FUTURE SPACE PROGRAMS 1975

HEARINGS

BEFORE THE

SUBCOMMITTEE ON SPACE SCIENCE AND APPLICATIONS

OF THE

COMMITTEE ON SCIENCE AND TECHNOLOGY U.S. HOUSE OF REPRESENTATIVES

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FUTURE SPACE PROGRAMS 1975

WEDNESDAY, JULY 23, 1975

HOUSE OF REPRESENTATIVES,
COMMITTEE ON SCIENCE AND TECHNOLOGY,
SUBCOMMITTEE ON SPACE SCIENCE AND APPLICATIONS,
Washington, D.C.

The subcommittee met, pursuant to adjournment, at 10:35 a.m., in room 2362, Rayburn House Office Building, Hon. Don Fuqua, chairman of the subcommittee, presiding.

Mr. FUQUA. The subcommittee will be in order.

Yesterday we held our first in a series of hearings on future space programs. It was an exciting and thought-provoking morning with Mr. Norman Cousins and Gov. Jack Campbell.

Today we look forward to another day of significant hearings with the distinguished Austrian Ambassador to the United Nations and chairman of the Committee on Peaceful Uses of Outer Space; and Dr. Gerard K. O'Neill, professor of physics at Princeton University.

We welcome you both to our Subcommittee on Space Science and Applications.

Our purpose in holding these hearings is twofold:

First, To gain the benefit of the view of witnesses with diverse backgrounds on the potential of space and its place in our society.

Second, To obtain recommendations of the criteria by which the Congress and committee can judge future space programs that are being advocated.

Our first witness today, Ambassador Jankowitsch, comes to the subcommittee from a series of highly significant sessions of the U.N. Committee on the Peaceful Uses of Outer Space. His skillful stewardship of the 37-nation committee is bringing closer the possibility of a Moon treaty, conventions governing direct broadcast satellites, and a better understanding of the legal implications of the remote sensing of the Earth from satellites. All of these are of the utmost importance to all nations in the future.

I would like to commend Ambassador Jankowitsch, on behalf of the subcommittee for his leadership in these areas, and welcome you here today and ask you to proceed.

[A biographical sketch of Mr. Jankowitsch follows:]

PETER JANKOWITSCH, D.D.L.

Austrian diplomatist; b. 10 July 1933, Vienna: *s.* of Karl Jankowitsch and Gertrude (née Ladsaetter) Jankowitsch; *m.* Odette Prevor 1962; ed. Vienna Univ. and The Hague Acad. of Int. Law.

Former lawyer; joined foreign service 57, worked in Int. Law Dept.; Private Sec., Cabinet of Minister of Foreign Affairs 59–62; posted to London 62–64;

We appreciate your taking your time. Thank you very much for being here.

Mr. JANKOWITSCH. Thank you very much, Mr. Chairman, and I should like to thank you and the members of the committee again for hearing me this morning and for the stimulating questions.

Mr. FUQUA. Thank you, sir.

Our next witness today is Dr. Gerard K. O'Neill, of the department of physics at Princeton University. Dr. O'Neill works in the area of high energy experimental particle physics.

Since 1967, he has also investigated the possibilities of research, manufacturing, and colonization in space. The first conference on these recent concepts for space colonization was held at Princeton in May 1974. Since then, the topic has received increasing attention in both the scientific and popular press.

We welcome you, Dr. O'Neill, to these hearings and invite you to share with the subcommittee your views on space colonization and other topics which you believe should be brought to our attention. We're happy to have you here this morning.

[A biographical sketch of Dr. O'Neill follows:]

DR. GERARD K. O'NEILL

Professor of Physics at Princeton University and works in the area of high-energy experimental particle physics. Since 1967 has also investigated the possibilities of research, manufacturing and human habitation in space. In 1956 Professor O'Neill originated the principle of colliding-beam storage rings. In the period 1959–65. Dr. O'Neill and a team of physicists from Princeton and Stanford Universities constructed the first high-energy particle storage ring and in 1965 completed the first experiment in which the colliding-beam principle was applied to a problem in elementary particle physics. In 1967, Dr. O'Neill became interested in space research and in 1968 published in the magazine, Science, a paper on high-resolution orbiting telescopes. Since 1969, while continuing to lead a group doing a series of experiments in particle physics, he has also maintained an interest in space applications. The first conference on this new concept of "space colonization" was held at Princeton in May 1974, and was supported by a grant from the Point Foundation. The first publication on this subject appeared in September 1974, in Physics Today. Since the May 1974 conference, the topic of space colonization has been widely discussed in the scientific and popular press. He received his BA Degree from Swarthmore College in 1950 and his Ph.D Degree from Cornell University in 1954. He joined the Princeton faculty as an instructor in 1954 and has been a Professor since 1965.

STATEMENT OF GERARD K. O'NEILL, PROFESSOR OF PHYSICS, PRINCETON UNIVERSITY

Mr. O'NEILL. Thank you, Mr. Chairman and members of the committee.

I appreciate the opportunity to speak with your group today, and with your permission during part of this discussion I'm going to use slides and a short film. I'm not going to duplicate my written testimony, which you already have.

Mr. FUQUA. We will make that part of the official record.

[The complete prepared statement of Gerard K. O'Neill follows:]

SPACE COLONIZATION AND ENERGY SUPPLY TO THE EARTH

TESTIMONY OF

DR. GERARD K. O'NEILL
PROFESSOR OF PHYSICS
PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

BEFORE THE

SUB-COMMITTEE ON SPACE SCIENCE AND APPLICATIONS

OF THE

COMMITTEE ON SCIENCE AND TECHNOLOGY

UNITED STATES HOUSE OF REPRESENTATIVES

July 23, 1975

Author's Note

In my opinion it is possible to set forth the essential ideas and basic rationale of a new technical concept without resorting to formulas or technical jargon. In this document I attempt to do so, striving for readability rather than for technical detail. The technically-inclined reader may wish to consult the appendix and bibliography, or to write for further information.

ABSTRACT

Studies beginning in 1969 have so far confirmed the possibility that large-scale, earthlike human communities could be built in space. The space-colonies would orbit L5, a location on the lunar path equidistant from the earth and moon. Nearly all the materials for these communities and for their manufactured products would be transported from the low-gravity surface of the moon by an automated materials launcher. No lift-rocket more advanced than the space-shuttle and a simple derivative of it would be required. A space-community development program could therefore begin soon, on the basis of known technology, with construction starting as early as 1981-2.

The first L5 community could support a workforce of 10,000 people in comfort, even in some luxury, within a large enclosed volume having a climate where flowers, trees, birds and animals could flourish, and in which gravity could be provided by slow rotation.

The L5 "Beachhead in space" appears capable of building, more economically than could be done in any other way, satellite solar power stations to supply electrical energy to the earth by low-density microwave beam transmission. Economic analysis so far indicates a benefit/cost ratio much higher than one, at a discount rate of 10%. The investment would be 5% to 15% of the cost estimated for Project Independence.

Eleven to fifteen years after the start of construction of the first colony, energy to the earth from space could reach and exceed the peak capacity of the Alaska pipeline. Busbar costs initially of 15 mils appear capable of reduction to 10 mils or less, opening the possibility of synthetic fuel production and of a true permanent "energy independence" without strip-mining or nuclear-power proliferation.

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 ever more increasing detail, that the answer to all four of these questions is a strong "yes."

GEOMETRIES

The largest colonies now forseeable 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 (Figure 2), 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 (Figure 4), 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 (Figure 4), 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 ever-present 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 (Figure 7): 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 at L5 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 Apollo 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 11 landing site:

TABLE 1

UNSELECTED APOLLO 11 SOIL SAMPLE

Oxygen	40%
Silicon	19.2%
Iron	14.3%
Calcium	8.0%
Titanium	5.9%
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 meters deep, and 200 meters 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.

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 Figures 3 and 9; I am indebted to Field Enterprises, Inc., for permission to show these figures, which are 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:

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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 on 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:

TABLE 2

APPROXIMATE COSTS OF ENGINEERING PROJECTS, IN 1975 DOLLARS

a)	Panama Canal	2 Billion Dollars
b)	Space Shuttle Development	5-8 Billion Dollars
c)	Alaska Pipeline	6 Billion Dollars
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.

TABLE 3

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

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)	Internal unpublished report, NASA/MSFC, January 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. Yardley, J. Disher, R. Freitag and others) 140 Billion Dollars (3.6A)	High. Unnecessary lift systems 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.

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 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 earth-launched 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.

TABLE 4

SATELLITE SOLAR POWER STATION DESIGN PARAMETERS

(required for economic viability)

	Earth-launched turbogenerator (Boeing Aircraft Study)	Earth-launched photovoltaic (A.D. Little Co.)	L5-built turbogenerator (this report)
'ower plant mass ›er unit power	5 KG/KW	0.8 KG/KW	10-15 KG/KW
:omponent lift :ost from earth	$77/KG	$220/KG	($940/KG)
:fficiency of :ransmission	70%	65%	55-63%
:nterest rate	8%		10%
lusbar power cost initial)	25 mils		15 mils

In Table 4, the lift 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.

Figures 14-16 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 2 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 two, even if vehicle development costs and later operating costs are assumed to be very low. Benefits 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 laboratories, at funding levels of many millions of dollars, 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 a 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 has 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 elitism 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 strip-mining 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 mid-point 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

(This section is keyed to the titled headings of the main text, and is intended for the reader with technical training, who may wish to check independently some of the most important numbers or statements).

INTRODUCTION

L5: An orbit about L5, stable in the four-body problem of the sun, earth, moon and colony, has been shown by Kamel and earlier authors. Cf. references in PTA (ref. 2). Occultation of the sun in that orbit is rare and brief. L4 is equally usable.

High-orbit products: The possibility of returning material products to the earth's surface from L5 is not considered in this document.

THE SPACE-COLONY CONCEPT

Authors: Tsiolkowsky in Russia, Bernal in England, and Cole in the U.S.A. all wrote books which bear on the concept of space colonies. Clarke, Stroud and others have also considered portions of the problem.

GEOMETRIES

The image of the sun's disc would rotate about its center, but the disc is so nearly circular that this rotation would not be detectable by the naked eye.

Civil engineering limits: A standard safety factor of 1.67 is used, as in the building industry on earth. (Corresponding factors are 1.5 for commercial aircraft, and as low as 1.2 for military aircraft.) For aluminum/silicon alloy, cold-drawn, with an ultimate strength of 60,000 psi, the yield point is 50,000 psi and the working stress is here taken as 30,000 psi. For hot-formed aluminum, 20,000 psi is used. The same safety factor is used for iron and titanium. Diameters up to four miles are assumed, with total atmospheric pressure of 5 psi minimum. See PTA for formulas. (Mass table in PTA for model 1 has a non-propagating error: for 20,000 tons aluminum read 80,000 tons metals.)

INDUSTRY

Axis of rotating habitat contains avenue-passage and passes through a hollow bearing. Bearing forces are small, typically one ten-millionth of colony weight in one gravity.

LIMITS OF GROWTH

M.I.T. Studies: Cf. references in PTA. Asteroidal materials: Total volume of proven asteroids is estimated as 1/2500 of volume of the earth (Cf. Allan, Astrophysical Constants). Economic imperative is construction of a new colony adjacent to an asteroid, so that economic productivity can be achieved without prior moving of materials. Relocation of a colony to L5 from the asteroidal region would require about 30 years at an expenditure of 7% of total colony mass.

ENERGY WITHOUT GUILT

The energy intensity (insolation) in space is 1.4 Kw/m^2, or 1.23×10^8 KWH/year for a 100 meter square. This would cost $\$1.8 \times 10^6$ at a busbar rate of 15 mils. The lower figure used in the text allows for reflection losses. Mirror assumed is .001 inches aluminum, with a factor three multiplier for support frames.

For an initial community of 10,000 persons, an electrical power plant of 100 megawatts is assumed (10 Kw/person). For the USA in 1975, average usage of electrical energy is at the rate of about 2 Kw/person, and peak capacity is equivalent to 2.5 Kw/person.

THE BOOTSTRAP METHOD

The velocity intervals from low earth orbit to lunar parking orbit (LPO), to L5 or to geosynchronous orbit (GSO) are all approximately equal, in the range 11.1 - 11.4 Km/sec for minimum-energy two-impulse burns. Escape velocity from the moon is 2.4 Km/sec. With kinetic energy = $1/2\ mv^2$, escape from the earth therefore requires 21.4 times as much energy as from the moon. Spiral orbits (low thrust) require more energy.

The mass driver: A description and table of parameters for this machine is listed in PTA. Further study results will be available in references 4 and 6.

Magnetic fields are held below 10,000 gauss, and accelerations to less than 29 gravities. The nominal repetition rate is 1 Hz, for payloads of 9 Kg each. The peak transfer rate is therefore 780 metric tons per day. The range of a factor 4 quoted in the text allows for turnoff during the lunar night, and for reliability down to 50%.

Guidance is by magnetic trimming during a one-kilometer inertial drift-space,roll/pitch/yaw and position sensing being done by laser interferometry before payload release.

In PTA an estimate of 10,000 tons for lift-needs from earth to L5 was given, and 3,000 tons for transfer from the earth to the moon, based on a "Spartan" approach: oxygen atmosphere, construction work force stay time until completion of the first community, and food supply in dehydrated form. Another extreme was given by NASA/MSFC, based on a nitrogen-mix atmosphere, extensive atmospheric make-up from earth, frequent crew rotation and food resupply in wet form. It was about a factor three higher (unpublished internal report, no number). The extremes are therefore 2% - 6% of an estimated 500,000 ton total mass.

In current discussions of vehicle-systems, a distinction is drawn between lift vehicles made of building-blocks each of which is already under development for the space shuttle (e.g., SRB's, SSME's, avionics) and lift vehicles requiring extensive new development. For the space-colonization program only the former are required. Several papers in ref. 5 (Tischler, Davis, Salkeld) cover this topic.

Construction station: PTA estimate was 1000 tons. A more detailed estimate (G. Driggers, ref. 5) gives 2500 tons.

LUNAR MATERIALS

The source for Table 1 is ref. 7. Samples from other Apollo landing sites have generally greater amounts of aluminum and smaller amounts of iron. The lunar surface rocks often have higher metal content, but are neglected here.

The structural aluminum considered for use in colony-building is an alloy of aluminum and silicon, the most plentiful of lunar elements after oxygen.

The fuel estimate made is based on the usual 6:1 oxygen/hydrogen mixture (fuel-rich) commonly used for LOX-hydrogen rocket engines.

D. Criswell (ref. 5) has calculated the yields of carbon, nitrogen and hydrogen which could be obtained by sifting lunar soils for the fine-grained material, and then heating that material. The rare light elements are concentrated in the finer grains, and can be extracted by that process.

In this report no advantage is taken of that option.

Asteroidal materials: As noted earlier, the velocity interval from the earth to L5 is about 11.4 Km/sec. A selection of ten asteroids, whose orbital elements are well-known,was checked. It was found that in all cases the total velocity interval required for transfer to L5 was close to 10 Km/sec. Correction to match the orbital plane with that of the earth was an important term.

ISLAND ONE

The design of Figures 10 and 11 has a habitat-interior diameter of 540 meters and a circumference of 1.05 miles. Total interior non-window surface area is over 900,000 m^2, about half of which is at 70% or more of earth gravity. The counter-rotating toroidal agriculture ring provides 400,000 to one million $meters^2$ for photosynthetic crop-growing, plus additional covered areas for processing and storage.

In order that the entire colony maintain its axis always pointed toward the sun, yet not require thrusters, the total rotational angular momentum must be zero. In the "Sunflower" design this is accomplished by devoting about 20% of the total mass to the agricultural ring.

The low-gravity work areas described are nominally 40 meters in diameter (412 ft. circumference or floor width) and can be of any desired length. Six of them, each 200 meters long, would provide approximately three times the total high-bay assembly area of the General Electric Large Turbine Division plant at Schenectady, New York, where a large fraction of the turbogenerator capacity of the USA is built.

COST-DRIVERS IN SPACE-COLONY CONSTRUCTION

Atmospheric composition: A typical design for a hemisphere diameter of 540 meters has the following contributions to total internal pressure:

Aluminum weight	3.2 cm	0.13 psi
Soil or structures weight	30 cm	1.08 psi
Atmosphere		7.50 psi
Total		8.71 psi

In this typical case the atmospheric pressure accounts for 86% of the total structural requirement. With a full 14.7 psi of atmospheric pressure the figure would be 92%.

COSTS AND PAYOFFS

In Table 2, items (a) and (c) are from the Exxon Corporation (Smithsonian Magazine, April 1975, p. 117).

Item (e) assumes a cost of 23 Billion Dollars as of 1967 and an average of 7% inflation since that year.

Item (f) is based on an unpublished NASA/MSFC Study Document, "Space Colonization by the Year 2000 - An Assessment."

Item (g) is from J.N. Wilford, New York Times, July 13, 1975, quoting Vance Brand, U.S. Astronaut.

Value added by location in high orbit: A fully employed population, a productivity of 20 tons/person-year, and lift costs in the range $100 - $400 per pound are assumed.

Busbar power costs: Present figures average 15 mils/Kwh for nuclear power, 17 mils/Kwh for fossil-fuel power. Peak-shaving power earns revenue at a much higher rate, but the energy generated by peak-shaving generators is a small fraction of the total.

Solar energy arriving on the land area of the continental U.S. averages about 1/10 of the amount which intercepts equal area in free space. For base-load power, the capital cost of the system must provide for a December/January day length, storage for extended bad weather, and a high demand.

Fifty-four percent efficiency has been demonstrated in 1975 by a JPL group, in cooperation with Raytheon (also Cf. ref. 8).

Microwave power transmission has its own environmental problems, but they appear to be less serious than those of nuclear or fossil-fuel power (Cf. refs. 8 and 9).

The velocity interval from L5 to geosynchronous (spiral orbit transfer) is 1.1 Km/sec and is in full sunshine. Transfer could be by a mass-driver, powered by the SSPS itself and used as a reaction engine. The reaction mass could be the wastes (for example liquid oxygen) from the industrial processing at L5. A transfer time of one month or less appears feasible.

