The Coming Age of Human Settlements in Space

# COLONIES IN ORBIT

BY DAVID C. KNIGHT

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illustrated with photographs and diagrams

Could a million people be living in space colonies, orbiting the earth at a distance of 240,000 miles, by the year 2000? After years of intensive study, several scientists, among them Princeton's Gerard K. O'Neill, think that such a plan would make a practical and desirable way to alleviate our planet's crowded conditions.

First Mr. Knight looks at the ideas early writers and scientists have held about living in space. Then he uses research findings of Dr. O'Neill and NASA to describe the best locations for the colonies, their geometric shape and interiors, and their power and living facilities. He also covers the advantages of life on the colonies, especially if the venture becomes a multinational one, recreational possibilities, the strange phenomena resulting from zero-gravity conditions, and intercolony transportation. Finally, Mr. Knight explores the fascinating idea of preserving earth as a "wilderness" vacation area for colonists.

Written with expertise and enthusiasm, *Colonies in Orbit* gives the reader a comprehensive look at a revolutionary concept of what life might be like in space.

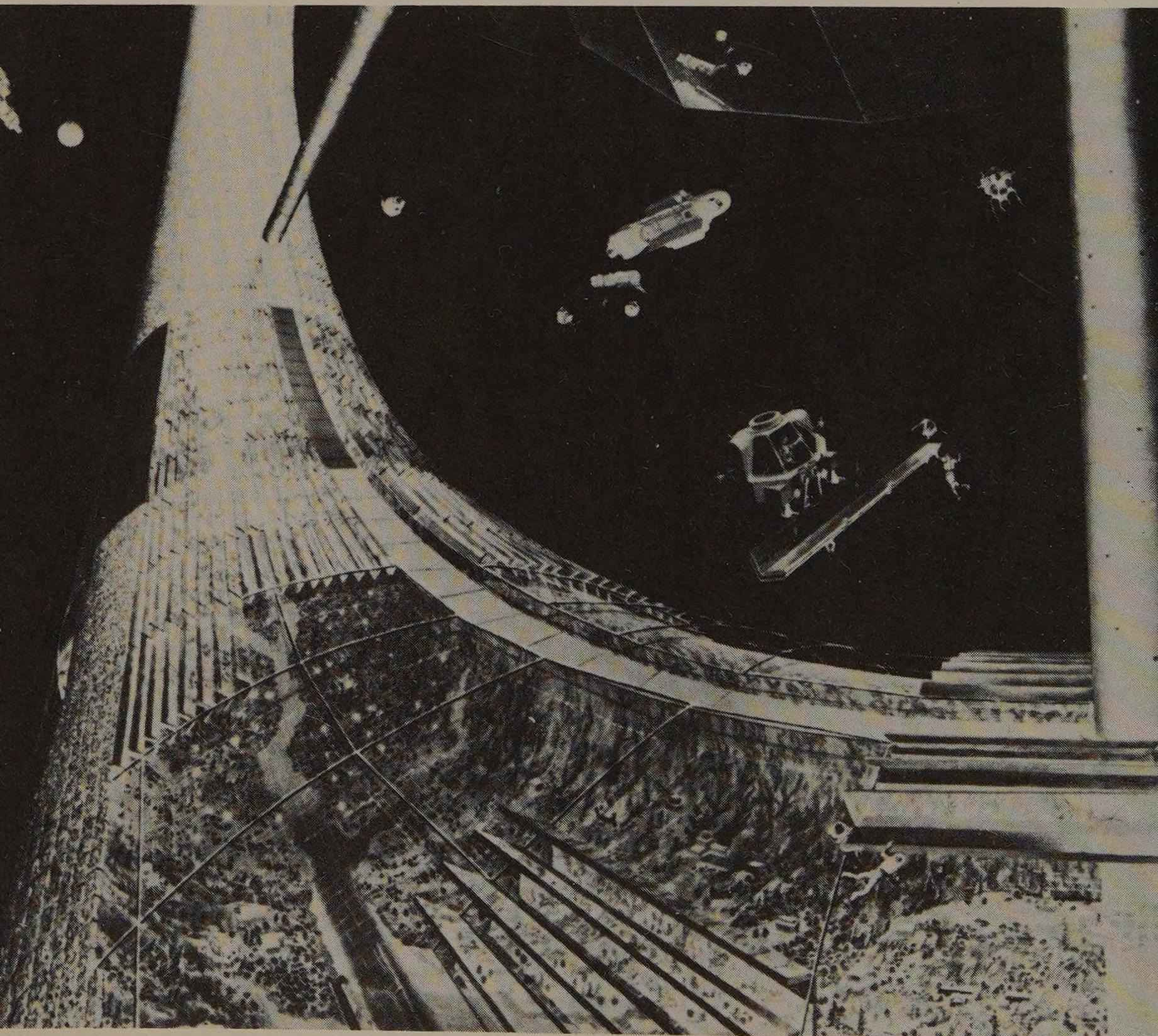
*Cover photograph:*
*model of a torus-shaped space colony,*
*courtesy NASA*

# COLONIES IN ORBIT

BY THE SAME AUTHOR

Eavesdropping on Space
Harnessing the Sun
Thirty-Two Moons
The Tiny Planets

Segment of the torus-shaped space colony during final construction, as conceived by the Ames study group. Built to accommodate 10,000 inhabitants, the earthlike interior with lake, rivers, and farming areas can be seen through 100-foot strip windows encircling the wheel. Louvers, shown being installed, would absorb cosmic radiation, while allowing sunlight to be reflected inside. *(NASA)*



David C. Knight

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## The Coming Age of Human Settlements in Space

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*Dieses Buch ist meinen Neffen*
*Axel und Ralph*
*in München*
*gewidmet.*

# CONTENTS

Earth is the cradle of the mind,
but one cannot live in the cradle forever.

KONSTANTIN E. TSIOLKOVSKY

Chapter One

# WHY HUMAN SETTLEMENTS IN SPACE?

The notion of human beings living in space, or traveling long distances through it, is not especially new. Imaginative writers, thinkers, and scientists seriously began to consider such ideas over one hundred years ago.

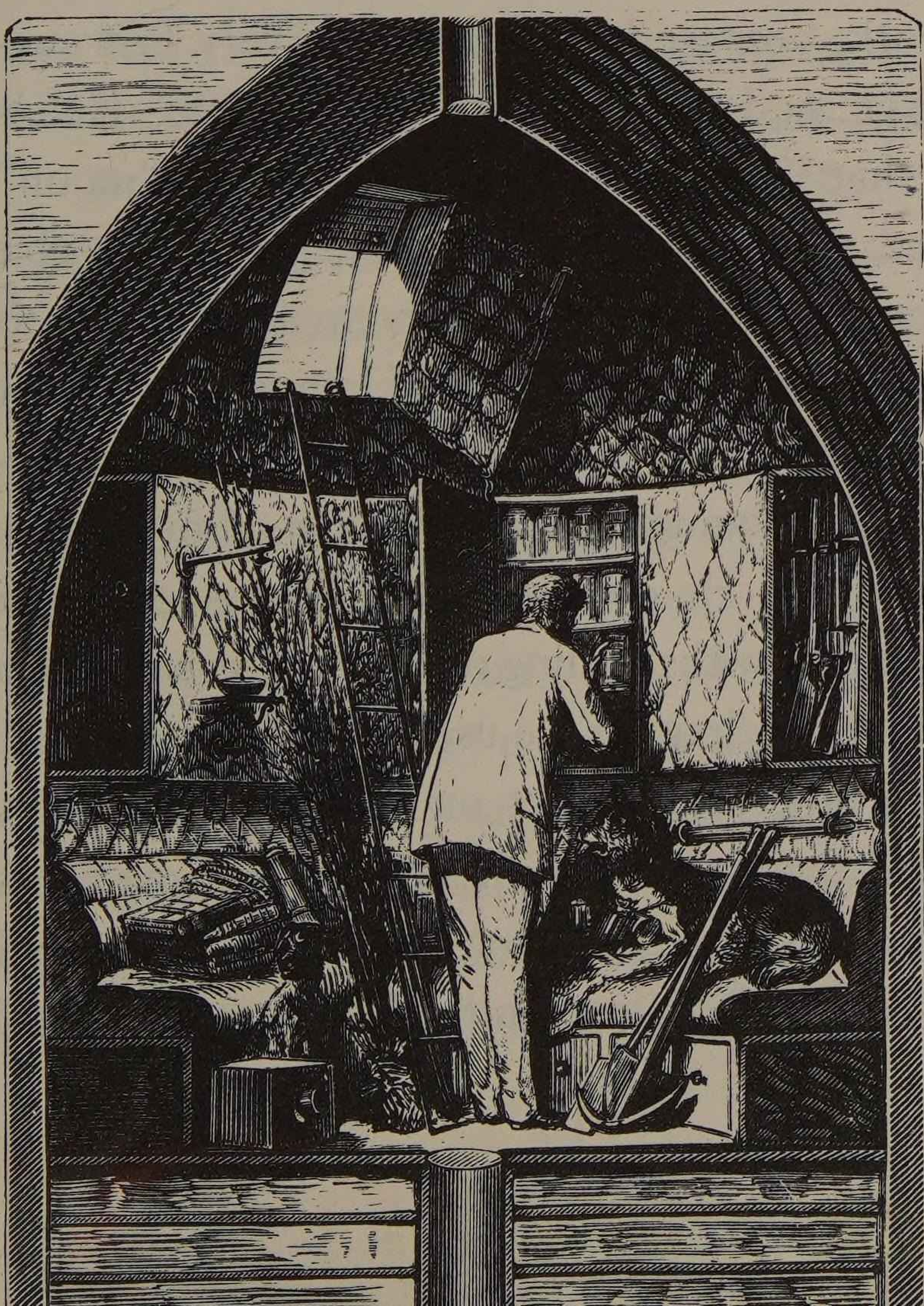
Aside from purely literary flights of fancy, such as the poet Cyrano de Bergerac's flight to the moon in the seventeenth century, the French writer Jules Verne was the first to put the notion of space travel into practical terms. Verne's novel *From the Earth to the Moon,* published in 1865, was virtually an engineering blueprint of an early space project. Included were techniques of rocketry to solve the basic problem of space flight: namely, achieving sufficient initial velocity to escape earth and the friction of its atmosphere. The giant cannon Verne proposed for this feat was a poor solution, but in an odd, futuristic coincidence of literature, he placed his fictional launching device within a few dozen miles of Florida's Cape Canaveral, site of today's major U.S. space lift-offs.

In all other respects, Verne, a student of science and engineering, was entirely scientific in his approach to space in his famous story. Indeed, the novel radiates a confidence that technology could ultimately solve any problem presented to it. Among other innovations, Verne was the first to suggest modern space medicine by using animals in acceleration tests. Further, Verne correctly predicted that a space capsule would become white hot in the atmosphere due to friction, that it could be steered in flight by rockets, and that there would be a condition of weightlessness in space.

Anyone familiar with the original illustrations in

*From the Earth to the Moon* will note that Jules Verne provided well for his characters' comfort on a long space trip, with an upholstered cabin replete with pets, games, and other luxurious appointments.

This illustration from Jules Verne's *From the Earth to the Moon* shows the well-upholstered interior of Verne's spacecraft, or projectile, with all the comforts of home including a pet.
*(Culver Pictures, Inc.)*



Similarly, in the works of another early science-fiction writer, H. G. Wells, comfortable provisions for lengthy space voyages were also standard plot embellishments.

In considering the origins of space travel, another historic piece of writing is well worth mentioning. It is a tale published in a leading American magazine, in 1870, by Boston clergyman Edward Everett Hale. Called *The Brick Moon,* it was a remarkably far-sighted work, because it contained the very first suggestion ever made for an artificial satellite. Hale's idea was that if a 200-foot-wide man-made "moon" constructed of brick could be launched into orbit around the earth, it would be an invaluable aid to navigators at sea. Hale's method of launching—a sort of mammoth flywheel arrangement—was as impractical as Verne's cannon, but his choice of brick was well thought out. He concluded that it would be the best material for withstanding the heat of atmospheric friction, thus anticipating the use of ceramics for heat shields and other equipment on modern spacecraft.

With the advent of the twentieth century, man was on the threshhold of mastering flight. But in a small Russian town 100 miles south of Moscow, a deaf schoolteacher named Konstantin E. Tsiolkovsky was already dreaming of the opportunities that awaited mankind in *outer* space. Born in 1857, he became passionately obsessed with the problem of space travel. As early as 1898, he had derived the fundamental laws of rocket motion, which form the basis for all space vehicle designs. In 1903—the year of the Wright brothers' famous flight at Kitty Hawk—he published the main results of his work and in doing so laid the foundations for astronautics, the science of locomotion outside the earth's atmosphere.

But Tsiolkovsky did much more. He foresaw space exploration as part of a continuing social process that would eventually transform human life and enable man to settle throughout the solar system. Even today the scope of his work is most impressive. When the first airplanes were staggering off primitive airfields, Tsiolkovsky was writing about artificial satellites, solar energy, ether suits (by which he meant space suits), and the use of plants to provide food and oxygen on long space journeys. In these writings, he also spoke of the colonization of the solar system and even suggested that men could create artificial habitats in space. Long ignored and often ridiculed by his contemporaries, Tsiolkovsky's genius finally became recognized in the Soviet Union, and by the 1930s he was considered a national hero by many.

In the United States, the noted rocket pioneer Professor Robert Hutchings Goddard conducted his research independently and succeeded in actually launching the first liquid-propelled rockets. They were precursors of the giant Agena boosters that were to propel American astronauts to the moon in 1969. Goddard's brilliant mind also toyed with the possibility of men living and working for extended periods in space.

It is significant that the Rumanian scientist Hermann Oberth, like Tsiolkovsky and Goddard, also earned his living as a teacher. Presumably the academic life afforded all three men both the leisure and training necessary for their speculations on space. In 1923, Oberth published his slim ninety-two-page pamphlet entitled *The Rocket into Interplanetary Space,* which sparked ideas in many space-minded persons. He arrived at the same conclusions as Goddard and Tsiolkovsky, but in some respects he went far beyond them. Oberth not only outlined theoretical designs for high-altitude research rockets and man-carrying spacecraft, but he also revived the notion of the large satellite, or space station. Oberth's speculations attracted surprising interest and led to concrete rocketry experimentation, which finally produced the highly successful space programs both in the United States and the Soviet Union.

Writers of modern science fiction, building on the ideas of men such as Tsiolkovsky and Oberth and using their own fertile imaginations, have long employed the idea of men living in artificial habitats in space. Usually the plots of such stories are tied to an overpopulated earth of the future from which people must escape in order to survive. One memorable example is Robert A. Heinlein's intriguing story "Universe," published in 1941. In this story, a gigantic spaceship, capable of supporting thousands of people, is slowly making its way to some distant star system in the galaxy. The craft has been in deep space for so long that many generations of inhabitants have died. Their modern successors, with whom the story concerns itself, no longer remember the original purpose of their ancestors' voyage. The story's title becomes obvious when the reader discovers that the people aboard have come to look upon their ship as the entire universe.

Today the concern over our dangerously overcrowded earth is science fiction no longer. It is fact. In 1976, the population of the earth was about four billion. Barring any catastrophes, this figure will increase to five billion in 1986, six billion in 1996, seven billion about the year 2003, and so on. Even now, with four billion people on the earth, it is difficult to feed and clothe large segments of the world population. Moreover, the planet's energy resources are steadily dwindling so that eventually they will not be adequate for transportation, heating, and industrial needs. It is clear that somehow the world must reduce its birthrate and lower the burgeoning population, but that will take time. Meanwhile, the population bomb ticks relentlessly on. What can man do about it? Where can he go?

One solution for him is to move on to new lands. But, since there are no more new lands on the planet capable of supporting life to any extent, he must look toward space for new frontiers in which to settle and establish colonies.

