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SPACE COLONIZATION AND ENERGY SUPPLY TO EARTH

TESTIMONY

OF
DR. GERARD O'NEILL BEFORE THE SUBCOMMITTEE ON SPACE SCIENCE AND APPLICATIONS OF THE COMMITTEE ON SCIENCE AND TECHNOLOGY UNITED STATES HOUSE OF REPRESENTATIVES JULY 23, 1975

INTRODUCTION

Within the past year a new possibility for the direction and motivation of our thrust into space has reached the stage of public discussion. It is called space colonization, or the development of space manufacturing facilities. Our present American leadership in space technology gives us a unique opportunity to play a central role in that new development, if we act with decision and speed.

The central ideas of space colonization are:

1. To establish a highly-industrialized, self-maintaining human community in free space, at a location along the orbit of the moon called L5 (Figure 1) where free solar energy is available full time.
2. To construct that community on a short time scale, without depending on rocket engines any more advanced than those of the space shuttle.
3. To reduce the costs greatly by obtaining nearly all of the construction materials from the surface of the moon.
4. At the space community, to process lunar surface raw materials into metals, ceramics, glass and oxygen for the construction of both additional communities and of products such as satellite solar power stations. The power stations would be relocated in synchronous orbit about the earth, to supply the earth with electrical energy by low-density microwave beams.
5. Throughout the program, to rely only on those technologies which are available at the time, while recognizing and supporting the development of more advanced technologies if their benefits are clear.

THE SPACE COLONY CONCEPT

Although it has precursors in the works of many authors, the modern idea of space colonies originated from several questions, posed six years ago as an academic exercise:

1. Is it possible, within the limits of 1970's technology, using only the ordinary construction materials with which we are already familiar, to build communities in free space rather than on a planetary surface like the earth, the moon, or Mars?

2. Can these communities be large enough, and sufficiently earth-like, to be attractive to live in; small worlds of their own rather than simply space stations?
3. Would such colonies have unique advantages from an economic viewpoint, so that they could justify the costs of their construction and contribute in a productive way to the total human community?
4. If such colonies were built, would their further development be such as to relieve the earth of further exploitation by the industrial revolution, and to open up a new frontier to challenge the best and highest aspirations of the human race?

Surprisingly, six years of continued research has confirmed, in even more increasing detail, that the answer to all four of these questions is a strong ’’yes."

GEOMETRIES

The largest colonies now foreseeable would probably be formed as cylinders, alternating areas of glass and interior land areas. From those land areas a resident would see a reflected image of the ordinary disc of the sun in the sky, and the sun’s image would move across the sky from dawn to dusk as it does on Earth. Within civil engineering limits no greater than those under which our terrestrial bridges and buildings are built, the land area of one cylinder could be as large as 100 square miles. Even a colony of smaller dimensions could be quite attractive.

Rotation of the cylinder would produce earth-normal gravity inside (Figure 3), and the atmosphere enclosed could have the oxygen content of air at sea-level on earth. The residents would be able to choose and control their climate and seasons.

Agriculture for a space community would be carried out in external cylinders or rings, with atmospheres, temperatures, humidity and day-length chosen to match exactly the needs of each type of crop being grown. Because sunshine in free space is available 24 hours per day for 12 months of the year, and because care would be taken not to introduce into the agricultural cylinders the insect pests which have evolved over millennia to attack our crops, agriculture in space could be efficient and predictable, free of the extremes of crop-failure and glut which the terrestrial environment forces on our farmers.

INDUSTRY

Non-polluting light industry would probably be carried on within the cylindrical living-habitat, convenient to homes and shops. Heavy industry, though, could benefit from the convenience of zero gravity. Through an avenue on the axis of the cylinder, workers in heavy industry could easily reach external, non-rotating factories, where zero gravity and breathable atmospheres would permit the easy assembly, without cranes, lift-trucks or other handling equipment, of very large, massive products. These products could be the components of new colonies, radio and optical telescopes, large ships for the further human exploration of the solar system, and power plants to supply energy for the earth.

LIMITS OF GROWTH

In the early years of this research, before the question of implementation was seriously addressed, it seemed wise to check whether an expansion into space would soon encounter "growth limits" of the kind which humankind is now reaching on earth, and which have been vividly described for us by Professor Jay Forrester of Massachusetts Institute of Technology, in studies supported by the Club of Rome.

If the space colonization program is begun, its technical and economic imperatives seem likely to drive it rather quickly toward the exploitation of asteroidal rather than lunar materials. Long before the results of mining activity on the moon became visible from the earth, the colony program would be obtaining its materials from the asteroids. Given that source, the "limits of growth" are absurdly high: the total quantity of materials within only a few known large asteroids is quite enough to permit building space-colonies with a total land area more than ten thousand times that of the earth.

