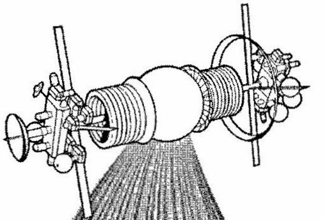

THE HIGH FRONTIER

Human Colonies In Space

3rd Edition

Gerard K. O'Neill

with contributions by
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Presented by
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To the O'Neill grandchildren
Niko
Luke
and Ian

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by Gerard K. O'Neill

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Chapter 4
New Habitats For Humanity

Biologists and botanists talk of the "range" of a species — the limits, on the surface of Earth, over which a species can survive, grow and reproduce. For our ancestors of the remote past, the range was the tropical ocean. It was a major step in the development of living beings when the early amphibians evolved into air breathers. Now, when we are about to design new habitats for man, we must question what limits are set by our own physiology. As we ask those questions, we must be conservative in our answers — we're not asking for extremes: not for the limits that apply to highly motivated athletes in superb physical condition, to mountain climbers, astronauts, or deep sea divers, but for those that apply to quite ordinary people – ultimately, to "Aunt Minnie in her rocking chair." That conservative approach should apply even to the first habitat we build, for a practical reason that has a basis in hard economics: when people are called upon to work under hardship conditions, in miserable climates or exposed to disease, they have every reason to leave their families at home, and to demand high pay for their hardships and deprivations. Pay scales on the Alaskan pipeline construction job have to be very high. Even our first space colonies must pay their way, and they can only do so if they do not price themselves out of their markets. They must be places to which people will come by choice, and to which their families will enjoy coming also — places where it will be possible to live and work and raise children in ease and comfort.

With this conservative approach, we must then ask what constitutes a human environment — what is the "range" of mankind as a species? Most of us are accustomed to living near sea level. A large fraction of humanity, though, in mountainous areas of every continent, lives at altitudes as high as Denver, Colorado, where the pressure is 20 percent lower; and that fraction includes people who are elderly — a slightly lowered pressure doesn't seem to bother them.

The Federal Aviation Agency, to assure that pilots will be in a state of full alertness, requires that oxygen be used for any flight above 12,500 feet lasting more than a half hour. As a sailplane pilot, with my oxygen mask always at hand, I like to take a few breaths of oxygen at the tops of Western thermals, which are often a good deal higher than that. Serious mountaineers, climbing by muscle power and carrying packs, go far higher without oxygen, some to as much as 25,000 feet. Few human habitations, though, are more than twice as high as Denver, and in those few, within the Andes and the Himalayas, the population has adapted through natural selection over many generations to life at low pressure. In space habitat regions where people may be called on to do very light work not lasting more than a few hours, we can take the Federal Aviation Agency's limit as a guide, and for conservatism we should probably maintain in space habitat living areas an oxygen pressure at least as rich as Denver's, a mile high.

As deep sea divers and astronauts have shown, the nitrogen that makes up most of the atmosphere is unused by our bodies. On Earth, nitrogen serves to inhibit flames, and acts as part of our cosmic ray shield, but we do not consume it except through the food we eat. Curiously, neither do many plants: they take up nitrogen through their roots, from the soil, rather than from the air. If we provide some alternative way to inhibit flame and to protect ourselves from cosmic rays, the range of the human atmospheric environment will go as far as an oxygen atmosphere with the same oxygen pressure that is found in Denver. Though astronauts have lived in such atmospheres for several days while on the lunar surface, long-term tests with larger numbers of people will be needed before we can be sure that no respiratory problems will develop.

First we have considered air, the medium without which we would be dead in a few minutes. Next we can think of the range of temperature and climate over which humans can live and work. That range is wide, from the deep freeze of the "Pole of Cold" in Siberia to the heat of the Sahara in midsummer. The range of comfort, and of easy operation without heavy clothing, is much narrower — just the few degrees where we set our room thermostats when we have the choice. Outside that range our efficiency goes down, and the steady migration to regions of mild climate without great variations suggests that the human desire for a comfortable temperature runs deep. We'd better plan on a narrow temperature range for most human activities, but allow for the variations needed for sports like skiing.

With atmosphere and mild climate, we can survive for one or two days. Without water, though, we can't last much longer than that. Nearly all of the mass of our bodies is water, and in desert areas the inhabitants seldom deal with more than a few pounds of extra water per person. We're looking toward a pleasant, not a parched environment however, so we'll be much more generous — for the moment we will think in terms of several tons of water per person.

In extreme conditions people can go for several weeks without food, but in the space communities there will be no difficulty in providing food of a richer abundance, and with greater reliability, than exists over most of Earth. Water and food are not limits on the range of the human species in space.

Zero gravity requires acclimatization, and for some people the adjustment takes several days. All three men of one Skylab crew were ill during the first twenty four hours. Skylab tested a small sample of very healthy human beings for 90 days, and during that time their bodies underwent definite physiological changes: a loss of blood volume, degeneration of certain bones, loss of bone marrow, and a slackening of muscle tone. Those changes were reversed and recovery was complete after some weeks when the men returned to Earth, but the advisability of exposing people to zero gravity for many months without change seems doubtful. It's likely that a heart which has grown used to the easy conditions of zero gravity might be prone to failure when gravity is restored. We don't want to make emigration into space a one-way trip, without the option of return at will.

Curiously, we all have the experience of what amounts to zero gravity every day of our lives. Physiologists have found that bed rest takes the load off the body at least to the same extent as does zero gravity, and that all the same types of degenerative changes occur in the two cases. We know that it is not necessary to be subjected to one gravity all the time — a few hours each day may be quite enough. How much less, we don't yet know, but it seems wise to plan that the areas where people will spend their time when they're not working will be at approximately Earth-normal gravity. Ordinary people won't put up with the Skylab substitute for it, which was an intense program of exercise occupying more than an hour every day. Fortunately again, gravity is easy to find in space: rotation can provide it. On the inside of a hollow, rotating vessel the gravity can be made to be the same as on Earth, and if the vessel is big enough the human body will find the artificial gravity indistinguishable from the real thing.

On Earth, sensitive, delicate organs within the inner ear have evolved to measure changes in the position of our bodies. Although they have their limitations, these organs can detect rotation about any of three axes.

