form is believing - and the habitat natutrally attracts a great deal of attention although it is only one part of a much larger system. Moreover, the reader may already be aware of one or more possibilities: the rotating cylinders proposed by O'Neill (ref. 1), the torus of Von Braun (ref. 2), and their corresponding entities in the science fiction of Arthur C. Clarke (refs. 3, 4). The subject is also one particularly suited for systematic treatment and can serve as an excellent example of the methodology of systems design.

Some General Considerations

Because it is expedient, although not entirely justified, to treat the shielding which protects against the dangerous radiations of space separately from the choice of the geometry of the habitat's structure, that problem is left to a subsequent section. Subject to possible effects of the shielding, the choice of habitat geometry is determined by meeting the criteria of the previous chapter at minimum cost. In considering how different configurations may supply enough living space (670,000 m^2) and how they meet the physiological and psychological needs of people in space, the following discussion uses the properties of materials outlined in appendix A. Throughout, aluminum is assumed as the principal structural material.

The Habitat Must Hold an Atmosphere

The simple fact that the habitat must contain an atmosphere greatly limits the possible forms. For economy in structural mass it is essential that large shells holding gas at some pressure must act as membranes in pure tension. There is, in turn, a direct relationship between the internal loading and the shape of the surface curve of such a membrane configuration. Also when the major internal loads are pressure and spin-induced pseudogravity along the major radius of rotation, R. the possible membrane shapes must be doubly symmetric, closed shells of revolution (refs. 5, 6). The possible "smooth" shapes are the ones generated from the curves in figure 4-1.

Four fundamental configurations arise:

1. A sphere-by rotating curve 1 about either axis
2. A cylinder-by rotating curve 2 about the z axis
3. A torus-by rotating curve 3 about the r axis
4. A dumbbellby rotating curve 3 about the z axis

Neglecting secondary effects from variations in pseudogravity and localized bending stresses from discontinuities in deformations, the study group concluded that all possible membrane shapes, that is, any possible habitat, must be one of the four simple forms described above or some composite of them as shown in figure 4-2.

The desire to keep structural mass small favors small radii of curvature. As figure 4-3 shows, the wall thickness to contain a given pressure drops quickly with decreasing. Of course, structural mass can also be reduced by lowering the pressure of the gas. Both possibilities turn out to be useful.

A Rotating System With 1 g at Less Than 1 rpm

Rotation is the only feasible way to provide artificial gravity in space. Pseudogravity depends upon both rotation rate and radius of rotation, and figure 4-4 shows the lines of constant pseudogravity as functions of these two variables (ref. 7). On the graph are shown a number of rotating systems: C-l through C4 are the rotating cylinders proposed earlier (ref. l) by O'Neill; T-1 is a torus and S-1 is a sphere described later in this chapter; Arthur C. Clarke's Rama (ref. 4)

is shown, as are space stations of Gray (The Vivarium) (ref. 8), Von Braun (ref. 2) , and Tsiolkovsky (ref. 9). Obviously only systems with radii of rotation greater than 895 m can lie on the line g= 1 below 1 rpm.

An aluminum cylinder like C-3 would weigh about 42,300 kt and have a projected area of 55 X I0^6 m^2, enough to hold 800,000 people - rather than the 10,000 people of the design criteria. Similarly a sphere of radius 895 m would hold 75,000 people and weigh more than 3500 kt if made of aluminum. A dumbbell shape has the advantage that the radius of curvature of the part holding the atmosphere can be made small while the radius of rotation remains large. However, in this configuration people could only live on the cross section of the spheres, and to hold 10,000 people with 670,000 m^2 of projected area the spheres would have to be 326.5 m in radius. Together they would weigh about 380 kt.

A torus also permits control of the radius that contains the atmosphere separately from the radius of rotation. Moreover, the torus can distribute its habitable area in a large ring. Consequently, the radius needed to enclose the 670,000 m^2 of projected area can be quite small, with a correspondingly small mass-about l50 kt for a torus of major radius 830 m and minor radius 65 m (where the mass of internal structure is neglected). The advantages of the torus compared to the sphere and cylinder are discussed further in appendices B and C which define some criteria and parameters useful for such comparisons. The important point is that for a given radius of rotation about four times more mass is required to provide a unit of projected area in a cylinder or a sphere than in a torus of small aspect ratio. Thus, among the simple, basic shapes the torus is clearly superior in economy of structural mass.

If minimum structural mass were the only concern, composite structures would be the choice. Twenty-five pairs of dumbbells would supply 670,000 m^2 with spheres 65 m in radius and a total mass of 72 kt. The spheres could be made smaller still and formed into a ring to make a beaded torus. Alternatively, the toruses themselves could be made with quite small minor radii and either stacked and connected together to form a kind of banded torus, or built separately to form a group of small, independent habitats.

However, as pointed out in the previous chapter, it is desirable to compensate for the artificial and crowded nature of the habitat by designing it to give a sense of spaciousness. Composite structures are rejected largely on architectural criteria of environmental perception. Not only would they be more difficult to build than the simpler shapes, but also their short lines of sight, little free volume and internal arrays of closely-spaced cables and supporting members would produce an oppressive ambience.

If the colony were composed of a number of small structures, there would be problems of communication and transport between them as well as the drawbacks of small scale. Nevertheless, as table 4-1 shows, multiple structures (and composite ones too) offer substantial savings in mass, and it might well be that some of their undesirable aspects could be reduced by clever design. It would be an attractive option to be able to build up a colony gradually out of smaller units rather than to start off with an initial large scale structure. The subject of multiple and composite structures is worthy of more consideration. The various properties of possible configurations are summarized in table 4-1. The parameters show the mass requirements and indicate the degree of openness of the different structures. The single torus, although not the best design in many respects, seems to give the most desirable balance of qualities. Relative to the sphere and cylinder it is economical in its requirements for structural and atmospheric mass;

relative to the composite structures it offers better esthetic and architectural properties. Because of its good habitability properties, large volume, a variety of possible internal arrangements, the possibility of incremental construction, a clear circulation pattern, access to zero gravity docks and recreation at the hub, agriculture as an integral part of the living area, and a clear visual horizon for orientation, the torus is adopted as the basic form of the habitat. The dimensions of this single torus are given in the first column of table 4-1.

TABLE 4-1 (a) (gif format)

TABLE 4-1.- PARAMETERS OF POSSIBLE HABITATS, 1 RPM

(a) Single component

	Single torus, R maj=830 m, R min=65 m	**Cylinder with spherical endcaps, R = 895 m, L = 8950 m**	**Sphere, R = 895 m**	**Dumbbell, R = 895 m, R sphere =316 m**
Number of components	1	1	1	1
Structural mass at 1/2 atm, kt	150	42,300	3545	380
Projected area, m^2	6.8 X 10^5	550 X 10^5	50.3 X 10^5	6.3 X 10^5
Surface area, m^2	2.1 X 10^6	60.3 X 10^6	10.1 X 10^6	2.5 X 10^6
Shielding mass, Mt	9.9	23.3	46.7	33.5
Volume, m^3	6.9 X 10^7	2265 X 10^7	300 X 10^7	13.2 X 10^7
Mass of atmosphere, kt	44	14,612	1930	85
Segmentation	Easy, optional	Difficult	Difficult	Difficult
(Vistas) Longest line of sight, m	640	10740	1790	732
(Vistas) Solid angle of 50 percent sight line, sr	0.5	0.09	4.2	4.2
(Vistas) Fraction of habitat hidden from view	0.70	0	0	0.5
(Communication), Longest distance of surface travel, m	2600	11,800	2800	1800
(Communication), Fraction viewable by internal line of sight from one place	0.3	1	1	0.5
Interior: Openess	Good	Good	Good	Good

Interior Population capacity at 67 m^2/person	10,000	820,000	75,000	10,000

SHIELDING

The need to shield humans adequately from the ionizing radiations of space imposed some significant design decisions. An ideal shield would bring the radiation dosage below 0.5 rem/yr cheaply and without impairing the contact of the colonists with their environment. However, after considering active shields which electromagnetically trap, repel or deflect the incident particles, and a passive shield which simply absorbs the particles in a thick layer of matter, the study group chose the passive shield for their design.

Active Shields

When a charged particle passes through a magnetic field, its path curves. Thus, as figure 4-5 shows, the proper configuration of magnetic field lines can form a shielded region which particles cannot enter.
Since for a given magnetic field the curvature of the path of a particle is inversely proportional to its momentum, the region is shielded only against particles below a certain cutoff momentum or cutoff energy. Particles above this cutoff energy can still penetrate (ref. 10).

The problems of magnetic shielding become apparent when the cutoff energy has to be chosen. Protection against heavy ion cosmic rays, the so-called high-Z primaries (i.e. the iron nuclei and others mentioned in chapter 2) and most solar flares would be achieved with a cutoff of 0.5 GeV/nucleon. The difficulty is that most secondary particles are created from the primary flux above 2 GeV/nucleon which can penetrate the shield and generate secondaries in the mass of the shield itself. As a consequence a magnetic field around the torus with a cutoff of 0.5 GeV/nucleon and a structural mass of about 10 kt, corresponding to a thickness of matter of 0.5 t/m^2, would actually increase the exposure to about 20 rem/yr. Only the addition of shielding to an extent of 1.3 t/m^2 could reduce the dosage to a level equivalent to there being no secondary particle generation by shielding, that is, about 8 rem/yr. Furthermore, even then a specially heavily shielded shelter would be required as protection against secondaries produced by the strongest solar flares. The consequences of the production of secondary particles are shown in figure 4-6.

A cutoff of 10 or 15 GeV/nucleon would eliminate so many of the high energy particles that even with secondary production the dose would not be above 0.5 rem/yr. A shield of this capability would also protect against the effects of the strongest solar flares, and no shelter would be needed. The difficulty is that the structural mass required to resist the magnetic forces between superconducting coils precludes this design even for the most favorable geometry, namely, a torus.

Similarly, electric shielding by a static charge seems infeasible since a 10-billion-volt potential would be required for even moderate shielding. On the other hand, a charged plasma which sustains high electrical potential in the vicinity of the habitat is a more promising approach (ref. 11). However, means to develop such a plasma requires extensive research and technical development before a charged plasma might be considered for design. Some further details of

this approach are given in appendix D.

Passive Shield

Passive shielding is known to work. The Earth's atmosphere supplies about 10 t/m^2 of mass shielding and is very effective. Only half this much is needed to bring the dosage level of cosmic rays down to 0.5 rem/yr. In fact when calculations are made in the context of particular geometries, it is found that because many of the incident particles pass through walls at slanting angles a thickness of shield of 4.5 t/m^2 is sufficient. Consequently it was decided to surround the habitat with this much mass even though it requires that many millions of tonnes of matter have to be mined and shipped to the colony.

TABLE 4-1 (b) (gif format)

TABLE 4-1.- PARAMETERS OF POSSIBLE HABITATS, 1 RPM

(b) Multiple components

	Multiple dumbbells, R sphere = 65 m, R = 875 m	**Multiple torus, R maj =880 m, R min = 15 m**	**Banded torus, R major = 880 m, R min = 15 m**
Number of components	25	4	1 (7 bands)
Structural mass at 1/2 atm, kt	75	100	112
Projected area, m^2	6.6 X 10^5	6.6 X 10^5	6.6 X 10^5
Surface area, m^2	2.7 X 10^6	2.1 X 10^6	1.7 X 10^7
Shielding mass, Mt	9.9	9.7	7.0
Volume, m^3	5.8 X 10^7	1.6 X 10^7	2.1 X 10^7
Mass of atmosphere, kt	37	10.4	13.2
Segmentation	Unavoidable	Unavoidable	Easy
(Vistas) Longest line of sight, m	130	45	161
(Vistas) Solid angle of 50 percent sight line, sr	4.2	0.11	0.11
(Vistas) Fraction of habitat hidden from view	0.98	0.94	0.82 to 0.94
(Communication), Longest distance of surface travel, m	1800	2600	2600
(Communication), Fraction viewable by internal line of sight from one place	0.02	0.06	0.06
Interior: Openess	Poor	Poor	Poor
Interior	10,000	10,000	10,000

Population capacity at 67 m^2/person			

Table 4-1 shows the shielding masses required for different configurations; the single torus requires 9.9 Mt of shield. This much mass cannot be rotated at the same angular velocity as the habitat because the resultant structural stresses would exceed the strength of the materials from which the shield is to be built. Consequently the shield must be separate from the habitat itself and either rotated with an angular velocity much less than 1 rpm or not rotated. To minimize the mass required, the shield would be built as close to the tube of the torus as possible, and therefore the rotating tube would be moving at 87 m/s (194 mph) past the inner surface of the shield from which it is separated by only a meter or two. The consensus of the study group was that the engineering necessary to assure and maintain a stable alignment between the moving torus and its shield would not, in principle, be difficult. However, no attention in detail was given to this problem.

WHAT IF THE CRITERIA CHANGE?

The conservative design criteria presently adopted for permanent life in space are derived from research on Earth and in space, especially Skylab missions, that gives very little indication of the actual effects of living in space for many years. In the time leading up to the colonization of space more information will become available, and it may lead to substantial changes in the configuration proposed in this study.

Higher Population Density

A very simple change would be to reduce the amount of area available per person. Under these circumstances several of the structures described in table 4-1 would be made less massive. By placing the agriculture outside the shielded area and by reducing the remaining projected area available from 47 m^2 per person to 35 m^2, substantial savings could be made in both structural and shielding mass (table 4-2).

This 25 percent increase in crowding may not be so drastic as it appears, since use can be made of the three dimensionality of space in a way more effective than is done on Earth. With sufficiently large overhead spaces between levels, several levels could be included in a habitat while maintaining an impression of openness. This approach would be particularly advantageous if the gravity criteria were relaxed as well.

Lower Simulated Gravity and Higher Rotation Rates

It is particularly interesting to examine the consequences of simultaneously relaxing the requirements of pseudogravity and rotation rate. If instead of 0.95 +/- 0.05 g and 1 rpm, the design allows 0.85 +/- 0.15 g and 1.9 rpm some interesting possibilities emerge. Under these new conditions, parameters for the same geometries discussed earlier are summarized in table table 4-2

TABLE 4-2 (a) (gif format)

TABLE 4-2.- PARAMETERS OF POSSIBLE HABITATS WITH OTHER CRITERIA (EXTERNAL AGRICULTURAL)

(a) Single Components

	Single torus, R maj=209m, R min=27 m	**Cylinder with spherical endcaps, R = 236 m, L = 2360 m**	**Sphere, R = 236 m**	**Dumbbell, R = 236 m, R sphere = 33.3 m**
Number of components	1	1	1	1
Structural mass at 1/2 atm, kt	4.6	775	64.6	0.4
Projected area, m^2	0.7 X 10^5	38.5 X 10^5	3.5 X 10^5	0.07 X 10^5
Surface area, m^2	2.2 X 10^5	42.0 X 10^5	7.0 X 10^5	0.07 X 10^5
Shielding mass, Mt	1.0	19.4	3.3	1.4
Volume, m^3	0.3 X 10^7	46.8 X 10^7	5.5 X 10^7	0.031 X 10^7
Mass of atmosphere, kt	1.9	299	35.2	0.20
Segmentation	Unavoidable	Difficult	Difficult	Unavoidable
(Vistas) Longest line of sight, m	206	2800	470	67
(Vistas) Solid angle of 50 percent sight line, sr	0.9	0.09	4.2	4.2
(Vistas) Fraction of habitat hidden from view	0.65	0	0	0.5
(Communication), Longest distance of surface travel, m	720	3100	740	540
(Communication), Fraction viewable by internal line of sight from one place	0.35	1.0	1.0	0.5
Interior: Openess	Fair	Good	Good	Fair
Interior Population capacity at 35 m^2/person	2000	110,000	10,000	2,000

TABLE 4-2.- PARAMETERS OF POSSIBLE HABITATS WITH OTHER CRITERIA (EXTERNAL AGRICULTURAL)

(b) Multiple components

	Multiple	**Multiple torus**	**Banded torus,**

	dumbbells, R = 236 m R sphere = 33.3 m	**R maj = 209 m, R min = 27 m**	**R maj =209 m, R min = 27 m**
Number of components	50	5	1 (8 bands)
Structural mass at 1/2 atm, kt	20	23.2	26
Projected area, m^2	3.5 X 10^5	3.6 X 10^5	3.6 X 10^5
Surface area, m^2	13.9 X 10^5	11.2 X 10^5	8.2 X 10^5
Shielding mass, Mt	7.2	5.2	3.6
Volume, m^3	1.5 X 10^7	1.5 X 10^7	1.8 X 10^7
Mass of atmosphere, kt	9.9	9.5	11.3
Segmentation	Unavoidable	Unavoidable	Easy
(Vistas) Longest line of sight, m	67	100	100
(Vistas) Solid angle of 50 percent sight line, sr	4.2	0.9	0.9
(Vistas) Fraction of habitat hidden from view	0.99	0.93	0.9
(Communication), Longest distance of surface travel, m	540	720	720
(Communication), Fraction viewable by internal line of sight from one place	0.01	0.07	0.1
Interior:Openess	Good	Fair	Poor
Interior Population capacity at 35 m^2/person	10,000	10,000	10,000

A major consequence is that the radius of rotation now becomes 236 m as figure 4-4 confirms.

With this new radius of rotation neither a single torus nor a single dumbbell can supply sufficient space for a colony of 10,000. A cylinder, as before, supplies far too much. The sphere, on the other hand, supplies exactly the right amount and becomes an attractive possibility for a habitat. As the table shows, however, multiple and composite structures would still be contenders although they would be even more deficient in the desirable architectural and organizational features.

To be more specific, figure 4-7 illustrates a possible spherical design with the agriculture placed in thin toruses outside the shielded sphere.

This configuration has been named the Bernal sphere in honor of J. D. Bernal (ref. 12). When the Bernal sphere is compared with its nearest competitor, the banded torus, it is seen to be particularly efficient in its shielding requirements, needing 300,000 t less than the banded torus

and millions of tonnes less than any other configuration. The Bernal sphere, however, requires from 3 to 4 times as much atmospheric mass as the other possible forms, and from 2 to 4 times as much structural mass.

Higher Radiation Exposures

As more is learned about the effects of ionizing radiation, it is possible that larger exposures to radiation might be found to be acceptable. Such a change in this criterion would make active magnetic shielding an interesting possibility and might also favor the development of a plasma shield. Of course, if higher levels of radiation became acceptable, a smaller amount of passive shielding would be needed so that the mass of shielding might become less significant in determining habitat design.

Any of these changes might shift the favored emphasis from one geometry to another. A choice of a particular form would again have to balance aesthetic against economic requirements, and it is certain that more investigation of this problem will be necessary. A particularly important question is the relative cost of shielding mass, structural mass, and atmospheric mass. Knowledge of these costs is basic to deciding which geometric alternative to select.

FABRICATION TECHNIQUES

Although the construction of large structures in space places strong emphasis on fabrication techniques, relatively little attention was devoted to the subject by the summer study group. The few alternatives considered did not seem to be mutually exclusive, but instead mutually supportive. Only a brief description of these alternatives is given.

Initial Construction Facilities

Fabrication facilities needed to build the habitat and supporting factories and power plants were described at a Princeton Conference, May 1975, on metal forming in space by C. Driggers.This proposal has been adopted. Standard tecnnology for hot and cold working metals is sufficient to form the sheet, wire and structural members needed. An extensive machine shop must be provided so that many of the heavy components of a rolling mill, extrusion presses, casting beds and other equipment can be made at the space colony rather than have to be brought from Earth.

Building the Habitat Shell

Assembly of the habitat from aluminum plate and ribs proceeds first from the spherical hub (including docking facilities) outward through the spokes to start the torus shell. Both the spokes and shell are suitable for construction by a "space tunneling" concept in which movable end caps are gradually advanced along the tube as construction proceeds. This allows "shirt-sleeve" conditions for workmen as they position prefabricated pieces brought through the spokes and make the necessary connection. Large pieces of shield are placed around the completed portions as the slag material becomes available from the processing plant. Internal structures are built when convenient. However, every effort must be made to complete the basic shell and the first layer of shielding as quickly as possible so that spin-up can begin, gravity can be simulated, and the construction crew and additional colonists can move in to initiate life support functions within the habitat. A critical path analysis will reveal the best sequencing of mirror, power plant, shield, and internal construction.

An alternative technology for fabrication in space, which deserves more investigation, is the

making of structures by metal-vapor molecular beams. This is discussed in more detail in appendix E. If proved out in vacuum chamber experiments, this technique may cut the labor and capital costs of converting raw alloys into structures by directly using the vacuum and solar heat available in space. Its simplest application lies in the fabrication of seamless stressed-skin hulls for colony structures, but it appears adaptable to the fabrication of hulls with extrusive window areas and ribs, as well as to rigid sheet-like elements for zero-gravity structures such as mirrors and solar panels.

A simple system might consist of a solar furnace providing heat to an evaporation gun, which directs a conical molecular beam at a balloon-like form. The form is rotated under the beam to gradually build up metal plate of the desired strength and thickness. While depositing aluminum, the form must be held at roughly room temperature to ensure the proper quality of the deposit.

Structures Inside the Habitat

To fulfill the criteria set forth in chapter 2, a lightweight, modular building system must be developed to serve as an enclosing means for the various spatial needs of the colony.

Modular building systems developed on Earth can be categorized into three general types: that is, box systems using room-size modules; bearing-panel systems; and structural-frame systems. A box system entails asembling either complete shells or fully completed packages with integrated mechanical subsystems. Bearing-panel systems use load-bearing wall elements with mechanical subsystems installed during erection. Structural-frame systems use modularized framing elements in combination with nonload-bearing wall panels and mechanical subsystems which are normally installed during erection. Other systems which have seen limited application on Earth but would be appropriate in the colony include: cable supported framing systems with nonload-bearing fabric and panel space dividers, and pneumatic air structures using aluminum foil and fiberglass fabrics with rigid, aluminum floor elements.

In selecting a baseline configuration, box systems were rejected because they normally involve the duplication of walls and floors and tend to be overly heavy. If metal vapor deposition is developed as a forming technique however, this type of system would become highly desirable. Bearing-panel systems were likewise rejected since they do not allow integration of mechanical subsystems except during erection, and since walls are heavy because they are load bearing. Cable and pneumatic systems were rejected due to their inability to span short distances without special provisions. However, they might be highly desirable because of their flexibility and lightness if a lower gravity environment proves acceptable in the colony.

The system that appears most suitable for use in the colony might involve a light, tubular structural frame (composed of modular column and beams) in combination with walls that are nonload bearing and with prepackaged, integrated mechanical subsystems (such as bathrooms) where needed. This system provides lightweight modularity to a high degree, good spanning capabilities, easily obtainable structural rigidity, and short assembly time since all labor intensive mechanical systems are prefabricated. A schematic (ref. 13) of some possible components of such a system is shown in figure 4-8. Applications of such a system to the colony are many and could be applied to all necessary enclosures with proper adaptation to the various specialized needs of life in space.

