

PNL-SA-6570

paper No. AAS 77-236

Conf-7710155--1



TWENTY-THIRD ANNUAL MEETING

MASTER

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USE OF OUTER PLANET SATELLITES AND ASTEROIDS AS
SOURCES OF RAW MATERIALS FOR LIFE SUPPORT SYSTEMS

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For presentation at the Space Industrialization Conference, 23rd Annual
Meeting of the American Astronautical Association, San Francisco, CA

October 18-20, 1977

The Industrialization Of Space

Planning for Profit at the High Frontier

Co-sponsored by

American Institute of Aeronautics and Astro-
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Airport Hilton Hotel

San Francisco

October 18, 19, 20 (1977)

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY
UNDER CONTRACT EY-76-C-06-1830

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THE USE OF OUTER PLANET SATELLITES AND ASTEROIDS AS
SOURCES OF RAW MATERIALS FOR LIFE SUPPORT SYSTEMS

Peter M. Molton and Ted E. Divine*

Industrialization of space and other space activities depend entirely on supply of materials from the Earth. This is a high cost route for materials supply. Space industrialization will require life support systems for maintenance and operation staff and these will of necessity be of a sophisticated nature. Use of raw materials obtained by an unmanned space shuttle, initially, and by manned shuttles later could significantly reduce the cost of life support in space. These raw materials could be obtained from small asteroids and satellites, and would consist of primary nutrients. Future development of such sources is discussed, including food production in automated asteroid-based facilities. The level of technology required is available now, and should become economical within a century.

INTRODUCTION

Examining some of the literature on space exploration currently appearing in various journals, it brings a sense of astonishment to realize that it was just over 20 years from this date that Sputnik 1 was launched into Earth orbit. Events in the subsequent 20 years have included manned lunar landings, close-up photographs of Jupiter and Mercury, and instrumented landings on Mars. Closer to Earth, we have seen satellite telecommunications displace undersea cables, global meteorology provide data on every

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TV set, and the beginnings of education in remote areas through satellites. With the coming of Skylab and the space shuttle, we are now prepared for using space on a relatively large scale. Five years ago the subject of this article could not have been seriously suggested at any scientific meeting without taking a considerable risk of meeting with ridicule. Even one year ago, this would perhaps also have been true. Today there is a marked swing away from conservatism in the field of space exploration--a healthy swing as witnessed by promotional articles in such respected business magazines as Business Week.¹ We are unlikely ever to reach the stars if we spend all of our time examining our feet.

Currently, there are a number of grandiose concepts in circulation on such topics as large space colonies and solar power satellites. Numbers as large as 100,000 people in a permanent colony at the L-5 point² and single solar power satellites delivering up to 20,000 MW of power to the Earth³ are frequently mentioned. Engineering on such a scale as this requires vast amounts of materials, orders of magnitude greater than the total mass lifted into space from the Earth's surface in the whole of the last 20 years. Where are these materials to come from? To lift 1 million tons of materials from the surface of the Earth at conservative space shuttle rates of \$100/lb would cost \$200 billion, and this is to a low Earth orbit rather than the geosynchronous or lunar orbit usually required! The answer, of course, may be to produce metals and other structural materials on the Moon, using plentiful solar energy, and then to make use of the Moon's lack of atmosphere by using the old concept of the 'electromagnetic gun'⁴ (now called a mass driver).⁵ In terms of energy, transport from the Moon costs only 5% as much as from the Earth. However, this concept requires a preexisting Lunar colony, itself no mean feat as the materials for this will have to be lifted from the Earth.

In this article, we assume the existence of a viable and self-supporting lunar colony, capable of exporting metals to other points in space. This assumption is basic to the L-5 colony concept and appears to have been adopted also by the proponents of the solar power satellite concept. We further assume that the 'energy crisis' on the Earth and the problems of atmospheric pollution by fossil fuels will make the solar power satellite

more and more attractive in the future, so that the probability of a large lunar colony being constructed will improve.

SOURCES OF RAW MATERIALS

The moon can theoretically be a source of all minerals available on Earth with the exception of carbon, hydrogen and nitrogen. In addition, oxygen is present in aluminum-based materials. The Asteroid belt could be a source of carbon, hydrogen, and nitrogen. The Jovian satellites could likewise be a source of ammonia, methane, and hydrogen. Recycling of human wastes of colonists could provide some essential minerals but not in sufficient quantities to rely solely on such sources. These features of materials supply in space are discussed below.

Availability of Minerals on the Moon

The lunar regolith has been extensively analyzed, albeit from a very limited number of sites. It appears that almost all of the elements available on the Earth will be readily available on the Moon, with the unfortunate exceptions of carbon, nitrogen, and hydrogen.^{6,7} It is still possible that deposits of graphite and water ice, and even kerogen (the highly condensed carbonaceous chondritic material) may be found and mined on the Moon, but the prospect at present is poor. There is also no theoretical reason why the elements C, H, and N should have remained on the Moon. According to the most widely accepted theory of the formation of the Solar System, planets and their satellites condensed from a nonhomogeneous cloud of gas which was rich in hydrogen.⁸ Thus, most elements would have been present in reduced form. In the case of the lighter elements, this would have been as methane, ammonia, and water (all hydrides). Because of their low molecular weight and the low lunar gravity, these would have been lost within 10^8 years of the Moon's formation. Oxygen is a somewhat different case, as it was present in sufficient excess to be retained in hydrogen-stable silicates and aluminates, despite the loss of some of the oxygen into space in the form of water vapor.⁸

The lack of these lighter elements on the Moon poses a problem for any future colony, since it is just these elements that are vital to life. Virtually all of our food is composed of compounds of carbon, nitrogen,

and hydrogen. Other important elements--oxygen, sulfur, and phosphorus--may be obtained on the Moon, but all of the C, H, and N will have to be lifted from Earth at considerable cost, in the form of food. There is no weight advantage to be gained by dehydration, either, since the water to rehydrate the food would also have to be brought up from the Earth.

Recycling of Wastes

Since the expense of bringing food up from the Earth will be so great, there is a great incentive to recycle human wastes from a lunar colony. This could not be in the form of highly inefficient 'organic gardening' since this leaves most of the carbon and nitrogen un-recycled in the form of humus. Neither could it involve any fermentation process such as anaerobic digestion, since much of the organic material remains as a useless sludge. Growth of Chlorella is also out of the question, since residues occur here also, and there is a major requirement for water, as well as salt imbalances.^{9,10} The only efficient recycle mode would be complete oxidation of the organic waste to water, carbon dioxide, and nitrogen, conversion of the nitrogen to ammonia with hydrogen from some of the water (generating oxygen by-product), and use of these simple materials for plant growth. This will almost certainly be practised once a thriving lunar colony exists, but there is equally certain to be material losses into the surrounding vacuum, and recycle inherently lacks the capability for colony expansion. Support for a slowly decreasing number of colonists would be all that could be achieved on this basis.

Other Sources of Carbon, Hydrogen, and Nitrogen

Since there will be a continuing demand for supplies of fresh food by the members of any colony, and since the only current source of this is the Earth, it is worth considering alternative sources of the necessary raw materials for food production, while realizing fully that these may be over a century in being developed. An additional reason for doing this is that space development is unlikely to stop at a lunar base or a 'local' space colony; bases and colonies further away from Earth are a logical second stage development. In particular, the utilization of the resources of the Asteroid belt seem to offer great possibilities.¹¹

The reasons for not expecting carbon, hydrogen, and nitrogen to be present on the Moon have already been briefly summarized. The same reasons, in reverse, can be used to predict that the Asteroid belt will be rich in such materials. The gas cloud from which the Solar System was formed was rich in hydrogen, reducing carbon, nitrogen, and oxygen to methane, ammonia, and water, respectively. The molecular weights of these compounds were too low to permit condensation or retention by bodies of low mass close to the Sun, such as the Moon, although the Earth had sufficient mass to permit retention and therefore the evolution of life here. At the distance of the Asteroid belt from the primary, some carbon, nitrogen, and hydrogen should exist as condensed organic compounds formed by further interaction of methane, ammonia, and water ('chemical evolution'),¹²⁻¹⁴ although at the black-body temperature of, for example, Ceres, only water ice and ammonia hydrates would condense. Further out, all three compounds should exist on the surfaces of the Jovian satellites as liquids or ices.