Within a rotating environment, with a rotation period measured in fractions of a minute rather than twenty four hours, our motion sensors can detect the fact that "all is not normal" as far as gravity is concerned. For a number of years, physiologists have conducted studies to find out how difficult it will be for people to adjust to a rotating environment. The principal centers for these studies have been the U.S. Naval Medical Center at Pensacola, Florida and the Soviet space program's ORBIT centrifuge facility in the U.S.S.R. Although there are limitations to the completeness with which such Earthbound tests truly duplicate conditions in space, there appears to be general agreement on the following points: first, almost no one has any difficulty in adjusting to rotation rates of one per minute or less. Second, as the rate climbs above two, three, four rotations per minute and even higher, more and more people find it difficult to adjust — they experience a variety of unpleasant symptoms ranging from motion sickness to drowsiness and depression. Some, though, are able to adapt to rotation rates as high as ten rotations per minute. In the case of a habitat in space, the range of interest is between one and three rotations per minute — high enough to be of concern, but low enough that most of the subjects so far tested have been able to adapt to it, usually within a day or two. For the larger habitats, which will almost surely follow the first small "models," the rotation rates can be kept below one rotation per minute without compromising efficiency of design. For the earliest habitats, economy appears to dictate that a rotation rate of about two RPM be chosen, for Earth-normal gravity, and that the applicants for jobs in the early habitats undergo tests to determine whether they are unusually vulnerable to motion sickness in space. The evidence from United States and Soviet space programs so far is that there is very little correlation between motion sickness as we encounter it in aircraft and boats, and the sort of "space sickness" that may be found when we substitute rotation for natural gravity. On the basis of the tests at Pensacola and in Russia, we can guess that only a few percent of the applicants for positions in the early habitats may find, after a few days or weeks in a low-orbital space station, that they are unsuited to life in space.

We have talked of the necessities of life, but if we are to work and live in space by choice, and enjoy doing so, we will ask for more: the age-old human desires of comfort, good food to eat and good wine to drink, room to stretch our legs, good places to swim and to get a suntan, and variety in travel and amusement. We humans have definite ideas about our needs for enjoyment and amusement, and any successful space community will have to accommodate them.

We evolved as a hunting / gathering species, in the light of the sun, and our bodies need some exposure to it for well-being. Without sunshine, children develop rickets, and without sunshine people tend to grow moody and depressed. Almost surely, the high suicide rate characteristic of the Scandinavian nations is, at least in part, connected to cloudy skies and long cold winters. A successful space habitat will have to admit natural sunshine, and that should not be hard to arrange. In space, remote from any planetary surface, full sunshine is available whenever we want it. But to avoid throwing off our internal biological clocks, evolved in a twenty four hour day, we will need to provide a day / night cycle.

When humans existed in small bands, they camped and always stayed near clear running water. Except for their own smoky campfires, the air they breathed was clean. In our pollution-ridden world, no longer can we take clean air and water for granted — most large rivers are dirty. In a space habitat we should make a fresh start, and set up our industry and economy to keep the air and water clean.

Our Earth is rich in plants and animals, but as industry and the human population crowd environments it is not as rich as it once was. City children become starved for the sight of a tree, and in desert areas the palms of the oases have an importance no dweller in a lush climate can imagine. For our psychological well-being, as well as for the cycling of the oxygen we breathe, we should have grass, trees and flowers. Many animal species are a pleasure to us, and if we move into space both we and they will benefit by our taking them along — perhaps, like Noah's passenger list, two by two. Along with the domestic animals, we will certainly want to bring squirrels, deer, otter, and many others. And birds, and some types of harmless insects for them to eat. In space, though, we have an option that doesn't exist to us on Earth — to take along those species which we want and which form parts of a complete ecological chain, but to leave behind some parasitic types. How delightful would be a summertime world of forests without mosquitoes! Perhaps, too, we can find less annoying scavengers than the housefly, and can take along the useful bees while leaving wasps and hornets behind.

Perhaps because we were originally a hunting and gathering species, the urge to travel and to seek out variety in habitat and environment is deeply rooted in many of us. Now that long distance jet travel has become commonplace, a large segment of the population in the developed nations travels regularly for vacations. Our young people are learning wide horizons at a much younger age than did their parents. Some of the results are unattractive — such as traveling drifters, subsisting on doles from home and roaming the world as what the East bloc nations call parasites — but if we believe in humanity we must also believe that the widening of horizons and the interaction of different lifestyles is, on the whole, a good thing, that it tends to cut away the hostilities and the myths that go with isolation, and so tends to reduce the likelihood of wars. Freedom to travel is precious, and adds greatly to human options. Its blockage by poverty or by dictatorial governments always constitutes a loss. We can be grateful, then, that the technical imperatives of the humanization of space are toward easy travel at low cost. We cannot prevent the occasional abrogation of that freedom by a suspicious or reactionary government, but we can at least make sure that no barriers of poverty or energy shortage act to prevent travel.

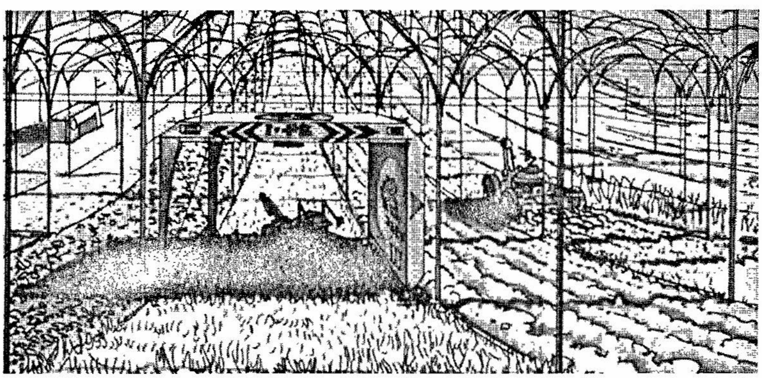
The growing of food is the most vital of all our industries, and now that we are freed of the planetary hang-up we must ask: What are the optimum conditions for agriculture?

An adequate source of clean fresh water must always be at hand. In a space habitat, water once introduced can be recycled indefinitely, given an inexhaustible source of cheap energy.

The uncertainty of the Earthbound climate is the great bane of all farmers — drought, frost or long continued cloudy weather can ruin crops. Worse still, farming has always been subject to the cycle of boom-and-bust: in a good year, every farmer grows too much, and prices drop for his produce, and in a bad year, he has little to sell although prices are high, and the consumer must pay highly for poor quality. In a space habitat, although people may want to live in climates that vary widely, crops should be grown in constant conditions, dependably unchanging from year to year.