Vehicle development costs: for an advanced (non-shuttle-derived) heavy lift vehicle, estimates of development cost from within the aerospace industry vary from 5 Billion Dollars to 25 Billion Dollars; of attainable launch costs to geosynchronous, from $77/Kg to $400/Kg.

The costs of SSPS construction at L5 (input for Figures 14-16) include lift costs for microwave transmitter magnets and initially for computers and controls, as well as items listed in the text.

Alaskan oil field comparison: 1 barrel of oil has an energy content of 5.24×10^9 joules (ref. 10). The peak capacity of the Alaska pipeline will be 2×10^6 barrels/day (ref. 11). For a high conversion efficiency of 48%, the pipeline will then supply 1.83×10^{18} joules annually. This is a rate of 5.8×10^{10} watts, or 58,000 megawatts, equivalent to less than 12 5,000 megawatt SSPS units.

The estimated total reservoir of oil in the Alaskan North Slope (the pipeline source) is 10^{10} barrels (ref. 11), or 2.1×10^{19} joules at 48% conversion efficiency. This is 134 SSPS-years, a total reached in the first nine years with the growth rates assumed for Figures 14-16. For comparison, the total proven reserve of oil in the Middle East is 33.8×10^{10} barrels (ref. 12).

CURRENT RESEARCH

One area requiring verification is semi-closed-cycle ecology. Many small islands have effective ecosystems more limited than that of the first colony, but verification is still required. Fortunately, total closure is unnecessary: "economic closure," the achievement of a closure level adequate to reduce to tolerable levels the lift costs for seeds, etc. from the earth, will be sufficient. Isolation and heat-sterilization can halt any runaway biological subsystem.

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Figure 2 is by Donald E. Davis.

Figure 4 is by F. Giudice.

FIGURE CAPTIONS

1. Location of the Lagrange points L4 and L5. Each is on the orbit of the moon and is the third point of an equilateral triangle, the earth and moon being the other two points. Space communities could be located on stable orbits about either L4 or L5.

2. Example of the scale and terrain possible in a large space community. The size shown (four mile diameter) is within the limits set by present-day structural materials. Slow rotation would provide gravity. Circular objects in distance beyond window-areas are external agricultural cylinders, where temperature, climate and seasons would be controllable independently for each crop.

3. Possible interior design of a first, small-size space community. It could be large enough to provide comfortable apartments, shops, parks, small rivers and lush vegetation.

4. Artist's concept of a large space-community. Planar mirrors control internal day-length and therefore seasons. Industrial activities located on the cylinder axis outside the habitat could be at low or zero gravity. Rings of independent agricultural growing areas would allow seasonal phasing, so throughout the year each crop could be ready for harvesting in some one of the external cylinders.

5. Schematic of a closed-cycle turbogenerator using helium as a working gas. A large fossil-fuel power plant using this kind of turbine is now being installed for commercial power generation at Oberhausen, in West Germany.

6. Schematic of transportation flow for space colonization. With the space-shuttle and simpler vehicles easily derived from it at low development cost, a lunar mining outpost and an L5 construction-station would be set up. A large fraction (over 95%) of all materials for colony-construction and later manufacturing would then be obtained from the lunar surface by an automated, high-efficiency launch system.

7. Schematic of an electromagnetic mass-driver. Small "Buckets" supported magnetically would each be accelerated to lunar escape velocity. Over a one-kilometer drift space the direction and speed of the bucket would be sensed and adjusted by additional magnetic coils. The bucket would then release its payload, and return to pick up another. The payload would climb out of the moon's gravity, arriving at a low speed for collection and processing.

8. 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 meters deep and 200 meters long and wide.

9. View of a large passenger-ship (titled, in a forthcoming Science Year article, the "Robert H. Goddard") nearing an early space colony. The ship would have been built at one of the colonies, mainly from lunar material, and would be used for transfer between low earth orbit and L5, passengers for it being ferried from the earth to low orbit by the space shuttle.

10. A new design, developed by the 1975 NASA/Ames-Stanford University Summer Study on Space Colonization, for an initial space community. Its petal-shaped mirrors, its tracking of the sun, its reliance on solar energy, and its property of being a warm habitat for life in the cold of space all suggest the name "Sunflower." It could house a 10,000 person work force in a comfortable earth-like environment.

11. An angle view of "Sunflower." The interior circumference of the habitat could be over one mile. Agriculture could be carried on in an external, counter-rotating toroid, shown here as an outer ring.

12. Schematic of a satellite solar power system. The power plant shown, being studied by the Boeing Corporation, uses turbogenerator machinery. An alternative, based on photovoltaic solar cells, is under study by the A.D. Little Co., Raytheon, Grumman Aircraft and the Jet Propulsion Laboratory.

13. Details of power-satellite turbomachinery. Total mass of the satellite depends strongly on the peak operating temperature of the system; for an earth-launched satellite, for which lift-costs are critical, the motivation toward high operating temperatures is strong.

14. Costs and benefits of a space-colonization program, based on conservatively high estimates for costs (178 Billion Dollars over 14 years) plus interest rates (10%). Cost estimates assume only shuttle-derived lift vehicles. A six-year construction time for the first community, and a two-year replication time thereafter, are assumed, with a productivity of two satellite power stations per colony per year after initial startup. By the 13th year, power plant capacity so produced would meet U.S. needs. In this scenario the benefit/cost ratio, including all construction, development and interest charges, would exceed 2.7. Power costs, initially 15 mils/Kwh, would be reduced in steps to achieve market penetration. Revenue would be obtained only from the sale of energy, not of power stations.

15. Effect of an early decision to drive toward space colonization at the earliest possible date. By year 11 from the start of the program the energy flow to the earth from satellite power stations built at L5 could exceed the peak capacity of the Alaska pipeline. By year 16, the total energy supplied to date could exceed the total estimated oil reserves of the Alaska North Slope.

16. Effect of delay in startup, to wait for advanced lift vehicles. The most optimistic estimates for low development and operation costs for such vehicles are assumed. Total program cost is reduced only by a factor 2, for a factor 12 reduction in lift costs. Benefits, including energy independence, are delayed by 7 years.