Some of the possible materials and components investigated as especially suitable for building in space are illustrated in appendix F. Elements that are light and strong and could be made from

materials available in space are favored. The exterior and interior walls and the floor components are built from these materials. The floor components are based on extremely light yet strong elements designed for Skylab.

THE PEOPLE IN THE COLONY

It is not usual to think of human population as something to be designed. Nevertheless the numbers, composition, age and sex distribution, and productivity of the colonists bear importantly on the success of the project and on the creation of a suitable design. The study had to consider who should be the colonists, how many there should be, what skills they must have, and how they should organize and govern themselves. The alternatives are numerous and the grounds for choosing between them not as definite as for the more concrete problems of engineering, but it was possible to make what seem to be reasonable choices based on the goals of having in space permanent communities of sufficient productivity to sustain themselves economically.

Size and Suitability of Population

It is possible in principle to specify a productive task, for example, the manufacture of solar power satellites, and then calculate the number of people necessary to perform it, the number needed to support the primary workers, and the number of dependents. The sum of such numbers does not accurately define the population needed to found a colony since the calculation is complex. Even a casual consideration of what is necessary for a truly closed society would suggest that a colony population be far in excess of any reasonable first effort in space.

A similar approach would bypass the calculation just described and simply copy the population size and distribution of a major productive urban center on Earth. The difficulty, however, is that such communities are quite large, on the order of some hundreds of thousands of people. Moreover, close inspection reveals that human communities on Earth are less productive by labor force measurement standards than what would be needed in at least the early stages of space colonization.

One way to have a colony more productive than Earth communities would be to make the colony a factory, populated only by workers. The colony would then be only a space station, with crews of workers rotated in and out, much as is done on the Alaska pipeline project. Aside from the serious problems of transportation, such an approach does not meet the goal of establishing permanent human communities in space.

In the face of these difficulties a rather arbitrary decision is made to design for a colony of 10,000 with an attempt to bias the population in directions that favored high productivity but does not compromise too badly the goal of setting up a community in which families live and develop in a normal human way. It is also assumed that the completed colony is not an isolated single undertaking, but is a first step in a rapidly developing program to establish many colonies in space.

Ethnic and National Composition

The possible variations in nationality or ethnic composition are in principle very great. The actual composition will depend largely on who sponsors and pays for the colonization. If colonization were undertaken as a joint international project, the composition of the population

would surely reflect that fact. On balance, however, it seems reasonable for the purposes of this design to assume that the first space colony will be settled by persons from Western industrialized nations.

Age and Sex Distributions

The initial population of the first colony is projected to grow from a pool of some 2000 construction workers who, in turn, bring immediate family members numbering an additional one to three persons per worker. Selective hiring of construction crew members tends to bias this population toward certain highly desirable skills, and toward the younger ages. In anticipation of the labor needs of the colony and the need to avoid the kinds of burdens represented by large dependent populations, a population is planned with a smaller proportion of old people, children and females than the typical U.S. population. It is a close analog of earlier frontier populations on Earth.

The proposed population is conveniently described in terms of differences from the population of the United States as described in the 1970 Census (ref. 14). These changes are illustrated in figure 4-9 which compares the colony with the composition of a similar sized community on Earth. The sex ratio is about 10 percent higher in favor of males, reflecting both the tendency of construction workers to be male and the expectation that by the time construction begins in space an appreciable fraction of terrestrial construction workers are female. Partly for this last reason and partly because of the anticipated need for labor in the colony, sizable increase in the proportion of married women in the labor force is assumed. Most striking is the substantial shift of the population out of the more dependent ages - from under 20 and over 45 into the 21 to 44 age class.

Export Workers

Productivity of any community is importantly influenced not only by the size of the labor force but also by the share of worker output going for export. Numbers on modern U.S. communities (see, e.g., appendix G) indicate that in our complex society the percentage engaged in export activity is generally less in the larger cities than in the smaller towns. The maximum activity for export seems to be about 70 percent. Without taking into account the peculiarities of life in space, the study group assumes that 61 percent of the workforce, or nearly 44 percent of the population of the initial colony would be producing for export (see fig. 4-9). This percentage declines as the colony grows. Conversely at an early stage in its development when the population is about 4300, the workforce is about 3200, with 2000 producing for export. Appendix G provides the data from which these assumptions are derived.

Social Organization and Governance

The form and development of governance depend strongly on the cultural and political backgrounds of the first colonists. The subject is rich with possibilities ranging from speculative utopian innovations to pragmatic copies of institutions existing on Earth. Among the alternatives easily envisioned are quasimilitary, authoritarian hierarchies, communal organizations like kubbutzim, self-organized popular democracies operating by town meetings, technocratic centralized control, or bureaucratic management similar to that of contemporary large corporations.

It seems most likely that government for the initial colony would be based on types of management familiar in government and industry today. There would be elements of

representative democracy, but the organization would surely be bureaucratic, especially as long as there is need for close dependency on Earth. But whatever the forms initially, they must evolve as the colonists develop a sense of community, and it is easy to imagine at least two stages of this evolution.

First there is the start of colonization by some Earth-based corporate or governmental organization. Later, as continued development leads to more and more settlement, the colonists form associations and create governance bodies which reflect rising degrees of community identity, integration and separation of decision making powers from organizations on Earth. These changes evolve first within a single habitat and then cooperative and governmental relations develop when neighboring habitats and a larger community grow. The rate at which this evolution occurs is uncertain.

LIFE SUPPORT

What do the colonists eat and how do they obtain this food? What do they breathe? How do they deal with the industrial and organic wastes of a human community in space? These questions pose the basic problems to be solved by life support systems. Richness of life and survival from unforeseen catastrophes are enhanced by diversification and redundance of food supplies, energy sources, and systems for environmental control, as well as by variety of architecture, transportation and living arrangements, and these considerations are as important in choosing among alternatives for life support as in making choices among other subsystems.

Food

Food supplies can be obtained from Earth or grown in space or both. Total supply from the Earth has the advantage that the colony would then have no need to build farms and food processing facilities or to devote any of its scarce labor to agriculture. However, for a population of 10,000 the transport costs of resupply from Earth at 1.67 t/yr per person is about $7 billion/yr. The preferred choice is nearly complete production of food in space.

Whatever the mode of production, it must be unusually efficient, thereby requiring advanced agricultural technologies (ref. 15). Direct synthesis of necessary nutrients is one possibility, but such biosynthesis is not yet economically feasible (J. Billingham, NASA/Ames, personal communication), [1]. Also, algae culture and consumption have long been envisioned as appropriate for life in space, but upon close inspection seem undesirable because algae are not outstandingly productive plants nor are they attractive to humans (ref. 16). The best choice seems to be a terrestrial type of agriculture based on plants and meat-bearing animals (ref. 17).

This form of agriculture has the advantage of depending on a large variety of plant and animal species with the accompanying improvement in stability of the ecosystem that such diversity contributes (ref. 18). Moreover, plants and animals can be chosen to supply a diet familiar to the prospective colonists, that is, a diet appropriate to a population of North Americans biased in favor of using those plant and animal species with high food yields. Photosynthetic agriculture has a further advantage in that it serves as an important element in regeneration of the habitat's atmosphere by conversion of carbon dioxide and generation of oxygen. It also provides a source of pure water from condensation of humidity produced by transpiration (ref. 19).

Choices of food sources within the general realm of terrestrial agriculture become a compromise between preference and diversity on the one hand and efficiency on the other. For

the colony, efficient use of area (even at expense of efficiency measured in other terms, i.e., as energy) is a critical factor to be balanced against a varied and interesting diet. For example, the almost exclusive use of rabbits and goats for animal protein previously proposed (ref. 15) for space colonies is rejected as being unnecessarily restrictive and seriously lacking in variety.

Recycling Wastes

High costs of transportation place great emphasis on recycling all the wastes of the colony. Because in the near future Earth appears to be the only practical source of elements fundamental to agriculture - carbon, nitrogen, and hydrogen - they must initially be imported from Earth. To avoid having to continually import these elements, all wastes and chemicals are recycled with as small a loss as possible.

Waste water can be treated biologically as in most terrestrial communities, physiochemically, by dry incineration, or by some more advanced technique such as electrodialysis, electrolysis, vapor distillation or reverse osmosis (ref. 20). Each of these alternatives is ruled out for various reasons. Biological treatment provides only incomplete oxidation and produces a residual sludge which must then be disposed of with attendant risks of biological contamination. Physiochemical treatment has no organic conversion, and is chemically a difficult process. Dry incineration requires an external energy source to maintain combustion and it produces atmospheric pollutants. All the advanced processes are incomplete in that the resulting concentrates require further treatment.

Wet oxidation (Zimmerman process) has none of the foregoing defects. Operating at a pressure of 10^7 MPa (1500 lb/in.^2) and a temperature of 260 degrees C, wet oxidation with a total process time of 1-1/2 hr produces a reactor effluent gas free of nitrogen, sulfur and phosphorous oxides; a high quality water containing a finely divided phosphate ash and ammonia. Both the reactor gas and the water are sterile (refs. 21, 22). At solids concentrations greater than 1.8 percent the process operates exothermally with an increase in the temperature of the waste water by 56 degrees C (personal communication from P. Knopp, Vice-President, Zimpro Processing, Rothschild, Wisconsin). These definite advantages lead to the choice of this process as the basic technique for purification and reprocessing within the space colony.

Composition and Control of the Atmosphere

The desired composition of the atmosphere is arrived at as the minimum pressure needed to meet the criteria for atmospheric safety stated in chapter 2. This results in the atmospheric composition detailed in table 4-3.

TABLE 4-3 - HABITAT ATMOSPHERE

T = 20 +/- 5 DEGREES C

Relative humidity = 50 +/- 10 percent

GAS	(kPa)	(mmHg)
O_2	22.7	170

N_2	26.6	200
CO_2	<0.4	<3
Total pressure	50.8	380
Water vapor	1.0	7.5

1 standard atmosphere = 101 kPa

Its outstanding features are: normal terrestrial, partial pressure of oxygen, partial pressure of carbon dioxide somewhat higher than on Earth to enhance agricultural productivity, and a partial pressure of nitrogen about half of that at sea level on Earth. Nitrogen is included to provide an inert gaseous buffer against combustion and to prevent certain respiratory problems. Because nitrogen must come from the Earth, its inclusion in the habitat's atmosphere means there is a substantial expense in supplying it. This fact, in turn, suggests that it is desirable to hold down the volume of atmosphere in the habitat, a factor taken into consideration in the discussion of the habitat geometry given earlier. The total atmospheric pressure is thus about half that at sea level on Earth.

Atmospheric oxygen regeneration and carbon dioxide removal are by photosynthesis using the agricultural parts of the life support system. Humidity control is achieved by cooling the air below the dewpoint, condensing the moisture and separating it. Separation of condensate water in zero gravity areas (such as the manufacturing area and hub) by hydrophobic and hydrophilic materials offers the advantage of a low pressure drop and lack of moving parts (ref. 23) and is the preferred subsystem.

Trace contamination monitoring and control technology is highly developed due primarily to research done in submarine environments. The habitat environment is monitored with gas chromatograph mass spectrometer instruments (ref. 24). Trace contamination control can be effectively accomplished by absorbtion (e.g., on activated charcoal), catalytic oxidation, and various inert filtering techniques.

SATELLITE SOLAR POWER STATIONS: NO ALTERNATIVES

An important goal for the design for space colonization is that it be commercially productive to an extent that it can attract capital. It is rather striking then that the study group has been able to envision only one major economic enterprise sufficiently grand to meet that goal. No alternative to the manufacture of solar power satellites was conceived, and although their manufacture is likely to be extremely valuable and attractive to investors on Earth, it is a definite weakness of the design to depend entirely on this one particular enterprise. A number of valuable smaller scale manufactures has already been mentioned in chapter 2 and, of course, new colonies will be built, but these do not promise to generate the income necessary to sustain a growing space community.

There is some choice among possible satellite solar power stations (SSPS). Two major design studies have been made, one by Peter Glaser of Arthur D. Little, Inc. (ref. 25), and the other by Gordon Woodcock of the Boeing Aircraft Corporation (ref. 26). Conceptually they are very similar, differing chiefly in the means of converting solar power to electricity in space.

Woodcock proposes to do this with conventional turbogenerators operating on a Brayton cycle with helium as the working fluid; Glaser would use very large arrays of photovoltaic cells to make the conversion directly.

There is not a great deal to argue for the choice of one system rather than the other, except perhaps that the turbogenerator technology proposed by Woodcock is current, while Glaser relies on projections of present day photovoltaic technology for his designs. In the spirit of relying on current technology, the Woodcock design seems preferable, but a definite choice between the two is not necessary at this time. A more detailed description of the SSPS alternatives with a discussion of microwave transmission and its possible environmental impact is given in appendix H.

WHERE THE COLONY SHOULD BE LOCATED

Chapter 2 surveyed space and described what is there and how space is shaped in terms of distance, propulsive effort and gravitational attraction. These aspects of space together with the location of needed resources are important to choosing a site for the habitat. The community should be located for convenience with respect to its resources-sunlight, weightlessness, and minerals - and also with access to and from its principal market, Earth. The site should be chosen by balancing the needs of production against the needs of marketing the product.

Near to but not on the Moon

The minerals of space are to be found in the distant outer planets, the asteroids, the nearer and more accessible planets like Mars, the moons of other planets, or our own Moon. Of course the Earth is a primary source of mineral wealth too. It seems reasonable to place the colony near one of these sources. For reasons explained in the next section, the Moon is chosen as the principal extraterrestrial source of minerals, hence the habitat should be near the Moon.

But where should the habitat be placed in the vicinity of the Moon? At first glance the Moon's surface seems a good choice, but any part of that surface receives the full force of the Sun's radiation only a small fraction of the time. Moreover, on the Moon there is no choice of gravity; it is one-sixth that of Earth and can only be increased with difficulty and never reduced. Space offers both full sunshine and zero gravity or any other value of simulated gravity one might choose to generate. An additional difficulty with a lunar location is related to the major product of the colonies, SSPS's. Transporting them from the Moon to geosynchronous orbit is not economically viable. For ease of exploitation of the properties of space, the habitat should be located in free space.

In Free Space at L5

Although there is no stable location at a fixed point in space in the Earth-Moon system, the colony could be located in any one of a number of orbits in free space. These orbits can be around the Earth, or the Moon, or both the Earth and the Moon. Those near either the Earth or the Moon are rejected because of the frequency and duration of solar eclipses which deprive the colony of its light and energy. Large orbits around the Earth make it difficult to deliver the large mass of material needed from the Moon, while large orbits around the Moon become orbits in the Earth-Moon system about which little is known at the present time. These last two options, while not chosen, present interesting alternatives which should be examined more closely.

There remain the orbits about the five libration points. Three of these, L1, L2, and L3, are

known to be unstable, and to maintain orbits around any of these three points for long periods of time requires appreciable expenditures of mass and energy for station keeping.

There do exist, however, large orbits around both of the remaining Vibration points, L4 and L5. These have been shown to be stable (refs. 27, 28). A colony in either of these orbits would be reasonably accessible from both Earth and Moon. One of these libration points, L5, is chosen for the location of the first space colony. This choice is somewhat arbitrary for the differences between L4 and L5 are very slight.

MINING, TRANSPORT, AND PROCESSING IN SPACE

From where will come 10 million tonnes of matter needed to build a colony? And where and how will it be processed, refined and shaped into the metals, glass and other necessary structural material? The topography of space shapes the answer to the first question; human ingenuity offers answers to the second. A major problem only partly solved is how to transport large quantities of matter from mines on the Moon to space. Some possible solutions to that problem are suggested.

Sources

As noted previously, lunar materials have been chosen to supply the great bulk of mass necessary for the first colony, including the shell and internal structure, passive shield, soil, and oxygen. As indicated in figure 4-10, only a small percentage of the mass, including initial structures, machinery, special equipment, atmospheric gases other than oxygen, biomass, and hydrogen for water, comes from Earth.

This decision has been made for a variety of reasons. Of the bodies in the solar system which might supply materials, the other planets are eliminated by the expense of transportation from their surfaces, and the moons of the outer planets by transport times of years and by costs. This leaves the asteroids, comets, and the moons of Mars.

While the composition of the moons of Mars is unknown, both the comets and asteroids are apparently abundant sources of organic materials in addition to rock and possibly nitrogen and free metals as well. For immediate future applications, however, the Moon's position makes it attractive and, compared to the asteroids, the Moon has advantages of known properties, a distance suitable for easy communication, and it allows perhaps simpler overall logistics.

However, when the space colonization program is begun, technical and economic imperatives seem likely to drive it quickly toward exploitation of asteroidal rather than lunar materials and toward much less dependence on Earth. Long before the results of mining activity on the Moon became visible from the Earth, the colony program would be obtaining its materials from the asteroids. Given that source, the "limits of growth" are practically limitless: the total quantity of materials within only a few known large asteroids is enough to permit building space colonies with a total land area many thousands of times that of the Earth.

Processing: Where?

A variety of alternatives exist for the processing of lunar ores to yield materials for the colony. These involve various combinations of processing site, materials to be produced, and chemistry. Optimization requires a detailed analysis of manifold possibilities. The study limited itself to choosing a plan which seems achievable and advantageous based on reasonable extrapolations

of current technology.

The decision as to whether to process at the colony or on the Moon is dictated by various factors. The lunar site has the advantage of being close to the ore source and having a gravity which might be used in some chemical processing. Lunar processing might be expected to decrease the amount of material to be shipped to the colony. However, closer examination reveals that the colony's shielding requirements exceed the slag production of the processing plant; hence, no transportation is saved by processing at a lunar site. Moreover, lunar processing also possesses certain definite disadvantages when compared to processing at the site of the colony. Plant facilities shipped from the Earth to the Moon require much greater transportation expense than for shipment to the colony site. In addition, solar furnaces and power plants are limited to a 50 percent duty cycle on the Moon. Without power storage this would curtail operations at a lunar processing site. Radiators for process cooling are less efficient and, therefore, larger when placed on the Moon, because they have a view of the Sun or of the hot lunar surface. Finally, even at only 1/6 of Earth's gravity, components of the plant have significant weight. On the Moon this requires support structure and cranes and hoists during assembly. But these are not needed if processing is done at the colony site. Based on these considerations, it appears that major processing should take place at the colony site.

Processing: What and How?

The colony requires various materials which are obtainable from the lunar soil. Silica is needed for windows and solar cells. Oxygen is the major component of the colony atmosphere and is required for manufacturing water. It is also a rocket propellant. Silica and oxygen are essential to the success of the colony and therefore must be extracted from lunar ore. However, there is some latitude for choice and optimization among the variety of metals available. Aluminum, titanium, magnesium and iron are all potential construction materials. Although aluminum is chosen as our basic structural material, a decision to refine titanium might have some special advantages. On the Moon, titanium is in the form of a magnetic mineral (ilmenite) which can, in theory, be easily separated from the bulk of the lunar ore. In addition, use of titanium for structure would result in significant savings in the total amount of refined material because, although more difficult to form and fabricate, its strength-to-mass ratio is greater than that of the other metals available. Since ilmenite is basically $FeTi0_3$, significant amounts of iron and oxygen can be extracted as byproducts.

These facts support a recommendation that the alternative of titanium refining should be studied in detail. Possible methods for refining titanium are presented in figure 4-11 and discussed in appendix I.

Most of the remaining metal oxides in the ore must be separated from one another by rather complex techniques before further refining of the metals. Aluminum is the only other metal which justifies detailed consideration. In addition to excellent structural properties and workability it has good thermal and electrical properties (see appendix A). It is chosen as the principal structural material only because information concerning titanium processing is somewhat less definite and, in particular, the magnetic separation technique for lunar ilmenite has not yet been demonstrated.

The various methods by which aluminum might be refined from lunar anorthosite are shown schematically in figure 4-12. The system chosen is melt-quench-leach production of alumina followed by high temperature electro-winning of aluminum from aluminum chloride.

Alternative paths are discussed in appendix I.

To provide window areas for the space structure, glass is to be manufactured from lunar materials. Silica (SiO_2), the basic ingredient in glassmaking, is found in abundance on the Moon. However, another basic constituent, sodium oxide (Na_20), which is used in the most common flat plate and sheet glass industrially produced, is found in only small percentages in the lunar soil. Glass processing on Earth uses Na_2O primarily to lower the melting temperature that has to be generated by the furnace (refs. 29, 30). Since the solar furnace to be provided for processing the lunar material will be capable of generating temperatures considerably higher than those which could possibly be needed for this process, it appears unnecessary to supply additional Na_20 from the Earth (personal communication, J. Blummer, Vice-President for Research, Libbey OwensFord Company, Toledo, Ohio, Aug. 1975).

To date, glasses made from lunar soil samples returned by the Apollo missions have been dark in color. The techniques necessary to manufacture glass from lunar materials which possesses the properties needed for efficient transmission of sunlight into a space habitat have not been demonstrated (personal communication, Pittsburgh Plate Glass Company, Pennsylvania, Aug. 1975). However, it is believed that additional materials research will permit glass of adequate quality for a space facility to be processed from the lunar soil with a minimum of additives (if any) brought from the Earth (personal communication, D. R. Ulrich, Air Force Office of Scientific Research, Washington, D. C., Aug. 1975).

A possible technique which may prove feasible in space for large scale production is the removing of almost all nonsilicate ingredients by leaching with acid. Again, the availability of high furnace temperatures is a prerequisite to meet the melting temperature of silica, and the manufacturing process will have to be shown to be manageable in space. The resulting glass, of almost pure silica (> 95 percent SiO_2), possesses the desirable properties of low thermal expansion, high service temperature, good chemical, electrical, and dielectric resistance, and transparency to a wide range of wavelengths in the electromagnetic spectrum.

Requirements for volume, mass, and energy of a glass-processing unit, a description of a sample process, and an elaboration of lunar soil constituents are given in appendix J.

Transport of Lunar Material

The construction of the colony depends critically on the capability of transporting great quantities of lunar material from the Moon to the colony without large expenditures of propellant. There are three parts to this problem: launching the material from the Moon, collecting it in space, and moving it to the colony. Two principal ways to launch have been devised, along with some variations.

One method is to launch large payloads, of about 60 t, by firing them from a large gas gun. The gun is operated by using nuclear power to compress hydrogen gas and then permitting the gas to expand the length of the launch tube. Because hydrogen must be obtained from Earth, its replacement is expensive, and consequently after each launch the gas is recovered through perforations in the end section of the launch tube which is encased in an enclosed tube. Further details are given in appendix K.