There is some experimental and observational evidence that there is a significant amount of carbon, nitrogen, and hydrogen in the Asteroid belt. The methane/ammonia/water condensate from the early period of formation of the Solar System may be the same as that recovered and analyzed on Earth from carbonaceous chondrites.¹⁵⁻¹⁸ This carbonaceous chondritic material is often loosely called 'kerogen'. An asteroidal origin of the meteorites has been suggested,¹⁹ and the potential value of this material on the asteroids for space life-support has been noted.²⁰

Further out in the Solar System, the giant planets are known to have a plentiful supply of methane, ammonia, hydrogen, and very probably water. Their gravitational fields are so intense that recovery of these materials directly from, e.g., Jupiter, is not ever likely to be economical. However, there is recent evidence that at least one of the primary satellites, Io, has ammonia on its surface. This evidence is based on the observation of sodium clouds on Io, perhaps generated by ammonia reactions within a tenuous atmosphere.²¹⁻²³ Loss of water from Io and the formation of a salt deposit from leaching of kerogen has been suggested as one explanation for the high albedo of the satellite.²⁴ Thus, carbon, hydrogen, and nitrogen appear to exist on the surfaces of the larger Jovian satellites. The same is probably true of the Saturnian satellites, where water ice at

least has been identified by spectral observation of the surfaces of Iapetus, Rhea, Dione, and Tethys.²⁵

FUTURE DEVELOPMENT OF SPACE PROCESSING AND RAW MATERIALS UTILIZATION

A lunar base would strive to establish itself as a self-sustaining manufacturing (aluminum) and fuel supply (O_2) facility for subsequent penetration by deep space shuttle to the Asteroid belt. Kerogen mining would occur as one of the first industrial and colonization activities on an asteroid such as Ceres. Ammonia and carbon dioxide could be derived from kerogen as the basic supplier for food production. The moons of Jupiter could possibly serve as additional sources of ammonia, methane, and water as part of colonization of space to establish a space economy and self-sufficiency outside of Earth.

Lunar Bases

Although not the primary focus of this article, a brief summary of probable lunar base development is pertinent. It seems logical to suppose that at first a lunar base will be set up on the same basis as those in Antarctica--supplied directly and continually maintained by a fresh influx of supplies from Earth, sometime about the year 2000.²⁶ This situation would be unstable, partly because of the long supply line from Earth and partly because of the great cost involved. A hostile Congress could kill such a base within a very few years unless there were some distinct advantage to be gained in maintaining it. Hence, the base would have to become economically or otherwise useful. This could be achieved by exploration for mineral deposits. At the same time, to reduce the dependency on supplies from Earth, waste recycle and growth of food would be practised, and additional buildings would probably be made directly from the lunar rock (for instance, using foamed basalt). Over a period of years the base would gradually change from an exploratory, dependent structure to a self-sustaining colony. Among the major innovations which would be made (apart from food production) are the construction of solar mirrors to generate metals from lunar minerals, and space manufacturing and power generation facilities.^{27,28}

This scenario is not new, but has implications for the future development of asteroidal resources. At present, the major implication seems to be the

generation of oxygen as a by-product of aluminum and other metal smelting by direct decomposition of aluminosilicates using concentrated solar energy. The oxygen by-product is not only useful as a life-support chemical, but as a rocket fuel--one half of the oxidizer/fuel combination which must be found in space to make transport economical between points which do not have available energy for 'mass driver' forms of propulsion.

Thus, after a number of years the lunar base would become a net exporter of aluminum, oxygen, and perhaps rough machined parts to Earth orbit stations and other space facilities. Over 95% of the energy required to lift the equivalent mass from Earth is saved by this route.

Kerogen Mining on the Asteroids

As has already been mentioned, the Moon could probably not become self-sufficient in the elements carbon, hydrogen, and nitrogen and their compounds in any sort of an expansion mode.^{5,6} Additional food, plastics, and fertilizer, would still have to be shipped up from Earth at considerable cost, continuing the dependence and vulnerability of the lunar and satellite bases. Some relief could be obtained in principle by mining carbonaceous chondritic material ('kerogen') from the Asteroids. In terms of fuel expended, there would be a slight advantage to doing this in preference to transporting the equivalent amount of carbon, nitrogen, and hydrogen from Earth--only 1/3 as much energy would be required for the one-way journey to Ceres from the Moon as for the journey from the Earth's surface to the Moon (Table 1).²⁹ But the two-way journey must be considered. Atmospheric braking would be used in the return journey to the Earth from the Moon, while rocket braking would be needed in the Ceres-Moon journey. This makes all the difference, the total energy involved in the return Moon-Ceres journey being 85% of that required for the return Earth-Moon journey. This of course takes no account of the additional factors of food and oxygen for the astronauts ('miners') during the 3-year return journey.³⁰ Hence, unless a non-terrestrial source of rocket fuel can be found, all additional carbon, nitrogen, and hydrogen-containing materials will continue to be brought up from Earth for the foreseeable future.

This gloomy picture is changed completely if we consider the chemical composition of kerogen and also the likelihood of finding water ice and

Table 1
APPROXIMATE VELOCITY INCREMENTS FOR SPACE TRANSPORTATION

From ↓	To ↗	E_s	E_o	L	C	J
Earth Surface (E_s)	(Landing uses atmospheric braking)	0.10.8 (0) [*] 0	10.8 (116.6) 0.036§	13.5 (182.3) 0.24	16.2 (262.4) 264	22.3 (497) 591
Earth Geosynch. Orbit (E_o)	(No landing)	2.9† (3.4) 0.036	0 (0) 0	2.7 (7.3) 0.204	5.4 (29.1) 264	11.5 (132) 591
Lunar Surface (L)	(Landing)	2.4† (5.8) 0.24	2.7 (7.3) 0.204	0 (0) 0	7.4 (54.8) 264	13.5 (182.3) 591
∞						
Ceres (Asteroid Belt) (C)	(No landing)	5.0† (25.0) 264	5.4 (29.1) 264	7.4 (54.8) 264	0 (0) 0	6.1++ (37.2) 327
Jovian Satellites (Landing) (J)		11.1† (123) 591	11.5 (132) 591	13.5 (182.3) 591	6.1++ (37.2) 327	0 (0) 0

* Minimum velocity increment in km/sec

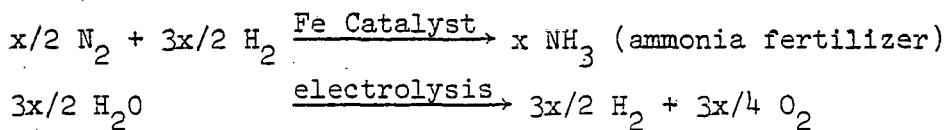
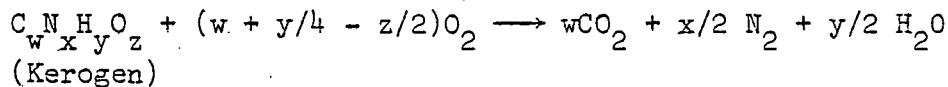
+ Figures in parentheses are $(\text{velocity increment})^2$

† Uses atmospheric braking on downhill journey

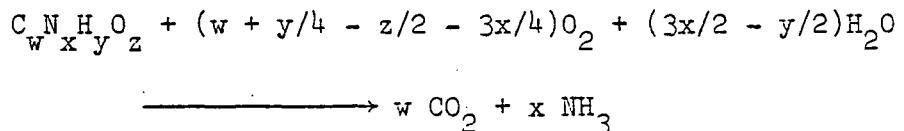
§ Distances in millions of km

++ Ceres orbit → Jovian orbit → satellite landing

ammonia hydrates on the asteroids in a minable form in a low-gravity environment. Ammonia could be recovered and used as a rocket fuel with lunar-derived oxygen as the oxidant. Water and kerogen would be mined and returned to the Moon to be oxidized to carbon dioxide, more water, and nitrogen. The nitrogen would be reacted with hydrogen to make ammonia for fertilizer (the hydrogen being made by electrolysis of water). Chemically the situation would look like this:



Net change:



Using this system, lunar oxygen would be transported out to the Asteroid belt to serve as life-support oxygen and oxidant; asteroidal kerogen and water and ammonia would be returned to the lunar base, using separated ammonia as the propellant (fuel). The kerogen would be used as a source of carbon dioxide and ammonia for plant growth to generate food for a growing colony. Other materials, particularly heavy metals such as nickel, would also be mined in the Asteroid belt and returned to the Moon,¹¹ using the same ammonia/oxygen fuel/oxidant system. The lunar base would then stand in the same position relative to the Asteroid belt mining base as the lunar base once stood with respect to the Earth--source of supply and lifeline to a small, completely dependent base.

Ceres Bases

Over a period of time we may see the development of a lunar manufacturing capability dependent on technology transfer from Earth. Only a very small part of the materials for this manufacturing facility will be physically transported from Earth, because of the great penalty incurred in costs in overcoming Earth's gravitational potential. Most of the materials that

cannot be mined on the Moon will come from the Asteroid belt. On the other hand, Earth will export information, primarily, since this requires no fuel. In exchange, Earth would receive an unlimited supply of rare metals and minerals and space-processed, high-cost products. The lunar base, however, would be dependent for expansion on this 260 million km pipeline for the return of kerogen and water and ammonia from the Asteroid belt. The reason for choosing the Asteroid belt as the source of these materials lies partly in the fact that even the largest asteroid, Ceres, has a negligible gravity field, and therefore return of materials mined on Ceres would be cheap in terms of energy. Planets such as Mars and Venus would be relatively expensive since not only the planetary gravitational field, but atmospheric resistance and the solar field would have to be overcome in order to return materials to the Moon. Also, there is unlikely to be an in situ source of fuel on either of these planets.