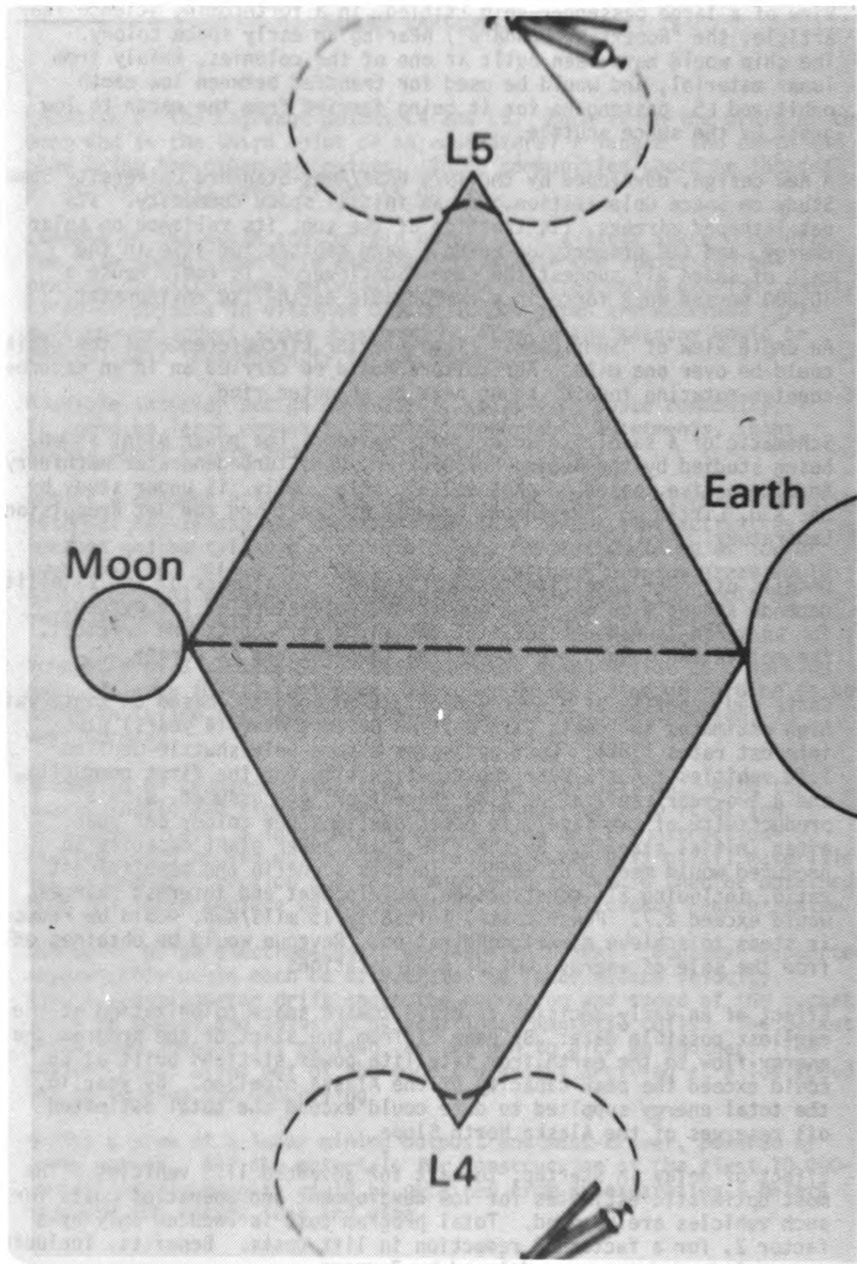


FIG. 1

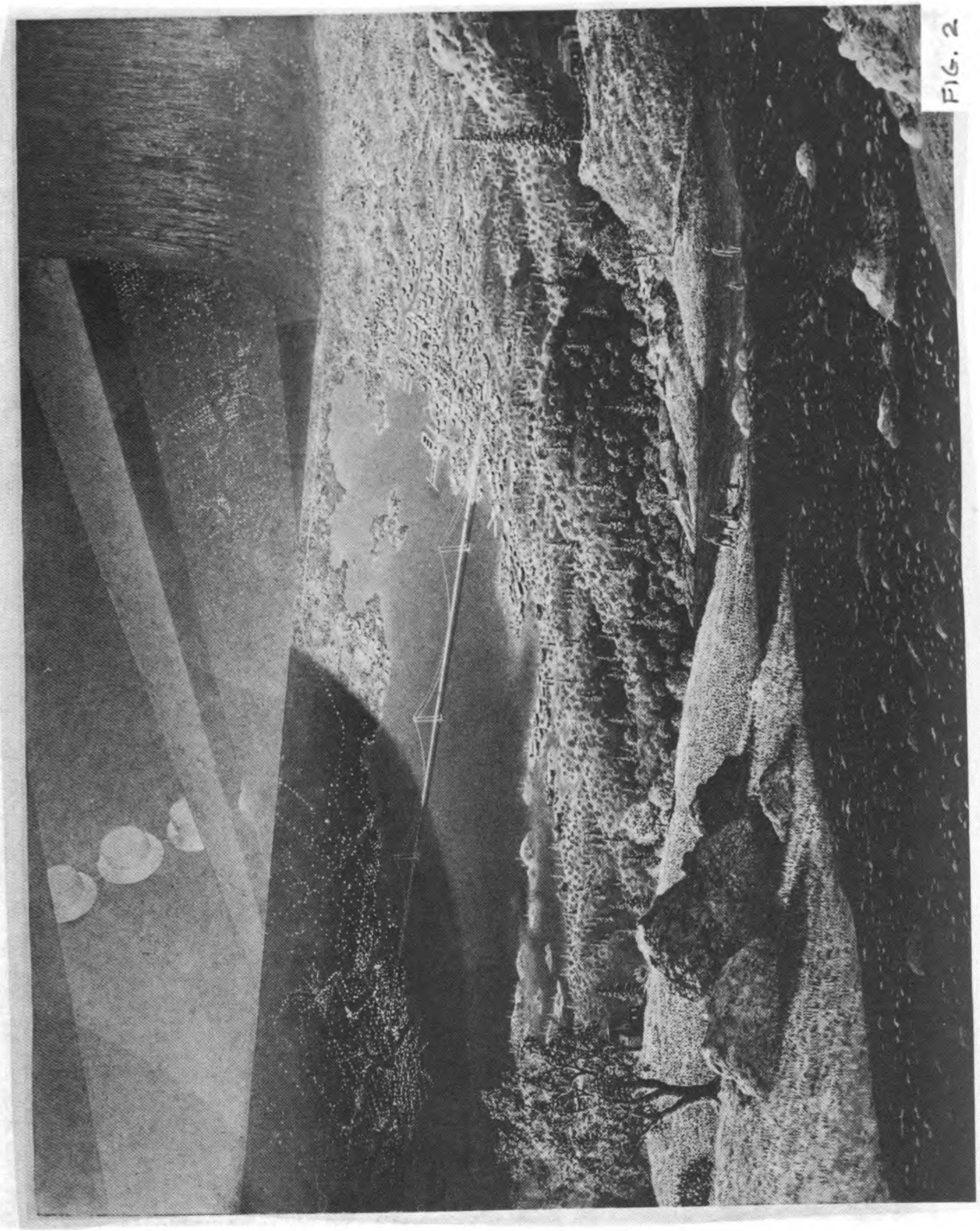


FIG. 2

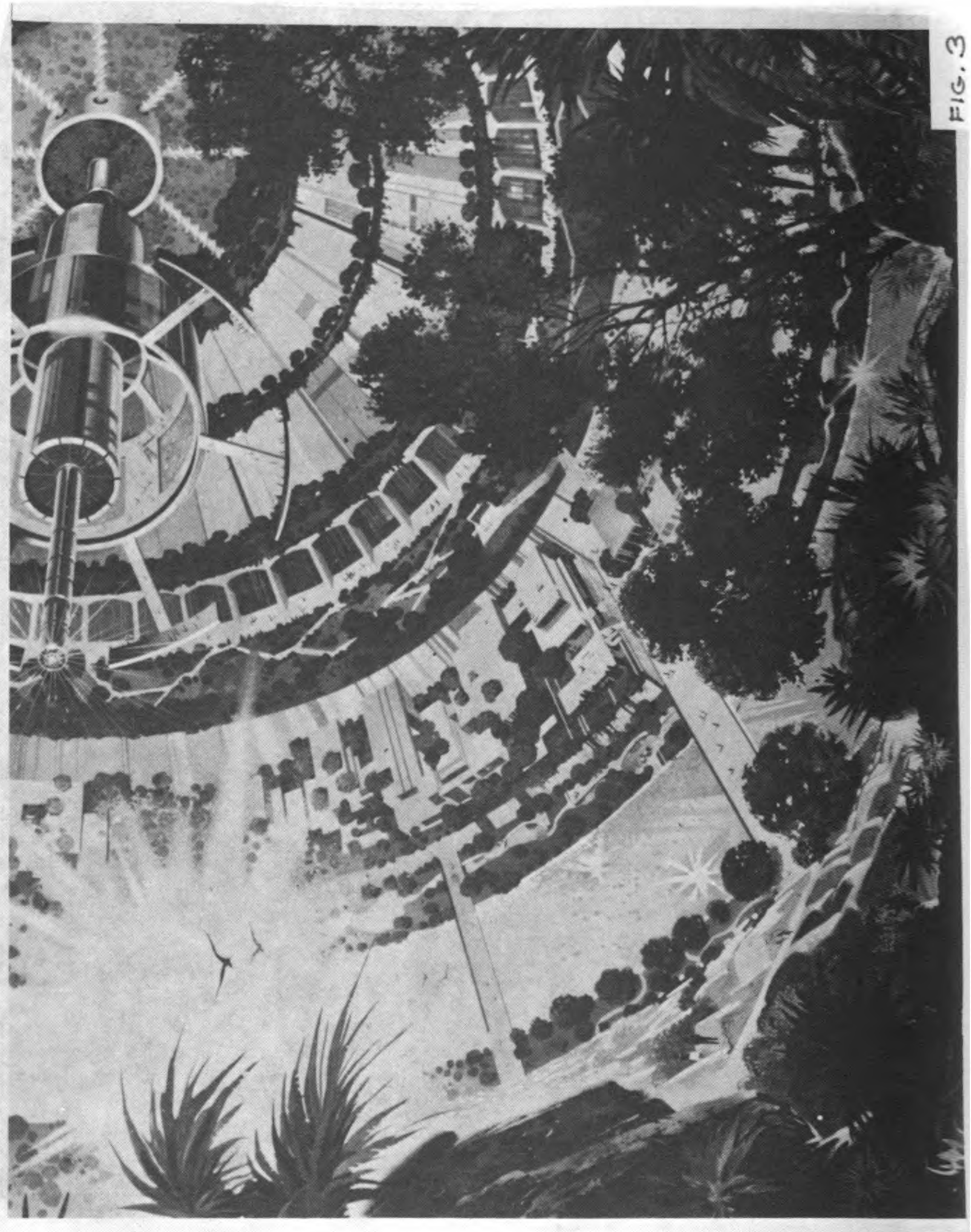


FIG. 3

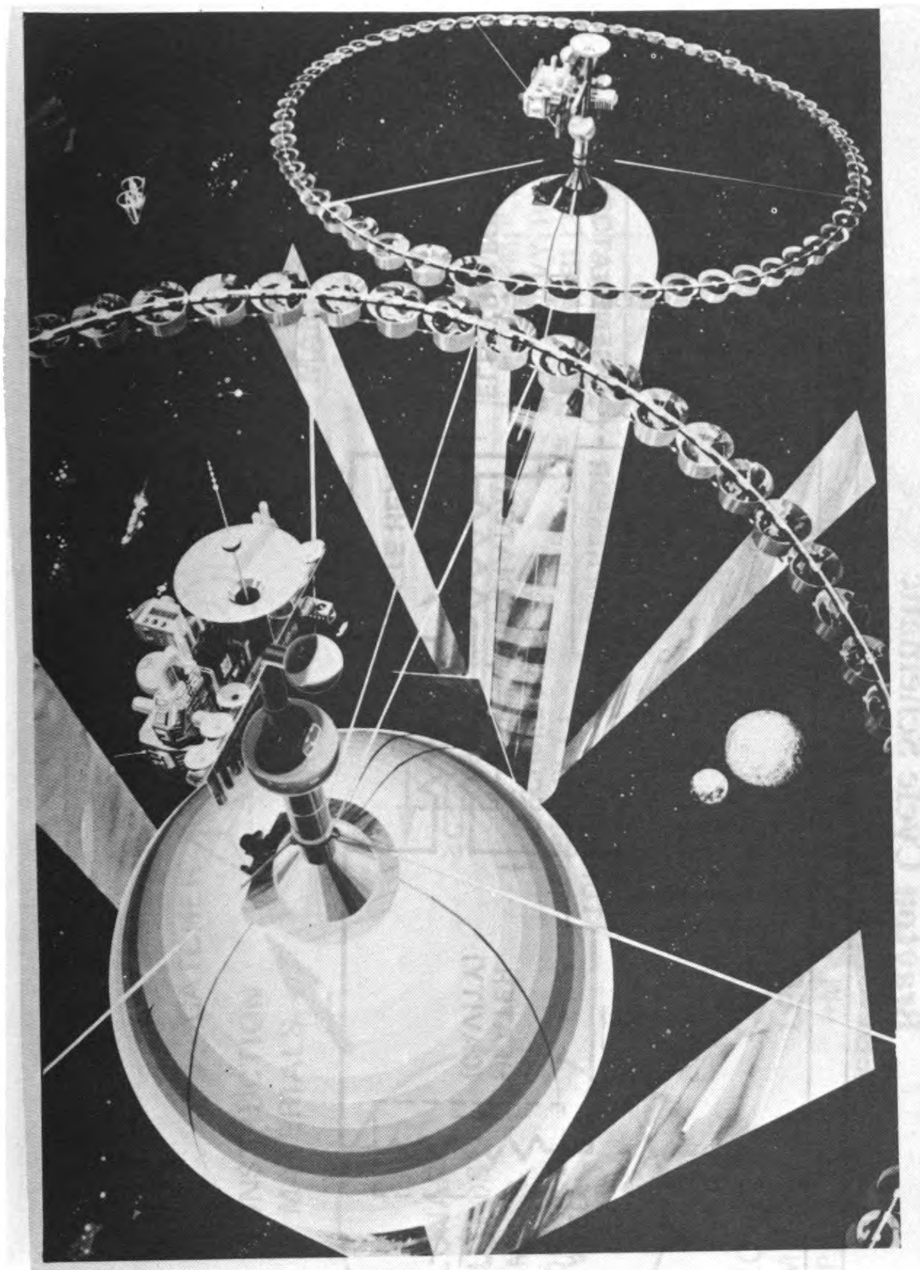
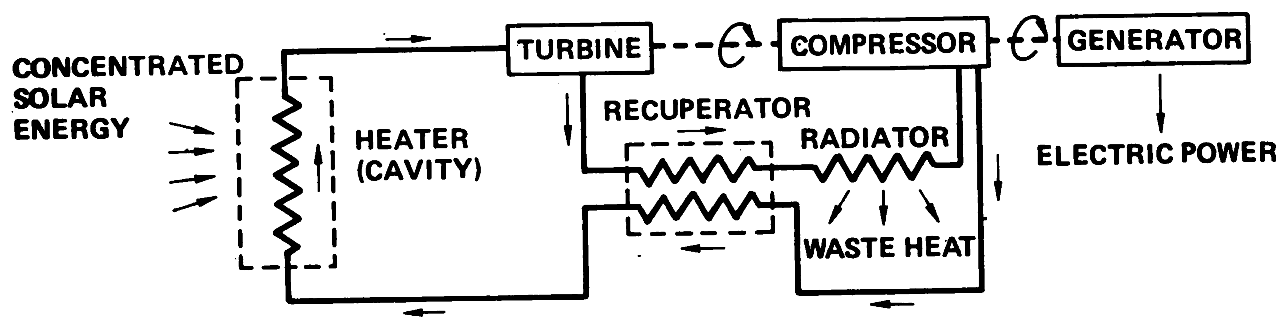
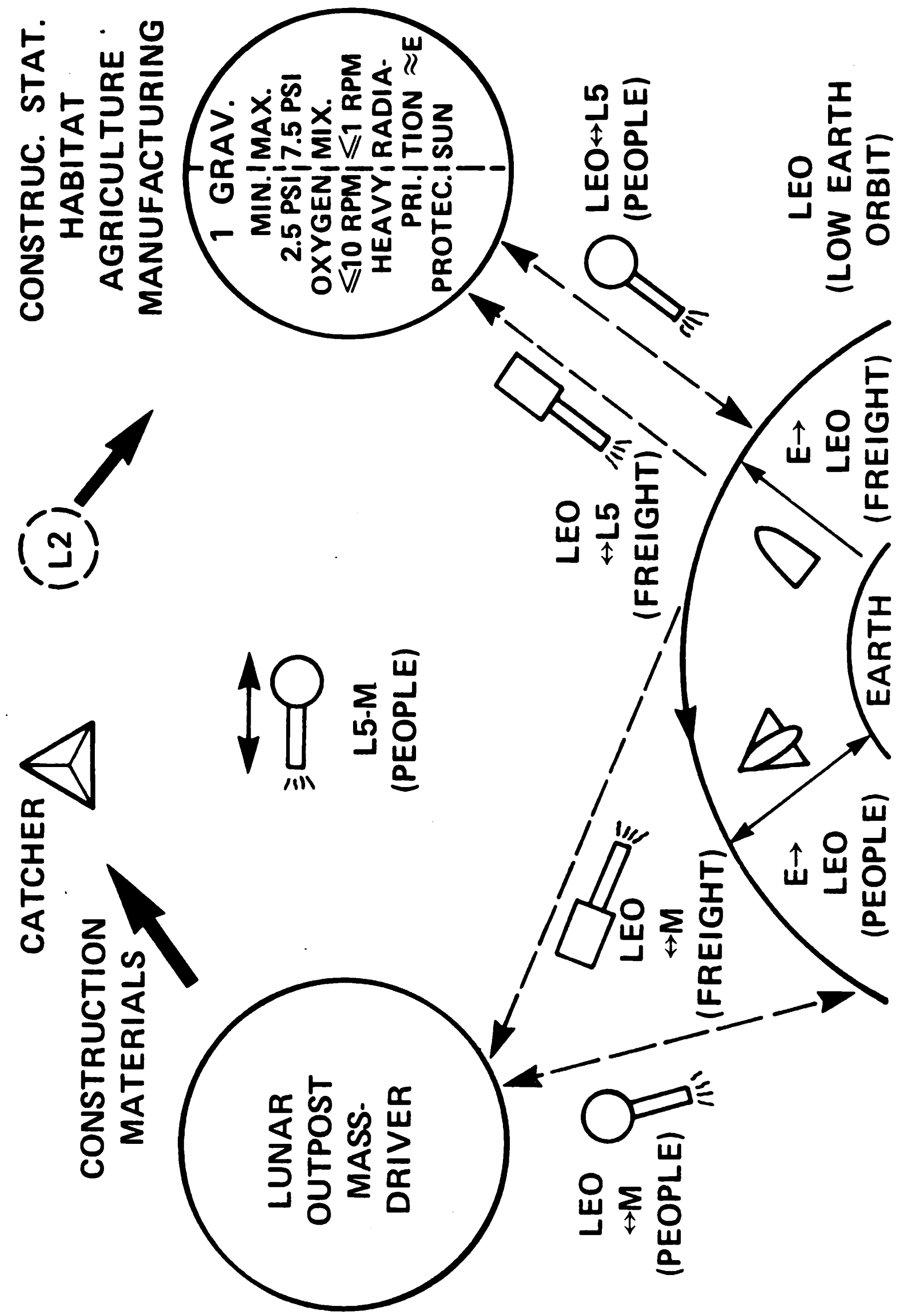
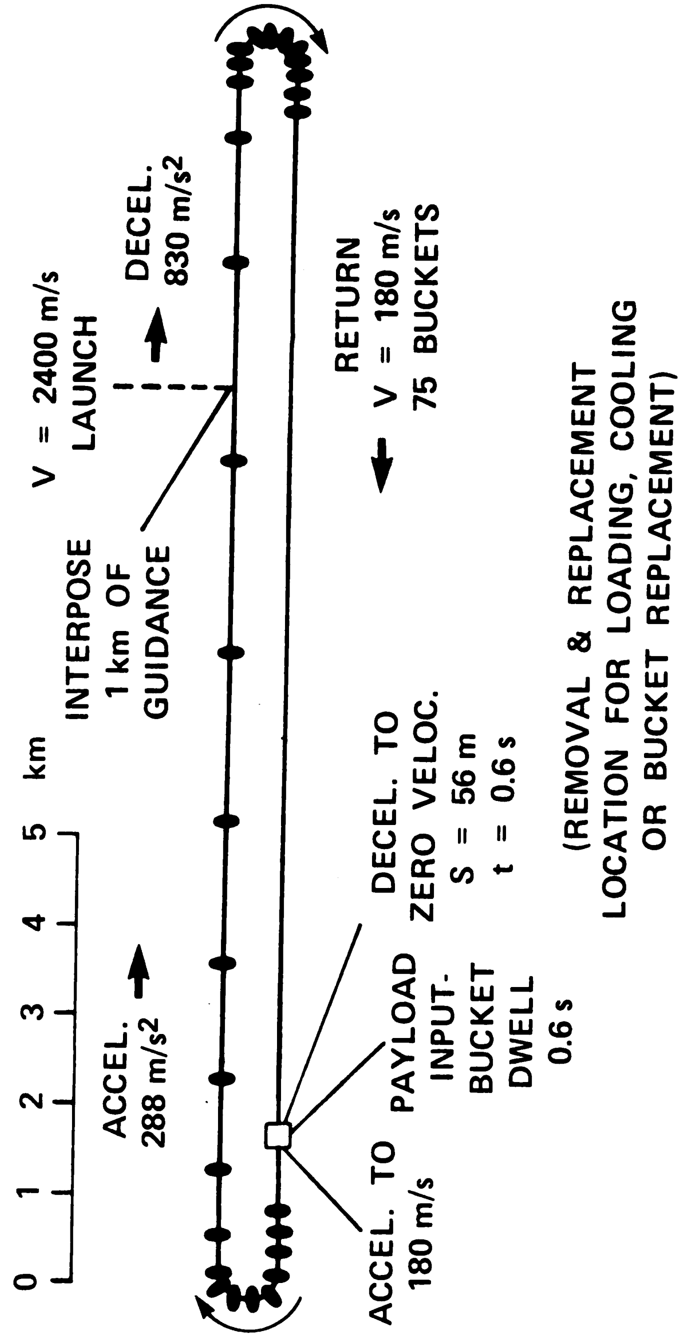


Fig. 4

Brayton Cycle Schematic




CONSTRUC. STAT.
HABITAT
AGRICULTURE
MANUFACTURING
1 GRAV.
MIN. | MAX.
2.5 PSI | 7.5 PSI
OXYGEN | MIX.
≤10 RPM | ≤1 RPM
HEAVY | RADIA-
PRI. | TION ≈E
PROTEC. | SUN
LEO↔L5
(PEOPLE)
LEO
(LOW EARTH
ORBIT)
L2
LEO
↔L5
(FREIGHT)
E→
LEO
(FREIGHT)
EARTH
CATCHER
L5-M
(PEOPLE)
E→
LEO
(PEOPLE)
CONSTRUCTION
MATERIALS
LEO
↔M
(FREIGHT)
LUNAR
OUTPOST
MASS-
DRIVER
LEO
↔M
(PEOPLE)


0
1
2
3
4
5
km
ACCEL.
288 m/s2
INTERPOSE
1 km OF
GUIDANCE
V = 2400 m/s
LAUNCH
DECEL.
830 m/s2
RETURN
V = 180 m/s
75 BUCKETS
ACCEL. TO
180 m/s
PAYLOAD
INPUT-
BUCKET
DWELL
0.6 s
DECEL. TO
ZERO VELOC.
S = 56 m
t = 0.6 s
(REMOVAL & REPLACEMENT
LOCATION FOR LOADING, COOLING
OR BUCKET REPLACEMENT)

