DEMANDITE, LUNAR MATERIALS AND SPACE INDUSTRIALIZATION

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Abstract

Terrestrial industry consumes a wide range of elements in producing the outputs which support and make industrial societies possible. "Demandite" is a conceptual or synthetic molecule which is composed of the weight fractions of the major elements consumed by industry. Demandite needed for mature industrial activities in space will differ from the terrestrial composition because solar energy must replace hydrocarbon-energy, lunar and asteroidal bulk compositions are different from mineral deposits on the earth, and the major bulk processing in space will be the creation of radiation shielding for human habitats to provide real estate in space complete with water, atmosphere and life-stock elements. Demandite cost may be dominated by earth to deep space transport cost of minor elemental constituents depleted in the lunar soils unless careful attention is given to substitution of materials, searches of the moon (polar regions) and asteroids for the depleted elements, and continuing lowering of earth to deep space transport costs.

Introduction

Industrialization is a major cultural activity of the human race. Bones of primitive men are always found in association with tools (ex. spear points made from flint, utensils made of stone). Skills have been developed by the human race over thousands of years in extracting basic minerals and elements from the sea, earth and air and using energy to separate, melt and form these extracts into an ever widening range of products. Figure 1 schematizes this flow of matter from the sources to the final products and losses. Wealth, personal freedom, and the overall adaptability/complexity of the industrial societies appears to be determined by how efficient these industrial activities are and on how much they can reduce the degree of human involvement necessary to run and operate the industrial activities. All this activity takes place in the context of the terrestrial biosphere (water, air, soil and bedrock). Until the recently recognized pollution and petroleum energy crises, no widespread attention was given to the extremely complex impacts and interrelations between man's burgeoning industrial culture and the finite resources of the earth's land area, hydrocarbon energy stocks, and ability to recycle fresh water, air and biological elements. A deliberate program to develop industry in space will force us to carefully examine all aspects of this cultural activity from the most fundamental level, because most of the ingredients (matter and energy) must be obtained from new non-terrestrial sources (the moon, asteroids, sun). In addition, available cultural skills must be applied and new skills developed to start all aspects of industry and habitation from the beginning at a region of space reasonably remote from earth. An immediate goal of space industrialization is the generation of solar electric energy to provide terrestrial energy (1, 2). However, the long term cultural benefits will be that the human race finally will know how to create from the basic elements and energy secure abodes for life and will no longer depend on the earth and Sol for survival (3., 4.).

One guide for the transition that must be made in converting industry from a terrestrial to a space basis is to examine the overall non-renewable materials input to the United States industrial economy. Figure 1 illustrates the synthesis of a unit of "Demandite" (the basic molecule of the overall industrial system) from the earth, oceans and atmosphere(5). Demandite is transformed by industry into capital goods (buildings, roads, computers, cups, etc.) and processing components (chemicals, computer paper, moving automobiles, liquid nitrogen, etc.). Portions of the products are permanently lost from the earth (ex. helium, Pioneer-10 spacecraft) and much is dispersed widely about the earth (ex. carbon from the burning of petroleum).

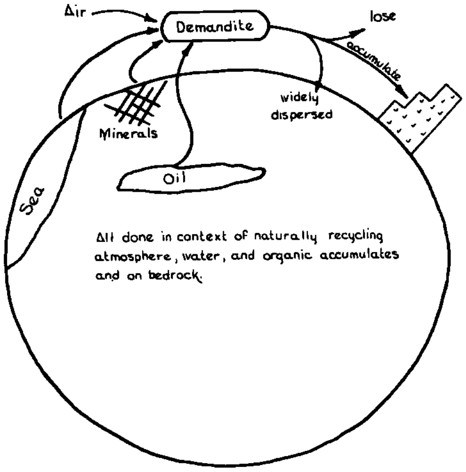

Figure 1.

