The Space Manufacturing Facility Concept

By Gerard K. O'Neill

We define a space manufacturing facility as a permanent or very long-term human community, in an orbit so high above the Earth or any other planetary body that it can use solar power continuously without frequent eclipsing. Such a community, once established, must be entirely self-sustaining rather than continuously resupplied from the Earth. It should be constructed almost entirely from materials available in space, such as those of the lunar surface or the asteroids. The space manufacturing facility uses its free solar energy and its easy access to the materials of space to produce manufactured products whose end use is in a very high orbit or at escape distance.

The economic rationale of a space manufacturing facility is based on three elements. The first is energy: in free space, in a high orbit, not only is solar energy available continuously without interruption, but the total amount received in a year is about ten times as much as arrives on an equal area on the Earth's surface, even in the most cloud-free portions of the American southwest.

The second element is materials. The energy cost of lifting materials from the lunar surface to escape distance is about one twentieth as much as for lifting materials from the surface of the Earth. In addition, the Moon has no atmosphere, so a stationary launching device on the lunar surface can operate without atmospheric drag, and can be optimized for the most efficient payload size. Our estimates indicate that these two advantages would permit the lifting of lunar material to escape distance for the order of one percent of the overall cost that launch from the Earth would require. We call the device that does that job a mass-driver.

The third element in the economic rationale for space manufacturing facilities is that in free space, one has the availability of zero gravity, in which very large objects could be assembled free of all constraints of payload size. At the same time, perhaps only a few meters away, a comfortable habitat for living could exist, providing Earth normal gravity by slow rotation.

The "bootstrap" principle is central to the idea of a space manufacturing facility; that is, we would begin by establishing a relatively small mining and mass-driver base on the Moon and a construction base near the eventual site of the first space manufacturing facility at L5. Once the material sent out by the mass-driver has been processed and used to build the first habitat, the industrial productivity of the habitat itself is used, in part, to build additional mass-drivers and their solar powerplants, to be sent to the moon to increase the mass throughput. In the third step, reducing costs still further, the mass drivers could be built on the Moon itself.

The fourth step, well in the future, would bypass the materials transport question completely; the production and processing equipment would be taken to the asteroid belt and used directly for the local construction of a new habitat. The essential advantage of that approach would be that the new habitat could be built and brought into production, and so begin to amortize its construction cost in advance of the time that its mass would need to be transported. On completion of a habitat near the asteroid belt, about one generation — thirty years would be required for the habitat to be relocated near the Earth-orbiting community of other habitats, or in some other orbit entirely. Though I mention this as an ultimate logical development, in this Conference we will be concerned for the most part only with the first step: the establishment and productivity of the first space community.

One measure of the newness of the concept of space manufacturing facilities is that we are still searching for a satisfactory name to describe it. The words "Community," "Habitat," "Facility," or "Frontier" fail to describe the economic rationale. "Colonization" suggests drive and purpose, but in the past has often meant the exploitation of one group by another. Yet in space colonization there need be no such exploitation, because the materials and energy of space are now unused.

Though I describe this concept as new, I would like to recognize the contributions of others who came before us, above all Konstantin Tsiolkowsky, who, in my opinion, saw even further than others who came years later than his own time. I cannot neglect to mention these others, among the most prominent of whom were J.D. Bernal, Dandridge Cole, and John Stroud.

It is beyond the scope of this conference to define optimized geometries or make detailed estimates of time or cost. In that regard, I am very grateful for the excellent cooperation of NASA, particularly the Office of Space Flight and the Marshall Space Flight Center. A preliminary guess, based on our discussions so far, would put the earliest technically possible date for the first space community at somewhere between 1988 and the year 2000. Cost estimates are from somewhat above Project Apollo to a maximum of one or two tenths of the cost of Project Independence.

Some goals which are suitable to be addressed at this Conference are as follows:

- First, and perhaps most important, the identification of any problems so fundamental as to invalidate the entire concept.
- Identification of steps which have the largest elements of uncertainty about them and which will require the greatest effort in further study.
- Identification of elements which are uncertain, but which could be brought to a much higher level of certainty by a relatively modest additional effort. These may be candidates for the earliest attack by an additional but still modest research effort.
- Assembly of vital pieces of information from fields which up to now have been isolated from each other.
- Identification of methods not yet explored by which savings in time or cost of habitat construction or manufacturing processes could be made.
- Identification of methods for realizing, in spite of our imperfect human institutions, the construction of the first space community.
- Identification of intermediate steps in engineering development which could lead toward a space manufacturing facility while also serving other purposes.