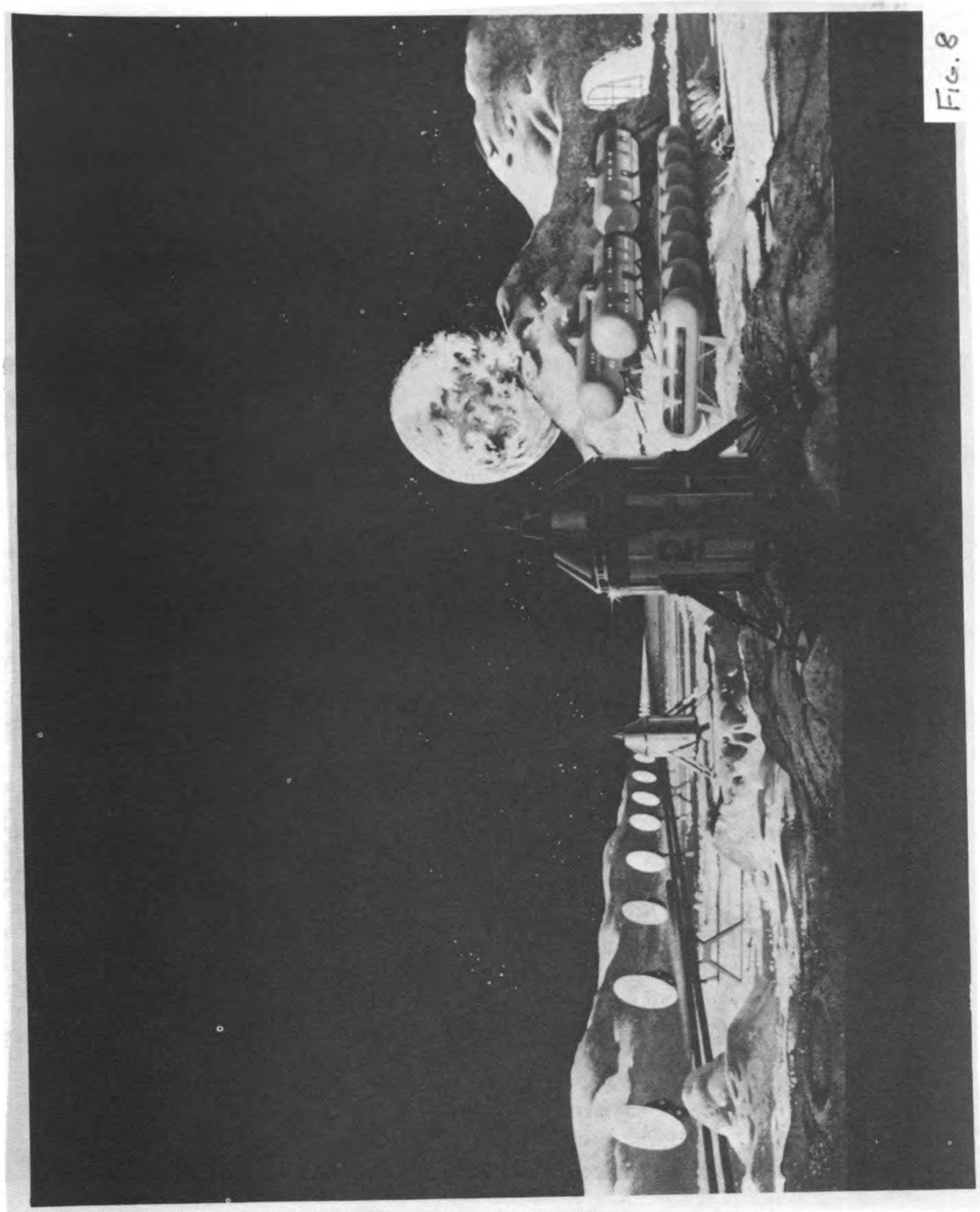


Fig. 8

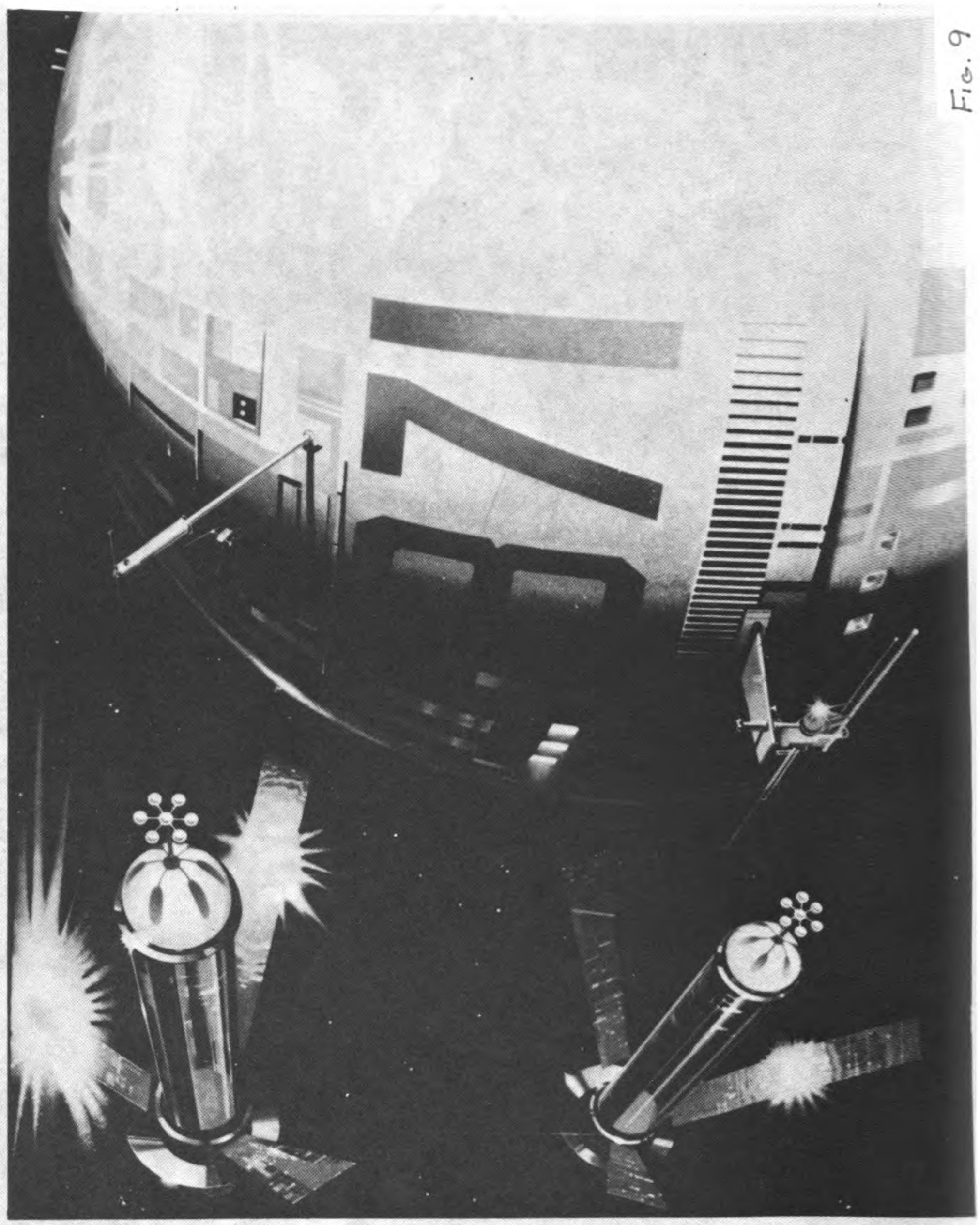


Fig. 9

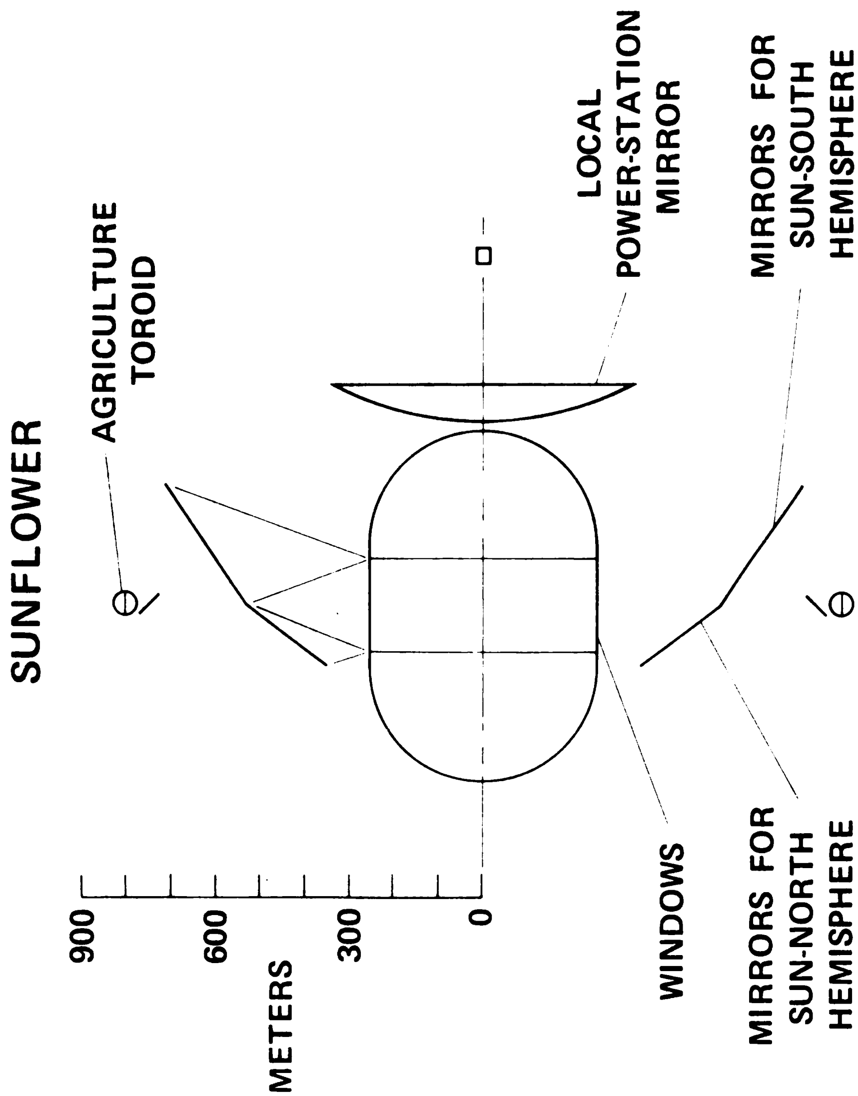

SUNFLOWER
AGRICULTURE TOROID
LOCAL POWER-STATION MIRROR
MIRRORS FOR SUN-SOUTH HEMISPHERE
MIRRORS FOR SUN-NORTH HEMISPHERE
WINDOWS
METERS
900
600
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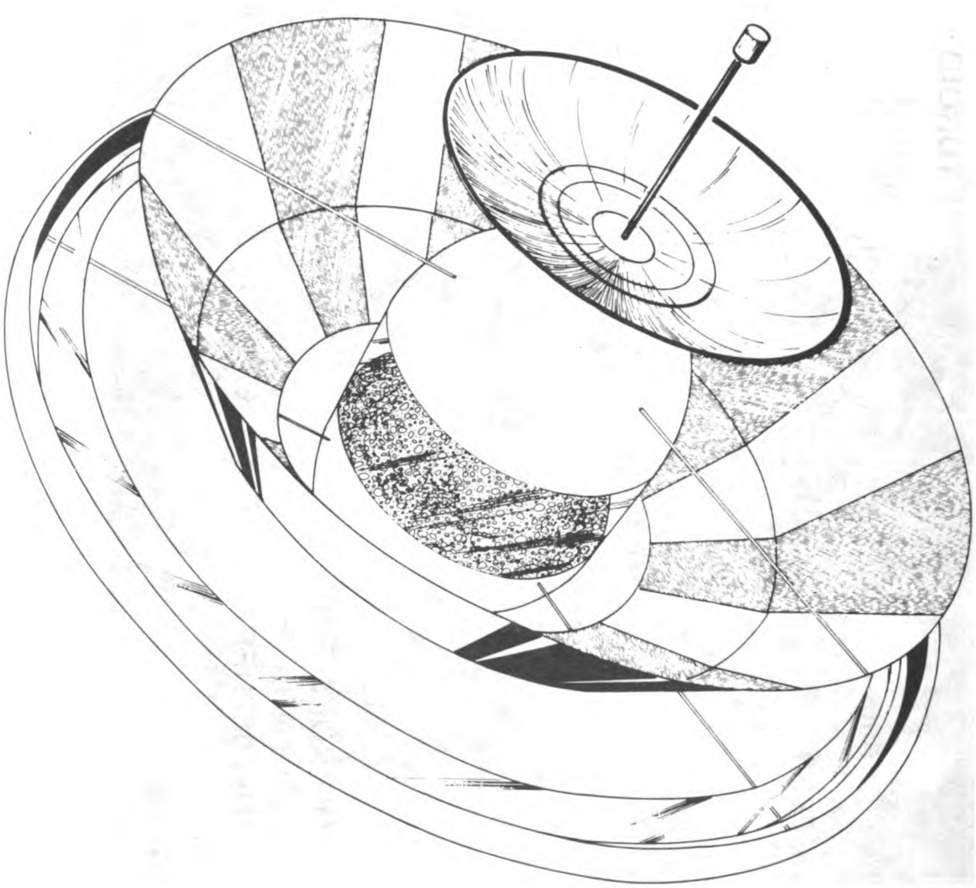
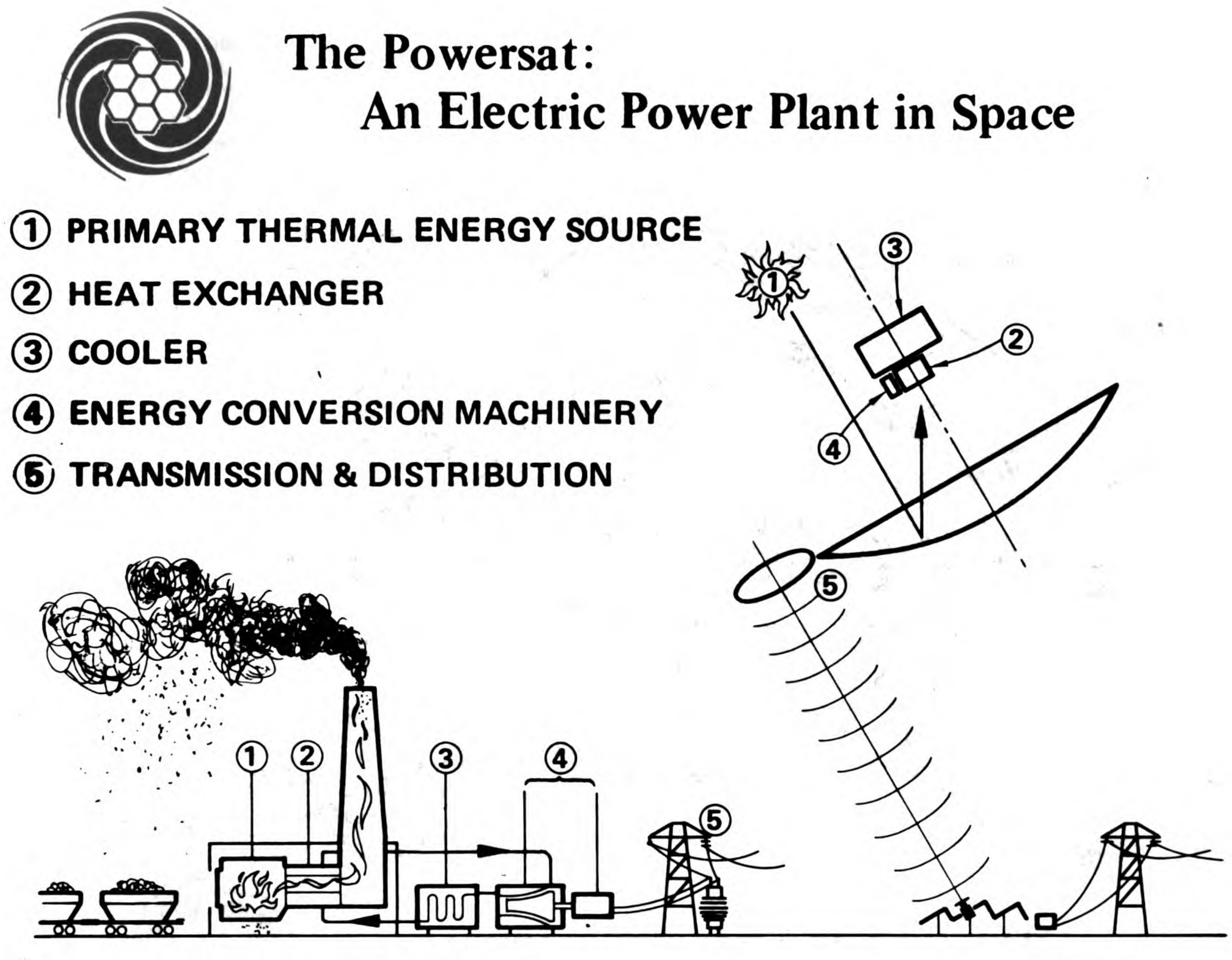
Fig. 11




The Powersat:
An Electric Power Plant in Space
1 PRIMARY THERMAL ENERGY SOURCE
2 HEAT EXCHANGER
3 COOLER
4 ENERGY CONVERSION MACHINERY
5 TRANSMISSION & DISTRIBUTION
1
2
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4
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1
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5

FIG. 12

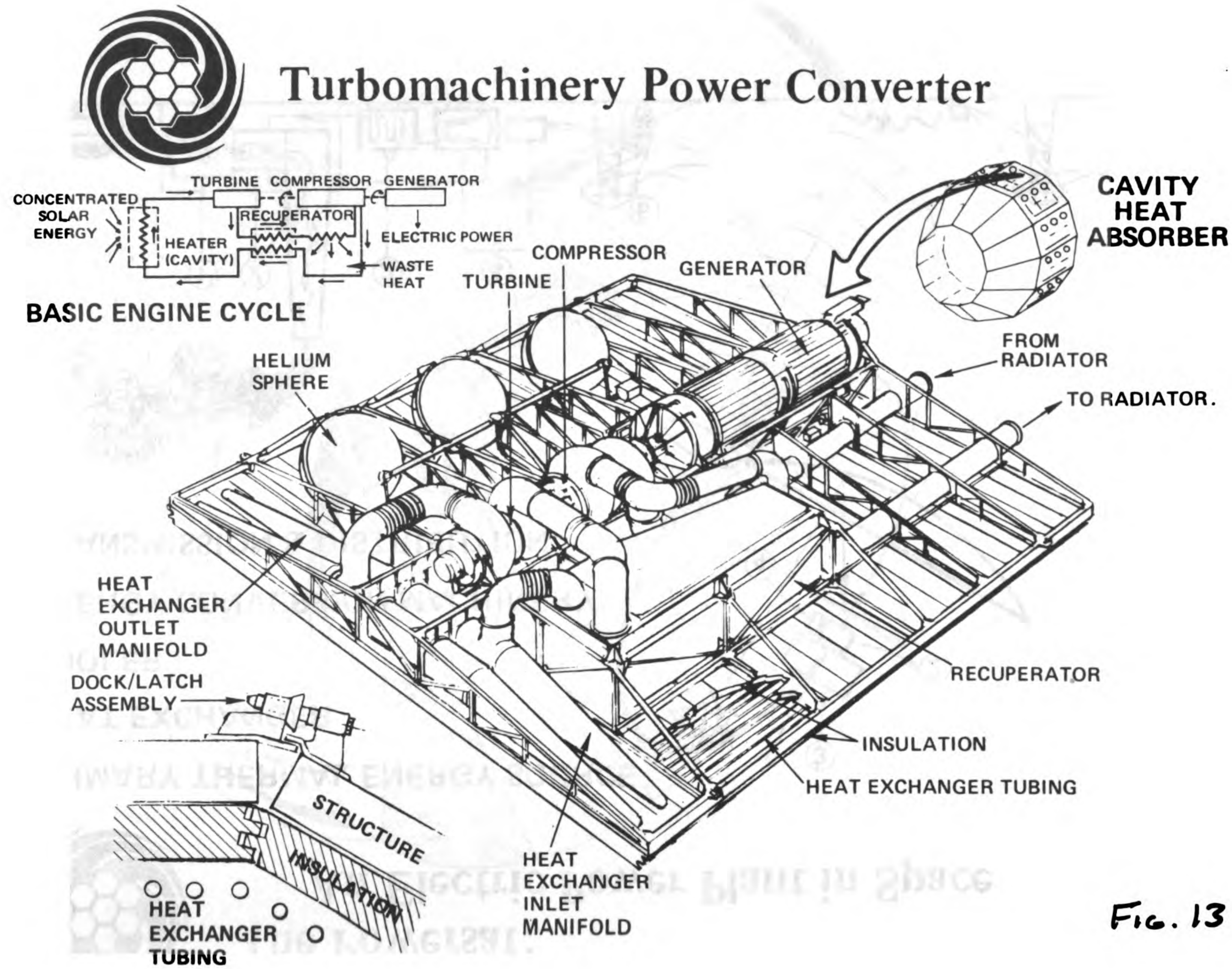
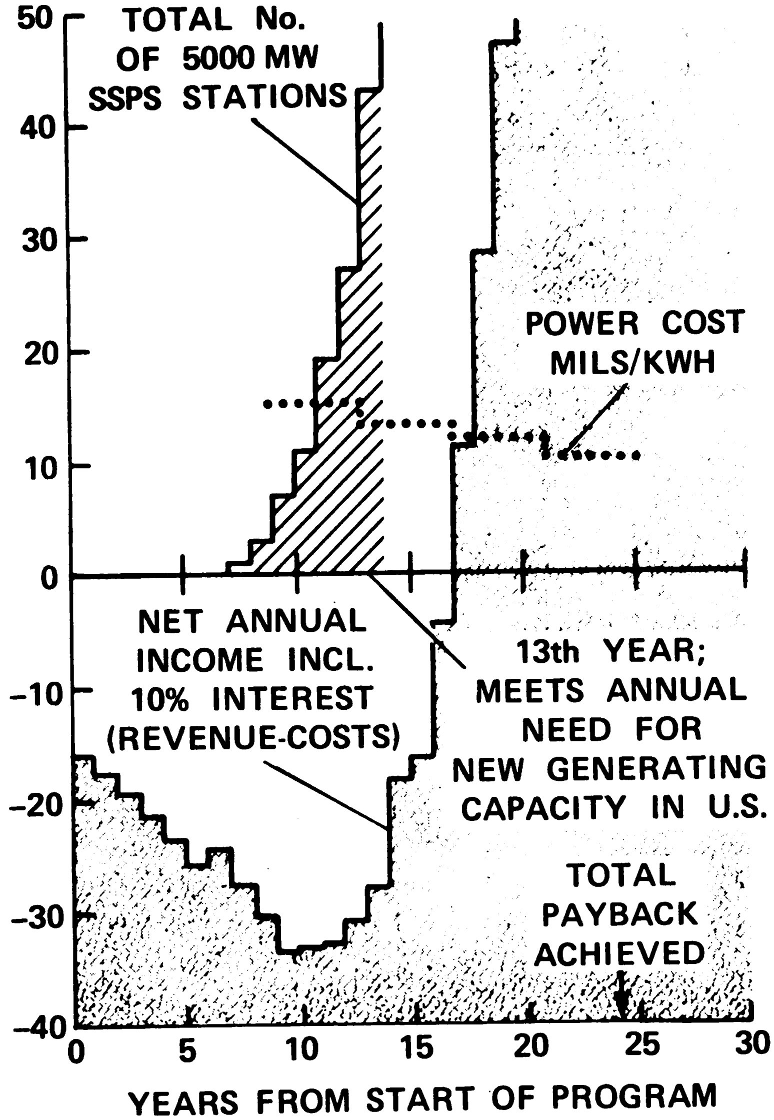

