THE ECONOMICS OF SPACE INDUSTRIALIZATION: A PHASED APPROACH

Dr. Klaus P. Heiss
ECON, Inc.
900 State Road
Princeton, NJ 08540

Abstract

The total systems cost of the first L-5 unit, comprising 10,000 people, with the function of generating 17 Quads/year* net energy output (equivalent to the total U.S. electricity production in 1975) is conjectured to be about $500 billion. This estimate is larger by a factor of 2 to 5 than hitherto estimated.

Nevertheless, even using these high cost estimates, the system can be proven to potentially break even economically by 2075, and regenerate itself thereafter with large potential cost reductions. No use of lunar bases or materials is made for the first L-5 unit.

If the economic break-even point indeed is reached by 2075, then an irreversible point for essentially unlimited expansion will have been crossed. It is furthermore pointed out that the technology base and necessary funding to bring an L-5 unit about by the year 2075 may be the simple outgrowth of the current and foreseeable U.S. space program. Five phases of space industrialization are outlined, that will lead to a space habitation capability, where each phase has economic merits all its own, i.e., not requiring large-scale and very long term, risky commitments.

I. Introduction

In a broad sense, the coming about of industrialization and/or the location of industries is determined by the following factors: Advantages in natural resource endowment (coal, iron ore, other resources), labor, (including human capital in the form of education and skills), and location (transportation convenience). From an Earth-based view, space offers one single unique advantage: an abundance of energy resources. Most other properties of space, today, are as yet little understood; for example, extremely low temperatures, low gravity, benign environment and possibly other attributes of space may turn out to be added incentives for future space industrialization. In the meantime, any large-scale space industrialization will necessarily be based on the key advantages of space, as a source of energy for mankind.

The theme of the following paper is built around establishing a rough order of magnitude estimate of the necessary magnitude and scale of an economically self-sustaining energy base in space. The questions asked include:

1. What are the likely costs of a space energy base such as proposed by O'Neill?
2. What is the break even annual net energy output from an "open" system to Earth to cover amortization, labor, interest, and other support costs before achieving autarchy? ("Open" in the sense of needing support from Earth.)
3. What level of economic activity, that is, value added, needs to be generated by a closed system for it to be self-supporting; and what is the expectation that it can repay Earth for this costly "entry" ticket?
4. What is the likely time scale for such a first unit, and for the establishment of a viable closed system? ("Closed" in the sense of no support from Earth, including repayment of all outstanding debt.)
5. What are the likely phases in the space program in moving toward a closed, self-supporting space system (i.e., the phases of space industrialization)?

II. Rough Order of Magnitude Estimates of Full-scale Space Colony

Any attempt to estimate the cost of a system as imaginative as an L-5 unit of 10,000 people, living on a self-sustaining basis in space many decades from now, may seem impossible. Nevertheless I will attempt to arrive at an estimate--within reason--by "brute" scaling of the proposed system from known--current or projected--facts and figures that can be checked and documented.

First, the cost estimates, rough as they are, are based on a detailed economic analysis of space-based solar power conversion and delivery systems (SSPS) performed by Arthur D. Little, Inc., Raytheon Company, Grumman Corporation, and ECON, Inc.** The baseline unit used for the rough order of magnitude cost estimates is a 5-gigawatt

---

*1 Quad = 10^{18} Btu.

**Space-Based Solar Power Conversion and Delivery Systems Study, (five volumes), ECON, Inc., prepared for Marshall Space Flight Center, NASA, March 1977.

photovoltaic SSPS, and assumes space transportation and solar cell production costs projected to the year 1995. This baseline is used for the order of magnitude systems cost estimate of an L-5 base unit.

The SSPS configuration assumes an assembly in low Earth orbit (LEO) requiring 700 to 800 people in low Earth orbit for assembly of four SSPS units a year (about 200 people per unit). No space manufacturing in the sense of processing of raw materials to final products is envisioned in this scheme. Rather, all components are launched from Earth. The energy output per year for this unit is about .33 Quads.