Two suggestions were made to the authors of papers presented at this conference, in the spirit of working hypotheses, to provide focus and coherence:

(1) To restrict the discussion to existing technology; that is, to processes and materials which already exist or which can be proven feasible on the basis of straightforward engineering practice.

(2) To think in terms of an early time-scale which, given adequate priority soon enough, could see the first manufacturing facility in space before the end of the 1980's. Such a schedule is realizable, and the facility will be built only if it offers an important payoff within a time scale of human decisions. Fifteen years is, in my opinion, such a horizon.

When we consider possible geometries, we must realize that the final actuality may look very different. To start the ball rolling, I have suggested the configuration shown in Figure 1. This is a side view of a possible first community; I'll call it "Island One" until someone suggests a better name. The length is about 1000 meters, its diameter about 200 meters. The rotation rate is once every twenty seconds, so gravity is Earth-normal inside. The axis is always pointed toward the Sun. Two such cylinders are linked by a light framework through bearings. Though the total mass is about half million tons, which is the same as the total mass of a modern supertanker, the bearing forces are only sixty pounds; about the same as on a child's bicycle wheel. Surprisingly, the excavation left on the surface of the Moon after removal of the half million tons of material needed to build this structure would be only about five meters deep and about 200 meters long and wide, not even enough to keep one small bulldozer fully occupied over a five or six year period.

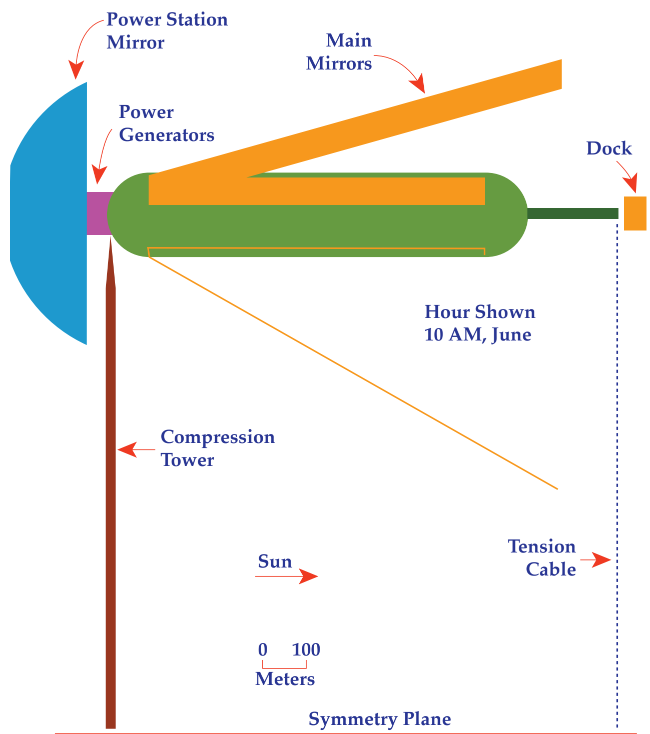

Figure 1 — Early Version of a "Model T" Space Manufacturing Facility

In this design, a population of about ten thousand people is located in four villages of 2500 each, located in the four end caps. These four villages have independent control of their day-night cycles and seasons. One efficient possibility is their operation on three different time-zones, eight hours apart. In that way the heavy industry, which is located just outside the habitat in zero gravity, can operate 24 hours a day, but with none of the workers on a night shift. One possible location for the community would be in orbit about the L5 Lagrange libration point of the Earth-Moon system. The stable orbit about that point has a length of about half a million miles, so there would be room for many thousands of communities in it.

We assume cosmic ray protection in the amount of about 130 grams per square centimeter for the end cap villages, to guard against heavy primary cosmic rays and solar flares. The cylinder areas in that design are left for agriculture and are protected against flares only.

To illustrate the possibilities for architecture, Figure 2 shows a possible design for a village. The shielding goes all the way around. It would all be terraced and planted. Sunshine comes in through the solars, and the apartments in which people would be living are located at the lower right. The apartments could provide around two hundred square meters of floor space for a family of five, which is equal to rather affluent suburban American living conditions. In addition, each family could have a garden, where good weather could be counted on, and where, presumably, there needn't be any mosquitoes, birds and animals, though, ought to flourish in this environment.