Table 1 gives one estimate of the composition of demandite on a mole fraction basis(5) Other estimates are available which differ in detail(6). Notice that 80% of the molecule is fuel for the industrial processes. We are in the middle of the short-lived petroleum age. However, on a weight fraction basis, the modern world is still in the Stone Age because over one-half the mass processed is sand, gravel, stone and clays for the construction segments of industry. World demandite differs from that in Table 1; it is lower in fuel and metals fractions and contains more non-metals. Space demandite must differ radically from the terrestrial distribution because of the virtual non-existence of free hydrocarbons in the lunar and asteroidal materials. Thus, the forced development of space industrialization can serve as a guide to terrestrial industry on how to sharply reduce the hydrocarbon portion of the demandite molecule to zero and convert the fuel to a renewable or recycleable commodity. It is interesting to note that the entire supply of demandite produced for the U.S. economy in 1968 could be packaged as a spherical mass approximately 0.8 km radius assuming a density of 1.33 gr/cm^3.

TABLE 1

Demandite

Average Non-Renewable Resources Used in U.S. in 1968.

Mole Fractions

Fuel	CH_2-CH_{14}-.8022
Building	SiO_2-.1115, $CaCO_3$-.0453
Metals	Fe=.0110, Al-.0011, Mg-.0004 X(1)-.0008, (Cu,ZN,Pb)-.0004
Agriculture	N -.0076 P-.0008 K -.0007
Others	O -.0053, Na -.0053 Cl -.0053, C -.0023
(1)	X~Mn, Ba,Cr,F,Ti,Ni,Ar,Sn,B,Br,Zr

Properties

Average Molecular Weight - 23.9
Average Recovery Energy-0.57 Kw-h/Kg-1.5·10^4 $\frac{\text{joules}}{\text{Kg}}$

Average Unit Cost - 0.014$/Kg=1.4¢/Kg

Total Quantity - 3·10^9 Metric tons
Total Value - 42·10^9$

Per Capita Consumption Mass:	-15.4 Metric Tons
Energy	-18,800 KwH
Power	-2.14 Kw

Transporting materials to deep space from the surface of the earth will cost approximately 1000$/Kg in the early 1980's using the Nasa Space Transportation System to low earth orbit (LEO) and chemical rockets for boost from LEO to geosynchronous (GEO) orbit or earth escape. This is approximately 60,000 times more than the cost of demandite (1.4¢/Kg) and 5,000 times the average costs (21¢/Kg) of refined metals in the U.S. in 1968. For this reason, it is (4,8) proposed obtaining the bulk of the materials for construction and industry in space from the moon where the lack of atmosphere and low escape velocity (2.4Km/s) will allow the direct ejection of materials into deep space at initial costs of 20$/Kg and the expectation that costs less than .1$/Kg could be achieved following the development of large industries in space. It has been proposed that earth crossing asteroids of more than 10^{+9} metric tons could be transported into orbits about the earth by a single space tug (solar powered with a mass driver reaction motor) which could be less massive than a single supertanker (10^5 metric tons)(9). Assuming retrieval times of three to five years a fleet of 5 such space tugs could supply an industrial park in deep space with the mass of material utilized by the entire United States in 1968. Costs of .01$/Kg are expected.

Clearly, there are immense potential cost advantages to acquiring the bulk of materials for space industry from the moon and the asteroids simply on the basis of savings in transportation costs. However, one must be aware of the differences in elemental distributions between the moon and asteroids and terrestrial demandite. If the demandite evolved for use in space requires a fraction of materials from earth and transport to space costs remain high, then the unit cost of space demandite may be much greater than the costs of retrieving the bulk material from non-terrestrial sources. Naturally, material substitutions can minimize the use of scarce elements; however, this implies extensive research and development, educating the user communities to the new solutions, and possibly severe limitations on the growth of space industry due to the extra money and lead time introduced across segments of the available, knowledgeable and capable terrestrial industrial communities. In order to lend substance to this point, let us examine the use of lunar materials as a source to provide the present terrestrial demandite molecule after it is renormalized to adjust for the elimination of hydrocarbon fuels, but retaining 2% of the hydrocarbon (CH_4) used terrestrially for plastics.