Turbomachinery Power Converter
TURBINE
COMPRESSOR
GENERATOR
CONCENTRATED SOLAR ENERGY
RECUPERATOR
HEATER (CAVITY)
ELECTRIC POWER
WASTE HEAT
BASIC ENGINE CYCLE
COMPRESSOR
TURBINE
GENERATOR
CAVITY HEAT ABSORBER
HELIUM SPHERE
FROM RADIATOR
TO RADIATOR.
HEAT EXCHANGER OUTLET MANIFOLD
DOCK/LATCH ASSEMBLY
RECUPERATOR
INSULATION
HEAT EXCHANGER TUBING
STRUCTURE
INSULATION
HEAT EXCHANGER TUBING
HEAT EXCHANGER INLET MANIFOLD

FIG. 13



50
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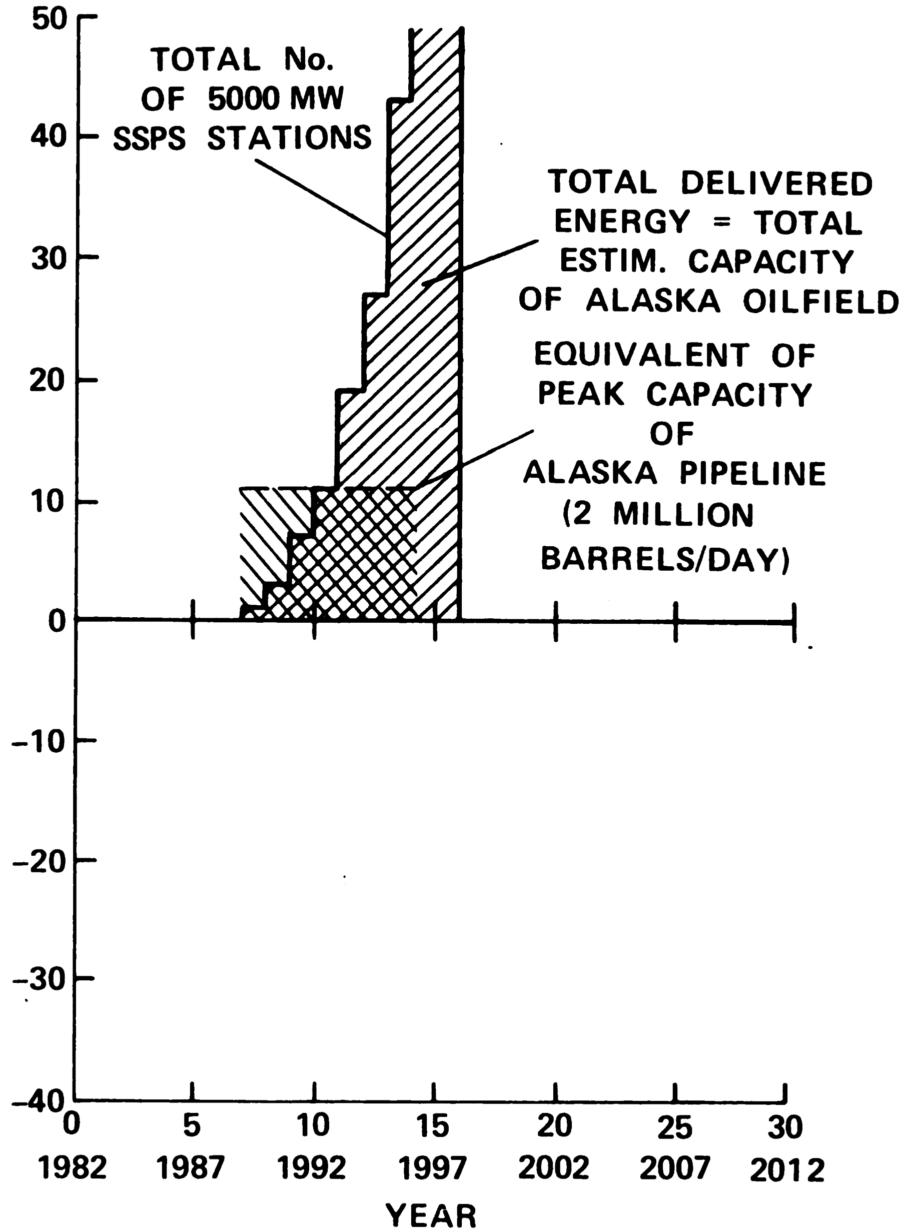
-40
TOTAL No.
OF 5000 MW
SSPS STATIONS
POWER COST
MILS/KWH
NET ANNUAL
INCOME INCL.
10% INTEREST
(REVENUE-COSTS)
13th YEAR;
MEETS ANNUAL
NEED FOR
NEW GENERATING
CAPACITY IN U.S.
TOTAL
PAYBACK
ACHIEVED
0
5
10
15
20
25
30
YEARS FROM START OF PROGRAM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−10
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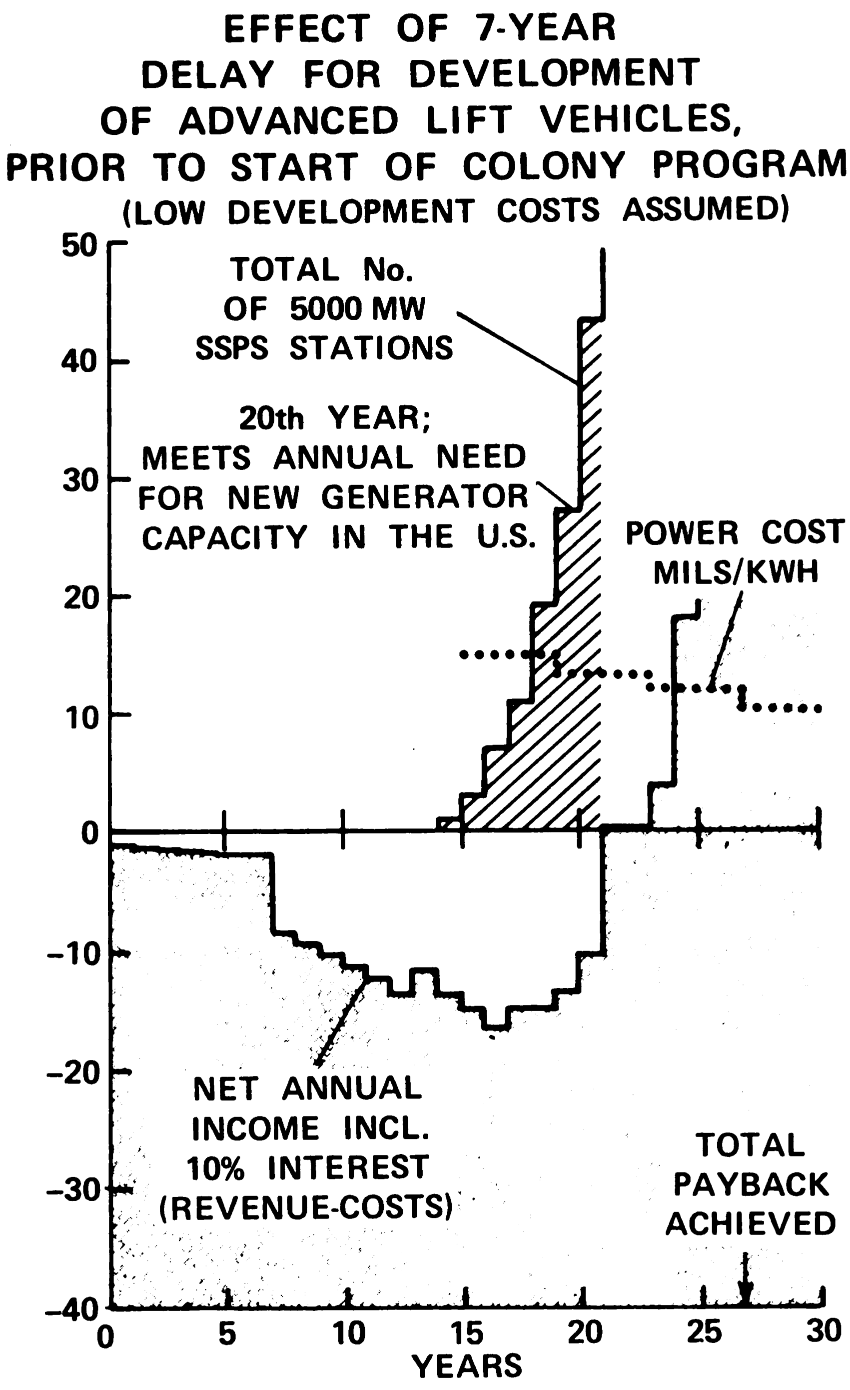
−30
−40
TOTAL No.
OF 5000 MW
SSPS STATIONS
TOTAL DELIVERED
ENERGY = TOTAL
ESTIM. CAPACITY
OF ALASKA OILFIELD
EQUIVALENT OF
PEAK CAPACITY
OF
ALASKA PIPELINE
(2 MILLION
BARRELS/DAY)
0 5 10 15 20 25 30
1982 1987 1992 1997 2002 2007 2012
YEAR


EFFECT OF 7-YEAR
DELAY FOR DEVELOPMENT
OF ADVANCED LIFT VEHICLES,
PRIOR TO START OF COLONY PROGRAM
(LOW DEVELOPMENT COSTS ASSUMED)
TOTAL No.
OF 5000 MW
SSPS STATIONS
20th YEAR;
MEETS ANNUAL NEED
FOR NEW GENERATOR
CAPACITY IN THE U.S.
POWER COST
MILS/KWH
NET ANNUAL
INCOME INCL.
10% INTEREST
(REVENUE-COSTS)
TOTAL
PAYBACK
ACHIEVED
50
40
30
20
10
0
-10
-20
-30
-40
0
5
10
15
20
25
30
YEARS

Mr. O'NEILL. Thank you, sir.

I'll try to make my spoken description very brief so we have plenty of time for questions.

Our traditional idea of America, I think, has been of a country growing in strength and expertise, but it's a long time now since we heard that old phrase "American know-how." We are told now that we must stop development. We are running out of energy, running out of materials—and fast. We are told that we must have a steady-state society.

But history tells us that nothing intelligent is static. Nations, species, and ideas must change and evolve, or they decline and eventually die.

We just had the Apollo-Soyuz demonstration of international cooperation. Where do we go from here? I listened closely on television last week to ex-astronauts, interviewers, and ordinary people saying "space has had it, it's time to hold a going-out-of-business sale."

But just within the past year a new option has opened up for us. It is so new that most people haven't heard about it yet. It's usually called space colonization, or the building of space manufacturing facilities, and I think we're really looking still for a good name.

It's natural for technically trained people to say "if we haven't heard about a new option before, it must be something out of the 21st century." But my topic today is the exception to that rule. We have the technology for it. We just have to put it together in the right way.

There is an inexhaustible source of energy not far away from us: sunlight in free space outside of the Earth's shadow.

As for materials, we didn't know it at the time, but Apollo was more than a scientific expedition. It was a prospecting survey, finding materials and minerals we need for practical use, not here on Earth but to build products whose end-use will be in high orbit.

A space colony would be a self-supporting, attractive, highly productive community in free space. Its construction costs would be cut greatly by using materials brought from the weak gravity of the Moon, instead of from the strong gravity of the Earth.

We would use what you might call the bootstrap method: The first space manufacturing facility would build more of them, as well as more of the products which would be needed in high orbit: First, Satellite solar power stations, to supply energy to the Earth; second, optical telescopes and radio telescopes, including the kind described by Mr. Norman Cousins yesterday; third, ships for the human exploration of the solar system.

These are physical products for which we can measure the space manufacturing facility by its cost-effectiveness.

But I believe that from the vantage point of several decades in the future, our children will judge the most important benefits of space colonization to have been not physical or economic, but the opening of new human options, the possibility of a new degree of freedom, not only for the human body, but much more important, for the human spirit and sense of aspiration.

We are, I think, at our best when we are most greatly challenged and given the widest freedom of choice.

In terms of immediate practicality, I must make an important distinction: We need good research on every lead toward solving our energy problem. But unlike, for example, hydrogen fusion power, where still after 25 years more basic physics research remains to be done, in space colonization we know the physics and now can do civil engineering on a large scale in a well-understood environment.

Here is where we might start—I'd like to show the first slide, if I may, Mr. Chairman.

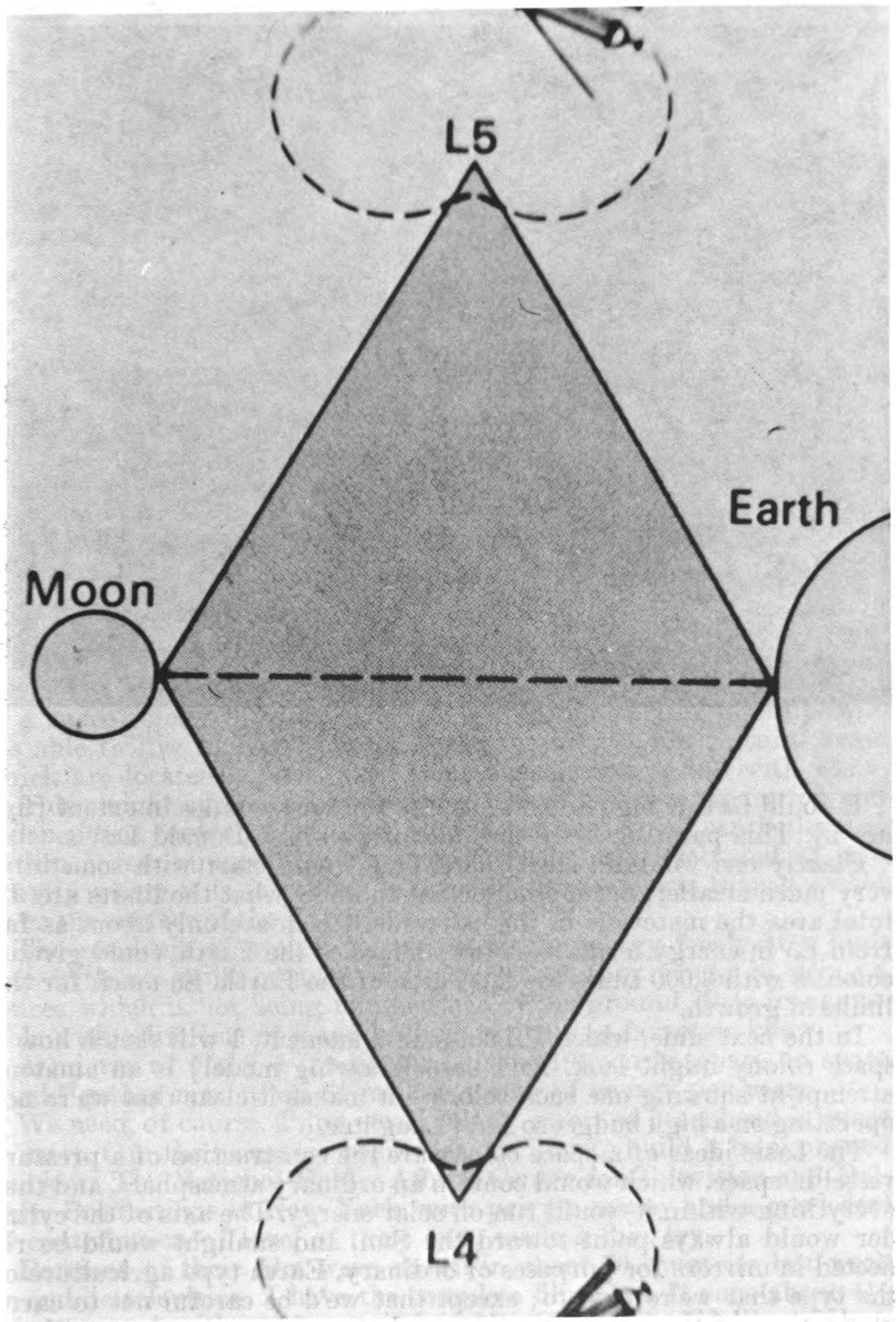


FIGURE 1

This is a sketch of a place on lunar orbit called L5. Around it there is a stable orbit on which a space manufacturing facility could be located [figure 1].

We have asked the question: Within ordinary civil engineering materials limits, of the sort within which this building is built, how big could a space colony be—not the first one, but an eventual colony. That is the first surprise, which is illustrated by the second slide.