Although ideas about migrating into space are as old as science fiction itself, there has existed among scientists, as well as science-fiction writers, a mental block about how this can be done. The belief has been that if man seriously wishes to establish colonies in space, he must necessarily choose planets or their large satellites, such as the moon, for sites.

Actually, establishing livable settlements of any great size on these bodies would prove fantastically expensive and difficult to carry out. The moon and the planets with solid surfaces have no breathable atmospheres, so human beings would have to burrow beneath their surfaces and set up underground living bases complete with an air supply. Certainly costs would mount to incredible heights if man attempted to hack out beneath the moon's surface living spaces for, say, just 10,000 people.

Moreover, the choice of such suitable planetary surfaces is limited in our solar system. Aside from our own moon and some of those of other planets, Mars and Mercury are the only bodies that could be colonized. Cloud-covered Venus, with surface temperatures of some 900 degrees Fahrenheit, is too hot. Pluto, the ninth planet out from the sun, is too far away. The other four giant planets of the solar system—Jupiter, Saturn, Uranus, and Neptune—are too far from the earth, have unfriendly, even deadly atmospheres, and their gravities are too powerful for human life. True, there are still the asteroids—tens of thousands of tiny planets in orbital paths between Mars and Jupiter—but they are also too distant for present colonization.

There is, however, an alternative open to man, if he wishes to leave the earth and make his home in the virtually limitless universe of space. The space pioneer Tsiolkovsky was one of the first to put aside the fixed idea of planetary colonization and seriously suggest building artificial abodes in space.

Today a small band of imaginative, yet determined and highly practical scientists are advising just this procedure. Instead of man's attempting to carve out bleak colonies on the moon or Mars, they are suggesting a better, cheaper way—creating man-made orbiting worlds in space that would be closer to our mother planet. New lands in space, they say, may be a possible, even inevitable, solution to the population problem.

At two major meetings in as many years, these scientists convened to discuss the possibilities of space colonization. The first conference met at Princeton University in 1974. The second gathered at the National Aeronautics and Space Administration's

(NASA) Ames Research Center in the summer of 1975 for an intensive ten-week study conference. Present were not only scientists but engineers, sociologists, economists, architects, and members of other disciplines.

Both of these conferences relied heavily on the imaginative work of Dr. Gerard K. O'Neill, a young professor of physics at Princeton University, who for several years has envisioned orbiting communities in space. The conclusion reached by Dr. O'Neill and his colleagues was that such communities would be eminently feasible; that practical planning for them by the United States should be commenced without delay; and that they could be built with the existing technological know-how of today, possibly in co-operation with other nations.

Interestingly enough, O'Neill's concepts of future space colonies began almost as a joke. In 1969, he had begun some calculations involving the setting up of such colonies as an exercise for some students in one of his physics courses. O'Neill's object was to make otherwise-dull computations more interesting to the students by applying them to a glamorous idea. But when, as O'Neill put it, "the numbers began to come out right," he was more inclined to take the space colony "joke" seriously. The more he turned his calculations over in his mind, the more he became convinced that space colonization in artificial habitats was a sound idea and one that the United States Government should pursue.

Sympathetic friends advised O'Neill to further publicize his admittedly way-out ideas. O'Neill began to do so in the form of delivering physics lectures at various universities. The encouraging response—especially from imaginative students—caused him to dig even harder for answers to such problems as meteoroid damage to space habitats, the viability of agriculture in space, materials sources, economics, and other questions. What caused more and more people—including NASA scientists—to become convinced that O'Neill was not just rattling on in science-fiction, visionary terms was the careful manner in which he had analyzed the masses of material necessary to do the job, the details of design, transportation methods, the assembly of parts in space, and many other matters, including the total cost.

If O'Neill's plan is acted upon soon, a work force of 2000 technicians in space, using raw materials from the moon and energy from the sun, could construct a prototype habitat for 10,000 people by the late 1980s. It would not be just an orbiting space station crammed with lab gear but an actual reproduction of an earthlike community complete with houses, schools, hospitals, stores, hills and valleys, trees and streams, roads and wildlife. With its natural sunshine, controlled weather, normal air, apparent gravity, and relative freedom from pollution, it would be as comfortable as the most desirable parts of the earth itself. Furthermore, O'Neill believes that the price tag for such a community would be comparable to the total sum spent on America's Project Apollo—about $33 billion in 1972 dollars.

Once this prototype habitat has been established in space, the colonists who settle there would set to work building another colony. By the mid-2000s, O'Neill thinks it is not inconceivable that hundreds of sister colonies would have been constructed because the plan would stipulate that each new colony would have to be self-supporting, with only minimal help from earth. Eventually there would come larger space communities with individual populations of 400,000 people circling the earth.

As the colonies proliferate, they would become more elaborate, comfortable, self-sufficient, and independent of earth. And as techniques and systems of construction improve, the initial expense incurred on the first colonies would tend to drop with succeeding ones. Within a few years after the prototype habitats are built and operating efficiently, O'Neill thinks that the power and products produced in space and sold to earth would pay for the cost of constructing newer sister colonies, thus making space settlements financially self-liquidating.

Should space colonization, as advocated by Dr. O'Neill and his colleagues, become fact in the decades ahead, what might some of its benefits be, both for those on earth and those who choose to live in these extraterrestrial settlements?

For earth dwellers the biggest initial advantage would be the constant source of clean energy from the sun. There would be no need for constructing additional power-generation plants. Huge solar power satellites, built by the colonists, would gather sunlight twenty-four hours a day and beam energy to earth by microwaves (radar), eventually providing all the electrical energy our planet would require. Scientists project that earth's energy crises would then be a thing of the past; nuclear power plants would no longer be needed; and our dependence on fossil fuels such as petroleum would be at an end.

In addition, the eventual existence of many space colonies would take the pressure off our current population explosion. By the mid decades of the next century, a significant fraction of all humanity might be living in space and the population of the earth would decline. As a result, both physical and mental problems associated with overcrowding would be lessened to a great extent.

The presence of the colonies would also minimize industrial pollution of our air and waters, because many of the industries now fouling the earth's biosphere would have been moved to special facilities in space, where they would run on nonpolluting solar energy. In addition, a thriving economic interchange between earth and the colonies could open up a new era of trade. It is also conceivable that in colonizing the vastness of space, the incidence of war would be diminished, for the desire to gain new lands could be redirected toward building colonies in the limitless expanse of space.

Aside from all the obvious physical advantages of space colonization, the greatest ultimate impact might be psychological. No longer tied to a specific location on earth, people would feel equally at home in all the colonies. With fresh hope for the future, man's progress in all levels of life could be as sweeping and vast as space itself.

Chapter Two

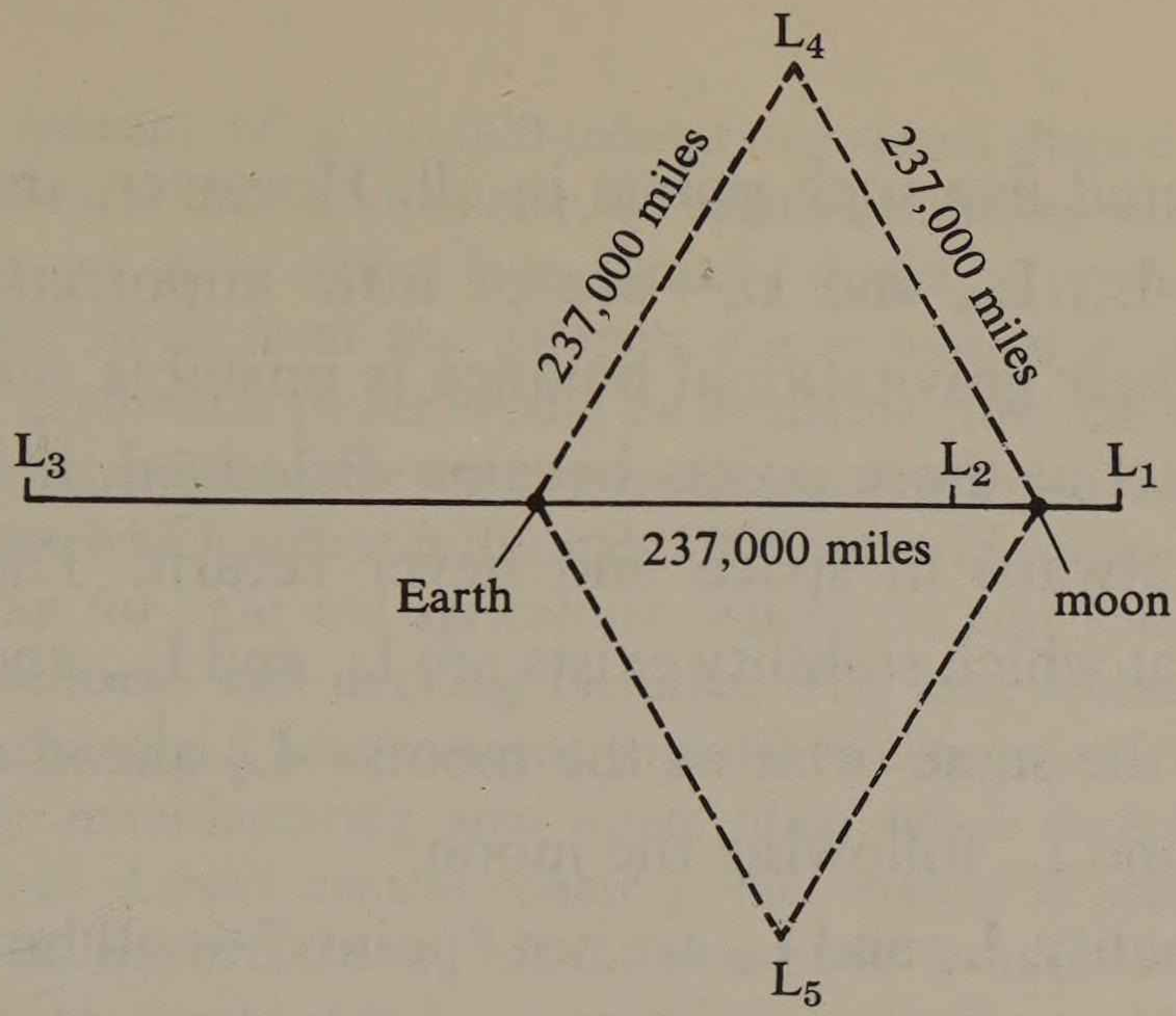
# LOCATION AND SHAPE OF THE COLONIES

Today's space stations—America's Skylab and the Soviet Union's Soyuz—circle the earth in conventional orbits only a few hundred miles above the earth's surface. The reasons for this placement are that the stations are easier to reach, their missions are temporary (at present they are not manned), and much of their work is concerned with observing the earth.

For future space colonization, however, there would be no need to anchor large settlements so close to the earth in low orbits. Dr. O'Neill and his fellow scientists are suggesting other places much farther out in space—places as far from the earth as the moon, but not the moon itself.

You can get a rough idea of where these locations are if you imagine that you are out in space at one of two special points. At either of these points, your body would form an equilateral triangle with the moon and the earth, as shown in the diagram. It is about 237,000 miles from the earth to the moon. Your body would also be about 237,000 miles away from the earth and 237,000 miles away from the moon. In either of these places, your body would, in fact, be at one of the so-called Lagrangian points.

What makes these places so special? In 1772, the French-Italian astronomer Joseph Louis Lagrange demonstrated that in those places in space any object would remain stationary with respect to the moon. As the moon moves in its orbit around the earth, any object in either of these two locations will also move about the earth in such a fashion as to keep exactly in step with the moon. Here the gravitational forces of the moon and earth compensate one another so




The Lagrangian points $L_4$ and $L_5$, where gravitational forces of the earth and the moon are compensated by one another, form equilateral triangles with those bodies. $L_5$ will be the probable site of future space colonies.

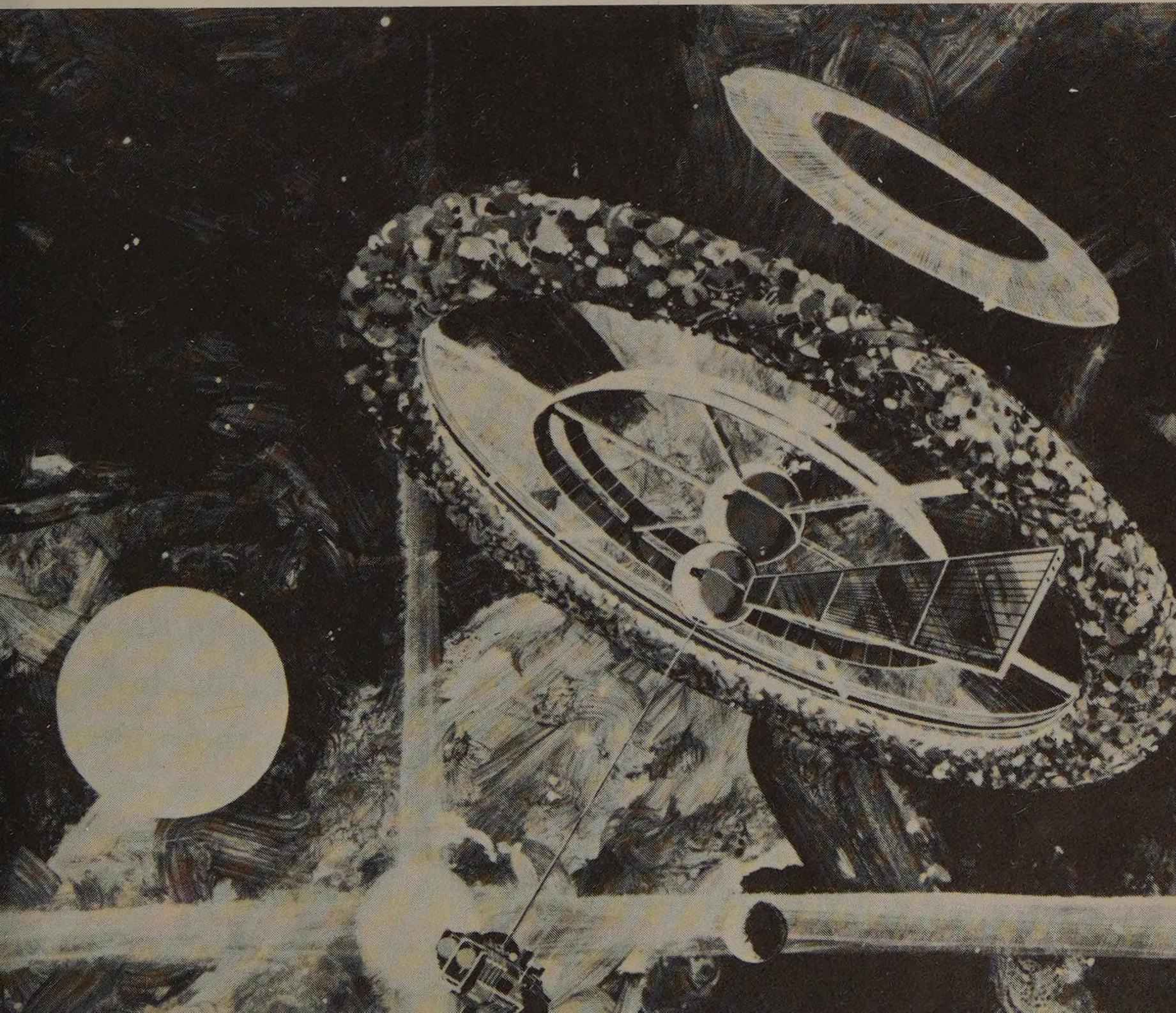
that an object is kept fixed, or locked, in that position. If anything happens to push it out of place, the object will move quickly back, wobbling back and forth, or "librating," as it does so. In other words, anything stationed at one of these pockets in space would tend to be trapped there, orbiting the earth forever without need for propulsion. These Lagrangian points are sometimes called "libration points" or "libration centers."