Lunar Materials

Weight fractions of non-fuel demandite are compared in Table 2 with the distributions of elements at three of the Apollo landing sites. Weight fractions are used because the cost of bringing supplemental elements from the earth will be basically proportional to the mass to be transported. Several points are worth noting. Surprisingly, the lunar soil is slightly deficient in oxygen and silicone. However, this is not a basic problem. It is very desireable to consider using liquid oxygen as the major source of reaction mass for inter-orbital vehicles (mass drivers, plasma or ion motors and chemical propulsion systems). Assuming that iron and aluminum and to a lesser extent titanium (in X) and magnesium are interchangeable, then it makes little difference where on the moon one lands. There will be a surplus of metals by as much as a factor of five (A-15 and A-14). Elements important for processing and in agriculture (Ca,Na, S,K,P) are deficient in the lunar soils by factors of 2 to 10. However, even these three sites display large variations (3-5) in elemental concentrations. This suggests that one strategy for supplementing the demandite complement would be to locate lunar regions especially enhanced in one or more of these key elements and beneficiating portions of the lunar fines prior to ejection of the bulk material from the moon. Approximate enhancement ratios necessary to bring Apollo 15 soil fractions up to the needed demandite fractions are given in the second column in Table 3. Remaining elements important in processing, agriculture and plastics (Cl, N, C, H) are present as less than one part in 60 (H) to 4600 (Cl). Again, there are large variations in soil chemistry from one site to the next, but very considerable benefication of various soil fractions would be required to complete these latter deficiencies. It should be remembered that the carbon and hydrogen listed in these tables do not include water or life-stock reserves, but only plastics production.

Costs of Space Demandite

Table 3 reorganizes the Apollo 15 data so as to permit a determination of the cost of a unit of demandite from the Apollo 15 site for two different processing strategies. This exercise will indicate that the costs of demandite in space are still dominated by earth to deep space transport costs. However, the appropriate reaction is to focus on the exact compositions of demandite during various developmental stages of space industrialization, effects of decreasing earth to deep space transport costs, alternate supply sources and materials substitution (R and D costs versus integral transport costs). The following costing examples will serve to promote examination of these alternative studies.

Table 2. Non-fuel Demandite (U.S., 1968) Compared to Elemental Distributions From Three Apollo Lunar Landing Sites (% Weight Fractions)(10)

Element	Non-Fuel Demandite	Apollo 15 Mare-Low Ti	Apollo 16 Highlands	Apollo 14 Basin Ejecta
Si	.2444	.2158	.2107	.2246
O	.4547	.4130	.4460	.4380
Fe	.0479	.1535	.0403	.1036
Al	.0023	.0546	.1438	.0921
Mg	.0017	.0681	.0352	.0571
(Cu,Zn,Pb)	.0020	2.2(-5)[1]	.0001	4.9(-5)
X [2]	.0030 Σ-.0569	.0189 Σ-.2951	.0053 Σ-.2247	.0250 Σ-.2778
Ca[3]	.1417	.0696	.1129	.0771
Na	.0095	.0023	.0035	.0052
S[5]	.0058	.0006	.0006	.0009
K[3]	.0021	.0008	.0009	.0046
P[3]	.0019	.0005	.0005	.0022
Cl	.0147	7.6 (-6)	2.1 (-5)	4.4 (-5)
N[3]	.0083	8 (-5)	8.9 (-5)	9.2 (-5)
C [4] [3]	.0574	9.5 (-5)	1.1 (-4)	1.3 (-4)
H [4]	.0025	6.4 (-5)	5.6 (-5)	8.0 (-5)
Others	.0001	.0023	-[5]	-[5]
	1.0000	1.0000	1.0001	1.0307

[1] (n) = 10^N

[2] X ~ Mn, Ti, Cr, Ba, F, Ni, Ar, Sn, Br, Zr
Ti is dominant element (1.20% A-15; .34% A-16; 1.02% A-14)

[3] Important agriculturally

[4] Concentrated in the smaller grains ($< 50\,\mu$) (11)

[5] Virtually the complete suite of elements are present in these areas, but their contributions (on the ppm and ppb levels) are lost in the errors of the sum over the listed elements.