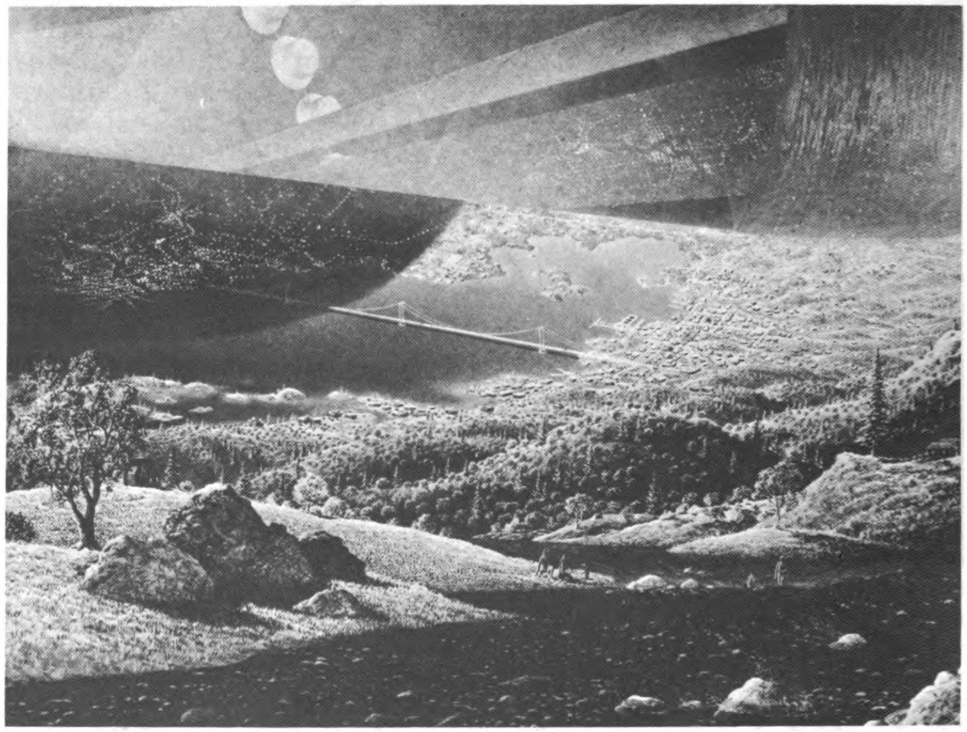


FIGURE 2

It could be this big: Something like 100 square miles in extent [figure 2]. This painting is by the California artist Donald Davis.

Clearly one wouldn't start there. One would start with something very much smaller, but it's important to know what the limits are. In total area the materials in the asteroids, which are only about as far from L5 in energy terms as is the surface of the Earth, could give us colonies with 3,000 times the land area of the Earth. So much for the limits of growth.

In the next slide, which I'll show in a moment, I will sketch how a space colony might look. And here [showing model] is an amateur attempt at showing one such colony—it makes it clear that we're not operating on a high budget so far. [Laughter.]

The basic ideas of a space colony are the construction of a pressure vessel in space, which would contain an ordinary atmosphere, and that everything within it would run on solar energy. The axis of the cylinder would always point toward the Sun, and sunlight would be reflected in mirrors for purposes of ordinary, Earth-type agriculture of the type that we're used to; except that we'd be careful not to carry along some of the agricultural pests that we have to put up with on the surface of the Earth.

The electrical power for the colony would be obtained by solar energy conversion, using a conventional system I'll describe a little later; this is the large mirror which would be one element of that conversion [indicating].

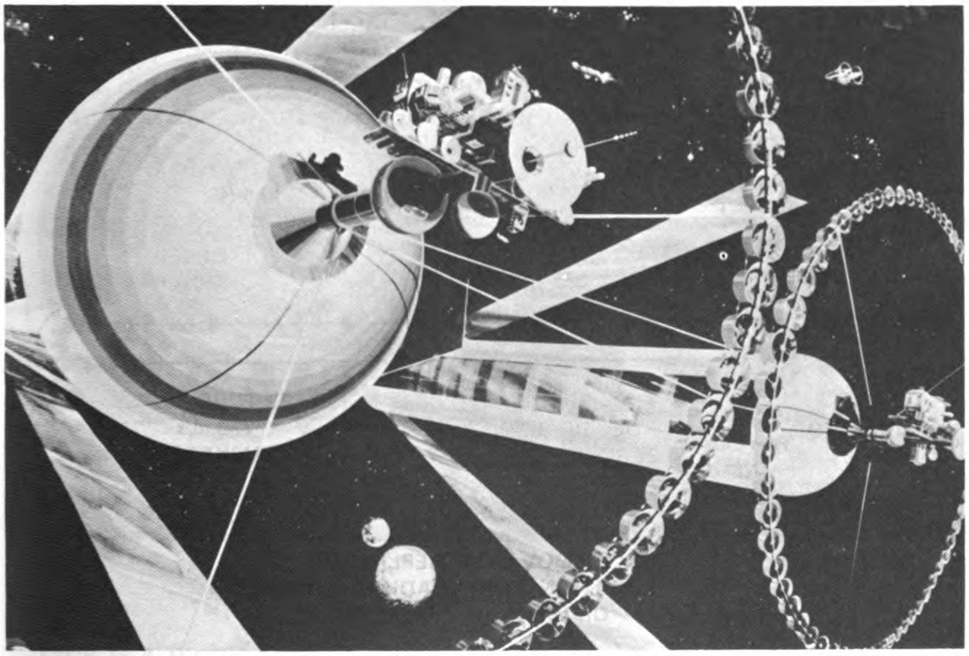


FIGURE 3

In the next slide [figure 3] we have a painting by Frank Giudice of the NASA-Ames Laboratory; it shows the fundamental separation of a space colony into regions: One a rotating habitat where people are able to live in Earth normal gravity; second, agricultural areas which are located outside, with their own gravities, and with whatever day-night cycles and seasons one wishes. There is separation and independent control. Last of all, the industries, which can be located within a few minutes' travel time of the habitat itself, but in zero gravity where it is far easier to assemble large objects than it would be on the surface of the Earth.

The residents of such a colony could use energy freely at a high rate with no guilt, because of the fact that they would be using a source which is not being pumped out of the ground. It is inexhaustible with a lifetime of many billions of years as far as we know.

A mirror of under 1 ton in mass, about 100 yards square, in space would gather more than $1 million worth of energy per year.

We need, of course, a first small colony, a sort of beachhead in space to start. Can the necessary basic ideas on how to build it be expressed quickly? The National Public Affairs Center for Television and Dolphin Productions in New York, with private money and a good deal of contribution of love, of their own, made a first try.

Portions of their film were shown in about 20 countries last week on public television. I have the complete film here. It runs about 4½ minutes, and with your permission, Mr. Chairman, I'd like to show it now.

Mr. FUQUA. I'd like to see it.

Mr. O'NEILL. Thank you. [Film shown.]

After seeing a film of that kind, I think the reaction that most of us would have is that it must be science fiction, something out of Buck Rogers, in the 25th century.

It will, therefore, come as a surprise that I'm talking in practical engineering terms, of things that we could do within the technology of the 1970's. The key to low-cost materials is a device which we call the mass driver, which was shown in schematic form in that film.

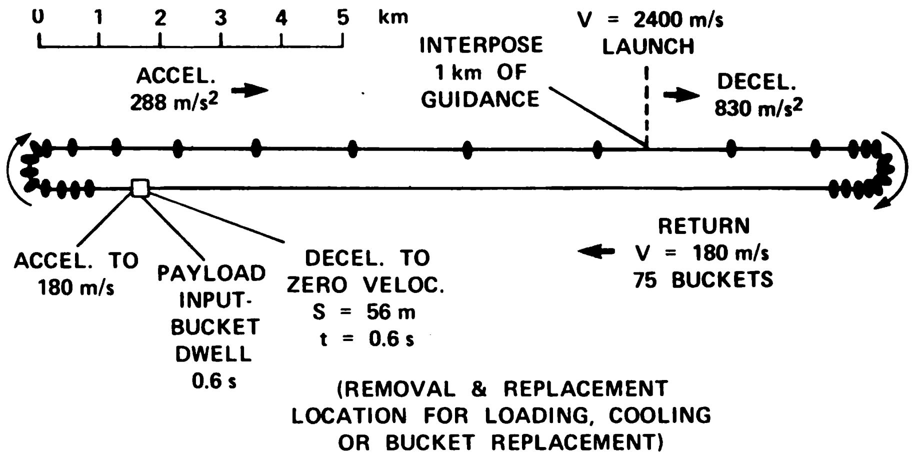


FIGURE 4

It is a machine for bringing materials from the surface of the Moon. The mass driver would be an efficient, linear electric motor—I'll sketch it in the next slide, if I may [figure 4]. In schematic form, it would be a long track on which small vehicles weighing only a few pounds would accelerate loads of lunar material up to the lunar escape speed, give them precise guidance, and then release them. The vehicle itself would return for re-use. It would be an economical system, because the vehicles would be used often, at a frequency of one every 2½ minutes. They would recirculate on the track and would never be thrown away.

Unlike our present launch vehicle systems, where hundreds of millions of dollars are thrown away with every launch, here nothing expensive would ever be thrown away.

The operation of the mass driver could be at a transport rate of up to 1,000 tons per day in the initial operations, with growth capability rather easily up to about 4,000 tons per day.

The next question is that of the lunar outpost; by courtesy of Field Enterprises and the 1976 edition of the Science Yearbook, before publication I am able to show some of the pictures that they're going to be using in an article which will come out in September. I would like to show one such painting next.

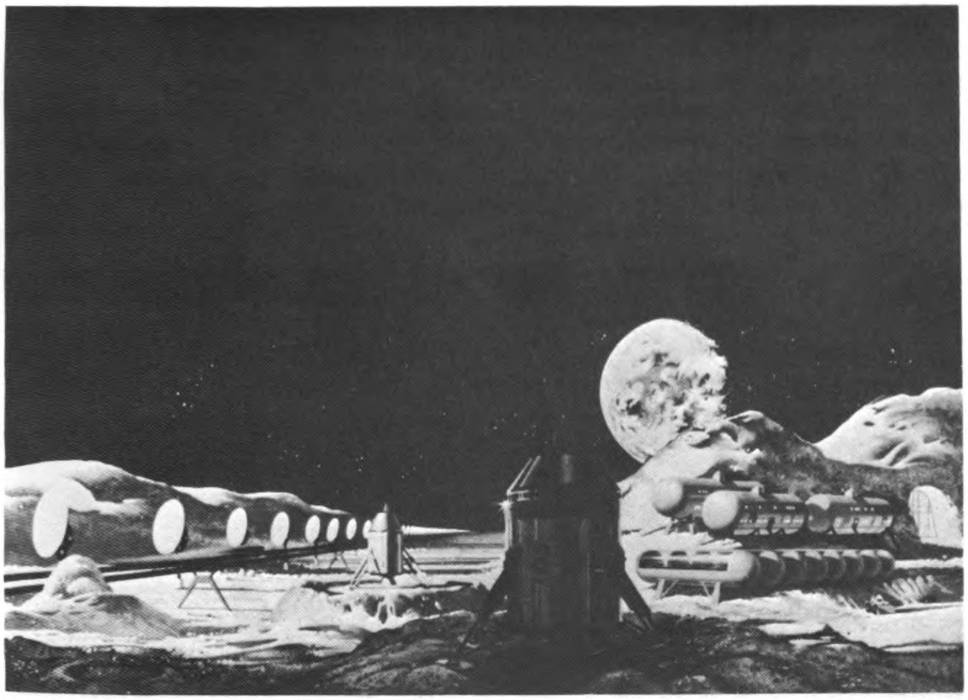


FIGURE 5

This is a picture of the lunar outpost, as conceived by a staff artist for Science Year [figure 5]. The outpost would be a relatively small operation, because the actual processing of the material would be done out at the L5 region, where solar energy is available full time for free use and where zero gravity is also available.

The launch track is shown on the left. It would be run by solar power, or perhaps by nuclear power.

Most people don't realize the richness of the surface of the Moon. The lunar surface—the unselected fines, so-called, the unselected dirt which the Apollo astronauts were able to scoop up in their gloved hands, contained 40 percent oxygen by weight and from 20 to 30 percent mentals by weight. To bring out the materials for the first community sounds like large-scale mining, but in fact, 500,000 tons to build the first colony—about the same as the mass of a modern supertanker—would leave a hole in the moon which would only be about 7 yards deep and 200 yards long and wide, not even as far as the astronauts could comfortably walk. The excavation of that much material would not even be enough to keep one small bulldozer operating full time over a 5-year period. In the course of years, slag from the industries at L5 would be added outside the colony to provide cosmic-ray shielding.

Mr. FUQUA. That wouldn't be referred to in any way as strip mining, would it?

Mr. O'Neill. I would hope not, sir, especially since there was nothing green growing on it before you did it. That's an important difference.

Travel to the later colonies would be by a ship built there, at L5. Logically, the L5 colonies would be the ideal locations for shipyards in space. The ship would be big, but still would not require understanding new physics. It could be designed right now.

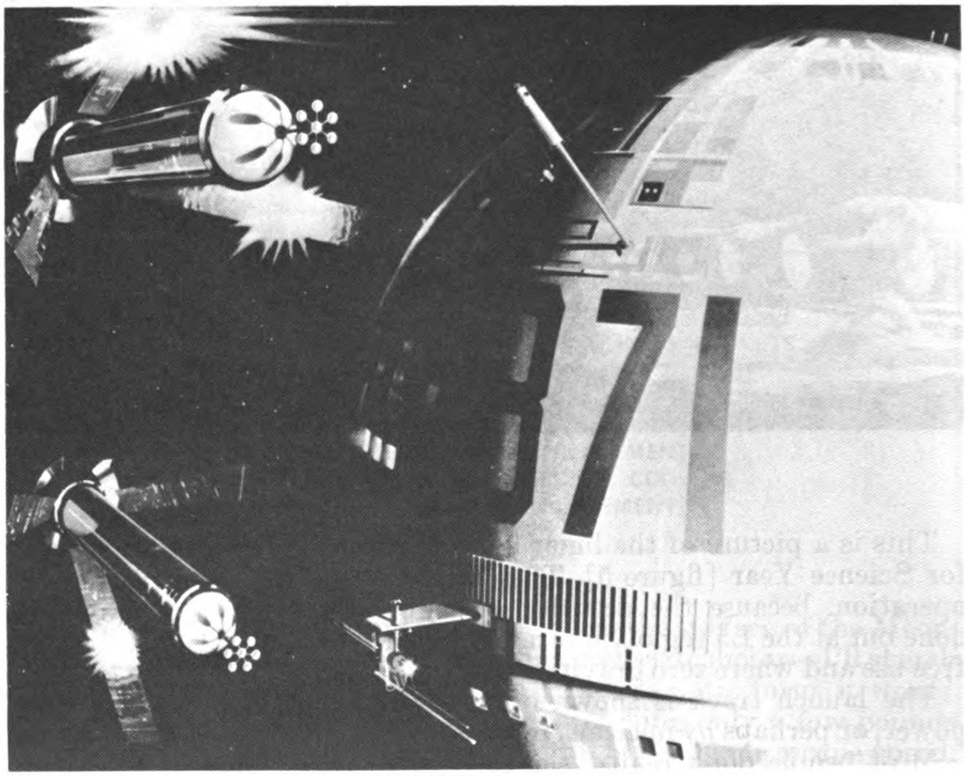


Figure 6

One such ship is shown in the next slide, along with one of the possible designs for an early colony [figure 6]. The ship is shown at the right, coming in from low Earth orbit and approaching one of the colonies—and, in recognition of the great American rocket pioneer, in that Science Year article I call that ship the *Robert H. Goddard.*

The colony will work only if talented and hard-working people choose to live there. Productivity is the real name of the game. The community must be far more than just a space station.

From the NASA-Stanford summer study in California, in which 28 people are now working on the subject for 10 weeks, there are new and perhaps better optimized designs for the first colony. I'd like to show one of those now.

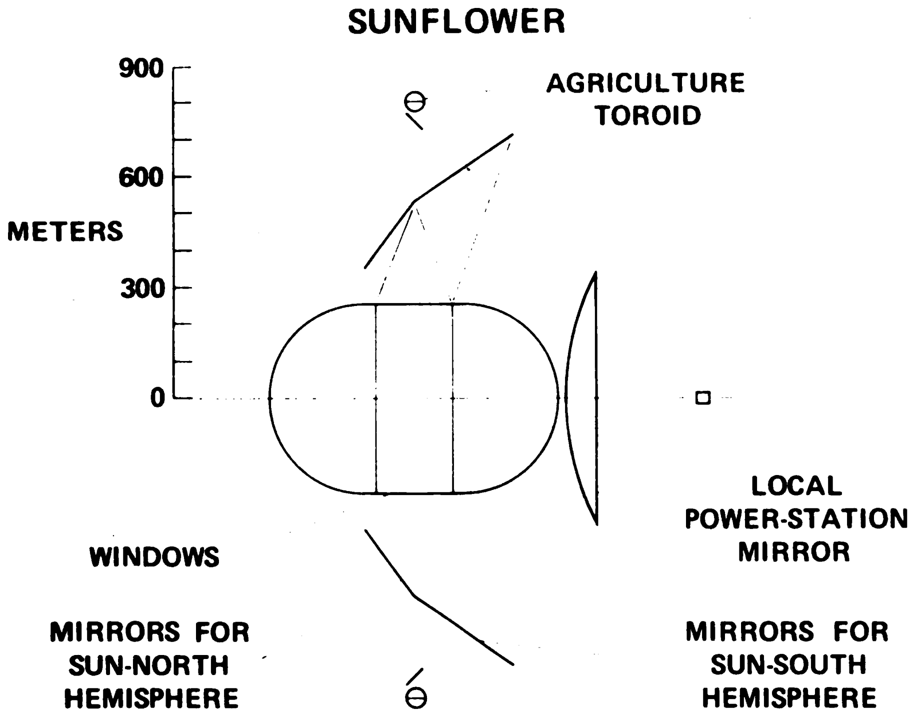


FIGURE 7

This is a design in which there is one large volume. We call it Sunflower, because it looks a little like the petals of a flower; it tracks the Sun and uses solar power for all its energy needs [figure 7]. It's surprising that within the mass budget which I just described, the internal circumstance of the habitat could be more than 1 mile.

In the next slide, there is shown a three-quarters view [slide] of that particular conception of a first space colony. It could house comfortably something like 10,000 people, working under conditions in which the population density would be comparable to attractive urban communities in, for example, the United States or Southern France.

Again, I must thank the Science Year people, because they've been kind enough to let me show one other slide, which is an interior of an earlier, much smaller design. It expresses the feeling of something which is lush and luxurient, not hard and metallic, as in the case of a space station. This is a possible interior design for an early space colony.