The cost estimates, for the 5-gigawatt SSPS configuration, allow for risk and cost uncertainties: While deterministic estimates have ranged somewhere between $7 and $8 billion, a risk and cost uncertainty analysis shows that, with the same performance requirements, the most likely cost of an SSPS unit is about $15 billion (see Table 1). Even at that level, the remaining cost risk is still $4 billion either way. In terms of man-years per unit, that corresponds to about 200,000 men at current aerospace man-year costs. (These range today from $50,000 to $75,000, including overhead.)

Taking the 200 people in low Earth orbit needed per SSPS unit (800 for 4 units a year), and the 200,000 man-years per unit of Earth-based workers, the work to date on SSPS clearly implies that at the estimated costs and the necessary support from the ground--200 people per unit can be sustained and can operate for extensive periods of time in low Earth orbit to provide useful, essential work. The SSPS estimates indicate roughly a ratio of 1,000 Earth-based man-years for every man-year in orbit.

This ratio of necessary ground support for space-based workers of 1:1000 is maintained for scaling purposes for any large structure, in low Earth orbit (LEO), geosynchronous orbit (GEO) or at L-5.

There are several ways of scaling cost estimates for an operational space colony comprising 10,000 people. For one, to assemble and support 10,000 people in orbit will require at least fifty times the workload and output of 200 people needed in low Earth orbit to assemble one SSPS unit. This all the more so, since the assembly and fabrication in low Earth orbit--requiring about 200 man-years per unit--does not comprise any materials processing;

Table 1 SSPS Baseline Cost: The Effect on Cost and Cost Risk* of Changes in the State-of-Knowledge (1995 Technology Base)

	Item	Range of Values ($ Billions, 1974)					
		Best		Most Likely		Worst	
		Mean Cost	Cost Risk	Mean Cost	Cost Risk	Mean Cost	Cost Risk
	Nominal**	3.76	--	14.92	3.86	144.83	--
Major Cost- and Risk-Driving Factors	Rate of Manned Assembly	11.56	1.90	15.57	2.87	21.91	5.16
	Fraction of Satellite Assembled by Man	13.05	2.43	14.53	3.05	17.56	4.56
	Rate of Remote Assembly	13.93	3.42	14.96	3.61	16.65	3.67
	Solar Cell Efficiency	13.74	3.26	14.27	3.59	17.04	4.13
	Specific Mass of the Solar Blanket	13.34	2.87	14.67	3.24	15.92	4.13
	LEO Space Station Unit Cost	12.99	2.83	14.34	3.07	17.74	4.77
	Solar Array Blanket Specific Cost	13.33	3.49	13.84	3.42	17.27	3.48

*"Cost Risk" is the standard deviation of the cost estimate

**The nominal case includes: for best value, a deterministic cost estimate using best values for each design factor; for most likely value, a Monte Carlo simulation using the full range for each design factor; for worst value, a deterministic cost estimate using the worst values for each design factor.

therefore, the L-5 unit cost scaled by 50 SSPS equivalents for 10,000 people supported from Earth, may be a lower limit estimate of the construction complexity and space-based manpower required to set up such a first base. On the other hand, a linear scaling of the SSPS estimates would indicate the feasibility of sustaining that number of people at fifty times the unit cost level of the baseline SSPS estimates (albeit at low Earth orbit).

Another estimate helpful to visualize the magnitude of such a project centers around the question of how many SSPS units are needed to supply the total electric energy production of the United States today: The total U.S. electricity production in 1975 was about 17 Quads. With a net energy output per SSPS unit of .33 Quads, again about 50 SSPS units of 5 gigawatts each would be required to provide 17 Quads of net energy output.

Assuming 10 percent learning, and a first production unit cost of $15 billion, the cumulative total cost of 50 SSPS units is $500 billion (1975). This makes possible operations of about 10,000 people in low Earth orbit, transported for purposes of this analysis to L-5 at no extra cost. Some economies of scale may be expected; some "diseconomies" of scale may be encountered as well, having to do with extremely large structure assembly, unanticipated problems of closed, self-supporting systems (e.g., physiological problems, high energy radiation) and finally the complete absence in the SSPS cost estimates of any manufacturing in the sense of processing raw materials to final products.