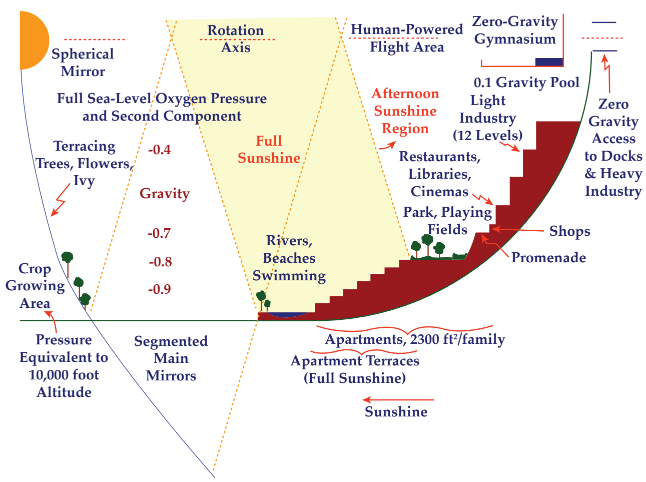

Figure 2 — One Proposal for the Interior Configuration of Living Quarters in Space

There could even be a river for swimming and boating, and beaches for sunbathing. Near the axis there are possibilities for low-gravity swimming and diving and human-powered flight. In summary, though Island One would be of modest size, it would be more attractive than nearly all of the industrial towns with which it could be compared on Earth.

During the past year, since the 1974 Conference reported in the Appendix, four studies were performed at Princeton. These are summarized as follows:

(1) The use of the "mass driver" (the Transport Linear Accelerator) as a space reaction engine has been explored. Table 1 shows the range of applications and performance figures for the mass driver used in this context. For the maximum magnetic field of ten thousand gauss, proposed for the mass driver to be built on the surface of the Moon, the reaction engine thrust would be about two tons and the exhaust velocity twenty-four hundred meters per second. That corresponds to a specific impulse of about two hundred forty seconds, which is just about right to move a large payload over the velocity interval of about twenty-one hundred meters per second which represents the difference between L5 and a geosynchronous orbit about the Earth. The growth potential of the mass driver appears sufficient for later tasks requiring specific impulses in the range from seven hundred to twelve hundred, as indicated by the parameters shown in Table 1.

(2) The habitat size has been studied as a function of structure mass and internal atmospheric pressure. Three facts push toward use of a low pressure atmosphere enriched in oxygen: (a) habitat structural mass is almost exactly proportional to pressure, though almost independent of the artificial gravity provided; (b) nitrogen is not used directly in human, animal or plant respiration, although it makes up 79% of our atmospheric pressure; and (c) the Moon is probably rather poor in nitrogen, but its surface is about 40% oxygen by weight.

It turns out that for a structure mass of about fifteen tons per person, one could reach a cylinder diameter of about seven hundred meters. A habitat of that size, with an internal pressure of two to three pounds per square inch of oxygen, could easily support one hundred thousand people. Before considering that possibility further, we will have to find out whether or not there are long-term physiological effects from a nearly pure oxygen atmosphere, and we're also going to have to learn more about fire protection in large volumes, at low oxygen pressure, in the presence of an abundant supply of water. None of the NASA studies performed to date covers that situation.

(3) A comparative estimate was made for construction of a large radio-telescope array at L5; equivalent, for example, to Project Cyclops. This would be a single paraboloidal dish five thousand meters in diameter, plus an occulting disc ten kilometers in diameter to block radio interference from the Earth. The total mass of aluminum would be eleven thousand tons. Estimates indicate that the array could probably

be constructed at L5 for around one twentieth to one tenth the cost of an equivalent structure on Earth, which would need smaller paraboloids braced against winds and gravity.

(4) The prospects have been examined for providing energy to Earth from powerplants manufactured and located in space. Satellite solar power stations have been considered since the mid-1960's. In concept, these would be large arrays of solar cells or large turbo-generator sets, located in geosynchronous orbit, transmitting power by a microwave link for conversion to power grid frequencies at the surface of the Earth. The principal difficulty is the cost of transporting such power stations from the Earth's surface. Reducing that cost requires very advanced lift vehicles of enormous size. However, using materials brought from the lunar surface to a space manufacturing facility by the same mass driver that brings up the original construction materials, the powerplant mass-to-power ratio no longer matters much, and economic feasibility appears to be achievable even with existing or near-term figures for powerplant mass.