ENERGY WITHOUT GUILT

The efficiencies of a space community, regarded as an island of a technological human civilization, stem from the abundance and full-time dependability of free solar energy in that environment, and from the possibility of controlling the effective gravity, over a wide range from zero to more than earth-normal, by rotation. In contrast, industrial operations on earth are shackled by a strong gravity which can never be "turned off"; those on the moon would be similarly limited, although the limit would be lower.

In a space colony, the basic human activities of living and recreation, of agriculture, and of industry could all be separated and non-interfering, each with its optimal gravity, temperature, climate, sunlight and atmosphere, but could be located conveniently near to each other. Energy for agriculture would be used directly in the form of sunlight, interrupted at will by large, very low-mass aluminum shades located in zero gravity in space near the farming areas. The day-length and seasonal cycle would therefore be controllable independently for each crop.

Process heat for industry would be obtained with similar economy; in space, temperatures of up to several thousand degrees would be obtainable at low cost, simply by the use of low-mass aluminum-foil mirrors to concentrate the everpresent sunlight. In space, a passive aluminum mirror with a mass of less than a ton and a dimension of about 100 meters, could collect and concentrate, in the course of a year, an amount of solar energy which on earth would cost over a million dollars at standard electricity busbar rates.

Electrical energy for a space community could be obtained at low cost, within the limits of right-now technology, by a system consisting of a concentrating mirror, a boiler, a conventional turbogenerator and a radiator, discarding waste heat to the cold of outer space (Figure 5). It appears that in the environment of a space community residents could enjoy a per capita usage of energy many times larger even than what is now common in the United States, but could do so with none of the guilt which is now connected with the depletion of an exhaustible resource.

THE BOOTSTRAP METHOD

Until recently, it had been assumed that the only practical way to locate or assemble an object in a high orbit was to build it or its components on earth, and then to lift it out of the earth’s gravity, through the atmosphere, by rockets. One might fairly call this the "brute force" method. In space colonization, we would like to use a far more economical alternative, a kind of "end run" instead of a power play through the middle. It is outlined in Figure 6

Here on the surface of the earth we are at a very low point in the gravitational map of the solar system. In energy terms, we are at the bottom of a gravitational well which is 4,000 miles deep. This is reflected in the fact that we must accelerate a spacecraft to a speed of more than 25,000 miles per hour before it can escape the earth’s gravity and go as far as lunar orbit. In a sense, we are the ’’gravitationally disadvantaged."

We are fortunate that we have another source of materials, which lies at a much shallower point in the gravitational map of the solar system. The energy required to bring materials from the moon to free space is only 1/20 as much as from the earth. Further, the moon has no atmosphere: a disadvantage if we wanted to live there, but a great advantage if we want to obtain from the moon materials at low cost. On the moon we could assemble a launching device for the acceleration to escape velocity of lunar surface raw materials. Such a machine does not require high-strength or high-temperature materials, and the methods for building it are well understood. One design of that kind is called a (mass-driver); it would be a linear electric motor, forming a thin line several miles long, which would accelerate small 10-pound vehicles we call buckets. At lunar escape speed the bucket would release its payload, and would then return on a side track for reuse. Only the payload would leave the mass-driver, so nothing expensive would be thrown away. The mass driver would be an efficient machine, driven by a solar-powered or nuclear electric plant, and our calculations show that in six years of time it could launch to escape distance from 300 to 1000 times its own mass. A collector at escape distance from the moon would accumulate materials, and there, with the full solar energy of free space, they would be processed to form the metals, glass and soil of the first space community.

With the help of that economy measure, the mass lifted from the earth need only be a few percent of the mass of the colony itself. We would have to bring the components of the mass-driver and of a lunar outpost (Figure 8), components of a construction station in lunar orbit for the processing and assembly of materials, and those elements, mainly carbon, nitrogen and hydrogen, which are rare on the moon. By so avoiding the need for prior development of advanced high-capacity lift vehicles, we could also carry out the construction of the first colony on a fast time scale, possibly beginning as early as 1980-82 when the space shuttle will come into operation. For the lifting of freight to low orbit, we would need one new vehicle, of a type which the aerospace experts call a "dumb booster": a freight rocket based on the same type of engines already developed for the shuttle. For operations in space above low orbit a chemical tug would be sufficient. My recommendation would therefore be strongly supportive of a recently initiated NASA study of the design of a shuttle-derived heavy-lift vehicle, and of a chemical tug whose segments could be lifted to orbit by the shuttle.