The cost estimate of $500 billion has to be put into perspective: The total gross assets invested in U.S. electricity production (plant, equipment, machinery, etc.) by 1975 was about $200 billion. This estimate is based on a fixed asset to sales ratio for utilities of about 2.5. This latter ratio was arrived at from an analysis of financial data of all publicly listed utilities as to gross fixed asset values, (adjusted to constant 1975 dollars), sales and production data. The production of 17 Quads of energy requires fixed asset investments on Earth of a magnitude corresponding to about 40 percent of the estimated costs of the same capacity in geosynchronous orbit or at L-5. (In either case, the fuel cost to operate systems does not enter at all since only the fixed asset costs [i.e., no operating costs] are included in these estimates.)

Another consideration around the $500 billion estimate is the following: Assuming the capital equipment (asset) requirements for 17 Quads of net energy output to be fixed at $200 billion--irrespective of where and how the energy plants are deployed or what energy sources they use (fossil, nuclear, solar)--only $300 billion remain to (1) develop, test and deploy a heavy lift vehicle to low Earth orbit, (2) develop, test and implement all the ensuing technology needed for space-based, self-supporting, closed and reliable habitat systems, (3) develop, test and deploy an entirely new energy technology system and (4) transport the equipment to L-5 (raw materials, preprocessed materials, prefabricated parts, subassemblies, etc.).

In the SSPS study referenced above, with launch costs to geosynchronous orbit assumed to be $80 per pound, transportation costs amount to about 45 percent of total costs. This amounts to $225 billion of the remaining $300 billion. With capital equipment costs of $200 billion and transportation costs to LEO and GEO and L-5 of $225 billion, only $75 billion are available to finance the rather fantastic advances in energy technology and space habitat systems.

In this light, the $500 billion capital cost of 50 SSPS units may seem reasonable, if not low, as the production technology for ground-based systems by now is well understood (after 200 years of industrial development), while the construction and manufacturing technologies in space remain yet to be tested, developed and then implemented.

The $500 billion is the expected cost for 50 SSPS units deployed at geosynchronous orbit. We know with some certainty, including limited technology projections to 1995, that fifty identical units most certainly could be built over some period of time (25 years) with, at most, linear scaling of costs, since no resource constraints, other than labor, seem indicated.

To get a physical understanding of what "$500 billion" means, and of the possible time dimensions involved, it is useful to look at the manpower equivalent of these funds. The $500 billion for the L-5 unit, or the $15 billion for the 5-gigawatt SSPS, constitute mostly labor costs: direct labor cost as shown in the cost estimates for the SSPS, and indirect labor for the machinery, tooling and raw materials used, most of which would have to be designed and developed from scratch. At average aerospace industry costs per man-year of $50,000 to $75,000 (with overhead) and somewhat lower man-year cost in support industries (say $40,000), $500 billion in these technology-intensive sectors constitute about 10 million man-years. Yet, total aerospace employment as of 1977 is less than 1 million people, constituting at that mostly defense-related and aircraft work: Even if the total U.S. aerospace manpower were to be dedicated to the space industrialization project, it would take at least ten years after the deployment decision has been made for the system to accomplish a project of this magnitude.

A much more realistic assumption is that only space-related employment would be dedicated to such an enterprise (i.e., roughly 100,000 people). Under this assumption, that is, no expansion of space-related manpower (engineers, scientists, workers), the same enterprise would have to be stretched out over 100 years to achieve the total of 10 million man-years in constructing such a facility.

The same time horizon of 100 years also results if one were to take the current NASA/DOD total funding of space projects of around $5 billion a year: With constant funding (i.e., no expansion of the level of effort), the cumulative budget of U.S. space expenditures will add up to the $500 billion after 100 years. Even with a doubling of space expenditures, and their sole dedication to space industrialization, the time horizon is still 50 years after the deployment decision has been made. The average funding would be $10 billion a year, and the production rate of SSPSs initially would be less than one unit a year which, with learning, will increase beyond one unit to achieve a total production of 50 SSPS units over 50 years, or one equivalent L-5 unit.