Actually, as can be seen in the diagram, Lagrange discovered five such points in all. However, three of them—$L_1$, $L_2$, and $L_3$—are of little importance because their gravitational balance is unstable there. If an object at those points became dislodged, it would drift outward in space and never return. The two points at which stability exists are $L_4$ and $L_5$, and they follow the same orbit as the moon—$L_4$ ahead of the moon and $L_5$ following the moon.

In reality, $L_4$ and $L_5$ are not "points" at all but vast, roughly spherical areas. It is here that many hundreds of orbiting space settlements could be constructed. O'Neill thinks that it would probably be best to locate the first colony on the $L_5$ sphere within easy range of both earth and moon but not so close that the colony would be eclipsed often. If a colony were to be shut off from the sun's rays by the earth or the moon with great frequency, the flow of solar energy so vital to its needs would be interrupted.

A varying number of geometrical shapes have been proposed by scientists for the vehicles that would house the colonies. Scientists at the 1975 Ames conference envisioned both spherical and torus-shaped containers. (In solid geometery, a torus is a doughnut, or wheel-shaped, body.) One type of proposed spher-

Artist's concept of a 10,000-inhabitant, wheel-shaped space colony. Over a mile in diameter, its earthlike interior would afford views of up to half a mile. Gravity would be provided by centrifugal force from the colony's one-revolution-per-minute rotation. Unlimited power would be available from the sun. A mirror floating above the colony reflects sunlight into ring mirrors below, which reflect it through 100-foot strip windows into the interior for light and agriculture. Above the core sphere are communications and docking facilities. The long rectangle in the foreground is a heat radiator, and the facility below the colony is the manufacturing area where lunar ore is melted with solar power. Lower central sphere is the original construction shack in which parts for the habitat were built. Exterior of moon rock and slag would shield colonists from radiation. *(NASA)*

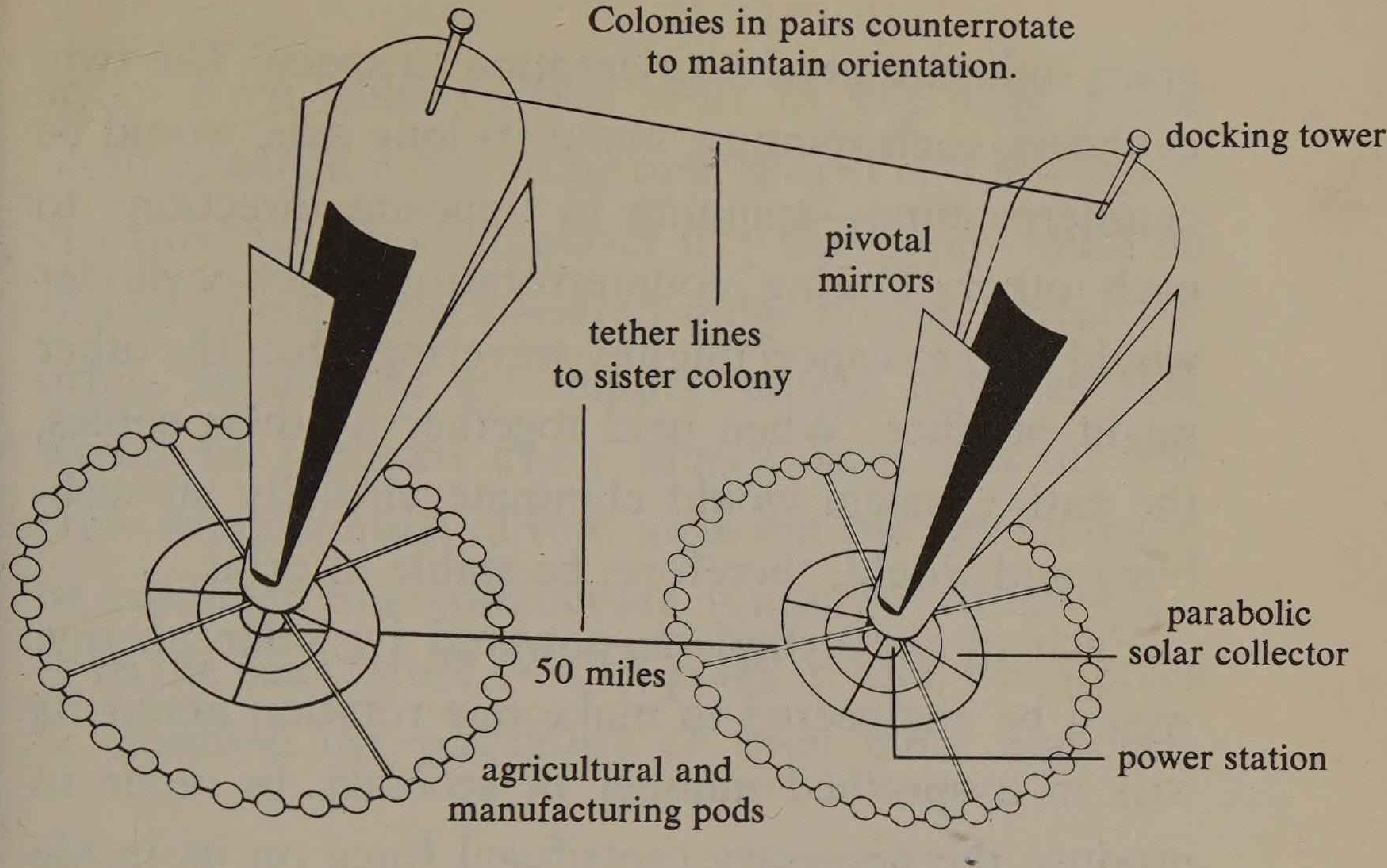


ical habitat considered at the meeting was about twelve miles wide and had an interior land area of approximately three hundred square miles.

The artist's concept on page 33 portrays another, smaller model developed by the Ames Group. The design calls for construction of a wheel-shaped habitat over a mile in diameter and located at a point on the moon's orbit some 240,000 miles from the earth and the moon. The wheel, or torus, would rotate around its hub at one revolution per minute, fast enough so that the centrifugal force felt by its inhabitants would simulate their normal weight on earth. Its "tire," or rim, would house 10,000 people along with shops, schools, light industry, and agricultural areas.

The mass, or total quantity of matter, of the torus and its contents would be about 500,000 tons, approximately the mass of a very large supertanker. Heavy industry would be placed outside the torus in order to make use of the weightlessness and high vacuum of space.

Dr. O'Neill, however, envisions space habitats of another kind and shape. He sees a pair of long, hollow cylinders with human beings living on their inside




Twin cylinder colonies as conceived by Gerard K. O'Neill.

surfaces. These surfaces would be set up and contoured into a familiar world with all the accoutrements of earth. O'Neill believes that his cylindrical geometry would best create the conditions desirable in a space community: normal gravity, normal day-and-night cycle, natural sunlight, efficient use of solar energy and of materials available.

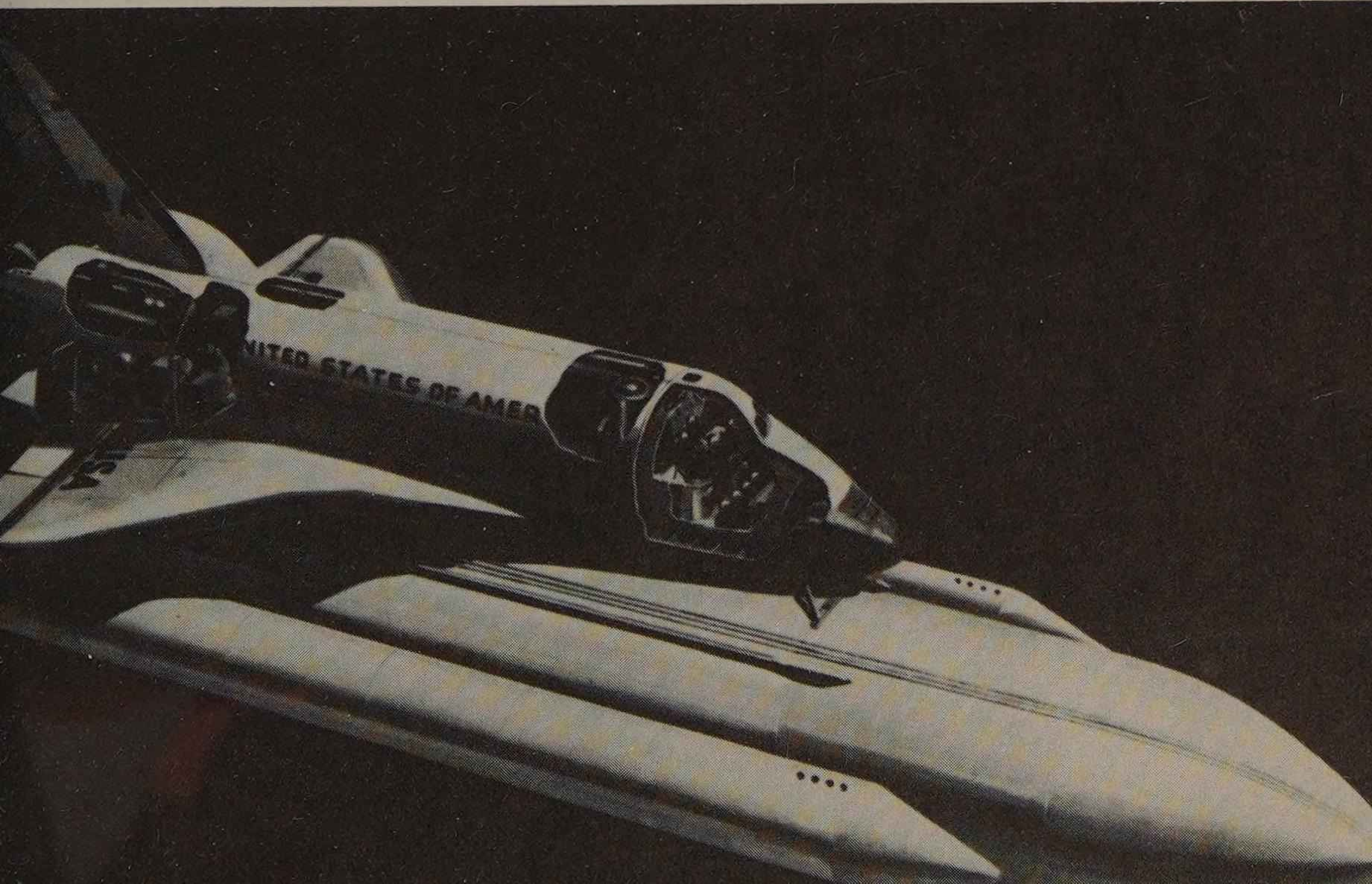
O'Neill has good reasons for using two cylinders rather than one. The pair of giant tubes would be tethered together by metal cables about fifty miles apart to insure precise orientation in space. The twin cylinders, each spinning about its long axis, would be counterrotating—spinning in opposite directions to each other. During counterrotation, each cylinder would tend to cancel out any wavering effect the other might produce. When held together by their cables, the entire system would eliminate virtually all wobbling and would, therefore, be stable in orbit.

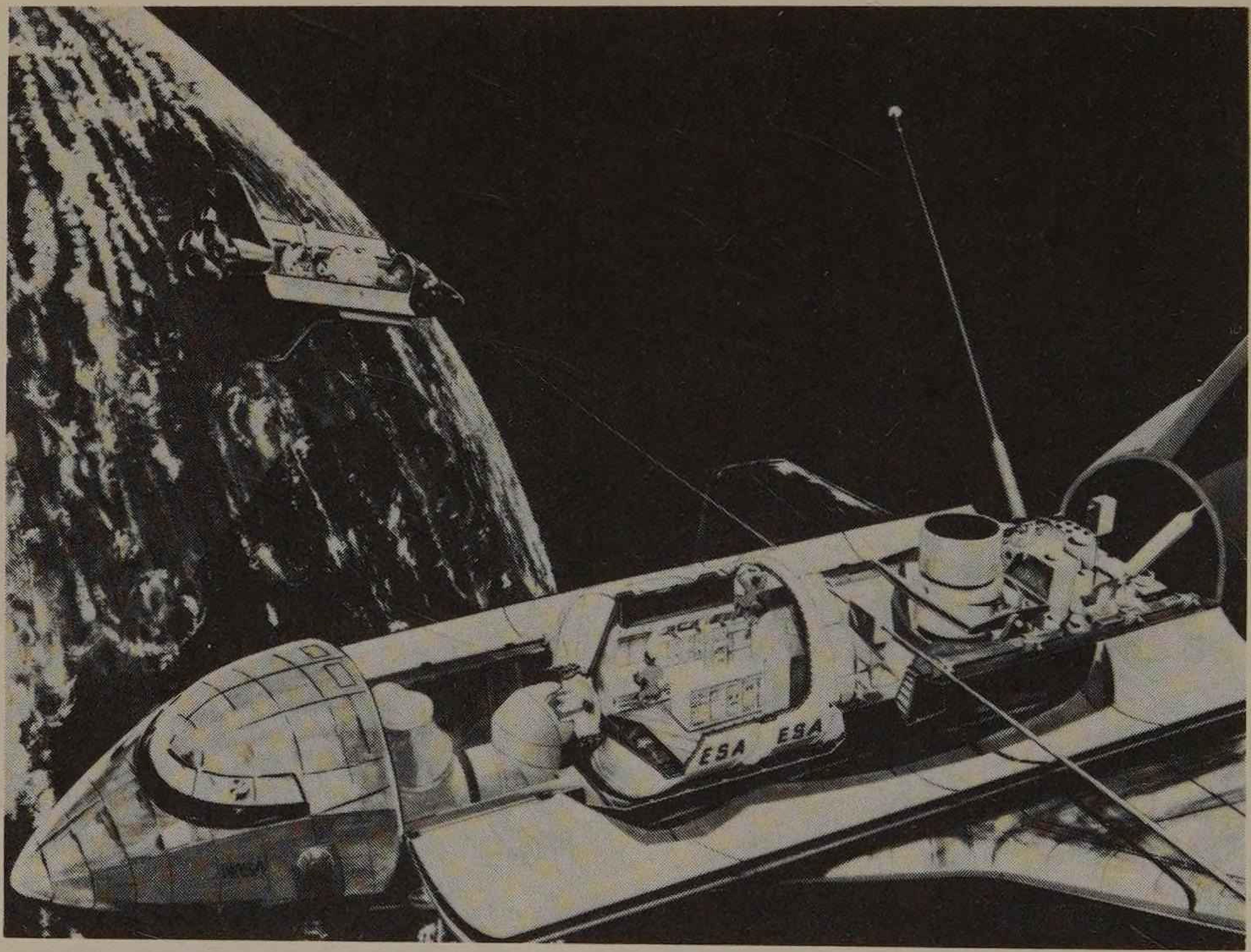
Each of the cylinders, powered by solar energy, would be engineered to make one rotation about its axis in a specified number of seconds, in order to produce the necessary centrifugal force on its inside surfaces to simulate earth gravity. For O'Neill's largest model habitat this would take about two minutes. In addition, the tandem cylinders would be oriented in space so that their same ends always face the sun; in this way they receive constant sunlight needed to manufacture electricity.

Less futuristic but still a step forward in establishing colonies in space are recent and upcoming studies for the National Aeronautics and Space Administration. In one study completed for NASA by the McDonnell Douglas Astronautics Company, scientists proposed that a sectional station be assembled in space from units carried aloft by the U.S. Space Shuttle, which is due to be operational in a few years. A cylindrical module about fifty feet long would be placed about three hundred miles up for a five-year orbit, augmented by smaller supply modules that would be replaced every ninety days. Initially the crew would consist of four men, but the system could be expanded to accommodate as many as twenty-four.