Table 3. Excesses & Deficiencies over Demandite Weight Fractions for Two Accumulation Strategies for the Apollo 15 Elemental Distribution

Element	Enhancement Required	Bulk Soil (1 unit)		Bedrock Processing (31 units Enhancement)	
		Excess	Deficiency (1)	Excess	Deficiency
Si	1.13	-	.0286	6.445 (2)	-
O	1.10	-	.0417	12.348	-
Fe	.31	.1056	-	4.711	-
Al	.04	.0525	-	1.690	-
Mg	.025	.0664	-	2.109	-
(Cu,Zn,Pb)	90.	-	.0020	-	.0013
X	.15	.0159	-	5.829	-
Ca	2.	-	-.0721	2.016	-
Na	4.1	-	-.0072	.0618	-
S	9.7	-	-.0052	.0128	-
K	2.6	-	-.0013	.0227	-
P	3.8	-	-.0014	.0136	-
Cl	1934	-	.0147	-	.0145
N	103	-	.0085	-	.0058
C	604	-	.0565	-	.0544
H	39	-	.0019	-	.0005
Others	.04	.0022	-	.0712	-
		(+) .2426	(-) .2411 (3)	(+) 30.08	(-) .0765

(1) Formula = -(Wt. Fraction Demandite) + (Wt. Fraction Lunar Element)

(2) Formula = -(Wt. Fraction Demandite) + 31.(Wt. Fraction Lunar Element)

(3) Round-off errors produce the .9% difference in the Excess and Deficiency columns.

Consider the "Bulk Soil" columns in Table 3. One kilogram of Apollo 15 soil will fractionate into 0.76 Kg of demandite and 0.24 Kg extra of oxygen and metals ("Excess" column). Assume the "Deficiency" of 0.24 Kg of demandite is supplied from earth. If the initial costs of acquiring the bulk lunar soil at an industrial plant in deep space is X=20$/Kg, the cost of extracting the demandite fraction is Y=.2$/Kg (the same as metal extraction in the U.S.), and the cost of bulk transportation from earth to the industrial plant is Z=1000$/Kg, then the unit cost of demandite composed of the extract from the bulk lunar soil and the terrestrial supplement will be soil and the terrestrial supplement will be (4) (5)

eq(1)

$$D(\$/Kg)=[X\cdot(\text{Units Refined}-\text{Excess}) + Y\cdot(\text{Units Refined})+Z(\text{Deficiency})]=$$

$$=240\$/Kg \text{ (for above example)}$$

whereas the cost of the excess material will be eq(2)

$$E(\$/Kg)=X+Y=20.2\$/Kg \text{(for above example)}$$

the cost of transporting and processing in space. Thus, the cost of the demandite is governed in this example by earth to deep space transportation costs. If by the year 2000 the lunar to space transport costs drop to 0.1$/Kg and the earth to deep space costs drop to 40$/Kg(8,12) and the processing costs drop to 0.1$/Kg, then demandite (in this example) would cost $D \simeq 9.78\$/Kg$ and the excess materials $E \simeq 0.2\$/Kg$. Thus, the substitution of materials, searches for resources and lower earth/space transport costs must be given high priority.

This example hints that the concept of demandite applicable to mass throughput on the earth (Figure 1 and Table 1) is not directly applicable to industry in space. Excess material in the terrestrial case is generally waste and discarded or dispersed. Figure 2 provides a more appropriate concept of "Space Demandite" and schematicizes the fundamental differences between the terrestrial throughput economy and a develbping space economy (industry and habitation).