Within the rough order of magnitude of the above estimates and considerations, the $500 billion number is not unrealistically high. In fact, it is not too different from the cost estimation results of, for example, Gerald W. Driggers (in "Establishment of a Space Manufacturing Facility") who estimates the cost of twenty 10-gigawatt SSPS units at about $200 billion (maximum uncertainty). The capacity of these 20 SSPS units is about 80 percent of that underlying the $500 billion cost estimate, while the risk and uncertainty considerations applied in our case to SSPS cost estimation are significantly larger than the numbers underlying his results. (The uncertainty ranges underlying our estimates are shown in Table 1.)

One major source of cost uncertainty may be the estimated lunar base cost for L-5 construction. A study performed by Aerospace Corporation in the early 1970s, assuming an advanced shuttle launch system to low Earth orbit as well as an advanced nuclear tug, estimated the transportation costs of maintaining a lunar base with three people on the moon, and six people in lunar orbit, with a 180-day turnaround cycle over a 10-year period, at between $7 to $8 billion (1969 dollars) or about $15 billion in today's dollars. While clearly a lunar base comprising from 100 to 300 people would not cost a hundred times as much in transportation cost, one has to consider on the other side that a lunar base would also imply the development of an entirely new, self-contained technology base in mining, chemical processing, manufacturing, transportation systems to L-5, life support, agriculture and environmental systems, the costs of which are not included in the "transportation cost only" estimate. Today, we have no detailed basis of knowledge to make any cost estimates with regard to sustained, long-term manned operations, in low gravity, in a completely alien environment such as the moon or L-5. Substantial research, development and testing will have to pay for such knowledge.

The above "brute force" cost estimate of the first L-5 unit, of course, does not envision the use of a lunar base--except if cost effective. Great caution on manufacturing materials and equipment for L-5 (or SSPS at geosynchronous orbit) is needed: it is one thing to prove that there are no technical reasons why mining and manufacturing of large masses of materials should not be possible--a significant finding; yet, to arrive at realistic total mining and manufacturing systems cost estimates is an entirely different matter. As a "rule of thumb"--bad as these usually are--any engineering cost estimate of a self-sustained lunar base industrial operation may have to be multiplied by five, on the simple observation that here on Earth--in a benign environment for man--a 1:5 ratio exists between manufacturing employment and rest of total population. The 5-factor may be regarded as a general inefficiency factor, or multiplier, or whatever. The fact is, only over very short periods of time do social systems, and groups, perform at 100 percent efficiency. In addition, a totally complete, new technology base has to be developed--highly energy intensive--and habitat for extensive, continued lunar base operations of many hundreds, if not thousands, of people. Hence some skepticism on the near-term economic feasibility of large lunar base operations.

III. Economic Break-Even Threshold

With an output of about 17 Quads, the gross revenue at 25 mills/kilowatt hour for this large facility would be about $50 billion a year. This revenue, reached when the fifty SSPS equivalent units are deployed (year 2075 on the outside), has at least to cover the total annual cost in steady state. Steady state in this case means that the system can cover all the costs incurred in operating, maintaining, as well as replacing the system, without any net growth. The key cost components have to include the following:

Depreciation

Allowing for economic, technical, as well as physical obsolescence, a depreciation schedule assuming a life of fifty years seems reasonable; that is, asset lives currently allowed for depreciation purposes of long-lasting structures. Obsolescence over fifty years would also be reached with a technological rate of innovation of under 2 percent a year. The depreciation cost then amounts to $10 billion a year, using a 50-year average life, and straight line accounting methods.

Manpower Cost

For a manpower of 10,000 people at L-5 and a ground support manpower of, say, ten times that with 100,000 people: While the ground support ratio in the deployment phase of the system is closer to 1 to 1,000, in fully operational systems a 1 to 10 ratio may be possible. At that rate, and expressed in today's dollars, the labor costs per year would be about $5 billion (at $50,000 per man-year).

Ground Systems/Distribution Cost

Ground systems/distribution cost is probably the most difficult part to estimate in this context. Reasonable estimates would indicate a number of about 20 percent of total gross revenues a year for such costs (Earth experience). This would mean about $10 billion a year.