Throughout most of the world only a part of the year is suitable for growing, and when winter strikes it stops all farming over a distance of thousands of miles. If we have a choice, we should provide that agricultural areas, in close proximity to each other and to the consumer, have the seasons and seasonal variations that are best for their particular crops. To make sure that our tables have fresh vegetables and fruit in all seasons, our growing areas should be staggered in phase — January in one while there is June in another. Impossible though that is on Earth, it will be easy in space.

On Earth, all of our high yield grains, and all of our fruits and vegetables, are subject to attack from various pests and viruses. Usually, these pests have evolved through centuries to attack certain plants, and on Earth winds and human travel threaten always to spread plant diseases to new areas. In space, it makes sense to start our agriculture with carefully inspected, pest-free seeds, and to introduce only those bacteria essential for plant growth. If our agricultural areas are separated from our living areas by even a few miles, and receive only sterile water and chemical fertilizers, the vacuum of space will serve as a perfect barrier to keep them pest-free. For the first time, we will be able to have agriculture of high yield without pesticides, insecticides, or crop losses due to raiding birds and animals.



Agricultural areas in space can have staggered, controlled seasonal variations so that fresh vegetables and fruit are available year round.

As agriculture has become more and more sophisticated, it has become ever more factory-like. In modern high yield agriculture, the soil in which crops are grown is relatively unimportant; it serves only as a matrix to hold the growing plants. The highest yields are obtained by intense application of chemical fertilizers, and by careful control of trace elements and the acidity of the soil. As the evolution from a pastoral economy to an agricultural industry has gone on, that industry has become continually more energy intensive. The cost of fertilizer production is dominated by the cost of energy.[1] In space a method for the production of fertilizer will become easy, though on Earth it is uneconomical — the simple heating of an oxygen-nitrogen mixture, in a tube at the focus of an aluminum foil mirror in sunlight, to a white hot temperature. At that heat about 2 percent of the molecules will dissociate and recombine to form nitric oxide, an energy rich precursor of chemical fertilizer.

It appears, therefore, that space can provide the ideal conditions for a highly efficient, totally recycling agriculture, no longer at the mercy of weather and climate.

We are examining the needs of an industrial civilization, so we must look toward the conditions in which industry can work efficiently, at low cost, and free of pollution.

Industry is energy intensive, and with increasing sophistication and the continuation of the industrial revolution, that hunger for energy also grows. Here on Earth, where our energy sources are limited, we have come to think of intense energy usage as very nearly immoral. But if we have a truly unlimited energy source, there is no reason to curtail the natural development of the industrial revolution.

Industry uses energy in two forms: electrical and thermal. Thermal energy is used for melting metals, for raising chemicals to temperatures at which they react, and for making ceramics. On Earth most of the fossil fuels that industry uses are burned to provide this thermal energy. In zero gravity, far from a planet, the concentration of the unvarying, intense sunlight of space by very lightweight, inexpensive mirrors can provide all the energy that industry will ever need. A simple reflector the size of a football field, weighing no more than a car, when extended in space can provide a great deal of process heating. To equal it, an Earthbound factory would have to burn a million barrels of oil every thirty years — but the reflector in space will go on supplying that same power at no cost, as long as the Sun shines.[2]

I spoke of the ease of obtaining electric power in large quantities from sunlight in space. We can be more quantitative about it: given an industry in space, at which large turbogenerator power plants can be built, we can expect to build them for about the price of a coal-fired plant on Earth.

The space power plant, running at zero gravity, will need less maintenance than its Earthbound counterpart; even though its turbine rotor and generator armature may have a mass of thousands of tons, they will weigh nothing in zero G, and can be supported, with no direct frictional contact, on air or magnetic bearings which should have an infinite lifetime. The fuel cost for a plant in space will be zero, so the entire cost of power will be that of amortization, maintenance and distribution. In space the industries that use electric power can locate anywhere in a volume, rather than on a flat surface, so they can be much closer to the power plant, reducing distribution costs. Maintenance should be low, because there will be no fuel handling machinery to service and no friction bearings to wear out.

Putting all the numbers together, a turbogenerator plant running on solar energy in space should be able to supply electricity to nearby industries at a fraction of a cent per kilowatt-hour. That figure is lower than the cost of electricity in all parts of the U.S. except where hydroelectric power is available. After amortization, costs should drop to those of maintenance. The cost of power enters into every part of an industrial economy, so in space it should be possible to produce most goods more cheaply than on Earth.

There is an additional component to energy costs, a component whose force we are starting to appreciate — the cost of uncertainty. When the planners of a new industry cannot predict how much electric and thermal power is going to cost at the time a new facility will be finished, they find it very difficult to make the decision to build, and even more difficult to persuade a lending agency to advance the money for construction. In space, that uncertainty will be removed, because fuel costs will be zero and can be guaranteed to remain so for the life of the Sun — several billion years at the best estimate. Lloyds of London should be very willing to insure a new industry against its power costs going up with that kind of backing!

We should examine whether nuclear fission or fusion power on Earth can ever equal the low costs of solar power in a space colony. The answer seems to be, No, Earthbound nuclear power will not compete successfully with solar power in space. First, for all process heating needs, in space a simple mirror with no moving parts, located at the point of use, will be sufficient. On Earth one would have to go through the expensive and inefficient intermediate step of converting from nuclear power to electricity and then back to heat, since nuclear plants cannot be made in small sizes. For electric power on Earth from fusion, we will overlook for a moment the fact that billions of dollars and twenty years of effort have so far failed to make nuclear fusion a practical reality. Even if it succeeds, its cost will almost surely be much higher than those of a solar plant in space. In a fusion plant, one will first have to spend energy to separate the one part in 5,000 of heavy water from ordinary water, then obtain deuterium from it. Then it will be necessary to pass through a stage of complicated, high technology machinery, involving either lasers or giant magnets. In the end, one will have heat — only to put it into the boiler of a turbogenerator plant. The space borne solar plant will bypass all the hard part of this complicated sequence because it will begin with free solar energy. Finally, the distribution costs in space will be far lower, because distances from power plant to industry will be only a few miles, and because solar electric plants, unlike nuclear stations, can be made in small, convenient sizes adjacent to heavy power users.

In addition to the advantages of zero gravity for the handling of massive objects, for the heating of materials to high temperatures without the contamination of confining crucible walls, for the formation of uniform mixtures of heavy and light materials[3] and for the growing of large single crystals, industry in space will have an additional degree of freedom. By gentle rotation, it will be possible to maintain very thin surfaces accurately in the form of cylinders and cones. That may be especially useful in the case of large mirrors made of thin foil.