In this approach, we would establish a productive beachhead in space as early as possible, and as the resulting traffic increased would let its revenue assist in paying for the further development of more advanced launch vehicles.

LUNAR MATERIALS

At the time of the Apollo project we did not think of the moon as a resource base. The moon landings, originally motivated by national pride and a sense of adventure, became scientific expeditions and as such returned a high payoff in knowledge.

Now, though, it is time to cash in on Apollo. It was impossible to plan in a rational way a program of space colonization until the Apolio lunar samples were returned for analysis. From those samples we now have the analyses of the lunar soil and rock. Table 1 summarizes representative data from soils at the Apollo II landing site:

UNSELECTED APOLLO II SOIL SAMPLE

TABLE 1

Oxygen	40%
Silicon	19.2%
Iron	14.3%
Calcium	8.0%
Aluminum	5.6%
Magnesium	4.5%

This unselected sample is more than 30% metals by weight.

The baseline mass-driver would be capable of transferring from the moon from 1/2 million to 2 million tons of such materials within a six-year period: that is, from 28,000 to over 100,000 tons of aluminum, 70,000 to 280,000 tons of iron, and corresponding amounts of the other lunar materials. Strangely, though the lunar surface is devoid of life, its most abundant element is the one which we need in every breath we take: oxygen. That oxygen, transported to free space and unlocked from its binding metals by solar energy, would be usable not only for an atmosphere but to fuel rocket engines, reducing by 85% the requirement for fuel carried from the earth.

The lunar surface materials are poor in carbon, nitrogen and hydrogen; in the early years of space colonization these elements would have to be brought from earth. They would be reused, not thrown away. For every ton of hydrogen brought from earth, nine tons of water could be made at the colony site, the remaining eight tons being oxygen from the processing of lunar oxides.

The removal of half a million tons of material from the surface of the moon sounds like a large-scale mining operation, but it is not. The excavation left on the moon would be only 5 yards deep, and 200 yards long and wide: not even enough to keep one small bulldozer occupied for a five-year period.

A few years after the first space community is built we can expect that transport of asteroidal materials to L5 will become practical. No great technical advance is required for that transition; the energy-interval between the asteroids and L5 is only about as great as between the earth and L5. Once the asteroidal resources are tapped, we should have not only metals, glass and ceramics, but also carbon, nitrogen and hydrogen. These three elements, scarce on the moon, are believed to be abundant in the type of asteroid known as, carbonaceous chondritic. Therefore I add my support to those who for several years have been recommending an unmanned rendezvous-probe mission to a selected asteroid. Such a mission has already been studied in detail by NASA, and is well within present technical feasibility If conducted in the late 1970’s or early 1980’s, with the aim of assaying a carbonaceous chondritic asteroid for its C, N. H content, such a mission would serve the same function that oil well prospecting now serves on earth: the finding and proving of necessary resources for subsequent practical use. No great technical advance is required for that transition; the energy-interval between the astroids and L5 is only about as great as between the earth and L5. Once the astroidal resources are tapped, we should have not only metal, glass and ceremics, but also carbon, nitrogen and hydrogen. These three elements, scarce on the moon, are believed to be abundant in the type of astroid know as carbonaceous chondritic. Therefore I add my support to those who for several years have been recommending an unmanned rendezvous-probe mission to a selected asteroid. Such a mission has already been studied in detail by NASA, and is well within present technical feasibility. If conducted in the late 1970’s or early 1980’s, with the aim of assaying a carbonaceous chondritic asteroid for its, C, N, H content, such a mission would serve the same function that oil well prospecting now serves on earth: the finding and proving of necessary resources for subsequent practical use.

ISLAND ONE

The first space community will be economically productive only if talented, hard working people choose to live in it, either permanently or for periods of several years It must therefore be much more than a space-station; it must be as earth-like as possible, rich in green growing plants, animals, birds, and the other desirable features of attractive regions on earth.

Within the materials limits of ordinary civil engineering practice, and within an overall mass budget of 1/2 million tons (about the same as the mass of a super-tanker), several designs for this first

’’Island in Space" have evolved. One such geometry is shown in Figure 3. I am indebted to Field Enterprises, Inc. for pemmission to show this figure, which is from the 1976 edition of **Science Year**.

All of the geometries we have studied are pressure vessels, spherical, cylindrical or toroidal, containing atmospheres and rotating slowly to provide a gravity as strong as that of the earth. With gravity, good long-term health can be maintained; the colonists should experience none of the bone calcium loss suffered by the Skylab astronauts in their zero gravity, non-rotating environment.