Interest Cost

This cost is as "real" as any of the other aforementioned numbers. Interest cost reflects the opportunity costs of the resources put into space facilities, as against alternative uses of these resources for other purposes on Earth. While estimates of the real interest rate vary widely between industries and between government agencies, a 10-percent interest rate is used, for purposes of this evaluation. This implies an average interest cost of about $25 billion a year.

The total cost, grouped roughly as listed above, amounts to $50 billion a year, the estimated amount of gross revenues from the system.

This finding is of extraordinary significance. It means that even if the $500 billion estimate, high as it may seem, is the true cost of establishing such a system in space, with a net energy output by the year 2075 of 17 Quads, the L-5 colony will reach at that time a critical economic threshold: The gross revenue a year suffices to cover the total cost of the system! It means that with these cost estimates, and productivities per man-year as assumed in the above calculations, the system can sustain itself albeit with substantial support from Earth (100,000 man Earth based versus 10,000 man at L-5). The system becomes economically self-sustaining, although by no means independent of Earth.[*] The same $500 billion estimate also means that, to the extent current space expenditures contribute to a solution of "subsystem" problems in assembling an L-5 facility (large structures, rate of manned assembly in Earth orbit, EVA capabilities, space-based prototype power systems, and so on), no significant increase in financing of space expenditures is needed to indeed make a deployment of an L-5 community feasible by the year 2075. Rather, it would be the evolutionary result of space activities in a variety of fields over the next 100 years, a theme we will return to.

IV. Regeneration Capabilities and Costs

The above considerations, however, only show that the system will be and can be economically self-supporting by the year 2075. Nothing is said as yet whether the 10,000 people at L-5 can regenerate the system without physical support from Earth. The following considerations seem indicated by a total labor force limited to 10,000 people: The productivity of space colonists in reproducing a $500 billion unit over 50 years (the depreciation horizon) would be an extraordinary $5 million per man-year. Current productivity per aerospace man-years is roughly one hundredth of that. With a 2-percent productivity increase per year for aerospace workers, the productivity per man-year in the year 2075 would reach a level of $600,000. (In fact, if we project 100 years backward from 1975 to the year 1875, we see that indeed such productivity increases have occurred, even when expressed in constant dollars.) Thus the total "value added" capacity (ability to produce net value) of the space colonists in the year 2075 will be limited to about $6 billion a year.

Concurrent with increases in the productivity of space colonists, one can also expect further technology advances to reduce the second unit cost of the $500 billion system at L-5: Whereas the $500 billion estimate reflects 1995 technology (i.e., in space transportation, in solar cells and a variety of other items), technology innovation will continue after 1995. The long-term trend in the rate of technology change in the United States over the past decades has been about 2 percent; averaged over the past 100 years the rate of technical innovation may be closer to 3 percent. With such a range of the rate of technical innovation, the cost of the second L-5 unit, that is, the reproduction cost for the same capability of net energy output of 17 Quads a year, can be expected to drop by the year 2075 to a range of between $50 to $70 billion (2- to 3-percent cost decrease per year between the year 1995 to the year 2075). With first-unit costs of $500 billion, the reproduction of the same capability (not necessarily the same physical unit!) after the year 2075, can be expected to substantially profit from rates of innovation typically experienced in economic systems.

The conjectured annual second (replacement) unit costs for a decision in the year

---

[*] If only for pure economic self-interest, "Earth" would make quite sure of continued Earth dependence of L-5, certainly until repayment of all costs--with interest. There are many simple schemes to accomplish this.

2075 are shown in Table 2. The total costs per year are shown to range between $4.7 billion to $6.1 billion a year, whereas the value-added potential of 10,000 people by then will be about $6 billion a year. This indicates that indeed by the year 2075, after we have incurred the $500 billion in the deployment of the first L-5 system, and on top of that exported probably 10,000 of our most efficient and productive people to L-5, the colony can declare "independence" and reproduce its habitat over the following fifty years. While the establishment of the first L-5 unit has to occur in an "open" system, with economic and technical support from Earth, by the year 2075 technological change and productivity increases per man-year may make it possible that the second unit to replace L-5 can be accomplished entirely by relying on the resources, manpower and other support available in space, without any support from Earth. This point, when reached, will be the true threshold to unlimited expansion for mankind even when limited to rates of technical innovation and growth of between 2 and 3 percent a year, rates which we experienced on earth with all the constraints imposed by a very finite energy and resource base.