There would thus be an incentive to support a permanent mining base in the Asteroid belt. Ceres is the largest asteroid and would be a likely candidate. The situation of this base would be the reverse of the lunar base: Oxygen would be imported from the Moon, kerogen would be mined locally, and food would have to be either imported or grown on the base from wastes and mined carbon, nitrogen, and hydrogen. Apart from the lack of intense solar energy, the Ceres base would have everything that the lunar base has.

Ammonia, Methane, and Water Mining on the Jovian Satellites

It is unlikely that Solar System exploitation would stop at the Asteroid belt for two reasons: These are that kerogen is deficient in hydrogen, and that ammonia is not as good a fuel as methane. Hydrogen could be obtained from water by electrolysis, but there is a lack of cheap solar power to generate electricity on Ceres. The Jovian satellites, while distant from Ceres in space (330×10^6 km minimum), require no more than 2/3 as much energy for a return trip from Ceres as does the return trip to the Moon, with landings at both ends (Table 1). This takes into account the gravitational fields of the satellites, Jupiter, and the Sun. Of course, there is a time penalty using a minimum energy transfer--a period of some years for the round trip (Table 2). However, with plentiful fuel, there

Table 2
ENERGY COST AS A RATIO OF EARTH:EARTH ORBIT = 1

<u>Trip</u>	<u>Energy Cost Ratio</u> ⁺	<u>Trip Time*</u>
$E_s \rightarrow E_o$	1	~ 1 day
$E_s \rightarrow L$	1.56	~ 4 days
$L \rightarrow E_o$	0.06	~ 3 days
$E_o \rightarrow C$	0.25	472 days (1.29 yr)
$E_o \rightarrow J$	1.13	937 days (2.57 yr)
$C \rightarrow J$	0.32	1384 days (3.79 yr)
$C \rightarrow L$	1.56	~ 472 days (1.29 yr)
$J \rightarrow E_s$	1.05	~ 937 days (2.57 yr)
$C \rightarrow E_s$	0.21	~ 472 days (1.29 yr)
$J \rightarrow L$	1.56	~ 937 days (2.57 yr)

*Based on minimum energy (Hohmann) transfer orbit.

+ $\div 116.6$, energy cost from earth \rightarrow Earth orbit (as $f(v^2)$).

E_s = Earth surface

E_o = Earth orbit (geosynchronous)

L = Moon surface

C = Ceres surface

J = Jovian satellite surface

is no reason to use the minimum energy trajectory, and the journey time could be significantly shortened with only a relatively small additional expenditure in fuel and oxygen.

The Jovian satellites, Io, Europa, Callisto, and Ganymede could therefore be used to supplement the Ceres base supplies with methane, ammonia, and water. At present, there seems no reason to postulate a permanent base on these satellites for other than exploration purposes.

THE QUESTION OF FOOD SUPPLY

The technology exists to maximize food production in a defined volume of space (not necessarily just on a two-dimensional plane as on the Earth's surface). Soil, as a source of plant nutrients, is not essential since all the necessary nutrients can be provided via the irrigation solution. Only a structure for support of the plants is necessary.

Critical growth factors such as lighting, temperature, variety selection and structure are discussed in the following paragraphs culminating in a summary of the vertical agriculture system being investigated and demonstrated at Battelle-Northwest by the authors. Vertical growth surfaces can lead to maximization of crop production in a three-dimensional space, particularly in a low-gravity situation as would occur in the proposed life support system.

Availability of Light and Heat

In the relatively near future, there is little prospect for production of animals or animal products for food in lunar colonies. Food will initially be brought directly from Earth, and may be dehydrated to preserve freshness. However, water for rehydration would have to be recycled, brought from Earth, or obtained from an asteroid base or from buried lunar deposits of ice. Once the lunar base is established, there would be ample light and heat to provide for growth of conventional fruit and vegetables in a highly intensive enclosed environment. In fact, the sunlight and heat would have to be extensively reduced and harmful short-wave radiations stopped in order to avoid killing the crops.

At the orbit of Ceres (coincidentally named after the Roman goddess of Agriculture), the sunlight would be approximately 1/10 as intense as at

the top of the Earth's atmosphere. This is more than ample to support plant growth. In fact, it has been shown³¹ that in an algal system, 2×10^4 erg/cm²/sec will saturate the photosynthetic system, compared to an Earth surface intensity of 5×10^5 erg/cm²/sec in full sunlight, and a Ceres sunlight intensity of about 5×10^4 erg/cm²/sec. Thus, there is no anticipated problem in the generation of food at an enclosed Ceres base, except that once again, harmful short-wave radiation would have to be stopped. When the temperature is considered, however, there is a problem. The black-body temperature of a planet at the orbit of Ceres is about -36°C, too cold for any form of growth. Ceres rotates in 9 hr, and so the night-time temperatures would be much lower. Sunlight must therefore be concentrated and/or converted into heat in a Ceres base before any conventional food can be grown.

At Jupiter's orbit or on one of the Jovian satellites, the problem is even more acute. There would be both insufficient light and heat, with radiation intensities of only 4% that at the top of the Earth's atmosphere, and temperatures of about -150°C. Both light and heat would have to be produced artificially, which would require an in situ energy source that could obviously not be solar. Nuclear heat is a possibility in this situation.

Suitable Crops for Space Industrial Bases

Much has been made of the possibility of producing enclosed ecologies capable of supporting human beings, based on the recycle of human wastes. Generally such systems have involved either bacteria such as Hydrogenomonas or algae such as Chlorella.⁹ There are major problems in this, not only in converting human waste into a form suitable for microorganism growth and in attaining a good material balance, but in the actual nutritional value of the products. Microorganisms, particularly single species, do not have the correct mineral, fat, carbohydrate, vitamin, or protein composition to sustain human life alone. Moreover, they have indigestible cell walls and high nucleic acid contents which cause gastrointestinal difficulties in anyone using them for more than about 20% of the diet. In addition, they require large volumes of water, a scarce commodity in any space or satellite colony.

From the point of view of the most effective form of food, capable of being produced most intensively, we turn to the normal vegetables grown on Earth. Psychologically, nutritionally, and economically, these are the most capable of sustaining large colonies reliably and continuously. Their yields per hectare are highest and their nutritional values are closest to that which we know well. Thus, little or no research is needed in the nutritional area before they can be used. A variety of crops can be grown together in one enclosure, something which is rarely true of microorganism colonies. The disadvantage, of course, is that space colonists would all have to be vegetarians until synthetic vegetable fiber-based meat substitutes could be produced or animals grown in space food facilities. This would require some time to achieve, but, here again, the technology exists. However, early American colonists had no better. Cattle and fruit generally came after basic vegetable crops. It was so on the Earth, so why should it be different in space?

For these reasons, we expect space colonies to grow their own vegetables. In the absence of weeds and pests, with total environmental control, the reliability of such farming should be far greater than that which could be expected from periodic food shuttles from the Earth, with the high probability on repeated missions that one load would be destroyed or lost with potentially disastrous consequences for the totally dependent colony. This is true to a great extent for a lunar colony, and very true for a colony as far out as Ceres or Jupiter.

Being more specific about actual crops, we would choose to grow those crops initially with the highest demonstrated yield of useful food value and the lowest crop residues. A representative cropping combination might include potatoes, soybeans and leaf vegetables (cabbage, spinach, etc.). Potatoes would form the basic starch (carbohydrate) and selected protein base. Soybeans could be processed for fats (oil), protein isolates or textured vegetable proteins (meat substitutes), and soymilk. In addition they could be harvested as a green vegetable. Specific leaf vegetables could be produced for essential vitamins and selected protein supplement.

The Structure of a Space 'Farm'

Certain features of space farming activities are common to all such structures. For instance, they must be enclosed and pressurized to protect the crops from vacuum; a near-normal environment must be maintained, so that temperature and illumination must be similar to those experienced on the Earth's surface. The internal atmosphere must contain carbon dioxide and water vapor, and the 'soil' must contain necessary mineral nutrients, including supplies of ammonia and phosphorus. Beyond these limitations, details of the structure are widely variable and depend to a large extent on the location of the 'farm'.

In order to present a detailed description of a space farm, a system has been chosen in which we have experience and which represents the most highly intensive form of farming available today. The location chosen is on the asteroid Ceres, where black-body temperatures in full sunlight would be about -36°C , gravitation about 1% of Earth normal, illumination is approximately 0.1 of that at the top of earth's atmosphere, and has the same spectral features, the asteroid rotates once every 9 hr, and there is no natural atmosphere. Although highly speculative in substance, the scenario presented is within current knowledge in the sense that the same system could be constructed on Earth today and would produce the yields of crops assumed for a Ceres farm, given the same inputs in the form of kerogen, oxygen, water ice, ammonia, and minerals.