The system is of interest because of its conceptual simplicity and light weight. But the principal drawback of the gas gun system is the difficulty of collecting the payloads once they have been launched because their dispersion is large. Collection needs a fleet of automated interceptor

rockets. The propellant requirement for interception is about 1 percent of the total mass launched. In terms of technology that may be available in the near future, these interceptor rockets have to use chemical propulsion with hydrogen as fuel. The second drawback is that the gas gun requires the development of sliding seals able to withstand high pressures and yet move at high velocities and still maintain acceptable leakage rates. Despite the uncertainties about precision of aim, the difficulties of automated rendezvous and interception, and the associated propulsion requirements, the concept appears fundamentally feasible and worthy of more study. However, the uncertainties are sufficient to make another alternative more attractive at this time.

The alternative method, which is the one chosen for this design, involves an electromagnetic mass accelerator. Small payloads are accelerated in a special bucket containing super conducting coil magnets. Buckets containing tens of kilograms of compacted lunar material are magnetically levitated and accelerated at 30 g by a linear, synchronous electric motor. Each load is precisely directed by damping the vibrations of the bucket with dashpot shock absorbers, by passing the bucket along an accurately aligned section of the track and by making magnetic corrections based on measurements using a laser to track the bucket with great precision during a final draft period. Alignment and precision are the great problems of this design since in order to make efficient collection possible, the final velocity must be controlled to better than l0^-3 m/s. Moreover, the system must launch from 1 to 5 buckets per second at a steady rate over long periods of time, so the requirements for reliability are great. This system is considerably more massive than the gas gun. More details about it are given in the next chapter.

The problem of catching the material launched by the electromagnetic mass driver is also difficult. Three possible ways to intercept and gather the stream of material were devised. Two so-called passive catchers (described in more detail in appendix L), involve stationary targets which intercept and hold the incoming material. The other is an active device which tracks the incoming material with radar and moves to catch it. The momentum conveyed to the catcher by the incident stream of matter is also balanced out by ejecting a small fraction of the collected material in the same direction as, but faster than, the oncoming stream.

An arrangement of catching nets tied to cables running through motor-driven wheels permits rapid placement of the catcher anywhere within a square kilometer. By using a perimeter acquisition radar system, the active catcher tracks and moves to intercept payloads over a considerably larger area than the passive catchers. Unfortunately this concept, described in more detail in the next chapter, has the defects of great mechanical complexity. Nevertheless, although many questions of detail remain unanswered and the design problems appear substantial, the active catcher is chosen as the principal means of collecting the material from the mass launcher on the Moon.

Despite possible advantages it seems desirable not to place the catcher at the site of the colony at L5. For three reasons L2 is chosen as the point to which material is launched from the Moon.

First, the stream of payloads present an obvious hazard to navigation, posing the danger of damage if any of the payloads strike a colony or a spacecraft. This danger is particularly acute in view of the extensive spacecraft traffic to be expected in the vicinity of the colony. The payloads, like meteoroids, may well be difficult to detect. Hence, it appears desirable to direct the stream of payloads to a target located far from the colony.

Second, L2 is one-seventh the distance of L5 permitting use of either a smaller catcher or a less accurate mass-driver.

Third, to shoot to L5 requires that the mass-driver be on the lunar farside. For launch to L2, the mass-driver must be on the nearside. By contrast, a nearside location for the mass-driver permits use of our knowledge of Moon rocks brought back in Apollo flights, and there are a number of smooth plains suitable for a mass-launcher. The nearside also permits line-of-sight communications to Earth.

Catching lunar material at L2 means that transport must then be provided to L5. It appears most practical to use mechanical pellet ejectors powered by an onboard nuclear system of 25 MW. This same system is used to offset the momentum brought to the catcher by the payloads arriving at up to 200 m/s.

THE TRANSPORT SYSTEM

The transportation requirements of a colony are much more extensive than merely getting material cheaply from the Moon to the factories of the colony. There must be a capability for launching about 1 million tonnes from the Earth over a total period of 6 to 10 years. There must be vehicles capable of traversing the large distances from Earth to L5 and to the Moon. There must be spacecraft that can land equipment and people on the Moon and supply the mining base there. Fortunately, this is a subject to which NASA and the aerospace industry have given considerable thought; the study group relied heavily on this work. A schematic representation of the baseline transportation system is shown in figure 4-13.

From Earth's Surface to Low Orbit

The space shuttle is to be the principal U.S. launch vehicle for the 1980s. However for space colonization applications, the shuttle has low payload per launch and requires too many flights with excessive launch costs per kg. At the other end of the launch vehicle spectrum, a number of advanced concepts have been studied. These include a large winged "Super-Shuttle," fully-reusable ballistic transporters resembling giant Mercury capsules, and even use of a laser rocket with a remote energy source. Such concepts are not considered in this primary study because of uncertain technologies, excessive development costs, and long leadtimes. However, one concept for the "F-l flyback" is discussed in appendix C of chapter 6.

The colony has to rely on lift vehicles derived from and, therefore, dependent on the shuttle and other already-developed boosters. Studies have been made on shuttle-derived heavy lift launch vehicles with two and with four solid boosters (fig. 4-14). In these, the manned shuttle vehicle is replaced with a simple vehicle having automated avionics and increased freight capability. The four-booster configuration has a payload of 150 t at under $20 million per launch.

A discussion of the environmental impact on the ozone layer of Earth by launch vehicles is given in appendix N.

Transport Beyond Low Earth Orbit

For routine transport of people and freight, the system uses single-engine vehicles employing space-storable, liquid-gas propellants in modular tankage. The NERVA nuclear rocket is rejected in favor of the space shuttle main engine (SSME). NERVA offers high performance but represents a new development, and involves the safety considerations associated with nuclear systems. The SSME represents an available, well-understood engine. Moreover, with oxygen for refueling available at L5 from processing of lunar ores in industrial operations, the SSME vehicle performance would approach that of NERVA. Consequently the SSME as shown in

figure 4-15 has been selected. Details are given in appendix M.

For passenger transport, the launch vehicle cargo fairing accommodates a passenger cabin holding 200 people. A single SSME could also be used to land over 900 t of cargo on the lunar surface.

For transport of major systems involving their own large power plants, electric propulsion is feasible. Such systems include the L5 construction shack with its 300 MW power plant, and the solar-power satellites to be built at the colony for delivery to geosynchronous orbit. Candidate propulsion systems include ion rockets, resistojets, and mechanical pellet accelerators. In particular, for the baseline system, large numbers of standard ion thrusters are clustered, thus permitting application of current electric-propulsion technology. It is possible in the future that a Kaufman electrostatic thruster could be developed with oxygen as propellant. As described in the next chapter, a rotary pellet launcher is proposed to power the tug which brings the lunar ore from L2 to the processing plant at L5.

SUMMARY

Thus the system described in chapter 1 is arrived at. It carries 10,000 colonists in a toroidal habitat positioned at L5 orbiting the Sun in fixed relation to the Earth and Moon and exploiting the paths through space in figure 4-16. Mining the Moon for oxygen, aluminum, silica, and the undifferentiated matter necessary for shielding, the colonists ship a million tonnes per year by electromagnetic mass launcher to L2. There, with the active catcher, the material is gathered and transshipped to L5 to be refined and processed. With small amounts of special materials, plastics, and organics from Earth, the colonists build and assemble solar power stations which they deliver to geosynchronous orbit. The colonists also raise their own food and work on the construction of the next colony. The following chapter gives a more detailed picture of how the various parts work together.

5. A Tour of the Colony

During the final stages of construction of the habitat, colonists begin immigrating to L5. Within a few years a small but thriving human community is established. Its architecture, agriculture, commerce, culture, and even the individual people reflect a dedicated emphasis on productivity.

Imagine that you are a visitor on a tour of this colony. Your experiences during such a visit are shown in italics in this chapter to act as counterpoints to the continuing technical descriptions which conform with the arrangement of the other material in this report.

EARTH TO LOW EARTH ORBIT

Preparation for your trip is a difficult period; it eliminates those who are not serious about their intention of going to the space colony. You undergo weeks of quarantine, exhaustive physical examinations, stringent decontamination, and interminable tests to make sure that you do not carry insects, bacteria, fungi, or mental problems to L5. Only then are you permitted to board a personnel module of a heavy-lift launch vehicle which everyone refers to as the HLLV, along with 99 prospective

colonists who have gone through even more rigorous tests than you have as a mere visitor.

In the following hour events move at breakneck speed. Your vehicle is launched. Acceleration thrusts you into your contoured seat. Minutes later it ceases and you are in orbit 240 km above the Earth and having your first experience of being weightless. The orbit is a staging area at which an entire section of the HLLV, the personnel carrier containing you and the colonists, is transferred to an inter-orbital transport vehicle known as the IOTV. This is the workhorse transporter that moves people and cargoes between points in space, and never lands upon any planetary body. Its structure seems frail and delicate compared with the airplane-like structure of the HLLV.

During the construction phase of the colony, the staging area handled replacement supplies at the rate of 1000 t a year. The growth and increasing population loading of the colony required transshipment of an average of 50 people per week together with their personal belongings and the additional carbon, nitrogen, and hydrogen needed to sustain them in space. Oxygen, and other elements, are obtained from the Moon. Later the big demand was for lightweight, complex components fabricated for satellite solar power stations. Initially the supply of the lunar base also came from Earth. The 150 people on the Moon require 250 t of supplies and rotation of 75 people to Earth each year. Furthermore, there is traffic from the colony to Earth. Studies of past colonizations on Earth have shown that discontent with frontier life is usually such that many colonists wish to return home.

Cargo was brought up on earlier flights of HLLV's so that you do not have to wait long in the staging orbit. This reduces the amount of consumables needed to support the people between Earth and the colony. Every effort is made to get you to the colony as quickly as possible once you have attained Earth orbit. The freight had been transferred to the IOTV before your arrival, so no time is lost in moving the personnel carrier from the HLLV to the IOTV. The rocket engines of the IOTV begin to thrust and the vehicle breaks from Earth orbit and begins its 5-day journey to L5. You find that conditions within the personnel carrier are crowded, somewhat like the transcontinental charter flights you experienced on Earth.

THE HABITAT AT L5

Like countless other tourists over the years you look for the first view of your destination. Just as European immigrants looked for the concrete towers of New York and the torch-bearing statue, you now anxiously await your first glimpse of the wheel-like structure spinning amid the black backdrop of space. Only in the last day before your arrival is your search rewarded And then you are surprised at how small the space colony looks Since you cannot judge distance in space, the colony appears first as a mere point of light that gradually exceeds the other stars in brightness, and then it forms into a narrow band of sunlight reflected from the radiation shield. Later you see the spokes and the hub. But still the 10 million tonnes of slag and Moon dust that have been compacted and placed around the habitat like a bicycle tire, seem no larger than the rim of a balance wheel in a ladies' watch.

Only in the last few hours of the trip, when the IOTV has matched its orbit with that of the colony and is waiting to dock, do you see the true extent of the habitat and begin to comprehend the immense nature of this man-made structure in space.

The View From the Outside

The space colony appears as a giant wheel in space. Still you cannot comprehend its size, but you know it must be huge. One of the other passengers who has been on the trip before tells you it is 1800 m in diameter. He points to the six spokes connecting the wheel rim to its hub and tells you each is five

times as wide across as is the cabin of your space transport. You look in awe. He tells you that the rough-looking outer "tire"is really a radiation shield built of rubble from the Moon. It protects the colony's inhabitants from cosmic rays.

In reply to your question about the burnished disc that hangs suspended above the wheel of the space colony, he explains that it is a big mirror reflecting sunlight to other mirrors which, in turn, direct the light rays through several other mirrors arranged in a chevron form to block cosmic rays.

As you watch you become aware that the spokes are rotating, but you cannot see any motion in the rim. Again your companion explains; the habitat rotates within the outer shield. Rotation is needed to simulate gravity, but rotating the massive shield would produce high stresses that would require a much stronger structure. The inner habitat tube is accurately positioned within the outer shield so that the two do not scrape against each other.

He points to the hub of the wheel and tells you that is where your transport is heading to dock with the space colony, explaining that local custom has named the docking area the North Pole.

Figure 5-l presents a general perspective of the principal components of the habitat. The torus provides the space for housing, agriculture, community activities, and light industry within a 130-m-diam tube bent into a wheel approximately 1800m in diameter. Six spokes, each 15 m in diameter, connect the torus to a central hub and accommodate elevators, power cables, and heat exchange pipes between the torus and the hub. The spokes also act as diametric crossties to resist excessive deformations of the torus from internal concentrations of masses on opposite parts of the wheel. Glass windows mounted on aluminum ribs cover 1/3 of the surface of the torus and admit sunlight "downward" onto the agricultural and residential areas. The remaining 2/3 of the shell of the torus is constructed of aluminum plates. Details are given in appendix A.

Passive shielding against cosmic rays is a separate, unconnected shell with a gap of approximately 1-1/2 m between it and the torus. The shield, 1.7 m thick, is constructed from large "bricks" of fused undifferentiated lunar soil held together by mechanical fasteners. Over the window region the shield is shaped in the form of "chevrons" with mirrored surfaces which pass light by a succession of reflections but block cosmic rays. The shield and chevron configuration is illustrated in figure 5-2. (For a more detailed explanation see appendices E and K.)

If the shield is used as a reaction mass during spin-up of the torus it would counter-rotate at approximately 0.07 rpm; the relative velocity between the shield and the torus, would thus be about 100 m/s. The torus is prevented from scraping against the shield by a positive positioning device.

The stationary main mirror located above the docking area of the space colony reflects sunlight parallel to the axis of rotation onto the rotating ring of secondary mirrors which illuminate the windows (see figs. 5-1 and 5-2). The secondary mirrors are segmented and each segment is individually directed to regulate the amount of light entering the habitat. The flux of light in space is 1400W/m^2, but requirements in the torus vary from 200 W/m^2 in the residential areas to 1000 W/m^2 in the agricultural areas. Furthermore, a diurnal cycle is required in residential and some agricultural areas, while other agricultural regions require continuous solar radiation. This is achieved by directing the light away from certain windows to obtain darkness and by concentrating the light from several mirrors onto other windows to meet the high flux demands.

As your ship moves smoothly toward the docking area, you become aware of the details of this gigantic wheel-like structure. You see the 100-m-diam fabrication sphere on the "south" side of the central hub. Your companion tells you this is where metals are shaped and formed and where much of the assembly

and construction takes place. To one side of the fabrication sphere is a 200 MW solar power plant and furnace used in fabrication; in the opposite direction you see the dimly visible 4.9 X 105 m^2 expanse of the habitat's radiator with its edge toward the Sun. It radiates into space the waste heat of the habitat delivered to it by a complex of heat exchangers passing through the spokes from the torus to the hub. Like the docking area at the North Pole, the fabrication sphere and radiator do not rotate. (See fig. 5-3.)

As the IOTV passes over the spokes toward the hub you see areas of silicon solar cells suspended between the spokes, central hub, and secondary mirrors. Because they look northward toward the main mirror, these cells are sheltered by the other mirrors from the degrading effects of the solar wind. Your fellow passenger tells you they supply 50 MW of electric power required by the habitat. If control of the main mirror were accidently lost or some other accident should cause loss of solar power, the 200 MW solar power station at the extraction facility, would supply emergency power.

The IOTV moves almost imperceptibly through the last few meters and gently attaches itself to one of the docking ports. All people and equipment for the habitat pass through these ports. There is an unexpected lack of officials and there are no landing formalities. One agent oversees unloading; a second acts as a guide to the passengers. Labor is scarce so that the colony cannot support a bureaucracy, explains your companion.

Passing from the docking module, you see the walls of the central hub moving slowly by you as you float freely under zero-g. You are now in the rotating habitat, but because you are near the axix of rotation, the rotation rate of 1 rpm gives no appreciable sensation of weight. In fact, a few workers on their lunch break can be seen cavorting in the almost zero-g of the central hub playing an unusual type of ballgame, invented by earlier construction workers.

The hub is, howver, much more than a playground, it is a crucial crossroads for the whole colony. Six spokes converge from the torus to this 130-m-diam sphere and emerge from its walls. They carry the power cables and heat exchangers that connect the interior of the habitat to the external power supplies and the radiator. They also serve as elevator shafts through which several thousand commuters travel each day to and from their work in the fabrication sphere or outside the habitat. Now with the other new arrivals you enter an elevator in one of these spokes and begin the 830-m trip out to the torus. As the elevator moves and the sense of "gravity" begins, you realize that "out" is really "down."

A Residential Area

Emerging from the elevator your fellow passengers go their varous ways as you enter a busy community without skyscrapers and freeways; a city which does not dwarf its inhabitants. The human scale of the architecture is emphsized by the long lines of sight, the frequent clusters of small fruit trees and parks, and the sense of openness produced by the broad expanse of yellow sunlight streaming down from far overhead. This is the central plain running the full circumference of the torus along the middle of the tube.

Houses are the most numerous structures. You are impressed by the architectural achievement in housing 10,000 people on 43 ha {106 acres) while maintaining a spacious environment. Spaciousness is achieved by terracing structures up the curved walls of the torus and also by placing much of the commerce (e.g., large shops, light industry, mechanical subsystems) in the volume of the torus which lies below the central plain on which most inhabitants live. Houses have plenty of window area to provide a sense of openness. Walls and doors are only needed for acoustical and visual privacy and not for protection from the weather.

Housing in the space colony (see fig. 5-4) is modular, permitting a variety of spaces and forms - clusters of one- or two-level homes, groups of structures as high as four and five stories, and terraced homes along the edges of the plain. Use of the modular components is illustrated in figures 5-5 to 5-7. (For more information see appendix B.) As noted in chapters 2 and 3 the total projected area (defined in appendix B of ch. 3) required in the torus is 43 m^2/person for residential and community life, 4 m^2 /person for mechanical and life support subsystems, and 20m^2/person for agriculture and food processing. Figure 5-8 (overleaf) illustrates these projected areas in terms of total surface area and the number of levels required for each function. By making use of multiple layers above and below the central plain, the apparent population density in the colony is reduced. Layers below the central plain are illuminated artificially. Figure 5-9, a longitudinal section of the toroid's tube, illustrates schematically the layers of the colony below the central plain. All the architecture within the enclosure of the torus must be distributed to satisfy several requirements:

1. the need for residences to be near the transportation spokes to the hub,
2. the need to balance masses around the rim of the torus,
3. the desirability of acoustically isolating residential areas from noisy commercial and service activities,
4. the need for fire prevention, and
5. the need to facilitate pedestrian traffic.

The total projected area within the torus is 678,000 m^2. If the height between decks is 15 m, the volume needed for agriculture and life support is l0 X 106 m^3. A volume of 8 X 106 m^3 needed for residential and community living brings the total volume (18 X 106 m^3) to only 26 percent of the total of 69 X 106 m^3 which is enclosed by the torus. The "extra" 74 percent of the volume helps to reduce the apparent population density. The areas and volumes required and available are summarized in table 5-1.

TABLE 5-1 (gif format)

TABLE 5-1.- FUNCTIONAL DISTRIBUTIONS OF AREAS AND VOLUMES IN THE STANFORD TORUS

Description	Surface area, m^2	Projected area, m^2	Volume, m^3
Community Area	980,000	430,000	8 X 10^6
Agriculture, processing and mechanical	650,000	240,000	10 X 10^6
Total required	1,680,000	670,000	18 X 10^6
Total available		678,000	69 X 10^6

You are aware that the colony has filled up over the preceeding 4 yr at the rate of about 2000 people per year. Consequently, the houses close to the elevator are already occupied. Since you are a latecomer and also only a temporary visitor, your apartment is some 400 m from where you enter into the torus. This is about the greatest distance anyone resides from an elevator, and the walk takes only 5 min. You might buy a bicycle if you were staying longer. Alternatively you can choose to walk 60 m to the ring road which passes around the torus at the edge of the plain and catch a transport car to the

stop nearest your destination. Since you are a tourist and want to see what is going on, you decide to walk and start off down a tree-lined pedestrian way following the directions on the map you were given when you landed.

Equally as striking as the lack of traffic and wide roads is the presence of a flourishing vegetation. Stimulated by plentiful sunshine, brilliantly colored flowers bloom in profusion along winding walkways. You meet a colonist heading in the same direction as yourself. She tells you she is an engineer at the habitat controls center and is one of those responsible for the maintenance, modification, and control of the mechanical and electrical systems. A few questions about this gigantic and complex structure bring forth a flood of information from your companion. To resist the atmospheric pressure and the centrifugal forces of its own mass as well as the internal masses, the shell has a skin thickness of 2.1 cm. The windows through which sunlight streams are some 65 m "above" you and are 2.8 cm thick. Buried in the walls and under the decks of the torus are thousands of kilometers of wires and piping for electrical power distribution, water supply, waste disposal, and air dehumidifying.

The shell of the torus is designed to resist loads of 50 kPa of atmospheric pressure and the centrifugal forces of its own mass as well as 530,000 t of internal mass. Including the ribbed portion, the mass of the aluminum shell is 156,000 t. (Details of the design are presented in appendix A.) For the windows to resist the pressure of the atmosphere across a span of 0.5 m, the distance between ribs, the glass is 2.8 cm thick. This requires 48,000 t of glass. The masses of the main components of the habitat (except for the extraction plant) are listed in table 5-2; the principal internal masses are summarized in table 5-3.

TABLE 5-2 (gif format)

TABLE 5-2.- SUMMARY OF HABITAT COMPONENT MASSES

	Mass, t	
Item	**From lunar ore**	**From Earth**
Shield	9,900,000	---
Torus shell	156,000	---
Glass solars	48,000	---
Spokes	2,400	---
Central hub	1,600	---
Docking module	100	---
Fabrication sphere	---	500
Radiators	2,400	---
Habitat power station	700	---
Main mirror	200	7 (Mylar)
Secondary mirrors	90	3 (Mylar)

TABLE 5-3 (gif format)

Table 5-3.- SUMMARY OF INTERNAL MASSES

Item	Mass, t
Soil (dry) - 1,000,000 m^2, 0.3 m thick 721 kg/m^3	220,000
Water in soil (10% soil)	22,000
Water, other	20,000
Biomass - people	600
Biomass - animals	900
Biomass - plants	5,000
Structures	77,000
Substructures (20% of structures)	15,000
Furniture, appliances	20,000
Machinery	40,000
Utilities	29,500
Miscellaneous (extra)	80,000
Total	530,000

Arriving at your apartment house you bid the other colonist goodbye. The house is a combination of two duplexes and two studio apartments (see appendix B). Each of the studio apartments on the third floor has a small balcony on which some plants are growing. On a neighbor's balcony is an impressive stand of cherry tomatoes and lettuce in a few pots Small patios below each balcony are surrounded by dwarf apple and peach trees. Although small (49 m^2) your apartment is completely furnished in a compact, convenient and attractive way. Furniture and the few ornaments are made of aluminum and ceramics, a constant reminder that wood and plastics must come from Earth, or be made from carbon, nitrogen and hydrogen brought from Earth It takes a while to become accustomed to the almost complete absence of wood and plastics.