The key weakness in these considerations may be the assumption of 100-percent manpower use implied in the above calculations. A more realistic assumption would be that, of the 10,000 people at L-5, only 2,000 will be productively active. A ratio of 1 in 5 for "closed populations" may already be a courageous assumption: As of 1976 only 40 percent of the total U.S. population pursued any employment at all, and of those employed less than 40 percent were active in manufacturing activities or farming. That is only 16 percent of the total population were "productively active", in the sense of producing goods. The rest of a population is taken up by services (24 percent of total population), while 60 percent of the population are either too young or too old, or otherwise not active in the labor force. If anything will not change in space colonization, it is these general numbers of the efficiency of human society. If a 1 to 5 ratio (20 rather than 100 percent) for efficient manpower use is assumed, indeed the threshold of self-regeneration may be postponed by another 75 to 100 years beyond the year 2075. In any case, with the rough order of magnitude numbers indicated and shown above, the economic space colonization threshold seems to lie somewhere around the year 2075, and not before that date. This is not a long time span if we consider that the age of industrialization on Earth, initiated 200 or more years ago, has been completed at most only for 10 percent of mankind today. Why should industrialization in space proceed at any faster pace?

V. An Evolutionary Path: Likely Phases of Space Industrialization

Of course it is totally and completely unrealistic to expect today any commitment to investing $500 billion of our resources to the establishment of even such a lofty goal as space habitation. This is not to say that social systems in the past, even in the very recent past, have not dedicated similar amounts of their annual resources to the pursuit of national security interests, religious interests or mere pleasures of architectural design: The building of the largest pyramid in Egypt was a project extending over hundreds of years, and employing a large portion of the total available labor force. The building of the Chinese Wall was an enterprise of similar

Table 2 Second (Replacement) L-5 Unit Costs (Closed System Reproduction)*

Second Unit Total (Replacement) Cost ≈	$50 Billion	$70 Billion
Depreciation ≈	$ 1 Billion	$ 1.4 Billion
Sustenance Activities (1 out of 5 people) ≈	$ 1.2 Billion	$ 1.2 Billion
Interest (10 percent opportunity costs for investments on Earth)	$ 2.5 Billion	$ 3.5 Billion
TOTAL ANNUAL REPLACEMENT COSTS	$ 4.7 Billion	$ 6.1 Billion
Total "Value Added" Budget Available (10,000 people, $600,000/man-year)	$ 6.0 Billion	$ 6.0 Billion

---

[*] A "closed" system is defined not to require any Earth support. Support from the Moon or asteroids is allowed. In later generations, even such support may be excluded for totally closed systems.

magnitude, again extending over many hundreds of years, and equivalent to certainly much more than 10 million man-years needed for the L-5 facility. In more recent times, up to 80 percent of the gross national product was dedicated by the United States in World Wars I and II to the pursuit of national security matters, adapting rapidly from a peacetime level of effort of between 10 to 20 percent of GNP. It is equally likely that any advanced society of the turn of the century (75 years ago) clearly would have committed tremendous resources to such a scheme--if given the technical option to do so. However, no such dedication, even by the wildest imagination, can be expected in the pursuit of space colonization today.

But there also is no need for any such drastic acceleration of space expenditures to bring about space colonization over the next 100 years. Rather, many of the programs and activities in space will logically evolve some of the most important building blocks necessary for the accomplishment of space industrialization: Using opportunities offered by the Space Shuttle and related technologies over the next decades, many of the technology components needed to commit to a full-scale space industrialization will come about by the utilitarian and scientific (is there any distinction?) uses of space. Table 3 indicates a rough outline of five phases of space industrialization that are likely over the next several decades:

The Information Phase (1960s-1990)

This phase is geared toward using space and space sensing systems to gather, transmit and evaluate information on a worldwide basis. This phase of space industrialization began in the 1960s and will extend in the development and the initial deployment phase well into the 1980s and 1990s. It comprises programs such as communications, weather and climate, earth observation, sea and ocean measurements, as well as military surveillance. The space science program also is built around similar themes of information gathering, transmission and evaluation. The information technology in space will evolve substantially beyond the year 1990 and make important contributions to the organization, control and general feasibility of space habitation itself.