Physiology experiments in rotating rooms on earth indicate that humans can acclimatize to quite high rotation rates, some to as much as one rotation every six seconds. A fraction of the space-community population will, though, "commute" daily between the rotating earth gravity environment and zero or low gravity work areas. We must therefore hold the rotation rate to a rather low value, to avoid inner ear disturbances. It is quite possible that our lack of information is forcing us toward unnecessary conservatism on this point. It would be quite useful to carry out long term physiology experiments during the space-shuttle program, to examine rotation effects in the space environment. on earth our simulation of these effects can never be more than approximate.

Conservatism on this requirement has, though, led us quite recently to a new and possibly more attractive alternative design (Figures 10, 11). It allows for natural sunshine, a hillside terraced environment, considerable bodies of water for swimming and boating, and an overall population density characteristic of some quite attractive modern communities in the U.S. and in southern France.

It is startling to realize that even the first-model space-community could have a population of 10,000 people, and that its circumference could be more than one mile. From the valley area, where as in Figure 3 streams could flow, a ten-minute walk could bring a resident up the hill to a region of much-reduced gravity, where human-powered flight would be easy, sports and ballet could take on a new dimension, and weight would almost disappear. It seems almost a certainty that at such a level a person with a serious heart condition could live far longer than on earth, and that low gravity could greatly ease many of the health problems of advancing age. In Figures 10 and 11, the outer ring is a toroidal volume used for agriculture. It too would rotate to provide earth gravity, but more slowly; its rotation would compensate for the gyroscopic action of the main living habitat, and permit the axis of the habitat always to point toward the sun.

Just beyond the hemispherical ends, a few minutes from the residential areas, there could be large assembly areas, with low or zero gravity. In one design now being studied these areas would be cylindrical, rotating once every 70 seconds, and would provide 1-1/2% of earth-gravity. There, a ton of mass would weigh only 30 pounds, but tools and equipment would stay put when set "down." Workers commuting to those areas would experience rotation-rate changes of no more than one rpm.

COST DRIVERS IN SPACE-COLONY CONSTRUCTION

During the past six months, independent cost estimates for the construction of Island One have been made by the NASA Marshall Space Flight Center. These are not at the stage of an official report, but excellent cooperation and communication between Princeton and NASA/MSFC has allowed identification of some important cost-drivers in the construction of a first colony. These are:

1. Frequency and efficiency of crew-rotation between the earth and L5, and between the earth and the moon, during the construction period.
2. Extent of resupply needed during construction: This item can vary over a wide range, depending on the atmospheric composition needed at the construction station, and whether food is brought in water-loaded or dry form.
3. Atmospheric composition: The structural mass of Island One is proportional to the internal

> atmospheric pressure, but independent of the strength of the artificial gravity produced by rotation. Nitrogen constitutes 79% of our atmosphere on earth, but we do not use it in breathing: to provide an earth-normal amount of nitrogen would cost us two ways in space colony construction, because structure masses would have to be increased to contain the increased pressure, and because nitrogen would have to be imported from the earth. A final choice of atmospheric mix would be based on a more complete understanding of fire-protection.

Parenthetically, the tragic Apollo fire of 1967 is not a valid guide in making this choice. It occurred in a confined capsule, with no water supply available, and in an atmosphere of nearly pure oxygen at almost 15 pounds per square inch of pressure - nearly five times earth-normal. A space colony would operate at 1/5 to 1/6 of that oxygen pressure, in a very large environment, with abundant water available everywhere.

A modest program of experiments on earth could add greatly to knowledge on this point, and might save a great deal of money. Lacking such experiments, present designs are conservative, based on carrying a substantial pressure of nitrogen.

COSTS AND PAYOFFS

A range of costs for large-scale engineering projects is listed in Table 2, for scale:

APPROXIMATE COSTS OF ENGINEERING PROJECTS,
IN 1975 DOLLARS

TABLE 2

a) Panama Canal	2 Billion Dollars
b)Space Shuttle Development	5-8 Billiion Dollars
c) Alaska Pipeline	6 Billion Dlloars
d) Advanced Lift Vehicle Development	8-25 Billion Dollars
e) Apollo	39 Billion Dollars
f) Super Shuttle Development	45 Billion Dollars
g)Manned Mission to Mars	100 Billion Dollars
h) Project Independence	600-2000 Billion Dollars

(The re-or devaluation of the dollar forward or backward to 1975 makes each of the numbers in Table 2 uncertain by at least 25 %)

The Apollo project provided trips to the moon for a total of twelve men, at a cost of about 3 billion dollars per man. In space colonization we are considering, for Island One, a thousand times as many people for a long duration rather than for only a few days. With the cost savings outlined earlier, it appears that we can accomplish this thousand-fold increase at a cost of at most a few times that of the Apollo project. It does not appear worthwhile to make a new, detailed cost estimate at this time for the establishment of Island One. Design details are changing as additional people join the studies, new optimizations and new solutions to technical problems are being found, and the actual cost of construction will clearly depend not only on that work in progress, but on the details of project management. Rather, I will summarize in Table 3 estimates made up to this time, characterizing the approach used for each estimate.