In the near future, NASA plans to fund two studies to examine the possibility of even more elaborate

A conceptual view of the U.S. Space Shuttle, slated to be operational in the 1980s, showing the complete system including the airplanelike orbiter, which detaches from the shuttle for special missions. *(NASA)*





Spacelab is a payload facility that is carried into space by the space shuttle and remains in its cargo bay for missions of up to thirty days. This space station project is a planned joint venture of NASA and the European Space Agency (ESA) when the space shuttle becomes operational. *(NASA)*

stations. These stations would be designed to spend at least a decade in orbit, with the capability of operating from positions some 23,000 miles above earth. Like the much larger space habitats proposed by O'Neill, these fledgling stations are being considered for tasks such as microwave transmission of solar energy to earth, as well as for other research projects.

Chapter Three

# SIZE, DESIGN, AND INTERIOR ENVIRONMENT

Assuming that the O'Neillian twin cylinders become the prevailing shape of future space habitats, how big would they be? What design elements would be engineered into them to make them functional and livable? And what would their interior environments be like?

As for size, O'Neill has worked out four basic models. Model 1, the first of the habitats, would be only large enough to be workable. The dimensions of each of its spinning tubes would be about 3300 feet long and some 700 feet in diameter. As a double unit, it would support about 10,000 people, and if construction began soon, it could be operational by about the year 1990. Model 2's cylinders would be approximately two miles long and about 2100 feet in diameter. It could support a population of some 150,000 people and could be ready for habitation about the year 2003.

Model 3 would have twin cylinders some six miles long and be perhaps as wide as one and a quarter miles. Capable of supporting about two million people or more, Model 3 could conceivably be ready for habitation between 2002 and 2004.

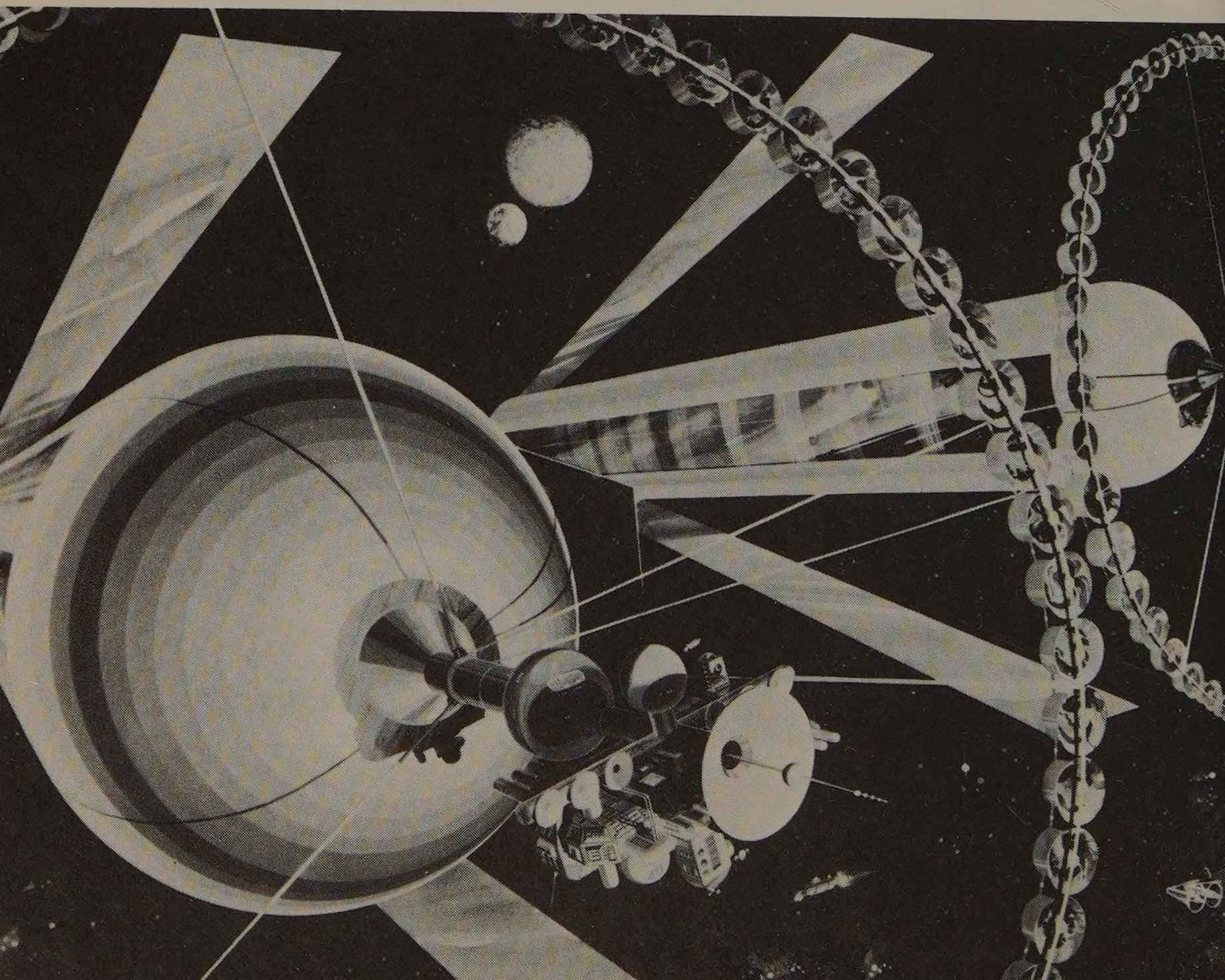
The largest cylinder pair envisioned by O'Neill is Model 4. Each tube would be some twenty miles long and approximately four miles in diameter. As a rough comparison, such man-made worlds would be about eight miles longer than the length of New York's Manhattan Island and more than twice as wide in diameter. The total inner surface of each cylinder would, however, be over ten times the area of Manhattan. If Model 4 were utilized to its fullest capacity, it could support up to twenty million people, although, as O'Neill points out, five to ten million might be a more comfortable figure. According to O'Neill's timetable, Model 4 could be ready for occupation sometime around the year 2010.

For each of the four models, the period of a cylinder's rotation about its axis needed to create artificial gravity would be different. The smaller the model, the less time it would take to rotate. Thus, a Model 1 cylinder would complete one rotation in about 21 seconds, while a gigantic Model 4 tube would take 114 seconds for a complete turn.

Actually, there is no definite limit on how large a space habitat could ultimately be. As size increases, however, a larger part of the mass of the twin-cylinder community would be taken up by the supporting cables that tether the two units together. In the end, the size of the colony would depend upon the objectives of its designers and builders. If economy is the goal, the builders would favor a smaller size habitat that would, in turn, have fewer earth comforts. But if economy were no object and a more terrestrial environment were desired, the builders would plan a larger and more elaborate community.

Ideally, O'Neill believes, the economics of efficient use of materials and other considerations would tend to limit the size of a typical colony to about sixteen miles in length and four miles in diameter. Inside these huge tubes, an environment like the earth's could be created. In addition to living space, there could be

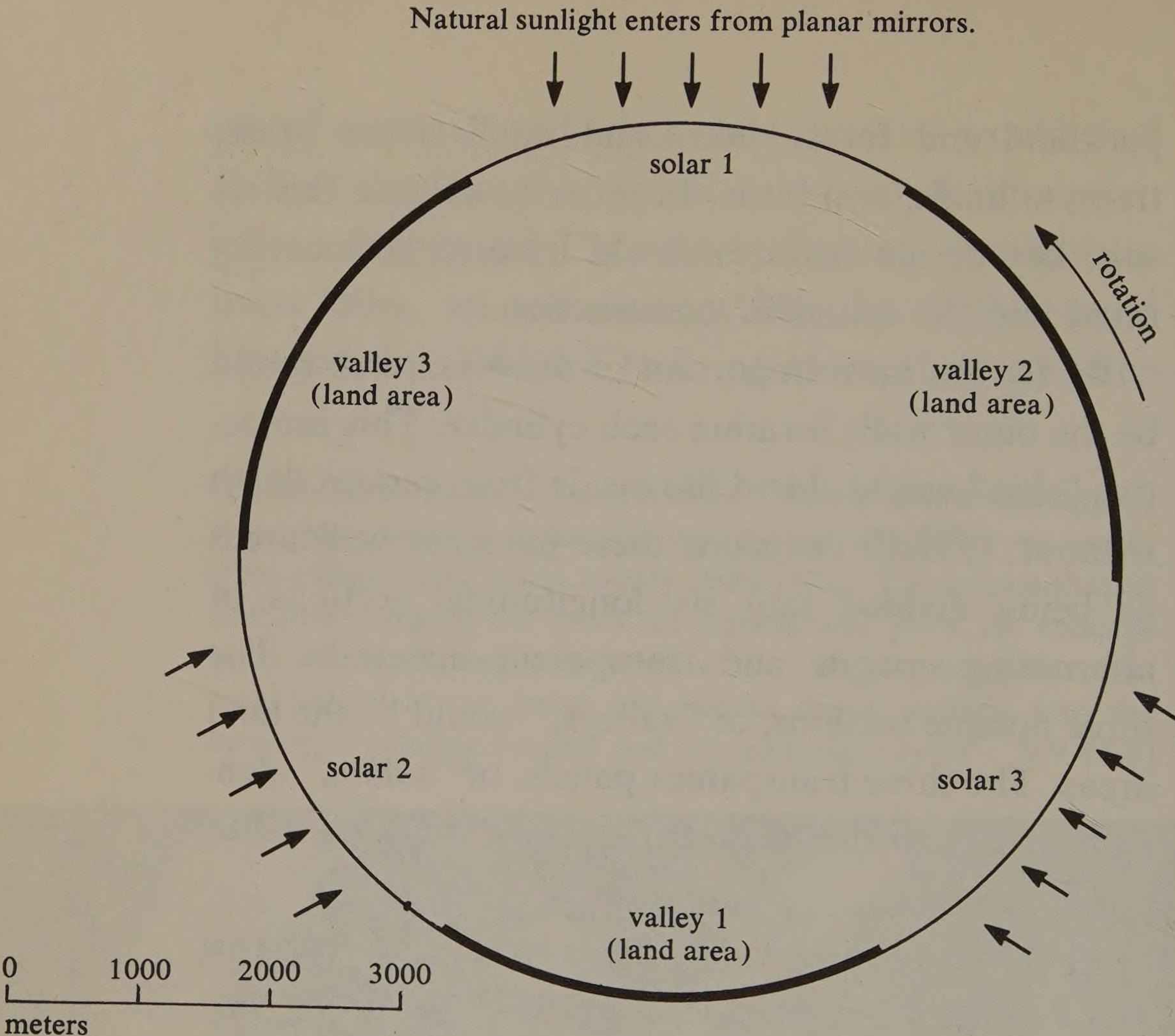
An O'Neillian twin cyclinder Model 4 colony as it would appear to a space colonist returning home after a holiday on earth, from a distance of about twenty miles away. The teacup-shaped containers ringing the tubes are agricultural pods. At endcaps are a manufacturing and power station. Huge rectangular mirrors, hinged at the lower end, would direct sunlight into the interior, regulating seasons and day-and-night cycle. *(NASA)*



parkland and forest, lakes and small rivers, grass, trees, animals, and birds. In order to achieve this result, key design features would have to be incorporated into the cylinders' construction.

By far the most important of these features would be the outer walls forming each cylinder. This protective "skin" would shield life inside from certain death without. O'Neill envisions these immense wall areas as being divided into six longitudinal sections of alternating opaque and transparent materials. The three opaque sections, or "valleys," would be the land areas. The three transparent panels, or "solars," identical in size to the land strips, would be designed to admit sunlight.

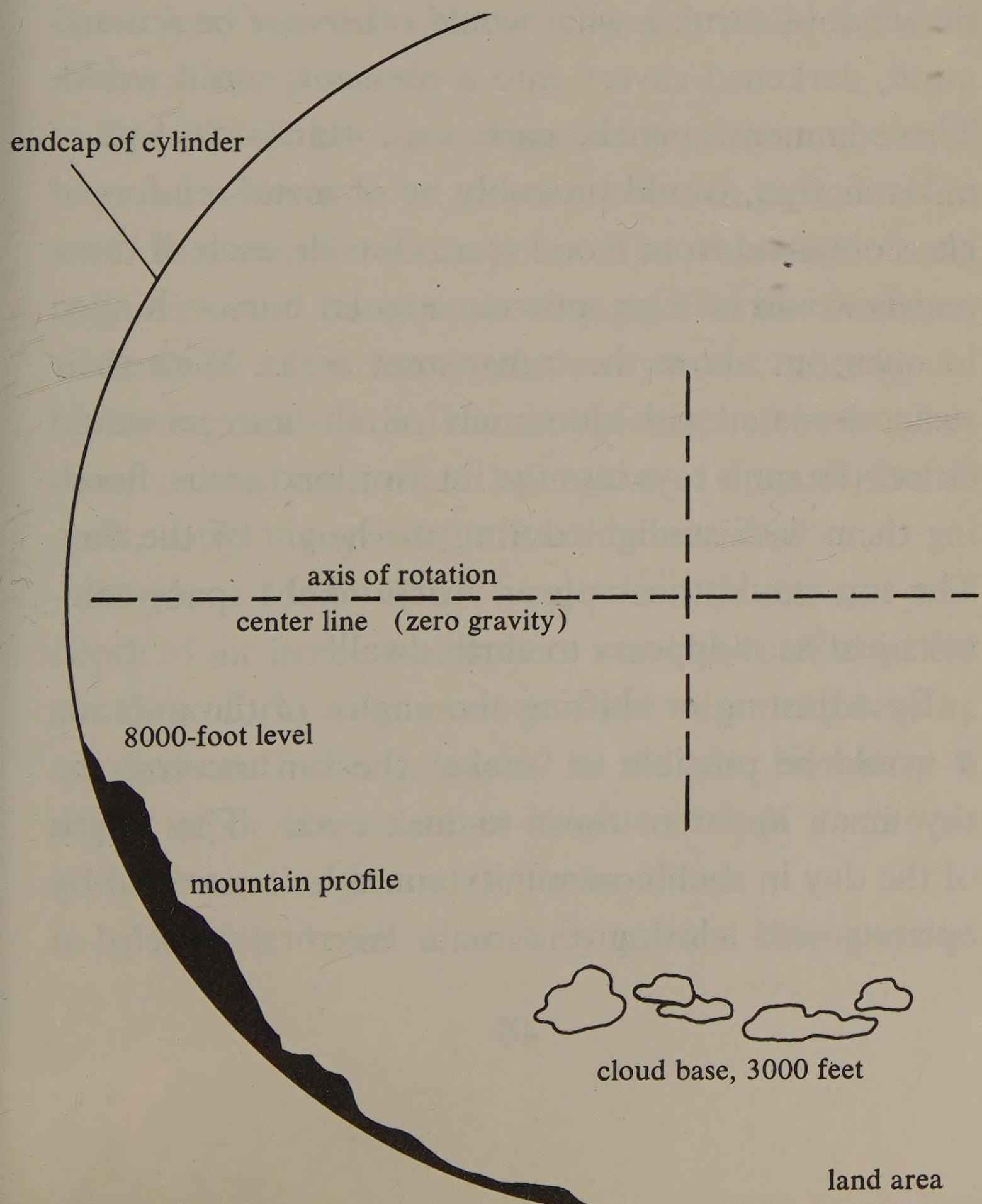
Each of the three valley areas would measure two miles wide by sixteen miles long. They would be constructed of metal, largely aluminum, obtained from mines located on the moon. Their inner surfaces would be spread with soil brought from the moon and built up higher with lunar rock in whatever places desired. Virtually any type of earth terrain could be simulated—from rolling Berkshire hills to sweeping Western plains, from lush tropical isles to well-kept suburban acres—according to the builders' intentions and wishes.




A sectional view of a cylindrical space habitat. The inner surface is divided into alternating strips of land area (valleys) and window area (solars).