Although the apartment has a kitchenette, you decide it will be more convenient and pleasant to eat in one of the neighborhood community kitchens where you can meet and get to know neighbors as you dine with them. So you walk to the closest of these kitchens.

A glance around the dining area reveals young adults and a few children. Briefings before you left Earth had informed you that the community of the space habitat consists of men and women between the ages of 18 and 40, a few hundred children who came with their parents from Earth, and about a hundred children who were born in the colony. The popupation mix is that of a typical terrestrial frontier - it is hardworking, concentrating intently on the manufacture of satellite solar power stations and the construction of the next colony, a replica of this one.

As you sit down to eat, one of the few colony elders tells you of the philosophy behind the productivity and growth in the colony.

Despite the narrow focus of activities in the colony, he explains, there is considerable stimulation and

innovation by the new settlers The rapid growth of the settlement sustains a sense of dynamic change; but he warns that the stabilization of the community upon reaching its full size may result in the dissipation of that sense (ref. 1). A community as small and as isolated as the colony may stagnate and decline in productivity and attractiveness The answer to the problem is continued growth by the addition of more colonies. Growth is important economically as wed as psychologically, because as time passes the population will become more like that of Earth in its age distribution, with the productive fraction of the population diminishing from about 70 percent to between 30 percent and 40 percent. If more colonies are not established, the amount of production will decrease with time. He points out that only if the total number of people grows rapidly can production in space be maintained at its initial level and be increased sufficiently to meet growing demands of Earth's markets for satellite solar power stations Furthermore, he explains, the aggregation of habitats into larger communities will enable the colonies to develop cultural and technological diversity similar to that which permits the larger cities of Earth to be centers of innovation and disseminators of cultural and technological change.

The colony experiences the egalitarianism of a frontier reinforced by the esprit of a group of people working together with a sense of mission on a common task. His face glowed with enthusiasm as he declared that this spirit, more than heroic adventures or romanticized challenge, is what makes the colony a rewarding place to live. Egalitarianism is tempered by certain realities within the colony. The entire colony has a sense of elitism simply because each individual colonist was selected as a settler. A distinction developing between those with clean and "shirtsleeve" jobs and those who work in hazardous, heavy industry, or zero atmosphere jobs, has only small effects and will not produce marked socio-economic differentiation for a number of years.

He excuses himself, saying he has a meeting of the "elders" to attend.

You continue eating alone. Your meal is satisfying- chicken, peas, and rice followed by apple pie for dessert - hardly the fare which science fiction writers led you to expect. There are no dehydrated "miracle" foods or algae cake because the colony is equipped with extraordinarily productive farms that raise food familiar to people on Earth Your interest is aroused and you decide to tour the agricultural area next to see how this food variety is achieved.

An Agricultural Area

To promote diversity and to build in redundancy for safety's sake the torus is divided into three residential areas separated by three agricultural areas. The latter is segmented into controlled zones which may be completely closed off from other zones. This arrangement permits farmers to use higher than normal temperatures, carbon dioxide levels, humidity and illumination in the controlled zones to force rapid growth (fig. 5-10). Partitioning also inhibits the spread of any disease of plants or animals from one zone to another.

A couple of minutes walk brings a view of tiers of fields and ponds and cascading water (fig 5-11). The upper level where you enter is surrounded by a number of ponds holding about 90,000 fish. There are similar ponds in the other two farms. From the ponds the water flows down to lower levels where it irrigates fields of corn, sorghum, soy beans, rice, alfalfa, and vegetables, and provides water for livestock. The multiple tiers triple the area of cropland (fig 5-12).

On the second tier down a farmer shows you around. The wheat growing on this tier, he tells you, will be ready for harvesting next week. Each of the three agricultural areas in the colony grows essentially the same crops; however, harvests are staggered to provide a continuous supply. On another tier enormous tomatoes grow in a special control zone with elevated levels of carbon dioxide, temperature,

and humidity. On one of the lower levels, the farmer impresses you with the fact that this farm, like the others, contains some 20,000 chickens, 10,000 rabbits, and 500 cattle. The lowest level is enclosed and kept at very low humidity to permit rapid drying of crops to hasten produce flow from harvest to consumption. Because of its high productivity the colony's agriculture feeds 10,000 people on the produce of 61 ha (151 acres). You marvel that so fruitful a garden spot is actually in barren space, thousands of miles from any planet.

The agricultural system supplies an average person of 60 kg with 2450 cal (470 g of carbohydrates and fats and 100 g of protein) and almost 21 of water in food and drink each day (ref. 2). Plants and animals are chosen for their nutritional and psychological importance (ref. 3) (e.g., fresh fruits, vegetables, and beef). The principal crop plants and animals and the areas devoted to each are given in tables 5-4 and 5-5.

TABLE 5-4 (gif format)

TABLE 5-4.- PLANT AREAS

	Amount required, g/person/day	Yield, g/m^2 /day	Area, m^2 /person
Sorghum	317	83	3.8
Soybeans	470	20	23.5
Wheat	225	31	7.2
Rice	125	35	3.6
Corn	50	58	.9
Vegetables	687	132	5.2
Totals	1874	359	44.2

Notes: Fruit in colony provides 250 g/person/day.
Grains and soybeans - dry weights.
Sugar is obtained from sorghum, perhaps from honey.
Cattle use part of the plant roughage.

TABLE 5-5 (gif format)

TABLE 5-5.- ANIMALS AREAS

Animal	Number/ person	Area/ animal, m^2	Area/ person, m^2
Fish	26	0.1	2.6
Chickens	6.2	.13	.8
Rabbits	2.8	.4	1.1
Cattle	.15	4.0	.6

Total	-	-	5.1

Notes: Sources for areas required per animal.
Fish: Bardach, J. E.; Ryther, J. H.; McLarney, W. O.:*Aquaculture*: The Farming and Husbandry of Freshwater & Marine Organisms. 1972 (Wiley-Interscience: New York).
Chickens: Dugan, G. L.; Golueke, C. G.; Oswald, W. J.; and Risford, C. E.; Photosynthesis Reclamation of Agricultural Solids and Liguid Wastes, SERL Report No.70-1, University of California, Berkeley, 1970.
Rabbits: Henson, H. K., and Henson, C. M.; Closed Ecosystems of High Agricultural Yield, Princeton Conference on Space Manufacturing Facilities, May, 1975.
Cattle: Kissner, Wm.: Dept. of Civil Engineering, University of Wisconsin - Platteville: Personal Communications.

Fruit is not included in these tabulations. The trees are grown in residential areas and parks where they provide beauty as well as fruit. The crops are grown in a lunar soil (ref. 4) about 0.3 m deep. This soil is made into a lightweight growth matrix by foaming melted rock. The yields are greater than those achieved on Earth because of improved growing conditions and the ability to grow crops on a year-round basis. The higher levels of carbon dioxide, improved lighting, and temperature and humidity control increase productivity to approximately 10 times that of the typical American farm. Terrestrial experiments (ref. 5) have produced fivefold increase in yield for production of vegetables in controlled greenhouses. (For more details on the agricultural system, see appendix C.)

Life Support Systems

Next stop on your tour is the waste processing facility at the bottom of the agricultural area. It is an important part of the life support system because it maintains a delicate balance between the two opposing processes of agricultural production and waste reduction A sanitation technician explains the operation of the facility.

He points out that on Earth production and waste reduction are balanced, at least partly, by natural processes. Water is extracted from the atmosphere by precipitation as rain; biodegradable materials are reduced by bacterial action. In space neither of these processes is fast nor reliable enough. The colony, lacking oceans and an extensive atmosphere in which to hold wastes, is limited in its capacity for biomass and cannot duplicate Earth's natural recycling processes. Instead, it uses mechanical condensation of atmospheric moisture and chemical oxidation of wastes to reduce the recycling time to 1-1/2 hr. This approach minimizes the extra inventory of plants and animals necessary to sustain life and to provide a buffer against breakdowns in the system.

Agriculture uses sunlight, carbon dioxide, and chemical nutrients to produce vegetation and from that, to raise animals Oxygen and water vapor released as byproducts regenerate the atmosphere and raise its humidity. A considerable amount of vegetable and animal waste is produced along with human

wastes of various kinds - sewage, exhaled carbon dioxide, and industrial byproducts - and all these have to be recycled

Waste processing restores to the atmosphere the carbon dioxide used up by the plants, reclaims plant and animal nutrients from the waste materials, and extracts water vapor from the atmosphere to control the humidity of the entire habitat and to obtain water for drinking, irrigation, and waste processing. He tells you that balancing waste generation and waste reduction is a major accomplishment of the designers of the colony, for it eliminates any need to remove excess wastes from the habitat thereby avoiding having to replace them with expensive new material from Earth.

The technician explains that water is processed at two points in the system. Potable water for humans and animals is obtained by condensation from the air. Because evapotranspiration from plants accounts for 95 percent of the atmospheric moisture, most dehumidifiers are located in the agricultural areas. Because of the rapidity with which plants replace the extracted water it is important that the dehumidification system be reliable. Otherwise the air would quickly saturate, leading to condensation on cool surfaces, the growth of molds and fungi, and an extremely uncomfortable environment. Several subunits are used for dehumidification.

The dehumidifiers work in conjunction with the heat exchange system which carries excess heat from the habitat to the radiator at the hub. For water condensation in the torus' gravitational field, normal condensation techniques are used. Figure 5-13 shows schematically (ref. 6) how water is removed in zero-g areas such as the hub. The humidity is controlled by varying the temperature of the coolant and the rate at which air is passed through the unit. To cool and dehumidify it, the atmosphere must be passed through a thermal processor several times per day.

Water is also a byproduct of the continuous wet oxidation process (ref. 7) shown schematically in figure 5-14.

The complete water supply illustrated in figure 5-15 provides 25 times the potable water needed to satisfy the metabolic requirements of the colonists and their animals. (Figure 5-16 considers only metabolic requirements and does not include water for waste transport.) In addition, some 250 kg of recycled water per person per day is used for waste transport. In spite of this extensive dilution, the total per capita water use in the colony is only 75 percent of U.S. domestic water usage. Consumption is limited by use of recirculating showers, low volume lavatories, and efficient use of water in food preparation and waste disposal. Any increase in water for waste transport reduces the amount of condensed atmospheric water which can be used for irrigation, and increases the recycle water. In addition, 200 kg/person of water is set aside for emergencies and fire protection.

Water condensed from the air is heated to 16 degrees C and fed into the fish ponds. After flowing through the ponds, the water is continuously screened to remove fish waste, mixed with warm recycled waste water, and used for irrigation. Since the water drains through soil and collects under the "field" it is further used to transport animal and human wastes to the waste processing facility.

The temperature difference of the influent and effluent for waste processing is 34.5 degrees C. Heat exchangers are used with the cool, condensed atmospheric water and the recycled water to reduce the cooling necessary for recycled water to 22.2 MJ/person/day. (See fig.5-17.)

In addition to water the wet oxidation process produces exhaust gases rich in carbon dioxide which are scrubbed to remove trace contaminants. The carbon dioxide is fed into the agricultural areas to maintain high concentrations and improve agricultural yields. Solids in the effluent are filtered and returned to the system as animal feed and fertilizer. A high concentration of solids is desirable to make

the wet oxidation reaction self sustaining; that is, the difference in temperature between the effluent and influent depends upon the concentration and heat value of the solids. The balance between mass input and output to permit the life support system of the colony to operate in a closed loop is shown in figure 5-16.

The flow of energy in the colony is of major importance since energy is required both for production of manufactured goods and for agriculture, and the waste heat must be removed by radiators. In addition, industrial processes and the normal amenities of life (e.g., stoves, refrigerators, and other appliances) require electrical energy, the heat of which must also be removed.

Within the habitat itself the largest energy input is the insolation of the agricultural areas (the bulk of which is transferred to water evaporated from the foliage) and the residential areas (see fig. 5-18). A smaller but significant portion of the total input is the electrical power supplied to the colony from its solar-electric power station. The habitat's electrical power consumption per capita is 3 kW, a figure obtained by doubling that of the current U.S. per capita consumption to account for the need to recycle all materials in the colony.

The energy removed from the atmosphere is transferred to the working fluid of the radiator. Assuming a radiator temperature of 280 K, corresponding to a black body radiation of 348 W/m^2, the required area of a 60 percent effective radiator is 6.3 X 105 m^2 . An increase of 50 percent in the area to handle peak daytime solar loads is appropriate; therefore, the required area is 9.4 X 105 m^2. Woodcock's estimate (ref. 10) of 2.5 kg/m^2 for the mass of a radiator leads to the habitat requiring 2400 t of radiator mass.

Production at L5

Stopping for a mug of Space Blitz on the way back to your apartment you happen to catch the Princeton-Stanford ball game on television from Earth and learn that, to everyone at the bar, the three-dimensional ball game played in the central hub is much more thrilling. You find that really only the name of the game played at the colony is the same since the liberating effects of low gravity and the Coriolis accelerations make all shots longer, faster, and curved, thus completely changing the rules and the tactics of the game.

Later the TV news carries a story on difficulties encountered in building the new SSPS. There have been several unforeseen problems with all phases of the production process but in particular with the extraction facility which, to avoid pollution of heavy industry and to isolate a possible source of industrial accident from the habitat, is placed outside the habitat, south of the hub some 10 km away. Although the plant is operated remotely so that it can be left exposed to the vacuum of space, there are a number of small spheres attached to the plant where maintenance can be performed in a "shirt sleeve" environment. The plant has its own solar furnaces and a 200 MW electric power station run by solar energy. Bulk products such as aluminum ingots, oxygen gas, plate glass, expanded soil and shielding material, are brought to the fabrication sphere by small tugs. However, small items and people make the trip through a pressurized transport tube which seems to be developing structural problems near its remote end. In the bar, a construction foreman tells you he is convinced the problem derives from torsional fatigue, but no one seems to be worried since many such problems in the system have been quickly solved in the past. On learning you are a newcomer the foreman offers to act as guide on a quick visit to the fabrication facilities where the major effort of the colony is concentrated and, if possible, down the connecting tube to the extraction plant. Pleading fatigue you head home. At your apartment, you put your feet up and read some descriptive material on the fabrication facilities.

Productivity in Space Construction

Productivity in space is difficult to estimate (see appendix D). The zero g and high vacuum in some situations increases productivity above that obtainable on Earth and decreases it in others. The only basis for estimation is experience on Earth where the models of industrial productivity used are based on factors of manhours of labor per kilogram, per meter, per cubic meter, etc.

Table 5-6 presents estimates of productivity of humans performing some basic operations of industry and construction.

TABLE 5-6 (gif format)

TABLE 5-6.- REPRESENTATIVE PRODUCTIVITIES

Industry	Productivity
Primary aluminum (Hall process)	97 kg/man-hr
Titanimum mill shapes	8.8 kg/man-hr
Household freezers	20 kg/man-hr
Light frame steel erection	28.57 kg/man-hr
Piping, heavy industrial	0.26 m/man-hr

These numbers were derived from estimating factors commonly used on Earth (ref. 8) in 1975, which were modified somewhat on the basis of limited experience in the space program.

Generally, because cost estimating factors are closely guarded proprietary figures in terrestrial industry, reliable information is difficult to obtain. Therefore, the estimates in table 5-6 are used, recognizing appreciable uncertainty in their values. A more detailed discussion of estimated productivity is given in appendix D.

Manufacture of Satellite Solar Power Stations

In addition to constructing new colonies, the manufacture of satellite solar power stations is the second major industry. Such power stations provide the chief commercial justification of the colony. Placed in geosynchronous orbit they satisfy the Earth's rapidly increasing demand for electrical energy by capturing the energy streaming from the Sun into space and transmitting it to Earth as microwaves where it is converted to electricity and fed into the power grids. While such satellite power stations could be built on Earth and then placed in orbit (refs. 9 and 10), construction in space with materials from the Moon avoids the great expense of launching such a massive and complex system from Earth to geosynchronous orbit. The savings more than offset the higher costs of construction in space.

Analysis shows that 2950 man-years are needed to build a satellite solar power station to deliver 10 GW to Earth. A summary of the man-years required for different options for constructing part of the system on Earth and part in space, or for using a photovoltaic system rather than a turbogenerator, is given in table 5-7.

TABLE 5-7 (gif format)

TABLE 5-7.- OFF EARTH LABOR REQUIREMENTS FOR SPSS'S

	Labor, man-years
Thermal SPSS, 10 GW Complete SPSS	2950
Generator (SPSS w/o transmission)	1760
Heating furnace only	1600
Photovoltaic SPSS, 5 GW Complete SPSS	2540
Generator (SPSS w/o transmission)	1800

Notes: Assumes the use of lunar material in productive facilities already in place and high-technology equipment supplied from Earth. The thermal data are based on Woodcock (see ref. 26, ch. 4) and the photovoltaic data on Glaser (see ref. 25, ch. 4).

Other Commerce

There are commercial activities of the colony other than those of constructing satellite solar power stations or new colonies. The easy access to geosynchronous orbit from L5 puts the colonists in the satellite repair business. Communications satellites, which otherwise might be abandoned when they fail, can be visited and repaired. Furthermore, the solar power stations themselves require some maintenance and may even have crews of from 6 to 30 people who are periodically rotated home to L5.

There are also commercial possibilities only just being appreciated. In high vacuum and zero g adhesion and cohesion effects dominate the behavior of molten material. Products such as metal foams and single crystals are more easily made in space than on Earth. In fact in 1975 McDonnell Douglas Astronautics Company (ref. 11) concluded that the growing of single-crystal silicon strip using an unmanned space factory would be economically advantageous.

Certain features are common to all commercial ventures in space. High cost of transportation makes shipment of goods to Earth from space uneconomical except for products with a high value per unit mass that are impossible to make on Earth. Advantages of high vacuum and reduced weight often enhance productivity. Availability of large quantities of low-cost solar energy permits production processes in space which consume such large amounts of energy that they are impractical on Earth. The expense of providing human workers encourages reliance on automation which, because of the expense of repairs and maintenance, is pushed to extremes of reliability and maintainability. The expense of replacing lost mass places strong emphasis on making all production processes closed loops so that there is very little waste.

Extraction Processes for Lunar Ores

Production at L5 is strongly influenced by the processes available by which to refine needed materials from the lunar ores. These processes in turn specify the mass of ore required, necessary inventories of

processing chemicals, and masses of processing plant.

Figure 4-25 depicts the sequence of processing to produce aluminum from lunar soil. The soil is melted in a solar furnace at a temperature of 2000 K then quenched in water to a glass. The product is separated in a centrifuge and the resultant steam condensed in radiators.

(Table 5-8 lists the process radiators and their sizes.) The glass is ground to 65 mesh and leached with sulfuric acid.

TABLE 5-8 (gif format)

TABLE 5-8.- RADIATORS FOR PROCESS COOLING

Process	Temperature, K	Power, MW	Area, m^2 X 10^3	Mass, t
Quench	363	20.9	24.0	144
Acid leach	363	7.1	8.1	49
Acid cooking	363	38.3	44.0	262
Leach water	283	7.9	21.8	131
Chlorination	1123	10.1	.6	4
Electrolysis	973	23.1	2.6	15
Carbon reform	1123	19.8	1.3	8
Total	---	127.2	102.4	613

The pregnant solution containing aluminum sulfate is separated from the waste material in a centrifuge and then autoclaved at 473 K with sodium sulfate to precipitate sodium aluminum sulfate. This separation again requires centrifugation. The precipitate is calcined to yield alumina and sodium sulfate, the latter washed out with water and then the hydrated alumina cabined and coked. The mixture of alumina and carbon is reacted with chloride to produce aluminum chloride and carbon dioxide. The aluminum chloride is electrolyzed to yield aluminum. The melt-quench process with acid leaching was studied and experimentally demonstrated by the U.S. Bureau of Mines (ref. 12). The carbochlorination and electrolysis processes were developed and patented by the Aluminum Company of America (refs. 13-17).

The following four tables (5-9 to 5-12) present the logistical requirements of a processing plant capable of producing about 150 t/day of aluminum, that is, about 54 kt/yr.

The electrical requirements of the system are summarized in table 5-9, while the solar heating requirements are given in table 5-10.

TABLE 5-9 (gif format)

TABLE 5-9.- ELECTRICAL POWER REQUIREMENTS FOR PRODUCING ALUMINUM

Process	Power, MW
Electrolysis	70

Carbon reform	40
Other	5
Total	115

TABLE 5-10 (gif format)

TABLE 5-10.- SOLAR HEATING REQUIREMENTS FOR ALUMINUM REFINERY

Process	Power, MW	Temp, K	Mirror projected area, m^2 X 10^3
Melt	27	1973	19
Autoclave	32	473	23
Decomposition	12	1173	9
Calcination	5	1073	5
Totals	76	-	56

Table 5-11 indicates the mass inventory for process chemicals as determined by detailed evaluation of the flow chart. The equipment masses were determined through discussion with industrial contacts.

TABLE 5-11 (gif format)

TABLE 5-11.- MASS INVENTORY FOR PROCESS CHEMICALS

Chemical	Mass, t	Mass excluding oxygen, t
H_2O	225	28
H_2SO_4	55	19
Na_2SO_4	30	17
NaCl	235	235
LiCl	70	70
Cl_2	25	25
Carbon	2	2
Totals	642	396

The mass of the entire system is presented in table 5-12.

TABLE 5-12 (gif format)

TABLE 5-12.- MASS REQUIRED FOR REFINING

Item	Mass, t

Structure	500
Chemicals	650
Equipment	3000
Radiators	600
Flare shield	50
Solar furnace	20
Powerplant	2800
Total	7620

Relations to Earth

Tired of reading the technical literature, you still find it difficult to fall asleep in this new world which is so much like Earth superficially yet completely man-made. It is clear that this space colony of people with new life styles, interests and visions of the future is still tied to the Earth economically. You decide that it is, in fact, the commercial activities of the colony and economic relations to Earth which explain several of the striking features of life at L5. Long term economic self-sufficiency and growth require manufacture of products suffeiently useful to Earth to attract capital and, ultimately, to create a favorable balance of trade in which the value of exports exceeds that of imports. While great effort is concentrated on construction of solar power plants and new colonies, the colonists also seek to minimize imports by producing goods for internal consumption and by maintaining a major recycling industry. The conflict between using resources and manpower for production for internal use and using them for production for export calls for many management decisions. In these early years of the colony the balance seems to be definitely in favor of production for export. Consequently, reliance on Earth as a source of the products and services of highly developed technology as well as for carbon, nitrogen, and hydrogen continues to be great. Moreover, concentration on exports greatly limits the diversity of human enterprise in the colony, because the majority of productive workers are engaged in heavy construction. Like most of the frontier communities in history, the colonists at L5 are chiefly concerned with repaying borrowed capital, increasing their standard of living, and expanding their foothold to develop further their mastery over the environment of space.