Here on Earth our lowest cost transportation is that of crude oil in supertankers. Though the rates fluctuate wildly, tanker construction being about as speculative as pulling the handle on a Las Vegas slot machine, the bare operating costs amount to about 0.06 cents per ton-mile.[4] For shipment of commodities in bulk from one space colony to another, at a speed typical of highway driving on Earth, a tanker-size payload can simply be put in one large motorless container, and accelerated by an electric motor and cable to its drift speed. No crew need go with it, because in the vacuum of space its trajectory and its time of arrival will be known exactly, and there will be no weather or navigational hazards to contend with. The energy cost of such a shipment will be absurdly small — only about a thousandth of the cost per ton-mile that a supertanker works for on Earth.

Commuting to work from a space colony should be correspondingly easy and inexpensive. The typical vehicle can be a sphere, protected from cosmic rays by a dense, foot thick outer shell. It may contain seating on three levels, and be entered by three airliner-type doors. With a comfortably generous amount of elbowroom and leg room for each passenger, about like those of first class seating on a long distance airliner, the sphere can accommodate a hundred passengers. In less than a half minute, an electric motor and cable can accelerate the sphere to the speed of a jet plane, and the flight to a factory a hundred miles or so from the colony will take only a few minutes of vibrationless flight. Just time enough to skim the morning news, and an arresting cable will slow the sphere to its destination. The energy cost? Less than fifty cents per passenger.

Each time the balance is tipped for a particular industry, so that production in space becomes cheaper than on Earth, we will be relieving Earth in two ways: we will be removing the burden of energy usage and materials mining for that industry, and we will be generating an additional force to draw away population — the work force of that industry, and the families of the work force. For many years, the only industries in space that will compete directly with those on Earth will be industries that require no material shipment of material products back to Earth. There are at least two of these: fabrication shops to produce satellite solar power

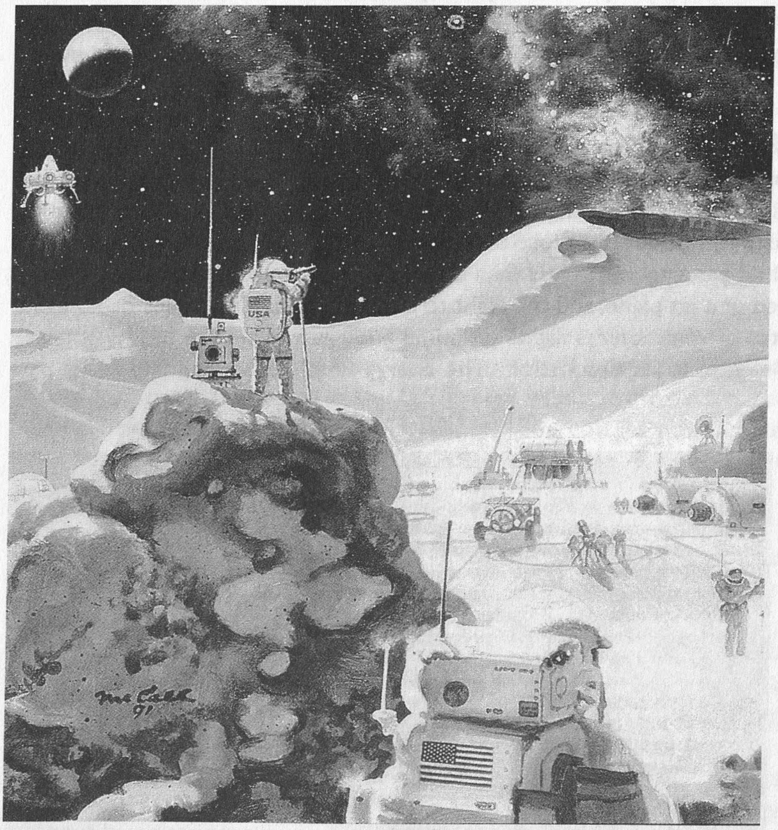
One of the first large-scale space industries will be solar power satellites to relieve the burden on the world's dwindling energy sources and associated ecological damage.

stations, for location in geosynchronous orbit above a fixed point on Earth's surface to beam down power for Earth's electric systems; and assembly plants for the aerospace industry, building ships for transport among the colonies and from Earth out to the colonies.

For energy in the United States alone, we now burn literally billions of tons of irreplaceable fossil fuels every year. From a conservation viewpoint, it makes little sense to blow away this oil and coal in the form of smoke. It should probably be conserved for use in making plastics and fabrics. That environmental consideration, reinforced by a powerful economic drive, suggests the construction of solar power stations for Earth as perhaps the first major industry for the space colonies.

Within the colonies themselves, no conflict need ever arise between using carbonaceous materials for energy and using them as they should be used: for the petrochemical industry. As we have seen, the cost of solar power in a space colony will be so low that it will be ridiculous there to obtain energy in any other way.

For the continued growth of wealth, a developing economy must have an assured source of materials. On Earth, we are already forced to work poorer sources to obtain our metals. For iron in the United States we have long since depleted the Mesabi range in upper Michigan. As we work poorer veins, the conflict of mining with the environment rapidly becomes more serious. When the ore content is only a tenth of that in a rich vein, we must mine and process ten times as much material to get the same quantity of the metal we seek.



Raw materials mined from the Moon can provide most of the necessary resources for space manufacturing and construction.

In space, our first mines will almost surely be on the Moon. Particularly on the lunar Farside, enormous quantities of materials could be removed without ill effects of any kind. It comes as a surprise to most people to learn how rich a source of industrial materials the Moon is. I believe that in the long run the Apollo Project, much criticized as it was during its lifetime, will be seen to have been of enormous value for its lunar prospecting function. A typical Apollo sample contains, by weight, more than 20 percent silicon, more than 12 percent aluminum, 4 percent iron, and 3 percent magnesium. Many of the Apollo samples contained more than 6 percent titanium by weight. Titanium is in great demand as a strong, light metal, which holds its strength up to a very high temperature. Its present use is mainly in the aerospace industry. Processing it requires high vacuum, high temperature, and a lot of energy — all things which are expensive on Earth but will be cheap in space. Finally, the lunar surface is more than 40 percent oxygen by weight. Strange to think that such a lifeless, sterile landscape contains, locked in its soils and rocks and waiting to be used, the one element we need most to sustain our lives.