The Environmental Control System

The basic design of the farm is a plastic hemispherical dome (Fig. 1), 36 m in radius (to enclose 0.4 hectare, or one acre in more conventional units). The plastic could be fabricated on the Moon by conversion of kerogen by a series of steps into ethylene or other organic petrochemical intermediates, according to conventional technology. It would be double-walled honeycomb to serve the dual purpose of heat insulation and protection against accidental blowout. The opacity of the dome could be controlled by dyes in the plastic to shield against very short wave radiation and ultraviolet, although plants have some tolerance to this. In order to provide a near Earth-normal illumination, we have assumed a

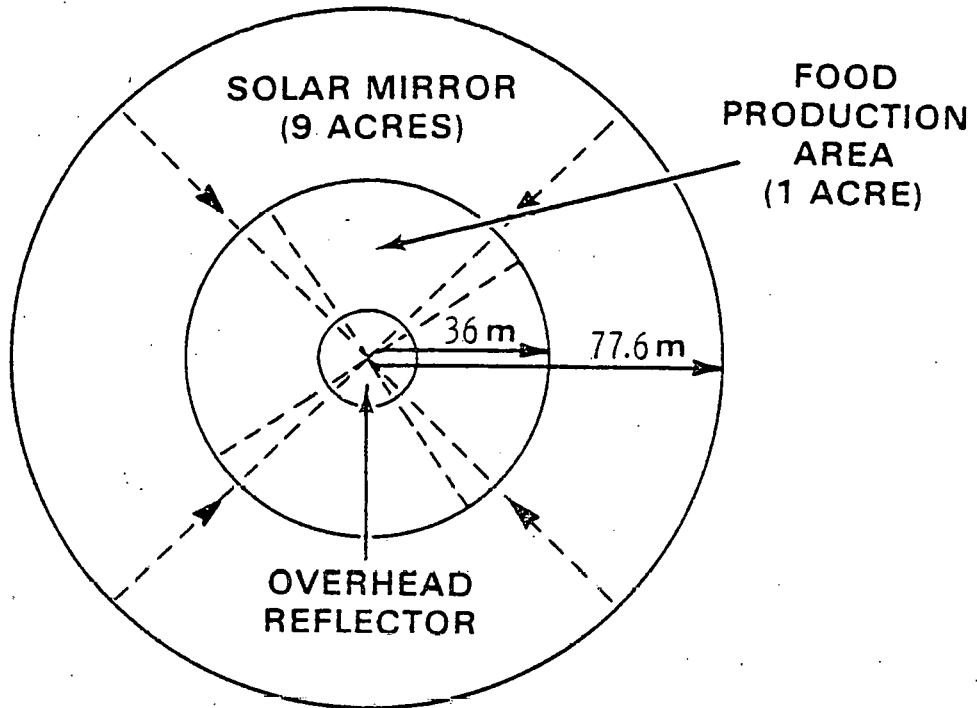


Fig. 1 Asteroid-Based Mirror for 120-Person Permanent Colony Food Supply

9:1 solar collector/reflector ratio to concentrate sunlight from a surrounding annulus into the dome, where it would illuminate the crops (only a very diffuse focus into the dome is assumed). Also, chemical additives (e.g., carbon black) in the soil would absorb sunlight and re-radiate it as heat to maintain the internal temperature of the dome at a steady 25-35°C. The reflector itself inside the dome would be aluminized plastic--no more refractory material is required since only a minimal temperature increase above ambient is required during 'daylight'. During the short night, a slow decrease in temperature would occur.

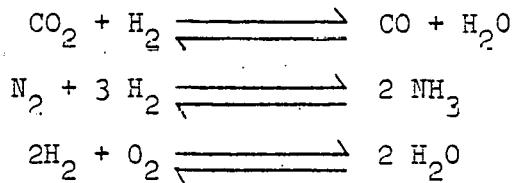
The solar collector consists of an annulus around the dome. To produce a 9:1 collector/dome illumination ratio, the annulus would have to be 3.6 ha (9 acres) in area, and would therefore be 77.6 m wide. To some extent, the sunlight impinging on the collector would be converted into heat, as already noted. At Ceres orbit, there is sufficient natural sunlight to provide for plant growth without enhancing illumination. There

is a strong possibility that these figures are conservative, and that a much smaller area of collector could be used. The collector itself would be curved to concentrate sunlight onto the top of the inside of the dome, where it would be reflected diffusely to the crops below. The collector would be made by grading the annulus in the surface of Ceres and laying down a sheet of aluminized plastic. No great accuracy is required in this, as only diffusely concentrated sunlight is required. As long as the collector directs most of the light impinging on it inside the dome to the secondary reflector, no further mirror alignment is needed. In fact, too good a focus would be detrimental to the crops at the focus!

The dome and mirror system is thus of a 'passive' variety, all necessary environmental control being built in to the structure of the plastics used. It would also be very light and easy to transport from the Moon in a collapsed condition, to be inflated on arrival at Ceres.

The Environment

Mined kerogen would be oxidized to carbon dioxide, water, and nitrogen using lunar oxygen, and these gases would constitute the atmosphere of the dome. For psychological reasons and for ease of harvesting, the dome could also contain oxygen, permitting colonists to walk around unprotected. There is some inbuilt flexibility in the system, since carbon, carbon dioxide, water, and hydrogen are essentially interconvertible through a gasification cycle³² (which could also be used to generate ammonia from nitrogen, if this were ever in short supply):



Kerogen, ammonia, water, and methane should all be readily available from the Ceres surface or from the Jovian moons, but they should only be required for the initial colony startup and for making good production losses from the dome, for colony expansion, and for export to the Moon. For routine colony existence, non-edible carbonaceous residues such as human wastes and plant wastes may be treated identically to kerogen, and burned back to simple chemicals which may be re-used by growing plants.

There is some question concerning the optimum dome atmosphere for obtaining maximum plant growth, since this is required for the survival, and not merely the convenience, of the colonists. For instance, higher carbon dioxide levels than the 0.03% present in Earth's atmosphere will increase plant growth, oxygen is inhibitory in high concentration, there is an optimum humidity at a given temperature, and there will be at present unknown effects due to solar radiation components not present on Earth, cosmic rays, and the low gravitational field,³³ as well as the short 'day'. These effects need to be investigated on Earth or in Earth orbit before setting up a colony, but they represent no inherent difficulty in resolution for any given base. Also, if it is possible to obtain maximum plant growth at lower than 1 atm pressure, there could be a considerable saving in dome structural mass.

Thus, temperature, nutrient supply, illumination, and growth medium would all approximate Earth normal in the farm, but there would be differences due to day length, gravitation field strength, and composition of the artificial atmosphere.

The Growth-Supporting Structure

Agriculture in space is going to be very unlike anything normally practised on Earth, because transportation costs from Earth will far exceed the value on Earth of the food produced. Having made a 1 acre farm at huge expense, every part of the volume should be used to obtain maximum return on investment. The aim is maximum food yield, with very little consideration being given to costs of water, fertilizer, harvesting equipment, or other items which are normally paramount in terrestrial agriculture.

Given these parameters, the obvious conclusion is that horizontal farming as practised on Earth is not the most efficient way of farming in space, where the entire volume of enclosed and controlled environments should be used. Vertical agriculture is a logical extrapolation of the requirement for maximum space utilization. Our concept of a Ceres 1-acre farm using vertical agriculture is shown in Fig. 2, and consists of parallel rows of vertical cylinders of variable height (increasing towards the center of the dome). This concept is currently under intensive development in our laboratories for food production in highly mountainous areas of the world