Large Structures Phase (1980s-2010)

The area of large structures will be opened with the advent of the Space Shuttle. With an ability of repetitive flights, the ability to assemble larger structures in space operations, the capability to maintain, repair and refurbish large systems, the 1980s and 1990s will see the establishment of entirely new antenna systems, optical systems, initial prototypes of space power and space manufacturing systems. The space lab program, as currently envisioned for the 1980s, will include a variety of research important to answering some of the

Table 3 Stages of Space Industrialization

	Information Phase	Large Structures Phase	Industrial Prototype Phase (with ground support)	Industrialization Phase	Space Habitation Phase
	Collection, Transmission	Assembly/Support Technologies	Testing/Costing Open Systems	Closed Systems Designs/Tests	Economic Balance of Closed System (with Net Energy Output)
	1960s - 1990	1980s - 2010	1990s - 2025	2010s - 2075	2075 Islands I - III
Economic/ Scientific Activities	INTELSATS DOMSATS TIROS NIMBUS GEOS LANDSAT SEASAT ATS Surveillance	● Antennas ● Optical Systems ● Spacelabs ● Information Processing ● Space Power Support Systems	● SSPS Prototype ● Processing: LG Capillary Forces ● Cryogenic Refrigeration ● Biocultures ● Space Station/Base	● Lunar Base ● Closed Agriculture Systems ● Environmental Balance ● Net Energy Output of Closed Systems	● 10,000 People ● $50 Billion/ Year Gross Product ● 17 Quads Net Energy Output
Space Transportation System Needs	Expendable Systems	Space Shuttle IUS, Tugs	Chemical/Laser LLV Large Seps Mass Driver RDT&E Space Shuttle Derivatives	● Laser Fusion Propulsion ● Modified "ORION" Systems ● Lunar Mass Driver RDT&E	
Costs (1975 $)	$75 Billion	$100 Billion	$150 Billion	< $200 to $250 Billion	Total > ≈ $500 Billion

key questions with regard to any space habitation: How do organisms grow in low gravity; what is the effect of capillary forces; what is the ability and role of man in EVA; how long can man operate in space without adverse physiological effects; is there a high energy radiation problem; what will be the role of automated assembly and remote control through teleoperators?

Industrial Prototype Phase (1990s-2025)

This phase, starting in the late 1990s or early decades of 2000, will see the deployment of economic prototype and operational SSPS systems, space processing systems, justified by economic uses on Earth and the establishment of biocultures, as well as a permanent space station and construction base. Most of these activities will be undertaken by governments, with substantial industry participation. Elements of a space construction base will evolve much earlier in the large structures phase, beginning in the mid-1980s.

Industrialization Phase (2010s-2075)

In the following decades, industrial space activities, with or without financial participation by government, will develop and sustain themselves entirely, based on pursuits of economic interests. Once this point is reached, the space program will have become truly irreversible: Economic self-interest, again and again, has proven to be the most lasting historical motivation to human activity. The most likely and obvious application will be space-based solar power systems--of the SSPS type--financed by utilities and industry. Another area of substantial economic activities may be waste disposal for extremely toxic chemical, biological and nuclear wastes, vaccine and enzyme production, cryogenic refrigeration, long-term storage, crystal growth, and possibly entirely novel space production processes. At the same time, closed space agriculture and habitat systems may be established, including possibly a permanent lunar base.

Space Habitation (2075)

This phase of space industrialization will be the threshold phase of space colonization. It means achieving the levels of economic output (value added) with a labor force sustained in space sufficient to regenerate closed systems (i.e., without support from Earth), in economic, technical, environmental and social balance. After the crossing of this threshold, no physical resource limitations (energy, materials) seem likely to limit the growth of such communities from then on for thousands of years. It will be the achievement of the ultimate project independence for mankind.