In the "long" run, within one or two decades after the human use of space begins, we will begin to exploit the resources of the asteroid belt. For transport in space we must think in terms of energy rather than distance, because travel in space is without atmospheric drag. To bring a ton of material, efficiently, from Earth's surface to the site of a space community would cost about the same, in energy, as to bring that ton of material to the same point from the asteroid belt. The difference is that lifting it from the surface of Earth requires a rocket able to supply more than a ton of thrust, and further requires elaborate fast acting control systems operating with split-second precision. By contrast, moving a load of freight from the asteroids to the colonies can be done in a leisurely fashion, with efficient, low thrust engines. If the engines break down, there will always be plenty of time to fix them, just as a freighter on Earth's oceans can lie dead in the water for days if need be while its engines are being repaired.

Bringing materials from the lunar surface to the site of the space communities will be even easier. The energy cost per ton will be only about one twentieth as much as for shipment from Earth or from the asteroids. As we shall see in later chapters, materials can be brought from the Moon at an initial cost of only a few dollars per kilogram. Later, when space borne industry is well established, the ultimate costs should drop to only a few cents per kilogram.

The Moon is poor in three elements that we need for life and for a full industrial base: hydrogen, nitrogen, and carbon. Apparently, during its lifetime the Moon was subjected to baking at a very high temperature. Fortunately, it has been shown by analyzing the spectra of sunlight reflected from asteroids that some of them are rich in carbon, nitrogen and hydrogen — they are about as good a source for petrochemicals as oil shale.[5] Corroborating evidence for the presence of these elements in the asteroids comes from about twenty meteoroids found on Earth's surface; of a type called "carbonaceous chondritic." The normal economic decisions that govern industrial operations will therefore probably lead to mining the lunar surface for most elements, and the asteroids only for the materials which the Moon lacks. Long before an appreciable fraction of the lunar surface has been mined, it will become easiest to obtain all the materials for colony construction at the asteroids themselves.

Although the total volume of the asteroids is far smaller than Earth's, it is a volume much more accessible than the depths of our planet. On Earth only a thin skin of material is available to us without deep mining under high pressures and intense heat. Even if we were to excavate the entire land area of Earth to a depth of a half mile, and to honeycomb the terrain to remove a tenth of all its total volume, we would obtain only 1 percent of the materials contained in just the three largest asteroids. A striking contrast: we would have to disfigure the entire Earth to obtain only a hundredth of the material contained in three now useless, lifeless asteroids — and there are thousands of those minor planets. Moreover, to bring material into space even from the biggest asteroids requires climbing a gravitational hill only five to ten miles high, instead of Earth's 4,000 miles.

As a reader of science fiction in childhood, I gained no clue that the future of mankind lay in open space rather than on a planetary surface. Later, when logic and calculation forced me to that conclusion, I searched for evidence that others before me had come to the same realization. More than five years after my studies on this topic began, I found the references I needed. A friend obtained for me copies of two books, out of print in their English editions, by the self-educated Russian scholar Konstantin Tsiolkowsky.[7,8] Born in 1857, Tsiolkowsky wrote pioneering works on reaction motors, multistage rockets and many other basic concepts of the space age.

Tsiolkowsky's novel *Beyond the Planet Earth*, written at the turn of the century, serialized, and finally published in book form in 1920, is a thinly veiled treatise on basic physics. As such it is short on characterization, and should be read for what it is: a daring but logical feat of the imagination. At a time when transportation was still almost exclusively horse drawn, it required a bold thinker indeed to speak casually (and accurately) of the necessary orbital speeds of kilometers per second.

As a novelist, Tsiolkowsky could skip lightly over the problems whose solution he could not then see — the rocket on which his voyagers lift off from Earth is powered by a mysterious explosive of a nature left unexplained. But the circumstances of the flight show surprising parallels to our present predicament on Earth. Tsiolkowsky postulates an Earth on which a growing population is beginning to feel the ecological limits. His travelers visit the Moon only incidentally; they realize from the start that the place for settlement is well away from any planetary surface:

> "Meanwhile the new colonies, five and a half Earth radii or 34,000 kilometers away, grew and were peopled. Mansion-conservatories of the type we have described were filling up with fortunate men, women and children. . . ."

They see the advantages of free space for establishing gravity convenient for particular tasks:

> ". . . nothing could be simpler than to create it artificially, you see, by rotating the house. In space, once you start a body rotating, it goes on rotating indefinitely, there is no effort involved; so the gravity is also maintained indefinitely, it costs nothing. Moreover, the amount of gravity depends on us; you can make it lower than terrestrial gravity, or higher."

On their first flight, Tsiolkowsky's travelers foresee accurately many of the possibilities of industry and habitation in space:

> "The space around the Earth which we can use — assuming we count only half the distance to the Moon — gets a thousand times more solar energy than the Earth . . . it only remains to fill it with dwellings, greenhouses — and people. By means of parabolic mirrors we can produce a temperature of up to 5,000 degrees centigrade, while the absence of gravity makes it possible to construct mirrors of virtually unlimited size, and consequently to obtain foci of any area we choose. The high temperature, the chemical and thermal energy of the Sun's rays, not weakened by the atmosphere, makes it possible to carry out all kinds of factory work, such as metal welding, recovering metals from ores, forging, casting, rolling, and so forth."

Sensibly enough, the travelers spend much of their first voyage in a search for usable asteroids. As a novelist, Tsiolkowsky has no difficulty in filling the asteroids with gold, platinum and diamonds, but in our more practical day we will be glad enough to find there such homely elements as carbon and hydrogen. Of all the prophecies Tsiolkowsky made during his long life, I am glad that one in particular was selected for the obelisk marking his grave in Kaluga:

> "Man will not always stay on Earth; the pursuit of light and space will lead him to penetrate the bounds of the atmosphere, timidly at first, but in the end to conquer the whole of solar space."

Chapter 7
Risks And Dangers

Almost every human activity carries with it some element of risk. Occasionally, in a rare macabre frame of mind, I have reflected on the fact that at any time almost every human being, however healthy, is within one or two minutes of death if the wrong combination of circumstances were to come to pass. When I lecture on the topic of habitats in space, it is natural that some of the questions that follow relate to the possibility of violent catastrophe in a space community. Given the fragility of life, that possibility will always be there, so we must be quantitative and estimate the risks that will attend the human settlement of space. It's reassuring to find that in fact they are rather less than those to which we are exposed every day here on Earth.