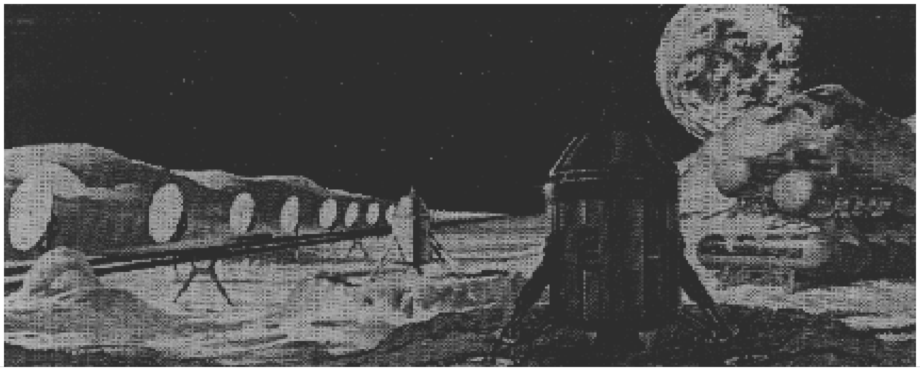
PRELIMINARY ESTIMATES OF COST FOR L5 PROJECT
(ESTABLISHMENT OF ISLAND ONE) IN 1975 DOLLARS

TABLE 3

a) Physics Today, September 1974 (G.K. O'Neill) 33 Billion Dollars (0.85A)	Spartan. No crew rotation; oxygen atmosphere; little resupply. Power plants on moon and L5 at 10 Kg/Kw.
b) International unpublished report, NASA/MSFC, Jan. 1975 (E. Austin, et al.) as modified April 1975. 200 Billion Dollars (5.1A)	Luxurious. Includes chemical and nuclear tugs, super shuttle development, orbital bases, oxygen/nitrogen mix, extensive crew rotation, resupply at 10 lbs./man-day, power plants at 100 Kg/Kw.
c) NASA/MSFC re-estimate April 1975 (E. Austin) as reported to meeting at NASA Headquarters (J. Yardly, J. J Disher, R. Freitag and others) 140 Billion Dollars (3.6 A)	High, Unnecessary lift system removed, but still includes oxygen/nitrogen mix, crew rotation, resupply at 10 lbs./man-day, power plants at 100 Kg/Kw.

(Note: the unit "A" is the cost of Project Apollo in 1975 dollars.)

Detailed conversations with NASA personnel involved in cost estimation indicates a desire on their part, natural enough, to include in the estimates a contingency factor for problem areas not yet identified. The higher estimates listed above appear to include such contingency factors. Within the uncertainties characteristic of the early phase of any project, a figure of 100 billion dollars with limits of 50 billion dollars either way may be as close an estimate as can be made at this time; that is, 5% to 15% of Project Independence, or 2.5 times the cost of Project Apollo.



Artist’s view of a lunar mining outpost and mass-driver, powered by solar energy. All the materials for construction of the first 10,000 person space community could be obtained from an excavation 5 yards deep by 200 yards long and wide.

The payoffs from the existence of Island One can be estimated in several ways. One, crude but reasonable, is to assign to the material output of Island One’s industries an added value, per pound of finished products, equal to the lift cost of bringing similar products from the earth. For shuttle-derived heavy lift vehicles, and productivities typical of heavy industry on earth, that added value is in the range of 40-160 billion dollars/year; equal, that is, in one year to the whole cost of construction of the first colony. That added value exists only for those finished products whose end use is in high orbit (geosynchronous, L5 or beyond). One such product, of prime importance at this time, is satellite solar power stations.

ENERGY FOR THE EARTH

Both the oil-consuming nations and the underdeveloped third world are vulnerable to the threat of supply cutoff from the Middle East. The only permanent escape from that threat lies in developing an inexhaustible energy source with a cost so low that the source can eventually be used to produce synthetic fuels economically.

The intensive development of nuclear energy does not seem to be an adequate solution: nuclear power is moderately expensive (15 mils/KWH) and its use encounters considerable public resistance. Nuclear proliferation and radioactive waste disposal are real problems. Fossil fuels are scarcer now, and intensive strip-mining for coal will almost inevitably further damage the environment. Solar energy on the earth is an unreliable source, suitable for daytime peak loads in the American southwest, but not clearly competitive in most applications.