Finally, you drift off in sleep, dreaming of yourself as an early American pioneer, clearing a small stand of trees for your new farm.

THE LUNAR BASE

After several days of touring the colony you have been continually reminded of the role of the Moon. The soil in which food is grown came from the Moon. The aluminum used throughout the colony for construction once was part of lunar ore. Even the oxygen you breathe has been extracted from lunar rocks. During the construction of this colony 1 million tonnes of lunar ore were shipped each year, and the colony still processes roughly the same amount annually to construct new colonies and satellite solar power stations.

The mining and transport of this material on and from the Moon is a major part of a successfully functioning system for space colonization. You accept an invitation to travel to the Lunar Base, and start at the module at the colony's North Pole where you board an IOTV carrying supplies to the Lunar

Base. The same type of transport vehicle brought you from low Earth orbit to L5 in 5 days; however, it takes about 2 weeks to reach the Moon from L5.

The Site of the Lunar Base

When the IOTV has entered lunar parking orbit, it is joined by a smaller ship known as the LLV (lunar landing vehicle). You transfer to it through a docking port and then the LLV descends to the lunar surface in a few minutes and settles gently down with the retrorockets creating a huge cloud of dust which settles back to the surface quickly in the absence of any atmosphere. You have arrived at the Lunar Base. (For more information concerning the impact on the lunar atmosphere, see appendix G.)

You join several off-duty staff members in the lounge of the lunar base for a snack and a cup of coffee. The base provides many services to the people operating on 2-yr tours of duty. These services include recreational facilities, private apartments, and an excellent dining hall - to make their stay as pleasant as possible. Living conditions at the lunar mining base, while comfortable, reflect those of a work camp rather than a family habitat. The base is a monolithic structure composed of prefabricated units. It is covered with lunar soil 5 m deep to protect it against meteorites, thermal fluctuations, and ionizing radiation.

Since primary activities here are mining ore, compacting the ore and launching it to L2 (the base also supports exploration and research efforts), you are anxious to see the facilities. Walking in the Moon's weak gravitational field is so effortless that you are quite willing to don a spacesuit and join the base commander in a walking tour outside the pressurized area of the base.

Mining and Processing Ore for Shipment

Soon you arrive at the edge of a large hole in the lunar surface which is now almost 2 km across and 10 m deep, from which the ore is scooped. The base commander explains that to supply the I million tonnes per year to L5 a surface area the size of about 8 football fields must be mined each year. The mining machinery operates 50 percent of the time, requiring a mining rate of about 4 t/min (about 1 m^3/min). Soil is scooped and carried to the processor by two scooper-loaders (refs. 18-20). Ore is carried from the mining area on a conveyor system. At the launch area it is compacted to fit into a launcher bucket, and then fused.

The site for the base is in the Cayley area at 4 degrees N. 15 degrees E. where Apollo 16 landed. This site was selected because of richness of lunar ore, suitably flat terrain for the launcher, and the near-side equatorial region gives a suitable trajectory to L2. Apollo samples had an aluminum content between 4.5 and 14.4 percent, the highest percentage being from this site. The Apollo missions did not provide any evidence of rich ore veins below the lunar surface.

Lunar bases have been the subject of many design studies (refs. 18-20). The total mass of housing and life support equipment is approximately 2000 t brought from Earth to accommodate the construction crew of 300 persons. During the mining operations, there are only 150 persons at the base of whom approximately 40 are support personnel. Consumables of 495 kg (including 0.45 kg for losses) per person-day are supplied from Earth. The mass imported each year is given in table 5-13.

TABLE 5-13 (gif format)

TABLE 5-13.- ANNUAL MASS IMPORTS

Imports	Mass,

	t/yr
Crew consumables	270
Maintenance supplies	100
Crew rotation*	14
Atmosphere leak replacement	18
Total	402

*The same mass is also transported from Moon to Earth.

Almost all activities are in a "shirt sleeve" environment within the shielded structure. A large area is provided for repair work. The mass and power required for these operations on the Lunar Base are summarized in tables 5- 14 and 5-15.

TABLE 5-14 (gif format)

TABLE 5-14.- LUNAR BASE EARTH-SUPPLIED MASS

System	Mass,t
Mining and conveyor system	250
Housing and life support	2,400
Technical Support	500
Launcher	4,000
Power plant (200MW + 10%)	9,900
Total	17,050

TABLE 5-15 (gif format)

TABLE 5-15.- LUNAR BASE POWER REQUIREMENTS

System	Power MW
Launcher	192.00
Mining	0.70
Compaction	7.15
Living quarters	.15
Total	200.00

The Mass Launcher

Critical to the success of the entire system of colonization of space is the ability to launch large amounts of matter cheaply from the Moon. There are two aspects: launching the material from the

Moon by an electromagnetic launcher using the principle of the linear induction motor, and gathering the lunar material in space by an active catcher located at L2.

Each second the mass launcher accelerates five 10-kg masses of lunar material to lunar escape velocity of 2400 m/s. Errors in launch velocity are kept within 10^-4 m/s along the flight path and 10^-3 m/s crosswise to it.

The masses are carried in an accelerating container or "bucket." Built into the walls of each bucket are liquid helium-cooled superconducting magnets which suspend it above the track. The buckets are accelerated at 30 g over 10 km by a linear electric motor running the length of the track. The bucket then enters a drift section of track, where vibrations and oscillations lose amplitude enough for the payload to be released with great precision of velocity. The velocity of each bucket is measured, and adjusted to achieve the correct value at release.

During acceleration the payload is tightly held in the bucket, but when lunar escape velocity is reached and the velocity is correct the payload is released. Since the bucket is constrained by the track to follow the curve of the lunar surface, the payload rises relative to the surface and proceeds into space. Each bucket then enters a 3 km region where a trackside linear synchronous motor decelerates it at over 100 g. It is returned to the loading end of the track along a track parallel to the accelerator.

At the load end of the track the liquid helium used to cool the superconducting magnets is replenished, and a new payload loaded. Then the bucket is steered to the start of the accelerator for another circuit. Figure 5-19 (overleaf) shows the mass launcher schematically. More details are given in appendix F.

With a 70 percent duty cycle, this system can launch 1.1 Mt/yr. To assure this duty cycle during lunar night as well as lunar day, two complete mass launchers are necessary. A nuclear power plant rather than a solar plant is required so the operation can continue through the lunar night.

Power and Supply

Several nuclear reactor single-cycle helium-Brayton plants of 10 to 50 MW each are used instead of a single big plant because the smaller plants can be transported assembled and become ready to operate by use of space shuttle main engines. The redundancy of several smaller systems is attractive, especially since the plants need to be taken off-line for refueling every year or two.

The total capacity is 220 MW and the total mass is 9900 t, including a 10 percent design factor.

The mass of the power plant is estimated using the value of 45 t/MW, which is projected to be applicable to nuclear plants within the decade [1]. Shielding will be provided by lunar material.

THE MASS CATCHER AT L2

The problem of collecting the stream of material launched by the mass-driver is solved by a kind of automated "catcher's mitt, " the mass catcher, located at L2. Although the catchers are fully automated there is a 2-person space station at L2 for maintenance personnel. This station is adequately shielded against possible hits by stray payloads.

Because it would be dangerous to navigate in the vicinity of the catcher while the launcher is operating, you are not able to visit the catcher personally. Instead you learn about it from an operator who is at the Moon base on recreation leave.

He tells you that the mass catcher is an active device to capture payloads of lunar material shot by the

mass launcher. The payloads are solid blocks 0.20 m in diameter, made of compacted and sintered lunar soil. Each payload has a mass of 10kg and arrives at L2 with a speed of 200 m/s.

The catcher is in the form of a thin, light net, 10 m^2 in area, which is manipulated by three cables to position the net anywhere within an equilateral triangle. The cables are wound on reels which move on three closed loop tracks Each side of the equilateral triangle is 1 km, thus providinga 0.43 X 106 m^2 catch area The total mass of the catcher is 220 t.

Station-Keeping With the Rotary Pellet Lanucher

You learn that the mass catcher uses an unusual propulsion device - a rotory pellet launcher - to position the catcher so that it is always facing the incoming stream of payloads Furthermore, this device provides a counterthrust to the force of some 2000 N imparted to the catcher by the stream

Further details of the mass catcher are provided in appendix G. and because of their importance the trajectories from the Moon to L 2 and their relation to station-keeping are described in appendix H. The mass catcher is illustrated in figure 5-20.

The rotary pellet launcher is a heavy tube rapidly rotating to accelerate and eject small pellets of rock. (See fig. 5-21).

Velocities as high as 4000 m/s may be attained, equal to the exhaust velocities of the best chemical rockets. The pellets themselves are sintered or cast directly from lunar rock, with no chemical processing required. The launcher uses 5 percent of the mass received as propellant. (For further analysis see appendix I.)

This rotary pellet launcher is mechanically driven by an onboard nuclear power system rated at 20 MW. The power plant radiator is situated in such a manner as to radiate freely to space while being shielded from impacts of stray masses. The inner surface of-the radiator is insulated and made highly reflective, so as to avoid heating the catcher.

The transport of lunar material from the catcher to the colony is accomplished using a space ore-carrier. The trip from L2 to L5 requires some 2 months. The rotary pellet launcher is the primary propulsion system since a thrust of only several thousand newtons must be obtained over a period of weeks to perform the mission. Of course, the rotary launcher cannot be used in the vicinity of either the colony or the mass-catcher, because of the danger from its exhaust of high-velocity pellets. For low-velocity maneuvers in these vicinities chemical rockets can he used.

You express concern to the operator of the mass catcher over the possible hazard of using high velocity pellets as propellant mass because they constitute artificial meteoroids They are ejected with high velocity, not so high as to escape the Solar System, but sufficiently high to escape the Earth-Moon system and take up solar orbits. Typically, they will range inward as far as Venus and outward to Mars' orbit.

The operator's response is reassuring. He reminds you that the astronomer George Wetherill (ref. 21) studied the lifetimes of meteoroids in such orbits, or the times before collision with Earth He found a mean lifetime of 10^7 years. The Earth presents a surface area of 5 X 108 km^2, while a colony's area is some 1 km^2 or less, and a spacecraft's area much less. Using a standard that no more than one impact from a pellet per square kilometer every 10 yr may be allowed, then 5 X 10^14 pellets may be permitted to orbit the Sun following ejection. If each has a mass of 10g, the allowed mass of ejected pellets is 5 X 10^9 t. This is some 10,000 times the mass of pellets to be ejected in the course of carrying material for building the colony. He assures you that the rotary pellet launcher will be a

useful propulsion system for many years, before the environmental effect of ejected pellets becomes noticeable in comparison to the effect of meteoroids naturally present in space.

HOME TO EARTH

It is now 2 months since you left Earth. In that time you have traveled over 750,000 km, you have another 386,000 to go to get home to Earth. You have seen a tiny community of 10,000 men and women crowded into the colony and in small bases on the Moon and at L2 separated by vast distances which are in turn dwarfed by the immensities of space. Homesickness is inevitable. It is time to leave the realms of the colonists. Their tasks and their will to do them are enormous, and only those people can be colonists who have a large capacity to work hard and long when, as soon happens, tedium replaces the initial excitement. You speculate that it will be mostly their children and grandchildren who will master space. The great mass of mankind will remain in the cradle of Earth; only a few will go into space.

You are fortunate to get a berth in one of the ships that brings supplies to the Moon and rotates personnel from the Moon base directly back to Earth In the early years all the men and women of the base went straight back to Earth and so the personnel transporter was full to capacity. Now increasing numbers choose to spend their rotation time at L5 instead of on Earth and berths are available on the run to Earth. You wonder whether this seed of human society planted in such an unlikely environment will flourish, and settling back into your seat to read a terrestrial news magazine you conclude that only time will tell.

6. Building the Colony and Making It Prosper

For the functioning system described in the previous chapter to become a reality much preparatory work must take place to fill in the gaps in current knowledge. Initial efforts toward space colonization begin on Earth, move into low Earth orbit (LEO) and continue later to the lunar surface, the site of the mass catcher (L2), and finally to the site of the colony (L5).

Critical gaps in present knowledge and experience, such as physiological limitations of a general population and dynamics of closed ecological systems, require extensive basic research before space colonies can be established. Parallel engineering efforts are also needed to develop suitable techniques, processes, and materials for colonization of space. Pilot plants for extraction of materials, for fabrication in space, and for power production are necessary to provide design and operations experience. Finally, transportation systems, in particular the mass launcher and catcher, and the rotary pellet launcher which are necessary for transporting lunar ore to L5, must be developed early in the space colonization effort.

This chapter describes the projected preparations, operations, schedules, and costs to establish a permanent colony in space. While not optimized with respect to any criterion, they have been conservatively developed to demonstrate feasibility. The sequential activities needed for space colonization and the costs for such a program are summarized in figures 6-1 and 6-2.

Also included in this chapter is a discussion of the satellite solar power stations (SSPS's) as a potential economic justification for space colonization. If production of SSPS's were to become the central activity of space colonists, several modifications of the system logistics would be likely.

PREPARATORY WORK

There are three sites for research, development, demonstration, testing and evaluation (RDDT&E): Earth, LEO, and the lunar surface. There is no activity at L5 during these activities because LEO provides a similar environment to L5 but at one quarter the cost. This is because materials must come from the Earth during this preparatory work and it would cost more to transport them to L5 than it does to LEO.

Activities on Earth

Systems not requiring zero-g can be developed in pilot plants on Earth. These include systems for materials extraction and fabrication, power generation, transportation, and habitation. Techniques for processing lunar soil into structural materials are especially critical for the colonization program since they differ significantly from those currently used on Earth (see chapter 4, appendix I and appendix J). Those processes which require vacuum can be tested on a small scale on Earth. In addition, many of the large subsystems, while ultimately dependent upon the features of the locale in space, may be studied or partially developed on Earth. For example, a large facility or manufacturing plant may use lighter structures and different heat radiators in space; nevertheless, its internal processes can be studied in detail on Earth. These preliminary RDDT&E efforts are critical milestones for most major elements of space colonization.

Both nuclear and solar power sources of large scale must be developed, even though solar electric power is generally preferred since a specific plant mass of 14t/MW is estimated for solar plants as compared to 45 t/MW for unshielded nuclear generators. Nuclear power is planned for the station in LEO and for the lunar base so that continuous power can be supplied during frequent or prolonged periods of being in shadow.

Two basic transportation systems must be developed; one to lift large and massive payloads, the other to transport lunar ore to L5. The first system includes a heavy lift launch vehicle (HLLV) capable of lifting 150 t to LEO; an interorbital transfer vehicle (IOTV) with a 300 t payload for missions from LEO to high orbits; *e.g.*, to L2, L5, or to lunar parking orbit; and a lunar landing vehicle (LLV) with a 150 t payload capacity. These vehicles can be developed using the technology developed for the space shuttle. Development of the lunar mass accelerator, the mass catcher at L2, and the interlibration transfer vehicle (ILTV) is less certain but is still expected to use to use current technology. Major research, as opposed to the above technological development, is required on physiological effects and ecological closure. The physiological effects that are amenable to research on Earth include long-term exposure to reduced total atmospheric pressure, to reduced pressures of certain gases, and effects of rotation on vestibular function. Research into questions of ecological closure is vital to the long-range colonization of space. The mix and quantity of flora and fauna needed to maintain closure or partial closure together with humans must be quantified. Moreover, research into intensive agricultural techniques is important in the colony's efforts to provide its own food. Particular attention must be directed to microbial ecology; the varieties, amounts, and interactions of bacteria and other microbes needed for healthy agriculture, animals, and people, are today imperfectly understood.

Activities at LEO

Pilot plants for materials extraction and fabrication, techniques for materials assembly, solar and nuclear power generation systems, the mass catcher, the ILTV and IOTV, and the habitats are all tested in LEO which provides vacuum and zero-g with relatively rapid access from Earth Research on physiological effects of rotation and reduced gravity is conducted there also.

Activities on the Moon

Preliminary efforts on the surface of the Moon are minimal because the lunar systems can be evaluated and tested near Earth. Moreover, only limited lunar exploration is required (though more may be desirable) since undifferentiated lunar soil supplies the colony with sufficient minerals.

MATERIALS AND SUPPLIES

Materials for the total colony could come from the Earth. However, by using lunar raw materials as soon as possible, the costs to Earth of constructing the colony are greatly reduced, though the time required for completion of the colony is increased. Such a strategy is implemented by constructing only the essential components of the colony system from Earth materials. These subsystems - the lunar mining facility, the ore mass transport system, the L5 materials extraction and fabrication facility, and the construction shack - are then taken to their respective positions in the system. Here they are made operational to process lunar raw materials for the major construction of the habitat. During this construction phase minor construction materials and supplies, as well as crew resupply, must come from Earth.

Fabrication on Earth

Low Earth orbit (LEO) serves as a vital point in the construction and supply of the first space colony. There, a space station consisting of a crew quarters, a construction shack, and a supply depot is assembled from materials made on Earth Additional materials are then launched from Earth to LEO for assembly of the lunar base. They include a nuclear power station, a mass launcher and auxiliary equipment, mining equipment, crew quarters, and maintenance equipment. Also launched is equipment for L2, the mass catchers and the interlibration transfer vehicle (ILTV). The construction shack, the solar power station and the supplies and facilities used in materials extraction and fabrication are launched to LEO for transfer to L5.

Raw Materials from the Moon

Lunar mining operations proceed as described in chapter 5. Oxygen is an important by-product of the refining of lunar materials at L5. It can be used there as rocket propellant immediately (resulting in a significant reduction in costs of transportation) or can be stored for later use in the atmosphere of the space colony and in its water.

Full use of all of the mass obtained from the Moon is assured by the manufacture of metals, glass, and soil, and by the use of ore and the slag in the cosmic ray shield.

Raw Materials from the Earth

The completed habitat must be outfitted with supplies and raw materials which are available only from the Earth, including highly specialized equipment and personal belongings of the immigrants to the colony. The atmosphere, water, and chemical systems also require raw materials from Earth; mostly hydrogen, carbon, and nitrogen which are not present in lunar ore. The initial agricultural biomass must be transported from the Earth to complete the outfitting of the habitat. From the time when immigration of colonists begins, only the resupply and new materials not available from the Moon are required from the Earth.

TRANSPORTATION AND CONSTRUCTION

Initially all of the supplied materials must be sent from Earth to LEO for transshipment to the point of

activity. As operations begin at L5 raw materials must be sent there from the surface of the Moon so that metals can be extracted and the construction of the colony can start.

Transshipment and Assembly in LEO

After the effort of research, development, demonstration, testing and evaluation there is a LEO station with pilot plants for processing materials and for producing nuclear and solar power. Because of the volume and weight limitations of HLLV payload capacity, large items are launched in subunits to be assembled in space. The payload capacity of the IOTV nominally equals that of two HLLV's, but in space neither volumes nor acceleration forces limit the configuration. Assembly tasks at LEO range from repackaging the mass launcher to setting up the complete solar power stations.

A propellant depot must also be established at LEO for use by the IOTV. When this additional propellant is taken into consideration, the mass which must be brought from Earth to LEO is roughly 4 times the payload delivered to L5 and 8 times the payload delivered to L2 or to the lunar surface. However, with the eventual availability of oxygen for rocket propellant as a by-product of refining at L5 the mass which must be brought to LEO becomes approximately twice the payload to L5 and 3.3 times the payload to L2 or to the lunar surface (Austin, G., Marshall Space Flight Center, Alabama, personal communication, Aug. 15, 1975). These factors include return of transportation hardware to its point of origin following each mission.

Lunar Operations

Portions of the lunar base and the propellants for the lunar landing vehicle (LLV) are carried by the IOTV to a lunar parking orbit from which the LLV's ferry material to the lunar surface. As shipments arrive there, an assembly crew successively assembles the power plant, an underground habitat, the lunar soil scoop, and the mass launcher. Two separate nuclear power systems and 2 mass launchers are used to achieve the reliability needed. Their construction is timed to provide substantial operational experience with the first system before a second system is completed. The lunar base also includes a repair shop and a supply of spare parts for timely preventive maintenance and repairs.

Build-up at L5

The construction shack and the first power plant are delivered to L5 by the IOTV and are assembled by the construction crew. Thereafter, the materials extraction system and the fabrication system are constructed and made operational. Any lunar material received before the processing facility is completed is simply stockpiled.

ESTIMATING COSTS AND TIME

The subsystems, materials, supplies, and operations required for the build-up of the colony system have been outlined in the previous sections. It now remains to schedule the sequencing and timing of the events, and to determine the costs involved with this build-up. The scheduling and costing activities are interdependent.

System Considerations and Constraints

The scheduling and costing presented here are for the establishment of the baseline colony system described in chapter 5 through the completion and population of one habitat.

To allow ample lead time consistent with other large scale projects, the colony's development is scheduled with a gradual build-up of effort and with minimal fluctuations from year to year. Alternative strategies by which costs or project duration may be minimized are outlined briefly in appendix A. In

general these results indicate that short durations are accompanied by large system costs. If interest costs are included, there is some minimum cost strategy. However, no optimization is attempted on the schedule presented here.

Automation is included only to the extent that it is now practiced in the industries involved. Bootstrapping (the use of small systems to build larger systems which, in turn, are used to build still larger systems) is not used in the cost estimate for the colony development, with the exception that pilot plants serve mainly to gain design and operational experience. The factors of additional time and added complexity of increased construction in space both caused the rejection of extensive bootstrapping.

Methods Used for Estimation

The scheduling and costing of a space colony require estimation of labor, size, and cost. First, labor: the personnel required in space for each major step of colonization is estimated from a composite of similar elementary tasks performed on Earth but derated or increased by the effects of vacuum and weightlessness. The methodology for estimating labor requirements is described in appendix D of chapter 5; the major results are summarized in table 6-1.

TABLE 6-1 (gif format)

TABLE 6-1.- PERSONNEL REQUIREMENTS

	Number of people	**Resupply,* t/yr**	**Time period,** yr**	**Rotation, people/yr**	**Tasks**
LEO station	200	330	5-14	400	Physiological testing - rotation, gravity; pilot plant operations and testing; assembly systems for L5 and Moon depot fuel
LEO station	100 (+ 100 transient)	250	15-25	200	Way station Supply transshipment
Lunar base	300	500	10-14	300	Assemble lunar systems
L5 construction station:	100 2270	167 3784	9-11 12-18	100 2270	Set up L5 site Build shell and 60% shield
L5 colony	10,000	{4200 I 1000 II	19-22 23-25}	100	Complete interior and shield Live and work
Inter-librational transfer vehicle	10	-	11-25	-	Crew for transfer between L2 and L5

*Nominal resupply: 1.7 t/person-yr of normal Earth materials costing $5/kg.
**Times are years from start of the project; e.g., if the project began in 1990

the time period 5-14 means 1995-2004.
I. Colony resupply: Linear decrease from nominal value during 4-yr period of colony immigration.
II. Colony resupply: 100 kg/person/yr of imports.