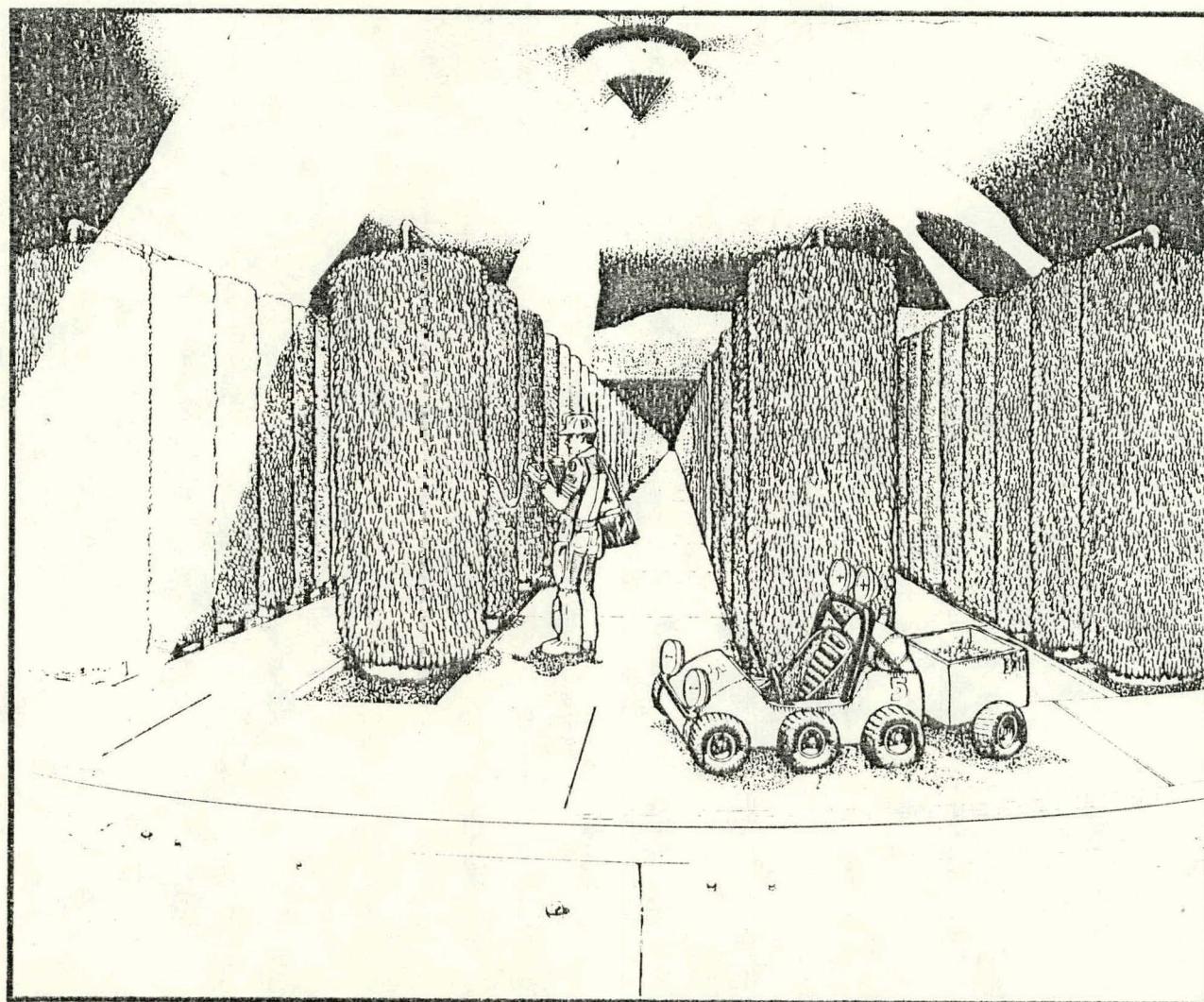


Fig. 2 Artist's Impression of the Interior of a Vertical Agriculture Ceres Base Complex

where there is a high population density. It is called the 'Pullulator' system, meaning 'to grow upwards profusely'. An experimental prototype is shown growing miniature Chinese cabbage in Fig. 3. Pullulators for the Ceres base food supply may be able to achieve 10-20 times conventional crop yields new obtained with Earth's intensive horizontal farming, and do this on a year-round basis. The system also permits isolation of various crops, arrangement according to optimum required illumination and heat, easy harvesting (particularly in low gravity conditions), and leaves a significant proportion of the ground area free of crops so that it can be used for heat generation from sunlight by absorption on carbon black. Any disease that could occur can quickly be isolated by removal of the entire Pullulator from the dome. Finally, the non-crop ground area would serve as a park for the colonists, relieving them of the drab monotony of the inside of a work area. The disadvantages of the Pullulator on Earth--high cost of a vertical system due to a requirement for high structural strength to maintain crops against Earth's gravity field, and sensitivity to wind, are either helpful or irrelevant in the Ceres environment. Our impression of the inside of the Ceres dome is shown in Fig. 4. We calculate that one such dome should easily be capable of supporting 100 colonists on a permanent, year-round basis, providing them with a variety of foods which is simply not possible on any less efficient system. Additional colonists could be supported simply by using more domes. If it ever became possible to raise meat animals and poultry, Pullulators would be ideal because the crops could be raised out of reach of the animals, which would be fed on the uneatable roughage!

Dealing with the far future, we can speculate that Ceres could become a net exporter of food to the Moon, in exchange for supplies of oxygen and fabricated products, thus fully justifying the naming of this asteroid after the Roman 'goddess of Agriculture'! In fact, energetically, it would be practicable even to ship food to other points in space from Ceres rather than from the Earth. Shipping food to Earth itself is unlikely except on a strictly oneway basis, using a non-returnable spacecraft shell filled with dehydrated food grown on Ceres from readily available carbonaceous and nitrogenous resources, and thrown towards the Earth like a stone from a slingshot, to land by atmospheric braking. Only this way could food ever



Fig. 3 Battelle-Northwest's Experimental Pullulator
Vertical Growth System Shown with Mature
Miniature Chinese Cabbage

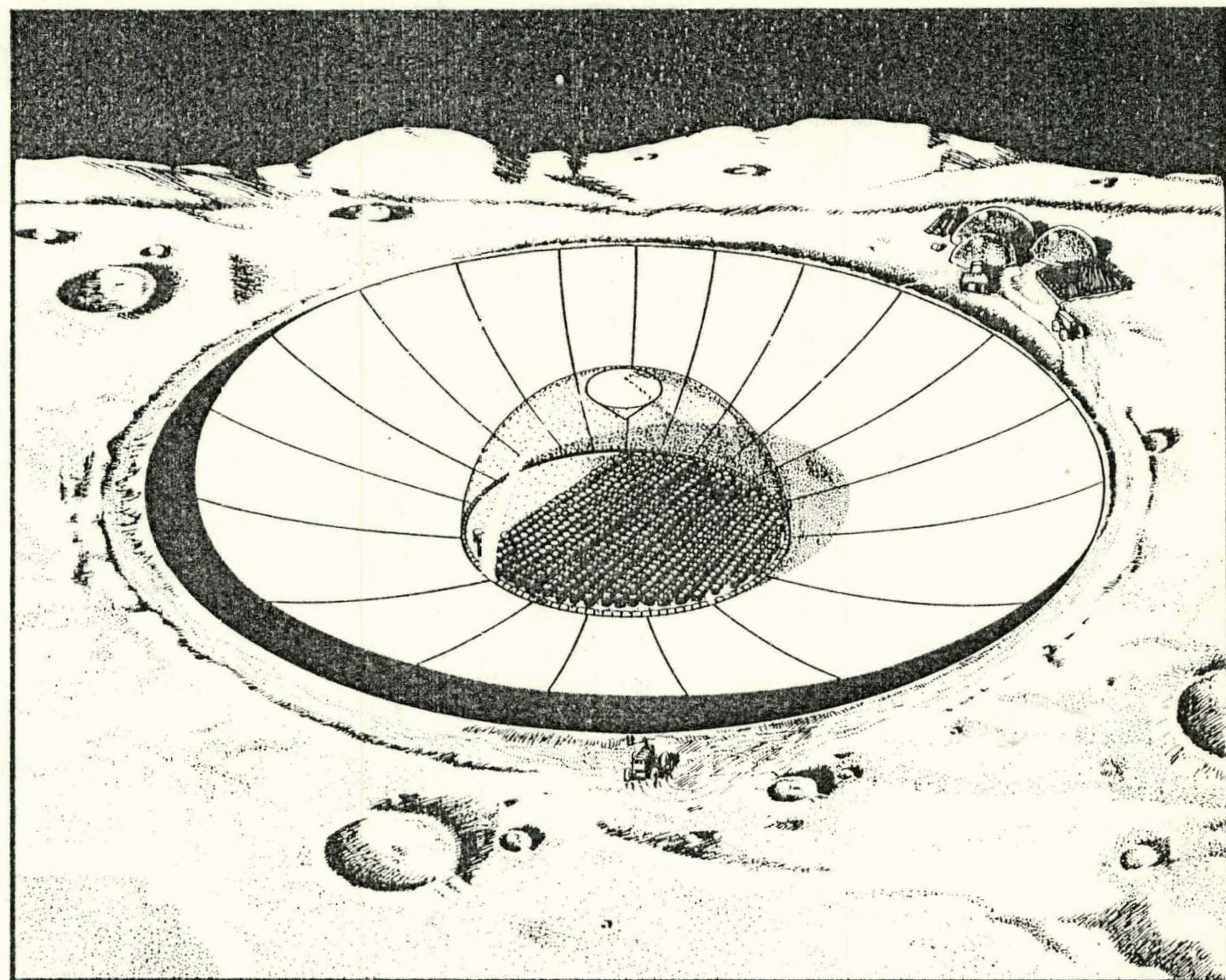


Fig. 4 Artist's Impression of the Ceres Base Food Production System
(not to scale)

be exported to Earth, and even so it is likely to be extremely expensive. This point is mentioned in case anyone feels that terrestrial food problems can be solved using space resources--in fact, the Earth will have to solve its own food and population problems for a very long time to come. However, with this exception, Ceres could become the breakbasket of our Solar System outside of Earth.