Almost invariably the first question that is asked about space habitats concerns meteoroids. These are, for the most part, grains of dust which have been in the solar system since its formation several billion years ago. As our Earth revolves around the Sun each year we travel at a near constant speed of about thirty kilometers per second — higher than any of the relative speeds needed for launching a satellite or traveling to L5, or even for voyaging to an asteroid. Most of the grains of dust which we encounter in our annual passage around the Sun are moving relatively slowly, so typical relative speeds with which we meet them are just our own. Almost the highest speed meteoroid which has ever been measured corresponds to a dust grain moving in a circular orbit around the Sun, but in a direction contrary to our own; combined with our own velocity that gives an encounter at doubled speed.

Most of these meteoroids are of cometary rather than asteroidal origin, and can be thought of as dust conglomerates, possibly bound by frozen gases.[1] If present scientific ideas are correct, therefore, a typical meteoroid is more like a mini-snowball than like a rock. Even a very small meteoroid carries, because of its velocity, a great deal of energy, but fortunately almost all meteoroids are of microscopic size. In the frequency curve of their occurrence, as the size increases their number goes down rapidly. Spacecraft sensors have collected abundant and consistent data on meteoroids in the range from one gram (that is about one thirtieth of an ounce) down to a millionth of a gram.[2] Above that size, there is so small a chance of finding a meteoroid that even in a voyage of years a spacecraft records almost no data.

For relatively large meteoroids, the series of Apollo flights has left us with a scientific legacy especially important for just this question — the Apollo seismic network, a series of very delicate seismometers left on the Moon. These instruments continued to record for many months after the flights which installed them, and they have recorded not only Moonquakes but the collisions of meteoroids with the lunar surface. So sensitive are these machines that their builders claim to be able to detect every strike occurring anywhere on the Moon by a meteoroid of soccer ball size or larger. Fortunately these two independent means for measurement of the meteoroid size distribution agree quite well, and allow us to estimate with some accuracy the chance of a strike on a space habitat, for a meteoroid of any given size.

There is a third method for the measurement of meteoroid size distribution. It is ingenious and relatively inexpensive: an array of wide angle cameras, forming a pattern which is called the "Prairie Network" is distributed over about one million square miles of lightly populated farming states in the central part of the United States. When a meteoroid enters our atmosphere, leaving the luminous trail which we call a meteor, the Prairie Network sky cameras photograph the trail with such accuracy in space and time that the position, altitude and velocity of the meteor can then be calculated. Some of the best measurements of speed distributions come from data of this kind.[3] Unfortunately, it is much harder to obtain from that source accurate figures on size distributions. Those have to be based on the brightness of the trails observed, and then on a crucial assumption: how much of the energy of the incoming meteoroid is converted to heat and light.

The Prairie Network data agree with those of the other two methods quite well for meteoroids the size of a marble. They aren't in such good agreement for the larger or smaller ones, probably because of the assumptions made about luminous efficiency. If one assumes, as is consistent with the most common modern view, that the typical meteoroid is a dust conglomerate, then the efficiency of conversion of the incoming energy to heat and light should be rather high. With that assumption the camera data agree better with those of the other two methods than they do if a low efficiency is assumed.

Averaging the data from what seem to be the most reliable sources, one finds that in order to be struck by a meteoroid of really large size, one ton, a large Island Three community would have to wait about a million years. Such a strike should by no means destroy a well designed habitat, but it would certainly produce a hole and cause local damage.

In order to find meteoroids that would strike at a frequency high enough to worry about, we have to consider much smaller sizes, of about the weight of a tennis ball. On one of the big communities, there'd be a strike by one of those about every three years. Curiously, there is a reason why a habitat of given size would be struck less often than an equal area at the top of Earth's atmosphere — the gravitation of Earth is so strong that it "sweeps out" meteoroids, sucking them in from a region of space much larger than its own area. The space habitats, far enough away from Earth not to be in the affected region, and having almost no gravity of their own, would be stuck relatively less often.

The most vulnerable parts of a habitat will be its windows. They will occupy a large area and, being made of glass, will be relatively fragile. They will naturally be subdivided into small panels, for two reasons: to guard against the possibility of catastrophic damage, and to allow the aluminum, steel, or titanium supporting structure to carry all the structural strength in the window regions. A window panel may have an area two or three times that of a window on a jet aircraft. With such a size, the metal frames that carry all the structural loads can be so thin that they will be invisible from a valley floor, and the windows will appear continuous when viewed from that distance.

For panels of that size, the loss of one will certainly not be catastrophic for the community. For what we have called Island Three, if one panel were blown out entirely it would be several years before the atmosphere would leak out. Detection of a blowout should be almost instantaneous — it would result in a plume of white water vapor, condensing to ice crystals in vacuum, visible from the sister habitat. If a patch were put on the blown out panel within an hour, the loss of water vapor would be economically tolerable (the oxygen would cost far less to replace) and probably no one but the repair crew would even know of the event.

Even for the smallest community, Island One, the corresponding numbers would be quite tolerable. There it would be several thousand years between strikes by a meteoroid big enough to break a window panel. When a panel blew, if it were patched within an hour the loss of atmosphere would reduce the pressure by only about as much as we would find on Earth in climbing a hill two hundred feet high — not even enough for us to detect a pressure change on our eardrums. For the most recent design of Island One, these risks would be further reduced by a large factor. We now assume a design in which heavy shielding, provided for cosmic ray protection, would protect the window areas from any direct "view" of space.

At the surface of the Earth we are exposed to radiation from three different sources: emanations from the soil, rocks, bricks, and other structures which make up our environment; radiation from small quantities of radioactive substances within our own bodies; and cosmic rays which penetrate our atmosphere. Radiation is measured in units of Roentgens, and for biological damage the unit rem (roentgen equivalent man) takes account of the differing amounts of damage done by radiations of various kinds. For total dosage over a period of time, the unit is the rad (radiation dose). On Earth's surface the amount of radiation to which people are exposed varies over an enormous range, depending on where they live.

Oddly enough, most of the radiation the average person gets comes from inside — trace amounts of radioactive elements in the body. The radiation from outside depends on such details as whether one lives in a brick house (bad) or a wooden house (good). Most of all, though, it depends on geographical area. In the monazite sands region of India the residents get a natural dose of almost one rad per year.[4]

By comparison, our normal dose from cosmic rays is relatively small — least of all at sea level near the equator, but still only a small fraction of a rad per year for a mountain elevation in a temperate latitude. At the poles it is much higher; the latitude differences arise from the fact that Earth possesses a magnetic field which provides it with a substantial amount of protection against the lower energy cosmic rays.

