Conquest of Space

The leading expert on space colonies unveils his plan for building factories in orbit by 1992

By Gerard K. O'Neill

Trends that cannot be reversed make the decades ahead very dangerous — potentially catastrophic-here on our planet. Our land area and mineral resources are limited and can never be extended. They are being pressed more and more severely by a world population that will double in 40 years and rise to three times today's population 30 years after that.

We human beings are problem solvers by nature, and our response to those threats should not be a wringing of hands but an exploration of the ways to solve serious resource and environmental problems. We must find unlimited low-cost energy and make it available to everyone, not just the nations favored with large fuel reserves. And we must tap mineral resources to sustain new industries without damaging Earth's environment.

There are limited short-term solutions to some of the world's major problems. But the only viable long-term solution is to begin using the energy and material resources that lie beyond our finite planet — in space itself. That will be a healthy development for another reason: It will draw us outward, encouraging the human settlement of space. For those who already look toward the space colonies that will result from space industry, the immediate question is, "what form will that industry take?"

If research under way continues to meet its goals, we could establish a substantial industry in high orbit, 200,000 miles above Earth, before the end of this century. Within decades the products of space industry could exceed 1 million tons per year — small compared to the great industries of Earth but worth more than $100 billion annually. The raw materials to feed that industry would come from the surface of the moon. Lunar materials would be separated into pure elements in high orbit, where constant sunlight would supply the energy for extracting metals and fabricating them into finished products. At first, many of the workers for that industry would remain on Earth, monitoring and controlling robotic machines through radio and television links. A few, mainly highly skilled troubleshooters, would live in orbit for duty·tours of six months or more.

The initial products of industry in space will be solar-power satellites, giant arrays that collect the bountiful sunlight of high orbit and convert it to radio energy. That radio energy will then be sent to Earth for conversion to electricity, ultimately providing our civilization with all the electrical power we need, without polluting planet Earth's biosphere.

Up until now, of course, there has been just one valuable product of commercial activities in space: information. Satellites equipped with sensors produce data on large-scale weather patterns, including tropical storms. And satellites orbiting just above Earth's atmosphere use sensitive television cameras to take pictures of the land. From that detailed imagery computers can pick out subtle color changes, which indicate the presence of oil, metals, and fresh or salt water beneath the earth's surface. Satellites also relay information from one ground location to another or to entire continents. There are now more than 100 of these satellites. and more of them rocket into orbit every month.

The success of information satellites and the dearth of any other space industry — can be explained by a fundamental fact. Information has great value, but it weighs nothing. The cost of launching a satellite from the earth to geostationary orbit (an orbit in which a satellite stays at a fixed point in the sky as seen from Earth) is currently about $18,000 per pound of satellite weight. But once a satellite is up there, it can produce or relay information for virtually nothing. For such established information products as telephone messages or TV program time, a relay satellite can pay back its entire cost of manufacture and launch in a year or less.

As soon as we look beyond the area of information, commercial opportunities in space become far more limited because we are up against the costs of lifting raw materials into orbit. Rates to lowEarth orbit for shuttle cargo range from $1,250 per pound to $11,000 per pound. The low figure is for high-density cargo in bulk. The high figure is more typical of shuttle payloads so far and applies to complex low-density objects, of which satellites are the prime example. Any product made of materials that must be brought from Earth on the shuttle, processed in orbit, and returned to Earth for sale must include that high price of lift as an item in its production cost. Pharmaceuticals, which NASA has targeted for early commercial production, are among the few products on Earth that sell for such rarefied prices.

If the industrialization of space is to play a significant role in the total economic picture, it must compete in one of the major markets on Earth. It cannot do so in most of the new, high-technology markets, including electronics and robotics because such products couldn't be manufactured more efficiently in the space environment than in factories on Earth.

Yet there is one large-scale market for which space industry makes sense: energy, which, like information, can be transmitted without the flow of materials. More than five years ago, power at a level of 100 kilowatts was transmitted by radio waves over a distance of one mile in tests at Goldstone, California. While that transmission would have to be scaled up by 10,000 to 100,000 times to reach the power level of a typical electric-generating station, the feat would require no new physics. The energy beam would be larger in area but would not have to be more intense.