In conclusion, the above estimates and cost schedules may prove in time to be quite encouraging: While to some the cost estimates may seem exceedingly high, nevertheless, in rough outline form the feasibility of achieving these levels of investment and commitment over the next hundred years, in an evolutionary approach, seems assured, even with funding of space activities held at roughly current levels. The establishment of space habitation will be an evolutionary outcome of the current United States space program, with many intermediate steps already outlined. Several of the necessary steps will be self-supporting from an economic as well as technical-engineering viewpoint. With further innovation beyond the year 1995 (the technology and cost base assumed for the SSPS estimates), indeed a self-supporting community of 10,000 people seems possible a hundred years hence. However, for many of the reasons outlined above, this threshold is also not likely to be passed much sooner than that. In either case, mankind, through the efforts of the space program, will achieve in the next 100 years the most significant accomplishment yet: True Earth-independent, self-supporting systems which will invariably lead to the establishment of a multitude of new, different, varied and enterprising civilizations.

Q. I would like to see your statement of costs for the lunar base. To put 3 people on the Moon with an Apollo vehicle cost $500 million. To put 100 people on the Moon with Apollos would cost around $18 billion. You have stated a cost which differs by a factor of fifty.

A. But the Apollo mission was only able to support those three people for seven days.

Q. But you could send out parallel missions. You could send out a supply ship for even less than that. I think you're scaling the wrong thing.

A. I have a detailed study backing up the $15 billion in transportation costs, reflecting post-Apollo technology. It is open for scrutiny. To really support 3 people on the Moon, 6 people in lunar orbit, and to exchange the life support systems up there, on a continuing basis, using Apollo-type technology, you would end up with a very large number over ten years.

Q. You seem to be scaling by the number of people. Most of your tonnage is not going to be people-related; it's going to be related to the mass of the support equipment.

A. The life-support system <u>is</u> included, but not the payload costs; e.g., mass-drivers and other equipment.

Q. But the cost of all those developments on a per unit/mass basis is going to be their delivery cost.

A. To support 3 people on the moon, and 6 people in orbit for over 10 years, for less than $15 billion (in 1977) would not be reasonable. The $15 billion is a correct number for the <u>first unit</u> cost. Now for the SSPS costs, I scaled linearly up to 50 units, so there may be some economies of scale in there. But then I also allowed 10% learning, and found you can put those 50 units into GEO for roughly $500 billion dollars. That assumes 1995 technology.

Q. With those kind of predictions you should state your basic assumptions very explicitly so that they can be considered.

A. But when you talk about a magnitude of supply and support you can't scale up from a space station in lunar Earth orbit to get numbers that are reasonable for L-5.

Q. What assumptions went into your space industrial time-lines?

A. The time-line was manpower-limited if you take a $500 billion investment at scale. If that number is right, and you now look at the manpower required for 100 million man years, it is not possible. If you scale it down to 100 man years, which is the aerospace sector, you get a hundred years with no population growth.

Q. What is the basis for the thousand-to-one ground over space population work force assumption?

A. It's the manpower requirement if you look at the cost structure of the SSPS. You have about 200 people per SSPS in high Earth orbit. But to produce all the rest of the system that you assemble up there the manpower required turns out to be 200, 000 down here.

Q. What do the people on the ground do?

A. They send up food, they assemble, they load large launch vehicles with the structures and materials that are then deployed and assembled up there. The first unit is put up there using a "brute force" approach, for which a reasonable estimate is $500 billion. I think many people would consider that to be conservative.

But the final message, a positive message, is that using these numbers the system can generate a net energy output of seventeen quads per year. This implies a breakeven by the year 2075.

Q. Has it ever taken a century to do what we could conceive of doing in fifteen years?

A. The SSPS already assumes 1990-95 technology, and those assumptions are very courageous and imaginative. Beyond that, I assumed a rate of technological improvement of 2% per year. Since the historical rate in the past ten or twenty years was less than 3%, I have built in a technological improvement rate that is not unreasonable. And there's nothing to indicate that over the next hundred years we should suddenly become much more intensive.