When all the sources of natural radiation, internal, external and cosmic, are added, they amount to an average dose of about a third of a rad per year for a typical Earth dweller. After a great deal of testing and years of discussion, to which many physicists and biologists contributed, the Atomic Energy Commission (in the days long before it was called ERDA) settled on an allowable annual dose for its workers of five rad per year, and of a tenth that for the total U.S. population.

Clinically, only the most sensitive and delicate laboratory tests can detect effects in humans from average radiation of less than about twenty rad per year, and far larger average exposures are required before a human individual is aware of any consequent illness or discomfort.

In space, far from the protective shield of Earth's magnetic field, the level of steady, highly penetrating cosmic rays (the so-called primary galactic radiation) is about ten rad per year. If there were no other radiation to consider, it would be reasonable to consider building the first space habitats with no shielding at all.

If a large fraction of the world population were to live in those conditions for many centuries, we should be concerned about the resulting increase not only in cancer but in the rate of mutations. That would not occur, though — the buildup in the size of habitats to the point of thorough shielding would take place over at most a few decades of time, and during that brief time only a small segment of the human population would be exposed to enhanced radiation levels.

There is however a more serious cosmic ray problem, arising from a type of radiation to which we are never exposed on Earth. These rays are the "heavy primaries": nuclei of helium, carbon, iron and the whole range of elements found on Earth. They form only a tiny fraction of the total cosmic radiation, but they are far more damaging than the rest.

When heavy primary cosmic rays pass through material, they leave a dense trail of ionized atoms. These atoms are highly active chemically, and are so numerous that in living cells they cause cell death. The same property of intense ionizing power which is responsible for the biological damage done by heavy primaries is also a protection against them — in our atmosphere they lose energy so quickly by ionization that they are absorbed at high altitudes, never penetrating to sea level.

The only direct human experience with heavy primaries has been that of the Apollo astronauts, who ventured outside not only the atmosphere but also the protective magnetic shield of Earth. In that open region they observed flashes of light, visible especially when they adapted their eyes to total darkness. Most scientists who have studied the subject agree that these light flashes were almost certainly caused by heavy primaries. On Apollo 17 a systematic study was made of this effect. When I asked Dr. Harrison (Jack) Schmitt, who went to the Moon as an Apollo 17 scientist-astronaut (and later was elected U.S. Senator from New Mexico) about his observations, he reported an odd fact: although the light flashes were visible at a rate of one every few minutes throughout most of the voyage, during the period of one deliberate experiment none were seen for an interval of an hour or so. At present no one has come up with a good explanation for how they could have vanished, even temporarily.

On Apollo 12 the astronauts were exposed to the heavy primaries for about two weeks. Estimates based on direct radiation measurements and the known sizes of body cells suggest that during that period their loss of brain cells was a few in a million. A similar figure holds for retinal cells, and for the very largest body cells (neurons) the fraction is perhaps as much as one in ten thousand.[5] These are small numbers, but there is still reason for concern about them — the cells involved are nerve cells, and as such are not replaced by the normal body repair mechanisms. We have then one "data point" which we could take as conservative for our further calculations: the Apollo 12 crew was exposed to a certain known dose of the heavy primaries, and suffered no apparent ill effects from them. To be on the safe side, therefore, our design of even the first space habitat should be based on the requirement that in a working career of several decades a human being would be exposed to a total dose no greater than that which was received in only two weeks by the Apollo 12 astronauts.

Occasionally, for reasons we are only slowly coming to understand, the Sun emits sudden bursts of radiation called flares. These rays travel almost as fast as light, and reach Earth within minutes. When they do, they cause brilliant auroral displays in the upper reaches of our atmosphere. Very rarely, every few decades, particularly intense flares occur, which saturate Earth with radiation, temporarily blank out much of our long distance radio communications, and even affect Earth's magnetic field. Such an event last occurred in the 1950's. If there had been astronauts on their way to the Moon at that time, they would almost surely have been killed by that flare. Therefore, even the first space community must be protected against solar flares and heavy primaries. This could be done by passive shielding, using lunar surface material or the slag from the industries of the early colonies. The thickness required would be some fifty centimeters (twenty inches) of sand or its equivalent. That would be enough to increase noticeably the required mass of Island One.

The effect of that shield thickness, oddly enough, would be to enhance to an unacceptable level the radiation from the galactic primary rays. The reason is that on encountering dense matter those particles would break up into many more, of lower average energy but much greater total numbers.

In the end, then, we must do the entire job and get rid of all three components of radiation. When the numbers are worked out, we find that the shielding needed is substantial — equivalent to about two meters (over six feet) of soil. Once that problem is thoroughly understood, it constitutes a serious restriction on the design of the first habitats. Fortunately, a geometry has been found that fully satisfies even the most severe shielding requirement, without sacrifice of desirable design features.

The later space communities, of the size of Island Three or larger, will have atmospheric depths and thicknesses of structure below the ground great enough that they will afford to their inhabitants protection from cosmic rays comparable to that of Earth. Their building materials, the lunar soils, are already known to be fairly similar to those of Earth in natural radioactivity.[6]

To summarize, with proper design, both the early and the later space communities can be shielded against all types of radiation to levels comparable with what is found here at the surface of the Earth.

In order to minimize costs, probably the early habitats will have atmospheres composed mainly of the material most plentiful on the Moon: oxygen. The National Aeronautics and Space Administration has reason, though, to be apprehensive about pure oxygen atmospheres. In 1967 three prospective Apollo astronauts died in a flash fire in an Apollo module at Cape Kennedy, during a test conducted in pure oxygen.

The conditions of a space community will be different in several ways. First, the oxygen pressure will be only one fifth as high. At the Cape in 1967 the disastrous test was conducted with oxygen at the full sea level pressure which is normally made up mostly of inert nitrogen. Second, the volume of a habitat will be millions of times larger than that of an Apollo module, so that any small fire which starts within it cannot build up the gas pressures which were destructive in the Apollo test.

Possibly, though, these two differences will not be enough. To be on the safe side we want an additional security factor. One approach is to add a special component to the atmosphere, something that is harmless to humans but that either would not support combustion, or would actively damp it. We should first consider obtaining a damping gas from lunar materials. On Earth, fires are partially damped by the presence in our atmosphere of nitrogen. The lunar surface materials are known to contain small amounts of volatile gases, so that in processing a million tons of lunar materials a few thousand tons of gases will be evolved.