Painting by John Berkey

Some 15 years ago Peter Glaser, of the Arthur D. Little international consulting company, in Cambridge, Massachusetts, suggested transmitting energy from space. Large satellites fitted with solar cells could be located in geostationary orbit. There they would convert sunlight to radio waves which could be beamed back to the earth. The idea made sense. Sunlight is an intense, reliable resource in high orbit, available 24 hours per day during most of the year. Only in the spring and autumn is a geostationary array eclipsed and then only for predictable periods of less than 40 minutes each midnight.

> *"If research continues to meet its goals, we could establish a substantial industry in high orbit before the end of this century. The products of space could exceed 1 million tons a year."*

Unfortunately Glaser's good idea never gained acceptance, and the problem lies with its friends as well as its enemies. NASA and its aerospace contractors latched on to the Glaser plan as a wonderful reason for a massive new space program. Engineers drew up designs for monster versions of the shuttle — wholly reusable space planes that could carry payloads of several hundred tons. The giant rocket planes were to weigh 20,000 tons at liftoff — ten times as much as today's shuttle.

Companies working on NASA study contracts drew up plans for solar-power satellites that would be as light as possible. Their components could be lifted from Earth in those giant super-shuttles and assembled in orbit. The program planners worked up a schedule of several flights per day for the huge rocket planes. That schedule would have had to be maintained for a year if even one power satellite were to be installed.

During the seventies, many studies of solar-power satellites were carried out. In the most comprehensive investigation, the Department of Energy (DOE) spent three years and about $15 million to explore the concept. About two-thirds of the funding went into environmental impact studies. Somewhat to its own surprise the DOE found no serious environmental impact from the transmission of energy by radio beams. There are two reasons for the clean bill of health. First, the intensity of the radio beam was only about the same as the intensity of sunlight. Second, at the frequency of the radio waves, the packets of energy in the beam — in physics terms, the quanta — were only 0.001 percent as strong as those of sunlight and therefore much too weak to damage living tissue. There had never been a question of danger to humans, because the receiving antenna would be mounted on posts above ground level and inside a fenced enclosure. But no one could prevent birds or insects from flying through the beam. The DOE-sponsored experiments found that the radio waves had no effect on birds. And in another experiment, no effect was found on even so subtle a natural phenomenon as the dancing pattern of bees.

Despite the fundamental attractiveness of the solar-power satellite, it was shot down by the National Research Council (NRC) of the National Academy of Sciences. The NRC's negative conclusion resulted from its analysis of economics. With evidence of escalating shuttle-flight costs fresh in mind, the reviewers concluded that the super-shuttles could never operate as inexpensively as the people at NASA hoped. They also refused to believe that solar cells, the basic energy-conversion mechanisms for power satellites, could ever be made cheaply enough. The NRC study concluded that power satellites could probably be built and would probably be acceptable environmentally, but that they could never compete economically with coal or nuclear electric power.

In my view, that entire sad history, played out over more than a decade, was a classic example of asking the wrong question and getting a useless answer. Although I believe the power-satellite concept is fundamentally sound, NASA's approach to making it happen collided head-on with basic physics. The energy cost of lifting a power satellite into geostationary orbit is huge because we on Earth are at the bottom of a gravity well that is 4,000 miles deep. Fighting gravity forced NASA's designers into two traps. One, the direct cost of lift, was obvious. The other was a little less apparent. Because the designers had to fight those high lift costs, they proposed lightening the satellites by using complex, costly designs and exotic, equally costly materials. For example, in converting solar energy to electricity, they had to use lightweight but extremely expensive pure crystal silicon solar cells. They could not use the much less expensive amorphous silicon solar cells. because those would have been heavier per watt of power. Nor could they use heavy turbogenerators, producing electricity from sunlight concentrated by mirrors, though that would have been a relatively simple, low-technology solution to the energy-conversion problem. But if NASA got the wrong answer by asking the wrong question, what is the right question?

The right question. I suspect is, "What is the simplest, lowest-risk design for a solar power satellite that could be made out of materials already at the top of Earth's gravity well?" We have a large mine of materials up there, and it has already been assayed more carefully than all but a few mines on Earth. The mine is the surface of the moon. From the Apollo project. we know that the material of the lunar surface is about 30 percent metals by weight, 20 percent silicon, and 40 percent oxygen. The metals and silicon are just right for building a solar-power satellite, and oxygen is the "gasoline of space," constituting about 86 percent of the weight of rocket propellant. Continuing to ask what we hope are right questions, we should explore methods for building solar-power satellites from lunar materials within the limitations of the space shuttle transportation system.