In space two new industrial functions must be conducted on a large scale - (1) creation of real estate (i.e. habitats and industrial regions) complete with live-stocks and (2) provision of reaction mass for transportation. All long term human activity in space must be conducted inside massive shielding against solar and galactic cosmic rays. Approximately $4 Kg/cm^2$ of matter (the composition does not matter to first order) must be present between people and deep space. In early habitats which contain only 1 to 100 km^3 of volume shielding will constitute the major mass fraction of bulk material extracted from the moon. Thus, one can imagine that all the bulk lunar material is refined (100% elemental separation) and the separates utilized to (1) complete the demandite formulation, (2) provide reaction mass and (3) be used as cosmic ray shielding and perhaps as refined material for pressure vessels. One proposal for the first space manufacturing facility is for it to be scaled to contain 6,500 people and have a finished product output of approximately 500,000 metric tons/year or 5 space power stations (SPS) a year. Refining the habitat shielding material would provide an early, short term source of the demandite defficiencies. Habitat shielding would constitute approximately $12.5\cdot10^6$ metric tons of bulk material is provided from the moon over a 5 year period. Assume it is processed to remove the maximum amounts possible of the deficient elements in column 3 of Table 3. If this is done then we find that in order to convert one part in 3^1 of this refined material into terrestrial demandite (i.e., 500,000 metric tons) we must export from earth 0.8 parts (40,000 metric tons of Cu, Zn, Pb, Cl, N, H and C) of the definciency elements in column 6 of Table 3 to supplement the demandite molecule. Using the same values as in the previous example for transport and refining costs we find for this strategy of completely refining the bulk materials for the deficient elements that:

$$D(\$/Kg)=(20\$/Kg)(31-30.08)+0.2\%/Kg(31) +(10^3\$/Kg)\cdot(0.08\ Kg)=$$

$$\simeq 104\$/Kg$$

and as before the cost of excess materials

$$E(\$/Kg)=20.2\$/Kg.$$

The effects of decreasing lunar (.1$/Kg) and terrestrial launch costs (40$/Kg) and processing costs (.1$/Kg) result in demandite costs of D = 6.30$/Kg and refining costs and transport costs would be approximately the same.

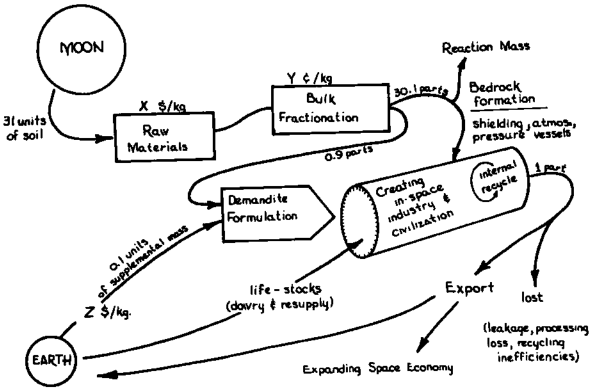

Figure 2

To summarize, $15\cdot10^6$ metric tons of lunar materials, supplemented by 40,000 tons of terrestrial exports will supply: (1) 500,000 metric tons of terrestrial demandite in deep space, (2) $12.5\cdot10^6$ metric tons of shielding and (3) $3\cdot10^6$ metric tons for reaction mass and/or production of specialized goods not requiring the terrestrial demandite fraction in their production. Figure 2 should show 4-6 parts or units of exportable mass exiting the industrial cylinder (1 part demandite, 3-5 parts metals, oxygen, etc.) and 1 to 3 units of matter being used as reaction mass.

Conclusion

Applying the demandite concept to space industry forces us to reexamine in detail the underpinnings of modern industrial societies. It is useful to reinterpret Table 1(Terrestrial Demandite) for a space economy compatible with Figure 2.

Table 4

CAPITAL (Long Duration Items)

Bedrock - Habitats, Transports, Energy Collectors, Deposits for Momentum, Angular Momemtum, Kinetic Energy, Thermal Inertia, Reserve Stocks, etc.

Life Stocks - Atmosphere, Water, Recycling biomass.

THROUGHPUT (Items used Immediately)

Demandite - Items in habitats, export materials, recycle losses, etc.