The general range of parameters is shown in Table 2 for a satellite solar power station delivering five thousand megawatts to Earth. The estimated market for new powerplants in the year 1990 in the United States alone is about seventy-five billion dollars per year, using the installed cost of $1200/kWe quoted by the National Geographic (April 1975 issue) for the most recent large hydroelectric project.

Because some of us think of the space manufacturing facility concept as real and immediate, we tend to be deep in engineering details, but we should not lose sight of the fact that such discussions are not the reason why this concept has aroused such an extraordinary amount of popular interest. The vistas offered by the flexibility of the living conditions in space habitats, which have appeared as artists' conceptions in a number of publications, constitutes a major incentive to "get on with the job." I do wish to remind you, however, that the authors whose papers follow have attempted to provide us with some of their knowledge, and that the presence of their papers here does not necessarily constitute their endorsement of a concept which is still, for many people, very rich in future shock.

Table 1 — Mass Driver as Reaction Engine

Maximum Field (Gauss)	Length (km)	Impulse Payload (kg)	Velocity Change (m/sec)	Exhaust Velocity (m/sec)	Specific Impulse (sec)
10,000	13	9	2,100	2,400	245
10,000	50	3	13,600	7,100	725
30,000	50	3	13,600	12,300	1,255

Table 2 — Cost Estimate for a Space Solar Power Station Manufactured at L5

Item	Total Needed	Unit Factor	Cost (Billions)
Power Plant	8,000 MW	$450/kW	$3.6
Lunar Materials to L5	160,000 tons	$3 / pound	$1.06
Amplitron Magnets (from Earth)	330 tons	$500 pound	0.31
Materials Processing	160,000 tons	$5 / pound	1.76
Microwave Tubes	8,000 MW	$25 / kW	0.20
Assembly at L5	80,000 tons	$5 / pound	0.88
Reaction Mass to L5	109,000 tons	$3 / pound	0.72
Processing Reaction Mass	109,000 tons	$1 / pound	0.24
1/4 Cost of Mass-Driver	(1/4) x 1,6000 tons	$200 / pound	0.18
Receiver Station (on Earth)	5,600 MW	$75 / kW	0.42
Total			$9.37

Discussion

Question: Why L5 and not also L4?

Answer: I have been placed in the position rather often recently of having to get up in front of a television camera and in thirty seconds give the entire concept of space manufacturing facilities. There just isn't time to say L4 as well as L5, but of course, you are absolutely right. The stable orbit around L4 is presumably just as big as that around L5.

Question: It is surprising that in establishing a habitat in space you seek to recreate as closely as possible conditions on the Earth. It seems much more imaginative to consider the many new opportunities that one would hope would be developed by the high-orbit habitat.

Answer: You are quite right. However, to turn this into a reality, it has to receive a tremendous amount of popular acceptance. If we were to say that it was necessary, or even advisable, to adopt very unearthlike surroundings, that would turn off a great many people. But I certainly believe that after you have built one of these facilities, particularly when another generation has grown up on it, there will be many possibilities which are much more attractive.

Anyone who takes the trouble to read Konstantin Tsiolkowsky's book "*Beyond the Planet Earth*" will find that he anticipated an enormous number of these possibilities, in numerical detail. (Tsiolkovsky, Konstantin, E., 1960. Beyond Planet Earth. Translated by Kenneth Sayers, Press, New York.) PG3470.T8 V52 1960

Question: It seems to be a common assumption that these facilities have to be located at the same distance from the Sun that the Earth is, in order that their temperatures be about right. Yet by controlling the color of the surface and the opening of the panels, it should be possible to put them either much closer to the Sun or fairly far away. Do you have an idea of what range of distances from the Sun would be practical?

Answer: Yes, I went through that calculation a few months ago. My talk did mention that it is practical to take production machinery out to the asteroid belt and build a habitat right there. It is easy, just by putting up bigger mirrors, to provide the Earth-normal solar constant. With reasonable limits on the amount of mass which is put into mirrors as opposed to the rest of the habitat, I calculated that it was possible to go out roughly a fraction of one percent of the distance to the nearest star; that is, far beyond the limits of our solar system.

Question: Your tables are in terms of dollar cost. In the space facility, what do dollars mean?

Answer: We tend to think of dollars as wealth, but they are not the real wealth. The real wealth, presumably, is productivity: energy, materials, and information. In the space facility, therefore, wealth is being generated.

Publishing History

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