Solar energy converted to electricity in space, beamed to earth by microwaves, and reconverted here to ordinary electricity, is being studied with increasing seriousness (Figures 12, 13). Already an overall transmission efficiency of 54% has been demonstrated in tests. Delay in realization of satellite solar power stations (SSPS) is mainly due to the problem of lift costs: even for the lightest power plants which seem attainable, and for the lowest lift costs which a very advanced (non-shuttle-derived) launch vehicle could achieve, the economics of the SSPS seem to be only marginal.

Our studies indicate that the construction of SSPS units at the space colony, from lunar material processed at L5, should be economically quite competitive even from the start. The energy interval between L5 and geosynchronous orbit is small, so SSPS units built at L5 could be relocated rather quickly and easily in operational orbits, to supply energy for the earth.

Construction of solar power plants at L5 would overcome four basic objections that have been leveled at the ground-launched SSPS concepts:

1. That they can demonstrate economic feasibility only if a whole series of goals can be reached, each within close limits.
2. That since those achievements could at best only be reached by pushing the state of the art very hard. there is no room for dramatic reductions of energy cost with further development.

3. Ground-launch methods depend critically on the achievement of very low lift costs to geosynchronous orbit. This would require development costs of some tens of billions of dollars, and the technology involved is not well enough understood that success would be certain.
4. In ground-launched SSPS concepts the entire weight of the power plant has to be carted up through the atmosphere. The quantities involved (up to half a million tons per year, if the SSPS program is to be of substantial benefit) are high enough that environmentalist objections, particularly regarding the ozone layer of the atmosphere, might be strong enough to hamper the program seriously, as has happened in the case of nuclear power.

With construction at L5, the technologies of power plant development and of rocketry need not be strained. No advanced rocket vehicles are needed, and power plant technology of the present day (Figure 5) is sufficient. This contrast is evident in Table 4, in which the critical parameters of SSPS design and construction are compared for two earthlaunched systems and for one built at a space community. In every case the target figure required for SSPS construction at L5 is more conservative than for either of the earth-launched systems, generally by a large factor.

SATELLITE SOLAR POWER STATION
DESIGN PARAMETERS
(required for economic viability)

TABLE 4

	Earth-launched turbogenerator (Boeing Aircraft Study)	**Earth-launched photovoltaic (A.D. Little Co.)**	**L5 built turbo-generator (this report)**
Power plant mass per unit power	5 Kg/Kw	0.8 Kg/Kw	10-15 Kg/Kw
Component lift cost from earth	$77/Kg	$220/Kg	($940/ Kg)
Efficiency of trans-mission	70%	65%	56-63%
Interest rate	8%	-	10%
Busbar power cost (initial)	25 mils	-	15 mils

In Table 4, the list cost from earth is not of great importance in the L5 construction case, because only a small amount of mass from the earth would be required in building an SSPS at L5. The figure listed is, though, the same one used for cost estimates of the construction of the space-colony itself.

The economics of SSPS construction at L5 requires a fresh viewpoint in that construction almost no materials or energy from the earth would be required. The colony itself, once established, would be self-sustaining, and its residents would be paid mainly in goods and services produced by the colony.

In the summary which follows, the economic input to the combined colony/SSPS program is taken as the total development and construction cost of the first colony, the cost of lifting the materials needed from the earth for subsequent colonies and for non-colony-built SSPS components, a payment in dollars on earth of $10,000/person-year to every colonist, representing that portion of salaries convertible to goods and services on earth (for subsequent use on visits or, if desired, on retirement) and a carrying charge of 10% interest on the total investment (outstanding principal) in every year of the program.

The economic output (yield) from the program is taken as the revenue from power at busbar rates, initially 15 mils/Kwh. The SSPS plants are assumed to be in base-load service, at 95% utilization. To support that assumption, busbar rates are reduced at four-year intervals, to 10 mils/Kwh.

This should be regarded as only the first approximation to an accurate economic analysis. It is equivalent to discounted economics with a 10% discount rate. Knowledge of the input parameters is not yet precise enough to justify analysis in greater detail.

We have examined several cases, in each of which the first space-colony is used as a production site for construction of additional colonies as well as for solar power plants. This "regenerative" effect is essential: a real solution to national and international energy problems can only be achieved by the production of many, not just a token few, satellite power stations. For a high production rate the total number of space colonies must be increased, so that a total work force of 100,000-200,000 people in space can be maintained.