Next, sizes: the main items to be sized include habitats, vehicle fleets, and resupply and mass flow rates. The L5 construction station and the LEO station are nominally 5 t/person with 7 t/person for the more permanent Moon base. The number of vehicles is twice that required for minimum turnaround time. Annual supply rates during construction are set at 1.7 t/person, which includes food, water, gases, and expendables. After the colony is available for habitation, the annual supply rate is reduced over the 4yr colony build-up to an estimated 0.1 t/person.

The mass flow rate from the Moon is sized to complete the shield in 10 yr (1.2 X 10^6 t/yr). The materials extraction and fabrication plants are sized by the completion of the colony's shell in 6 years (9 X I0^4 t/yr). Plant output is assumed (on the basis of an average of terrestrial industries) to be approximately 8.3 plant masses per year. Each power source is sized proportional to its respective power user.

These estimates for the transportation system, the mass and energy systems, and for the habitats are shown in tables 6-2 , 6-3, and 6-4, respectively.

TABLE 6-2 (gif format)

TABLE 6-2.- TRANSPORTATION SYSTEM

Vehicles	Route	Payload, t	R&D, TFU,* $10^9	Number of units	Cost/unit $10^9	Period, yr	Payload cost, &/kg
Space shuttle	Earth-LEO**	30	-	3	.03	5-25	440
Heavy lift launch vehicle (HLLV)	Earth-LEO**	150	0.3	6	.08	4-25	200
Interorbit transport vehicle (IOTV)	LEO-LPO**	300	.4	9	.03	5-25	See trip costs below
Lunar landing vehicle (LLV)	LPO-Lunar surface**	150	1.7	4	.03	9-25	See trip costs below

TRIP COSTS (Launch and fuel)	Without O_2 at L5		With O_2 at L5 (after year 12)***	
	Materials, $10^3 /t	People, $10^3 /person	Materials, $10^3 /t	People, $10^3 /person
Earth to LEO	200	440 *a*	200	440 *a*
LEO to L5	600	400 *b*	200	140 *b*
LEO to Lunar surface	1400	930 *b*	460	310 *b*

* Research and development through first unit at $5000/kg.
** LEO: Low Earth orbit; LPO: Lunar parking orbit.
***Austin, G., Marshall Spaceflight Center, Ala., personal communications, Aug.15, 1975.
a Earth to LEO for people via space shuttle, 30 people/flight (hamaker,J., Marshall Space Flight Center, Ala., personal communication, Aug. 8,1975).
b Crew transport module + people ≅ 2/3 t/person (Hamaker, J., Marshall Space flight Center, Ala., personal communication, Aug. 8,1975).
All Costs expressed in 1975 dollars.

TABLE 6-3 (gif format)

TABLE 6-3.- MASS AND ENERGY SYSTEMS - SIZE AND COST

	Output size	Specific mass	Total mass, t	Time period, yr	R&D TFU* $10^9	Numb of uni
LEO Nuclear power pilot plant Solar power pilot plant Pilot materials plant	10 MW 20 MW 2500 t/yr of Al	45 t/MW** 14 t/MW** 8.3 output mass/yr / plant mass	450 280*(a)* 300	6-25 6-25 7-25	2.3 1.4 1.5	
L5 Solar power plant 1 2 3 4 5 Materials plant	20 MW 50 MW 50 MW 50 MW 50 MW 90,000 t/yr of Al	14 t/MW** 14 t/MW** 14 t/MW** 14 t/MW** 14 t/MW** 8.3 output mass/yr / plant mass	280 700 10800	9-25 (from LEO) 9-25 10-25 11-25 12-25 12-25	-	4 1
Mass Transport Lunar Surface to L2 to L5 Nuclear power plant 1 2	120 MW 120 MW	45 t/MW** 45 t/MW**	5400 5400	10-25 14-25		2
Mass launcher 1 2	5X10^5 t/yr 5X10^5 t/yr	Track 1000 t Electrical 1000 t Repair shop 0750 t	2750 2750	12-25 14-25	5.0*(c)*	 1

Mass catcher 1 2 3 4	 2.5X10^5 t/yr 2.5X10^5 t/yr 2.5X10^5 t/yr 2.5X10^5 t/yr	Incl. solar power 10 M/W catcher, @ 14 t/MW	 340 340 340 340	 11-25 13-25 13-25 13-25	1.7	3
Interlibration transfer vehicle (ILTV) 1 (and crew module) 2	5X10^5 t/yr 5X10^5 t/yr	Includes solar power 20 MW/ILTV@ 14 t/MW; 4-crew modules for 10 men	400 400	11-25 11-25	2.0	1

(a) Moved to L5 in year 9
* Research and development through first unit at $5000/kg.
**NASA estimates for near term technology (nuclear plants are unshielded).
(b) Purchase at $500/kg.
(c) Active portions costed at $5000/kg for R&D TFU.
All costs in 1975 dollars.

TABLE 6-4 (gif format)

TABLE 6-4.- HABITATS

	Crew size	Mass/person, t/person	Mass, t	Time period,yr	R&D TFU,* $10^9	Unit cost, $10^9
LEO station:	200	5**	1,000	5-25	5.0	
Lunar base:	300***	7***	2,100	11-25	1.1 *a*	
L5 construction station:	2,270	5**	11,350	9-19	5.7 *a*	
L5 colony: Structures Shield	10,000	-	 500,000 10,000,000	20-25		
(L5 colony Interior:) Gas and H_2 from Earth Biomass Furnishings from Earth Colonists Soil			 21,100 5,900 25,000 600 220,000		 <.1 *b* <.1 *b* .1 *b* -	
Personnel transport modules: Number of units A:3 B: 4	 10 100	 0.6(+3) .6(+3)	 9 63		 .3 *c* .2 *c*	 0.30 *c* .08 *c*

*Research and development through first unit at $5000/kg.
** Mass per person used is between the 10 t/person of the NASA 100 person space base and the 3.5 t/person of the G.W. Drigger's design (paper presented at Princeton Conference on Space Manufacturing Facilities , May, 1975). The lunar base is expected to withstand the weight of lunar soil covering for shielding and to be more permanent.
***Designed for construction crew of 300; permanently occupied by operational crew of 150.
a Cost for first unit makes use of R&D done for LEO station; $500/kg purchased on Earth.
b Normal Earth materials costed at $5/kg.
c NASA estimates.
All costs expressed in 1975 dollars.

Finally, cost estimates are required for three categories of expenses - research and development through the first unit, purchase price of additional units, and transportation costs. A precise costing effort for the first two items is prohibitively complicated. However, previous space projects have shown that research and development costs vary from $1000 to $20,000 per kg; Apollo was $14,000/kg. In this study $5000/kg is used. Purchase prices are assumed to be $500/kg which is consistent with other large-scale systems. Transportation costs, primarily launch and propellant costs and exclusive of vehicle costs, are based upon a manned payload of 30 people in each shuttle and an unmanned payload of 150 t per HLLV leading to $4.4 X 10^5 per person and $2 X 10^5 per tonne delivered to LEO. Outward beyond LEO, costs depend upon destination. They decrease with increased availability of oxygen in space from processing of lunar material.

These data are summarized in tables 6-2, 6-3, and 6-4 along with the size data. All costs are expressed on 1975 dollars.

Schedule

Scheduling of the colony build-up requires special attention to several key elements of the system; these include the habitats, the lunar nuclear power station, the lunar ore transportation system, the L5 materials processing plant, the transportation costs, and the productivity of the L5 work force.

Very simply, these factors interact in the following manner. Physiologically adequate crew quarters must be developed before any extraterrestrial activities can take place. Thereafter, lunar construction and mining can proceed only with the availability of the lunar nuclear power station. The shipment of lunar ore to L5 requires that the mass launcher/catcher system be operational. Construction activities which use materials obtained from lunar ore depend crucially upon the development of materials extraction and fabrication techniques and upon the completion of the L5 processing facility. Reduced transportation costs are possible as soon as oxygen in space is available as a by-product of the materials processing facility at L5. Finally, the necessary work force which best matches the processing plant output, the desired rate of construction, and the available crew quarters requires careful consideration of the productivity of space workers.

These factors lead to the mission timetable which is summarized in figure 6-1. In brief, the schedule provides for 5 yr research on Earth, 3 to 5 yr for development and testing in orbit near Earth, 5 yr to build up operations on the Moon and at L5, 6 yr for habitat construction, and a final 4 yr for completion of the shield and the immigration of the colonists. The overall schedule projects a 22 yr completion of

the colony from the start of the project. Specific details of this schedule for the space colony are given in the tables listed below:

- Table 6-5 (gif format)
- Table 6-5 - Concluded (gif format)
- Table 6-6 (gif format)
- Table6-7 (gif format)

TABLE 6-5.- SCHEDULE OF TASKS

Task	Mass t	Manpower, persons	Cost, $10^6	Years after Go Ahead 1 2 3 4 5 6 7 8 9 10 11 12 1
RESEARCH				
Closed ecology	---	400	1000	E* ——►
Physiological effects	---	200	500	E ——► O* ——►
Material science	---	100	150	E ——►
DEVELOPMENT THROUGH FIRST UNIT				
Pilot plants				
● Solar power (20 MW @ 14 t/MW)	280		1400**	E ——► O [box] L *>>**
● Nuclear power (10 MW @ 45 t/MW)	450		2250**	E ——► O >>
● Materials processing (7.0 t/day)	300		1500**	E ——► O >>
Transportation systems				
● Heavy lift launch vehicle	(150)(a)		300 (b)	
● Interorbit transfer vehicle	(300)		400(b)	
● Lunar lander	(150)		1700(b)	E [box] >>
Mass system				
● Mass launcher	2750		5000**	E [box] O >>
● Mass catcher	340		1700**	E ——► O ——► M*>>
● Interlibrational transfer vehicle	400	10	2000**	E [box] O ——► M >>
Habitats	1000	200	5000**	

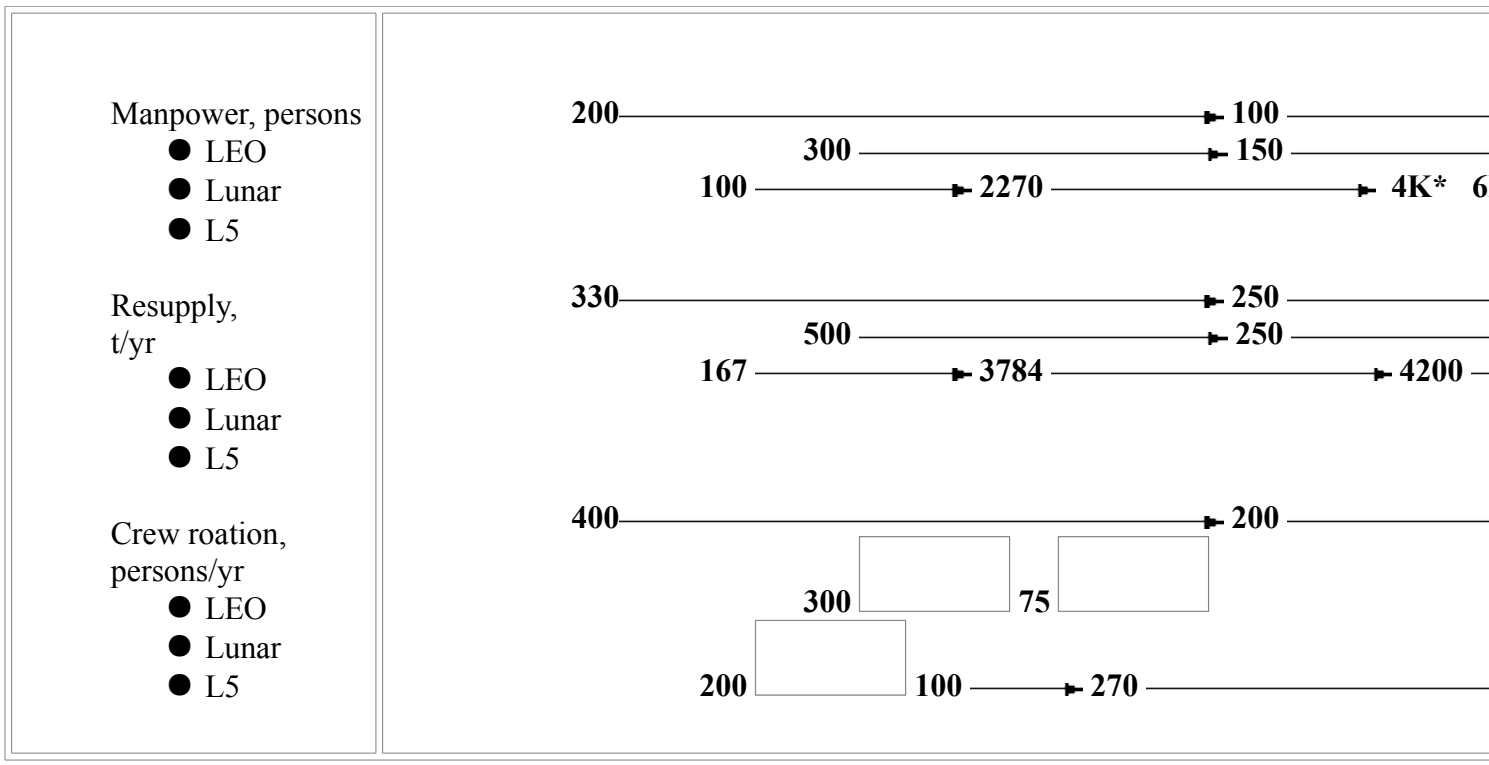
● LEO station (5 t/person) ● Moon station (7 t/person) ● L5 station (5 t/person) ● Crew transport module A ● Crew transport module B	2100 11350 9 63	300 2270 10 100	1100(c) 5700(c) 300(b) 200 (b)	E O L2 >> E → O → L2 >> E → O >> E → O → M >> E → O L >> E O >> E → O >>
PRODUCTION				
Solar power plant 1 (50 MW)	700	---	350	E O L >>
Solar power plant 2 (50 MW)	700	---	350	
Solar power plant 3 (50 MW)	700	---	350	E O L >>
Solar power plant 4 (50 MW)	700	---	350	
Nuclear power plant 1 (120 MW)	5400	---	2700	E O → L >>
Nuclear power plant 2 (120 MW)	5400	---	2700	
Materials plant (Fab. & Ext.)	10800	---	5400	E O M >>
Heavy lift launch				
● vehicle 1	(150)		80	E O → M >>
● vehicle 2	(150)		80	
● vehicle 3	(150)		80	E O M >>
● vehicle 4	(150)		80	
● vehicle 5	(150)		80	E → O → L >>
Space shuttle 1	(30)	(30)	30	
Space shuttle 2	(30)	(30)	30	
Space shuttle 3	(30)	(30)	30	E >>
Interorbit transfer				
● vehicle 2-4	(300)	(450)	30X3	E >>
● vehicle 5-9	(300)	(450)	30X5	
Lunar lander 2-4	(150)	(220)	30X3	E >>
Mass launcher 2	2750		1400	E >>

	340 400	 (10)	20X3 20	E >> E >> E >> E >>
Mass catcher 2-4 Interlibration transfer ● vehicle 2				E O >> E O >> E → O M> E → O E → O E → O

*E indicates effort on Earth, O in Earth orbit, M on the Moon, L and L5, L2 at L2.
**Research and development costs are $5X10^6 /t.
***>> denotes the time at which the system becomes operational.
(a)( ) indicates masses which are payloads.
(b)NASA estimates.
(c)Construction cost is $0.5X10^6 /t after experience gained at LEO.

TABLE 6-6.- LABOR SCHEDULE

Years after Go Ahead:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
TASK																		



*K denotes 1000.

TABLE 6-7.- SCHEDULE OF PAYLOAD MASS FROM EARTH (kt)*

Years from Go Ahead:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
MASS TO LEO																			
Materials					1.0	3.6	3.1	7.4	7.6	9.7	5.1	2.8	2.7	2.7					
Resupply					.3	.3	.3	.5	.5	1.0	4.6	4.6	4.6	4.6	4.4	4.4	4.4	4.4	4.8
Colony interior													.6	2.5	6.0	7.0	6.4	6.0	5.2
Total					1.3	3.9	3.4	7.9	8.1	10.3	9.7	7.4	7.9	9.8	10.4	11.4	10.8	10.8	10.0
Crew Rotation** (100's of people)					4	4	4	6	5	8	8	30	30	30	25	25	25	25	4
Colonists (100's of people)																			20
MASS TO LUNAR BASE																			
Materials									2.7	5.0	2.8	.3	2.8	5.4					
Crew rotation *(a)*										.2	.2	.2	.2	.2	.1	.1	.1	.1	.1
Resupply										.5	.5	.5	.5	.5	.3	.3	.3	.3	.3
Total									2.7	5.7	3.5	1.0	2.5	6.1	.4	.4	.4	.4	.4
MASS TO L5																			
Materials								5.6	6.7	1.0	6.5	6.1							

Crew rotation *(a)* Resupply								.2 .2	.1 .2	.1 .2	1.5 3.8	1.5 3.8	1.5 3.8	1.5 3.8	1.5 3.8	1.5 3.8	1.5 3.8	1.5 3.8	.1 4.2	
Colony interior Colonists (100's of people)																			20	
TOTAL								6.0	6.9	1.3	11.8	11.4	5.9	7.8	11.3	12.3	11.7	11.3	9.3	

* Excludes fuel needed for further transport, though it is included in costs.
** Crew @ 2.2 t/person effective transport cost.
(a) Crew @ 2/3 t/person includes crew module.

Cost Totals

The task, labor, and payload schedules of these tables are combined with the cost data of tables 6-2 through 6-4 to provide a schedule of costs.

- Table 6-2
- Table 6-3
- Table 6-4

These results are summarized in figure 6-2. In addition, the total costs are given as: research, $1.6 billion; development, $28.5 billion; production, $14.6 billion; and transportation, $114.3 billion. Including a 20 percent overhead charge of $31.8 billion, the total cost of the system is thus $190.8 billion, where all costs are expressed in 1975 dollars Figure 6-2 also shows that the availability of oxygen in space dramatically reduces the transportation costs which are still over half of the total system costs. A detailed breakdown of these cost data is given in table 6-8.

TABLE 6-8 (gif format)

TABLE 6-8.- COST TOTALS (1975 $B)

Years from Go Ahead:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
RESEARCH	0.9	0.1	0.1	0.1	0.1	0	0.1	0	0.1	0.1										
DEVELOPMENT TO FIRST UNIT																				
Pilot plants	.6	1.0	1.0	1.1	1.1	.3														
Transport systems	.1	.1	.4	.4	.5	.4	.5													
Mass system	.2	.3	.8	.9	1.0	1.1	1.2	1.1	1.1	1.0										
Habitats	.5	1.6	2.5	2.6	2.1	1.2	1.2	.3	.3											
Subtotal	1.4	3.0	4.7	5.0	4.7	3.0	2.9	1.4	1.4	1.0										
PRODUCTION																				
Power & materials																				
Transport				.3	1.0	1.6	2.3	2.8	2.1	.8	0.8	.05								
Mass		.1	.3	.3	.1	.1														

Subtotal		.1	.3	.6	.2 1.3	.2 1.9	.2 2.5	.3 3.1	.2 2.3	.2 1.0	.2 1.0	1.5								
TRANSPORTATION O_2 Available Crew to LEO LEO Lunar base L5 Subtotal Colonists					.2 .3 .5	.2 .8 1.0	.2 .7 .9	.3 1.6 3.4 5.2	.2 1.6 3.8 4.2 9.8	.4 2.1 8.0 .8 11.3	.4 1.9 4.9 7.1 14.3	1.3 1.5 1.4 6.8 11.0	1.3 1.6 1.7 1.2 5.8	1.3 2.0 2.9 1.6 7.8	1.1 2.1 .2 2.3 5.7	1.1 2.3 .2 2.3 6.1	1.1 2.2 .2 2.3 5.8	1.1 2.2 .2 2.3 5.8	0.2 2.0 .2 1.9 4.3 1.2	0. 2. . 2. 4. 1.
Totals	2.3	3.1	5.0	5.6	6.5	5.9	6.3	9.8	13.5	13.3	15.3	11.5	5.8	7.8	5.7	6.1	5.8	5.8	5.5	5.
Miscellaneous and Administrative (20% overhead)																				
TOTAL																				

PRODUCTION OF ENERGY IN SPACE AS A POTENTIAL ECONOMIC JUSTIFICATION FOR SPACE COLONIZATION

The study looked into ways in which a space colonization program might be economically justified. One way, and perhaps the most promising, is production of SSPS's to satisfy terrestrial demands for energy. In the following sections the cost effectiveness of this production is discussed and important factors affecting economic viability are identified.

Beyond the Initial Cost Estimate

Costs can be reduced in several ways. Second and later colonies affect total costs, and space colonies have the ability to repay Earth for their initial and operating costs by supplying energy from space. Most of the repayment takes place after the first colony is finished and operating; in fact, the time horizon of the program has to be extended to 70 years. However, such an extension introduces cost uncertainties and suggests changes in the system that would be likely to increase its economic productivity.

Potential for Optimization Based on SSPS Production

A modified sequence to establishing colonies in space is to build several construction shacks first, and then begin building SSPS's and colonies at the same time. Additional workers (above the 4400 housed in the colony) should be housed in construction shacks. Shacks are more quickly built and cost less than colonies but have higher recurring costs of wages, crew rotation from L5 to Earth, and resupply. Colonies have less total cost; that is, initial and recurring costs taken together. As production activities expand, more lunar materials are needed until the capacity of the initial mass launching system is exceeded. To move more material from the Moon will require more power there. Rather than add another nuclear station, an SSPS in lunar synchronous orbit should be considered since nuclear stations are probably cost effective on the Moon only before SSPS's are built in space.

Incorporation of these changes modifies the baseline mission timetable of space colonization operations after year 12, by building additional construction shacks and a lunar SSPS at L5. Although start of construction of the first colony is delayed 3 years (see table 6-5), the colony is still completed by year 22.

The labor force in space also changes from the baseline system; it is smaller through years 12 to 14 and larger afterwards than that given in table 6-1. The initial construction shack houses only 500 people until year 15 when capacity is increased to 2000. By year 14, 3200 workers are needed, by year 15, 5389. No more construction shacks are required after year 15. New cost estimates reflecting these changes are given in column 3 of table 6-9 .