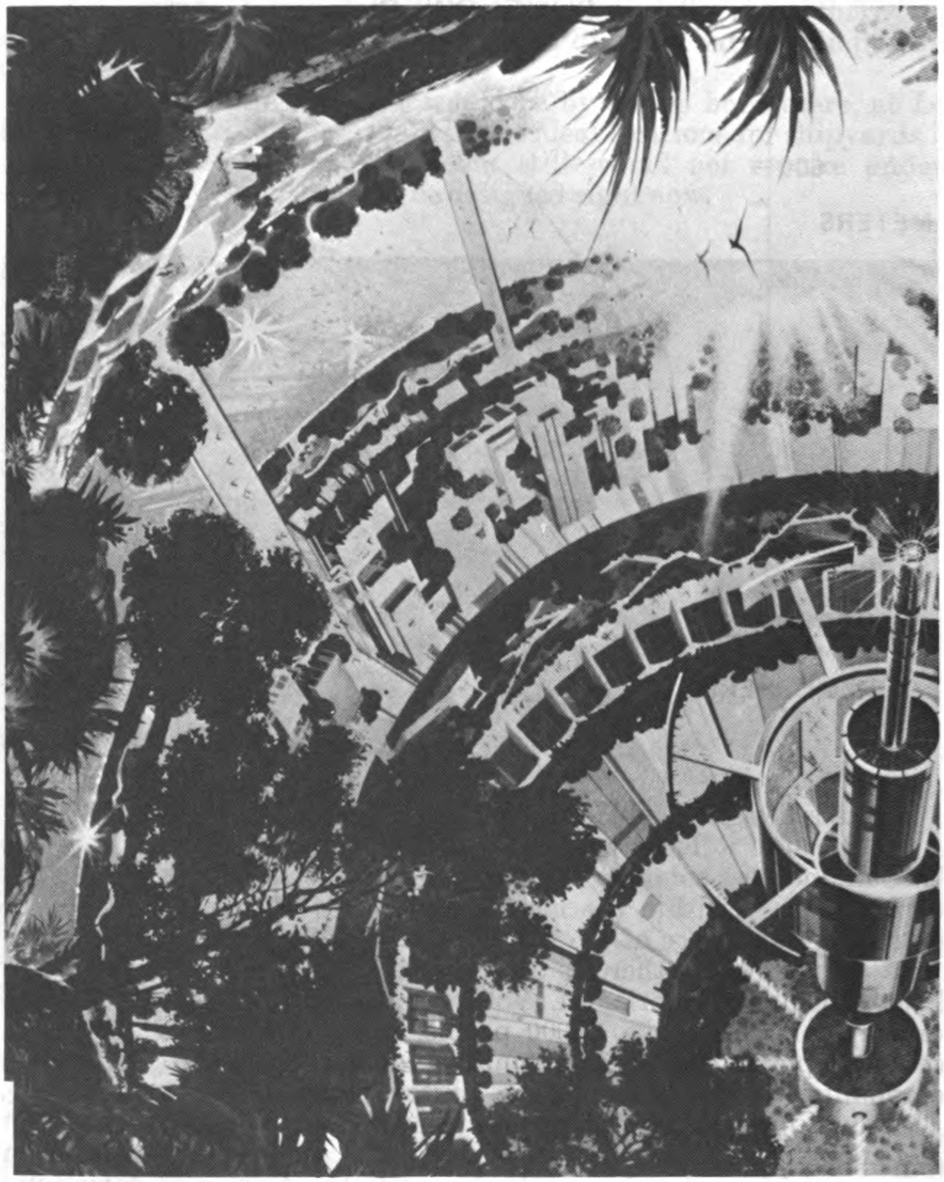


Figure 8

Some of the apartment areas, shops and streets, and so on, are shown [figure 8]. There are also, of course, regions up near the axis where gravity would be very low. There one could even enjoy such things as human-powered flight and some interesting variations on Earth sports and ballet.

One important study area for us is ecology. It does not, however, have to be stable ecology. As in all high-yield agriculture on the Earth, if crops change their characteristics humans will intervene. We need not have a completely closed ecology, which would be a very difficult thing to do, but only what we might call economic closure. That is, to reduce the imports of seeds and other necessary materials from the Earth to a sufficiently low value.

In calculating the costs of an initial beachhead in space, we should appreciate first that nearly all the rocket hardware which is needed is already under development for the space shuttle. We don't need anything much more advanced than that.

Space colonization would involve as participants about 1,000 times as many people as the number of astronauts in the Apollo project, but because of the cost savings I mentioned, it would cost only about one and one-half to four times as much as that project. NASA and private aerospace experts say something in the general range, roughly, of $50 to $150 million, about 15 percent of the estimated cost of Project Independence.

But it appears that, if our numbers are correct, the first space community and its daughter colonies can give us a true, permanent energy independence on Earth and pay back the development and construction cost. I do not want to make a promise that cannot be made good. The research must be done in greater depth and detail.

But I can say that so far, after a year of intense exposure to the technical community, none of the basic conclusions has seriously changed.

As to payback from this project, at this time both the industrial nations and the third world are vulnerable to the threat of cutoff of the energy supplies which we have to import. One way to supply energy to the Earth, free of nuclear radioactivity and nuclear proliferation problems, is by solar power converted to microwave energy in geosynchronous orbit, and beamed to the Earth for conversion to ordinary electricity.

For several years, groups at the Arthur D. Little Corp., and more recently, at Boeing Aircraft have studied this possibility. Dr. Peter Glaser, one of the leaders of this activity, was here until a few moments ago, when he had to leave for another meeting.

The environmental question must be studied as carefully, although so far it appears that the environmental impact would be much less severe from the low-density microwave beam than from nuclear power or from the strip mining of coal.

The problem is that it is too expensive to lift the solar powerplants from the Earth. For launch from here, it would be necessary to have lift costs of only one-quarter to one-twelfth of the figures possible with shuttle-derived hardware, and powerplant weights much less than are now attainable, even to make electricity at a rather high cost.

But with the space manufacturing facility, using lunar material brought out to L5 by the mass driver, it appears from all our calculations that we could build and locate powerplants at much lower cost and so supply low-cost energy to the Earth.

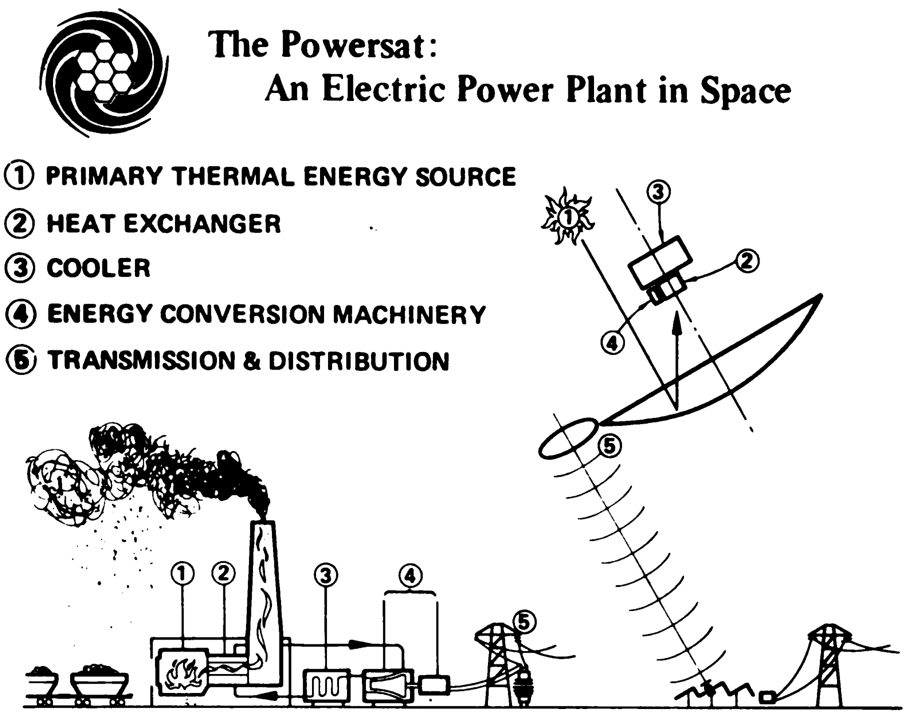


FIGURE 9

Here is a sketch of one such system: It and the following two slides are by courtesy of Boeing Aircraft. This is the outline of a satellite solar power system [figure 9] in which solar energy is concentrated on a boiler, which then drives a turbogenerator. There is a conversion to microwave energy and reconversion on the ground to ordinary direct current.

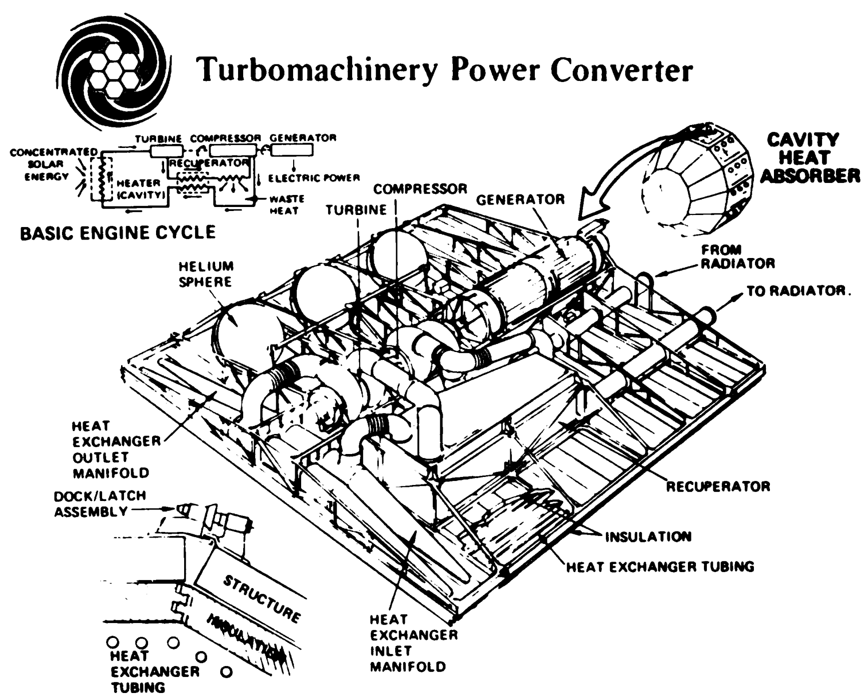


FIGURE 10

The next slide [figure 10] is of engineering interest. The basic idea is a turbine driving an electric generator.

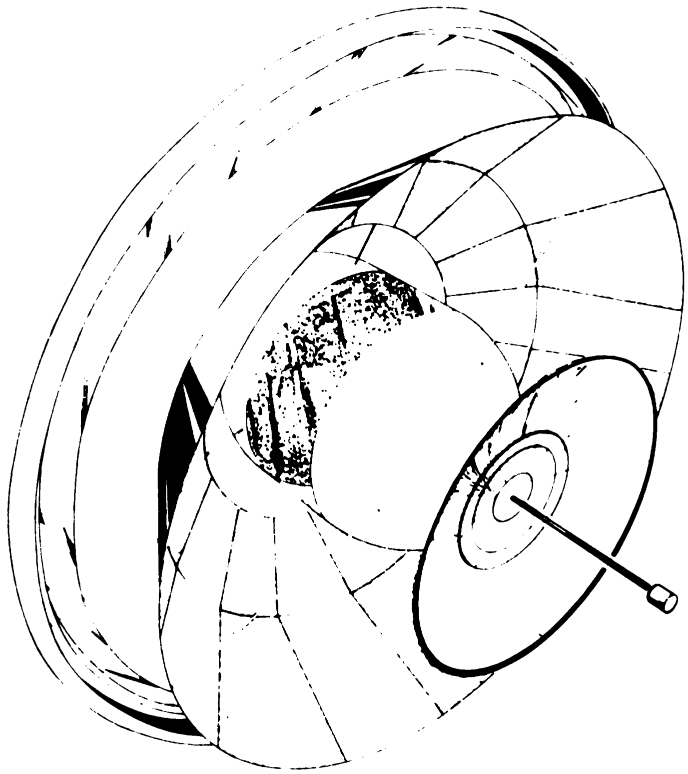


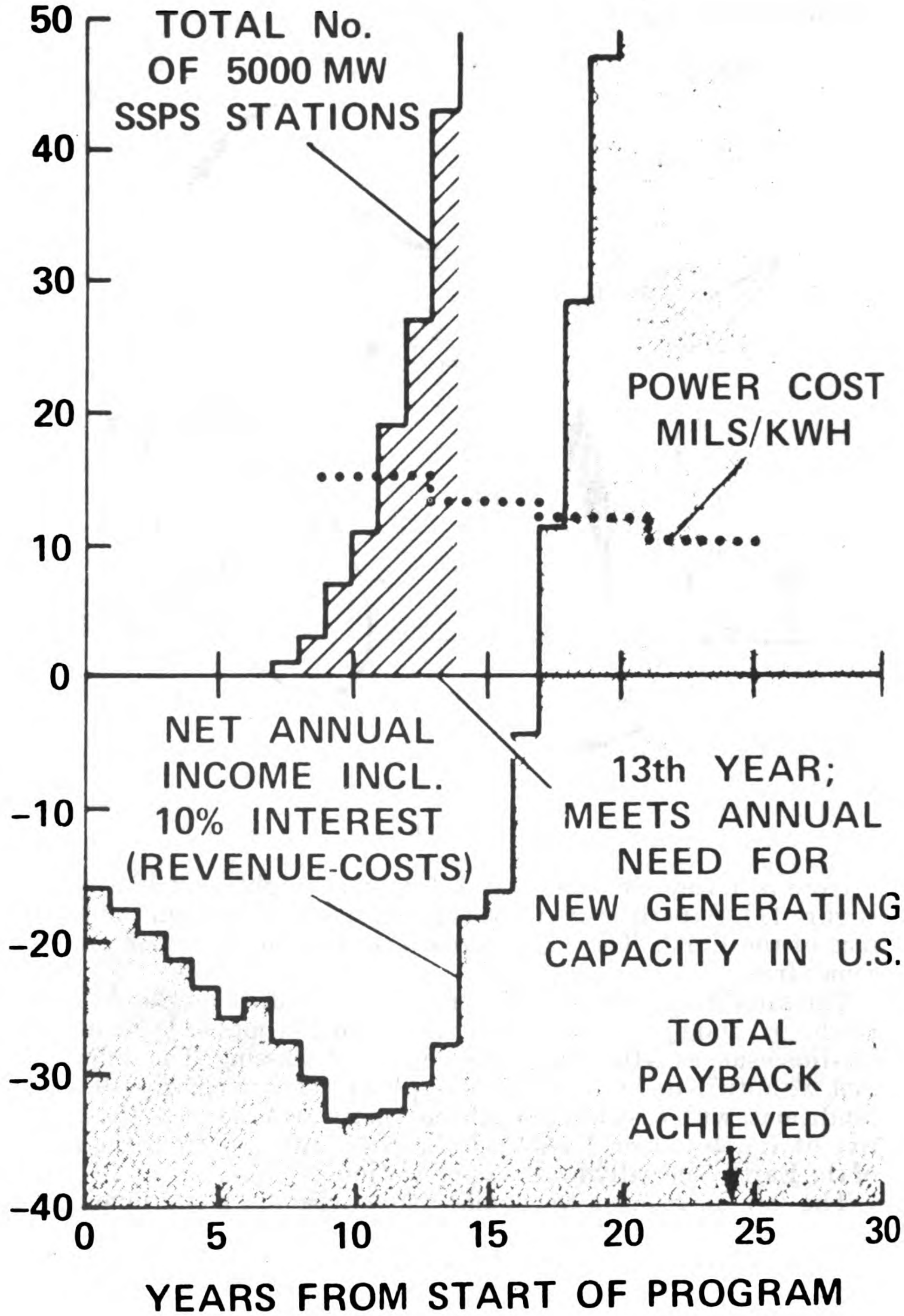
FIGURE 11

Here is a view of what one such system might look like in space [figure 11]. Superficially, it looks much like a powerplant on the surface of the Earth. The big difference is that the fire under the boiler comes free.

The satellite power station structure, as studied by the Arthur D. Little Co., and by Boeing Aircraft, is about 10 times as large in physical dimension as is the space colony we are discussing. The difference is that we anticipate having 10,000 people up there in comfortable living conditions, with easy access to the assembly area, whereas the alternative of Earth launch requires workers brought up from the surface of the Earth especially for the assembly jobs.

The key question is economics and payback. If our numbers are right, and we're asking for independent cross-checks on them, then we can pay back the entire initial investment, supply plenty of energy to the Earth, and, it appears, even make a substantial profit.

The next three slides emphasize the economics. Again, I should remind you that this research has been very small in scale up to the present time; we are asking mainly that it be studied carefully by other people.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TOTAL No.
OF 5000 MW
SSPS STATIONS
POWER COST
MILS/KWH
NET ANNUAL
INCOME INCL.
10% INTEREST
(REVENUE-COSTS)
13th YEAR;
MEETS ANNUAL
NEED FOR
NEW GENERATING
CAPACITY IN U.S.
TOTAL
PAYBACK
ACHIEVED
0
5
10
15
20
25
30
YEARS FROM START OF PROGRAM

FIGURE 12

The next slide shows an economic scenario which has been worked out [figure 12]. This is discounted economics with a 10-percent discount rate. That is approximately equivalent to saying that you're paying a 10-percent interest on the outstanding debt at any given time during the project. The total capitalization without interest payments was taken as being about $100 billion, and the development time is shown at the bottom, going zero years, 5, 10, 15, and so on.

In this scenario the first colony would be finished after about 6 years, and would then replicate initial colonies and satellite solar power systems within a very short time.

As you can see, the total number of 5,000-megawatt power stations goes to a fairly high value. That is because we would build, with the first space manufacturing facility, not only power stations, but more manufacturing facilities. So, it's a bootstrap process.

In a little over 15 years, with this time-line there would be a net income rather than an outflow. Within about 24 years total payback of the entire investment cost including all interest rates would have been achieved.

The selling price of power at the busbar on Earth is shown as 15 mils to start with, dropping at 4-year intervals from 12 to 10; it may be possible to reduce that price even further. We feel that low price is essential, because we must have a low power cost if we are to have market penetration, in baseload power.