On the thirty-two square miles comprising each land area would be ample room to duplicate, say, a California bay or an island coastline. At the endcaps in particular, there would be additional square miles of space that could be put to imaginative landform use. In one of Dr. O'Neill's prototype plans (shown below), an 8000-foot mountain profile, which was copied from the Grand Tetons in Wyoming, was proposed as a surface for one endcap area. Such moun-

Side view of a cylinder endcap showing how mountains could be built up in the habitat, after a drawing by Gerard K. O'Neill.



tains could be built up with accumulations of moon rock and soil using bulldozers and other earthmoving equipment. As seen in the illustration, the calculated cloud-base heights are typical of summer weather on earth.

By means of the three alternating transparent solars, sunlight would be admitted as if through a gigantic window, turning what would otherwise be a mammoth, darkened cavern into a pleasant, sunlit world. These immense panels, each some thirty-two square miles in area, would probably be of metal-reinforced glass obtained from moon ores. Outside each of these panels would be a gigantic rectangular mirror, hinged to open out above the transparent areas. With their surfaces coated with aluminum foil, the mirrors would reflect the sun's rays into the interior land areas, flooding them with sunlight during the height of the day. The sun would thus appear visible to the space colonists just as it appears to earth dwellers.

By adjusting or shifting the angles of the mirrors, it would be possible to "make" the sun traverse the sky in an apparent dawn-to-dusk cycle. The length of the day in each community could be controlled by opening and closing the main mirrors, which, of course, rotate along with the cylinders. With the mirrors in the open position, the sunlight admitted would warm the air in the habitat; when closed, the air would cool again. Thus, the amount of sunlight would determine the average temperature and seasonal variation within the cylinder. A community, for example, could have a perpetual shirt-sleeve atmosphere or, if the colony's government so chose, it could be laced with a dash of winter.

Dr. O'Neill has also suggested that there could be a phase difference in seasons between cylinders—a sort of seasonal counterpoint. The colonists of one cylinder could be experiencing midsummer weather, while those a few dozen miles away in the other would be having midwinter. Hence, colonists of both cylinders, visiting each other by means of a small shuttle craft, could enjoy brief, climatic vacations.

Inside a Model 3 or 4 cylinder, the amount and depth of air in the atmosphere would be sufficient for clouds to form from gaseous water vapor condensing on dust and other particles in the air. Normally if water vapor condenses at heights of half a mile or more above the ground, it forms clouds.

In Models 3 and 4, with cylindrical diameters of

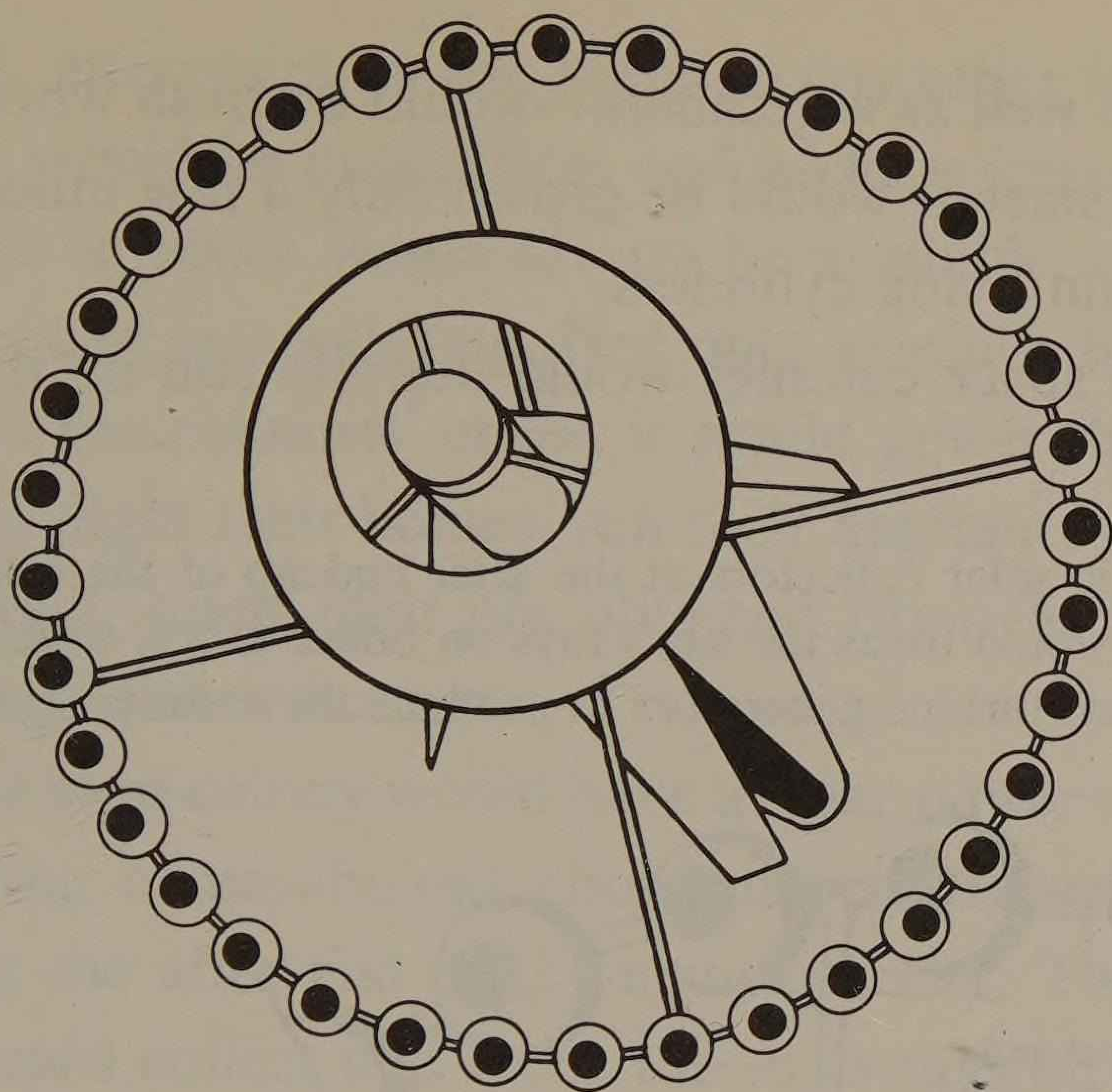
one and a quarter and four miles respectively, the volume of air would be more than enough to allow clouds to form, provided the temperature of the air was properly regulated. By adjusting the exterior mirrors to change the amount of sunlight entering the cylinder, the temperature of the air could be regulated to produce clouds. By further cooling the air with less mirrored sunlight to the proper dewpoint (the temperature at which water vapor becomes liquid), rain could be made to fall. A further reduction of mirrored sunlight would drop the air temperature to below freezing. Water vapor in the cylinder's air would then be directly converted into ice crystals, causing snow to fall in the colony.

But where, one might logically ask, would the vast quantity of air come from to fill these mammoth tubes? Air is a highly compressible mixture of gases. Earth's soil, rich in these gases, could be compressed

*Opposite:* Night is approaching in this artist's concept of the interior of a Model 4 space cylinder. The view is from one of the endcaps looking toward the other. Edges of the mammoth mirrors can be seen in all three window areas. Through the one at the top the earth is creating a solar eclipse. Clouds have formed above the half-mile altitude in the atmosphere. *(NASA)* in containers and released inside the habitat. Or, the air could eventually be extracted from oxides in the moon's soil.

Needless to say, people must eat in space as well as on earth. Thus, certain areas would be set aside for agriculture. Crops could be grown in the lunar soil (with nutrients added) of the three land areas, but doing so would drastically reduce the total living spaces for the colonists. Instead, O'Neill and his fellow scientists propose to place these growing areas entirely outside the main habitats in tiny cylinders, or "pods." There would be some seventy of these agricultural pods, and they would form a ring exterior to the main cylinder, as shown in the illustration. The ring, situated at the endcap that constantly faces the sun, would not rotate.

Each agricultural pod would be designed and built to offer the ideal climate for the particular crop to be nurtured in it. Grains and other plants grow faster if they receive more sunlight, and in space an agricultural pod could be provided around-the-clock sunlight. Further, by concentrating carbon dioxide and water vapor (vital to plant growth) in the pods, very high crop yields could be achieved.



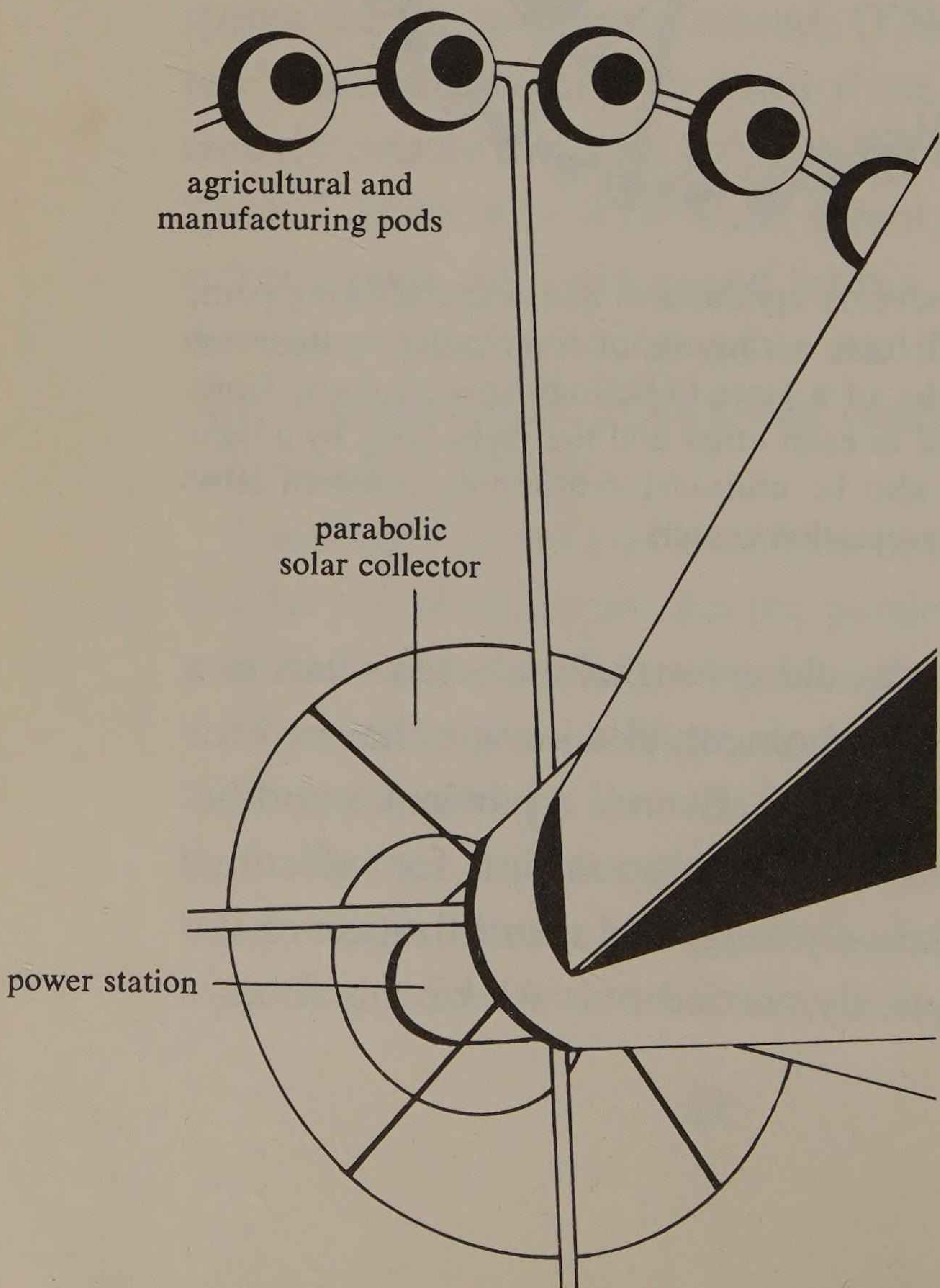
A "halo" of some seventy agricultural and manufacturing pods, or modules, would form a ring about forty miles in diameter around each cylinder of a large O'Neillian space colony. Units would be connected to each other and the main body by a light cable. Pods could also be utilized for hospitals, research labs, observatories, and recreation centers.

Space farmers would grow their selected seeds in a sterile, isolated environment, eliminating the need for insecticides or pesticides. Even if a particular pod became contaminated, the evolution time for infectious organisms is relatively long, and resterilization of the pod could be quickly carried out. All of this food—

fruit as well as vegetables—would be fresh when marketed, since it would be grown only a few miles from the main living cylinders.

The space colonies would literally run on the sun.

Parabolic solar collectors at the after endcap of the cylindrical habitat would focus the sun's rays on boiler tubes, which would run steam-turbine generators to produce the colony's electricity.



Indeed, attempting to run them on any other form of energy would be impractical and perhaps impossible. Sunlight in space would always be available, easy to handle, and nonpolluting. Not only would it be used to grow the colonists' crops, it would power their industries, light their homes, run their appliances, cook their food, smelt their ore obtained from the moon, and recycle their wastes.

Each twin colony would have a solar power station consisting of paraboloid (bowl-shaped) mirrors encircling the after end of the main cylinder. The mirrors would collect and focus the sun's rays on boiler tubes, which, in turn, would run conventional steam-turbine generators. These generators could provide the entire colony with a potential of ten times the electric power per person now used in highly industrialized areas of the earth.

Chapter Four

# BUILDING THE FIRST COLONIES

In order to build even a small Model 1 colony in space, a great many things would be needed—metals, glass, water, concrete, generators, special hardware, tools and machinery, soil and rock, hydrogen, food, and, of course, people. Dr. O'Neill has calculated that over half a million tons of such material would be sufficient for the job. It would probably require a thousand times more than that to put a larger, more complex Model 4 colony into orbit.

Where would all this material come from? Our own planet, with its key resources giving out and much of its population in want, could ill afford to give up such colossal quantities of supplies for construction in space. Fortunately for earth, however, it need supply virtually none of these materials after the initial stages —except for people. These gigantic habitats would not only be built in space but would largely utilize materials and energy found in space.

Luckily, the earth possesses a large, not-too-distant satellite, our moon. While the moon is an empty, lifeless, airless world, it is still close enough for us to reach; indeed, our astronauts have already walked on its surface several times and returned. With a mass of about one eightieth that of the earth, the moon represents for future space-colony builders an almost limitless, free quarry, which can be mined for vital materials. Because, for example, the moon is a rich source of titanium and aluminum, it is likely that these metals would be used extensively in construction of the colonies. It is also rich in oxygen from which the colonies could derive their water supply, and silicon from which glass and concrete can be manufactured. And the lunar surface soil, as mentioned, could be employed for agriculture, with the addition of nitrates and small amounts of other elements.

Not only is all this material available on the moon in massive quantities, but lifting it off the surface against the moon's weak gravity would require only about one twentieth of the energy necessary for lifting it off the earth's surface. Furthermore, it could be moved at a fraction of the cost. One scientist has calculated that to bring one kilogram of material from the moon to $L_5$ would take less than 5 percent of the energy, or cost, needed to move it from earth. Once the moon ore has been lifted off the lunar surface, all smelting, purifying, and other chemical reduction work would be carried out in space.

Practically speaking, what would be the actual tonnages of materials required to build a Model 1 colony? How much of it could come from the moon and how much would the earth be expected to provide? The table opposite lists masses of materials in metric tons worked out by Dr. O'Neill for such a project.