In the past five years, one organization has been working quietly and effectively to ask those right questions and to arrive at sensible answers. The organization which I founded in 1977, with the help of some friends, is the Space Studies Institute (SSI), a nonprofit corporation located in Princeton. New Jersey, just outside the Princeton University campus. The institute is supported by donations from thousands of members; it neither asks for nor accepts government money. Unlike most space-related organizations, SSI does not agitate for governmental action. Instead, it has taken on the responsibility for directly funding basic scientific and engineering research. That has kept SSI in a relatively low profile compared with most other space-related private groups, but it has also made it effective and consistent. Our organization's purpose: to find a practical approach to satellite power and the more general goal of space industry, beginning the peaceful human conquest of the high frontier.

Soon after SSI's formation, we held a series of workshops to develop a cost-effective plan for the development of space industry. The workshop ground rules included staying within the limitations of the shuttle. which can lift only about 29 tons of cargo to orbit on each flight. We developed a scenario for space industry through those workshops.

Pilot plants, remote-controlled and small enough to be transported by today's rockets, would carry out the key industrial functions: material transport, extraction of pure elements, and fabrication of finished products. The pilot plants would be of several kinds. One would scoop up lunar-surface soil and sinter it with heat and pressure into solid, durable spheres. The second would transport the spheres of lunar soil to a point in high orbit above the moon. A third would process the lunar soil into pure elements. alloys, and composites. And the fourth would fabricate those industrial materials into finished products. The products would be the heavier, simpler components of more pitot plants identical to the first. In that way space industry could grow geometrically, 1, 2, 4, 8, ..., through eight doublings. until 256 pilot plants would have been built. That scheme would provide us with sufficient industrial capacity to build solar-power satellites.

The results of the SSI workshops were published in two articles in the journal Astronautics and Aeronautics. According to those articles an investment of $7 billion or $8 billion over a five-year period, comparable to the investment that built the Alaska pipeline, would be enough to produce about one power satellite per year. Each power satellite could be sold to a nation or a utility for about $10 billion. And each could supply the earth with continuous electric power equal to the output of ten nuclear plants. The potential world market for power satellites that undersell coal and nuclear-power plants is well over $200 billion a year. During the course of our workshops, we also reasoned that two other products, less complex than power satellites could be marketed in the short term: liquid oxygen, for use as rocket propellant, and raw lunar soil, excellent for shielding orbital space stations and factories from cosmic radiation.

In a separate research effort, Hannes Alfven, an adviser to SSI, suggested that there might be asteroidal material trapped in the earth's orbit around the sun by the combined gravitational forces of those two bodies. It was easy to calculate the energy cost of retrieving that material, and it was very low — about 0.05 percent of the energy cost for lifting materials out of Earth's gravity well to the same high orbit. It was far more difficult to decide whether asteroids in that orbit could have remained trapped since the formation of the solar system. given the perturbations of all the other planets. Under an SSI grant to Princeton University, Scott Dunbar studied the problem mathematically and concluded that despite all perturbations, asteroidal materials could very probably still be within Earth's orbit. Dunbar received his Ph.D. from Princeton on the basis of that research. Then he received an NRC fellowship to work with Eugene Shoemaker and Eleanor Helin at Caltech, in part to search for that material with the large Schmidt telescope at Mount Palomar.

Whether the raw materials for space industry come 1rom the moon or from trapped asteroids, they must be separated into pure elements for most industrial uses. In 1981, SSI made a substantial grant to Rockwell International, the builders of the space shuttle. Under that grant, Rockwell's Robert Waldron measured the key reactions for separation of lunar minerals into pure aluminum, iron, titanium, silicon, oxygen, and other elements. Waldron's results, now being written up as a final report, indicate that a processing plant in space or on the moon could process roughly 100 times its own weight in soil each year and that very few chemical materials would have to be brought from the earth to keep such a processing plant running.