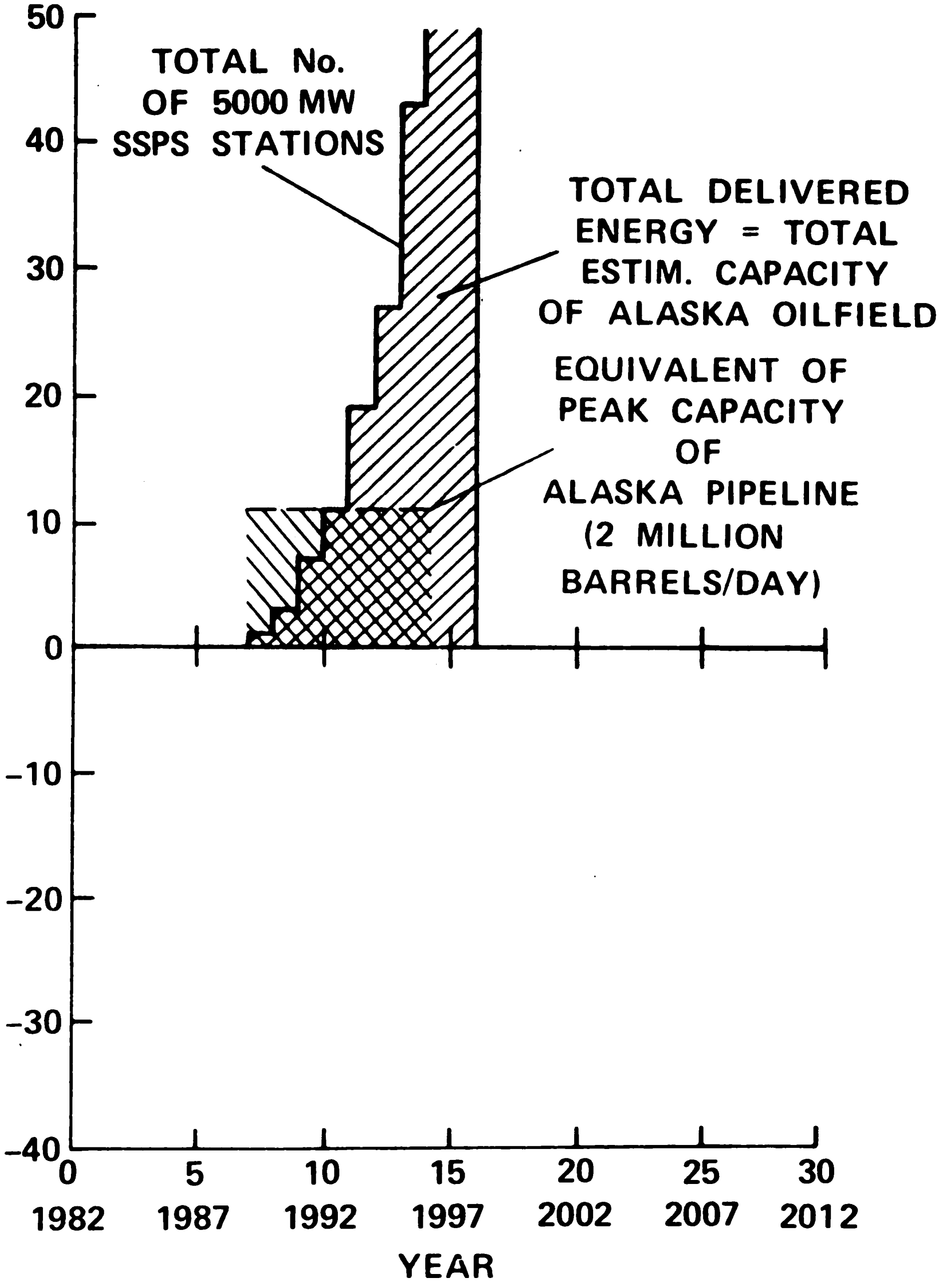
50
40
30
20
10
0
−10
−20
−30
−40
TOTAL No.
OF 5000 MW
SSPS STATIONS
TOTAL DELIVERED
ENERGY = TOTAL
ESTIM. CAPACITY
OF ALASKA OILFIELD
EQUIVALENT OF
PEAK CAPACITY
OF
ALASKA PIPELINE
(2 MILLION
BARRELS/DAY)
0
1982
5
1987
10
1992
15
1997
20
2002
25
2007
30
2012
YEAR

FIGURE 13

We are not dealing with a token amount of power. This slide illustrates that [figure 13]. About 12 years after the colony-building program is begun, the total input of energy from space would exceed the peak capacity of the Alaska pipeline; and within about 7 years after that time, we would reach the point, with the power curve still going up, at which the total energy which had been supplied to the Earth from space would exceed the total capacity of the Alaskan North Slope. These are not small amounts of power.

On the same slide is shown a time scale. It starts with construction in 1982 and runs to a first power station coming on line by the 1990's, and to an effective energy independence reached sometime later in the 1990's. This is an ambitious time scale. I believe that it is realizable. Many people disagree with me. I think that we have to recall such examples as Robert Oppenheimer's successful completion of the Manhattan project in 3 years, from a standing start with much more unknown physics than we have in this case; and the very rapid development of the nuclear submarines.

In the field of high-energy physics, the case that comes to mind is Robert Wilson and his successful, rapid completion of the National Accelerator near Chicago, again under a short time scale and at a low budget.

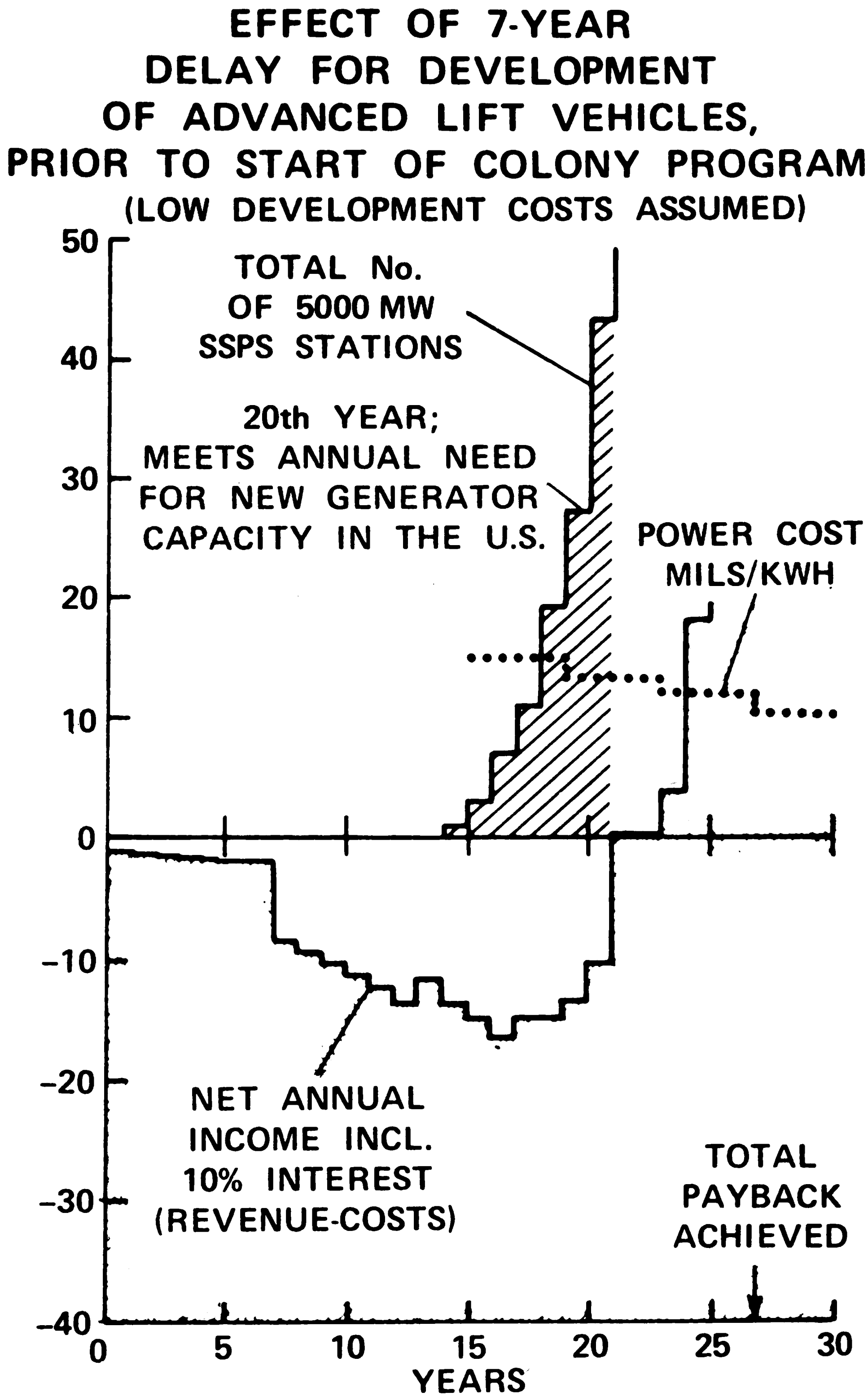

FIGURE 14

The last slide in that series [figure 14] shows the effect of waiting for more advanced lift vehicles prior to the start of the colony program. These are the sort of advanced lift vehicles which are assumed already to be available in the Earth-launched power satellite discussions so far.

The net result is that the benefits, as well as the cost, are all delayed by about a 7-year period.

The result of dropping power rates through this approach would be that when the rates were less than 12 or 13 mils, we could begin to phase out coal plants and nuclear powerplants. Eventually the intention would be to get down to power rates low enough so that we could begin to manufacture synthetic fuels and reduce our dependence on the Middle East for oil.

The benefit-to-cost ratio has been calculated in a number of these scenarios. Except for extreme cases is comes out to be greater than 1, typically from 1.2 to 3.0, depending on the details of the assumptions made in the calculations.

These have been logical points Mr. Chairman, but what it would take to start a project like this is people, and how they feel. The mail that I get, from many nations around the world, as well as from the United States, runs 100-to-1 in favor of doing this project.

A volunteer organization in Tucson, Ariz., spent an intensive week trying to get information to people in that city a few weeks ago, and 2 weeks later carried out a random sampling telephone survey. They have told me that 45 percent of the people in that city now know about this project, and of those who know about it, two-thirds of them are already in favor of it.

I'd like to close now on a more humorous note, with a photograph [slide] of some people squinting in the Alabama sunshine, the kind of people that this sort of project will matter a great deal to—and that is young people. I don't count the guy in the background when I say that.

I had a very nice experience when I went down to talk to a student group of about 30 17- and 18-year-olds at that time. They all met us at the airport, waving and carrying signs, and shouting, and all very, very happy—but the thing which impressed me about these young people carrying signs is that we have had a great deal of experience in recent years with young people carrying placards and waving and shouting. Usually they're complaining about something.

It is a remarkable feature of the response to this project so far that we have examples of enthusiasm, and of people wanting to do something positive. Thank you, Mr. Chairman.

Mr. FUQUA. Thank you, Dr. O'Neill. We appreciate your very mind-stretching presentation this morning—and I say that with kindness. It's something that will happen, and even though it kind of boggles the mind at the present time, it is not beyond the realm of possibility. I hope I live to see it.

I have a commitment that I must go to, but I'm going to ask Mr. Winn to take over. I apologize for our delay this morning in getting started, but I do have a commitment, and I must excuse myself.

Mr. Winn?

Mr. WINN. Thank you very much, Mr. Chairman.

Mr. FUQUA. Thank you very much, Dr. O'Neill.

Dr. O'NEILL. Thank you.

Mr. WINN. Thank you very much for a very fine testimony, Doctor. It certainly is interesting. I'd like to live just to see part of it.

You bring to mind the fact that Dr. Wernher von Braun has been talking for years about colonization on the Moon. As a matter of fact, the members of this committee have heard him discuss that. And, of course, your theory is that colonization in space—and, offhand, it appears that possible colonization on the Moon might be a little more practical, at least a starting point.

What would your comments on the Moon concept be?

Dr. O'NEILL. Sir, it's an example of the fact that we accept, more or less without question, ideas which have been around for a very long time, whether in fact they're logically justified or not, whereas we tend to react with shock when a new idea comes along, even if it has logic behind it.

The reasons why a colony in space is more practical than one on the surface of the Moon are several:

1. The first of them is the availability of energy. On the surface of the Moon there is a 14-day night; therefore, there is a serious problem of obtaining energy. Convenient, low-cost solar power is cut off because of the fact that energy storage over a 14-day period is extremely difficult. On the Moon one is probably forced to rely on nuclear power, so one loses one of the principal advantages of working in space.

2. The second difficulty is that the Moon is more expensive to get to. To reach a planetary surface, like the surface of the Moon, you first have to go into free space, and then go down again.

The anology that I use is that in our old-fashioned talk about colonizing planetary surfaces, we were rather like a small animal which was deep down in a hole in the ground. The animal climbs at great cost up to the top of the hole and looks out and sees all the grass and flowers and sunshine, and walks across the grass. Then he finds another hole and climbs down to the bottom of that hole again. And in gravitational terms that is exactly what we are doing if we go into free space and then climb down again to the surface of the Moon.

The transport costs to get to the Moon are about twice as high as they are to go out into free space; that means that the capitalization for productive equipment is up by the same factor of 2.

3. The last reason why manufacturing on the Moon is less advantageous than in free space is that one has no control over the gravity there. The Moon has one-sixth the Earth's gravity, you have to take it as it comes, and you can never cut it off. Even to get higher gravity than that is a lot more complicated and expensive on the surface of the Moon than it is in free space, where you can simply rotate a vessel to get any gravity that you want.

So, for all three of those basic reasons, Congressman Winn, we feel that logic favors the colony in space, rather than on the surface of the Moon.

I had a very interesting discussion with Dr. von Braun a few weeks ago. Although his attitude should be confirmed with him personally, my understanding that he is quite in favor, and indeed enthusiastic, about this project.

Mr. WINN. Included in your paper that you submitted to us in advance, there were some preliminary estimates of cost for the project, both by yourself and NASA. One of them was in the $33 billion range in Physics Today, by yourself in 1974; NASA and the MSFC have seen, in January 1975, $200 billion; and NASA-MSFC, April 1975, $140 billion, a reestimate.

Could you please comment on these large differences of these cost estimates, after first giving us an idea how we could sell Congress on this thing, and the present budget for NASA is only $3.6 billion—and that's down from $5.2 when I got here in 1967.

Dr. O'NEILL. Let me answer the second question first, if I can, Mr. Winn. I think the real difference is payback. We have a product for which there is a big market, and which satisfies a need. Where there is a big market there is reason and justification for a big investment.

We're talking about something which is more like the kind of decision which a large manufacturing company has to make when it decides whether to invest in a new plant, than like the traditional idea of our space program: a research-oriented effort from which you never expected to have a direct-dollar return.

The question about the costs which have been estimated so far relates to differences in style. I think it is encouraging that the differences are not larger than they are. The program which I estimated in the Physics Today article was based on a very Spartan approach. It's one which I probably would take myself if I had the option and if I had to answer to stockholders. It's one in which there would be little resupply; we would go to self-supporting status as quickly as possible. There would be very little crew-rotation involved, and so on. It's a Spartan approach to the whole program.

In the $200 billion estimate which NASA outlined, a great many vehicle-development programs were included: not only the easty-to-develop shuttle-derived vehicles, which I would rely on in the Spartan approach, but also much more advanced nuclear-powered vehicles, and also the super shuttle, at $45 billion. That was one line in their estimate.

They also included other things, like a demonstration satellite solar power station, which might or might not be appropriately charged to the construction of the first colony.

So, it is a question of how you do it. I don't want at all to imply criticism of the NASA approach by saying that. This concept is mind-boggling for them, too, and there is a strong feeling even among people in NASA who are favorable toward this project—and fortunately many are—that it's important to have a safety factor built in. I sympathize with them on that. Anyone would be very scared to start on a project where there was no safety factor, so that he might get caught later on.

Mr. WINN. You've mentioned the tremendous possibility for energy and, of course, that intriques all of us these days. But if I remember, other than one or two slides there, you basically showed how the energy could be picked up and get converted, and I don't believe I saw anything on storage of the energy, the tremendous potential energy of the Sun, and of course that's one of our problems. We can pick it up today.

Dr. O'NEILL. The difference is, sir——

Mr. WINN. And actually we can convert some of it.

Dr. O'NEILL. Yes, some of it, although the land-use problems for Earth conversion of solar energy are severe. In the conversion that we're talking about, the satelllite itself would be in geosynchronous orbit where sunshine would be available practically all the time.

Mr. WINN. So, you wouldn't have much demand for storage?

Dr. O'NEILL. There would be almost no demand for storage in our system. The energy would be transferred from microwaves to direct current in such an efficient fashion that the conversion losses on the surface of the Earth would only be about 10 percent. The release of waste heat into the environment would also——

Mr. WINN. Compared to what now?

Dr. O'NEILL. Compared to either fossil fuel or nuclear fuel plants in which you throw out as waste heat about 150 percent.

Mr. WINN. 150 percent?

Dr. O'NEILL. Of the power which you put into the lines.

Mr. WINN. Mr. Emery?

Mr. EMERY. Thank you; no questions at the present time.

Mr. WINN. Thank you again, Doctor, for appearing before the committee. Your testimony really is going to have a lot of us thinking for quite some time, and I only wish that other members of the subcommittee had been able to be here and ask you questions, because I'm convinced that neither Mr. Fuqua nor I nor Mr. Emery could answer the questions of the other members of the committee and their staffs when they read the final report that you turned in.

We thank you for taking the time.

This concludes the hearings for today.

I would like to announce that the hearings on future space programs will resume tomorrow morning in this same room at 10 o'clock, and the two experts to testify will be Arthur C. Clarke, a very well-known science writer, and Michael K. Evans of the Chase Econometrics Associates, Inc.

The meeting is adjourned.

[The hearing in the above-entitled matter was adjourned at 12:20 p.m., to reconvene at 10 a.m., Thursday, July 24, 1975, in room 2362, Rayburn Building.]