From the table it is clear that out of a total mass metric tonnage of 510,000, approximately 98 percent can be obtained from the moon. Only about 2 percent, or 10,000 metric tons of supplies, need come

| | Total mass required | Mass required from earth |
|---|---|---|
| Aluminum (container, structures) | 20,000 | — |
| Glass (solars) | 10,000 | — |
| Water | 50,000 | — |
| Generator plant | 1000 | 1000 |
| Initial structures | 1000 | 1000 |
| Special fabricated hardware | 1000 | 1000 |
| Machines and tools | 800 | 800 |
| Soil, rock, and construction materials | 420,000 | — |
| Liquid hydrogen | 5400 | 5400 |
| 2000 people and equipment | 200 | 200 |
| Dehydrated food | 600 | 600 |
| Totals | >510,000 | 10,000 |

from earth, including certain materials and special construction machinery initially needed to launch the program.

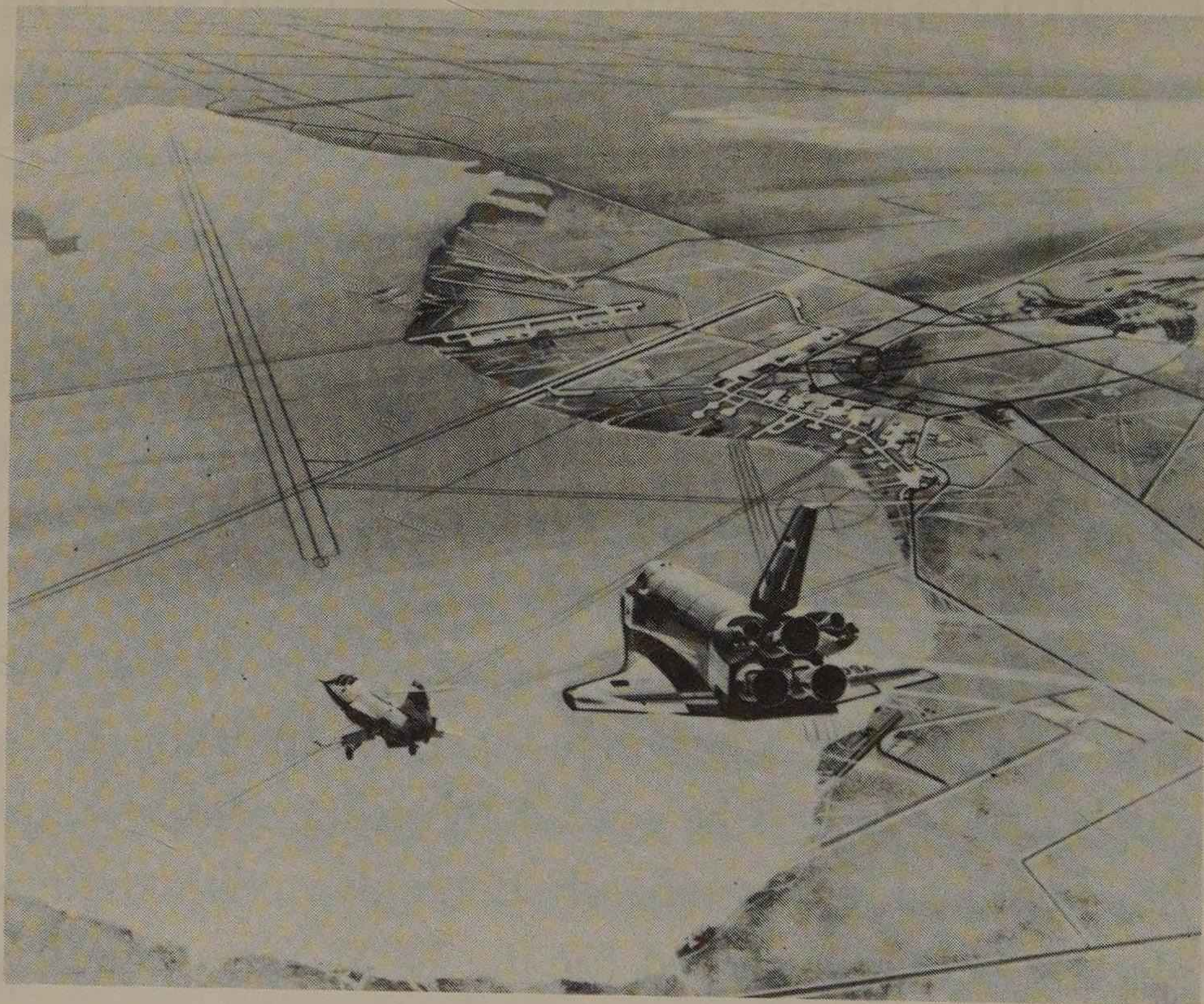
By far the largest single item on the list required from earth is 5400 metric tons of liquid hydrogen. This would be used to supply the large amount of water necessary for a Model 1 colony and its eventual population of 10,000 people. Pure ordinary water contains by weight about 89 percent oxygen and 11 percent hydrogen. The plentiful oxides in the soil of the moon can yield, through chemical reduction, the 89 percent oxygen, but the remaining 11 percent needed to form water would have to be supplied as liquid hydrogen brought from earth. Fortunately, our planet can easily spare that much, for liquid hydrogen can be extracted by chemical means from seawater. Nearly three fourths of the earth is covered by oceans, and extracting hydrogen from this supply would not, it is felt, appreciably tax earth's resources.

Conceivably, however, as future colonies multiply, giving up great quantities of hydrogen could become burdensome for the earth. But by that time, scientists project that space transportation techniques would have improved to the point where hydrogen, and other elements of which the moon has an insufficient supply, could be mined farther out in the solar system. They could be obtained from some of the closer asteroids or possibly from passing comets during their long orbits around the sun.

The first Model 1 habitat would be by far the most expensive to build because earth would have to supply the advance machinery and equipment, the various life forms, and the basic energy and food supply, in addition to the raw materials, such as hydrogen, not found on the moon. Furthermore, the earth will have to pay the cost of a dual transportation program: first, getting freight shipments from the earth out to $L_5$, the colony site; and secondly, transferring lunar ore from the moon to $L_5$. After completion of the first colony, cost would tend to decline due to leap-frogging—that is, qualified colonists once established in space and trained for the work would help build the next habitat, and so forth.

O'Neill and other space scientists think that the first transportation problem—getting material from earth to $L_5$—could be solved by using conventional chemical rockets, specifically the high-quality engines already being developed for the U. S. Space Shuttle. This powerful new delta-winged spacecraft, pictured on page 60, is being assembled by space technicians in California. Essentially a reusable rocket vehicle, the shuttle will initiate economical round-trip service between earth and orbital locations in the 1980s. One of the locations it could reach is the $L_5$ site, where it could be employed to ferry out supplies from earth to build the first Model 1 colony.

Getting supplies from earth to $L_5$ via space shuttle is one thing, but how about the great quantities of



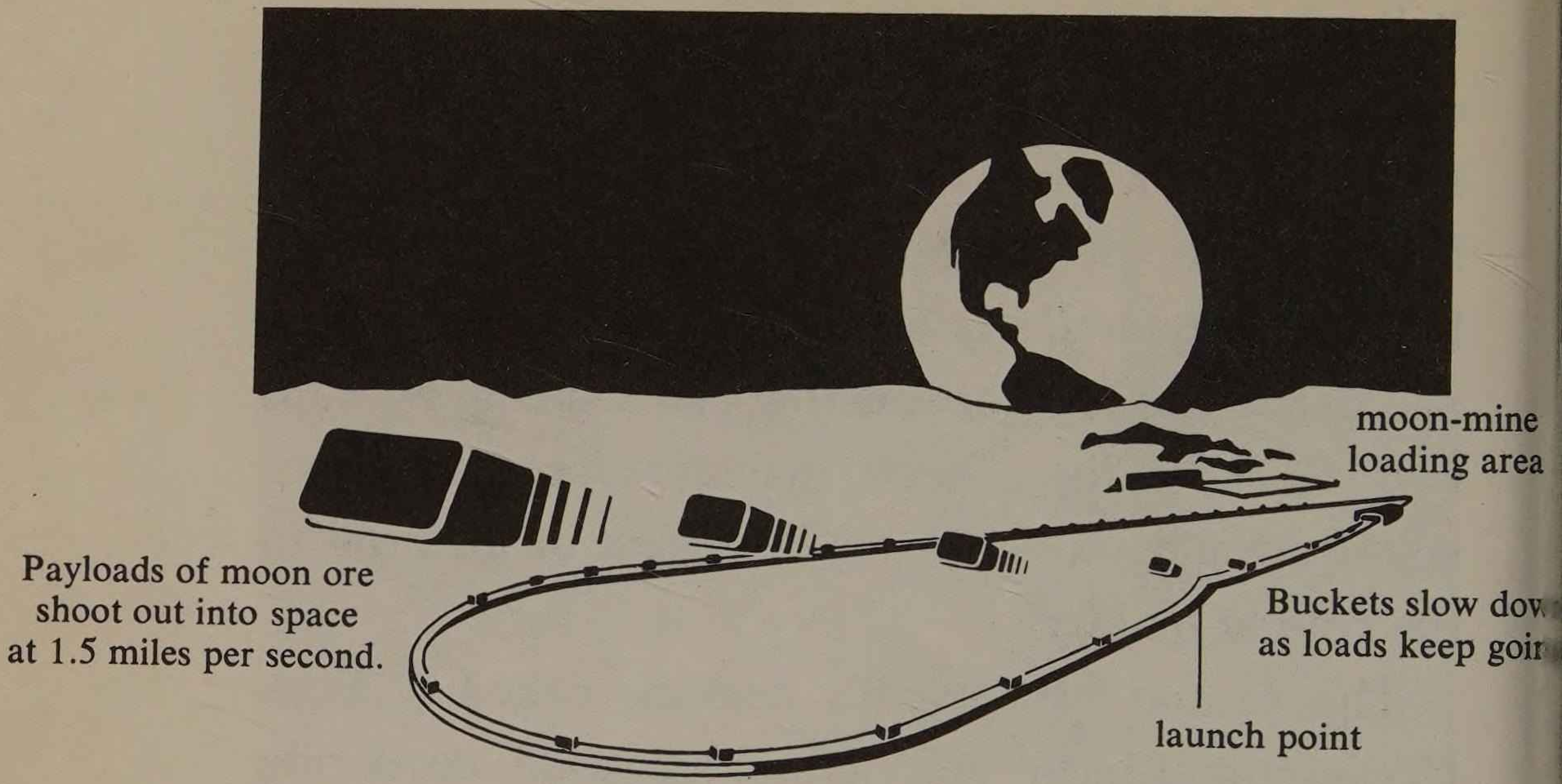
A conceptual view of U.S. Space Shuttle coming in for a landing, with a conventional aircraft alongside for escort. *(NASA)*

lunar ore that would also have to get to $L_5$ from the moon? It would be costly indeed to send a space-shuttle craft all the way to the moon every time a shipment of moon ore was needed. Dr. O'Neill has proposed two unique machine devices that could transfer lunar material to construction sites in space.

The first of these machines, called an RPL (Rotary

Pellet Launcher), would be designed as a symmetrical, two-arm propellerlike arrangement that would run at constant speed. It would launch pelletlike payloads of moon ore off the moon's surface. They would be electromagnetically thrust to the construction site and collected there for smelting and refining. Perhaps two dozen of these lunar machines operating constantly would supply a steady stream of material to the colony builders.

The second of O'Neill's devices, called a TLA (Transport Linear Accelerator), would accelerate continuous buckets of compacted moon ore along a six-mile course shaped something like an oval racetrack. When the buckets reach a certain point on the track and are traveling at escape velocity (the speed that any object must acquire in order to escape from a planet's gravitation), they are suddenly decelerated, slinging their moon-ore payloads out into space to a colony under construction. Precise steering after launching would be controlled by an electromagnetic system. At the construction site, pickup vehicles would scoop up the bundles of ore and ferry them into the colony. Back on the moon, the empty buckets would recirculate and receive new payloads.




The Transport Linear Accelerator (TLA), a system for mining moon ore for the construction of colonies and launching it into space toward the construction site.

Another advantage of the TLA would be that it could serve as a reaction-propulsion system—that is, by using the hurled payloads as a reaction mass, it could also push matter in the opposite direction. (The reaction-mass principle works according to Newton's Third Law, which states that for every action, there is always an opposite and equal reaction. For example, if you fire a rifle, the forward thrust on the projectile equals the backward thrust on the rifle, which is called the recoil, or kick, of the rifle.) In the case of the TLA, great chunks of pure nickel-iron in the asteroid belt could actually be moved to an $L_5$ construction site and used as on-hand quarries. The TLA would be secured to one of these chunks and, by spewing bits of it out in one direction, the whole asteroid would move in the other direction toward a colony site.

Both would employ the two great advantages of the moon's environment—an excellent vacuum (which reduces friction) and a very low escape velocity, less than one quarter of the speed necessary for spacebound vehicles to escape the earth. Both devices would also run on electric power produced from solar energy. To set up and maintain these devices on a regular basis for supplying construction sites, a small moon colony of perhaps one hundred men would have to be established.

Dr. O'Neill and others are convinced that space-colony construction techniques will rely heavily on automation and mass production. Why? Because a colony's structural form—irrespective of its ultimate shape—would consist mainly of cables, fittings, and exterior and interior panels made up of standard modular (unit) pieces. These items would be manufactured over and over again many thousands of times and then assembled by workers in a zero-gravity environment that is free of the vicissitudes of terrestrial weather and hampering gravity.

To make construction of habitats in space possible without the need of cumbersome space suits, O'Neill has envisioned giant aluminum spheres, which could serve as workshops to turn out the thousands of modular pieces needed for final assembly. These work spheres would be pressurized and heated, allowing technicians inside to work in a shirt-sleeve atmosphere. As each module is completed, the work sphere would swing open in halves to allow its removal, as shown in the illustration. Afterward, the halves would join again when the workers begin to manufacture the next module.

The basic construction of a typical O'Neill cylindrical habitat would follow a regular pattern. Each giant tube would consist of a weblike framework of steel cables and ribs. The cables, or "longerons," would run lengthwise to form the longitudinal members that would hold the massive endcaps in place. The ribbands would run around the cylinder's circumference as girdles, to hold the air pressure and centrifugal force exerted against the sides. Over this skeletal framework would be fastened aluminum or possibly titanium modular panels that would make up the outer, opaque walls of the land areas. The transparent solars, or window strips, between the land areas would probably be glass reinforced by woven-steel meshing; later tough plastic might be used.

By their very presence in space, the habitats would be subject to certain hazards. Among them would be the possibility of damage from passing meteoroids. Although the space containing the earth-moon system is full of meteoroidal dust, this material is not likely to cause serious calamities. More bothersome would be meteoroids the size of a pinhead or a little larger, which could pit the exterior paneling and craze the glass-window areas. Increasing the thickness of the exterior skin of the tube, however, would solve the problem.

Fortunately, a meteoroid large enough to cause serious injury to a colony is quite rare. NASA scientists have calculated that the chances of a one-ton chunk of space debris colliding with an orbiting space colony would be about once in a million years. Another researcher has estimated that if a hole were torn in the skin of a habitat the size of a house window, it would take about three hundred years for "leak-down," or depressurization, to take place. In any case, a sizable strike from a passing meteoroid should produce only local damage to a well-designed structure. As a precaution, sensing devices and proper damage-control techniques would be in regular use so that any strikes could be handled quickly and efficiently.

A far more serious problem is the danger of cosmic-ray radiation. Cosmic rays are always present in space, and they are extremely penetrating. However, it is thought by scientists that space communities would be amply protected from them by the depth of the atmosphere within the cylinders, their protective metal skin, the thick land areas of lunar soil, and the steel-support structure itself. In the wheel-shaped colony envisioned by the Ames Research Center scientists, a massive outer layer of rickrack sheathing—composed of moon rock and/or slag from processed moon ore—would shield the inhabitants from cosmic radiation. It would ultimately be possible to build large spherical habitats with diameters as wide as twelve miles. Such habitats, built of titanium found on the moon or the asteroids, would be structurally thick enough and have sufficiently deep atmospheres (comparable to that of the earth) to provide protection against deadly cosmic rays.