RESOURCE ECONOMIC CONSIDERATIONS

The cost of food and material transportation will be the overriding factor in cost of operations in intercolony trade. In addition, a long-capitalization period (of up to 5 decades) should occur to provide resources and "domestic" food supplies for colonies in Earth orbit, the lunar surface, Ceres, and on a Jovian satellite. Following a period of capitalization, a self-sustaining industrial economic activity might occur at a level of materials flow and transport to be able to effectively serve marketplace Earth with needed items of high value manufacture.

The Basic Cost of Transportation

To transfer a pound of material from one point on the Earth to another, the transportation cost is usually a small fraction of the total product value. (Present rule-of-thumb values for truck transportation in the U.S. is 5-7¢/ton-mile.) In space, the situation is completely different. Transportation costs are expected to be so high as to be many times the total value of the product, with the possible exception of rare metals and highly sophisticated materials such as enzymes. Thus there is a 'leveling effect', meaning that for most situations a pound of water will have the same value as a pound of steel. This factor profoundly affects the future economics of space industrial development.

A further factor which is likely to have great significance in relation to the economics of space processing is that of the expected lifetime of an automatic, unmanned space shuttle compared to that of a manned shuttle on a regular Earth-to-orbit trip. In the one case, a period of two or three years may elapse with the shuttle in a powered-down mode while traveling between distant points in the Solar System (for instance, between Ceres

and the Jovian system). At both ends of the journey, relatively mild accelerations would be used for landing and takeoff. In the other case, periods of weeks at most would occur between highly stressful and energetic takeoff and landing on Earth. While the lifetime of the shuttle in Earth-to-orbit journeys is estimated to be about 100 trips lasting over a period of a few years, it is conceivable that the lifetime of the unmanned deep space shuttle could be in terms of a century or more. What fair accounting period could be chosen for amortization of the initial cost of such a shuttle?

In any case, to obtain the elements carbon, hydrogen, and nitrogen from sources other than the Earth, and in a more economical manner, it is necessary that the energy cost for transportation from these other sources be less than the competitive cost of transportation from the Earth's surface, since transportation cost for almost all conceivable materials useful in space greatly exceeds their value at the surface of the Earth. Transportation cost currently has been set by NASA at \$20,000,000 for a 65,000 lb payload (\$300/lb) on the space shuttle to Earth orbit. If we assume a future minimum cost of payloads to a geosynchronous orbit of \$100/lb, we are not being unduly pessimistic (this gives a generous allowance of 2.8 km/sec in terminal velocity of the payload as well as dividing the initial cost by 3!). For a better understanding of the situation regarding transportation costs in terms of energy, Fig. 5 shows approximate velocity increments required for transfer of payloads between various points in the inner Solar System, using the 'gravity well' concept. The gravitational field of the Sun may be neglected for a first approximation in transferring materials between the Earth and the Moon, but becomes significant when journeys to the Asteroid belt are contemplated, being approximately 5 km/sec. Similarly, for a journey to the moons of Jupiter, both the gravitational fields of Jupiter and the Sun take additional increments of energy beyond that required to take off from the Earth and land on a satellite. In fact, for this journey, about 22 km/sec are required. Since velocity increment is a measure of energy requirement in terms of fuel expended [energy = $f(v^2)$], and most of the recurring costs of a space shuttle journey are fuel costs rather than amortization or maintenance costs, we have chosen to equilibrate costs for various transfers of materials within the Solar System

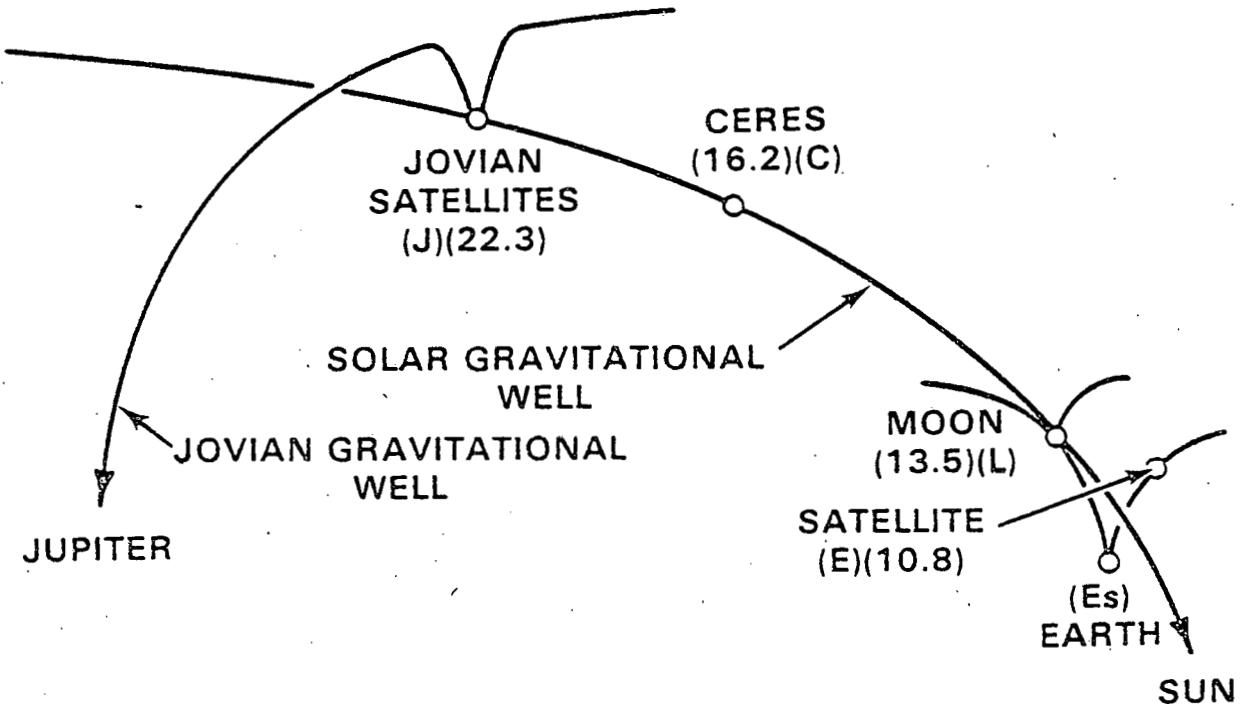


Fig. 5 Approximate Velocity Increments for Space Craft Leaving Earth (km/s)

directly to the total velocity increment squared. The figures were previously shown in Table 1. (Note that these figures at closest proximity of the transfer points to destination points, were calculated on the assumption that minimum energy (Hohmann) transfer ellipses would be used, and take no account of perturbations by other planets, 'slingshot effects', etc. They are therefore very approximate).

As an example of the importance of fuel costs in determining the economics of space transportation of materials between distant points within the Solar System, it has been claimed¹¹ that the transfer to Earth of a 1 km diameter nickel-iron asteroid would supply \$5 trillion ($\5×10^{12}) in metal value at current prices. (We calculate a value of $\$17 \times 10^{12}$ for pure nickel at \$2.00/lb). However, the mode of transportation to the Earth is important. If fuel for this can be derived from the asteroid belt itself, then the economics are somewhat different from those assuming that fuel has to be carried up from the Earth. In the latter case, assuming a cost of \$100/lb/10 km/sec impulse, the impulse required to bring this volume of asteroid at a mean density of 8.5 back to the Earth by atmospheric braking would be about 21.2 km/sec, (assuming zero impulse

for landing on Earth). The cost would then be about \$4 quadrillion ($\4×10^{15})! The economics are obviously impossible unless a viable self-supporting base at the Asteroid belt is assumed, and that it is further assumed that the necessary fuel to provide the impulse can also be obtained from this region. It cannot be argued that the cost of fuel from Earth will decrease by the necessary factor of 10^3 , as this is likely to increase rather than decrease unless some exotic propulsion method is discovered. Current fuels include kerosene, hydrogen, or other hydrocarbons and are generated either directly from petroleum or indirectly via electricity. Nuclear fuels are also rising in price and are in any case unlikely to be permitted for use within Earth's atmosphere.

From the discussion already presented in this article, it should be apparent that if fuels can be derived from low gravity asteroids or satellites far out in the Solar System, then we feel that the economics of space transportation of materials become far more favorable than if we assume that all fuel must be raised from Earth. It is pertinent to consider more comprehensive engineering economics now, based on an assumed historical development of Solar System exploration, colonization, exploitation, and processing.