Their composition is not as accurately known as we would like, but it is thought to be mainly carbon dioxide, nitrous oxide and a small percentage of water. We might be able to get a useful amount of nitrogen from that source. It doesn't seem likely, however, that nitrogen will be a very effective fire retardant. Even if we find a cheap source for adequate quantities of it (which seems unlikely), we cannot put much nitrogen into the space community atmosphere without raising the pressure enough to increase the habitat structural requirements.

There are gases which are harmless to humans at least for short times, but which actively retard fires; some of the freons have this property. But these are chemicals made of elements not all of which are found on the Moon, and we lack adequate data on their long-term physiological effects.

It appears now that the simplest solution would also be the best. To maximize the day-to-day pleasures of life in the space colonies, as well as their safety, it seems wisest to bring along from Earth enough hydrogen so that the atmosphere will have a comfortable relative humidity, and so that there will be plenty of lush green vegetation. Structures there will be made of non-burning materials, similar to brick or cinder block on Earth, so with a combination of reduced atmospheric pressure, large total volume, and plenty of water the fire danger appears reducible to an acceptable level. This is an area in which actual laboratory research here on Earth will be required before the answers are certain.

With regard to war we must be speculative. I hesitate to claim for the humanization of space the ability to solve one of mankind's oldest and most agonizing problems: the pain and destruction caused by territorial wars. Cynics are sure that mankind will always choose savagery even when territorial pressures are much reduced. Certainly the maniacal wars of conquest have not been basically territorial. When Genghis Khan conquered most of Europe and Asia he had no plan in mind for the conquered lands, and therefore simply destroyed their cities and murdered their people. Yet the history of the years since the second world war suggests some changes relative to the past. If anything, warfare in the nuclear age has been strongly, although not wholly, motivated by territorial conflicts — battles over limited, non-extendable pieces of land. It appears that the territorial drive to conquer someone else's land should be muted under the conditions of the space communities. They will be free of the age-old associations which fuel territorial wars on Earth, they will be replicable so that no one need feel constrained by a fixed boundary, they will be independent of each other for their essential needs, and they will be movable. In the long run, when new habitats may be built most economically at the asteroids themselves, upon completion their residents will have a choice: to move, by low thrust engines over a period of decades, to an area in which other, culturally congenial communities are already located, or — go the other way.

From the viewpoint of international arms control, two reasons for hope come to mind. We already have an international treaty banning nuclear weapons from space, and the space communities can obtain all the energy they could ever need from clean solar power. The temptations presented by nuclear reactor by-products need never exist in space.

From the viewpoint of a military man, the space habitats will seem rather unpromising as sites for weapons or military bases. First of all they will be quite vulnerable militarily, so that no one in such a habitat can be tempted into believing that he can attack someone else without risk to himself. Second, their distance from Earth, and their consequent separation from it by at least one or two days of travel time, will mean that they can never be used as effective sites for an attack on the home planet. In summary, the probability of wars between the habitats seems, to me at least, considerably smaller than that of wars between nations on Earth.

At lectures on space communities, an occasional question concerns the possibility of attack on a colony from within, by some insane person or extremist group bent on mutual annihilation. The possibility is there, at some level, but probably it will carry with it some safeguards of its own. I suspect that many habitats may choose to have some sort of "customs inspection" which would eliminate or greatly reduce the likelihood that explosives or weapons could be introduced into them. In the past years on Earth we have come to take inspections of this kind as a matter of course at all airports. If, in spite of such precautions, a terrorist were somehow to import or manufacture explosives, he would have to do so on a fairly large scale to produce a major catastrophe. Like airplanes, bridges, and ships, the habitats will be designed so that loss of a single supporting band, or of a single longitudinal cable, will not result in a major rupture but only in the redistribution of loads to the supporting members nearby. As discussed earlier, the destruction of one or even several window panels would result only in a loss of atmosphere slow enough that there would be plenty of time for evacuation to communities nearby.

The external tension and compression towers, which may provide for each cylinder the forces necessary for its precession about the Sun, would not be very vulnerable to terrorists, located as they would be in space where no one could move without a space suit. If, though, one of them were to be destroyed, either by accident or by intention, it wouldn't result in catastrophe to the habitat. The precession would be arrested, so if repairs took as much as a day the residents would see the image of the Sun's disc wobbling by about two solar diameters, though the intensity of sunlight would be undiminished. On completion of repairs the precession rate could be speeded up to a rate greater than normal, until the community "caught up" to the correct orientation. Such an event would be seriously damaging only if repairs took more than one or two weeks, so that Sun angles were changed by many degrees and crop growth was correspondingly affected.

Certain dangers exist on Earth but would not in a space habitat. Earthquakes and volcanoes are among these. Often they wipe out thousands of people at a time, particularly in seacoast areas. Tornadoes, hurricanes, and typhoons also kill, and numbers of people are killed every year in small boat accidents through weather or violent waves. Among the risks which our technical society has added are those of automobile accidents. Because of good roads, safe automobiles, and relatively strict traffic laws, in the United States we have about the lowest accident rate per passenger-mile that is found anywhere in the world. Yet even our rate results in the death of 50,000 people per year, out of a population of two hundred million. One comparison between the risks on Earth and those in a space habitat is instructive: even in the extreme case in which it is assumed that a meteoroid strike of one ton size on a space habitat would result in total destruction and the loss of all the inhabitants, the risk of death from that cause would be only one sixtieth of that which we run in the United States by the existence of our automobiles.

If the space habitat option is followed on the earliest possible time scale, the result could be that within a few decades the nations of the world would all be dependent on solar energy from satellite solar power stations built at space communities. Nuclear energy, under those conditions, would be confined mainly to the laboratory. Dependence on a relatively vulnerable but inexhaustible power source would remove one of our present causes of international tension and the threat of war, and at the same time would deter any would-be adventurer nation from carrying out an attack on a neighbor.

In contrast, if for our energy we are forced to rely on a rapid, large scale development of liquid metal fast breeder reactors, within a few decades every industrial nation and every developing nation will have such devices. Plutonium will be in production in large quantities in every such nation, and the temptation to divert it to weapons production will be very strong for at least some political leaders. With so much fissionable material being produced and shipped, it seems likely indeed that some of it will be diverted by terrorist groups, and consequently Earth may become a much more dangerous place than it is now.[7]

In terms of risk, therefore, the alternative appears to lie between a development of space communities, relatively safe from catastrophe, in which an increasing fraction of the human race would be widely dispersed and consequently safe from simultaneous destruction, and an Earth ever more crowded with population, on a strictly limited land area, under conditions in which the probabilities both of war and of terrorist acts would be enhanced.