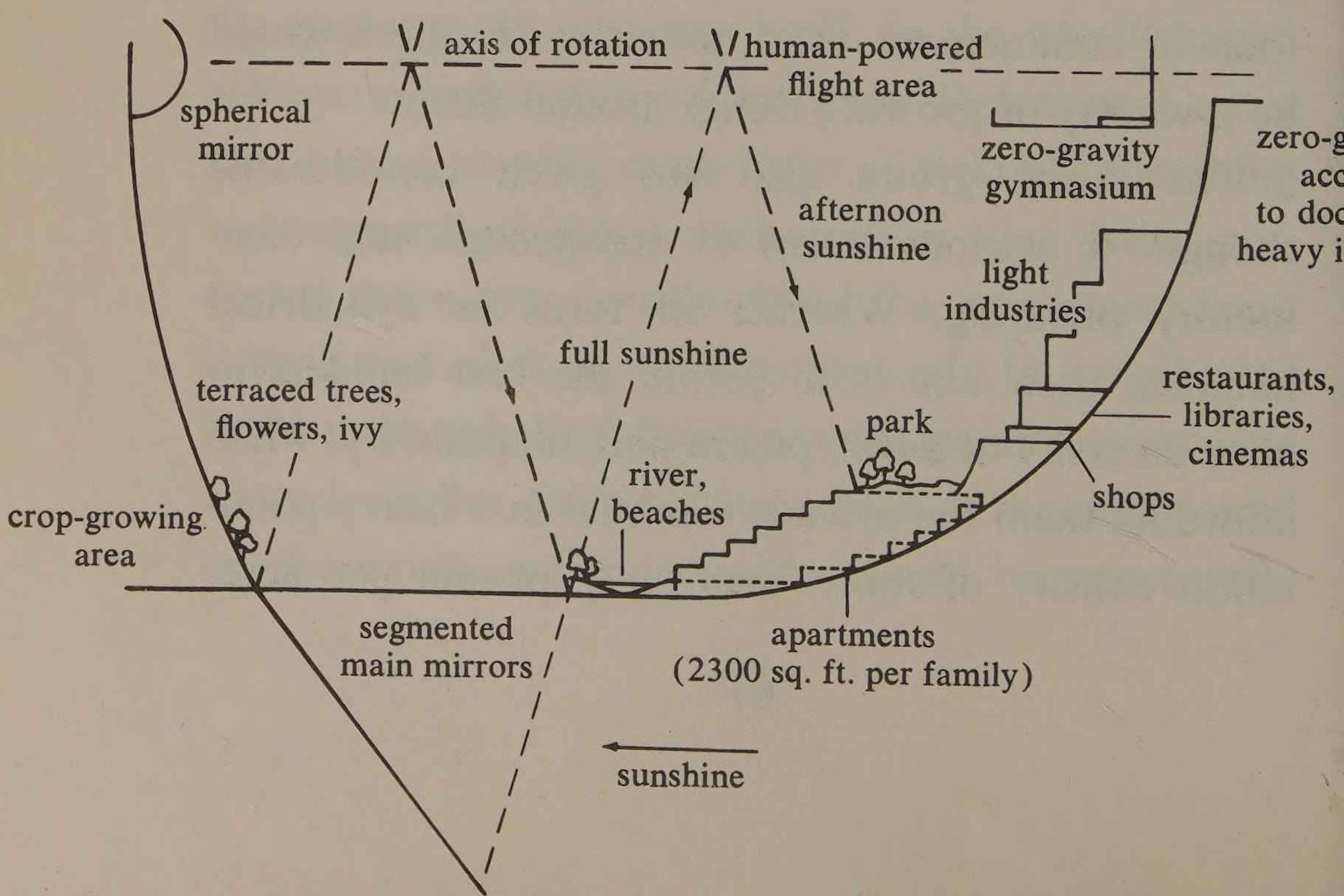
Apart from the purely constructional problems of the first colonies, space scientists have also weighed a few of the human and social factors that will face the first builders. Living in an entirely man-made structure at high initial population densities remote from other human communities could lead to serious psychological problems. Thus, the Ames study group indicated certain standards of esthetic design that would forestall these possible difficulties. For example, if the habitat were constructed so that colonists had lines of sight of at least half a mile, they should then enjoy a feeling of spaciousness rather than of confinement. And, as on earth, there would be a variety of growing things around them.

The Ames group also has given considerable thought to various forms of architecture and community planning. Whether in torus or cylindrical habitats, their aim is to permit the first builders to have diversity of development and adaptability, while affording them the privacy essential in a heavy population density of more than sixty people per acre.

The diagram below shows in cross section how one of four villages contained within a Model 1 colony might be laid out. Each village would have a population of about 2500 colonists.

Although the Model 1 colony would be too small to carry out a broad variety of manufacturing processes, those it could perform would produce a large return in total tonnage. For example, it could conceivably manufacture up to 20,000 tons of aluminum in two years—enough for the exterior structure of another Model 1 habitat. It could also engage in ex-

Cross-sectional view of how one of four villages might be laid out within the first colony.



tracting oxygen from lunar-oxide ores, or to be combined with hydrogen imported from earth to make water for the colony. O'Neill has estimated that with some 50,000 tons of water, a Model 1 colony could have lush vegetation, as well as streams and small lakes. He and his colleagues speculate that once a space-colonization program is under way, the first human colony in space could be established in about twenty years. This schedule would include a three-year "spin-up time"—the estimated time required for the cylinders to rotate fast enough to create the proper artificial gravity for occupants.

The economics of freight transport would probably dictate relatively early in the development of the colonies that the expensive "up" shipments from earth consist only of people and labor-intensive, miniaturized products, such as computers and calculators. The "down" shipments of products destined for earth would be less expensive because of two factors: there would be no necessity for expensive lift-offs through earth's dense atmosphere, and the friction provided by the earth's air would allow an earthbound craft to brake easily for landing. Later, by the time other colonies were established, travel and shipping costs between habitats should be very economical.

During the early years of the program, the Ames group speculated that the number of colonies would grow rapidly, each one serving as a construction facility to build new ones. They also thought that, with the passage of time, habitats would be larger and less densely populated, as the costs of automation-produced parts would become reduced. Eventually, perhaps beginning with later Model 3 types, colonists would begin to exploit the asteroids for carbon, nitrogen, and hydrogen elements, which are scarce on the moon.

Given the diversity of direction in which an individual colony could develop, the colonists sharing these opportunities and adventures in a number of closely interacting habitats would be able to insure their survival and growth, in what once had been the forbidding environment of space.

Chapter Five

# LIFE IN THE COLONIES

What kind of people would the first colonists in space be? The Ames study group judged that they would probably be young and vigorous men and women in their prime working years, with only a small number of children and older people. But as time passed, the population of the colonies would more closely approach the age distribution found in a productive community on earth, with a substantial number of children and older persons. Such a progression would parallel the history of communities—mining towns, for example—in the American West and other frontier areas during their early settlement.

The Ames group also expressed concern that offering high wages to the initial construction workers might not necessarily attract the kind of colonists best suited to long-term space habitation. Rather, the group suggested that these workers be granted certain rights of settlement, perhaps in combination with additional payments for transporting their families to and from earth. In any case, it was thought probable that some kind of screening and selection process for recruiting personnel would be necessary to obtain desirable people. And, as in the colonization of the western United States and Alaska, it was thought probable that some reverse flow would take place of people who find that they are unable to cope with life in space.

If space colonization is carried out as a purely American undertaking, it would seem likely that American cultural habits and customs would prevail. Similarly, if the Soviet Union planned a unilateral space-colonization program, the colonies would develop along existing Russian cultural and political lines. However, should several nations band together and pool their people and resources to build a large community in space, a wider range of culture and mores would result. If, let us say, the United States, England, France, and Germany combined their talents and energies to construct a torus-shaped habitat at $L_5$ at some time in the future, this diversified mixture of peoples and customs would result in colonists adapting to a multinational way of life.

Such an international colony would probably be trilingual, with the offspring of all colonists being taught French, English, and German in the school system. Their colonial government would probably be composed of representatives of all four nations. Yet, while cooperating together closely for the sake of maintaining a well-run colony, these men and women of different terrestrial nationalities would still cling to many of their individual customs and institutions.

Possibly nations may feel that their ideals and destinies could better be fulfilled by settling in space. Densely overpopulated India, for example, might seek aid from other nations to launch its own space colonization program or perhaps offer large numbers of specially trained Indians as recruits to multinational ventures already established in space. The Japanese, now so dangerously overcrowded within the confines of their home islands, might well be among the first to appropriate funds for constructing new homes for their people in space. But whether nations take up residence in space individually or as joint undertakings, the nearly limitless world of space beyond the earth's atmosphere offers man a new frontier, a promise of a new beginning.

Assuming the first colonies established in space are of the O'Neillian type, what would life be like on these twin cylinder habitats? How would the colonists live, and what might they see around them?

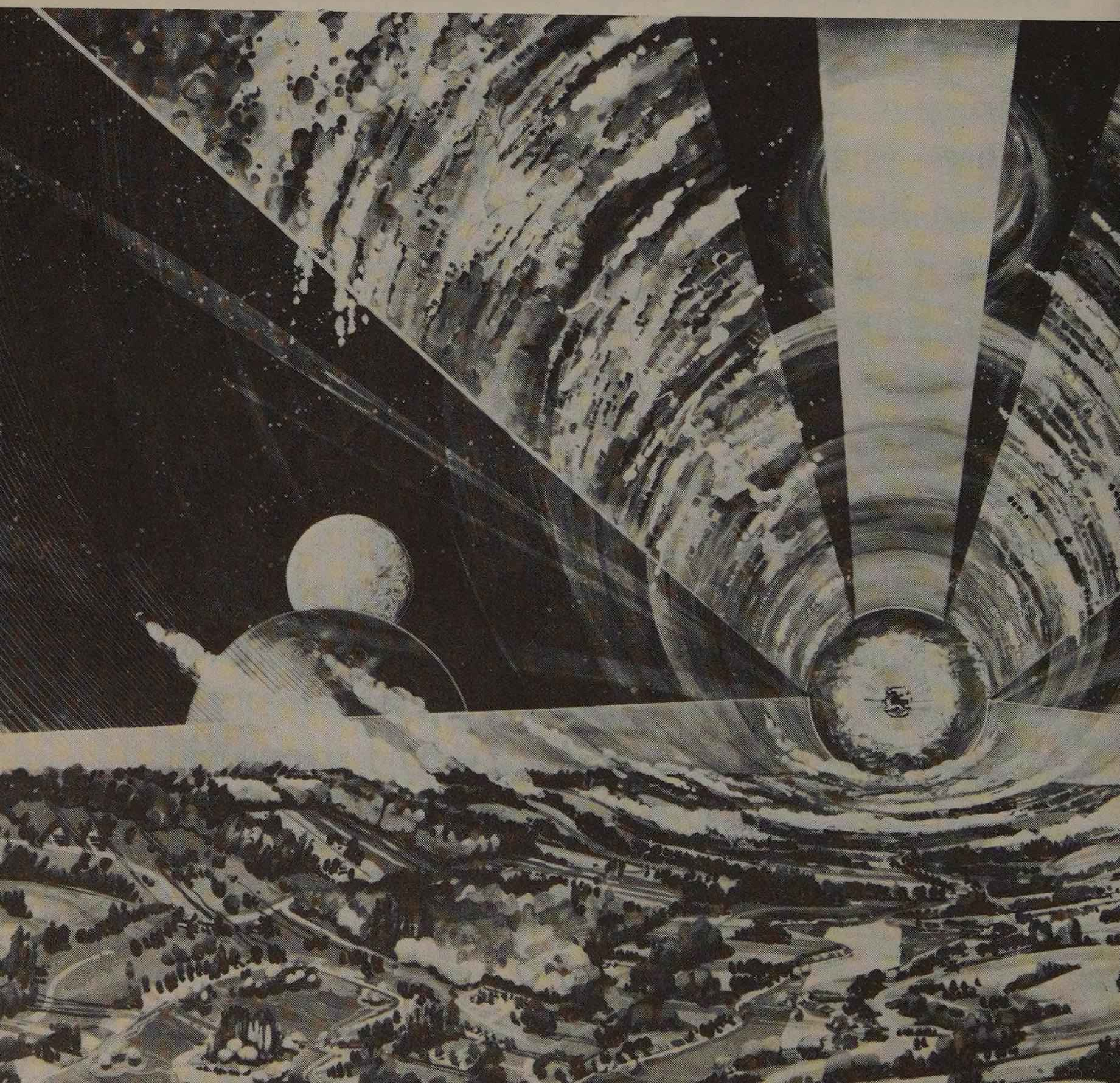
In many ways, the space dwellers would find their life very similar to what it was like on earth. They would feel the pull of gravity on their bodies exactly as it was on their native planet because of the slow rotation of their cylindrical home. This rotation would produce a centrifugal force—a force that tends to impel objects outward from the center of rotation on the long axis of the cylinder, which would in turn press their bodies downward on the inner shell of tube precisely as earth gravity pulled them to the earth's surface. But colonists would not notice this rotary motion, only the sensation of artificial gravity that it produces.

As on earth, the colonists would live in cottages or perhaps terraced, low-rise apartment houses. Outside would be lawns and gardens planted in fertile lunar soil. In a controlled climate, colonists could stroll through parks and woodlands filled with birds and small wildlife brought from earth, fish in a stream stocked with terrestrial fish, or take a swim in a small lake.

There would also be some pleasant differences between life in space and life as the colonists had known it on earth. The air in the habitat would be free of smog and industrial pollution, and no fuel-burning cars or engines would be allowed in the main cylinders.

However, some sights at first would seem bizarre. Perhaps the strangest would be the change in perspective created by living on the inner surface of the rotating cylinder. Because of this inward orientation, all objects would point toward the center core of the cylinder. Thus, people living on one land area would have an "upside-down" view of their neighbors on the

How residents of a Model 4 colony would view their earthlike world in space. Standing on their own 32-mile-square land area, they would see two similar land areas above, where everything would be in bird's-eye-view perspective. Between the two land areas are the three, gigantic glass solars—windows on space. Moon and earth are visible through the solar at left. One of the mammoth mirrors reflecting in sunlight, thereby regulating day and night, and the temperature, can be seen through the topmost solar. At the far endcap mountainous regions are visible, and carefully landscaped villages and parklands stretch away in the distance. *(NASA)*



other two living areas. When looking up, colonists would look down on the roofs of houses located over half a mile across the expanse of their cylindrical home.

Rain falling in all directions at once would be another oddity. As the raindrops condensed from the clouds that would form in the habitat's atmosphere, they would be caught up by the centrifugal force produced by the rotating cylinder and swirled outward, around and finally down toward the inner surface of the cylinder. And as the fallen rain collected in streams and brooks, the flow of water would often appear to be uphill to the colonists looking at opposite land areas a half mile away.

Other fantastic spectacles would also have become commonplace to the colonists. Directly overhead and to the left and right of their own land area, they would see—unless louvered off or blocked by the towering mirrors outside—the three gigantic glass windows looking out into space. Once every half minute or so the bluish atmosphere of earth and the yellow-cratered moon would slide into view, then vanish. Much of the time, however, the great mirrors would be reflecting the sun and angling it into the habitat. But if, as sometimes would happen, the mirrors were turned away from the sun for repair or adjustment, the reflected stars would present a problem, for they would appear to rotate so quickly that the colonists would grow dizzy looking at them.

As for occupations, many colonists would be engaged in the construction industry and would commute from their homes in the main cylinder to the exterior factory pods. There, working under zero-gravity conditions, they would turn out modules and other basic items for new habitats and assemble them in nearby $L_5$-orbital locations. Other colonists would also work at exterior jobs, as supervisors and technicians in research labs, grain farmers in agricultural pods, astronomers in observatory pods, physicians in hospital pods, and as solar-energy physicists stationed on one of the power-generator satellites.