Reaction Mass - Dependent on energy/unit ejected mass and power source mass/unit of energy produced for propulsion.

In this formulation we must view everything as a flow of matter driven by solar energy and organized directly or indirectly by human skill. The basic difference between bedrock, life-stocks and demandite is one of duration of usage of identifiable items or products. Bedrock and life-stock items should generally have a longer existence or period (T) of identity than that (t) of demandite items and reaction mass. The loss of materials in processing, recycling and as reaction mass probably places fundamental limits on the ratios of these four categories of mass. Determination of the limits would be very useful in defining the limits on space habitation. For example, a space community typified by a particular rate of demandite usage could be spread over a wider range of gravitation potential differences as the energy per unit mass of the rocket systems used to transport goods and raw materials increased. Or, conversely, the communities'throughput of demandite·could increase. An especially interesting problem is to determine the maximum ratio of life-stock to bedrock mass and to the rates of flow of demandite and reaction mass. Tables 1 and 2 should be carefully reviewed in terms of schemes for the chemical processing of lunar and asteroidal materials and the production of final products, especially bedrock and life-stocks. One must identify alternate production techniques which avoid the use of scarce elements. Also, the refining strategies must be optimized to minimize total demandite costs in terms of terrestrial and non-terrestrial components. Earth to deep space transport costs should be continually decreased. High priority should be given to locating sources of the life-stocks and elements which are deficient in lunar demandite. The asteroids, lunar polar regions and possibly material located at the L-4 and L-5 points should be investigated (R. Vondrack - this conference).

Sources of early industrial operations in space do not depend on the creation of a "cheap" source of demandite. Economic profits from space solar power can be anticipated to be sufficiently great to pay for the transport from earth of the necessary supplemental elements (example - Table 2). In addition, the supply of certain elements (Ni, Fe, Cu, Zn) from the asteroids to terrestrial markets may be economically attractive in the next decade(7). Application of the concepts of demandite, bedrock, life-stocks and reaction mass descriptions of space economies will aid in determining under what conditions a self-sufficient economy becomes possible in space.

The concept of demandite is useful not only in focusing attention on particular problems in preparing for space habitation/manufacturing, but also because it is clear that the answers to these questions will be extremely valuable in revising the terrestrial economy as the age of petroleum energy comes to an end. It may well be that the flow of innovative information back to earth on how to work with matter at all scales under a new set of conditions will be of far greater economic and cultural value than even the enormously valuable streams of solar energy which could be transmitted from space. Operations in space provide a defined and rigorous environment within which to create the gigantic test tubes necessary to develop complete control over the creation of abodes of life, industry and the next expansive advance in human culture.

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Acknowledgement

It is a pleasure to acknowledge the discussions with Drs. W. Phinney (Johnson Space Center), P. Vijk (Science Applications, Inc.) and J. Arnold (Univ. Calif. San Diego) and Mr. G. Driggers (Southern Res. Inst.) which contributed to the final form of this paper, to Mr. Kinsler for preparation of the figures and to Mrs. D. Brandt for typing of the manuscript. This is Lunar Science Institute contribution #276. The Lunar Science Institute is operated by the Universities Space Research Association under contract number NSR 09-051-001 with the National Aeronautics and Space Administration. The author gratefully acknowledges the travel support provided through Princeton University which made possible his participation in this conference.

DISCUSSION

Q. Do you have ideas as to how to get raw material cost down to 20¢ per kilogram?

A. The long-range costs can be brought down to less than $1 per kg. using lunar mass drivers produced in space, perhaps by the 2nd or 3rd generation. There are also Earth-approaching asteroids which may be a very cheap source of mass, as will be discussed by O'Leary later, which might drop the cost to 20¢ kg. And that would be for the first 100-meter asteroid returned to Earth/Moon space. Later generations of asteroid retrieval systems might decrease the costs to fractions of a cent per kilogram and deliver total tonnages comparable to the total usage of materials in the United States per year.