TABLE 6-9 (gif format)

TABLE 6-9. - ADJUSTMENTS IN BILLIONS OF 1975 DOLLARS TO THE COSTS GIVEN IN FIGURE 6-2*(a)*

(1)*(b)* Year of program	(2) Figure 6-2 costs	(3) Construction shack adjustments	(4) Lunar expansion & lunar SSPS power costs	(5) Transportation adjustments
1	2.8			
2	3.7	-0.9		
3	6.0			
4	6.7			
5	7.8			
6	7.1	-2.2		
7	7.6	-3.3		
8	11.8	-3.3		
9	16.2			
10	16.0		2.29	
11	18.4	2.54	1.47	
12	13.8	1.14	1.47	
13	9.0	2.07	8.96	
14	9.4		8.96	
15	6.8			
16	7.3			1.3
17	7.0			
18	7.0			
19	6.6			
20	7.1			-4.5
21	7.1			
22	7.1			

(a) Cost of SSPS's which are built after year 14 and costs of second and later colonies are not included in this table. All costs given in this chapter include a 20 percent surcharge in miscellaneous items and administration.

(b) Indicates columnar numbers referred to in text.

At year 11 a rectenna must be built on the Moon to be ready to receive power from the lunar SSPS in year 15. Its receiving capacity is increased as needed in subsequent years. Parts of the rectenna can be fabricated on the Moon from lunar materials, for which chemical processing and fabricating equipment would be placed on the Moon at year 10. This equipment would also be used to expand the lunar base and to produce additional mass drivers. Costs of these lunar expansion activities are given in column 4 of table 6-9, including the cost of producing the lunar SSPS at L5. (See appendix B for technical details of the power system.)

Profitable commercial production of terrestrial SSPS's at L5 would not begin until year 22, although 9 demonstration units, each full scale, would be completed to prove the system during the previous 6 years.

Simultaneously with the SSPS demonstration, a second-generation shuttle system needs to be developed with lower operating costs than the current shuttle. The second-generation system would be justified by the increased traffic into space needed in a space colonization program. As an added benefit, the new shuttle could use propellants that would not pollute the Earth's atmosphere. The effect on costs of one candidate for a second-generation shuttle is shown in column 5 of table 6-9. (See also appendix C.)

Schedule, Costs, and Benefits of SSPS and of Additional Colonies

The U.S. market for electrical energy from space is assumed to be equal to the need for new plants because of growth in consumption and obsolescence of existing plants. The foreign market is assumed to be half of the U.S. market; that is, the same proportionately as for nuclear plants (ref. 1). Uncertainties in new technology delay its acceptance so that markets have to be penetrated. Ten years are assumed for full penetration of the electricity market by SSPS, which may be optimistic based upon current experience with nuclear power.

The market size is assumed to increase 5 percent per year, consistent with the intensive electrification scenario of the Energy Research and Development Administration (ref. 2). Figure 6-3 gives the number of 10GW capacity SSPS's needed each year to meet the terrestrial demand and the number of them actually transmitting energy (based on the assumption that each has a lifetime of 30 yr and begins to deliver power as soon as it is built in space).

Figure 6-4 shows the growth of the number of people and colonies in space if the only aim is to produce electricity for Earth Other additional scientific or industrial activities in space would require larger populations.

Figure 6-5 shows production costs for SSPS's and colonies, and the benefits from electricity generated to terrestrial-based Americans. The economic advantage of space operations would be improved if benefits to foreign nationals from lower electricity costs, and to colonists, are included in the analysis.

An international organization to fund the colonization program would bring even greater benefits to terrestrial Americans as discussed later. But even an American funded program would produce sufficient benefits, based on revenue obtained from sale of electricity and lower price of the electricity to the consumer. The costs for electricity (ref. 3) are discussed in appendix E. A competitive cost for space-derived electricity is 14.1 mils based on the assumption that the most economically produced terrestrial electricity (from nuclear plants) will be 14.1 mils during the period under consideration. It is assumed that electric power consumption will not increase with price decreases and that all nations will be charged the same price.

Cash Flow and Other Results

A summary of cash flow - defined as the benefits less the costs for each year of operation in space - is given in figure 6-6. After year 12, costs are found to be dominated by building of SSPS's when mass starts to be transported from the Moon. The following 3 yr would be spent expanding the initial construction shack at L5 and building an SSPS to be used to beam energy to the Moon.

By year 22 a new shuttle system is to be operating and commercial production of SSPS's begun. Colonists would start to arrive in year 20 and number 10,000, 3 years later. Costs then would be subsequently proportional to the number of SSPS's produced each year, and benefits proportional to the total number built, increasing more rapidly than costs.

Through completion of the first colony the program would cost $196.9 billion, excluding costs directly related to SSPS's and more colonies (columns 1 and 5 of table 6-9). An additional $14.7 billion would be needed to prepare for production of the demonstration SSPS's (columns 3 and 4 of table 6-9) which would cost $21.7 billion more than the value of the electricity they produce.

By year 28 annual benefits would exceed costs. Payback in costs would be achieved.

Busbar cost of electricity produced from energy gathered from space is calculated to be 8.5 mils at year 22 falling to 4.8 mils by year 70 as shown in figure 6-6 (see also appendix D). The analysis is quite sensitive to the real discount rate (including inflation) which at 10 percent gives a benefit-to-cost ratio of 1.02. If the discount rate is lowered to 8 percent, the benefit-to-cost ratio is 1.5 (see appendix G).

Still Other Alternatives

The date at which a second-generation shuttle system becomes available is important. If development started at year 3 instead of year 15, the benefit-to-cost ratio could be increased to 1.3 and the cost of the program for the initial colony would drop to $112.7 billion, but with greater annual expenditures in the early years of the program.

There are alternatives to space colonization for generating electricity from space-building the SSPS's on Earth, and using construction shacks only without building any space colony. But space colonies win over terrestrial building because they use lunar materials which cost hundreds of times less at the use point in space than do terrestrial materials. While construction shacks cost less and can be built more quickly, in the long run they are more expensive because of their operating costs.

Some Other Energy-Related Benefits

While electricity from space and lower costs of electricity to U.S. consumers may be extremely desirable and sufficient to justify a space colonization program, there are other benefits that have not been fully evaluated in the study but may be significant. Environmentally, microwave transmission of power from space for conversion into electricity at Earth, is a very clean form of energy production (see appendix H). It avoids emission of pollutants into the Earth's atmosphere and minimizes the waste heat introduced into the terrestrial environment. The conversion of microwave energy to electricity is far more efficient than any thermodynamic process - 85 percent compared with a maximum of 50 percent.

Electrical energy from space may also be the only way in which the nation can become energy independent within the same time scale of 70 years, for not only can it supply the needed quantities of electrical energy but also inexpensive electrical energy that might be used for electrolysis of water to produce transportable fuels and thereby reduce dependence on petroleum products in transportation systems.

Another subtle energy-related benefit is the widespread nature of its application to mankind. Low-income people spend a comparatively greater percentage of their income on electricity than do affluent people. Thus lower priced electricity would benefit an enormous number of people and not just a few. This benefit from space colonization offers the potential of reaching vast numbers of people in the U.S. and providing relatively low cost energy to many more in the developing nations of the world. It offers a real alternative to limited growth scenarios for underdeveloped peoples.

7. View to the Future

In earlier chapters conservative projections are made on the possibilities of space colonization. The view is that the potentialities of the concept are substantial even if no advanced engineering can be employed in its implementation. Abandoning a restriction to near-term technology, this chapter explores long-term development in space, mindful of a comment made many years ago by the writer Arthur C. Clarke. In his view, those people who attempt to look toward the future tend to be too optimistic in the short run, and too pessimistic in the long run. Too optimistic, because they usually underestimate the forces of inertia which act to delay the acceptance of new ideas. Too pessimistic, because development tends to follow an exponential curve, while prediction is commonly based on linear extrapolation.

What might be the higher limits on the speed and the extent of the development in space? First, consider some of the benefits other than energy which may flow from space to the Earth if the road of space colonization is followed. To the extent that these other benefits are recognized as genuine, space colonization may take on added priority, so that its progress will be more rapid.

From the technical viewpoint, two developments seem almost sure to occur: progress in automation, and the reduction to normal engineering practice of materials technology now foreseeable but not yet out of the laboratory. Those general tendencies, in addition to specific inventions not now foreseen, may drive the later stages of space colonization more rapidly and on a larger scale than anticipated in the other chapters of this report.

BENEFITS NOT RELATED TO ENERGY

Space colonization is likely to have a large favorable effect on communication and other Earth-sensing satellites. Already communication satellites play an important role in handling telex, telephone, computer, and TV channels. They provide data-links and track airplanes and ships as well as rebroadcast TV to remote areas. In the future even more of these data-link applications can be expected. Not only will planes and ships be tracked and communicated with by using satellites, but trains, trucks, buses, cars, and even people could be tracked and linked with the rest of the world continuously. Currently, the main obstacle blocking direct broadcasting of radio and TV to Earth from orbit is the lack of low-cost power in space. SSPS's would produce such power. In addition, their platforms could be used to provide stability. Currently, up to 40 percent of the in-orbit mass of communication satellites consists of equipment used to provide power and maintain stability. Finally, colonists could carry out servicing and ultimately build some of the components for such satellites.

Space manufacturing such as growing of large crystals and production of new composite materials can benefit from colonization by use of lunar resources and cheap solar energy to reduce costs. Space

manufactured goods also provide return cargo for the rocket traffic which comes to L5 to deliver new colonists and components for SSPS's.

Within the past half-century many of the rich sources of materials (high-grade metallic ores in particular) on which industry once depended have been depleted. As the size of the world industrial establishment increases, and low-grade ores have to be exploited, the total quantity of material which must be mined increases substantially. It is necessary now to disfigure larger sections of the surface of the Earth in the quest for materials. As both population and material needs increase, the resulting conflicts, already noticeable, will become more severe. After the year 2000 resources from the lunar surface or from deep space may be returned to the Earth. Much of the lunar surface contains significant quantities of titanium, an element much prized for its ability to retain great strength at high temperature, and for its low density. It is used in the airframes of high performance aircraft, and in jet engines. Given the convenience of a zero-gravity industry at L5 a time may come when it will be advantageous economically to fabricate glider-like lifting bodies in space, of titanium, and then to launch them toward the Earth, for entry into the atmosphere. The transportation of material to the Earth in this form would have minimum environmental impact, because no rocket propellant exhaust would be released into the biosphere in the course of a descent. (Some oxides of nitrogen would be formed as a result of atmospheric heating.) Titanium may be valuable enough in its pure form to justify its temporary fabrication into a lifting-body shape, and its subsequent retrieval in the ocean and towing to port for salvage and use. If such lifting-bodies were large enough, it might be practical to employ them simultaneously as carriers of bulk cargo, for example, ultra-pure silicon crystals zone-refined by melting in the zero-gravity environment of the L5 industries. It has been suggested that the traditional process of metal casting in the strong gravitational field of the Earth limits the homogeneity of casts because of turbulence due to thermal convection. Quite possibly, in space, casting can be carried out so slowly that the product will be of higher strength and uniformity than could be achieved on Earth. A titanium lifting-body might carry to the Earth a cargo of pure silicon crystals and of finished turbine blades.

RESEARCH IN DEEP SPACE

The foundries of the Earth fabricate heavy machinery in an intense gravitational field simply because there is no other choice. The ideal location for the construction of a very large object is almost certainly a zero-gravity region. The L5 colonies, furnished with abundant solar power, relatively conveniently located for access to lunar materials, and with zero gravity at their "doorsteps" will very likely become the foundries of space, manufacturing not only satellite power stations but also radio telescope antennas many kilometers in dimension, optical telescopes of very large size, and vessels intended for scientific voyages to points farther out in space. Research probes to the asteroids and to the outer planets could be built, checked out and launched gently from L5 colonies and with none of the vibration which attends their launch from the surface of the Earth. Once the principles of closed-cycle ecology have been worked out thoroughly, as they almost surely will be during the first few years of colonization, a vessel large enough to carry a "laboratory village" of some hundreds of people could be built at L5 and sent forth on an exploratory trip of several years. On Earth, villages of smaller size have remained stable and self-maintaining over periods of many generations, so there seems no reason why a trip of a few years in the spirit of one of Darwin's voyages could not be undertaken in deep space.

Lunar resources, when available, will have a profound impact on the cost of travel between low Earth orbit (LEO) and L5. Indeed, an ordinary chemical rocket, able to reload with liquid oxygen at L5 - and to carry only hydrogen as a propellant component from the Earth, would perform as a LEO-to-L5

shuttle. For a trip from L5 out to the asteroids, it may be that eventually each exploratory ship will carry enough propellant for only a one-way trip, relying on the carbonaceous chondritic asteroids as inexhaustible "coaling stations" for hydrogen and oxygen, thereby making longer voyages possible.

ROCKET ENGINES FOR DEEP SPACE

For operations from Earth a rocket engine has to be compact and very strong, capable of withstanding high temperatures and pressures. For voyages between L5 and the asteroids there is no need for rapid acceleration, and in zero gravity there is no reason why an engine could not be many kilometers in length and quite fragile. One obvious candidate for a deep-space rocket engine is the "mass-driver" which would, presumably, be proven and reliable even before the first space colony is completed. For deep-space use a solar-powered mass-driver could be as much as 50 km in length, made with yard-arms and guy-wires, much like the mast of a racing vessel. Note that on the surface of the Earth, in one gravity, it is possible to build very lightweight structures (television towers) with a height of 500 m. For deep space an acceleration of l0^-4 g would be sufficient, so it should be possible without excessive structure to build something much longer.

A mass-driver optimized for propulsion rather than for materials transport would have a lower ratio of payload mass to bucket mass than is baselined for the Moon. For a length of 50 km an exhaust velocity of as much as 8 km/s (in rocketry terms, a specific impulse of 800) should be possible without exceeding even the present limits on magnetic fields and the available strengths of materials. A mission to the asteroids, with an exhaust velocity that high, would require an amount of reaction mass only a little more than twice as large as the final total of payload plus engine.

A mass-driver with a length of 50 km could hardly be made in a miniature version; it would probably have a mass of some thousands of tonnes, a thrust of about 10,000 newtons, and would be suitable as the engine for a ship of several tens of thousands of tonnes total mass.

TRANSPORT

In the course of the first decades of colonization it seems likely that solar-cell power-plants for space vehicles will decrease in mass, ultimately becoming very light. It will not be economically reasonable to continue using rocket engines which exhaust hydrogen, scarce as it is on the Moon. The rocket engines of that period will very likely be solar-powered, and must exhaust as reaction mass some material that appears naturally as a waste-product from the processing industries in space; further, that material must not be a pollutant. One good candidate may be oxygen; it constitutes 40 percent by weight of the lunar soils.

At least two types of rocket engines satisfying these conditions seem good possibilities: the mass-driver, used with liquid or solid oxygen payloads for reaction mass, and the colloidal-ion rocket, which would accelerate electrically small micropellets having a ratio of charge to mass which is optimized for a particular mission. The mass-driver, as a rocket engine, only makes sense for large vehicles or loads; its length would be comparable to that of an SSPS, and its thrust would be several thousand newtons. The colloidal-ion rocket would have much lower thrust but could be compact.

When traffic between the Earth and the colonies becomes great enough, the most economical system may consist of a single-stage-to-orbit shuttle between Earth and LEO. Because there would be no need for the transport of large single structures, shuttles of that kind could be sized for optimum efficiency. From LEO to L5 the transport problem is entirely different, transit times are several days rather than a

few hours, and high thrusts are not required. The most economical vehicles for that part of space may be large ships built at the colonies. These ships, mass-driver powered through solar energy, could carry a round-trip load of oxygen as reaction mass when they leave the colonies, and could then rendezvous with shuttles in low orbit. The outbound trip would be faster than the inbound.

THE ASTEROIDAL RESOURCES

The evidence is mounting that a substantial fraction, if not actually a majority, of the asteroids are made up of carbonaceous chondritic material. If so, the asteroids contain an almost inexhaustible supply of hydrogen, nitrogen and carbon. In energy (namely: in velocity interval squared) the asteroids are about as distant from Ls as is the surface of the Earth: the velocity change to either destination, from L5 is 10 to 11 km/s. This is about four times that between L5 and the Moon. For some time, then, it seems likely that the asteroidal mines will be exploited mainly for the "rare" elements rather than for those which can be obtained from the Moon. Ultimately, as industry shifts from L5 out toward the asteroids, lunar resources may be used less as materials are mined and used directly, without the necessity of prior shipping.

NEW METHODS OF CONSTRUCTION:

Construction methods which are now only at the stage of laboratory test may be practiced only in the space environment. In zero gravity and with a good vacuum, it may be practical to form a shell by using concentrated solar heat to melt aluminum or another metal at the center of a thin form. Evaporation over a period of months or years would build up on the form a metal shell, for which the thickness at each point would be controlled by masking during the evaporation. This process would lend itself well to automation.

Alternatively, or in addition, habitat sections could be constructed of fiber-composites. On Earth, the most familiar example of such a material is fiberglass, a mixture of glass threads in an organic matrix. Boron filaments are used in place of glass for high strength in aerospace applications. Glass fiber could easily be made from lunar materials. As a matrix, a silicon compound might be used in the space environment similar to a corresponding carbon-based organic. Such a compound might be attacked by the atmosphere if it were used on Earth, but could be quite stable in vacuum.

HABITAT DESIGN

In the long run, as colony size approaches diameters of several kilometers and individual land areas of more than 100 km^2, the cosmic-ray shielding provided by the colony land area, structure, and atmosphere becomes great enough so that no additional shielding need be added, allowing the development of large-size colonies earlier than can otherwise be justified on economic grounds. Mankind's descendents who may live in space during the next century will probably be far more adventurous in their choice of styles of habitation than can now be projected, and in the spirit of this section, a relaxation of strict choices of physiological parameters seems permissible.

The assumption that the retention of artificial gravity in the living habitat continues to be necessary may be rather conservative. This assumption is based on human nature. Most people do not keep in good physical condition by self-imposed exercise. Return to Earth, whether or not occurring, must remain an option with strong psychological overtones. To rule it out, as might be the case if bones and muscles were allowed to deteriorate too far by long habitation in zero gravity, would be to make of the colonists a race apart, alien to and therefore quite possibly hostile to those who remain on Earth.

Habitation anywhere within a range of 0.7 to 1.0 g is assumed to be acceptable, and in the course of a normal day a colonist may go freely between home and zero gravity work or recreation areas.

As colony size increases, the rotation-rate criterion ceases to be a design limit. Atmospheric pressure is important to large colonies. With increasing experience in an environment of very large volume, with an abundant source of water, and with artifacts made for the most part of minerals rather than organics, fire protection is expected to be practical in an atmosphere having a total pressure of 36 kPa, of which half is oxygen. The oxygen at Denver, Colorado (which is 18 kPa), is normal for millions of human beings in that area. It is no great leap to assume an atmospheric mix of 50 percent oxygen, 50 percent nitrogen with appropriate amounts of water vapor.

From the esthetic viewpoint, people might prefer an "open" nonroofed design habitat (sphere or cylinder) when it is available to one of the more mass-efficient roofed designs. It may be possible to get some better information about public preference after further exposure of the ideas to the public. Architectural design competitions could be a means to yield valuable new ideas. It seems certain that over a time-span of several decades new designs will evolve. Some may combine mass-efficiency, achieved by optimizing the shape of the pressure shell and the cosmic-ray shield, with visual effects which are tailored to meet the psychological needs of the colony's people. The ways in which sunlight is brought into a habitat may be adjusted to suit psychological needs which we on Earth do not yet appreciate. Similarly, the degree of visual openness of a habitat may be separated from the structure itself; it is possible to divide an open geometry into visual subsections, and to provide visual horizons in a variety of ways, though a closed geometry cannot easily be opened.

To estimate the total resources of land area which could ultimately be opened by space colonization requires a model. An example from what might be a class of geometries is the "Bernal sphere" discussed in

AUTOMATION AND PRODUCTIVITY

As the space community produces increased revenue, the standard of affluence is expected to increase. Increased use of automation and adjustment of levels of employment may permit the construction of habitats with a greater amount of area per person. Also, esthetic considerations will have greater impact on habitat design and architecture as habitat construction continues and per-capita wealth increases.

If automation permits a moderate increase of productivity to a value of 100 t/person-year, which is twice the value now appropriate for processing and heavy industries on Earth, the large Bernal sphere could be built for an investment of 50,000 man-years of labor. That is equivalent to the statement that 12 percent of the maximum population of one such sphere, working for 3 yr could duplicate the habitat. Automation is much better suited to the large scale, repetitious production operations needed for the habitat shell than to the details of interior architecture and landscape design. It seems quite likely, therefore, that the construction of new habitats will become an activity for specialists who supply closed shells, ready for interior finishing, to groups of prospective colonists.

LIMITS TO GROWTH

From the viewpoint of economics, the logical site for colony construction is the asteroid belt itself. The construction equipment for colony-building is much smaller in mass than the raw materials it processes. Logically the optimum method is to construct a new habitat near an asteroid, bring in its population, and let them use the colony during the period of about 30 yr it takes to move it by a

colloidal-ion rocket to an orbit near L5. They may, however, prefer to go the other way, to strike out on their own for some distant part of the solar system. At all distances out to the orbit of Pluto and beyond, it is possible to obtain Earth-normal solar intensity with a concentrating mirror whose mass is small compared to that of the habitat.

If the asteroids are ultimately used as the material resource for the building of new colonies, and if by constructing new colonies near asteroids relatively little reaction mass is wasted in transportation, the area of land that is made available on the space frontier can be estimated. 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. For a very long time at least mankind can look toward resources so nearly inexhaustible that the current frustration of limits to growth can be replaced by a sense of openness and the absence of barriers to further human development.

Size of an Individual Habitat

The structural shell which contains the forces of atmospheric pressure and of rotation need not, in principle, itself be rotated. In the very long term, it may be possible to develop bearings (possibly magnetic) with so little drag that a structural shell could be left stationary while a relatively thin vessel containing an atmosphere rotates inside it. Such a bearing cannot be built now, but does not seem to violate any presently known laws of physics. An invention of that kind would permit the construction of habitats of truly enormous size, with usable areas of several thousand km^2.

Even in the absence of a "frictionless" bearing, the size possibilities for an individual habitat are enormous. As an example, a large titanium sphere seems technically feasible of a diameter of 20km. It would contain an atmosphere at about 18 kPa pressure of oxygen and be rotated to provide Earth normal gravity at its equator. The usable land area is several hundred km^2, comparable to the size of a Swiss canton or to one of the English shires.

The Speed of Growth

It may be that the residents of space, enjoying a rather high standard of living, will limit their population growth voluntarily, to zero or a low value. Similar populations, on Earth, underwent a transition of that kind in passing from an agrarian to an affluent industrial society. Economic incentives for having a substantial workforce in space may, however, drive the rapid construction of new industries and new habitations there. An upper limit to the speed of growth of space colonization is estimatedby assuming 3 yr for the duplication of a habitat by a workforce equivalent to 12 percent of a habitat's population. Only 56 yr are required at this rate for the construction of communities in space adequate to house a population equal to that of the Earth today.