Probably over half the colony's work force would hold jobs outside the main cylinder. In this way all industrial and experimental activities could be separated from the living spaces in the main cylinders so as to keep them as free of pollution as possible.

The products produced in many of these external factories and laboratories would be sold to earth, including some highly sophisticated items that would be easier to manufacture in space. For instance, delicate artificial crystals needed for electronics equipment could be grown more quickly and efficiently in the high-vacuum environment of space. And much of the power produced in the satellite power stations would also be sold to earth, beamed down through the planet's atmosphere by microwaves.

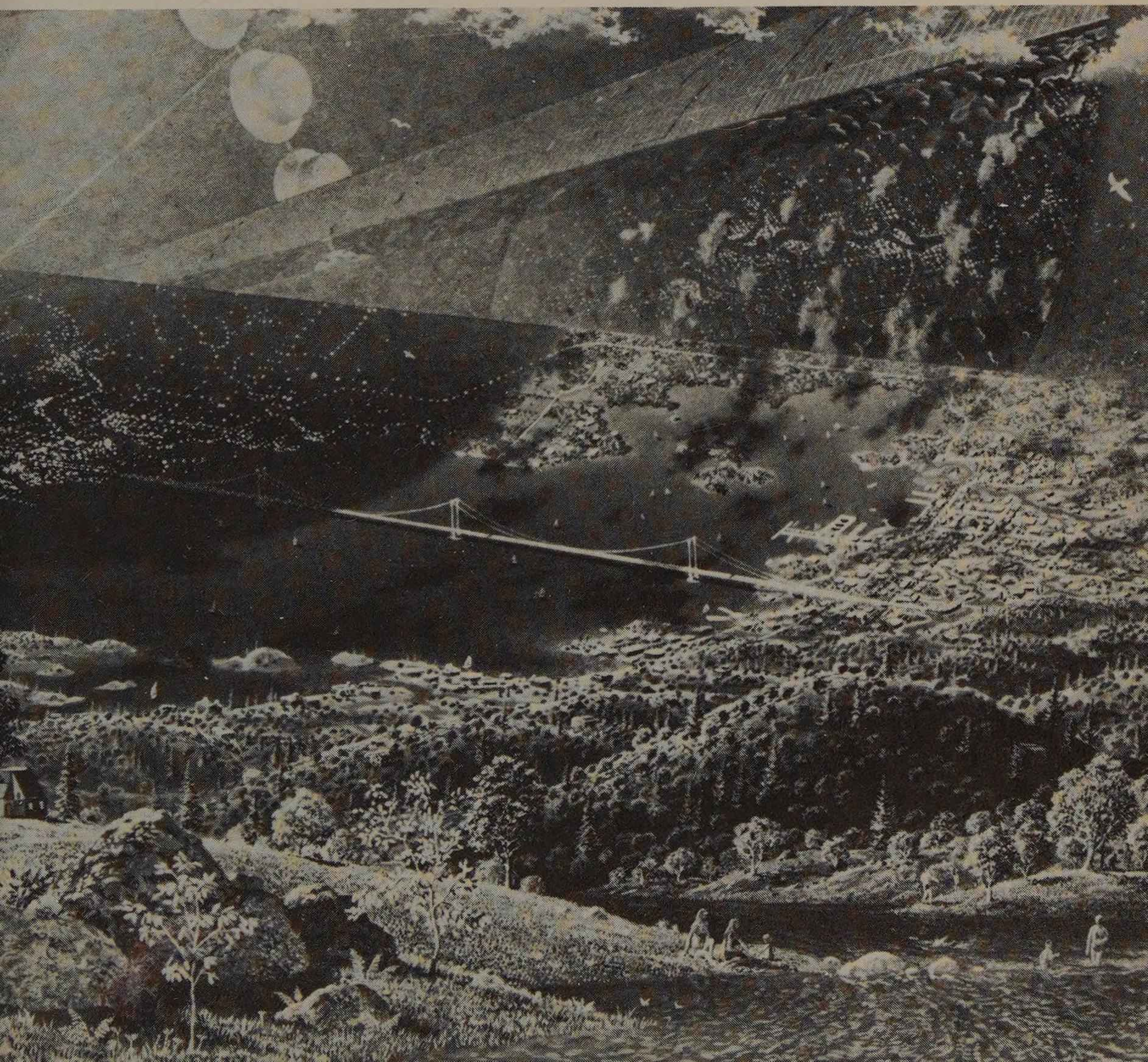
In addition, an active recycling program would always be in operation in the habitats, for it would pay in the long run to break down every waste product into constituent elements. Thus, animal, plant, and human wastes could be daily turned into water and agricultural chemicals through an oxidation-sewage system. This system would combine the wastes with oxygen, changing them chemically into simpler elements, which then would be recombined into needed substances, like water. With such perpetual recycling methods, only small supplies of water and other essential elements would have to be shipped from earth.

The colonists would not lack entertainment. The latest films from earth would be shown at local cinemas, and colonial film makers would produce pictures dealing with life in space. Radio programs could be received from earth, and habitats having transmitting stations could broadcast their own radio and television programs. There would also be restaurants, concerts, and amateur theatrical groups, just as on earth.

Unlike anything on earth, however, colonists could watch ballet in which ballerinas dance with unbelievable dreamlike grace in conditions of one-tenth gravity. On such evenings, colonists might choose to treat their families to dinner in one of the hotels in the nonrotating ring of pods outside the main cylinder. Seated next to the restaurant's spheroid glass windows, they could gaze out into interplanetary space and see breathtaking sights—the moon, earth, Mars, Jupiter, the Milky Way slashing across the sky like a great white scythe, the immense solar generators in orbit around the earth, and the slowly rotating twin of their own cylinder a few dozen miles away.

At one time or another, most colonists would sample the wide variety of sports available to all in the habitat. Here would be everything they could do on earth—plus a few sports that earth could never offer. By adjusting the climate for wintertime conditions, snow could be made to fall for skiing in the

Eventual sizes of large O'Neillian colonies can be conceptualized in this painting by NASA artist Don Davis. On one of the three land areas of this habitat, a city the size and style of San Francisco has been built, complete with a bridge approaching the dimensions of the actual Bay Bridge. Above the city and its rural environs looms the great solar window looking out on interplanetary space. Inside the habitat, picnickers lounge beside a stream; gulls wheel overhead. Outside, the towering reflector-mirror is turned away from the sun to create oncoming dusk. But enough light is still reflected from three of the agricultural pods outside to reveal their presence. *(NASA)*



lunar-rock mountains at the endcaps. In those same mountains, colonists and their families could do some mountain climbing, but the sort that earth conditions would never allow. As the families scaled higher and higher peaks, they would notice their backpacks getting lighter and the going becoming less strenuous. This is because the effect of the centrifugal force created by the spinning of the cylinder would grow less and less on their bodies the closer they got to the central axis, about which the cylinder spins. If the mountain climbers chose to climb to the center of the cylinder, the pull on their bodies would disappear and they would be totally weightless. Yet the air, being of uniform composition and temperature within the cylinder, would grow neither thinner nor colder, as in very high altitudes on earth.

Soaring in gliders would also be possible in the higher altitudes in the habitats. In fact, man-powered flight—a nearly impossible feat on earth—would become ridiculously easy here. Colonists could soar like birds simply by launching pedal-powered gliders from a hillside. Or they could fly with artificial wings made of light plastic stretched over frames. Either way, the lift provided by atmospheric currents and reduced gravity (because of lessened centrifugal force at these altitudes) would keep them aloft until they chose to land.

The phenomenon of low gravity would create unique forms of familiar sports. Divers in low-gravity pools would remain in the air several seconds longer before hitting the water. In the same way, a tennis ball would take seconds longer to reach the other player.

For traveling short distances inside their habitat, colonists would not need fuel-burning cars or powered aircraft. Bicycles and low-speed electric runabouts would be adequate.

If colonists wished to visit their twin cylinder, several miles away, they could hop into a public-service shuttle craft at the loading dock of their habitat. With no air friction or gravity to overcome, these vehicles would need no pilot or engine. They would be engineless because no fuel would be required for free flight through space, and no pilot would be needed because the vehicle would be computer-operated.

These shuttle crafts would unlock from the outer surface of the revolving tube at a preprogrammed instant and be flipped into space at 400 miles an hour.

After a few minutes the craft would lock onto the other cylinder at zero-relative gravity. Each of the twin habitats would always have docking and launching facilities at one of their endcaps for these shuttle vehicles, as well as for long-distance flights arriving from and departing for earth.

Traveling between cylinders via electric cable car would be another possibility. Like the shuttle craft, it would be pilotless and engineless, for it would require no fuel, maintenance, or crew. The vehicle would be accelerated in a computerized direction by a stationary, cable-pulling, electric motor and then, at its destination, decelerated by an arresting cable.

Travel outside the main cylinder to distant colonies, thousands of miles away, would be accomplished by the same engineless, pilotless, cable-type spacecraft used for travel between cylinders. These vehicles would be accelerated to a high cruising speed by a cable at one colony, and after a trip of several thousand miles could be slowed to a halt by an arresting cable at another colony. The simplicity of these vehicles would mean that individuals and families could easily afford private spacecraft for low-cost travel to distant communities. Vehicles of a later colonial age would be roomy, well-furnished, pressurized shells, needing little else beyond a system to provide recirculating air for the passengers.

By the time several hundred colonies had been built, colonists would be attracted to various ones for different reasons. Tourism would become more popular—and infinitely easier—than it is on earth today. Vacations could be spent in habitats offering a variety of climates and settings.

In times closer to our own, however, when colonists would be spending their first decades in space, they might find themselves experiencing periods of isolation in the remoteness of space. They might feel an intense longing and homesickness for earth. Yet the lives of these first generations of space dwellers would be enriched by their shared adventures. Certainly the opportunities for survival and growth, in what once had been the forbidding environment of interplanetary space, would be vast and rewarding.

Chapter Six

# WHAT OF EARTH AND THE FUTURE?

If the space-colonization program advocated by Dr. O'Neill and his colleagues is started reasonably soon and building schedules are held to with reasonable tenacity, what might be some of the logical results of that program? For one thing, as the space communities increased in number, the room available for human beings in them would naturally increase at a rapid rate.

By the middle years of the next century, the rise in emigration to the colonies could begin to reverse the rise in the population of earth. By about the year 2080, O'Neill projects that more than 90 percent of the human population could be living in space. As for earth, the people left there might have dwindled to about a billion—approximately the total population of the planet in the year 1910.

Always assuming that new construction would be going forward, the reduction in population density in the space communities themselves could be equally rapid. After the passage of another forty years, say about the year 2120, ongoing construction could achieve a stable density of about 1.5 people to every 2.5 acres. At that future time, O'Neill believes, the total land area in all the settlements in space would be more than three times that of earth.

By the dawn of the twenty-third century, in that case, what kind of place might earth be? It would probably have become a place largely dependent on, and supported by, tourism. It would be a beautiful place to visit. But, with more desirable living areas available in space, most people would not want to locate there permanently. They would prefer the variety and excitement of the hundreds of space habitats that would be ready for occupancy in that future day.

Devoid of its once-humming factories and industries—most transferred decades ago to various sites at $L_5$—the planet would be slowly recovering from the near deathblow it received as a result of prolonged industrialization. Free at last from pollutants and contaminants, earth would slowly restore itself by natural means to its original pristine condition, before the advent of man.

The sights and sounds of earth would have greatly changed since its bustling heyday in the twentieth and twenty-first centuries. Much of the planet's scarred lands would have been relegated to parkland and wilderness reserves. The traffic on its once-vast networks of highways, many now overgrown with vegetation, would have slowed to an occasional trickle of vehicles. The once-great cities of Europe, Asia, and the Americas, with few citizens to occupy them, would be partially dark at night. The throbbing oil- and coal-burning utilities would be still, except for the low hum of turbogenerators providing electricity beamed by solar power from space. In the air, the whine of commercial aircraft would be rare, but the shuttle spaceports, strategically located around the planet, would be very busy. Every day spacecraft would arrive and depart, picking up or discharging eager passengers from space, looking forward to a relaxing vacation.

Yet the green hills of earth would always beckon men and women home. These future generations of space dwellers would regard their planet with great nostalgia. For them, the earth would remain a perpetual monument to man's origin and history.

# GLOSSARY

artificial habitat—in astronautics, a man-made dwelling place in space.

artificial satellite—a man-made satellite in orbit around a planet or other heavenly body.

asteroids—tens of thousands of tiny planets orbiting the sun between the orbits of Mars and Jupiter.

astronautics—the science of locomotion outside the earth's atmosphere.

centrifugal force—that force which tends to impel a thing, or parts of a thing, outward from a center of rotation.

cosmic rays—radiation always present in space that comes from undetermined sources.

cylindrical habitat—an artificial habitat in space having the form of a long, hollow tube.

endcap—that member of the end of a cylindrical habitat that seals off the cylinder.

escape velocity—the initial speed necessary for a spacecraft to escape the earth and the friction of its atmosphere.

extraterrestrial—not of or relating to the earth.

Lagrangian Points—places in space where the gravitational forces of the moon and the earth compensate one another so that an object is kept fixed, or locked, in position.

longerons—lengthwise steel cables that make up the skeleton of a cylindrical habitat.

meteoroid—a rocky particle in space.

mirror—in an artificial space habitat, the huge reflective surface designed to angle the sun's light into the interior of the habitat.

module—a unit, usually of a larger system.

pods—small cylindrical habitats outside of the main habitat.

prototype habitat—a proposed first artificial habitat that would be a model for later habitats.

Rotary Pellet Launcher (RPL)—a propellerlike device proposed by Dr. Gerald K. O'Neill designed to launch pelletlike payloads of moon ore off the moon's surface.

solar energy—radiant energy continually produced by the sun.

solar power satellite—an orbiting satellite that transmits solar energy, via microwaves, to the earth.

solar system—the system of the sun and the planets, their satellites, the asteroids, comets, meteoroids, and other objects revolving around the sun.

solars—large transparent areas designed to admit sunlight into a cylindrical space habitat.

space colonization—the establishment of colonies of human beings in artificial habitats in space.

space colony—a group of people who leave the planet Earth and establish a settlement in space.

space station—any spacecraft in permanent orbit around the earth in which human beings can live and work.

spherical habitat—an artificial space habitat that has a spheroid form.

terrestrial—of or relating to the earth.

torus-shaped habitat—an artificial habitat that is shaped like a doughnut.

Transport Linear Accelerator (TLA)—a device proposed by Dr. Gerald K. O'Neill that employs buckets on an oval track for slinging payloads of moon ore off the lunar surface.

twin colony—a pair of cylindrical space habitats tethered together.

valley—a large land area spread with lunar soil in a cylindrical space habitat.

zero gravity—in astronautics, the state that prevails at the point or region where the pull of gravity is compensated, or equalized, by centrifugal force, resulting in a sensation of weightlessness.

# INDEX

** indicates illustration*

## ABOUT THE AUTHOR

Born in Glens Falls, New York, David C. Knight received his education both in this country and abroad. After earning his BA degree at Union College, Schenectady, New York, he spent a year at the Sorbonne, in Paris, then continued his studies at the Engineering Institute, in Philadelphia, and at the University of Pennsylvania.

After serving in the U.S. Army during World War II, Mr. Knight worked as an editor and production man with Prentice-Hall. Later he was for sixteen years senior science editor at Franklin Watts. Science has been one of Mr. Knight's major interests, and he has written more than twenty-five books on various scientific subjects. He also has written a number of science articles for the *New Book of Knowledge*.

At present Mr. Knight lives in Dobbs Ferry, N.Y., with his wife and two daughters.

Knight, David C.

Colonies in Orbit

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