Figure 14, Figure 15 and Figure 16 present the results of the analyses. In all cases, it was assumed that the construction of the first colony would require six years of effort, and that thereafter each colony could replicate itself in two years. This tripling of production rate represents devoting 4000 people of a 10,000 person colony to new community construction (vs. 2000 people available at the construction site during the building of Island One) and in addition, an assumed learning-curve efficiency increase by a modest factor of 1.5.

The remainder of the work force, 6000 persons, was assumed to be committed to SSPS construction, and to produce two SSPS units per year. The productivity implied, 13-25 tons/person-year, is similar to that of heavy industry on earth (The use of photovoltaic cells, if their progress makes them competitive, is not ruled out. Silicon, their principle constituent is abundant in the lunar raw material.)

The question of productivity and the effects of automation within the weather-free, zero-gravity environment of a space community’s assembly region deserves intensive study; so far it has been possible only to verify that the estimates given are consistent with earthbound experience. I anticipate that the residents of the early space communities will be nearly all employed in production, support services being automated as far as possible.

In Figure 14 a time-line is developed based on making an early start, with the shuttle and a shuttle-derived freight vehicle. A medium-to-high estimate (96 Billion Dollars) of the cost of Island One is assumed, and an additional 82 Billion Dollars for the transport of carbon, nitrogen, hydrogen and colonists to the later colonies is added. New colony construction is halted after the 16th colony, due to market saturation.

By the 13th year of this program (the year 1995, given a starting date of 1982 for major construction activity, implying intensive design beginning by 1976) the L5-built SSPS plants could fill the entire market for new generator capacity in the U.S. Given the rapid growth of the manufacturing capacity and the possibility of busbar power cost reductions, true "energy independence" for the nations taking part in the L5 project could occur before the year 2000, with a shift to production of synthetic fuels. In the words of one exuberant young economist at the NASA/Ames-Stanford University 1975 Summer Study, "We can put the Middle East out of business!" In my own view, I would far prefer to see a cooperative multinational program formed, based on participation by all interested nations. If the L5 project continues to look feasible, it would be in the interest not only of energy-consuming industrial nations, but of the OPEC nations to take part in it, because if these numbers are correct, the market value of Middle Eastern oil could drop irreversibly before the end of this century.

A cost-benefit analysis of the Figure 14 case has been made, and yields a benefit/cost ratio of 2.7. A favorable benefit/cost ratio also results from a variety of different input assumptions, with assumed total program costs up to 280 Billion Dollars. The favorable result is sharply sensitive to only two parameters: speed and interest rates. An interest-rate reduction to 8% approximately doubles the benefit/cost ratio; an increase to 13% reduces it to near 1.0. A stretch-out of the program would be disastrous as regards both energy benefits and the benefit/cost ratio.

Figure 15 indicates how rich a source of wealth the space-colony program could become. By year 11 (1993 on the fastest-possible time-scale) the energy flowing to the power grids on earth from L5-built SSPS units could exceed the peak flow rate of the Alaska pipeline. By year 17 the total energy so provided could exceed the total estimated capacity of the entire Alaska North Slope oil-field.

Figure 16 shows the effect of delay (as for example to develop advanced lift vehicles prior to space-community construction). The benefit/cost ratio would not be greatly improved, and total program costs would be reduced only by a factor of two. even if vehicle development costs and later operating costs would be delayed by the full 7-year development time of the new vehicles. This does not, therefore, seem to be a wise route to take, but requires further study.

THE U.S. AS ENERGY EXPORTER

The underdeveloped third-world nations are now trying to industrialize, in order to increase their living standards and economic security. If the example of the industrialized world is valid, their success in that attempt may be a powerful element in reducing the runaway population growth rates which now threaten their progress and, in the long run, political stability.

Because of widespread concern over decreasing energy and materials supplies, we are now viewed by many as exploiters of scarce resources. This has been a significant factor in hostility toward the U.S. and toward other industrial nations. With a program of power plant construction at L5 we could return, at little cost in energy and materials from the earth, to our traditional role as a generous donor of wealth to those in need. In this case the wealth we could provide would be in the form of energy to third-world nations, and ultimately of "beachhead" colonies for their own progress. The L5 project would give us the opportunity to act with generosity, yet with little cost to our own national resources.

RESPONSE FROM GOVERNMENT AND THE PUBLIC

It is a tribute to some remarkably perceptive men within NASA and the NSF that, despite their unfamiliarity a year ago with the modern concept of space colonization, they have now encouraged its development and have even begun to support it with a small amount of funding (approximately $40,000 in 1975).

For a person with a technical education, it is logical to assume, given a new concept, that "if I haven’t heard of it before, it must be as far off as the 21st Century." Usually that attitude is justified. Space colonization, though, is a curious exception. It is a technical concept realizable without any new breakthroughs in materials technology or technical understanding. We are unfamiliar with it only because, until the Apollo samples were returned, no one could have put together all the necessary components of a space colony program in the form of a complete system with defensible numbers.