A Method of Colony Resource Capitalization

All complex organisms grow and develop from an initial capital stock of resources whether this be plants starting from seed (a storehouse of initial energy, nutrients, and genetic information) or human colonies in space. Propagation of a species occurs as surrounding resources are converted and consumed in the growth cycle of the organism (energy and material). New, adaptive space industrialization colonies should not occur any differently, once the first one is "capitalized" and brought into existence with "seed" resources from the Earth (people, energy, life-support systems, industrial technology, space transport, etc.).

A combination of goal setting (projected "pull" decisions) and empirical, adaptive growth (decisions based on known "push" information) will most likely occur during colonization.²⁶ For purposes of illustration, let us select a goal of establishing a self-sustaining Lunar colony of 100,000 people within a specified time, say five decades from now. What must be done to achieve (and economically justify) this goal?

First, a goal of a 100,000 population Lunar industrial colony five decades hence will require multiplication of population in space by a factor of 10 each decade starting now with a population of 10 astronaut-colonists in Earth orbit. This magnitude of population growth via adult emigration from Earth poses little transportation difficulty over the selected 50-year planning period. (This is, on average, 166.7 persons per month shot into space once a month for 50 years--hardly a good 747 load!). For present purposes no "throwbacks" are permitted.

A colonization/bootstrapping sequence is projected in Table 3 to characterize this possible situation over a 50-year period. No significant impact on Earth's situation is anticipated, i.e., E_s population = ∞ .

Table 3
COLONY POPULATION GOALS

<u>End of Decade</u>	<u>E_s</u>	<u>E_o</u>	<u>Colony L_s</u>	<u>C_s</u>	<u>J_o</u>
0	∞		Shuttle/ skylab		
1	∞	10			
2	∞	100	100		
3	∞	1000	1000	1000	
4	∞	1000	10,000	10,000	1000
5	∞	1000	100,000	10,000	10,000
	Market	RD&D	Mining & MFG	Agric	Mining

The philosophy of growth is that establishment of an Earth orbit, E_o , skylab with a permanent population of 10 within the first decade from project time 0 would permit sufficient knowledge and experience to be accumulated so that a Lunar colony of 100 could be effectively supported and managed by the end of the second decade, together with growth to 100 of the E_o colony.

Skylab might represent the start of this growth process. Subsequent technology, resource accumulation, etc., with the Lunar colony and the Earth orbit colony might permit a second order of magnitude jump in space

colonization skills so that by the end of the third decade a food production (life support resource) colony of 1,000 population might be in place on Ceres. Likewise, the fourth decade might see a 1,000 population mining industry colony come into being on a Jovian satellite, as mentioned earlier. This would provide the capital resource base of four space colonies as a self-sufficient economy so that by the end of the fifth decade, the 100,000 population industrial colony on the moon would be a producing reality, ready to penetrate market Earth with advanced manufactured products or new material resources. Note that our thinking has been in decades, not years. Also, note the "functional" industrial activities expected to dominate or characterize each colony. (See Table 3).

Life Support Requirements

Food (plant) requirements for astronauts being sustained in Earth orbit for Decade 1 are estimated to require approximately 1,500 g/person/day (adult male).³⁴ Ten astronauts, on average, over a ten-year period would require about 55,000 kg (55 metric tons) of food material, total, delivered over this period. Drinking water requirements add another 2.5 kg/person/day or ~91,000 kg (91 metric tons) delivered over ten years (assuming no recycling). Oxygen consumption is estimated at 0.862 kg/astronaut/day or ~32,000 kg (32 metric tons) in ten years.³⁵ These basic life support supply requirements are therefore about 178 metric tons/decade or ~18 metric tons/year for the ten-astronaut space station in Earth orbit (E_0). This is rounded up to 20 metric-tons/year/ten astronauts for conservatism and conceptual convenience in the remarks to follow.

The next decade at E_0 with 100 astronaut-industrial technicians would require at least 10 times this amount or ~200 metric tons/year (2,000 metric tons/decade). A similar supply line would have to be maintained for a Lunar surface colony, L_s of 100 population, also. Extrapolation from these figures for initial 1,000 population colonies on the surface of Ceres and a Jovian moon provides a total requirement and annual transport requirement for our space colony industrial complex for the next five decades as listed in Table 4.

Table 4

ANNUAL AND DECADE FLOWS OF LIFE SUPPORT (FOOD)
 SUPPLIES REQUIRED TO MAINTAIN PROJECTED COLONY
 POPULATIONS, METRIC TONS

<u>Decade</u>	<u>E_s</u>	<u>E_o</u>	<u>L</u>	<u>C</u>	<u>J</u>	<u>Total Annual Cumulative</u>
0	∞					
1			200 20			20
2		2000 200	2000 200			400
3		20,000 2000	20,000 2000	20,000 2000		6000
4		20,000 2000	200,000 20,000	20,000 2000	20,000 2000	26,000
5		20,000 2000	2,000,000 200,000	200,000 20,000	200,000 20,000	242,000
Total Project Cumulative	∞	62,200	2,222,200	222,000	220,000	2,726,400 242,000

These objective data are the inflow food and water requirements for the five-decade colonization project assuming no recycle of waste product (but perhaps storage for accumulative purposes or conversion to specialty chemicals.)

Now, if the assumption is relaxed that all food requirements are to be transported to these colonies from Earth's surface (E_s), and instead assume that by the end of the fifth decade all food and water supplies originate from Ceres and all oxygen supplies originate from either Ceres (from ice) or the Lunar surface (from aluminum manufacture), then an annual flow pattern for life support and material supplies might occur as illustrated in Figure 6 by the fifth decade.

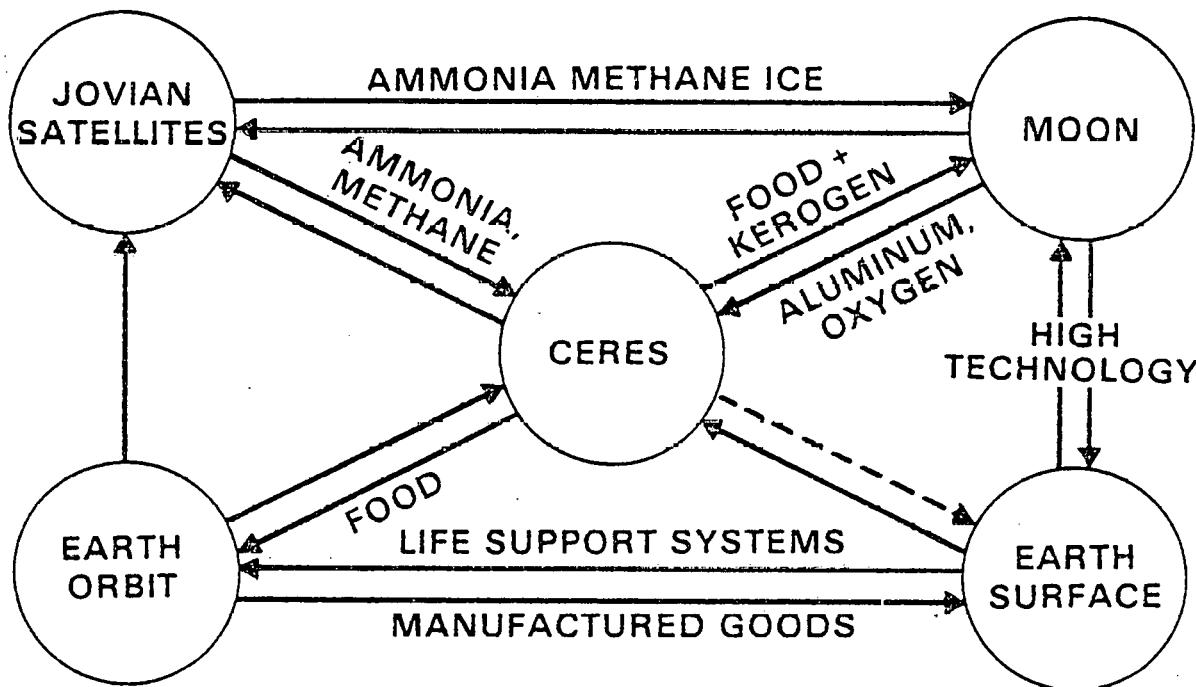


Fig. 6 Materials and Manufacturing Exchange Between Bases

Let's put this 250,000,000 kg/year of food, water, the oxygen production and transport requirement in perspective. If yield factors of 20 over conventional Earth surface agriculture can be achieved in space using vertical agriculture Pullulator techniques, this means that one horizontal hectare of surface area producing 70 metric tons of fresh food on Earth would be capable of 20×70 or 140 metric tons of product on, say, Ceres, as illustrated earlier. This implies that only 1,800 ha of surface area would be required to be under cover on Ceres to effectively feed the complex of space-industry colonies in Earth orbit, on the Lunar surface, on Ceres itself and on a Jovian satellite.