Although our energy cost for bringing. materials from the moon to an orbital industrial site would be only 5 percent of the cost of bringing them from Earth, we would still need a machine to carry out that transport. For the past several years SSI has funded development of the "mass driver," an electromagnetic catapult. In a mass driver, electric current is pulsed through coils of aluminum wire, generating a magnetic field. This field accelerates a moving coil of wire, called a "bucket," which carries a sphere of sintered lunar material that's about the size and weight of a baseball. The material then leaves the bucket and accelerates toward its destination, a precise point in high orbit above the moon. There the sintered lunar material enters a very simple collector that has a closed cylindrical tube at one end.

The mass driver work took a big step forward in May 1983, when Les Snively of Princeton, completed the newest model Mass-Driver III — according to a computer design program that I had written. MassDriver III models the first half-meter of a fully operational lunar machine, which would be about 160 meters long. It is a simple device consisting of 20 circular drive coils, each 40 centimeters in diameter and about as thick as a bicycle tire. Stacked against one another, they form a hollow cylinder. Inside the cylinder, the bucket coil is free to move. When currents are discharged through the drive coils in a precise time sequence, they produce strong magnetic fields that accelerate the bucket and also guide it on the centerline of the cylinder. Functioning at a fraction of full power, Mass Driver III gave its payload carrier an acceleration of 1,100 g, enough to go from a standstill to 250 miles per hour in 0.01 second. Full-power tests scheduled for later this year should see the machine accelerate a payload to its design goal of 1,800 g. That acceleration will bring the payload carrier from a standstill to 300 miles per hour in 0.007 second.

Building on its successful track record, SSI will be funding second-generation development in key research areas during the next several years. Now that Mass Driver III has proven the accuracy of the computer program by which it was designed, the program will be used to extend the design to the full length of the lunar machine, or 160 meters. The acceleration of Mass Driver III is enough to bring payloads to a speed of 5,400 miles per hour, the escape speed from the moon, within just 160 meters. In addition, chemical-separation technology will be brought to the pilot plant stage. And SSI will soon be requesting proposals from aerospace companies for solar power satellites that can be built from lunar materials. If we at SSI maintain our research schedule, by 1987 we'll be ready to publish a consistent, logical overall plan for establishing large-scale industry in space.

When the road to productive, high-volume space industry has been paved by research of that kind, it will be time for action. Nations or groups of corporations are among the possible players at that stage. In order to minimize risks, they will choose products that the marketplace will still want five to ten years after investment begins. Given the pace of change in our technological society, only the most general products — energy, rocket propellants, and lunar soil for shielding space stations and colonies — will satisfy that condition. That is why SSI has targeted these three as the most viable products of space industry. On the fastest time scale, a nation or a consortium of industries could pick up the SSI plan and run with it in 1987. That would result in productivity in space at the 100,000-ton-per-year level by 1992. If events go more slowly SSI will broaden, deepen, and buttress its plan by constructing larger-scale demonstration experiments, until finally the investment opportunity becomes so tempting that a major investment source will commit itself to the development of space industry

I cannot be sure who will be the first to create wealth out of the constant solar energy and the abundant materials waiting for us at the top of Earth's gravity well. But

I am sure that the first group that succeeds will soon have its imitators. Whether the first program is led by Americans, Japanese, Europeans, or Russians, within a few short years, all the major space powers will compete in production. When the scale of industry in space becomes large enough to demand the presence of thousands of people in high orbit for long periods, it will pay to devote some of the productivity to the building of space colonies for workers and their families. Those colonies, in the form of spheres one mile in circumference, will rotate slowly to provide Earth-normal gravity for their residents. The space colonists will grow their own food and derive all the energy they need from the sea of constant sunlight. By the middle years of the next century, the first beachhead in space will have grown to include thousands of such colonies, each with a language and a cultural heritage drawn from a nation of Earth. Travel between Earth and its colonies will be as common by then as international travel is today. It will be a happy development for our tired and fragile planet when humanity's drive toward production and conquest is redirected outward onto thai high frontier.

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The Space Studies Institute can be reached by mail at Box 82, Princeton, NJ 08540. Membership is $15 per year.

Note: As of 2010, the SSI address is 1434 Flightline Street, Mojave, NM 93501, (661) 750-2774, http://www.ssi.org

Gerard K. O'Neill was a physicist at Princeton University, president of the Space Studies Institute, in Princeton, New Jersey, and a leading advocate of industry in space. O'Neill's 1976 book, *The High Frontier*, presented a persuasive argument for colonization of space.