In contrast to that situation, we have examples of development programs which do require breakthroughs in the understanding of new physical phenomena, but which have become accepted parts of our research effort simply because we have been hearing about them for a long time. One classic example is hydrogen fusion power. It has been discussed in public for thirty years, and has been worked on in research for more than twenty years. In effect, it has become institutionalized. Although no responsible advocate of fusion power will commit himself as to when fusion power will become economically competitive, the idea has been around for so long that its eventual success is accepted as inevitable by most people. (My own view is that fusion power research should continue to be supported, on what I would regard as the off-chance that it might someday be competitive with L5-built satellite power stations.)

Space colonization, and the construction of satellite power stations at L5, requires no such breakthrough in the understanding of a new physical regime. It is mainly civil engineering on a large scale, in a well understood, highly predictable environment. It does not even require the development of a new rocket engine. Some, fortunately a substantial number, of responsible administrators in NASA have been quick to grasp this distinction, and to see the potentialities of space colonization for the agency and for the public. For others, though, it has been almost an embarrassment, because the assignment of space colonization to its proper place in time sequence (that is, now) implies that all previous planning has omitted an important option. In the case of NASA, proper recognition of the space colony concept is further impeded by the orders previously given to the agency, and never rescinded: to plan on constant or decreasing funding levels, to bring up no surprises, and as far as possible to become invisible.

The evidence of the past year indicates that in terms of public response space colonization may become a phenomenon at least as powerful as the environmental movement. Since the first small, informal conference on that topic, in May 1974, a rapidly increasing number of articles about it have appeared, in many newspapers and magazines, and all have been quite favorable. Several are still in press at this time. Radio and television coverage has also increased rapidly.

Popular response in letters to Princeton has been strong. of these letters, more than 99% are favorable. Also, encouragingly, less than 1% of all mail is in any way irrational. Many of the correspondents offered volunteer help, and are actively working at the present time in support of the space colonization concept. The letters express the following reasons why this concept, in contrast to all other space options now extant, is receiving such broad support:

1. It is a right-now possibility It could be realized within the immediate future.
2. In contrast to the elitisim of the Apollo project or of a manned mission to Mars, it offers the possibility of direct personal participation by large numbers of ordinary people. Many of the correspondents, from hard hat construction workers to highly-educated professional people, see themselves as prospective colonists.
3. In contrast to such technical options as the supersonic transport, nuclear power or the stripmining of coal, it is seen as offering the possibility of satisfying real needs while preserving rather than further burdening the environment.
4. It is seen as opening a new frontier, challenging the best that is in us in terms of technical ability, personal motivation and the desire for human freedom. Many correspondents refer to space colonization by analogy to the discovery of the New World or to the settlement a century ago of the American frontier.

One letter, unusually well-expressed but otherwise not atypical, concludes:
"I would greatly appreciate being informed of your own personal assessment of what can and should develop out of your space colonization ideas. If they do in fact have the social and human potential

that they appear to me to have, any unnecessary delay in their realization would seem to me to be unthinkably irresponsible."

CURRENT RESEARCH

During 1975 the major events in space colonization have been the Princeton University Conference (co-sponsored by NASA, the NSF, Princeton University and the American Institute of Aeronautics and Astronautics. Cf. ref. 5 when available), and the NASA-Ames-Stanford University Summer Study on Space Colonization (ref. 6 when available).

Writing at the midpoint of the Summer Study, the principle results so far can be listed as:

1. Verification that shuttle-derived lift vehicles would be adequate for the establishment of Island One.
2. Verification that agricultural-yield figures used in ref. 2 were conservative by approximately a factor 2.
3. New, tighter requirements on allowable rotation rates.
4. Verification that productivity figures so far in use are in the right general range.
5. More detailed analysis of discounted economics, verifying a high benefit/cost ratio.
6. New, more detailed results in the areas of colony geometry, materials processing, and mass-driver payload guidance.

In the period since May 1974, when this concept first came to public attention, research on it has progressed at what I would describe as the fastest possible rate. In the year beginning in September 1975 this progress will slow unless some extraordinary mechanism is found to provide funding for in-depth studies to be carried out by the government agencies and the private sector. A level of 0.5 -1.0 Million Dollars is probably adequate; to provide more at this time would probably result in some waste and inefficiency.

APPENDIX

IS THE SURFACE OF A PLANET REALLY THE RIGHT PLACE FOR AN EXPANDING TECHNOLOGICAL CIVILIZATION?

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