The Decrease of Population Density With Time

Here on Earth it seems impossible for the population to increase without a corresponding increase in crowding because economics force concentrations into cities. It is expected that with the passage of time the population density must almost certainly decrease, irrespective of the total number of colonists. It is fundamental to the colonization idea that productivity can continue to grow in the colonies. As a consequence there is a continued growth of energy usage per person. As an example, suppose that there is a real (noninflationary) productivity growth rate of 2.5 percent per year and a 1:1 relationship between this productivity growth rate and the increase in energy usage. That implies a growth of a factor of 24 in total energy usage over a 128-yr period (1976 to 2104).

SOME ECONOMIC CONSIDERATIONS

Space colonization appears to offer the promise of near-limitless opportunities for human expansion, yielding new resources and enhancing human wealth. The opening of new frontiers, as it was done in the past, brings a rise in optimism to society. It has been argued that it may also enhance the prospects of peace and human well-being. Just as it has been said that affluence brings a reduction in the struggle for survival, many have contended that expansion into space will bring to human life a new spirit of drive and enthusiasm.

Space community economies will probably be extensions of those of Earth for some time to come. There is, however, room to speculate as to how locational differences may enhance organizational differences. There is, for example, some evidence that the societies in the lands settled in recent periods have tended to display differences from those settled further in the past; for example, one can compare the U.S. society and economy to that of the British, or the economy and society of California with that of Massachusetts.

It may be that the shared circumstances of risk associated with early colonization will bring the earlier settlers into a close relationship. This, and the problems of access to Earth-produced products, may foster a sense of sharing and of cooperation, more characteristic of a frontier than of a mature Western society. With the increase of colony population, the impersonality characteristic of modern terrestrial societies would be expected to emerge.

Ownership and proprietary rights may be somewhat different from those found on Earth in part because the environment within space habitats will be largely man-made. The balance of privately-controlled vs. publicly-controlled space may be significantly influenced by these closely similar environmental experiences. On the other hand, the cultural inheritance of social forms from the Earth will serve to inhibit utopian impulses toward leaving the ills of human life behind. For example, it is unlikely that any serious development toward egalitarianism in the personal distribution of income will be found to arise in the colonies of the future.

That boundless energy may lead to boundless wealth is a belief which will doubtless be tested in such future developments. Successful exploitation of the extraterrestrial environment is expected to enhance the standard of living not only of the population in space but the population remaining on Earth as well.

With the advent of the era of extraterrestrial communities, mankind has reached the stage of civilization where it must think in terms of hitherto unknown cultural options. In the extraterrestrial communities, many of the constraints which restrict the life on the Earth are removed. Temperature, humidity, seasons, length of day, weather, artificial gravity and atmospheric pressure can be set at will, and new types of cultures, social organization and social philosophies become possible. The thinking required is far more than technological and economic. More basically it is cultural and philosophical.

This new vista, suddenly open, changes the entire outlook on the future, not only for those who eventually want to live in extraterrestrial communities but also for those who want to remain on the Earth. In the future, the Earth might be looked upon as an uncomfortable and inconvenient place to live as compared to the extraterrestrial communities. Since a considerable portion of humanity - even most of it - with ecologically needed animals and plants may be living outside the Earth, the meaning, the purpose, and the patterns of life on Earth will also be considerably altered. The Earth might be regarded as a historical museum, a biological preserve, a place which contains harsh climate and uncontrolled weather for those who love physical adventure, or a primitive and primeval place for tourism. This cultural transition may be comparable to the transitions in the biological evolution when the aquatic ancestors of mammals moved onto land or when Man's quadrupedal ancestors became bipedal and

bimanual. The opportunity for human expansion into space is offered; it needs only to be grasped.

8. Recommendations and Conclusions

In the course of the 10-week study, it became apparent that there are many aspects of the design of a space colonization project for which the necessary data are not available. Many are critical to the design so that, in the absence of firm data, conservative assumptions had to be made. This forced the overall design in a conservative direction with considerable weight, size and cost penalties compared with what might be an optimum design.

RECOMMENDATIONS FOR RESEARCH AND DEVELOPMENT IN CRITICAL SUBSYSTEMS

Before a detailed practical design of a space colony can be undertaken, the following subjects must be researched to fill in the gaps in current design-related data.

1. *Acceptable Radiation Dose*. The 0.5 rem per yr radiation dose is achieved in this design study by accepting a considerable penalty in weight and system complexity. This dosage rate is the upper limit allowed for the general population in the United States and is chosen arbitrarily as a conservative measure. Extensive biological testing should be undertaken to establish a realistic dose limit taking into consideration the colony's population distribution and the scenarios for habitation of the colony. The effect of radiation on agricultural specimens also needs study to assure stable food supplies.
2. *Acceptable g Levels*. The physiological effects of zero-g are serious for long-duration exposure in space. For this reason and since little is known about exposure at intermediate g levels, 1 g was chosen as the design standard. The 1-g choice has significant influence on the design and may be unnecessarily high. An examination of physiology under partial g is required in the Spacelab and subsequent space station missions to determine the minimum g value for which there are no serious long-term physiological effects upon humans.
3. *Maximum Acceptable Rate of Habitat Rotation*. The rate of rotation required to achieve the desired pseudogravity has substantial impact on the design. Since the g-level and rate of rotation determine colony dimensions to a large extent (and thus the weight) determination of an acceptable rate of rotation is important. While it is difficult to test human vestibular functions in a realistic way on Earth, it is critical that a better understanding of the subject be obtained by studies both on Earth and in space.
4. *Closure of the Life Support System*. The critical role of agriculture in providing food and regenerating the atmosphere in the colony requires that it be undertaken with utmost confidence and understanding. The components of the agricultural system require study to determine their detailed characteristics and their suitability. While possible in theory, large living systems have never been operated in a closed loop. First on a small scale, and finally on a large scale, complete closure of a demonstration life support system should be accomplished before colonization begins. The requirements for microbial ecology need to be studied.
5. *Intensive Agriculture*. The support of the colony's inhabitants on the agricultural output from 150 acres is based on highly intensive photosynthetic production, beyond that realized to date. The exact enhancement of yields from lighting, increased carbon dioxide, and regular irrigation

needs to be determined, and actual prototype farming needs to be conducted prior to closed life support system tests.

6. *Methods of Radiation Shielding*. The requirement for 10 million tonnes of passive shielding resulted from uncertainty in the effectiveness and the complications of active shielding techniques. In particular, it is recommended that studies be undertaken with the plasma shield to achieve the acceptable dose with a workable system.
7. *Productivity in Space*. The size, cost, and schedule for colony (and SSPS) construction are critically dependent upon the number of workers and their productivity. Terrestrial examples of worker productivity may be unrealistic for colony construction. Significantly greater definition of worker productivity is required for the colony design and should be accompanied by actual experimentation in space to derive realistic quantitative data.
8. *Processing of Lunar Surface Material*. The aluminum and titanium extraction and refining processes suggested by this study are novel and largely unstudied because of the unusual nature of the lunar ores compared to terrestrial ores. The need to develop these processes in the laboratory, the terrestrial pilot plant, and eventually the space pilot plant is critical to the success of the program. Efficient production of glass from lunar rock is also required under the limitation of minimal additives. Physical and optical properties of the resulting glass need to be determined.
9. *Lunar Mass Launcher.* The efficient transfer of lunar ore to a space processing facility is essential to the success of the space colonization concept. Alternative methods (such as the gas gun) need further study so that a careful design analysis can be made of the entire subsystem. A scaled prototype should be tested. More detailed engineering analysis of the baseline system is required.
10. *Mass Catcher.* The location and operational principle of the mass catcher are critical to space colonization and weakly substantiated in this study. The entire subsystem needs much greater study and eventually testing in space.
11. *Minimum Acceptable Partial Pressure of Nitrogen and Oxygen in the Space Colony Atmosphere*. To minimize the quantity of nitrogen brought from Earth, the problems resulting from oxygen-rich atmospheres need detailed study to determine the minimum amount of nitrogen required in the atmosphere.
12. *Satellite Solar Power Station Design*. This study did not focus on the details of the SSPS design. The method of energy conversion (photoelectric vs. thermalmechanical) needs to be selected on the basis of detailed comparative study and perhaps on the basis of fly-off testing on small-scale prototypes. The methods of construction need careful examination from the viewpoint of efficient material and manpower utilization.
13. *Transportation System*. In addition to the main transportation elements (the HLLV, the mass launcher, and mass catcher), the rotary pellet launcher and the ferrying ion engines require research and development. While the HLLV is proposed within the current baseline, even more advanced vehicles with larger payloads and lower launch costs would be of enormous benefit to the space colonization program at any time in the program.
14. *Environmental Impacts*. The frequency of launches needed and the products from rocket combustion need to be studied to determine the impact upon the Earth. The high power microwave beam from the SSPS may have effects on certain biota in or near the beam, and rf interference with communications, terrestrial navigation and guidance systems, and radio astronomy should be examined.
15. *Human Physical, Psychological, Social, and Cultural Requirements for Space Community Design*. The diversity of options and the uncertainty of absolute requirements for various human

factors require considerable study, elaboration, and agreement. Factors governing design include habitat configuration, efficient utilization of area, methods and diversity of construction, visual sensations, and colonist activities. All need to be thoroughly evaluated.

16. *Political, Institutional, Legal, and Financial Aspects of Space Colonization*. The space colonization effort is of such magnitude that it requires careful analysis with respect to organization and financing. For this analysis competent, realistic, and thorough study is needed. National versus international, and governmental versus private or quasi-governmental organization, requires study and evaluation. The operational organization for space colony implementation is of sufficient magnitude to merit this study being made very early in consideration of a program to establish human habitats in space.
17. *Economic Analysis of Space Colonization Benefits*. A more sophisticated analysis is needed to determine whether the benefits of space colonization do or even should justify the costs. In particular, studies are needed which compare space colonization and SSPS production with alternate methods of producing electricity.
18. *Additional Topics for Later Study.* Space colonization in general covers such a wide spectrum of diverse topics as to allow many fruitful studies with varying depths of analysis. Examples of subjects that need to be investigated are:

a. Method of immigrant selection.
b. Effect of "deterrestrialization" of colonists.
c. Effects of large-scale operations on the lunar, cislunar, and terrestrial environment, and effects on the solar wind.
d. Disposal of nuclear waste on the lunar surface.
e. Alternate colony locations (such as lunar orbit, L2, LEO inside Van Allen belt, free orbit, near asteroids, Jupiter orbit).
f. Detailed metabolic requirements (input and output data) for plants and animals.
g. Suitability of condensed humidity for human consumption, for fish, and for crop irrigation.
h. Recycling of minerals from waste processing.
i. Production of useful products from plant and animal processing byproducts.
j. Characterization of trajectories from lunar surface to the various loci of potential activity.
k. Analysis of the potential foreign market for electric power.
l. Quantitative analysis of nonelectrical space benefits, for example, benefits from production of communication satellites in space.
m. Development of alternative mission profiles which increase emphasis on SSPS production or on colony production.
n. Effect of an established space colony on future space missions, their feasibility and cost.
o. Application of learning curves to space colonization.
p. Ecological balance within the colony, microbial and insect ecologies (including role of nitrogen fixation).
q. Chemical processing with nonaqueous or even gaseous techniques.
r. Determination of the proper safety margins for various systems.
s. Detailed design of windows and their optical properties.
t. Dynamics of atmospheres in rotating structures.
u. Tools and techniques for working in zero g.
v. Rendezvous with asteroids.
w. Remote assembly of large structures.
x. Halo orbits.
y. Description of everyday phenomena in a rotating environment.

z. Fire protection.
aa. Synthetic soils.
bb. Space manufacturing.
cc. Extension of economic geography to space.
dd. Adaptable and evolutionary aspects of habitat design.
ee. Atmospheric leakage rates and gaskets.
ff. A zero-g colony.
gg. Studies of work organization in remote locations.
hh. Studies of social and economic interdependence among communities in remote locations with respect to transportation.
ii. Studies of functional division of labor within human communities.
jj. Study of methods for transporting and storing gaseous materials such as hydrogen and nitrogen in various chemical forms such as ammonia, ammonium salts, or other compounds.
kk. Space viticulture and enological techniques.
ll. Heterogeneity as a desired or required characteristic.
mm. Rotation of habitat within the shield.
nn. Colony governance.
oo. Requirements for interior illumination. Is sunlight really needed in living and even agricultural areas?
pp. A detailed list of colonist activities and the land area usage dictated by analysis of interior illumination needs.
qq. Composite material fabrication techniques in space.
rr. Construction of lunar mass launcher from lunar materials using bootstrapped pilot plants.
ss. Detailed study and list of materials to be imported from Earth to support the everyday needs of the colony.
tt. Extrusion techniques for space.
uu. Alternative diet components.
vv. An acceptable name for the first colony.

RECOMMENDATIONS FOR SPACE VENTURES

A principal recommendation of this summer study is that a major systems study be made of space industrialization and space colonization. In addition, it is recommended that the following space ventures be undertaken as necessary preludes to space colonies.

1. Continue development of the space transportation system (shuttle) and of Spacelab.
2. Start development of the shuttle-derived Heavy-Lift Launch Vehicle.
3. Construct a large space laboratory for placement in low-Earth orbit in which experiments necessary to space colonization can be carried out.
4. Establish a lunar base to explore and to test for the availability of lunar resources.
5. Send an unmanned probe to the asteroids to determine their chemical composition.

CONCLUSIONS

Space colonization is desirable because of the hope it offers humanity. A sense of the limits of Earth has been heightened in recent years by growing awareness of the delicate ecological balance of the planet, its finite resources and its burgeoning human population. The sense of closure, of limits, is oppressive to many people. In America, growth has been the vehicle of rapid and often progressive change; it has been the source of opportunity for millions of people and has played an important role in

fostering American democracy and political freedoms. To have opportunities restricted and to be forced to devise political institutions to allocate equitably, resources insufficient to meet demand, are unpleasant prospects. Space offers a way out, with new possibilities of growth and new resources. Space offers a new frontier, a new challenge, and a hope to humanity, much as the New World offered a frontier, a challenge, and a hope to Europe for more than 4 centuries.

Space also offers riches: great resources of matter and energy. Their full extent and how they might be used are not altogether clear today. It is likely that solar energy collected in space, converted to electricity, and beamed to Earth would be of great value. The manufacture of the satellite power stations to bring this energy to Earth and of other commercial activities that use the abundant solar energy, the high vacuum, and the weightlessness available in space, might bring substantial returns to investors. It seems possible that the historic industrialization of Earth might expand and go forward in space without the unpleasant impacts on the Earth's environment that increasingly trouble mankind. On the other hand, the potential of space must not detract from efforts to conserve terrestrial resources and improve the quality of life on Earth.

On the basis of this 10-week study of the colonization of space there seems to be no insurmountable problems to prevent humans from living in space. However, there are problems, both many and large, but they can be solved with technology available now or through future technical advances. The people of Earth have both the knowledge and resources to colonize space.

It is the principal conclusion of the study group that the United States, possibly in cooperation with other nations, should take specific steps toward that goal of space colonization.

UNITS AND CONVERSION FACTORS

A	angstrom	a unit of length most often used in reference to the wavelength of light. =10^-10 m
atm	standard atmosphere	a unit of pressure based on a standardized sea level terrestrial atmospheric pressure = 14.7 psi = 760 mm Hg = 1.0132 bars = 101.325 kPa
AU	astronomical unit	a unit of length used in astronomy and astronautics,referenced to the mean distance between Earth and Sun = 149,600,000 km = 92,961,000 mi
C	coulomb	a unit of electrical charge equal to the amount of electricity transferred by a current of 1 ampere for 1 second
cal	calorie	a unit of energy equal to the amount necessary to raise 1 g of water 1 degree C

		= 4.1868 J
Cal	large calorie	a unit of energy used in reference to the energy content of food = 1000 cal
eV	electron volt	a unit of energy used in particle physics, the amount of energy acquired by an electron in being accelerated through a potential difference of 1 volt = 1.60219 X 10^-19 J
g	"gee"	the acceleration of gravity at the mean surface of the Earth = 980.665 cm/s^2 = 32.174 ft/s^2
g	gram	a unit of weight in the metric system = 0.03527 oz (avoirdupois)
ha	hectare	a metric unit of area used in field measurements = 100 m X 100 m, i.e.,10^4 m^2 = 2.471 acres
Hz	hertz	a unit of frequency = cycle/s
J	joule	unit of energy or work; the work done when the point of application of 1 newton moves a distance of 1 meter in the direction of the force = 10^7 ergs = 23.02 ft poundals
m	meter	metric unit of length = 3.2808 ft
mil	mil	a unit of cost
N	newton	unit of force in the meter-kilogram-second system; that force which gives to a mass of 1 kilogram an acceleration of 1 m/s^2 = 10^5 dynes = 7.015 poundals
Pa	pascal	a unit of pressure = 1 N/m^2 = 10^-5 bar = 0.0000098 atm = 0.0001372 psi
rad	rad	a unit of absorbed radiation dosage = 10^-2 J/kg = 100 ergs/g
R	roentgen	a unit of absorbed radiation based on the amount of ionization produced in tissue

		= 2.58 X 10^-4 coulombs/kg (defined strictly as the amount of gamma radiation sufficient to produce ions carrying one electrostatic unit of charge in one cubic centimeter of air; but loosely used to apply to any ionizing radiation producing the same effect)
rem	rem	the roentgen equivalent, man; expresses the relative biological effect of different types of radiation For X-rays, 1 rem results from the exposure of 1 roentgen.
t	tonne	used as a metric unit of mass for large masses = 1000 kg = 0.98 tons (long) = 1.10 tons (short)
T	tesla	a unit of magnetic flux density = 1 Wb/m^2
W	watt	unit of power = 1 J/s = 10^7 ergs/s = 23.02 ft poundal/s = 1.301 X 10^-3 horse power
Wb	weber	unit of magnetic flux; the flux which produces an electromotive force of one volt in a circuit of one turn when this flux is reduced to zero at a uniform rate in one second.

METRIC PREFIXES USED

Prefix	Name	Multiplication factor	Example
G	giga	billion (10^9)	GW = gigawatt GW = 1 billion watts
M	mega	million (10^6)	MeV = million electron volts
k	kilo	thousand (10^3)	km = kilometer (0.6214 miles) km = 1000 meters
c	centi	hundredth (10^-2)	cm = centimeter (2.54inches)
m	milli	thousandth (10^-3)	mm = millimeter
μ	micro	millionth (10^-6)	μm = micrometer μm = one millionth of a meter

Space Colony Art from the 1970s

A couple of space colony summer studies were conducted at NASA Ames in the 1970s. Colonies housing about 10,000 people were designed. A number of artistic renderings of the concepts were made. These have been converted to jpegs and are available as thumbnails, quarter page, full screen and publication quality images. There are 16 images presented below.

Cylindrical Colonies

Exterior view of a double cylinder colony

	Quarter Page jpeg image, 160 k	Full Screen jpeg image, 416 k	Publication Quality jpeg image, 800 k	NASA ID NUMBER AC75-1085

Exterior view of several two-cylinder colonies

	Quarter Page jpeg image, 160 k	Full Screen jpeg image, 352 k	Publication Quality jpeg image, 704 k	NASA ID NUMBER AC75-1921

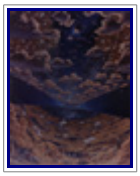
Interior view including looking through large windows

	Quarter Page jpeg image, 160 k	Full Screen jpeg image, 480 k	Publication Quality jpeg image, 960 k	NASA ID NUMBER AC75-1086

Interior view with long suspension bridge

	Quarter Page jpeg image, 160 k	Full Screen jpeg image, 512 k	Publication Quality jpeg image, 992 k	NASA ID NUMBER AC75-1883

Interior featuring clouds and vegetation

	Quarter Page jpeg image, 160 k	Full Screen jpeg image, 416 k	Publication Quality jpeg image, 800 k	NASA ID NUMBER AC75-1920

Toroidal Colonies

Exterior View

	Quarter Page jpeg image, 64 k	Full Screen jpeg image, 256 k	Publication Quality jpeg image, 512 k	NASA ID NUMBER AC76-0492.1

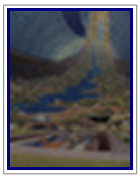
Cutaway view, exposing the interior

	Quarter Page jpeg image, 160 k	Full Screen jpeg image 480 k	Publication Quality jpeg image, 960 k	NASA ID NUMBER AC75-1086-1

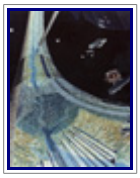
Exterior view of several neighboring colonies

	Quarter Page jpeg image, 128 k	Full Screen jpeg image, 320 k	Publication Quality jpeg image, 608 k	NASA ID NUMBER AC76-0525

Interior view

	Quarter Page jpeg image, 128 k	Full Screen jpeg image, 448 k	Publication Quality jpeg image, 864 k	NASA ID NUMBER AC75-2621

Part of the rim including many nearby space vehicles

	Quarter Page jpeg image, 160 k	Full Screen jpeg image, 448 k	Publication Quality jpeg image, 256 k	NASA ID NUMBER AC75-1886

Bernal Spheres

The Bernal Sphere is a point design with a sphere living area.

Exterior view

	Quarter Page jpeg image, 128 k	Full Screen jpeg image, 384 k	Publication Quality jpeg image, 736 k	NASA ID NUMBER AC76-0965

Photograph of a model of the Bernal Sphere

	Quarter Page jpeg image, 128 k	Full Screen jpeg image, 320 k	Publication Quality jpeg image, 608 k	NASA ID NUMBER AC76-0852

View with cutaway to see interior

	Quarter Page jpeg image, 160 k	Full Screen jpeg image, 480 k	Publication Quality jpeg image, 928 k	NASA ID NUMBER AC76-1089

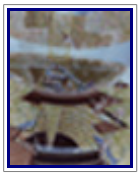
Interior including human powered airplane

	Quarter Page jpeg image, 160 k	Full Screen jpeg image, 480 k	Publication Quality jpeg image, 960 k	NASA ID NUMBER AC76-0628

View of Bernal Sphere agricultural module (multiple toroids) with cutaway to expose interior

	Quarter Page jpeg image, 192 k	Full Screen jpeg image, 384 k	Publication Quality jpeg image, 704 k	NASA ID NUMBER AC78-0330-4

Colony construction crew at work

	Quarter Page jpeg image, 192 k	Full Screen jpeg image, 608 k	Publication Quality jpeg image, 1.2 MB	NASA ID NUMBER AC76-1288

Please credit photos to NASA Ames Research Center