Industrial Material Requirements

Let us assume that it takes 8 metric tons of materials annually to effectively employ our industrial colonists (i.e., the productivity of each colonist is such that each must annually produce the equivalent by weight on Earth, of 4-to-5 large American-made automobiles). If the Jovian satellite mines produce raw material which is converted at 50% yield to material used in marketable product from the Lunar colony, and an additional 50% is mined and converted from Lunar resources, then the transportable tonnage from Jovian sources would be about the same as the desired transportable tonnages from the moon to the Earth's surface (market) at 800,000 metric tons/year. Other plausible material and/or product flows are also illustrated in Figure 6 for this situation and the other space colonies.

In total, 2 billion kgs of material flows must occur among the space industrial complex at a total transport energy value of about 180×10^9 $\frac{1}{2}mv^2$ energy units (SI) as accumulated in Table 5. For simplification purposes, let's assume it "costs" 100 energy units to produce and transport 1 kg of material flow in our space network.

Cost of Operations

Since transport costs are expected to exceed material values and manufacturing value-added by significant amounts, again let's simplify by saying that transport energy cost represents total manufactured and delivered product cost in this space colony economic system. This can be assumed to be"

Table 5
TOTAL INTERCOLONY LIFE SUPPORT AND INDUSTRIAL
MATERIAL FLOWS AND TRANSPORT ENERGY REQUIREMENTS

FROM:	KEY:	<u>TOTALS</u>			
E_s	(v^2) ----- Energy Units per Year $\times 10^9$ ----- Metric tons/year-----	5.8 4.64 800,000			4.64 800,000
E_o		7.3 0.03 1000	29.1 0.06 2000	132.0 0.53 4000	0.62 10,000
L_s			54.8 10.96 200,000	182.3 145.84 800,000	156.80 1,000,000
C_s		54.8 4.3E 80,000		37.2 0.74 20,000	3.24 100,000
J_o			182.3 14.58 80,000	37.2 0.74 20,000	15.32 100,000
TO:	E_s	E_o	L_s	C_s	J_o
					180.62 2,010,000

"operating cost" in the classical engineering economics sense. This would include a depreciation component for amortization of capital investment in plant, facilities and transportation equipment and an attractive rate-of-return on this capital industry infrastructure.

Revenues

Returning to our earlier resource example, assume that the colony export product to Earth market is the equivalent of pure nickel at \$4.41/kg (\$2.00/lb) delivered at the Earth's surface. Then, an 800,000 metric ton output of the Lunar industrial colony would be worth \$3.53 billion on the Earth's surface. This "market value" must not only cover the cost of operations but also the cost-of-capital (including a return-on-the investment above the cost of capital) and amortization (recovery) of this capital investment over an acceptable period.

Capital Investment

Let's assume that an attractive annual rate of return on invested capital in a project such as this is 20%. Let's also assume a project lifetime of 50 years (five decades) after full industrial capacity is reached is acceptable. This leaves unanswered the question of how much capital material (from Earth) must be transported into space to bootstrap the proposed industrial colonization.

Rather than dollars, let's discuss capital investment in metric tons of materials. First, we will make a broad assumption that it will require as much initial stock of material in plant and equipment as the volume of annual output from that same plant and equipment. That is, in order to produce 800,000 metric tons annually we must have 800,000 metric tons of manufacturing facilities in place. Thus to begin shipping 800,000 metric tons of materials from the Lunar surface to the Earth's surface 50 years from now would require that a manufacturing capability comprising 800,000 metric tons be in place by the end of year 50.

Now, if it is assumed that during the preceding 50-year colonization period, the colonies were able to accumulate this capital facility through their exploration efforts starting with 10% of this amount of material shipped from Earth between years 0-50, only 275 metric tons need be lifted into space annually from year 0 through year 50 and net facility increase (from space

sources) occur at only a growth rate of 6% annually for 50 years. If, on the average, growth rates of exploration and exploitation occur in space similar to these simplifying conditions, then the magnitude of the undertaking comes into focus with practical (and possible) economics.

Returns to Invested Capital

The competitive market value of material delivered to the Earth's surface from the Lunar industrial colony is \$4.41/kg (\$2.00/lb) starting in year 51. Thus, 800,000 metric tons delivered annually to Earth would have a value of \$3.53 billion as noted in Table 6. This amount would represent export sales or revenues of the industrial complex. It would need to cover normal rates of profit, depreciation, interest, cost of materials, labor, transportation, etc., in the usual engineering economics sense.

We previously mentioned that the cost of transportation (at present) is expected to far outweigh the cost of materials. However, the energy requirement to transport material from the Lunar surface to the Earth's surface is only about 1/30 that of the opposite transport direction. Thus, present projected costs of \$220/kg for a ($E_s \rightarrow E_o$) trip might be closer to \$7.30/kg for a ($L_s \rightarrow E_s$) trip. For 800,000 metric tons/year this would represent a freight bill for the colony of \$5.84 billion--still too high to be competitive on delivery.

Now, if transport energy costs are based on space-derived fuel sources, costs become relative so that fuel costs on Earth do not necessarily dictate fuel costs on the Lunar surface. Thus, it might be conceivable that costs of transport in space could be equivalent to or less than costs of transport on the Earth's surface (~20¢/kg). If this order of magnitude change were to occur, the freight bill for the Lunar colony might be only \$0.16 billion annually. If the value of the material on the Lunar surface prior to shipment is pegged at the present price of aluminum at 50¢/lb (\$1.10/kg) then the assigned material value for 800,000 metric tons would be only \$0.88 billion annually. Total annual operating costs could then be \$1.04 billion.

Continuing this situation for 50 years at 20% rate of return, annual pro-rata capital recovery would occur with the residual amount of \$2.49 billion.³⁷

Table 6
CAPITAL RECOVERY OF SPACE INDUSTRIAL COLONIZATION

	Annual Projected Payload (metric tons)	Assigned Transport Cost (\$ billions)	Assigned Material Value (\$ billions)	Total Value of Transport Energy + Material (\$ billions)
Annualized Present Value ($7\frac{1}{4}\%$) (years 0-50) (cal ~439)	182 ($E_s \rightarrow E_o$)	0.04	negligible	0.04 12.45
Capital (Resource) Accumulated (end of year 50)	80,000 ($E_s \rightarrow L$)	---	---	12.45
Annualized Capital Recovery ^(a,d) (years 51-100)	---	---	---	2.49
Annual Operating Costs ^(b) (years 51-100)	800,000 ($L \rightarrow E_s$)	0.16	0.88	1.04
Total Annual Cost (Revenues) ^(c)				3.53
Unit Costs				\$4.41/kg (\$2.00/lb)

(a) 50-year capital recovery period at 20% rate of return, crf = 0.20002

(b) Delivery of 800,000 metric tons/year of Ni equivalent material to Earth's surface from the industrial colony complex.

(c) Revenues include an operating profit component sufficient to provide for recovery of capital over a 50-year period plus 20% annual return on this investment.

(d) Does not include capital recovery on space-produced capital facilities, only the Earth debt.

Using a 50-year/20% capital recovery factor, this equilibrates to a total Earth investment in the space colony at the start of the material flow of \$12.45 billion. The present value of this \$12.45 billion discounted from 50 years, hence, to the present time at typical institutional financial rates ("municipals") of 6% is \$0.04 billion. Thus, at \$100/lb (\$220/kg) transport cost, we could only afford to lift about 182 metric tons annually into Earth orbit as an initial capital investment in space over the next 50 years. This is the equivalent of six-to-seven 65,000/lb space shuttle payloads annually for 50 years. (Also, 182 tons/yr increased at $7\frac{1}{4}\%$ is 80,000 tons in year 50).

This is the same order of magnitude as the 275 metric tons arrived at by the previous discounting methods. Thus, the magnitudes of materials flow for physical feasibility are tending to coverage with current economic feasibility values under these assumptions.

Costs of Life Support Versus Industrial Materials Supply

The \$4.41/kg transport cost allocation includes all transport costs incurred in getting the manufactured material to the Earth's surface. For example, the cost of transport of food, water, oxygen, etc. between Ceres and the moon would also absorb a portion of this cost. Thus, cost of the life support subsystem for the space colony complex is also accounted for in this relationship. In actuality it is expected to absorb no larger a share of the total economic activity than does the "food dollar" in the economy here on Earth at present. This presumes that a concentrated highly productive, completely controlled environment agricultural system, such as the Battelle-conceived Pullulator vertical growth system, is proven effective in a space-colony environment.

There are two keys to this convergence of physical feasibility and economic feasibility. These are that, first, life support systems can be created in the space industrial complex that represent no more than about 20% of material flows in the complex and second, that transport energy costs within the space complex need not be tied to the Earth's values for Earth surface to earth orbit material transport. As discussed previously, we believe that both of these conditions can be met with current or soon-to-be-achieved technology provided that an integrated approach is taken to

space industrialization, with concurrent development of lunar base, Ceres farms, and other asteroidal and satellite resources. Thus, everything discussed in this paper could become an economic and practical reality by the end of the twenty-first century.

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