Q. Why did you omit hydrogen from your lunar materials consideration? It seems to be quite a critical element.

A. Demandite is a molecule that is based on a terrestrial context. I did not mean that demandite used in industry on Earth would be the same as the demandites used to build space facilities and colonies (bedrock demandite), or that "through-put" demandite can be expected to most closely resemble terrestrial demandite initially. For all practical purposes it is necessary to develop immediately means to recycle hydrogen in each habitat, unless an extremely cheap source of hydrogen is developed. Therefore, the hydrogen supply to a habitat must be viewed as a input to the dowry of the habitat, and not as a component of non-renewable demandite.

Q. I'm surprised demandite doesn't have water in it.

A. The terrestrial demandite was defined for nonrenewable materials.

Q. Somewhere, it seems, you have increased the processed mass by at least an order of magnitude. You quoted a factor of 30 to 1 between the generation of the SPS and the total input in the factory. Last year another study used a 30% yield on raw material for construction, or 450,000 tons, 90,000 tons of which went to the SPS, and some additional materials brought from the Earth to complete the SPS. Above and beyond that, there were excess materials and oxygen at a 3 to 1 ratio. That's not 30 to 1.

A. I was referring to first-year conditions, where one can use the 125 million metric tons of materials required for radiation shielding as a source from which to obtain the needed "trace" elements in the demandite molecule, rather than bringing the deficient elements from the Earth. This is practical if your recovery costs for the missing elements are lower than the transport costs from Earth, and if the processing through-put rates are sufficiently large to meet annual needs for these "trace" elements.

Q. This point illustrates the complications of the program. You suggest generating the required shielding and habitat during the time when the SPS is being used initially. In the other study, the capability was being used to build up a factory to go into fullscale production. You are correct for the first year; after that your 30 to 1 becomes a factor of 3 to 1. Of course, the impact of economics is tremendous.

A. There is a growth phase, which may or may not be considerably longer than a year, in which the shielding can be used as a source from which the full complement of the demandite molecule can be formed. In the steady state case one must provide a source of elementally enriched grain fractions, either from the Moon or from the asteroids.

Q. The demandite for the Solar Power Satellite (SPS) is well defined now. How does it compare with terrestrial demandite?

A. The point of demandite is that it is defined not for one particular product, but for a complete variety of products to be produced in space. This is the whole space industrialization concept. We would expect these materials to differ from terrestrial demandite. Thus, it's a long range concept which goes well beyond any one product. I was surprised, for example, to find that sulfur was in short supply terrestrially, and therefore its supply from Earth would greatly increase the average cost of demandite over the nominal costs of launching materials from the Moon.

Q. According to a recent paper by W. Ward, the lunar axis of rotation has in geologic time been tilted up to 77°. What bearing does this have on the possibility of finding volatiles in polar craters?

A. That would have occurred when the Moon was closer to the Earth; perhaps 34 Earth radii. The Moon is presently 60 radii away. The present rate of recession would indicates 4.6 radii 5 x 10^9 years ago, and other data exist to suggest the Moon was 57 radii away in Cambrian times (5 x 10^8 years ago). This indicates the Moon went through most of its axis change perhaps 3 x 10^9 years ago, and this is what I'm basing my study on. It may be only 10^9 years ago, but that is unlikely. It would only change my estimate by a factor of three.

Q. What physical forms would the lunar polar ices take, and could they be retrieved?

A. I estimate 10^{17} grams, which means a meter of solid water ice. From gardening models we expect to find it mixed with 2 or 3 meters of lunar soil. The material would be about 40 K - clearly solid. These materials could be retrieved easily.

Q. Would metallic ores be in the form of domes, caves or other features?

A. This is not known. We can only speculate. In the summer study this year we hope to consider this, but we won't know until we look.

Q. Micrometeor impacts tend to stir and cover the ice material, but also to evaporate it. How do these effects compare?

A. They are both constructive and destructive. Each impacting micrometeor volatizes a few times its mass. Some of the ice ejecta may recondense. You garden 10^3 - 10^6 times the mass, and this helps to bury it safely.